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Benefits and Motivation of Spaceflight

A Comprehensive Assessment of its Present and Future Potential

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Preface

The origin of this work can be traced back to the late 1960s, when Harry O. Ruppe, former member of Wernher von Braun's team at Huntsville and founder of the Department of Astronautics at the Technical University of Munich (TUM), wrote the contribution "Astronautics: An Outline of Utility" in the book series "Advances in Space Science and Technology".

Ruppe's approach to the utilization of spaceflight made a strong impression on Robert H. Schmucker, his very first graduate, and then, close associate, at the Department of Astronautics in Munich. In 1990, Schmucker started a lecture on "Benefits, Civil Applications and Commercialization of Spaceflight" at the TUM, which shifted the focus from physical feasibility to the commercial application of spaceflight.

More than 10 years with new developments and insights had passed when Schmucker asked me for a reconsideration of the topic. This was done from a new perspective, but also taking into account the earlier insights and the experiences of almost 5 decades of actual spaceflight. The first results were quite unexpected, and soon, a completely new approach to the benefits of spaceflight emerged – though it still relied on the underline of engineering feasibility and commercial realism that were introduced both by Ruppe and Schmucker.

Abstract

Spaceflight is subject to two dominating characteristics: On the one hand, the word “space” alone inspires awe in the majority of the population. On the other hand, spaceflight – manned and unmanned – is extremely expensive.

And because these high costs are primarily covered with public funds, spaceflight is questioned for its cost-benefit-ratio. This regards manned as well as unmanned spaceflight: The discussion about manned flights exists only within the space community, concerning the distribution of existing budgets. But as soon as laymen are confronted with the actual numbers that are spent for any space activities, it is difficult to justify that these funds are used for spaceflight instead of other projects.

For the space enthusiasts, it is important to take one step back and analyze the current and potential future situation from an outside view, concerning the efforts that are required for spaceflight, the benefits that spaceflight can give, and the motivation of elements of society to actually realize spaceflight. This leads to a new evaluation of spaceflight: The efforts must be weighed against the expected benefits. If they outweigh the efforts, motivation to realize spaceflight is given.

Efforts are divided into transportation *to* space, and the hardware and operations *in* space. Both combined create a minimum threshold of efforts and costs that must be crossed before any activity can be done in space. Detailed analysis shows that this threshold is very high and will remain so in the future. Therefore, only actors with sufficient financial potential can actually realize spaceflight – wishful thinking of single space enthusiasts is irrelevant.

Following this approach, expected benefits are divided into four categories in this thesis: Subjective benefits, benefits that are created as a byproduct, quantifiable benefits, and potential benefits. In this thesis it turns out that:

1. Subjective benefits cannot be weighed against the required efforts. Their identified meaning as a pro-spaceflight argument mirrors the present civil spaceflight situation that depends on governmental funding (‘idealistic spaceflight’).
2. Quantifiable benefits are the key to extensive spaceflight activities (‘commercial spaceflight’). Profit oriented companies are the decisive actors. But detailed analysis shows that only very few promising topics exist.
3. The identified importance of randomly generated byproducts of spaceflight is quite different than usually suspected.
4. Potential benefits of risk prevention were, and still are, the most important category of benefits, with a higher meaning for every human than commonly suspected (‘preventive spaceflight’).

Spaceflight with its unique global characteristics enables numerous significant contributions that no terrestrial alternative can offer, and clearly is imperative for an ensured positive future development.

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List of Nomenclature, Indices, Acronyms

Nomenclature

a	Acceleration
A	Area
B	Bandwidth
B	Benefits
c	Coefficient
c	Engine exhaust velocity
c	Specific costs
c	Specific heat capacity
c	Speed of light
C	Channel capacity
C	Costs
d	Diameter
e	Specific energy
E	Efforts
E	Energy
f	Fraction
f	Frequency
F	Thrust force
$\vec{F}$	Directed force
G	Growth factor
g_0	Earth standard gravity (9.80665 m/s^2)
h	Altitude
h	Enthalpy
H_i	Heating value
I	Impulse
I	Investment
k	Factor
l	Length
L	Lift force
m	Mass
$\dot{m}$	Mass flow
M	Motivation
n	Number
N	Noise
p	Specific power
P	Power
P	Price
P	Probability
P	Profit
r	Radius
r	Rates
r	Ratio

R	Revenue
R	Universal gas constant
s	Distance
s	Market share
s	Thickness
S	Signal strength
S	Surface area
t	Time
T	Temperature
T	Turnover
v	Velocity
V	Volume

α	Thermal expansion coefficient
γ	Specific heat ratio
Δ	Increment
ε	Visible angle
η	Efficiency
λ	Wavelength
ρ	Density

Indices

0	Initial
a	Air
abp	Air breathing propulsion
ann	Annual
ant	Antenna
asc	Ascent
atm	Atmosphere
ave	Average
be	Break even
bu	Business
c	Combustion chamber
cir	Circular
$class$	Vehicle class
con	Control
con	Converter
com	Commercial
cra	Crater
D	Drag
del	Delivered
dev	Development
dis	Disposal
e	Exit
E	Earth
$E\text{-}M$	Earth to Moon

energy	Energy
exp	Expendable
f	Final
fu	Fuel
gra	Gravity
h&o	Hardware and Operation
H2O	Water
hab	Habitable
HLW	High level waste
i	Index
i	Stage
id	Ideal
ill	Illuminated
img	Image
ind	Induced
imp	Impact
kin	Kinetic
L	Lift
l/o	Launch operations
lau	Launch
los	Losses
M	Moon
max	Maximum
min	Minimum
mir	Mirror
mis	Mission
mol	Molar
NEO	Near Earth object
net	Net
nuc	Nuclear
o	Operation
obj	Object
obs	Observation
ODE	One dimensional equilibrium
OF	Oxidizer and fuel
orb	Orbital
out	Output
p	Payload
pax	Passenger
pow	Power
pr	Propellant
r/r	Recovery and refurbishment
re	Return
rx	Receiver
req	Required
res	Resolution
reu	Reusable
roc	Rocket

S-E	Sun-Earth
safe	Safety
sat	Satellite
SatV	Saturn V
sol	Solar
sp	Specific
SPS	Solar power satellite
STS	Space transportation system
sur	Surface
tx	Transmitter
tot	Total
tr	Transportation
vac	Vacuum
veh	Vehicle
vis	Visible
yr	Year

Acronyms

^{3}He	Helium 3 Isotope
A/C	Aircraft
A.D.	Anno Domini
ADAC	Allgemeiner Deutscher Automobil-Club
APM	Attached Pressurized Module
ATO	Abort To Orbit
ATV	Automated Transfer Vehicle
Av.	Average
B.C.	Before Christ
BFO	Blood Forming Organs
BGD	Bangladesh
BMD	Ballistic Missile Defense
CG	Center of Gravity
CIA	Central Intelligence Agency
Com	Communication
Comm.	Commercial
ComSat	Communication Satellite
COTS	Commercial Orbital Transportation Services
CPI	Consumer Price Index
CSM	Command and Service Module
CSTS	Crew Space Transportation System
D	Deuterium
DARPA	Defense Advanced Research Projects Agency
DBS	Digital Broadcasting Services
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DoD	Department of Defense
E-ELT	European Extremely Large Telescope
e.g.	Exempli Gratia (‘for example’)

ELV	Expendable Launch Vehicle
ESA	European Space Agency
ESO	European Southern Observatory
ETI	Extraterrestrial Intelligence
EU	European Union
EUR	Europe
EVA	Extravehicular Activity
FAI	Fédération Aéronautique Internationale
FRA	France
FSS	Fixed Satellite Services
FY	Fiscal Year
G	Giga (billion)
GCR	Galactic Cosmic Radiation
GDP	Gross Domestic Product
GEO	Geostationary Orbit
GLONASS	Global Navigation Satellite System
GMES	Global Monitoring for Environment and Security
GNI	Gross National Income
GPS	Global Positioning System
GTO	Geostationary Transfer Orbit
H_2	Hydrogen
HLW	High Level Waste
HNWI	High Net Worth Individual
HST	Hubble Space Telescope
HTV	H-2 Transfer Vehicle
ICBM	Intercontinental Ballistic Missile
IND	India
INT	International
IRBM	Intermediate Range Ballistic Missile
ISR	Intelligence, Surveillance, Reconnaissance
ISRO	Indian Space Research Organisation
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPN	Japan
JWST	James Webb Space Telescope
k	Kilo (thousand)
L1, L2, L3, L5	Lagrange Points 1, 2, 3, 5
LEO	Low Earth Orbit
LH_2	Liquid Hydrogen
LM	Lunar Module
LORL	Large Orbiting Research Laboratory
LOX	Liquid Oxygen
LRO	Lunar Reconnaissance Orbiter
M	Mega (million)
MDA	Missile Defense Agency
MEO	Medium Earth Orbit
MER	Mars Exploration Rover
Milspace	Military Spaceflight

mod.	Modified
MORL	Manned Orbital Research Laboratory
MOVE	Munich Orbital Verification Experiment
MRO	Maintenance, Repair, Overhaul
MSL	Mars Science Laboratory
MSS	Mobile Satellite Services
MTFF	Man-Tended Free-Flyer
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
Nav	Navigation
NCO	Network Centric Operations
NEO	Near Earth Object
NNSI	NASA New Start Index
NOAA	National Oceanic and Atmospheric Administration
NRO	National Reconnaissance Office
PAK	Pakistan
PHO	Potentially Hazardous Object
PPF	Polar Platform
PRC	People's Republic of China
Pu	Plutonium
RLV	Reusable Launch Vehicle
RUS	Russia
SEI	Space Exploration Initiative
SETI	Search for Extraterrestrial Intelligence
sl	Sea Level
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPE	Solar Particle Event
SPS	Solar Power Satellite
SRB	Solid Rocket Booster
SRBM	Short Range Ballistic Missile
SSME	Space Shuttle Main Engine
SSO	Solar Synchronous Orbit
SSS	Satellite Support Structure
SSTO	Single Stage To Orbit
SU	Soviet Union
Suborb	Suborbital
T	Tritium
TLI	Trans Lunar Injection
TRS	Teleoperator Retrieval System
TSTO	Two Stage To Orbit
U-235, …	Uranium Isotopes
UK	United Kingdom
U.S.	United States
USA	United States of America
USAF	United States Air Force
USSR	Union of Soviet Socialist Republics
US-STS	United States Space Transportation System (Space Shuttle)
VSE	Vision for Space Exploration

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“It means nothing to me. I have no opinion about it, and I don't care.”

Pablo Picasso
1881 – 1973
(On the first Moon landing)
The New York Times, July 21, 1969

1. Introduction and Overview

This work offers new insights on the historical development, the current status, and the expected future direction of spaceflight. The first chapter states the basic problem that is to be solved and gives an overview of how this is to be achieved.

1.1 The Fundamental Problem of Spaceflight

The word *spaceflight* is equivalent to high technology, future, and inspiration. People who are related to spaceflight in any way enjoy a high reputation, no matter if they are astronauts, engineers, technicians, or others. Space also has a high standing in our culture, with literature full of examples for space related tales and descriptions, ranging from educational books about astronautics for every age to the most incredible science fiction. In short: Spaceflight is fascinating.

But spaceflight also is extremely costly. This is true for unmanned activities, and even more for manned flights. Spaceflight still is an endeavor that is mainly financed by the government, and therefore by the taxpayer. This requires clear and understandable justifications for these expenditures. A way to justify space activities[1] is by finding clear **benefits** that outweigh the required efforts of spaceflight. This way, promising topics for future space activities may also be identified, thus allowing clear statements concerning the current situation and the potential future of spaceflight.

Many analyses from a social perspective were done about the pros and cons of spaceflight in the past years. But the actual realization of spaceflight is not primarily subject to social reasons, but to technical and economic restrictions: Proposed missions must be *technically feasible*, and someone has to *pay* for them. An engineer's approach that identifies the mentioned restrictions and the required efforts, as it is done in this study, could enable a new understanding of spaceflight, and justify the efforts by finding clear and convincing benefits of spaceflight.

To identify these benefits, a disambiguation of the word 'benefits' is recommended to clarify the use of this word for further considerations.

Benefits: The positively interpreted results of an activity.
Type and scale of the results are arbitrary.
Every space activity creates certain benefits for *someone*.[2]

This leads to a central question: Which are the benefits that are to be gained from spaceflight?

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[1] "Space activity" is not the perfect phrase, nor are other phrases like "activity in space", "space mission", "spaceflight topic", "utilization of space" and "application in space". These phrases are further used for any imaginable topic that creates potential benefits by the use of spaceflight: Exploration, spin-off, satellite navigation, tourism, resource mining, asteroid deflection, surveillance, …

[2] The engineer who designed the spacecraft, for example, is paid for his job – a personal benefit.

The postulated need for further considerations is comprehensible with the following comparison of two space projects with a non-space program.

1.1.1 Exemplary Space Projects

Two current examples may underline the current problematic situation of spaceflight: The proposed mission BepiColombo to the planet Mercury and the unmanned European Automated Transfer Vehicle (ATV) that is used to supply the International Space Station (ISS).

1.1.1.1 BepiColombo – Mission to Mercury

BepiColombo is a planned combined mission of the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA). It consists of two spacecraft that are to be launched together in 2013. After some years traveling to the solar system’s innermost planet Mercury, they will both enter a Mercury orbit and conduct scientific operations. As of January 2008, the total BepiColombo investment is estimated at 965 M € (at that time 1.415 M $).[3]

For this investment, detailed data about Mercury’s magnetosphere can be expected, as well as new high quality images of the planet’s surface. This will complement the data delivered by the MESSENGER spacecraft of the National Aeronautics and Space Administration (NASA) that made its first flyby of Mercury in early 2008 and will enter Mercury orbit from 2011 on.

Though this is certainly good news for the planetary scientists community, the BepiColombo mission might be seen from other perspectives, too:

- Relevance of data about Mercury’s magnetic field to others than a handful of planetary scientists?
- Need of additional (identical?) data besides the MESSENGER mission?
- Need of high resolution maps of Mercury’s surface (no one would map Antarctica or a remote desert on Earth with high resolution)?

Even more important is the financial side:

- The estimated costs of BepiColombo are equivalent to those of almost 20 000 kindergarten places over 10 years.[4]

It is important for spaceflight enthusiasts to be aware of these concerns and not to ignore them. If national space programs want to be sure of enduring public support, public funded space missions must be justified by arguments that are clear and understandable for everyone, and not only for spaceflight enthusiasts.

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[3] Space News 3-2008.

[4] Assuming costs of 5 000 € per child and year.

1.1.1.2 ATV – Space Station Supply Vehicle

The ATV is designed as an unmanned cargo delivery vehicle to supply the ISS, similar to the Russian Progress vehicle. So far, 1.9 G $ were spent by ESA nations on ATV development, including the cost of the first launch.[5] With a cargo load of 8 300 kg for the first ATV mission,[6] this is a specific cost of almost 230 000 $ for every single kilogram that is transported. Costs of subsequent missions are estimated at about a third – that is 80 000 $/kg – because development costs are regarded only at the first flight.

For these costs, a comparatively simple objective is achieved: Cargo is delivered to the very closest destination in space – Low Earth Orbit (LEO). Just for comparison: The cost for worldwide air mail, such as sending a 20 kg package from Europe to Australia, currently is about 15 $/kg.

1.1.2 Non-space Program: Automotive Sector

For a modern luxury segment car, the development cost including production facilities is between 1 and 2 G €. For a compact executive car, it is even higher, being between 2 and 4 G € (numbers in $ are respectively higher).[7] These costs are comparable with the previously mentioned two space programs.

But the development of new generations of automobiles is not subject to critical discussions about benefits. It is simply done, predominantly without the need of public funding.

1.1.3 Identification of the Fundamental Problem

Both mentioned spaceflight projects create benefits, as do the exemplary automotive programs. But while investments in space projects are soon subject to criticism, other programs are not – they are seemingly done without second thoughts.

This is due to a simple reason: Return of investments. If a return is expected that seems to justify the investments, then the endeavor is undertaken. This is the **motivation** to actually do projects. The return can either be objective and clearly measurable (sales, revenues, …), or subjective and difficult to measure (scientific insights, cultural effects, …).[8] Thus, ‘motivation’ can be defined for further use:

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[5] Space News 5-2008.

[6] ESA 2007.

[7] Schirmer, personal conversation.

[8] This classification is similar, but not identical, to the existing distinction between utilitarian and trans-utilitarian ends of spaceflight. (Gethmann et al. 1993, Gethmann 2006) Science is seen as utilitarian in literature, but here it is seen as subjective, as the previous example of BepiColombo illustrated.

Motivation: The willingness to actually do something (and pay for it). Motivation is given if a sufficient return of investment is expected. Motivation of the executor is required to actually *realize* a proposed project.

It is important to understand that – with regard to motivation – the total cost of a project is secondary, as will be proven later. To answer the question "Is it worth?", the efforts or costs of a venture (that must be seen as a primary investment) need to be matched against the expected benefits (that must be seen as a return of investment). This is as true for spaceflight as for any other area, while the efforts for space seem to be higher than for terrestrial activities, and the obvious returns seem to be lower. **Figure 1-1** further illustrates this.

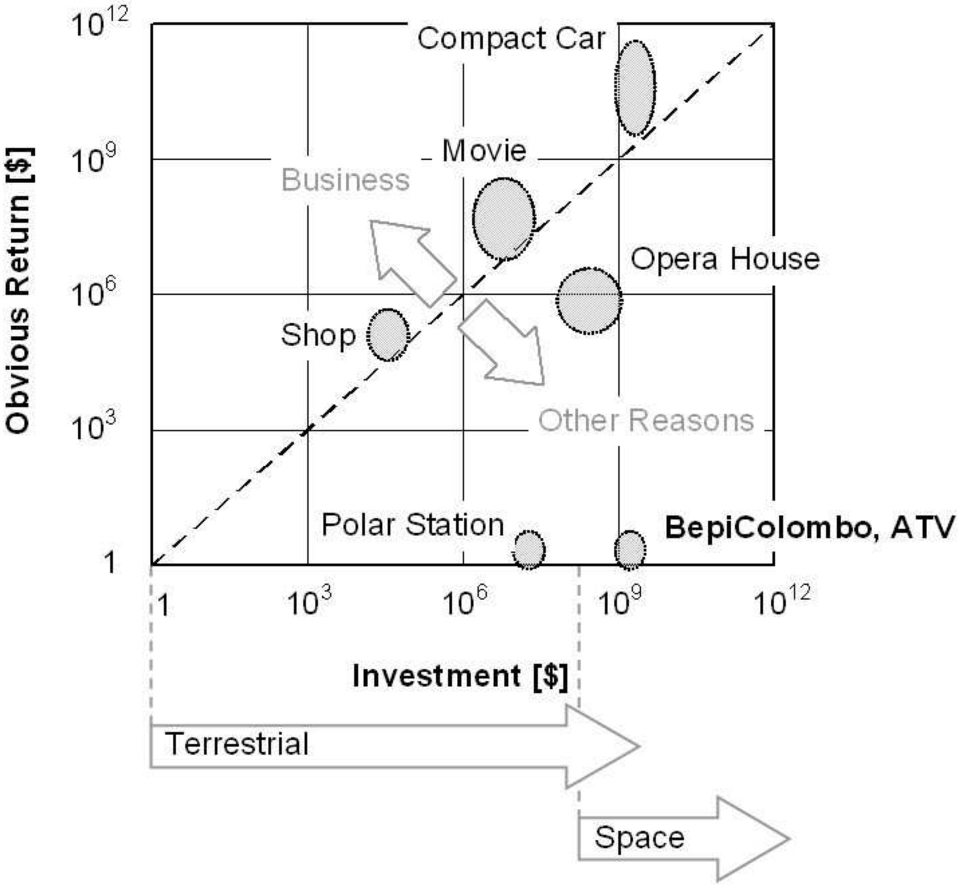


Figure 1-1: Return of Investment

With this, instead of the previously postulated question for the benefits of spaceflight, it seems sensible to solve a more fundamental problem for any spaceflight activity:

What is the motivation for spaceflight?

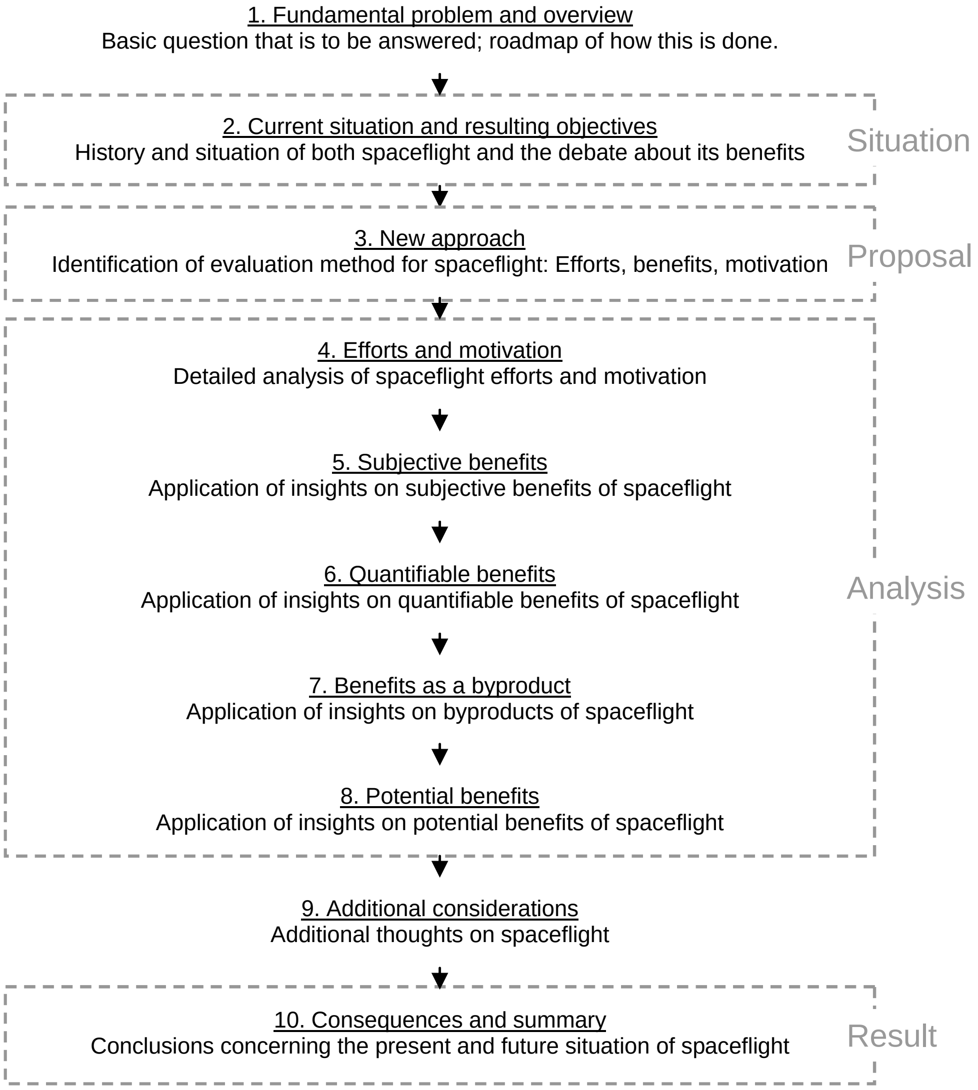
Finding an answer to this question is the fundamental problem of all proposed space activities. The answer allows conclusions on the future development of spaceflight.

1.2 Overview

The fundamental problem is to be solved in four steps:

- Identifying the current situation
- Proposing a new approach
- Analysing the identified items with the new approach
- Summarizing and discussing the results

The structure of contents is illustrated in **Figure 1-2**.



1. Fundamental problem and overview
Basic question that is to be answered; roadmap of how this is done.

2. Current situation and resulting objectives
History and situation of both spaceflight and the debate about its benefits

3. New approach
Identification of evaluation method for spaceflight: Efforts, benefits, motivation

4. Efforts and motivation
Detailed analysis of spaceflight efforts and motivation

5. Subjective benefits
Application of insights on subjective benefits of spaceflight

6. Quantifiable benefits
Application of insights on quantifiable benefits of spaceflight

7. Benefits as a byproduct
Application of insights on byproducts of spaceflight

8. Potential benefits
Application of insights on potential benefits of spaceflight

9. Additional considerations
Additional thoughts on spaceflight

10. Consequences and summary
Conclusions concerning the present and future situation of spaceflight

Figure 1-2: Structure of Contents

Chapter 2 illuminates the current situation of both spaceflight itself and the debate about its benefits. In a first step, the historical development of spaceflight up to the present situation is presented, followed by a view on previous assessments concerning benefits of spaceflight. Subsequently, the actual historical driving factors of spaceflight are identified. The resulting insights are then used to identify shortcomings and to clearly define the objectives of this work.

In chapter 3, the basic characteristics of spaceflight are stated. With this, a new approach to the assessment of spaceflight is derived that requires a detailed analysis of the three elements 'efforts', 'motivation' and 'benefits'.

Chapter 4 analyses the efforts and motivation for spaceflight in detail as a basis for further considerations. Efforts are separated into transportation to space and hardware&operations in space. After that, entities that might actually do spaceflight are identified as well as their motivations and capabilities to do large scale projects. Finally, four categories of benefits are identified: 'Subjective', 'quantifiable', 'byproducts', and 'potential'.

In chapters 5 to 8, the insights of chapter 4 are applied on the four categories of benefits to identify the motivation for actual realization of future spaceflight activities.

As a parenthesis, chapter 9 offers additional considerations that should also be taken into account.

Finally, chapter 10 summarizes the previous results and states the consequences, thereby classifying spaceflight in the three categories 'idealistic', 'commercial' and 'preventive'. The past and current meaning as well as the expected future development of each category is stated.

The current situation must be known to identify the required direction of the detailed analysis. Therefore, some basic questions about the motivation for spaceflight should be answered in the next paragraph (chapter 2) prior to further considerations:

- What is the history of spaceflight up to the present day?
- What were the results of previous works about the benefits of and motivation for spaceflight, and what is the current situation of the debate?
- What were the actual driving factors for spaceflight development?
- What is the true current situation of spaceflight?

The answers to these questions lead to clearly defined objectives for further analysis.

2. Situation of Spaceflight and its Motivation

After a short parenthesis about the general difficulty of predictions, this paragraph gives an idea of the current situation of spaceflight to understand the required direction of analysis. The history of spaceflight is presented, followed by an overview of the historical development of the debate about benefits of and motivation for spaceflight. After that, the true driving factors of past space activities are identified. Finally, the resulting objectives for further analysis are set.

2.1 The Difficulty of Predictions

Prediction of future events always proved to be difficult throughout history.

A) General Predictions

Humans have always wondered what developments the future would bring, and the number of historical predictions concerning every aspect of cultural, political, social, economical, technological, even biological developments, reaching from a timeframe of months to millennia, is infinite. Most of them proved to be wrong:[9]

- "...so many centuries after the Creation it is unlikely that anyone could find hitherto unknown lands of any value." – Committee advising King Ferdinand and Queen Isabella of Spain regarding a proposal by Christopher Columbus, 1486
- "The invention of aircraft will make war impossible in the future." – George Gissing, 1903
- "Airplanes are interesting toys but of no military value." – Marechal Ferdinand Foch, Professor of Strategy, Ecole Superieure de Guerre, 1904
- "Who the hell wants to hear actors talk?" – H. M. Warner, co-founder of Warner Brothers, 1927

But while the unpredictability of political or social events lies in their nature, because they are strongly influenced by human decisions and coincidences, the situation on the field of technology may be slightly different. Technology always follows the laws of physics and mathematics. The actual use and application of technology is a social topic, though.

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[9] Wikiquote 2006.

B) Technological Predictions

The present technological situation was never predicted. Technologies such as television, internet or satellite navigation were never forecast. Some quotes regarding future technological developments are amusing from today's perspective:[10]

- "I will ignore all ideas for new works on engines of war, the invention of which has reached its limits and for whose improvements I see no further hope." Sextus Julius Frontinus (40 – 103)[11]
- "What can be more palpably absurd than the prospect held out of locomotives traveling twice as fast as stagecoaches?" – The Quarterly Review, March, 1825
- "Heavier-than-air flying machines are impossible." – Lord Kelvin, British mathematician and physicist, president of the British Royal Society, 1895
- "That the automobile has practically reached the limit of its development is suggested by the fact that during the past year no improvements of a radical nature have been introduced." – Scientific American, January 2, 1909
- "That Professor Goddard with his 'chair' in Clark College and the countenancing of the Smithsonian Institution does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react – to say that would be absurd. Of course, he only seems to lack the knowledge ladled out daily in high schools." – New York Times, January 13, 1920
- "Where a calculator on the ENIAC is equipped with 18 000 vacuum tubes and weighs 30 tons, computers in the future may have only 1 000 vacuum tubes and weigh only 1.5 tons." – Popular Mechanics, March 1949

These quotes were related to developments that were not subject to physical laws. No law prohibited the lift effect of wings, no law stated that the sound barrier could not be breached as was widely believed in early times.

The spaceflight pioneer Eugen Sänger published an interesting example of spaceflight prediction in his book "*Raumfahrt – technische Überwindung des Krieges*" (1958).[12] The rapid development of the past decades convinced him of a continuous pace of technical development as seen in **Figure 2-1**.

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[10] Wikiquote 2006.

[11] Brainyquote 2006.

[12] Sänger 1958.

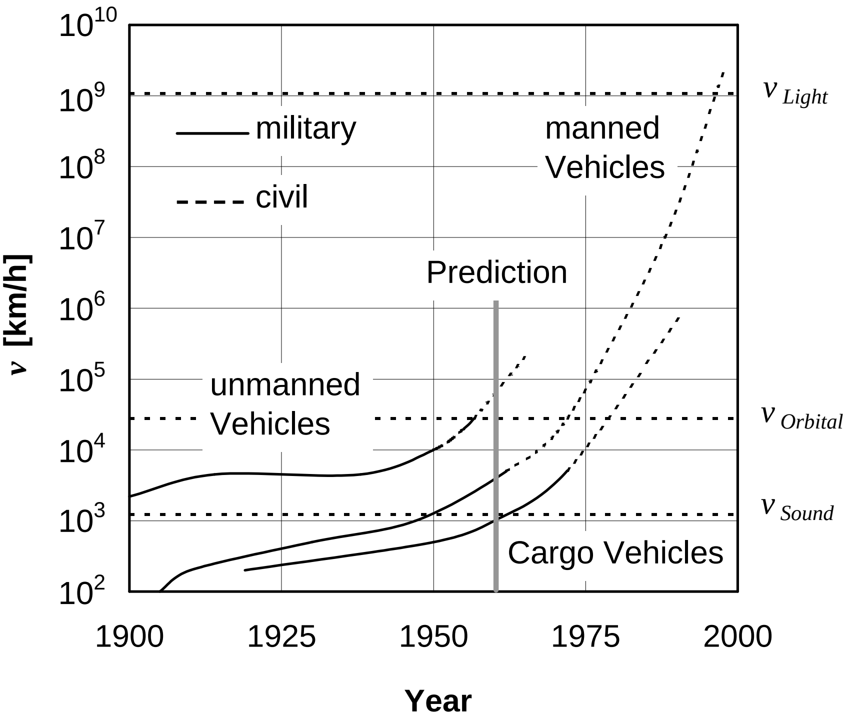

Figure 2-1: Historical Spaceflight Prediction[13]

But if a physical law and a mathematical equation give a straight “no” as an answer, it must be accepted that the proposed development will not be realized. This approach must be the underline of analysis: If an equation shows that something is not feasible, it must be ruled out.

C) Cost Predictions

Prediction of costs is the attempt to describe exact attributes of something that does not yet exist. Therefore, exact predictions are impossible – only educated guesses concerning orders of magnitude can be done.

Nonetheless, cost estimations are often given in exact numbers to underline their respectability and reliability, with true costs in the end differing significantly from early estimations. Examples are presented in **Table 2-1**.

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[13] Sänger 1958.

Table 2-1: Various Cost Predictions

Topic	Costs [M $]		False Estimation by Factor of
	Estimated	Actual/Present	
Interplanetary Rocket	0.0017*[14]	ca. 1 000	> 500 000
Manned Mars Expedition	2 000*[15]	ca. 400 000	200
US-STS per Launch	22.4[16]	1 000[17]	45[18]
Sydney Opera House	7	102	15[19]
ISS	8 100[20]	100 000[21]	12
V-22 Osprey Development	2 500	30 000	12[19]
JWST Telescope	500[22]	4 500[23]	9
Munich Olympic Stadium Roof			8[24]

* Early estimations by Wernher von Braun (1920s and 1950s).

Total cost C_{tot} is usually estimated by addition of numerous estimated costs C_i:

$$C_{tot} = \sum C_i \tag{2.1}$$

The costs C_i are normally estimated at the lower limit, and some costs are not considered because they are yet unknown. This leads to inevitable cost increase at project realization.[25]

D) Conclusions

Einstein vividly taught us that even the presently accepted truth about physics is not necessarily the absolute truth. New engineering approaches might also eventually evade physical laws in a way not yet foreseen. These thoughts should always stay in the mind while dealing with predictions, even if they seem well reasoned. The Club of Rome, for example, failed with many of its predictions made more than 30 years ago.[26] To use a statement that is often attributed to Nobel Prize laureate Niels Bohr:

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[14] Ward 2005.
[15] Neufeld 2007.
[16] Easterbrook 1980.
[17] Current annual NASA “Space Operations – Shuttle” budget (4 G $) divided by number of flights (4).
[18] Early estimations predicted costs ranging from 100 $/kg in 1969 to 10.5 M $ per launch in 1972. (Raumfahrtforschung 5/1969, 2/1972)
[19] Wikipedia 2007.
[20] Wade 2007.
[21] ESA ISS 2005.
[22] AW&ST Aug 28 2000.
[23] Space News 21/11/2005.
[24] Schmucker 1990.
[25] Mass estimations are subject to the same effect.
[26] Meadows 1972.

“Prediction is very difficult, especially about the future.”[27]

But Newtonian physics are still valid for special cases of Einstein. Therefore, results based on known physics and mathematics might still prove true for the future.

2.2 Historic Spaceflight Development

A brief view on the history of astronautics allows a better understanding of today’s public perception of spaceflight, of its challenges and its chances. The understanding of the historical development of spaceflight is important for an understanding of potential future developments and gives an idea of driving factors of space activities.

Before its realization in the middle of the 20th century, spaceflight was always regarded as an exciting journey for human explorers and adventurers. The journey itself was reason enough; no one ever thought about the actual utilization of space.

The first serious thoughts about utilization surfaced at the beginning of the 20th century – Hermann Oberth was one of the first who proposed thoughts based on engineering approaches on how spaceflight may be used for the benefit of mankind.

It took many more decades until utilization became an important topic. Serious discussions about justified reasons for spaceflight expenditures – especially for manned space programs – emerged after Apollo 11 landed on the Moon in 1969. The objective was achieved, and there seemed to be no more need for the tremendous expenditures for spaceflight of the 1960s. Ever since that time, the debate about spaceflight continued in a more or less intensive way up to the present day.

During the course of history, spaceflight slowly evolved from the adventurous journey to the expensive, admired, but contested high technology sector it is today. This development can be divided into five historical phases:

- Ancient world to modern times,
- Prophets, pathfinders and pioneers,
- Realization phase,
- Zenith,
- Stagnation and disorientation.

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[27] In this context, it will be interesting to see how the current predictions about climate change will be judged in the far future.

2.2.1 Ancient World to Modern Times

As far as we look back in history, the heavens have been stated as the home of the gods, with only few exceptions. For the major religions, the stars were of no special meaning and were referred to as tiny holes or lights at the firmament.[28] Only the Moon was identified as a spherical body in some cultures (for example by the ancient Greeks),[28,29] and so it was early referred to as a potential destination for a journey.

In the ancient world, it seems that the understanding of Earth as a sphere was commonly accepted.[30] The Hellenistic mathematician Eratosthenes of Cyrene, born 276 B.C., calculated Earth's total circumference with an accuracy that varied between 17 % to 0.5 % of the value accepted by modern astronomers, depending on the actual length of the units "stadia" that he used.[31] This understanding of the world inevitably lead to further thoughts about space in general and the existence of other celestial bodies.

Leaving Earth's surface and traveling to space, especially for journeys to the Moon, became a recurring motive in literature. There was no distinction between aeronautics and astronautics. Early examples include the famous myth of Icarus. At about 150 A.D., Lucian of Samosata tells of a journey to the Moon using wings of a vulture and an eagle; in another story, a sailing ship serves as a vessel for spaceflight.[28,29]

At the end oft the Medieval Age, the first technically oriented thoughts and drawings of rockets and other vessels for space exploration appeared. Some of them seem amusing, like the early 17th century description of the knight Don Quixote flying on a horse with fireworks attached to its tail.[29] Others, though, were quite advanced for their time: Conrad Haas proposed rockets with two and more stages, and sketched a rocket that might be used for manned space expeditions.[29,32] But all of these proposals remained of minor technical relevance.

In the year 1634, Johannes Kepler's work "*Somnium*" was published posthumously. It depicted a journey to the Moon in great detail. For the first time, the conclusion was stated that there was no atmosphere between Earth and Moon, hence barring the possibility of reaching the Moon by aeronautical means (wings). This seems to be the first distinct segregation of aviation and spaceflight in literature. But this insight soon was lost again.

From the 17th century on, an increasing number of lunar travel descriptions is observed. Journeys to the Moon become an increasingly popular motive in common literature, thus inspiring the first prophets of the space age.

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[28] Walter 2001.

[29] Miller 1993.

[30] This is an interesting example for the ever present degradation of knowledge.

[31] Encyclopædia Britannica 2007.

[32] Braun et al. 1979.

So, for many centuries, spaceflight remained just a motive for storytelling, appearing only in works used for entertainment purposes. These works were focused on the audience of wealthy social classes interested in amusement and entertainment, without any deeper thoughts of spaceflight utilization. The exotic adventure of space travels was reason enough for thoughts about spaceflight.

The technical side of early spaceflight depiction remains unimportant. Even though sporadically some potentially useful basic thoughts about spaceflight appeared, they never received special attention and soon were lost again in the ocean of technically worthless space travel proposals.

2.2.2 Prophets, Pathfinders and Pioneers

The starting point of modern physically and technically based spaceflight considerations may be seen in Jules Verne's "*De la terre à la lune*" (*From the Earth to the Moon*, 1865). Because rockets were too powerless at that time, a huge cannon was seen as the only technical means to reach Earth's escape velocity of 11.2 km/s. Thus, Verne's novel characters had to travel to the Moon inside of a giant bullet.

It is said that many famous prophets of the space age were inspired by Jules Verne's novel.[33]

The most famous of them probably is the Russian pioneer of cosmonautics, Konstantin Eduardovich Tsiolkovsky. As early as 1897 he is said to have developed his famous rocket equation,

$$v_{id} = c \cdot \ell n \frac{m_0}{m_f} \quad , \qquad (2.2)$$

that was first published in 1903 in his work "*следование мировых пространств реактивными приборами*" (*The Exploration of Cosmic Space by Means of Reaction Devices*). This equation is the most fundamental insight of modern astronautics and still dictates the basic requirements of space transportation systems. Tsiolkovsky discovered that rocket propulsion could be used as a realistic approach to space transportation; he proposed multi-staged vehicles propelled by liquid hydrogen and oxygen that would enable mankind to dominate the cosmos.[34]

Hermann Oberth, a German of Transylvanian heritage, independently came to conclusions similar to Tsiolkovsky, which he published 1923 in his famous book "*Die Rakete zu den Planetenräumen*" (*The Rocket into Interplanetary Space*),[35] just three years before the American Robert H. Goddard actually launched the World's first liquid fueled rocket.[36] And for the first time in history, thoughts about the utilization of

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[33] Braun et al. 1979.

[34] Hagemeister 2006.

[35] Oberth 1923.

[36] Though they developed their insights independently, Tsiolkovsky, Oberth and Goddard knew each

spaceflight were stated in Oberth's book including the perfect conditions for astronomical observations in space, and deployment of mirrors in space to reflect sunlight towards Earth's nightside and polar regions.

These first thoughts about utilization are remarkable, because at Oberth's time, spaceflight still was referred to as an adventurous entertainment, mainly driven by curiosity – no wonder considering the current state of Earth's exploration: Few white areas remained on the map of planet Earth. In the eyes of Oberth's contemporaries, the exploration of space (should it ever happen) certainly must be a continuation of the prestigious expeditions to Earth's remote areas. Contemporary literature often pictured the surfaces of other celestial bodies as dense, humid jungles or barren rocky landscapes with traces of vanished civilizations.

At about the same time that the first spaceflight societies were founded and the first scientists started serious research on rocketry, the first science fiction movies were produced. Most important was the movie "*Frau im Mond*" (*Woman in the Moon*) of the Austrian director Fritz Lang. Hermann Oberth was enlisted as technical adviser, and he designed the rocket that was used for the landing on the Moon. And for the first time, a countdown was used to launch a rocket – even though it was a fictional one.[37]

The insight that the technical realization of spaceflight activities was within reach by the means of rocketry was remarkable. The theoretical basis for the realization of spaceflight was prepared.

2.2.3 Realization Phase

The common interest in spaceflight activities was triggered by various characters and privately funded societies. Though Goddard's successes with liquid-fueled rockets were impressive, seen in a big context they had no further impact on German and, later, U.S. rocket engine development, and thus for spaceflight realization, because he was quite reluctant to give out technical information.[38] Though Wernher von Braun knew of Goddard's theories, and had read his paper "*A Method of Reaching Extreme Altitudes*" of 1919, he was not aware of the fact that Goddard successfully worked on the field of liquid propellant rockets.[39]

The group that formed around Oberth in Berlin in the late 20s and early 30s proved to be of major importance for spaceflight for many years to come. Gathering around the "*Verein für Raumschiffahrt*" (*Society for Spaceship Travel*), some brilliant scientists and engineers were drawn to Berlin, first of all Wernher von Braun. The motivation

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other. Oberth contacted Goddard in 1922 and Tsiolkovsky in 1924, and some of their later works may have resulted from their correspondence. (Barth 1974)

[37] As an advertising stunt, Oberth offered to launch a "small" rocket that should reach an altitude of 100 km at the movie's opening night in Berlin in 1929. He underestimated the technical difficulties, though, and had to content himself with a model rocket that was thrown down a chimney stalk, and photographed during its fall. The photograph was turned upside down and promoted as the rocket's successful first test flight. (Ruland 1969)

[38] Sutton 2006.

[39] Ward 2005.

for their work in Berlin was the development and launch of a rocket capable of reaching space, thus enabling journeys to the Moon and beyond[40] – besides Oberth's ideas published earlier, no deeper reasons for going to space were formulated.

In the beginning, Braun was convinced that an interplanetary rocket could be easily realized within a year to the cost of 7 000 marks (about 1 700 $ then).[41] But soon he realized that tremendous efforts were required. In 1932, the *Reichswehr* (*German Army*) started to show interest in rocketry and offered support to rocket projects. The main reason obviously was that the Treaty of Versailles, that had officially ended World War I, put major restrictions on Germany's military acquisitions – but ballistic missiles were not included.[40] Braun welcomed this development because he realized that only public funds would be sufficient for serious development of rocketry, and the defense sector seemed a perfect way to get access to public funding.[42]

At enormous expenses and efforts, the world's first large rocket – the A4 (*Aggregat 4*) that later became known as the V2 (*Vergeltungswaffe 2*) – was developed in Peenemünde and first launched in 1942. In its ballistic flight profile, it reached a speed of more than Mach 5 and an altitude of about 100 km, carrying a payload of 1 t at a range of 300 km. Hence the first step towards space was done by a weapon.

At the end of World War II, rocket technology was transferred to the USA as well as the USSR, and in a smaller scale to France and the UK. Braun and most of his team emigrated to the USA, while other experts were acquired by the Soviet Union.

Though some test launches were done in the U.S. using wartime A4 rockets from Germany, no intensive research and development work was conducted. There was no obvious need for further expenses concerning rocketry and spaceflight, though the first serious proposals for manned space stations, lunar landings and Mars expeditions were presented at this time.[43]

While rocketry stagnated for a decade in the USA, the Soviet Union intensely pushed a program for the use of rockets as ballistic weapons, because the air superiority of the U.S. required an alternate option for weapon delivery onto American soil. On October 4, 1957, the Soviet R-7 rocket – developed by Sergey Korolev and designed as an intercontinental nuclear weapon delivery system – made its first successful orbital launch and placed the satellite Sputnik 1 into Earth orbit, thus heralding the beginning of the "Space Age".[44]

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[40] Ruland 1969.

[41] Ward 2005.

[42] Ethical implications and resulting judgments are not further regarded.

[43] Stuhlinger et al. 1994.

[44] The first artificial object in space might have been a circular steel mineshaft cover that, according to simplified calculations, must have been accelerated to six times the escape velocity from Earth during a nuclear weapon test in Nevada on August 27, 1957. (Brownlee 2002) It is probable, though, that it was vaporized within milliseconds by atmospheric friction. The first object that definitely left Earth forever was a small metal pellet fired from an Aerobee rocket that was launched by Swiss physician Fritz Zwicky on October 16, 1957. (NZZ 15/10/2007)

2.2.4 Zenith

For a brief period of about 15 years, spaceflight advanced in a way that was unprecedented and never anticipated.

The Cold War was at its peak, and unlimited financial means and manpower were invested in the development of rocketry and spaceflight by the two enemies USA and USSR. Ultimately, the “Space Race” culminated in the Apollo Lunar Landing of 1969.

The technical basis of these years was provided by numerous parallel ballistic missile development programs in the 1950s and 1960s. Though the exact numbers are unknown, it can be estimated that the United States launched between 10 and 20 programs including Atlas, Delta and Titan, while the Soviet Union launched more than twice the number of programs during that period, including missiles that later became known as the Proton and Soyuz space transportation systems.

The actual progress in spaceflight led to the publication of infinite concepts for alternative launcher configurations, including air breathing systems, Single Stage To Orbit (SSTO), winged systems and reusable systems. But up to the present day, space transportation systems are derived from or based on ballistic missile systems, with only partial exceptions (US-STS, Ariane series).

With the public enthusiasm about Sputnik 1, the Soviets and the Americans recognized the propaganda potential of spaceflight and used it for their own goals. The superiority of the political system should be underlined by successes in spaceflight. The successes were achieved due to an interesting personal constellation that was similar in both countries:

- **USSR**
  Khrushchev (determined politician, not interested in spaceflight[45])
  Korolev (brilliant engineer and manager, obsessed by spaceflight)
- **USA**
  Kennedy (determined politician, not interested in spaceflight[46])
  von Braun (brilliant engineer and manager, obsessed by spaceflight)

The USSR had one big success after another, and less than four years after Sputnik 1, it successfully launched the first manned spaceflight of Yuri Gagarin on April 12, 1961. The USA knew they had to answer the challenge.[47] About six weeks after Ga-

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[45] Harford 1997.

[46] NASA History 2007.

[47] In 1960, Kennedy visited Huntsville. He was early, so Harry O. Ruppe took the chance to entertain Kennedy until von Braun arrived. During their conversation, Kennedy asked for the right way to beat the Soviets in space, and Ruppe answered: “There are three ways to beat them: A space station, a Lunar landing and a Mars landing. Mars is currently impossible. And for the other two options: If someone has a head start on you, you won’t beat him at a sprint. But you can beat him at a marathon.” Kennedy seemed impressed. (Ruppe, personal conversation)

garin's flight, John F. Kennedy presented the plan to put a man on the Moon within the current decade. His announcement of the Apollo program on May 25, 1961 is remarkable for two reasons:

On the one hand, after developing rocket technology and placing an object – and later, a human – into orbit, once more the spaceflight community had a clearly defined objective. There was a clear task to be fulfilled, an objective that was formulated by Kennedy in a simple, historical sentence:

> "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the Earth."[48]

On the other hand, in 1962, he implied that the enormous efforts to achieve this goal were the true reason for its stating:

> "We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard."[49]

This leads to an interesting conclusion: If the Soviets had tried to build a deep sea station, or started any other kind of challenging engineering project, the U.S. efforts would have been bundled in this direction. Spaceflight was just a tool for the political motivation to beat the Soviets. This is further backed by a statement Kennedy's at a meeting with NASA Administrator James Webb on November 20, 1962:

> "Now, this may not change anything about that schedule but at least we ought to be clear, otherwise we shouldn't be spending this kind of money because I'm not that interested in space."[50,51]

In the wake of these golden days of spaceflight, it was generally anticipated that the progress would continue. There were serious plans for manned expeditions to Mars, huge orbital stations, manned outposts on the Moon and settlements at L5 which required an annual transportation volume of several hundred thousands of metric tons of payload into space, as is seen in **Figure 2-2**. These proposals had no serious background of utilization and funding. Spaceflight was seen as something inevitable, as a reason in itself.

Science Fiction made a huge leap in this era, too. The quick successes of reality in-

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[48] JFKLibrary 2007.

[49] NASA JSC 2007a.

[50] This political disinterest in space continues to the present day and only reflects the general public interest. An excerpt of a commentary by Jeff Foust on the next U.S. presidential elections in "The Space Review" on July 23, 2007, gets it to the point: "It has long been a complaint of space advocates that presidential candidates spend little or no time discussing their space policy positions—if, in fact, they have bothered to develop any positions on the subject. Space is near the bottom of the list of topics of interest to the electorate in general, and one that is not a swing issue for all but a small handful of voters. […] Thus, even in the current campaign—which is shaping up to be the longest and perhaps the most contentious in US history—there's scant attention paid to space." (Foust 2007)

[51] NASA History 2007.

spired the storytellers as well as the public. New technical insights lead to new, "realistic" presentations of the spectacular future of spaceflight, supported by the increasing quality of Hollywood's visual effects. The borderline between reality and fiction began to blur more and more, with the differences becoming indistinctive. A good example is the movie "*2001: A Space Odyssey*" of 1968, based on Arthur C. Clarke's short story "*The Sentinel*" and directed by Stanley Kubrick.[52] The wheel shaped space station is clearly inspired by Braun's station design of the 1950s.

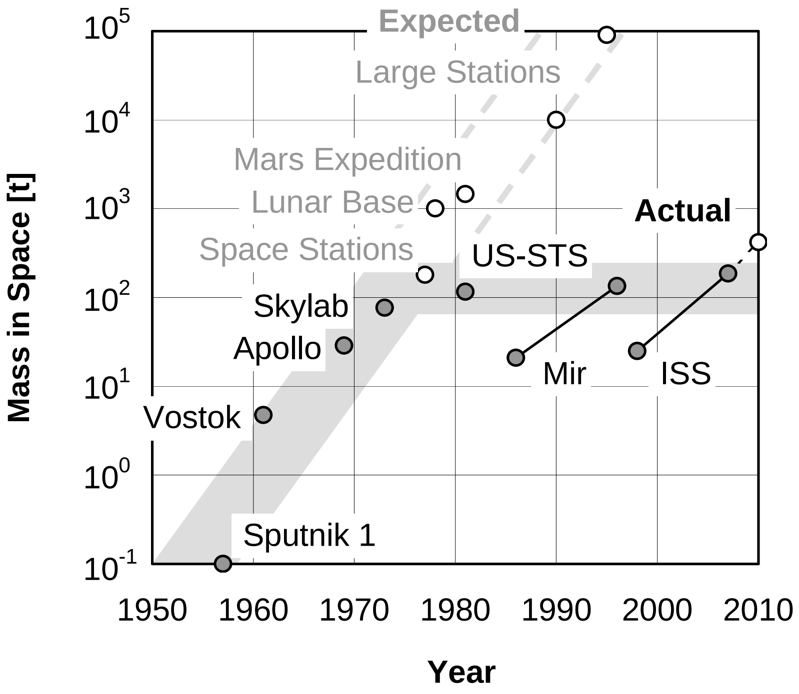

Figure 2-2: Actual and Expected Spaceflight Development[53,54,55]

The whole period was characterized by a basic optimism concerning the pace and type of future technical developments. It was widely assumed that the accepted technical and physical boundaries would soon be moved far outward.

But there also were early considerations and efforts to identify the possible benefits of spaceflight, as for example Harry O. Ruppe's "*Astronautics: An Outline of Utility*".[56]

2.2.5 Stagnation and Disorientation

With the budget size and the number of programs, the USA definitely gained the leadership in space during the Apollo days. Many of the other nation's proposed

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[52] IMDb 2007.
[53] NASA HQ 2006a.
[54] Braeunig 2006.
[55] Wade 2007.
[56] Ruppe 1970.

space related projects became mere copies of U.S. projects already in development. This state continues to present days, as seen in **Figure 2-3**.

Figure 2-3: Imitation of U.S. Space Projects

But with the achievement of the first human landing on the Moon and the obvious victory of the United States in the Space Race, worldwide public interest in the lunar landings, and in the space programs in general, declined.[57] The odyssey of Apollo 13 rose interest for a short duration, but with Apollo 17 on December 14, 1972, the sixth and last manned expedition left the Moon.[58] The American citizens were more concerned with indigenous problems and the Vietnam War.

Spaceflight highlights of the 1970s were the first unmanned Venus and Mars landings, some planetary flybys, the Apollo-Soyuz docking and the first manned orbital laboratories: The Soviet Salyut/Almaz series, first launched in 1971, and the U.S. Skylab station launched in 1973.

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[57] It is said that, after the success of Apollo 11, Braun lapsed into melancholy.

[58] NASA Apollo 2006.

The scientific activities seemed to continue at a more or less constant level, but the high hopes of extended manned activities in space were not fulfilled. The political motivation was lost, and there were many attempts from different directions for reorientation and justification of spaceflight. To name just a few:

- Focus on Earth – Utilization of spaceflight for Earth
- Human Spaceflight – Concept of a permanently manned large space station
- Spin-Off – Utilization of spaceflight technologies on Earth
- …

The last remnant Saturn V rockets were mothballed and later given to museums.[59] The new US-STS, often referred to as the Space Shuttle, should guarantee cheap and easy access to space. The promises were never held, and the classic expendable launch vehicles are still in use in all spacefaring nations.

Concerning future plans, the same ideas of the early days of spaceflight were proposed again and again, without really new approaches[60] and justifications: Lunar settlements, large orbital factories, Mars expeditions, … . A part of the efforts of the spaceflight community shifted to unimportant side shows, concentrating on details of projects that had no chance of realization due to very different reasons than those that were addressed: Details of asteroid mining processes, interiors of space hotels, configuration of pressurized Mars rovers, … . The true technical and financial challenges moved out of the public focus.

Perhaps, one reason may be the continuous improvement of the science fiction genre, and the widespread believe that space will be accessible soon anyway. In the mind of the public, the mastery of spaceflight in the near future became a certainty that was partially fortified by pseudo-scientific presentation of future technology (hyperspace jump, warp drive, …), sometimes with detailed technical drawings and explanations, so realization seemed just a few years away.

This resulted in ideas and objectives that were more and more distant from the actual technological state of spaceflight. For the majority of the public, fiction became part of reality. This might explain the ever repeating proposals of SSTO vehicles that promise cheap access to space within a couple of years. Many of these proposals did not even satisfy the Tsiolkovsky equation, thus ignoring the laws of physics. And there was always the same reason given for vehicle development: Reduction of transportation costs. The type of payload that was to be transported was unknown, but if the cost was low, the payload numbers would increase nevertheless – a position that will be analyzed later in detail.

None of these projects was ever close to realization, and all of them were cancelled due to financial reasons just before the technological breakthrough.

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[59] Wade 2007.

[60] Even the US-STS was not a new approach. There were numerous earlier concepts and programs for winged systems (Sänger, DynaSoar, …), and the proposed cheap access to space only included vague ideas of its actual utilization (Space Telescope, Space Station, Satellite Servicing).

It can be stated that, with the landing of Apollo 11 on the Moon, a clear, easily understandable, and simple objective was lost, and the following decades of spaceflight were characterized by aimlessness.[61] Remember, the real objective of Apollo was not to bring a man on the Moon someday for exploration; it was to bring a man on the Moon *first*, before anyone else did, and only for one reason: To verify the superiority of the own political system.

2.2.6 Present Situation and Planned Activities

The first so-called manned space flight of a privately funded vehicle, SpaceShipOne, on June 21, 2004 is seen as a turning point of astronautics development by some – as the end of the era of stagnation.[62] Others mark the tragic loss of the Orbiter Columbia during reentry on February 1, 2003 as a most incisive event for the future of spaceflight.

In any case, a flood of proposed mission scenarios emerged in the wake of NASA's new Vision for Space Exploration (VSE) of 2004, as seen in **Table 2-2**. Some of those date back to the pre-Columbia accident era, but they were reinforced with announcement of the VSE. It must be noted, though, that not all of the projects are confirmed projects with fixed timeframes.

Table 2-2: Various Governmental Spaceflight Projects (2007)

Country	Name	Topic	Target Date	Comment
USA[63]	VSE	Manned Lunar Landing, Lunar Base, Manned Mars Landing	2020+	Manned Exploration
IND[64]	-	Manned Orbital Flight, Manned Lunar Landing	2014, 2020	Awaiting Ratification
EUR[65]	Aurora	Mars Rover, Sample Return, Manned Mars Landing	2011, 2020, 2030	Stepwise Exploration of Mars
JPN[66,67]	-	Manned Lunar Landing, Lunar Base	2020, 2030	Proposal
PRC	-	Space Station, Manned Lunar Landing	?, 2024	Status unclear

Due to the numerous approaches to commercial spaceflight by private corporations and entrepreneurial companies, some current commercial projects are also pre-

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[61] As was stated by the Columbia Accident Investigation Board in 2003: "The U.S. civilian space effort has moved forward for more than 30 years without a guiding vision". (NASA CAIB 2003)

[62] Fawkes 2006.

[63] NASA 2007.

[64] Space Daily 09/11/2006.

[65] ESA Aurora 2007.

[66] Discover No. 12 2006.

[67] ABC 02/08/2006.

sented in **Table 2-3**.

Table 2-3: Various Non-Governmental Spaceflight Projects (2007)

Company	Name	Topic	Target Date	Comment
SpaceX[68]	Falcon 9, Dragon	Transportation	2008, 2008	Supported by NASA
Rocketplane Kistler[69]	K-1	Transportation	2008	Supported by NASA
RSC Energia[70,71]	Parom, Moon Base, MMC	Space Tug, Lunar Base, Mars Landing	2009, 2020+, 2025+	Proposal for Roskosmos
Bigelow Aerospace[72]	Sundancer, BA 330	Space Station	2010, 2012	Research and Tourism
Virgin Galactic[73]	Space-ShipTwo, -Three	Manned Suborbital, Orbital Vehicle	2009, ?	Tourism
Stone Aerospace[74]	Shackleton Energy Comp.	Lunar Mining	2015	Resource Mining

The numerous announcements – especially for a return to the Moon and a flourishing space tourism industry – and their continuous presence in the media result in great expectations of the public. It seems that a final breakthrough for spaceflight activities after years of disorientation is close.

2.2.7 Conclusion for Future Spaceflight Activities

Today's numerous ambitious projects may seem like a long overdue acceleration of spaceflight activities. The final departure of mankind to space on a grand scale seems only a few decades away.

But the brief look on history showed that similar projects existed for half a century. Most of them ceased in silence, and some of them were realized on a scale that was orders of magnitudes smaller than intended, for costs that were orders of magnitudes higher than predicted.

As an example, **Figure 2-4** presents the intended human Mars landing missions that were proposed since the 1950s with their year of announcement and the year of planned realization.

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[68] SpaceX 2007.
[69] RpK 2007.
[70] Energia 2007.
[71] Energia 2006.
[72] AW&ST Apr 9 2007b.
[73] Virgin Galactic 2007.
[74] Stone Aerospace 2007b.

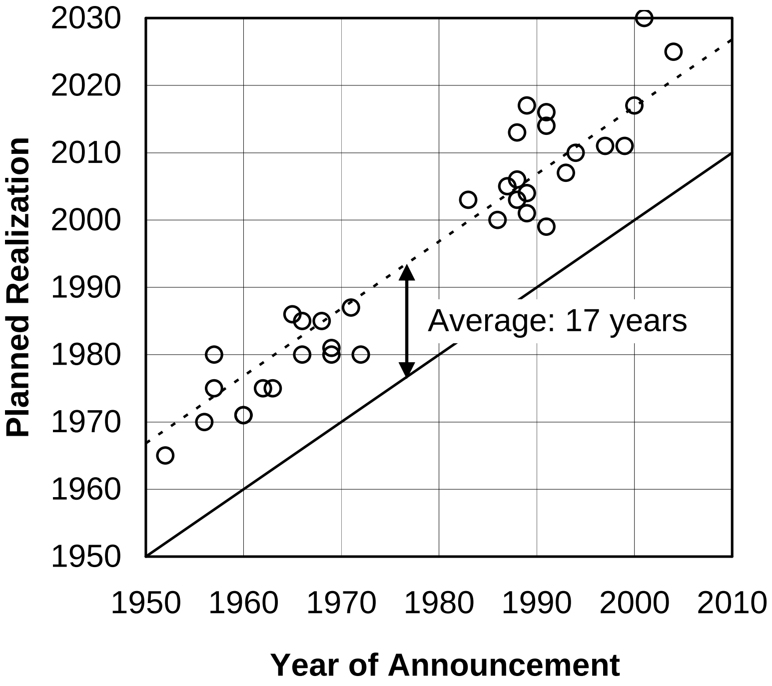

Figure 2-4: Announced Manned Mars Landings[75]

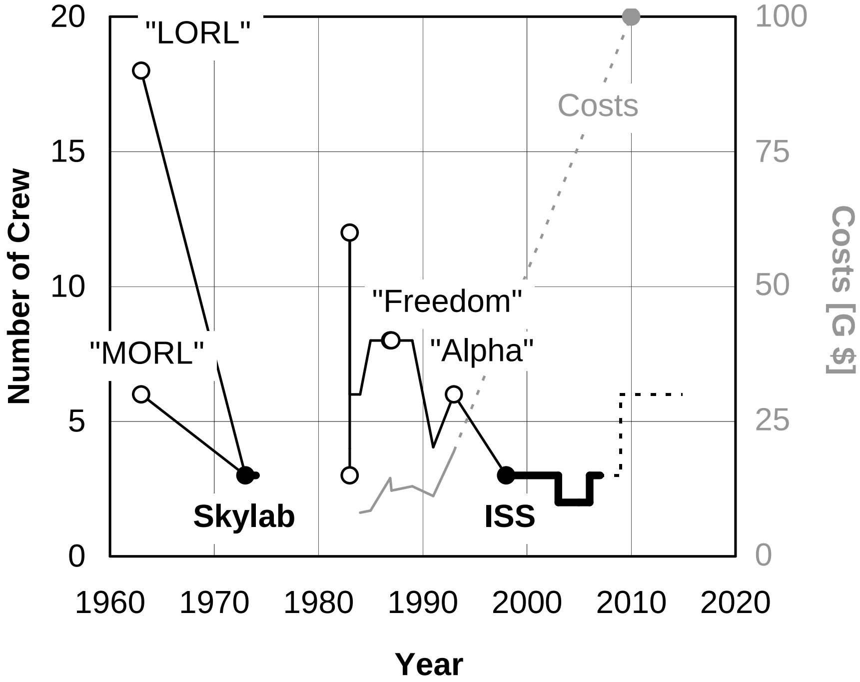

Figure 2-5: Realization of NASA's Orbital Laboratories[75]
(White: Planned, Black: Realized)

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[75] Wade 2007.

The number of announcements is high, and in average, the first landing should have been done 17 years after the announcement.[76]

The development of the International Space Station (ISS), first proposed under the names Freedom, and later Alpha,[77] is another example of great plans and weak realization, as seen in **Figure 2-5**.

As a third example, **Figure 2-6** illustrates the development of winged reusable space transportation systems by the major space agencies of USA, Soviet Union, Europe and Japan.

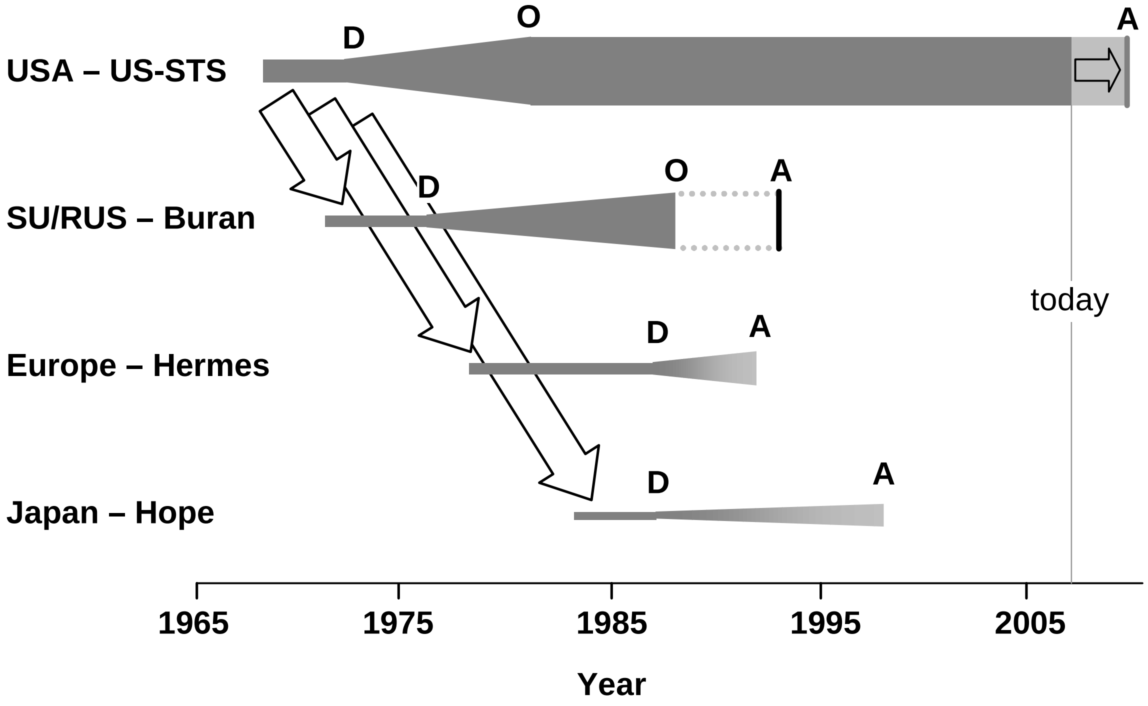

Figure 2-6: Development of Winged Space Transportation Systems
(D: Development Start, O: Operational Status, A: Program Abort)

All of the reusable spacecraft programs of Figure 2-6 were serious programs with strong governmental backing at their beginning. They were done on a scale much larger than most of today's spaceflight projects, but only one of them – the US-STS – ever became operational.[78]

Table 2-4 shows various other ambitious space related governmental projects that

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[76] Wernher von Braun's initial mission architecture for a Mars expedition was unrealistic from today's perspective. But his initial estimation of the timeframe, published 1954 in Collier's magazine, seems more realistic: "Will man ever go to Mars? I am sure he will – but it will be a century or more before he's ready." (Portree 2001)

[77] After significant program cuts to "Freedom" by President Clinton in 1993, the remaining station project "Alpha" was to be merged with the Russian "Mir-2". (Wade 2007, AW&ST Sep 13 1993)

[78] The Soviet Buran shuttle made only one unmanned orbital test flight on November 15, 1988.

were finally cancelled or significantly downsized.

Table 2-4: Various Previous Governmental Spaceflight Efforts[79]

Year	Country	Name	Topic	Comment
1957	USA	DynaSoar	Spaceplane	Parts of hardware built
1974	SU	Buran	Space Shuttle	One unmanned test flight
1985/87	EUR	Ariane 5/Hermes, Columbus (MTFF/PPF/APM)	Spaceplane, Space Station Modules	Only Ariane 5 and APM realized
1986	USA	X-30 NASP	SSTO	Wind tunnel tests
1989	USA	SEI	Space Station, Manned Lunar and Mars Landing	Parts of station realized as ISS
1996	USA	X-33/Venture Star	SSTO	Parts of hardware built

The previous examples presented governmental space programs. There are considerations that the present unique constellation of numerous entrepreneurial activities may eventually lead to a second Space Race similar to the first Space Race of the USA and the USSR.[80] The predicted future space tourism market would serve as an incitement. But the efforts of private companies to create a market for spaceflight are not new. Many other companies failed before, including:

- OTRAG – Orbital Transport- und Raketen Aktiengesellschaft, Germany, 1970s to 1980s
- AMROC – American Rocket Company, USA, 1980s to 1990s
- Beal – Beal Aerospace, USA, 1990s to 2000
- …

Therefore, it is possible that many of today’s space projects will meet the same fate as their predecessors: If they are not totally cancelled, they will be realized with significantly lower capabilities for much higher costs with many years of delay.

Since the days of Apollo, the same prediction as illustrated in **Figure 2-7** is made again and again: Spaceflight will grow exponentially, not now, but very soon.

There must be reasons for this continuous discrepancy between expectations and reality of spaceflight.

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[79] Wade 2007.

[80] Fawkes 2006.

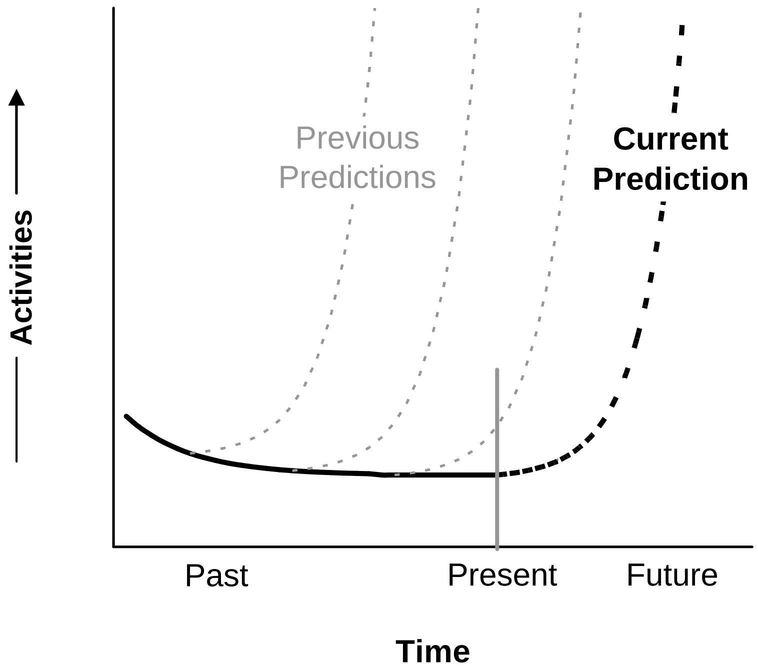

Figure 2-7: Common Spaceflight Predictions

2.3 Previous Assessments of Benefits and Motivation

An endless number of assessments ranging from books to newspaper articles already addressed the utilization of space, the benefits of spaceflight and the motivation for spaceflight, and tried to justify current and future funding.

2.3.1 Commonly Cited Motives for Space Activities

A list of various of motives that are attributed as decisive in literature for past, present and future space activities should give an idea of their multitude. An exact sourcing of each of the listed motives would go beyond the scope of this chapter, and the list is far from complete.

Selected examples for motives that are commonly cited in literature are:

- Science
- National pride
- Pioneering spirit
- Exploration
- Spin-offs
- Technology transfer
- Inspiration

- Leadership
- Technological progress
- Educational input
- International understanding
- International cooperation
- Environmental awareness
- Superiority
- Evolution of mankind
- Cultural imperative
- Spreading of life
- Business
- Creation of jobs
- Security
- Military dominance
- Commerce
- Reconnaissance
- Resources
- Exploitation
- Fun
- Challenge
- Adventure
- Curiosity
- Votes
- Religion
- Survival
- Entertainment
- Thrill
- Increase of quality of life
- …

It is necessary to assess the attributed and the actual meaning of these motives for the development of spaceflight to understand their importance.

2.3.2 Development of Thoughts on Spaceflight's Benefits and Motivation

As was mentioned in the historical overview, thoughts of adventure dominated space related considerations well into the 20th century. Adventure and pure fun were seen as the only use of spaceflight, which is obvious by reading tales from authors as different as Johannes Kepler and Jules Verne.

But *Konstantin Tsiolkovsky's* very first thoughts about rocketry for realization of spaceflight originated from a dubious other motive. He saw humanity as the dominating species of life in the universe which was destined to conquer every part of the world, including space, and thus requiring technologies to make this reality. The ever continuing progress of humanity would lead to an absolute reign of man over the cosmos, and the evolution of mankind into perfect godlike creatures up to loss of physicalness – and extinction of inferior life including plants, animals and parts of humanity. Man would then become immortal in time and infinite in space.[81] Though never formulated as dramatically as by Tsiolkovsky, the argument for spaceflight as a vehicle for advancement of humanity endured over the decades and still is present in today’s debates.

Some other arguments in the current debates about the need for spaceflight are quite old, too. As soon as 1923, *Hermann Oberth* introduces such an argument for spaceflight in general.[82] He claimed that the benefits of a scientific discovery cannot be predicted, and gave electricity as an example. Therefore, the true value of spaceflight could only be recognized when it is realized in greater scale – an argument that is still found in current assessments. But he also stated that his ideas can only be realized if the public was willing to spend money for them, and this could be done by two ways: The idea must ensure a direct and tangible advantage for the public, or it must be at least very popular. But Oberth saw his subsequent proposals for scientific research as insufficient to guarantee public funding, which would require “more than 1 million Mark” for a 100 times reusable space vehicle. Therefore, he proposed communication via and Earth observation from orbit, and he recognized the strategic value of spacecraft in armed conflicts. Finally, he stated that the greatest benefit of spaceflight that he could imagine would be the placement of large mirrors in space for various applications.

As a pupil of Oberth, *Wernher von Braun* adopted some of his views, including the requirement of massive public funding and support as well as the analogy of unknown benefits that are yet to come: He said that interplanetary exploration must be done on a grand scale,[83] and he once compared spaceflight with a newborn child whose course and future is equally unknown.[84] But interestingly enough, Braun never seemed to think intensely about potential benefits. His mind was always set on the inevitable conquer of space by humanity, but not for the reasons that Tsiolkovsky had offered. Braun’s ideas were dominated by adventure and personal interest: He wanted to conquer the last frontier just because it was there, and it seemed finally possible to realize it with the means of rocketry and spaceflight. His early proposals about utilization and resulting benefits remained vague and always included large space stations and Mars expeditions. During the 1960s, he listed common buzzwords like astronomical observatories, communication stations, Earth observation (for various purposes including navigation and military reconnaissance), and space docks (for integration of interplanetary ships).[85] But it seems that he used these arguments only to underline his earlier postulated need for large space stations and interplanetary expeditions.

In his early years in the USA, perhaps in the early 1950s, Braun came to the conclusion that he had to go public with his ideas of spaceflight to achieve broad public

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[81] Hagemeister 2006.
[82] Oberth 1923.
[83] Stuhlinger et al. 1994.
[84] Ruland 1969.
[85] Braun 1968.

support which would hopefully lead to political support and funding:

> "I will go public now, because this is where we have to sow our seeds for space exploration."[86]

In his efforts to gain public support, Braun was persuasive and diplomatic at the same time, which can be explained with his personal notion of diplomacy:

> "Diplomacy is the art of letting someone else have your will."[86]

It seems that he saw the public as just another tool to advance his personal crusade for spaceflight. Just as Oberth said: The idea must at least be very popular.

Just one year after the launch of Sputnik 1, a book of *Eugen Sänger* was published that also demanded space exploration on a grand scale, if only with other means than Braun proposed: Sänger thought of reusable winged transportation systems that would tremendously lower the efforts to go into space, and thus be the key for extensive space activities. Simultaneously, the resulting large scale exodus of mankind into space would concentrate the resources of our civilization on this endeavor, thus neutralizing preparations for armed conflicts as well as war itself as options for large scale governmental efforts.[87] Similar to Tsiolkovsky, Sänger saw spaceflight as a way for humanity to create a better world, and this was more than enough for him to justify space activities.

All these early ideas for large scale space activities originated from the time before the first realization of spaceflight, and all of these ideas were based on the assumption that spaceflight would soon become as common as aviation, and similar both in terms of cost and reliability.

With the public reaction on Sputnik 1 and the insight that spaceflight could be used as a tool to demonstrate the superiority of the political system, the discussion about benefits and motivation became obsolete. Civil spaceflight was actually *done* on a grand scale, and thus, no further arguments and justifications were needed.

But during these golden days of spaceflight, the first critical opinions were also stated. The large financial efforts for the space programs were soon questioned, and the first losses of human life (both Apollo 1 and Soyuz 1 in early 1967) contributed to a critical view of the Space Race.

In 1970, *Harry O. Ruppe* published his comprehensive assessment on the benefits of and motivation for spaceflight.[88] He divided the reasons for spaceflight into three groups: One group having to do with direct utility, one being speculative reasons, and one group of motives that goes beyond mere utility and roots in the fact that we are human. The first group included topics such as space mirrors, navigation and communication, but also military applications. The second group included such various

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[86] Stuhlinger et al. 1994.

[87] Sänger 1958.

[88] Ruppe 1970.

topics as national prestige and weather modification, while the third group considered human values, arts, challenge, religion and other aspects with similar character. Unlike in most other works about utilization of space, the actual technical feasibility of proposed topics was *critically* considered, including the resulting financial requirements. But even Ruppe assumed that the high costs of space transportation prohibited a buildup of transportation volume, and that space transportation costs to LEO would wind down significantly within a few years.

By achieving the preset goal of Apollo and beating the Soviets in the Space Race, the advance into space slowed down and the public funding for civil space programs was significantly cut. This ignited the debate about the benefits of spaceflight more intensely than ever before.

The high costs of Apollo combined with the achieved goal of “only” having two people collect stones on the Moon’s barren surface extinguished any governmental as well as commercial interest in ambitious space activities. Suddenly, the space advocates had to justify the continuous spending of large amounts of taxpayer’s money if the space program should continue in a similar order of magnitude.

This was the renaissance of arguments for spaceflight that went beyond numbers and profits.

While NASA postulated its mission to Earth with a clear focus on low Earth orbit (Skylab, development of Space Shuttle), the Soviets did similar with their series of Salyut stations and Soyuz flights. The number of unmanned missions to other planets and the Moon decreased significantly. Old pre-Sputnik arguments, mainly for human spaceflight, were resurrected to justify the “preparatory” activities that would enable a decrease of the costs of spaceflight and allow the conquer of space. These arguments included advancement of humanity, conquering new habitats, exploration.

But other arguments were introduced, too. In 1973, NASA started to offer at congressional budget hearings a report about spaceflight spin-offs which should further justify NASA’s budget requests. This soon became an annual report about successful technology transfer from space into daily life that is published by NASA by the name “*Spinoff*” in its present form since 1976. These reports – that were initially used to convince congressmen of NASA’s need of funding – generated keen interest by the public and are still used today as a tool to justify the importance of spaceflight.[89]

Unaffected by the public discussion about the need for funding of national space agencies, two other branches actually *did* spaceflight: While the commercial space industry, foremost satellite communication, blossomed in the 1970s and 1980s, military space silently continued its activities without any further notice.

There also were some specific considerations at that time about man’s role in spaceflight, for example *McDonnell Douglas*’ *THURIS* study from 1983 to 1985.[90] Being an acronym for ‘The Human Role In Space’, THURIS recommended a methodology for

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[89] NASA STI 2007.

[90] McDonnell Douglas 1985.

NASA to design space missions cost-effectively regarding the use of manned against unmanned approaches. Though potential benefits of basic research and individual missions were presented, the study was limited to the then proposed missions of NASA (orbital transfer vehicle, space station, orbital maneuvering vehicle, …). The study was clearly focused on the assets and drawbacks of humans in space. It was also stated that reusable vehicles obviously lower space transportation costs.

In January 1986, the loss of US-STS Orbiter Challenger and its crew finally destroyed the illusion of routine shuttle operations to space and initiated an intense debate about pros and cons of human spaceflight. But it did not hinder continuation or initiation of ambitious manned space programs that were justified again with the same old arguments. Foremost was expectation of new scientific insights that could only be achieved with a human presence in space. This was a major argument for the Spacelab program,[91] but also for ESA's participation on a proposed U.S. space station.[92]

But other motives were also used to plead for an increased level of activities in space. With resulting global leadership as a main argument, the *Ride Report* of 1987 requested NASA's engagement in at least one of four proposed space programs: The (predominantly unmanned) intense research of either planet Earth or solar system, and the (manned) options of an outpost on the Moon or sending humans to Mars. The construction of a space station that was already decided should not be affected by additionally realizing one of these options.[93]

The manned projects that originated from these arguments (science, leadership, …) were either cancelled before realization (Space Exploration Initiative of 1989) or realized on a significantly smaller scale than proposed (Spacelab, ESA program of 1988).

Meanwhile, assessments of space activities that seriously considered commercial utilization of space were rare, and those that were actually published came to the uncomfortable conclusion that the considered space activities were not profitable.[94]

The debate finally shifted completely to manned spaceflight, and how it must be justified by arguments and benefits that were beyond profits and scientific insights. This was especially true for Germany, probably as a result of the Spacelab experience and the costly participation at ESA's ambitious human space program (Ariane 5, Hermes shuttle, participation on space station with Columbus consisting of three elements). Two publications may serve as examples for this trend:

In 1992, a collection of essays concerning the purpose and reason of manned spaceflight was published in a German series of publications that dealt with ethics and social sciences. [95] *Jesco von Puttkamer* wrote a main article about the enormous bene-

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[91] DFVLR 1985.
[92] Lüst 1987.
[93] Ride 1987.
[94] For example Harr et al. 1990.
[95] Puttkamer 1992.

fits of spaceflight in scientific, economic and social aspects. These could nonetheless be neglected because the cultural dimension of spaceflight was sufficient and decisive to justify any space activities. This article was then discussed by various other authors including Edelgard Bulmahn, Jörg Feustel-Büechl, Ernst Högenauer, Heinz Hermann Koelle, Harry O. Ruppe, Robert H. Schmucker and Ernst Stuhlinger, with only few of them disagreeing with Puttkamer. And most authors saw the high space transportation costs as a restricting factor, thus demanding low cost space transportation.

An even better example is the 1993 *SAPHIR* study of the German space agency DLR. This very comprehensive analysis was done by a combination of space system analysts of DLR and chairs for philosophy of the universities of Essen and Marburg, and it was limited on technology assessment of human spaceflight. In this study, national identity, prestige and leadership were identified as political purposes that had been driving factors of the Space Race between USA and USSR, especially concerning Apollo and other manned programs. Written just a few years after the end of the Cold War, it was assumed that international cooperation could replace the competition between political systems as a high ranking motivation. Other than Puttkamer, SAPHIR stated that human spaceflight's direct, "utilitarian" benefits were not sufficient to justify manned activities, thus requiring additional "trans-utilitarian" benefits that take cultural, philosophical and social aspects into account. With these considerations, human spaceflight was an imperative option for the present as well as the future. Furthermore, high transportation costs were mentioned as a major limiting factor for human spaceflight, but were completely ignored at the considerations.

The tendency to justify the need for human spaceflight with increasingly scientific social and philosophical considerations continues to the present day.[96] Probably unaware of it, this trans-utilitarian argumentation continues Tsiolkovsky's early ideas of a better species of mankind by spaceflight.

A prominent international supporter of this argumentation is *Robert Zubrin*, who is a vigorous advocate for a human mission to Mars. In a publication of 1996,[97] he claimed that Mars as a new frontier could have a similar influence on global civilization that the frontier of the New World (America) had on the sound development of Western civilization: Only the challenges and opportunities of a new living space that is distant enough to be independent of the existing culture can lead to a positive development of human society. Zubrin also claimed that Antarctica and the deep sea were too close, and the Moon too barren to serve as the new frontier. And, like most others before him, he saw the efforts for Mars colonization as acceptable: The first human Mars exploration mission could have been launched within ten years at costs less than NASA's existing budget. After that, "bases could rapidly be established", finally leading to colonization. It was not mentioned who would finance this venture.

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[96] For example Gethmann 2006.
[97] Zubrin 1996.

This issue was already addressed by Zubrin one year earlier.[98] Stating that “a Mars base of even a few hundred people can potentially be supported out of pocket by governmental expenditures”, the follow-on settlements should then be economically self-sustaining. This was to be achieved by production of low tech goods and mining of resources on Mars that were to be transported to Mars orbit by SSTO vehicles, and on to Earth by interplanetary spacecraft. An even better option was the involvement of resource mining in the main asteroid belt: Earth would supply Mars with high tech goods, Mars would supply the asteroids with low tech goods (food, water, …), and mined resources would be transferred from the asteroids to Earth. The total costs to establish this venture were not mentioned. And again, low cost transportation of 100 $/kg from Earth to LEO were seen as given for the near future by using reusable SSTO vehicles. Further cost reduction was expected by using air-breathing supersonic ramjet propulsion.

Parallel to the mentioned trans-utilitarian considerations, the need for spaceflight was justified during the 1990s with the old arguments of the 1970s over and over again: Spin-off, science, and human attitude.[99] And because the reusable US-STS had obviously not reduced the costs for space transportation, numerous proposals and development programs for SSTO vehicles emerged, all of them claiming that this way, transportation costs would finally come down and large scale space activities could be enabled.[100] None of them were realized.

During that time, most publications that considered economical reasons for going into space – proposing specific ventures (space tourism,[101] asteroid mining,[102] …) or combinations of numerous activities (resulting in commercial space infrastructure[103]) – assumed drastic reduction of transportation costs, huge future market demands, and new, cheap technologies. These assumptions resulted in positive profit expectations for the proposed ventures. Especially reduction of the high space transportation costs was seen as essential and inevitable. This view continues to the current day.

In one aspect, the approach of *Gordon R. Woodcock* was a rare and noteworthy exception to these common views of space benefits.[104] Focused on lunar industrialization, he stated that “most papers about this topic neglect the issue of costs and what benefits may be great enough to sustain expected costs”, thus demanding increased cost and benefit analyses. But his request was limited to papers about lunar industrialization, as were Woodcock’s own considerations. And, as many others, he saw transportation costs to LEO as the dominant cost driver of these ventures, and stated that reusability was a prerequisite to reduce these costs. As many authors of the 1990s, he stated that SSTOs could reduce transportation costs by a factor of 10.

A sudden cut came with another loss of a US-STS Orbiter – Columbia – and its crew

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[98] Zubrin 1995.
[99] For example Korn 1992.
[100] HOTOL, X-30/NASP, Skylon, Delta Clipper, X-33/VentureStar, Roton, …
[101] For example Ashford 1997, Pearsall 1997.
[102] For example Lewis 1997.
[103] For example O’Dale 1997.
[104] Woodcock 1994.

of seven in 2003. The Columbia Accident Investigation Board finally came to the conclusion that the reason why seven astronauts died – "some small experiments in microgravity" – was "not an adequate vision to justify the risk of putting astronauts into space".[105] It seemed that a reorientation from the manned scientific LEO flights towards other goals was necessary.

With U.S. President Bush's announcement of the Vision for Space Exploration in 2004, exploration is now seen as the major reason for going into space. The arguments for exploration again include improvement of humanity, thus being the same old idea in a new (?) disguise, but at least with a given objective: Returning humans to the Moon. But in the present discussions about pros and cons of spaceflight, it is ignored that the argument of exploration is used mainly for human spaceflight which is financed by national space agencies.[106]

Currently, there are few considerations beyond this narrow view on manned flights of civil agencies. Some publications consider space tourism by private companies,[107] and few others analyse other commercial options like power generation for Earth.[108] Even less attention is paid on more specific topics that require different approaches, such as the chances of success for private equity investments in space related businesses.[109]

With the discussion's focus on potential impacts of manned spaceflight and exploration on society, the important questions of *why* space activities are actually done and *which* space activities should be done are currently ignored.

The potential effects of the *way* are discussed, but not the *objectives*.

2.3.3 This Work in Context with Previous Assessments

The new approach of this work and its results are set in context with selected previous works about benefits of spaceflight to identify relevant problems and new insights.

A) H. Oberth: Die Rakete zu den Planetenräumen/Wege zur Raumschiffahrt/ Menschen im Weltraum (1923/1929/1957)[110]

Oberth's considerations have a special meaning because he probably was the first who seriously thought about utilization of spaceflight and resulting benefits. Of his first and most famous publication, "*Die Rakete zu den Planetenräumen*" (*The Rocket into Interplanetary Space*) of 1923, he dedicated one of the three chapters to purposes of spaceflight: *III. Teil. Zweck und Aussichten* (*Part III. Purpose and Pros-*

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[105] Brumfiel 2007.
[106] For example Robertson 2006, Space News 11-2007.
[107] For example Fawkes 2006.
[108] For example Seboldt 2004.
[109] Mathurin et al. 2006.
[110] Oberth 1923, 1929, 1957.

pects).

Two other works are also considered here to get an insight of the development of Oberth's thoughts over the years: "*Wege zur Raumschiffahrt*" (*Ways to Spaceflight*) of 1929, which is an extended version of his earlier book of 1923, and "*Menschen im Weltraum*" (*Man in Space*) of 1957.

In each of the three works, Oberth's focus is on developing the theoretical basics for future realization of technical devices. His works on rockets in his 1923 publication are most famous, but he already mentions other devices that can be of use in combination with rockets, for example mirrors in space, stations for observation and communication, and pressurized suits for extravehicular activities (*§ 17 Ausblicke*).

This is also characteristic for the other two publications: In 1929, he refines his ideas for space mirrors and also proposes visits to other celestial bodies with potentially resulting benefits and mentions space telescopes and other devices; in 1957, he again gives very detailed descriptions of space mirrors, but also of space telescopes, space suits and moon cars, and he also considers terraforming, large scale space colonies and intersolar space travel.

This approach – to propose new ventures and roughly outline their potential realization – is adopted for some topics of this work, for example large advertising structures in space or space burial. But in contrast to Oberth, this is done with a potential investor in mind who could be interested in realization.

Oberth barely gives any reason for potential realization of his devices. As early as 1923, he proposes to realize his ideas first, and to see later if there is any resulting benefit. He justifies this approach by the impossibility to predict the unknown:

> "*Nun ist ja der Nutzen einer wissenschaftlichen Entdeckung vorher nicht abzuschätzen.*" (p. 84, 1923)

And Oberth also assumes that the public pays for realization and must therefore either have a direct advantage of, or at least be interested in the idea:

> "*Wenn man indessen von der Allgemeinheit für irgendeinen Zweck Geld haben will, so muß man entweder in der Lage sein, ihr einen direkten greifbaren Vorteil zu sichern, oder man muß die Sache wenigstens sehr populär machen können.*" (p. 84, 1923)

In 1929, he asks for a purpose of visiting other celestial bodies, and proposes scientific insights, resource mining and other aspects as answers. But a detailed and systematic analysis is missing.

In his later works, Oberth tends to other, more speculative reasons for spaceflight – perhaps because he assumes that his earlier arguments are insufficient. The complete first chapter of his 1957 book (chapter 1, *Die Evolution des Weltraum-Menschen*) is dedicated to the postulation that spaceflight would change human attitude and create a new species of man:

> "*So führt die Technik der Weltraumfahrt folgerichtig zur Evolution des Weltraum-Menschen.*" (p. 17, 1957)

With this, Oberth closes in on Tsiolkovsky's motive of advancement of humanity by spaceflight. Other aspects of justification seem to become more and more irrelevant in his view. This can be verified by another quote. At the very last page of "*Menschen im Weltraum*", subsequent to considerations about travels to other solar systems, Oberth finally asks for the basic motivation of spaceflight:

> "*Aber wozu das alles?*" (p. 201, 1957)

He sees the answer in an inherent drive of humanity for research and exploration that he calls *faustisches Streben*, and he postulates his ultimate objectives of spaceflight:

> "*Denn das ist das Ziel: Dem Leben jeden Platz zu erobern, auf dem es bestehen und weiter wachsen kann, jede unbelebte Welt zu beleben und jede lebende sinnvoll zu machen.*" (p. 201, 1957)

Oberth's thoughts clearly developed at a time where spaceflight seemed increasingly likely, but was not yet realized. This is clear by his estimations of required efforts, ranging from the early cost assumption of one million Mark for a 100 times reusable manned lunar rocket (p. 86, 1923) to the late statement of 500 Mark transportation cost to deliver one liter of propellants to lunar surface (p. 165, 1957).

Therefore, it is essential for this work to analyze the efforts for spaceflight on a realistic basis, with the experience of 5 decades of actual spaceflight. This enables a clear understanding of the interrelations of efforts, benefits and motivation regarding spaceflight.

Oberth's works were invaluable as they paved the way for the realization of spaceflight. They also initiated considerations on space medicine and on benefits of spaceflight. But Oberth's focus was on the proposal of technical devices. Their actual utilization and the motivation to realize them were secondary. Many decades later, a detailed review of these aspects seems necessary.

B) H. O. Ruppe: Astronautics: An Outline of Utility (1970)[111]

At first intended as a third volume of his "*Introduction to Astronautics*", Ruppe actually published his considerations in volume 10 of the book series "*Advances in Space Science and Technology*". The statement that the development of astronautics is costly in various ways serves as his initial point that leads to the question if astronautics' utility is worth all the efforts:

> "*But we know, also, that the successes come costly both in time and efforts in-*

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[111] Ruppe 1970.

> *volved – even human lives have been lost.*” (p. 140)

He then introduces three groups of reasons for spaceflight: Those having to do with direct utility, speculative reasons, and motives that “*are rooted deeper than utility: namely, in the fact that we are men*” (p. 140).[112]

Noteworthy is Ruppe’s use of the phrase *utility* instead of *benefits* of spaceflight as it is common today. This implies that his focus was on the potential *utilization* of astronautics for various applications, instead on the character of the utilization’s *results* as is the case in this work.

Similar to the view of this work, the value of science in general is not disputed by Ruppe, as it represents the first two sections of his view on spaceflight’s *obvious* utility. This is another indication that the actual results of space activities are not Ruppe’s major focus: For him, the *utilization* of space for science is an obvious reason to go into space. In this work, the *results* of future space related science and research are in the focus, which are unknown as well as afflicted with subjective value for each individual,[113] and therefore categorized as *subjective* benefits.

Physical interrelations play a major role in Ruppe’s work, considerably limiting the potential utilization of proposed spaceflight options (for example space mirrors). Actual technical implementation seems not to be a major aspect of Ruppe’s considerations. He certainly is aware of the requirements that the space environment imposes on hardware and operations, but the actual consequences for realization are not considered. Ruppe refers to potential availability in an undefined future:

> About utilization of extraterrestrial resources: “*[…] if lunar resources are available and can be exploited.*” (p. 239)
> About extraterrestrial settlements: “*If means are available to establish permanent settlements on the Moon or on Mars, or on other celestial bodies, then […].*” (p. 249)

In contrast, this work identifies the high requirements for realization of hardware resulting from the space environment as the key barrier for realization of space activities and deals with the consequences of this insight.

Required efforts for spaceflight are seen as roughly equivalent to costs in Ruppe’s work. Though he devotes a whole chapter to the *Cost of Astronautics* (chapter II.K), no relation of efforts and utility is considered.

Analogue to his colleagues at this time (and also to most current opinions!), Ruppe assumes a significant reduction of transportation costs in the near future and a constant decrease of costs, even without considering reusability, exotic propulsion and other technologies:

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[112] This wording is a notable anticipation of the *trans-utilitarian* purposes that are introduced about two decades later by Gethmann.

[113] The geology of Venus is interesting for planetary scientists, but not for the majority of people.

> "*[…] the transportation cost to the 96-min orbit can be reduced in 1970 to about 1000 \$/lb* [from Vanguard's 1.6 M \$/lb to LEO; note from the author]*, using the Titan 3C or Saturn 1B vehicles, and using them more than six times a year.*" (p. 199)[114]

And though he derives payload hardware costs as between 10^4 and 10^5 \$/lb, he assumes considerable reductions in the future analogue to space transportation. Thus it seems that, in contrast to this work, transportation costs are still seen by Ruppe as the major cost driver for the future.

Ruppe gives a comprehensive overview of the general potential of astronautics, with an early classification of reasons for spaceflight. But the proposed options are clearly influenced by the high spirits of the Apollo days during which his thoughts were developed, and a relation of efforts, benefits and motivation is not considered. Almost four decades later, a revisal seems clearly necessary.

Anyway, three characteristics of Ruppe's work are adopted for this work:

- Plenty of data is presented to give the reader an understanding of the according subject beyond the considerations of the author (for example presentation of previous space science missions to enable an understanding of the scale of scientific space activities).
- Ruppe's classification of reasons for spaceflight can be seen as a first rudimentary proposal of the categories of benefits in this work.
- Engineering considerations and computations verify or negate the technical feasibility of options, and additional equations and annotations allow additional considerations for the interested reader.

C) DLR: SAPHIR (1993)[115]

The comprehensive SAPHIR study that was initiated by the German aerospace agency DLR is sometimes seen as a benchmark for considerations about benefits of spaceflight. But though SAPHIR is very detailed, it covers only specific areas of spaceflight and neglects many aspects that were considered in this work.

SAPHIR is an acronym for "*Systemanalytische und philosophische Untersuchungen zur bemannten Raumfahrt*" (*system analytical and philosophical studies for human spaceflight*), with the actual main title being "*Technikfolgenbeurteilung der bemannten Raumfahrt*" (*technology assessment of human spaceflight*).[116] The title mirrors the focus of the study: Considerations of human spaceflight beyond economical and engineering aspects.

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[114] This number seems low at first sight. But applying common inflation factors and kg instead of lb, predicted cost is about 10 000 \$/kg to LEO – which roughly is the present transportation cost.

[115] Gethmann et al. 1993.

[116] Actually, the common term *Technikfolgenabschätzung* (*technology assessment*) is being replaced in the study by the enhanced term *Technikfolgenbeurteilung* (*technology evaluation*, literally *evaluation of consequences of technology*), which includes additional normative aspects, meaning consideration of ethical aspects.

The study's approach relies strictly on *Wissenschaftstheorie* (*philosophy of science*). It is therefore humanistic, in contrast to the engineering approach of this work. Certain prerequisites are stated in SAPHIR under which its systematic approach is developed.

First of all, the efforts of spaceflight are mentioned, but they are not further considered, though they are presented in two parts of SAPHIR: Chapter 3 *Bestandsaufnahme* (*survey*) and chapter 6 *Mensch – Systemtechnische Aspekte* (*human – system engineering aspects*). While cost numbers are derived for past and current human flights in chapter 3, these numbers are limited on space transportation only and are not further applied. Additional to transportation, chapter 6 also takes requirements for operations in space into account. But, consistent with the whole study, these requirements are limited on manned operations (including radiation limits, habitation volume, …). No cost numbers are mentioned in chapter 6, and consideration of costs is consequently neglected throughout the study.

This neglect of costs – and therefore of any economical aspects – is in compliance with the objective of SAPHIR. The focus is on technology assessment, with aspects that were disregarded in the then current debate about human spaceflight:

> "*Ökonomische Wechselwirkungen werden daher nur am Rande berücksichtigt. Denn es wird vorausgesetzt, dass eine rein ökonomische Rechtfertigung der bemannten Raumfahrt zur Zeit und in absehbarer Zukunft nicht möglich ist.*" (p. 100)

With this, a certain amount of efforts and costs is attributed to human spaceflight, but their meaning for actual realization of space activities is not further considered.

In contrast, this work states that efforts are analogue to costs, and that space activities are only realized if the costs are paid by someone. This is the initial point for detailed analysis of current efforts and costs, potential future reduction of efforts and costs, and the motivation of entities to meet these costs in anticipation of benefits. This part, which presents the baseline for the analysis of benefits, is completely eluded by SAPHIR. And while SAPHIR states that transportation costs are the major limiting factor for spaceflight (p. 412), this work identifies the hardware and operation costs in space as the decisive part of space activity costs: Even cost free space transportation would not result in extended spaceflight.

Another major difference concerns the prediction of future developments. In this work, the probable future situation of efforts and costs for spaceflight is derived, and in combination with various types of benefits, promising topics for future space activities are identified. SAPHIR is limited on potential future purposes of human spaceflight:

> "*[…] Konsistent mit diesen bedingten Einschätzungen ist der Verzicht auf quantitative Prognosen, etwa über den zukünftigen Bedarf an Raumfahrt, über die Entwicklung technischer Leistungsmerkmale oder die Kosten von Raumfahrt-*

projekten.“ (p. 106)

Furthermore, SAPHIR’s developed approach is applied to only three space ventures: Solar power satellites (SPS), resources from space, and exploitation of Mars. Results are that SPS and space resources can contribute to human development in the foreseeable future and continuation of present human spaceflight is therefore recommended to enable these options in the near future. Mars exploration and exploitation meets many trans-utilitarian purposes, but is not time critical, and the argument to continue human spaceflight “to enable the option” is not relevant.

This work includes the space endeavors considered in SAPHIR among numerous other topics that may create sufficient benefits to motivate an entity for engagement in spaceflight. And not potential continuation of public founded spaceflight is in the focus, but identification of promising new topics. That current manned space activities should be continued for various reasons is just one result of the applied approach of this work.

Finally, while SAPHIR is limited on human spaceflight, this work disbands the classification of manned and unmanned missions in favor of the mission objective: If human presence is required for (or might support the) achievement of the mission objective, it will be applied. But if the benefits resulting from the specific objective are insufficient, the mission will not be realized.

SAPHIR can be seen as an important supplement that gives detailed and valuable insights about trans-utilitarian benefits of human spaceflight. It is a guideline for ethical and philosophical considerations about manned missions that can rely on existing governmental funding. But this situation only occurs either when a government decides to actively pursue human spaceflight but is unsure of which approach to take, or when continued spending for an existing human space program must be justified.

D) R. H. Schmucker, M. Schiller: Nutzen der Raumfahrt (2005)[117]

In 1990 Schmucker started a lecture at the Technical University Munich on “*Nutzen, zivile Anwendungen und Kommerzialisierung der Raumfahrt*” (*Benefits, Civil Applications and Commercialization of Spaceflight*, now *Nutzen der Raumfahrt* or *Benefits of Spaceflight*). As a former student of Ruppe, he was inspired by his approach on benefits, which clearly had an influence on the lecture’s approach. The lecture was redesigned and renamed several times during the years, and – though it was already slightly influenced by the author – the print version of the lecture’s script that was created by the author in 2005 may serve as exemplary for the then state of Schmucker’s considerations. Though not published in scientific literature and therefore not an acknowledged contribution to the debate about space benefits, the script for the university lecture “*Nutzen der Raumfahrt*” is essential for this work.

The three characteristics of Ruppe’s work that were adopted for this work were also adopted by the lecture: Plenty of data, a rudimentary classification of reasons for

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[117] Schmucker et al. 2005.

spaceflight and typical engineering considerations.

A first statement of minimum efforts for spaceflight is introduced by Schmucker and applied on some of his considered topics. But these considerations are limited on transportation only. Contrary to this work, costs and efforts for hardware and operations are ignored. The continuously high level of transportation costs that is assumed by Schmucker is used to dismiss some selected proposals for future space activities, but there is no stringent application of a well-founded level of efforts in comparison to expected benefits.

Schmucker also introduces the three elements of society and postulates that spaceflight must somehow make a positive contribution for them, thus basically creating a need for motivation.

> "*Wie kann Raumfahrt zum Zusammenspiel von Individuen (Privathaushalte), Staat und Unternehmen einen positiven Beitrag leisten?*" (p. 10)

But this rudimentary approach towards motivation remains vague: Only profitability of space ventures has a central position in the lecture due to the baseline that any activity is only realized regarding to return on investment. Therefore, the commercialization of spaceflight is in the focus of Schmucker's considerations.

This work seizes this basic approach of profitability, but only for one of its four categories of benefits. And the considered topics are significantly more diverse and detailed than Schmucker's (for example, there is only one page of considerations on tourism and advertising in the script, and other topics such as space burial are not considered at all).

Compared to Ruppe, the classification of topics is extended, but not as fundamental as Ruppe's diversification of reasons. Schmucker classifies the considered topics into social and cultural topics (chapter 3 *Soziokulturelle Bedeutung*), spin-offs (chapter 4 *Erdgebundene Anwendungen von Raumfahrttechnologien*), and two parts focused on commercial aspects (chapter 5 *Kommerzielle Aspekte von Raumfahrtoperationen und -hilfsmitteln* and chapter 6 *Nutzung des Weltraums*). Contrary to this work, potential benefits that might have a major impact in the future are not considered; especially military space is only a short footnote among social topics (chapter 3.1.1).

As a consequent result of his approach, Schmucker sees Earth application satellites – with navigation, communication and Earth observation – and space transportation as spaceflight's most important topics:

> "*Die wichtigsten kommerziellen Themen sind Kommunikation, Navigation und Erdbeobachtung und Raumtransport.*" (p. 115)

But there also is an early hint on the potential utilization of spaceflight for individual safety which is not further considered:

> "*Raumfahrt als Mittel zur Befriedigung des Sicherheitsbedürfnisses des Individuums hilfreich und sinnvoll.*" (p. 115)

In <u>this</u> work, spaceflight's contributions to security and safety are identified as essential, with an almost insignificant role of commercial Earth application satellites.

Schmucker's lecture served as a basic outline for <u>this</u> work, but it can only incite further detailed considerations. Many of his considerations are incomplete, resulting in different conclusions than <u>this</u> work.

E) Summary of Comparison

The selected assessments compare to this work as is seen in **Table 2-5**.

Table 2-5: Key Characteristics of Considered Assessments

	Oberth 1923-1957	**Ruppe 1970**	**SAPHIR 1993**	**Schmucker 2005**	**Schiller 2008**
Baseline	Physics, Engineering	Physics, Engineering	Philosophy, Sociology	Engineering, Economics	**Comprehensive**
Analyzed Topics	Few	Various	Human Spaceflight Only	Comprehensive	Comprehensive
Identified Key Effort	None	Transportation	Transportation	Transportation	Transportation and **Hardware & Operations**
Key Effort Regarded	No	Yes	No	Yes	Yes
Expected Future Efforts	Low	Decreasing	Not Considered	Significant Reduction Unlikely	Significant Reduction Unlikely
Approach	Mathematics	Physical Feasibility	Ethical Considerations	Profitability	**M = B - E**
Regard of Motivation	No	No	No	No	**Yes**

In general, most authors of works about benefits of spaceflight focused their considerations on human spaceflight that is financed by governmental entities. Many authors did indeed recognize that extended space activities can never rely only on trans-utilitarian arguments alone. But no one ever developed an approach that allows a judgment of all arguments for spaceflight as well as any type of space activities – an approach that, if applied on the past, also explains the historical development of spaceflight and its current status.

Unification of utilitarian and trans-utilitarian arguments for spaceflight is one major achievement of this approach. Other contributions of <u>this</u> work that might give new inputs in the current debate about benefits of spaceflight are:

- Approach “Motivation = Benefits - Efforts”
- Introduction of a combined Spaceflight Threshold consisting of transportation and hardware&operations
- Insight that space transportation costs are not relevant for current and future activities (hardware costs for operations in space are decisive)
- Categorization of benefits: subjective, quantifiable, byproducts, potential
- Decisive role of military space and its resulting benefits
- Identification of “Distance to Earth” as the only relevant characteristic of the space environment
- Categorization of spaceflight: Idealistic, commercial, preventive
- Past and current meaning as well as future potential of the three categories of spaceflight
- Demand of a new term for “spaceflight” or “astronautics” that shifts the focus from transportation to functionality and activities in space

2.3.4 Summary of Previous Results and Shortcomings

The results of most current considerations about benefits of spaceflight are of a similar tenor, stating that human spaceflight is essential mainly due to social and cultural aspects.[118] And most of them have decisive shortcomings:

- Limitation on a small area of spaceflight (mainly human spaceflight done by space agencies)
- Concentration on benefits with stepmotherly treatment or complete ignorance of required efforts and costs
- No comparison of efforts and benefits
- Confusion of benefits and motivation
- View of spaceflight enthusiasts (with a shift towards subjective arguments by authors who are closely related to and clearly fascinated of spaceflight)
- Significant reduction of efforts anticipated for the near future

Throughout history, the high costs of space transportation were seen as the major barrier for extensive space activities, with the expectation that this barrier would soon be neutralized. This anticipation continues to the present day, as is illustrated by exemplary historic cost projections in **Figure 2-8**.

Additionally, many considerations are limited only on justifying the current budget level and activities of governmental space agencies, mainly NASA, and do not consider new tasks in space.

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[118] Marsiske 2005, Genta and Rycroft 2006 (Genta et al. 2006), Robertson 2006 (Space News 9-2006), Pagel 2006, Gethmann 2006, Thiele 2007, Griffin 2007 (Griffin 2007 and Space News 11-2007), … .

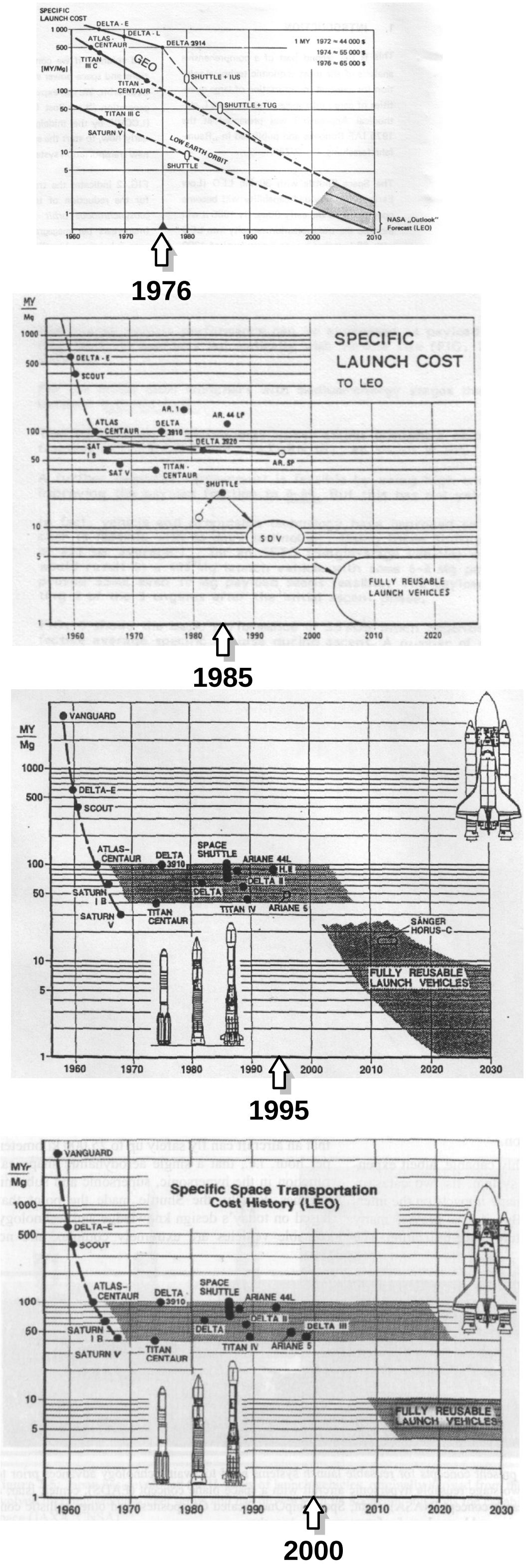

Figure 2-8: Expected Space Transportation Cost Reduction[119]

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[119] Koelle 1976, 1985, 1995, 2000.

It seems that in Germany, beginning in the 1980s, the debate about spaceflight drifted towards a justification of human spaceflight, and is now locked on the philosophical aspects of manned flights. But this is only a very small area of the wide field of spaceflight, of its utilization and its benefits.

In general, subjective topics are preferred in literature, resulting in soft justifications that depend on individual perception. Only very few, rarely noticed works consider the objective benefits of spaceflight and their resulting hard arguments pro or contra spaceflight. And if these arguments turn out to be negative, they withdraw to subjective topics to shed a positive light on spaceflight.

But this debate seems to be stuck. The long lasting pleading for increased spaceflight funding by using subjective, trans-utilitarian arguments seems not to have resulted in an increase of space agencies' budgets, and the role of trans-utilitarian and idealistic arguments for spaceflight was not decisive in the past, as is seen in the next paragraph and as was also stated by others.[120]

But the same idealistic arguments for manned spaceflight are repeated again and again. There seem to be no new arguments in the debate for the benefits of and motivation for spaceflight for many years now.[121]

Additionally, the efforts that spaceflight requires and the costs that inevitably result from the efforts are either ignored or seen as continuously decreasing in the near future. Most considerations that propose extensive space activities remain vague about their funding entity.

Therefore, it is necessary to understand the mechanisms for realization of large space ventures, and to analyze a number of topics to identify promising new space endeavors and their potential financiers instead of justifying a vague, general need for spaceflight.

A comprehensive assessment of *all* aspects of spaceflight is therefore required.

2.4 Identification of the Historical Driving Factors of Spaceflight

In combination with the historical overview of spaceflight, five categories of motivation can be identified that were decisive driving factors for the historic development of spaceflight. Each category contains numerous motives. This is important for later considerations.

The *adventure* aspect of spaceflight dominated from the first thoughts about journeys

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[120] "Attempts to find rationales for ambitious and expensive space exploration programs have appealed to intangible benefits such as national prestige, human needs to explore the unknown and various spinoffs, usually after a program has been proposed and funding is sought. These attempts have not brought about funding." (Woodcock 1994)

[121] "Es ist schon alles gesagt, nur noch nicht von allen [*Everything is said, but not yet by everybody*]." Karl Valentin, Munich comedian, 1882 – 1948.

to space up to the pioneers of rocketry – of course, Goddard, Valier, the VfR and all of their associates justified their studies and experiments with scientific reasons, and their scientific results still are of great value. But they would never have concerned themselves with rocketry and space without the one crucial aspect: *Personal interest* and the resulting pure *fun*.

But achieving a large scale breakthrough in rocketry and enabling the first contact with space required a different motive: *National security*, in this case armament. Rocketry was a small scale engineering “fun discipline” until the massive funding of the military enabled development of the first large rocket, the A4, being considered the ancestor of every successive ballistic missile and space launch vehicle.

After World War II, rocketry was extensively funded in the USSR to gain access to Intercontinental Ballistic Missiles (ICBMs) – again armament as a driving factor. This resulted in the launch of Sputnik 1 only as a byproduct that was declared as a scientific contribution to the international geophysical year.

The reactions to Sputnik 1 triggered the Space Race, seemingly adding national prestige to the continuously important military aspect. But Kennedy’s quotes that were presented in chapter 2.2.4 clearly show that he, as a politician, was only interested to beat the Soviets and demonstrate superiority and leadership. Spaceflight was just a handy tool to do this. The same must be assumed for the Soviet side, and so, for the creation of the Space Race. That the Soviet and U.S. people felt pride due to their achievements was only a welcoming byproduct, as was an increase of jobs, new scientific insights and technological spin-offs. Therefore, the driving factor of the civil side of the Space Race can be summarized as *politics*.[122]

Political support subsided after the triumph of the U.S. Apollo landings, and *science and research*, paired with the political aspect of job retention, became the driving factors for civil spaceflight activities.

Compared to aviation, *commercial* interests never got a real hold on spaceflight. For most projects, the expected revenues never seemed to justify the huge expenses. There are exceptions, such as various Earth satellite and launch service providers, and therefore, this motive is further considered as a driving factor. But even these examples rely heavily on previous and present governmental support in some ways, as will be shown later.

The current entrepreneurial activities for future space tourism are sometimes seen as an important driving factor for present and future spaceflight development. But in the end, space tourism – just as terrestrial tourism – is developed to generate profits for these companies, and thus for commercial reasons.

Therefore, the motivation for past spaceflight and rocket activities can be classified

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[122] “[The Space Race] was driven entirely by geo-political objectives and although space enthusiasts, led primarily by NASA, ascribed other motivations such as exploration and science to the space programme, particularly to the Apollo programme, its primary objective was purely political, to beat the Soviets.” (Fawkes 2006)

into the five categories

- Adventure, fun and personal interest,
- National security,
- Politics,
- Science and research,
- Commercialization,

which are depicted over time in **Figure 2-9**, with the thickness of the line as an indicator for the significance of the motivation.

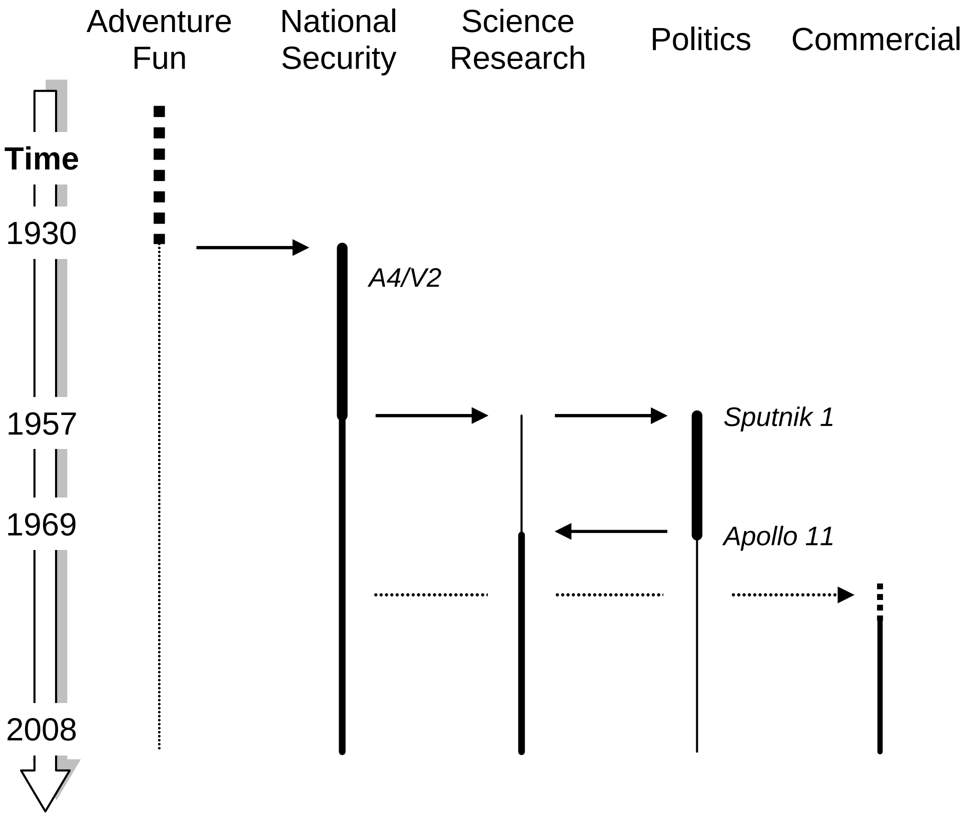

Figure 2-9: Significant Motivations for Spaceflight Over Time

A proposed relation of the postulated five categories and the motives that were listed in chapter 2.3.1 can be seen in **Figure 2-10**. The categories are overlapping and the attribution is subjective.

This gives a first glance on the importance of motivation for spaceflight. A pattern of correlation between the scale of spaceflight activities and their driving factor already seems visible. This must be remembered for further analysis, and will be discussed in detail in chapter 4.2.5.

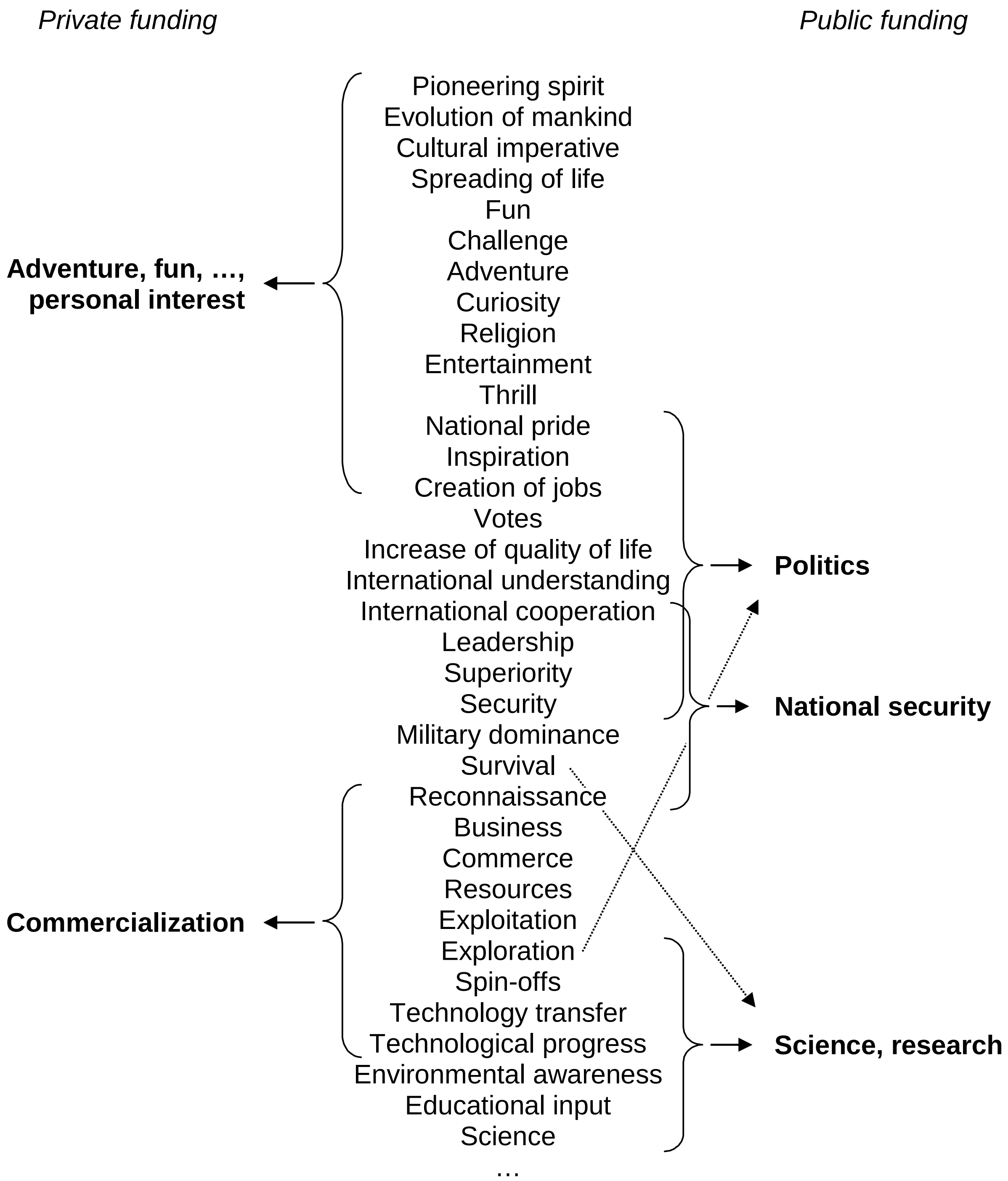

Figure 2-10: Attribution of Motives to Categories

2.5 The True Situation of Spaceflight

The discussion about spaceflight's benefits and motivation is currently focused on manned spaceflight and, to a lesser degree, on the scientifically oriented missions of national space agencies, presumably NASA. The public perception of spaceflight also seems to be focused only on the Space Shuttle and the Space Station. This focus is essentially wrong.

A) Scale and Type of Global Space Activities

Money spent is a clear indication of the scale of activities. With this, the current scale of activities and their distribution within the spaceflight sector is visible in **Figure 2-11**.

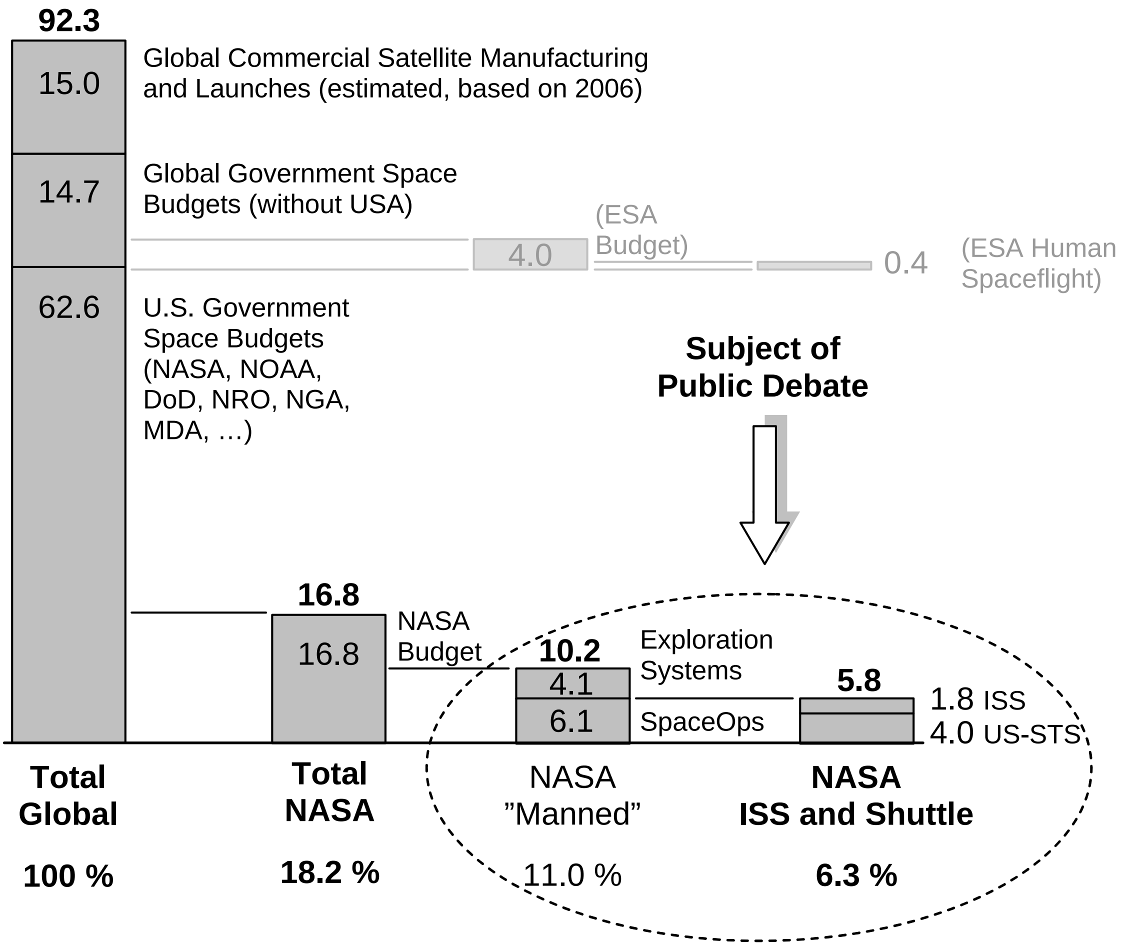

Figure 2-11: Scale of 2007 Space Activities [G $][123]

NASA spends about 10 G $ per year on human spaceflight, of which 40 % are spent on future VSE preparations. For the U.S., manned spaceflight is only roughly one sixth of governmental spaceflight spendings. Of the total global space budget 2007 of more than 90 G $ – including commercial satellite activities –, the fraction that is spent for manned spaceflight must be estimated as even less. Therefore, the major part of discussions about pros and cons of spaceflight is limited to less than one sixth

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[123] SIA 2006, Space Foundation 2008, Space News 6-2007, ESA 2007. Exact figures vary between sources, but accuracy is sufficient for qualitative statements.

of the global, space related activities.

To further underline the claim that current debates are focused on side shows: Costs for development and launch of Europe's first ATV supply vehicle was previously stated as 1.9 G $, and is subject of public discussion.[124] But the high costs of space programs that are not part of civil space agencies are never discussed, considered, or even mentioned: As an example, it is estimated that two Advanced KH-11 spacecraft to bridge a looming gap between USA's "KH-11" and "FIA" programs are currently built for 15 G $.[125]

It must be understood that current spaceflight is a lot more than launching Space Shuttles and communication satellites.

B) Meaning of Spaceflight for the Public

It is also important for any further considerations to understand the true meaning of spaceflight for the public. This will be especially important for pro-spaceflight arguments that assume a broad public interest in spaceflight.

The average citizen has a very low interest in spaceflight. This is repeatedly proven by various polls in diverse countries for several decades as well as in statements of celebrities and politicians concerning spaceflight. To give a few examples:

- German poll, 2004: "Would you like to fly into space and orbit Earth? If yes, how much money are you willing to spend for such a journey?"
  Only 11 % were willing to fly into space. And of those who were willing to fly, 20 % would spend no more than 500 €. Only 1 % was willing to spend up to 500 000 €.[126]
- German poll, 2004: "Should the wealthy industrial countries together undertake a manned mission to Mars?"
  Only 15.5 % said that they should. More than 75 % were against this proposal.
- U.S. survey, 2007: People were asked by the University of Chicago whether current spending for a wide array of government programs is too little, too much, or about right.
  Of 22 named government programs, 'space exploration' ranked on 21, with only 'foreign aid' doing worse.[127]
- U.S. poll, 2007: "If spending had to be cut on federal programs, which two federal program(s) do you think the cuts should come from?"
  Among 11 listed programs, 'space program' ranked first with 51 %. Second was 'welfare' with 28 %.[128]
- U.S. poll, 2008: "If you had to choose from the following categories, what do you believe should be the highest priority, in terms of investing money and

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[124] Space News 5-2008.
[125] AW&ST Feb 4 2008.
[126] GEO Wissen Nr. 33 2004.
[127] Smith 2007.
[128] HarrisInteractive 2007.

resources, in order to achieve a meaningful technological advancement in the next 10 years?"
Two thirds opted for 'fuel efficiency and alternative fuels' or 'medical'. Only 3 % opted for 'space exploration'.[129]

- The same poll was also done in Great Britain in 2008, with even more devastating results: Only 1 % opted for 'space exploration'.
- Commentary in "The Space Review", 2007: "Space is near the bottom of the list of topics of interest to the electorate in general, and one that is not a swing issue for all but a small handful of voters."[130]
- Reply of Pablo Picasso, being asked about the first Moon landing, 1969: "It means nothing to me. I have no opinion about it, and I don't care."

C) Trans-Utilitarian Benefits

The urge to justify space activities with arguments that go beyond direct and quantifiable benefits is old, but it gained support in the early 1970s when funding for manned spaceflight subsided in the wake of the Apollo program. Proponents of these arguments talk about spaceflight benefits of social, cultural and philosophic character. These types of benefits are also referred to as trans-utilitarian.

The proponents of these benefits claim that unmanned spaceflight is hardly subject to critics.[131] Trans-utilitarian arguments are limited to manned spaceflight, as the advocates of pro-spaceflight arguments with trans-utilitarian character frankly state themselves.[132]

With the current share of manned spaceflight on total space activities (see paragraph A), the trans-utilitarian arguments can be relevant for only about 15 % of the current total spaceflight activities.

Nonetheless, because they are central for the lasting debate about manned spaceflight, these arguments and the according benefits will still be discussed in chapter 5.

D) Consequences

For the most part, considerations and debates about spaceflight focus on a small area of space activities. Currently, this area is manned exploration. Because this specific topic is impossible to justify with economic cost-benefit approaches, other benefits are used for justification, preferably of social, cultural and philosophic nature. But spaceflight is a lot more than scientifically oriented human spaceflight.

This again means that a comprehensive approach to *all* aspects of spaceflight is required. Arguments that are limited specifically to human spaceflight should be covered, too, but they can only be of minor relevance.

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[129] Fairfax 2008.

[130] Foust 2007.

[131] Gethmann 2006.

[132] Puttkamer 1992, Gethmann et al. 1993, Marsiske 2005, Genta et al. 2006, Robertson 2006, Gethmann 2006, Griffin 2007 and many others.

2.6 Objectives and Outline of Further Analysis

Various questions are now to be answered:

- What are the basic characteristics of spaceflight?
- Under what aspects must space related topics be considered?
- Why is spaceflight so demanding and expensive?
- Can the required efforts be reduced in the future?
- Regarding the efforts, who is motivated *and* capable to do spaceflight?
- Which space activities create sufficient benefits to outweigh the efforts?
- What might be the future direction of spaceflight activities?

To answer these questions, the challenges of going to space must be analyzed and systemized first, creating a realistic basis of evaluation for *any* type of spaceflight activities. The results then need to be applied to numerous topics that might make use of spaceflight. This is achieved by the following steps:

- Identification of the basic characteristics of spaceflight resulting in the new definition of a threshold that is unique to spaceflight, and definition of the approach to the motivation for spaceflight (chapter 3).

- Detailed analysis of two decisive aspects for any spaceflight activitiy: Efforts (consisting of transportation and hardware&operation) and motivation. This gives a new basis for the subsequent evaluation of spaceflight topics that might create benefits (chapter 4).

- Evaluation of a large number of topics that spaceflight might make a contribution to. For reasons that are identified later, these topics are categorized into four classes (chapters 5 to 8).

- Discussion of the new results and conclusions for potential future space development mechanisms (chapter 10).

It is not the objective of this work to search selectively for benefits of spaceflight that might justify an increase of national space agencies' spendings for manned spaceflight.

The objective of this work is to understand the basic mechanisms of spaceflight and the benefits of various space activities. This is done to understand under which circumstances any type of spaceflight *was* done in the past and *is* done in the present, and to use this understanding to estimate *what* activities in space might be realized in the foreseeable future.

3. New Approach to the Motivation for Spaceflight

Identification of the basic characteristics of spaceflight leads to the definition of the new approach to the motivation of spaceflight.

3.1 The Basic Characteristics of Spaceflight

Though the first orbital flight was conducted about 50 years ago, spaceflight still is far from a breakthrough to routine operations comparable to other fields of transportation. Though the exact classification of events might be subject to discussion, **Figure 3-1** gives a rough idea of realization timeframes.

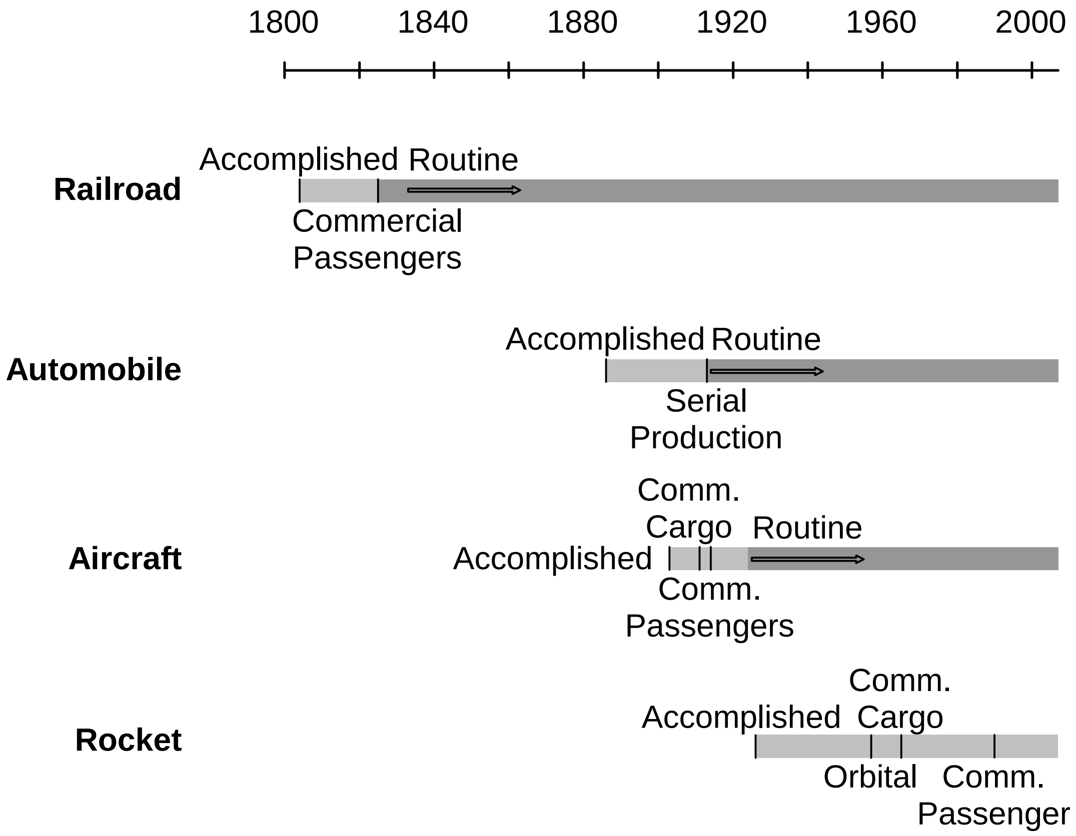

Figure 3-1: Realization of Modern Forms of Transportation

The comparison of astronautics with other forms of transportation in terms of the velocity v in **Figure 3-2** unveils another exceptional position of spaceflight.

The same is true for the average payload capacity m_p related to the total mass m_0 that is significantly lower for space vehicles than for other vehicles, as is presented in **Figure 3-3**.

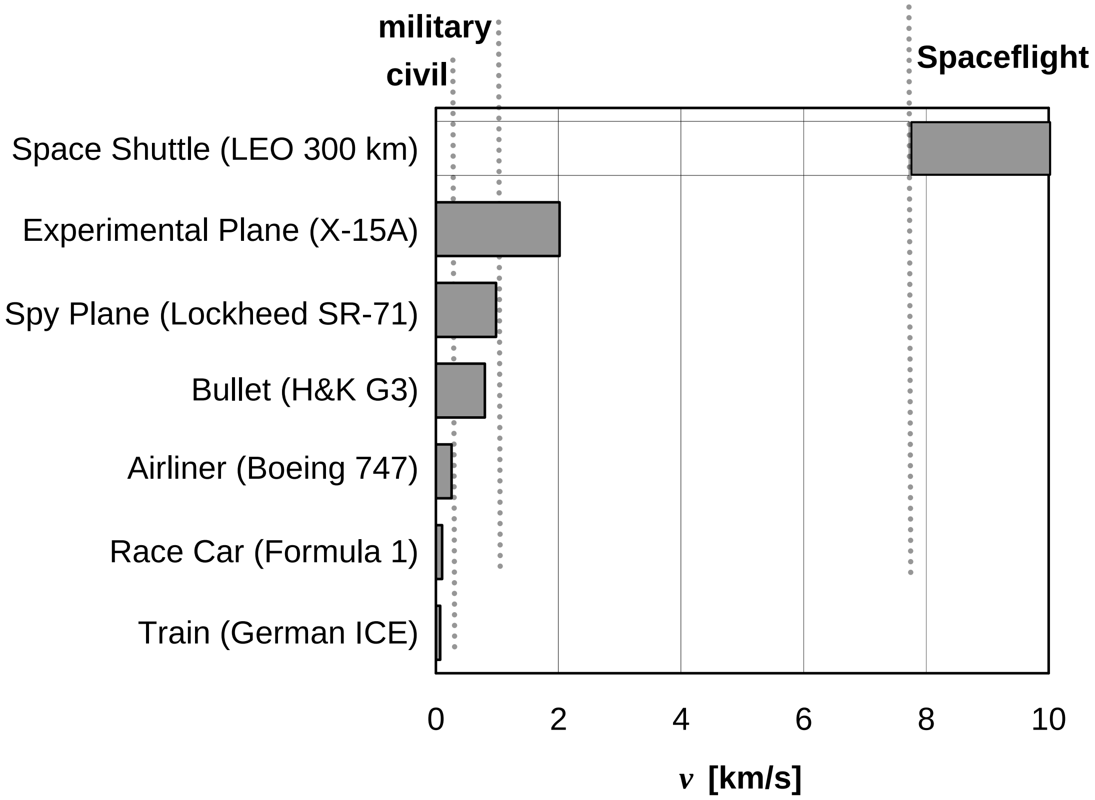

Figure 3-2: Velocities of Various Objects

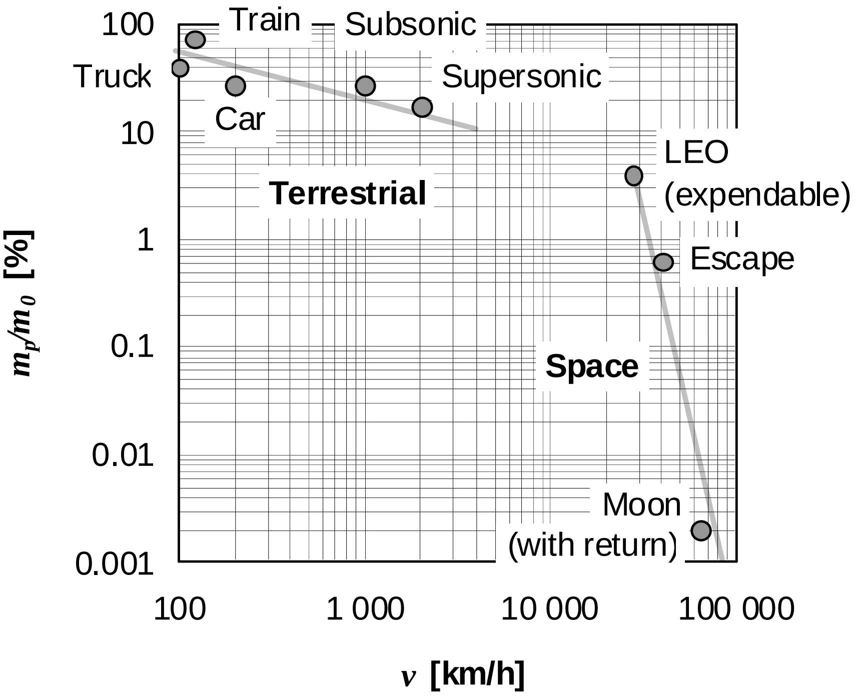

Figure 3-3: Payload Fractions of Various Fields of Transportation

These facts could lead to the conclusion that the technical development of space transportation systems is still at its beginning, and a breakthrough will be achieved if only the efforts are increased or better directed. A closer view on the past and present scale of spaceflight development efforts can verify or neglect this assumption.

3.1.1 The Order of Magnitude of Historical Spaceflight Efforts

Comparing spaceflight (and, with it, rocketry) programs of the past with other development and engineering programs, as in **Table 3-1**, the tremendous financial efforts and manpower that were required for realization become visible. The Apollo lunar landing and the A4 rocket development are confronted with the famous U.S. Manhattan Project for nuclear weapon development, and the greatest engineering project of the 19th century, the Suez Canal.

Table 3-1: Great Engineering Projects of the Past

	Suez Canal	**Manhattan Project**	**A4 Missile**	**Apollo Program**
Objective	Artificial Waterway	Nuclear Weapon	Ballistic Missile	Manned Lunar Landing
Achievement	1869	1945	1943	1969
Duration [a]	10	3	10*	8
Estimated Cost (ca. 2000) [G $]	0.25[133]	8[134]	20[134]	105[135]
Peak Employment Rate		130 000[136]	several 10 000s	300 000[137]

* Including pre-programs.

The comparison shows that efforts for rocket and spaceflight activities exceed those of other fields of technology.

This is underlined by the long development durations of space projects. **Figure 3-4** presents the timeframes for realization of spaceflight in selected countries. The “development start” dates may be subject of disputes, because the term is not clearly defined and the date is not easily determined.

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[133] In Deutsche Mark: 0.5 billion. (Walter 2001)

[134] Neufeld 1999.

[135] Griffin 2007.

[136] Wikipedia 2007.

[137] Brockhaus 1979.

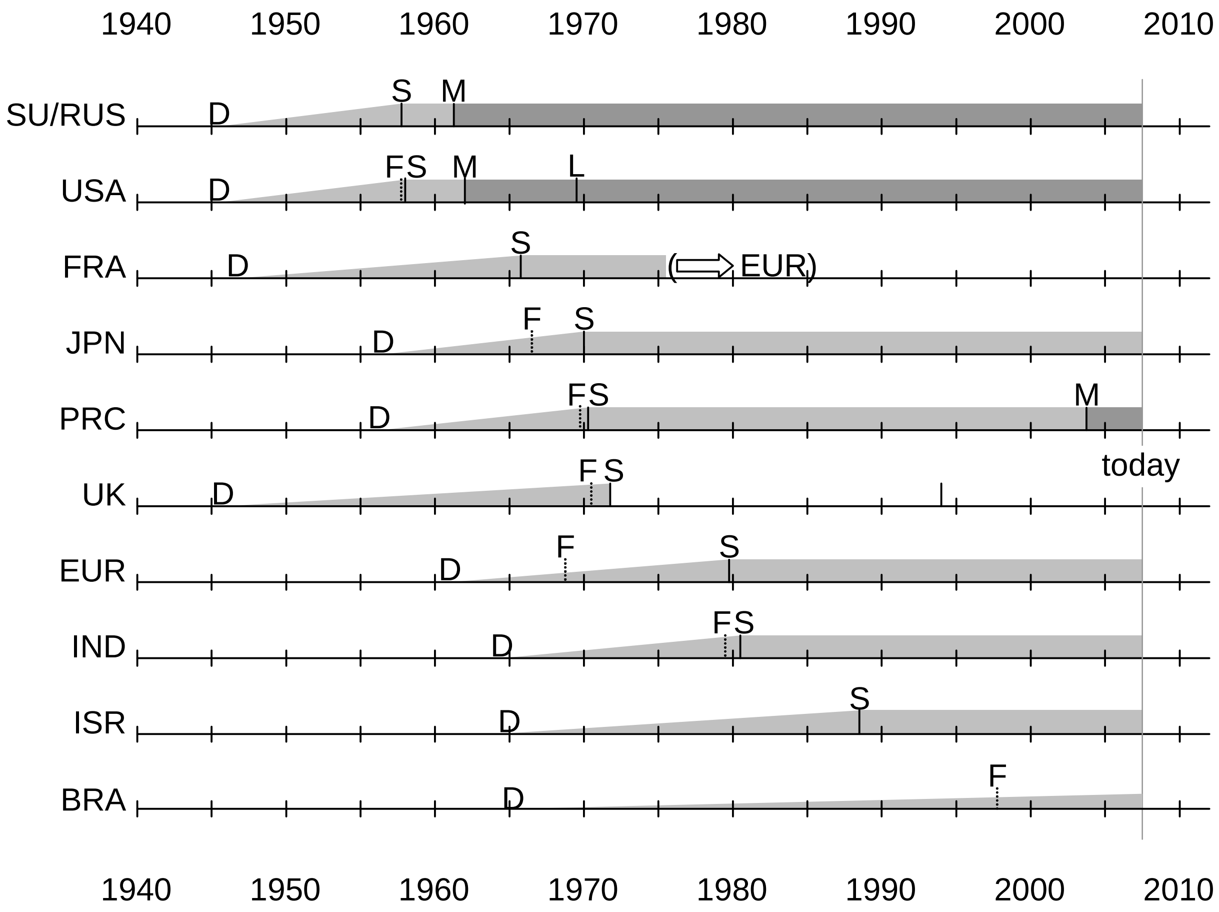

Figure 3-4: Realization of Spaceflight in Various Countries[138]
D: Development Start, F: First Orbital Launch Failure, S: Orbital Launch Success,
M: First Manned Orbital Launch, L: First Manned Lunar Landing

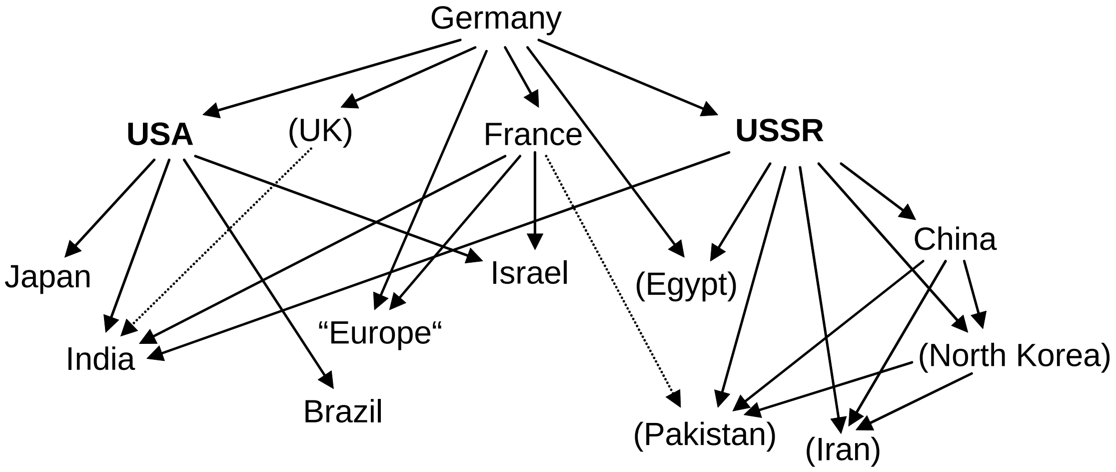

Figure 3-5: Support Lines of Rocket and Space Technology Development[139]

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[138] Wade 2007.
[139] Schmucker 2007.

It must be further noted that each of the listed countries achieved its successes only with support from other countries, as seen in **Figure 3-5**. This help included advice, instructions, documents, hardware and/or experts. There are no straightly indigenous developments on the sectors of rocketry, and thus, of spaceflight.[140] This underlines the challenging high requirements of the subject.

The first major rocket program was the German A4 missile development, beginning in the 1930s. Since then, spaceflight and rocketry were intensely promoted and funded in numerous countries. The first artificial satellite was launched five decades ago from now, and still, spaceflight is extremely demanding and one of the most challenging technical subjects of our time. Since astronautics are often seen as an extension of aviation, comparing both from an engineering perspective may unveil the reasons.

3.1.2 Aviation and Astronautics

Spaceflight is often seen as the next logical step of aviation. Most concepts of future space transportation systems are winged and resemble aircraft, and numerous studies as well as science fiction films and novels present the future spaceflight situation as similar to the present air traffic.

Table 3-2: Spacecraft and Aircraft Launches

		Boeing 747	**US-STS**[141]	**Ariane 5 ECA**[142]
Launch location		Numerous	KSC, Florida, USA	CSG, Kourou, French Guiana
Destination		Intercontinental	LEO	GTO
Straight Distance [km]		ca. 10 000	300	560 / 35 890
Flight Duration		ca. 12 h	8.5 min	24.5 min
Launch Preparations	Planning	Days	Years	Years
	Intensive	1 h[143]	min. 50 d	ca. 90 d
Turn-around time		1 h[143]	min. 50 d[144]	-
Number of Persons required per Launch		< 20	16 000[145]	
Launch Cost [M $]		< 0.5	1 000[146]	ca. 150
max. Payload [t]		246[143]	22.75[147]	10.05

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[140] Schmucker 2007.
[141] NASA 2007.
[142] ESA LVC 2004.
[143] Boeing 2002.
[144] Shortest turn-around: Orbiter OV-104 Atlantis, STS-51J to STS-61B, October to November 1985.
[145] NASA STS-116 2006b.
[146] Current annual NASA “Space Operations – Shuttle” budget (4 G $) divided by number of flights (4).
[147] Heaviest delivered payload, Chandra X-ray Observatory, STS-93.

But the efforts required for a single space launch are still far from daily routine activities such as transatlantic flights, as seen in **Table 3-2**.

Aviation and spaceflight differ in many more ways than commonly expected. These differences originate not only in the physical requirements, but also in more fundamental aspects, as seen in **Table 3-3**.

Table 3-3: Fundamental Differences between Aeronautics and Astronautics

Topic	Aeronautics	Astronautics
Atmosphere	Required	Interfering*
Wings	Required	Interfering*
Minimum Velocity Requirement	Sufficient Lift Force	Orbital
Maximum Velocity Restriction	Optional	Orbital
Av. Mission Velocity [km/h]	Hundreds	Tens of Thousands
Refueling Stops	Optional	Impossible
Propellant Carriage	Fuel only	Fuel and Oxidizer
Consequences of Minor Failures	None up to Unscheduled Landing	Catastrophic
Available Failure Correction Mode	Unscheduled Landing	None
Practical Flight Envelope Testing	Stepwise	Entire Mission

* Except for reentry.

The huge performance differences of aircraft and spacecraft become visible with a look on their operating altitudes and velocities, as illustrated in **Figure 3-6**.

The average cruise velocity of civil airliners is about 0.25 km/s; the velocity of a US-STS Orbiter is about 30 times higher. And the picture does not change for military aircraft: Though the flight envelopes of military aircraft extend those of civil aircraft, the difference is negligible compared to an orbital spacecraft.

And Figure 3-6 illustrates another interesting insight. The often stated “first commercial spaceflight” of Scaled Composite’s SpaceShipOne took place in June 2004. A maximum velocity of 0.98 km/s at an altitude of 64.9 km and a maximum altitude of 112.014 km (the flight profile leads to the assumption of zero velocity at peak altitude) were achieved at test flight 66L/17P in October 2004.[148]

North American’s X-15A reached a maximum altitude of 107.960 km on August 22, 1963 and a maximum velocity of 2.02 km/s at an altitude of 31.12 km on October 3, 1967.[149]

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[148] Scaled Composites 2006.

[149] Jenkins 2000.

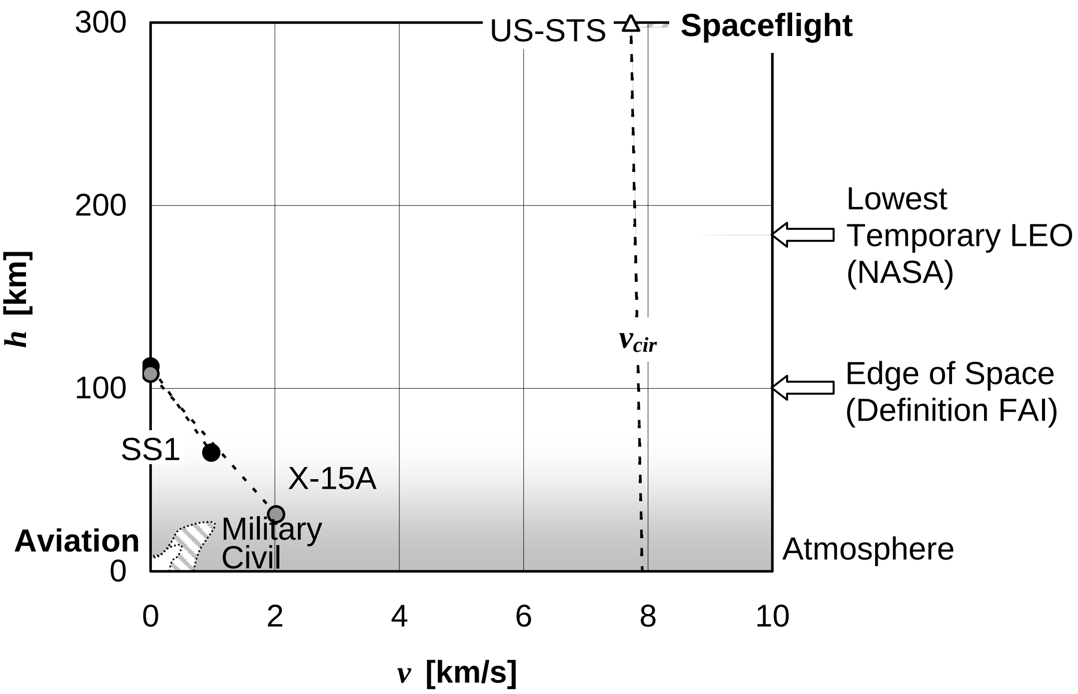

Figure 3-6: Velocity and Altitude of Aviation and Spaceflight

Both X-15 and SpaceShipOne are often referred to as a link between aircraft and spacecraft, but as is clearly seen in Figure 3-6, both so-called suborbital spacecraft remain close to the area of aviation. It seems that the early insight of Johannes Kepler in the early 17th century – that aviation and spaceflight are something completely different[150] – still remains buried in present times.[151]

So, for further considerations, a clear definition of spaceflight must be done to clarify its unique position compared to terrestrial disciplines, and to understand the resulting high requirements, and with it, costs, that come with any spaceflight benefits.[152]

3.1.3 A Clear Definition of Spaceflight

Space is commonly defined by minimum altitude. Two authorities are cited for the definition of space:

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[150] Miller 1993.

[151] There might be a simple explanation for the worldwide assumption that suborbital is as good as orbital: Alan B. Shepard is still regarded “first American in space” (Wade 2007) due to his suborbital Mercury flight of May 5, 1961. Regarding only orbital flights as spaceflights would have disgraced the U.S. space program and, at that time, further promoted Gagarin’s earlier orbital flight of April 12, 1961. Though John Glenn finally reached orbit on February 20, 1962, this view consolidated over the years.

[152] To illustrate the controversy and difficulty of defining “spaceflight”: In personal conversation with the author, astronaut Ulrich Walter saw no clear definition at all, while astronaut Gerhard Thiele proposed the US-STS Abort To Orbit (ATO) as a minimum spaceflight criterion. Robert Schmucker pledged for a minimum of one completed orbit, as demonstrated with Gagarin’s historical flight.

- The Fédération Aéronautique Internationale (FAI) defines the border to space at 100 km altitude.[153]
- The United States Air Force (USAF) defines the border to space at 50 miles altitude.[154]

Both definitions are insufficient for a clear definition of space*flight*. A stable Earth orbit must be reached to enable enduring operations in space – spaceflight as a stationary state to ensure enduring activities in space!

Spaceflight: Beyond Earth's atmosphere.
Stationary state.
Requires stable *Earth orbit* as a minimum.

Therefore, space transportation to Earth orbit is a prerequisite before any further activities in space – spaceflight! – can be done.

3.1.3.1 Space Transportation

Achieving velocities for a stable Earth orbit is the primary objective of space transportation. Reaching high altitudes is important, but secondary.

A) Minimum Velocity

To reach the least requiring Earth orbit, the Low Earth Orbit (LEO), an object has to achieve a given circular velocity v_{cir} depending on orbital altitude h_{orb} and Earth radius r_E; else it will fall back down to Earth.

$$v_{cir} = \sqrt{g_0 \frac{r_E^2}{r_E + h_{orb}}} \qquad (3.1)$$

The circular velocity v_{cir} of a 300 km LEO is therefore given as 7.73 km/s. This minimum velocity required for enduring operations is unique and does not apply for any earthbound type of transportation, including aviation.[155]

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[153] FAI 2006.

[154] Wade 2007.

[155] In contrast, the minimum velocity requirement for an aircraft depends on its aerodynamic configuration and its weight. It is derived from the formula of dynamic lift,

$$L = \frac{1}{2}\rho v^2 c_L S \ ,$$

with the lift force L at equal to the aircraft's weight,

$$L = mg_0 \ ,$$

and thus given as

$$v_{min} = \sqrt{2\frac{mg_0}{\rho c_L S}} \ .$$

But aircraft can also move at arbitrary velocities. Slow on-ground approaches to launch velocities are possible, followed by slow aerodrome circling and careful extension of the flight envelope. Spacecraft, The high spaceflight velocities can only be achieved outside of Earth's atmosphere, adding altitude as a second requirement.

B) Minimum Altitude

The aerial drag of residual atmosphere is traceable in altitudes much higher than FAI or USAF definition of space.

As an example, the altitude of the ISS varies between 400 km and 330 km, mainly due to atmospheric drag. Frequent re-boost maneuvers are required to keep the station within the altitude limits.[156]

The lowest stable Earth orbit of a major spacecraft was the Apollo Earth parking orbit of the Apollo lunar missions prior to their Trans Lunar Injection (TLI). Their altitude of 180 km (100 nm) was sufficient for space vehicle readiness checkout prior to TLI (injection usually occurred midway through the second parking orbit).[157] The abort to orbit (ATO) altitude of the US-STS is between 194 km and 148 km (105 nm and 80 nm), guaranteeing safe operations for 24 hours.[158] But this orbital altitude is not seen as sufficient for stationary operations.

To reduce atmospheric drag effects, an orbit altitude of 300 km is hereby defined as standard for the further considerations.

C) Conclusion

A circular low Earth orbit of 300 km is defined as standard orbit. This requires a circular velocity of approximately 7.7 km/s.

The further use of the term "LEO" refers to the defined standard orbit. The further use of the term "transportation" refers to transportation of a payload to the standard orbit.

With this, circular velocity and high altitude are minimum requirements for any space transportation mission that enables spaceflight and its resulting benefits. To meet these requirements, high technical efforts are required that inevitably lead to high costs – the more demanding the requirements are, the more demanding are the efforts, finally rising the costs. This means that a "transportation threshold" of efforts and costs must be crossed to enable any type of stationary space activity, as is illustrated in **Figure 3-7**.

Further restrictions and requirements that result from the only technical means of transportation that is presently available – rockets – raise this cost and efforts threshold even higher. These additional restrictions include maximum payload mass and volume, high acceleration, vibrations, noise, and many more.

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once launched, have no other option than either acceleration to orbital velocity or mission failure.

[156] SpaceRef 08/09/2006.

[157] NASA Apollo Press Kits 1968-72.

[158] NASA Shuttle 2002.

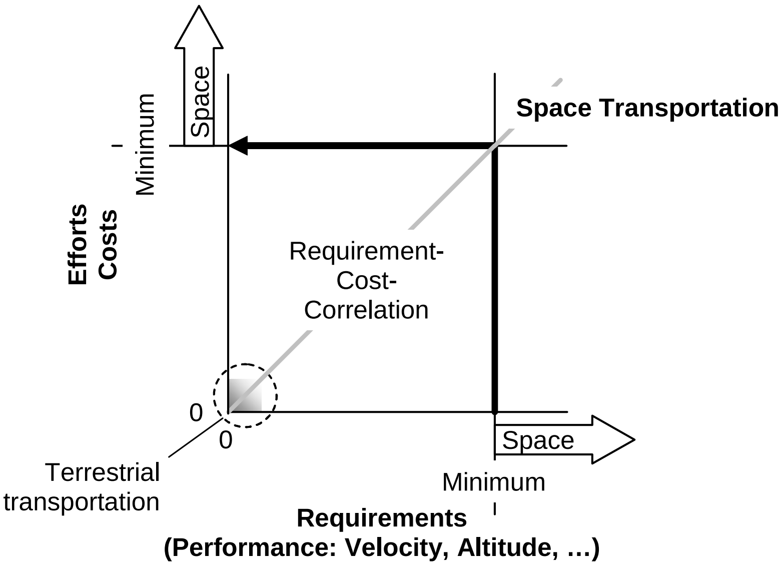

Figure 3-7: The Transportation Threshold

Transportation: Carriage of a payload (cargo) at least to a stable Earth orbit.
Mass and type of payload (cargo) is arbitrary.
Thus, the requirement to *be in space* is met for further utilization.

3.1.3.2 Operational Aspects Unique to Spaceflight

The standard mission of an aircraft is to deliver cargo to a defined destination. Cargo may include humans, goods, and even weapons (bombs). Some missions of scientific nature have additional objectives – the U.S./German SOFIA mission for example – but the majority of flights are transportation flights.

Spaceflight, in contrast, always has the additional component of *activities in space*. Spaceflight is much more than the task of transportation. Once the intended destination is reached, the true space mission only begins: The cargo – or payload – instantly begins with required operations.

An aircraft unloads its cargo at its destination, is refueled or refurbished and prepared for the next mission. A spacecraft *is* the delivered cargo.[159] It begins its mission operations after it was delivered to space, and it is strongly linked to the transportation. The spacecraft hardware must have endured the physical loads of ascent, and then it has to fulfill its mission in an environment harsher than any on Earth.

This extremely hostile environment sets very high engineering requirements on hardware, but also complicates any operations that are to be done in space. These

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[159] Even the US-STS Orbiter itself has to perform operations in orbit – in a sense, it is cargo that was delivered to orbit to perform further cargo delivery, attitude control, life support, docking, reentry, …

requirements (additional with ground based hardware, mission control, tracking stations, and any other component that is required to perform a space mission) result in a minimum limit of efforts, and thus in minimum costs. This creates a second threshold that must be crossed – as illustrated in **Figure 3-8** – to enable activities in space and, with it, mission success.

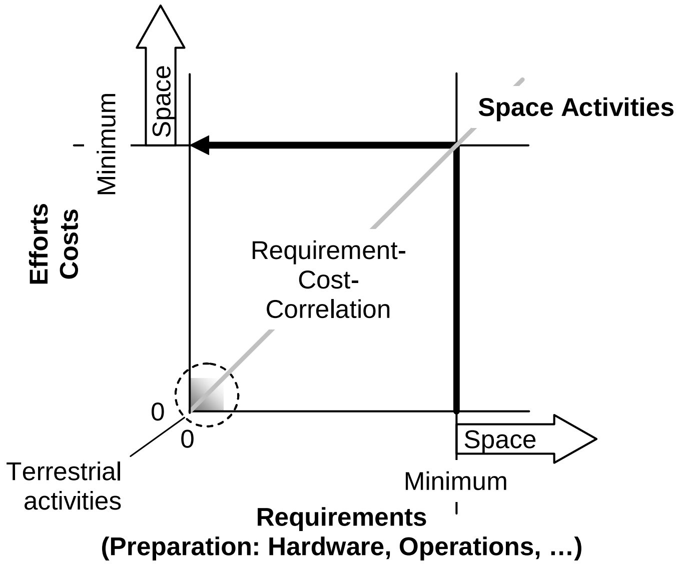

Figure 3-8: The Hardware&Operations Threshold

Hardware&Operations: All required components for desired operation in space.
Includes installations in space and on Earth.
This enables *utilization of space* for arbitrary activities.

3.1.4 The Combined Spaceflight Threshold

The two identified thresholds of transportation and hardware&operations add up to a “Spaceflight Threshold” that must be crossed for any space related activities.

This imposes high costs as well as restrictions concerning mass, volume, and other aspects on every device that will operate in space, even before the mission requirements themselves add their own restrictions.

The combination of transportation *to* and operation *in* space, both extremely demanding compared to earthbound activities, makes spaceflight so unique. **Figure 3-9** graphically illustrates this combined spaceflight threshold in a qualitative way. No terrestrial activity has such demanding basic requirements. This means that high efforts and resulting high costs are inevitable for any spaceflight activity that may later produce benefits!

The examples of the US-STS and the ISS vividly confront us with the required efforts.

Establishing and supporting a continuous human presence at the lowest level of space requirements (LEO!), just after crossing the combined Spaceflight Threshold, and doing this with the most mature transportation system available, takes financial efforts of 100 billion $,[160] and considerably more if US-STS and other transportation system development costs are added.

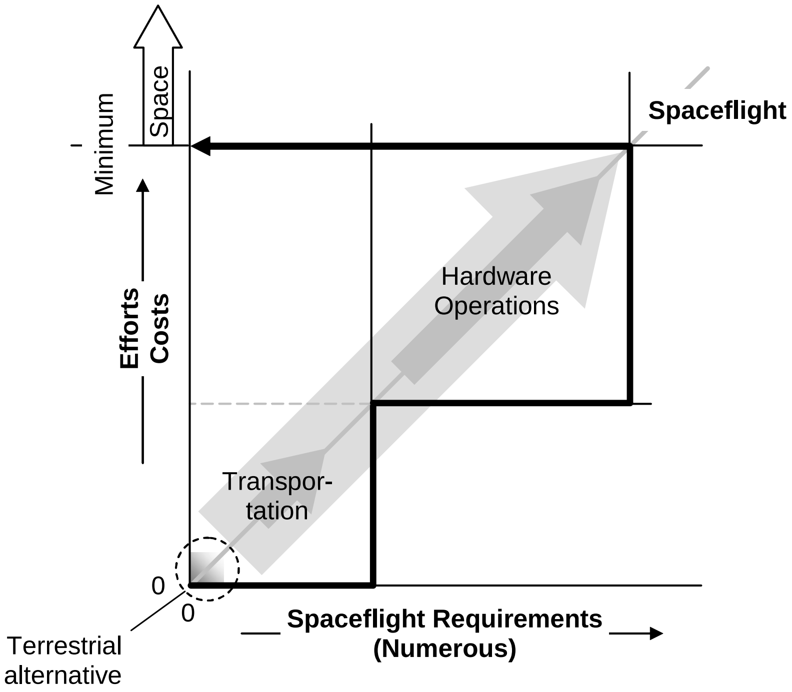

Figure 3-9: The Spaceflight Threshold – Qualitative Illustration

Another example is the Apollo program: Disregarding creation of jobs, technologies, inspiration and other peripheral results, the largest national space program (and one of the largest engineering projects) of all times did nothing more than enable the survival of two humans on the lunar surface for a maximum of three days.

3.2 Resulting Approach

To enable any activities in space, another aspect that is too often suppressed in our views of present and future spaceflight comes into play – the motivation: For its realization, someone must be motivated to pay the resulting costs of spaceflight.

The identified aspects "Transportation" and "Hardware&Operations" are subject to given technical restrictions. Their character is *restricting*. Combined, they form the Spaceflight Threshold of efforts that must be crossed for any activities in space.

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[160] ESA ISS 2005.

"Motivation" in contrast is inducing. It serves as a judging tool for the activities in space.

If the benefits that are created by spaceflight activities outweigh the restricting efforts of "Transportation" and "Hardware&Operations", a reason – and therefore "Motivation" – for spaceflight is given. This principle is illustrated in **Figure 3-10**.

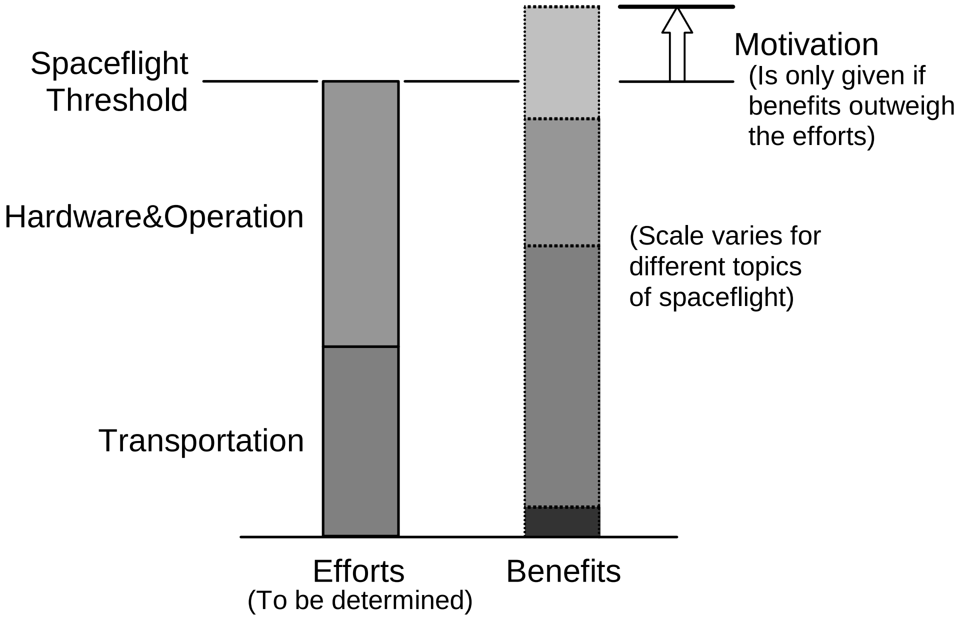

Figure 3-10: Motivation for Spaceflight Activities

This simple correlation of efforts E, benefits B and motivation M is intuitive and should be clear for any activity, but it seems it was never clear for spaceflight.

Consequently, it is assumed that

$$M = B - E \ . \tag{3.2}$$

This leads to

$$\frac{M}{E} = \frac{B}{E} - 1 \ , \tag{3.3}$$

which gives two insights:

- If the efforts are small, the benefits can be small, still creating considerable motivation.
- If the efforts are large, the benefits must be even larger to create noteworthy motivation.

As was shown in chapter 2.3.2, the efforts were either ignored or stepmotherly treated by the majority of previous assessments of spaceflight. From this perspective, equation (3.2) is seen as

$$M = B \quad , \qquad (3.4)$$

resulting in a motivation for spaceflight that seems given under any circumstances (because any space activity creates benefits for someone!). This is the perspective of the so-called “spaceflight enthusiasts”.

To apply these equations, the common unit of E, B and M must be determined:

The efforts are equivalent to workload, man years or costs, and will therefore always be given in estimated costs.

Quantification of benefits is not as simple. As will be seen later, some benefits can be measured in objective, clearly quantifiable financial means, too (for example in expected profits or averted damage). This results in quantifiable motivation and allows application of equation (3.2).

Other benefits are not quantifiable and vary for various interest groups. These benefits are subjective, resulting therefore in subjective motivation. Therefore, motivation must be seen in context of potential interest groups that might fund spaceflight activities.

The three aspects (transportation, hardware&operations and motivation), their restrictions, and their potentials, are analyzed in detail in the following chapter to create a basis for the subsequent evaluation of space related topics and their expected benefits. The scale of required efforts and the interest groups with their according motivations must be known before potential benefits can be related to them.

4. Detailed View on Efforts and Motivation

The previous chapter led to the conclusion that a combined Spaceflight Threshold consisting of transportation and hardware&operations exists that requires a basic effort for every activity in space. Motivation is required to overcome this threshold.

- **Transportation**: The journey form Earth to space that is required for every activity in space. *How do I get something into space*?[161]
- **Hardware&Operations**: The technical and operative challenges that must be mastered for any activity in space. *How can I do something in space*?[161]
- **Motivation**: The final purpose of both transportation and operation in space. *Why should I do anything in space*?[162]

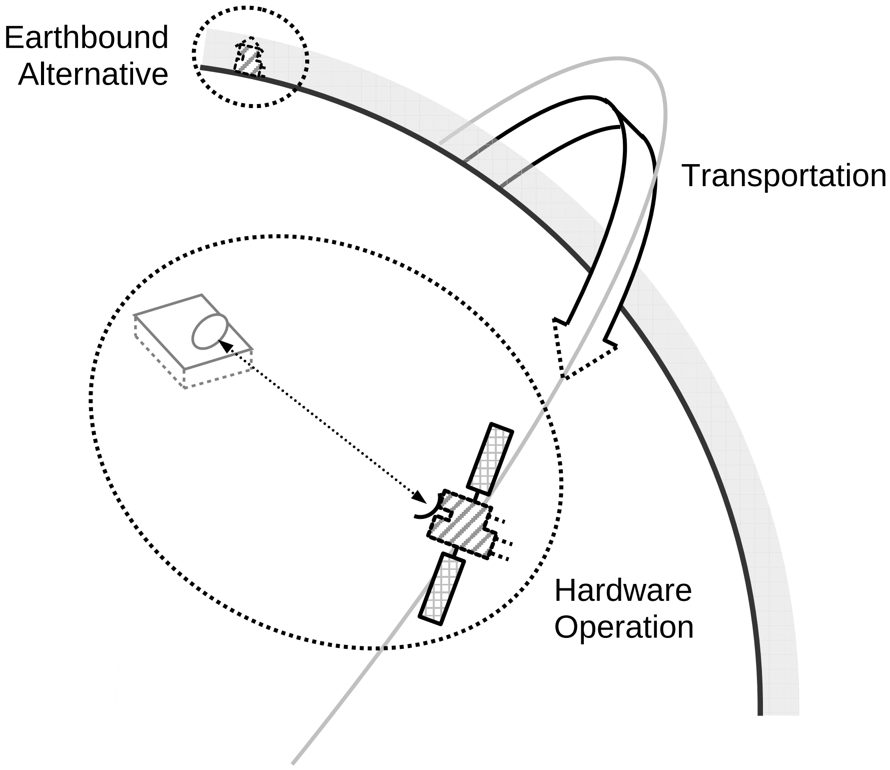

Figure 4-1: Transportation and Hardware&Operations Segment

The minimum efforts, and with them the present and future minimum costs for the restricting aspects “Transportation” and “Hardware&Operations”, are identified in chapter 4.1. Chapter 4.2 deals with potential interest groups, their capabilities and their basic motivations, and their meaning for spaceflight.

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[161] The question is *how* to do anything, not specifically *what* to do!

[162] This will lead to the question *what* to do in space and its answer.

The three aspects are analyzed by physical means and – where physics cannot give a straight answer – by a logical approach based on rational assumptions. All three aspects must be mastered for successful space activities.

4.1 The Efforts

4.1.1 The Transportation Segment

Space transportation is delivery of a payload (cargo) into space, as illustrated in **Figure 4-2**. A clear definition of transportation was done in chapter 3.1.3.1.

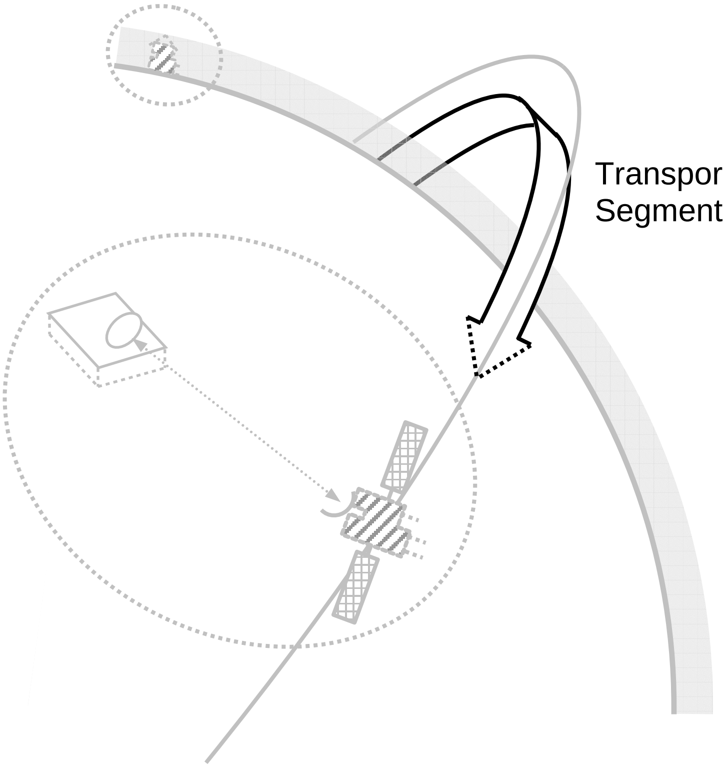

Figure 4-2: The Transportation Segment

Because space transportation follows physical constraints and can be formulated in a mathematical way, the following analysis gives a straight statement on performance of future transportation systems. The cost situation is more difficult to assess, but a qualitative statement concerning probable future cost development can be given.

A short introduction on access to space prior to detailed analysis gives an idea of the prerequisites of space transportation. This is followed by a view on the present situation, and then, on future developments concerning transportation.

As will be seen, space transportation will remain demanding and very expensive.

4.1.1.1 Access to Space

In general, space travel may be divided into ascent (launch), interplanetary, and interstellar travel. Currently, only ascent to Earth orbit is of importance, as seen in **Figure 4-3**. This underlines the previously defined focus on transportation to LEO. Interplanetary travel (including Moon) only happens on a small scale with scientific background. Interstellar travel is not yet realized.

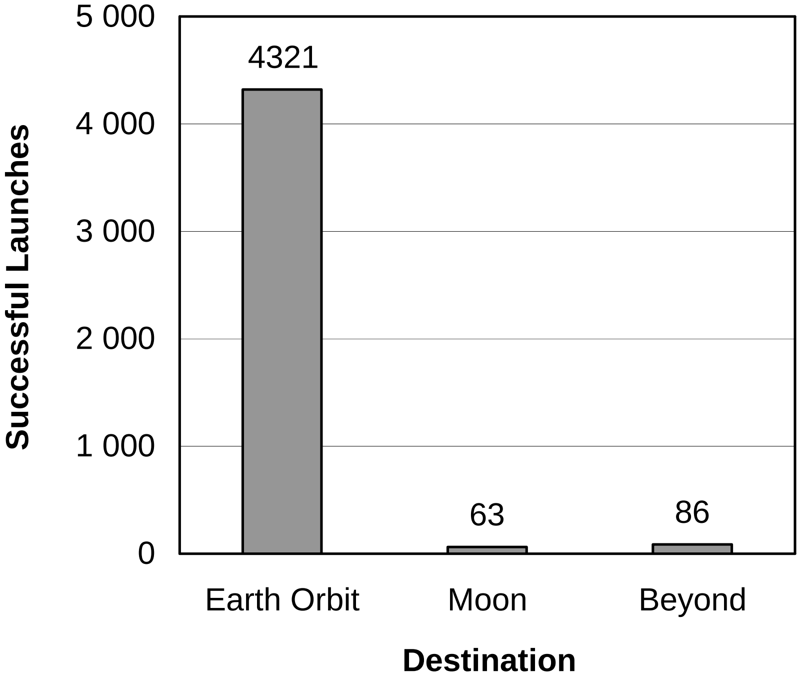

Figure 4-3: Successful Launches by Destination (Oct 1957 – Dec 2006)

4.1.1.1.1 Transportation Categories

Space transportation is the prerequisite of any spaceflight activity. It includes transportation

- into space,
- within space,
- back from space,

but with a clear focus on “into space”.

Currently, the only means for transportation of objects into space is rocket propulsion. As a supplement, gravity assist maneuvers are sometimes used for transportation within space, and support by atmospheric drag is used for Earth return and other planetary landing missions.

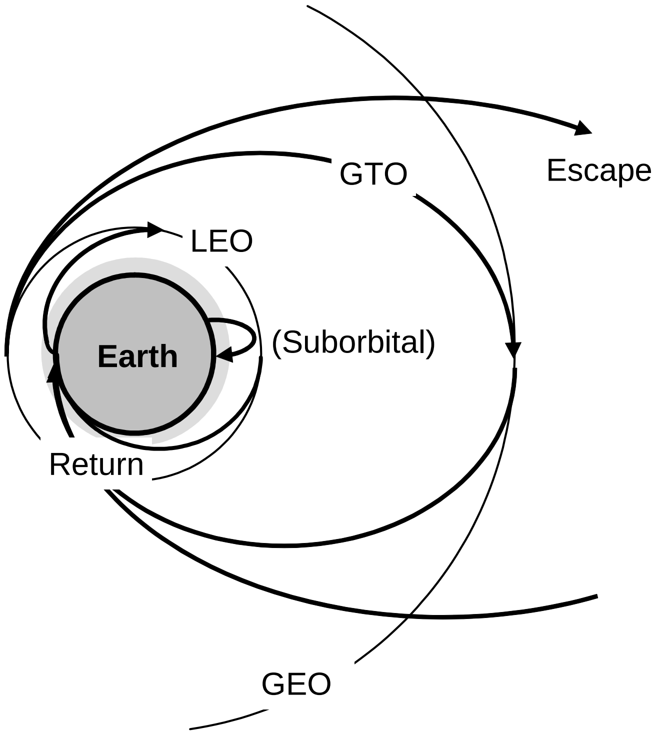

Figure 4-4: Areas of Space Transportation

The common areas of space transportation are illustrated in **Figure 4-4**: Suborbital, Low Earth Orbit (LEO), Geostationary Transfer Orbit (GTO), Geostationary Orbit (GEO), and everything beyond Earth orbit (Escape).

In public, every movement of artificial objects at high altitudes is seen as space transportation, ranging from suborbital to interplanetary missions. There is no understanding of the huge differences in requirements between the areas of transportation.

4.1.1.1.2 Payload Categories

The transported payloads may be categorized into information, cargo and humans. Each category has effects on mass and volume requirements, and with it, on the applied launch system.

A) Information

The recording and transportation of data is essential for space activities. Data signals themselves have zero mass, and thus, their transportation is basically cost free. The use of data transmission for transportation of physical objects is mentioned in science fiction (“beaming”), but will not be further considered here.

B) Cargo

Usually, payloads of space transportation systems consist of a complex technical support structure with numerous components (satellite bus, …), and the essential cargo itself. This might be materials or supplies as well as instruments or devices.

Mean density of supplies, for example oxygen and water or propellants, is usually high with about 1 000 kg/m³ (comparable to liquid water), resulting in domination of mass restrictions for transport.

Devices are usually mounted on functional support structures (satellites). Mean density is usually low with about 70 kg/m³ (comparable to liquid hydrogen), a result of extreme lightweight construction. An additional supportive mounting structure (payload adapter) is required, as well as a shroud for protection during launch, thus increasing total mass. The payload shroud is usually 10 to 40 % of the device mass.[163]

C) Humans

For human spaceflight, numerous additional requirements are imposed on the launcher and its payload, including:

- G-load restrictions during launch
- Additional system redundancies
- Life support systems
- Return to Earth

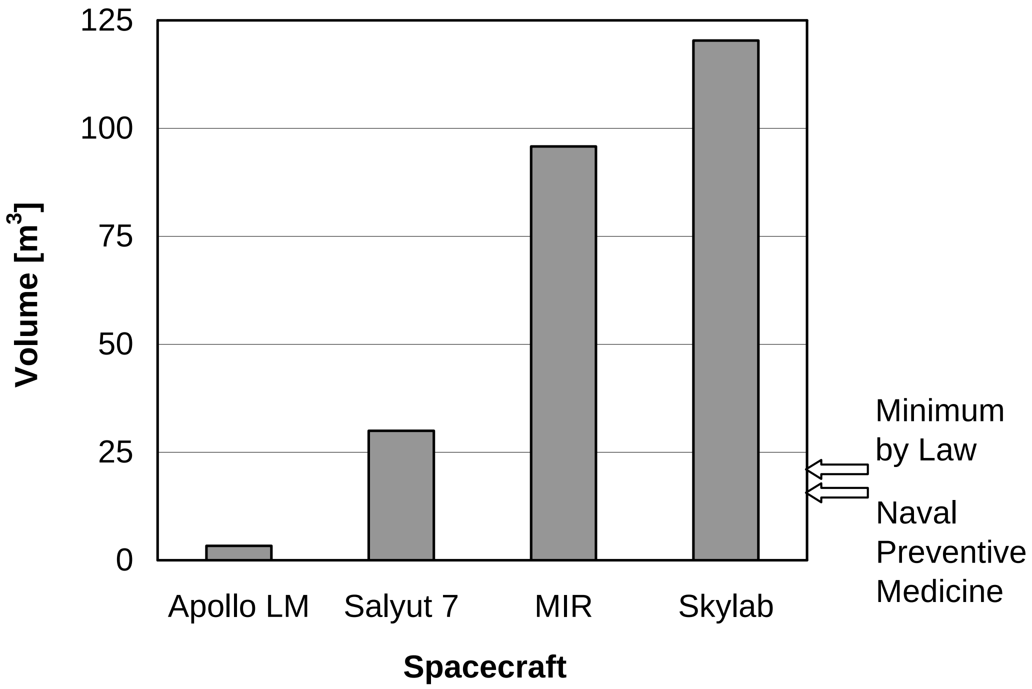

Figure 4-5: Habitable Volume per Person[164]

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[163] Schmucker Chr. 1999.
[164] Schiller 2005.

The volume required per person depends on flight duration. Short term missions have requirements of typical 1.15 (Gemini) to 2 m³ (Apollo).[165] Various habitable volume values per person are presented in **Figure 4-5**.

The approximate mass of a human with his pressure suit is about 100 kg, but total payload mass for one person including support systems is at least 1 500 kg (Mercury: 1 600 kg).[165] An increased number of crew might reduce the specific minimum mass, but in fact, specific mass of historical manned space vehicles increased with crew number.

Manned systems must be designed to perfection with close to 100 % reliability, but it is often ignored that unmanned systems are designed as flawless as possible, too.

4.1.1.2 Present Space Transportation Situation

This overview of facts should give an understanding of the current efforts for space transportation, and therefore, of the first defined threshold of spaceflight.

4.1.1.2.1 Launch Numbers

The worldwide number of launches declined significantly during the first 50 years of spaceflight, as seen in **Figure 4-6**.

Figure 4-6: Launches to Orbit and Beyond (Oct 1957 – Dec 2006)

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[165] Ruppe 1982.

Existing launch number databases differ significantly due to various reasons:

- Different success criteria
- Different space launch criteria (suborbital – orbital – escape)
- Classified launches
- Launch pad failures and pre-launch accidents
- …

A database compiled of various sources[166] gives the numbers of **Table 4-1** for orbital and escape trajectory launches, ranging from Sputnik 1 in 1957 to the end of 2006.

Table 4-1: Orbital Launch Facts (Oct 1957 – Dec 2006)

Launches	Number
Total Orbital and Beyond	4 851
Successful	4 470
Total Success Rate [%]	92.1
Total Manned	253
Failed Manned (launch/ascent only)	3[167]
Total Manned Success Rate [%]	98.8

4.1.1.2.2 Launch Vehicles

Virtually all currently available launch systems have the following characteristics:

- Chemical rocket propulsion
- Multi-stage design
- Expendable
- Ballistic
- Vertical launch
- Launch from the ground

Exceptions are Pegasus, which is launched horizontally by aircraft, and the US-STS, which is partially reusable. Most space transportation systems are derivatives of long range missile systems.

Table 4-2 presents the space transportation systems available in 2004, as of the ESA launch vehicle catalogue, with total launch mass m_0 and payload mass m_p to LEO and GTO.

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[166] Kyle 2007, Lozovina 2000, McDowell 2007.

[167] Soyuz 18, April 5, 1975, no fatalities; Soyuz T-10, September 26, 1983, no fatalities; STS-51L, January 28, 1986, seven fatalities.

Table 4-2: Available Launchers (2004)[168,169]

Name	Country	m_0 [t]	m_p [t]	
			LEO	GTO
KT-1	PRC	20	0.1	
Shavit	ISR	22	0.23	
Pegasus XL	USA	23	0.44	
Volna	RUS	35	0.1	
Minotaur	USA	36	0.64	
Start 1	RUS	47	0.45	
Athena 1	USA	66	0.7	
Taurus	USA	73	1.3	0.45
Taurus XL	USA	78	1.5	0.59
J 1	JPN	87	1	0.2
Strela	RUS	105	1.4	
Rockot	RUS	107	1.9	
Cosmos 3M	RUS	109	1.4	
Athena 2	USA	127	1.9	
M 5	JPN	128	1.8	
Tsyklon 2	UKR/RUS	180	2.8	
Atlas 2A	USA	188	7.3	3
Tsyklon 3	UKR/RUS	190	3.6	
CZ-2C	PRC	191	1.8	1
CZ-3	PRC	202	4.5	1.4
Dniepr-1	RUS	210	3.6	
Atlas 3B	USA	225	11.8	4.5
Delta 2-7920	USA	228	5.2	
Delta 2-7925	USA	231		1.8
CZ-2D	PRC	233	1.7	
CZ-3A	PRC	240	6.8	2.5
CZ-4	PRC	249	3.8	
Delta 4M	USA	256	8.6	4
Delta 2-7925H	USA	268	5.2	2
H 2A 202	JPN	285	10	4.1
PSLV	IND	294	3.2	0.9
Molnya	RUS	306	7	
Soyuz-Fregat	RUS	308	5.9	1.4
Soyuz	RUS	310	7.1	
Soyuz 2-1A	RUS	312	7.5	2.8
Delta 4M+(4,2)	USA	328	11.1	5.7
Atlas 5-400	USA	333	12.5	5
CZ-3C	PRC	345		3.8
GSLV MK I / II	IND	402		2.5
CZ-3B	PRC	426	13.6	5
Zenit 2	RUS	459	13.7	
CZ-2F	PRC	460	7.2	
CZ-2E	PRC	464	6.5	3.5
Zenit 3SL	RUS	466		6.1
Atlas 5-500	USA	542	20.5	8.7
Proton K	RUS	690	20.9	4.5
Proton M	RUS	691	20.6	5.5
Delta 4H	USA	733	24.7	13.1
Ariane 5 G	EUR	746	18	6.6
Ariane 5 ECA	EUR	780		10
Titan 4B	USA	939	21.7	5.8*
US-STS[170]	USA	2 030	24.4	(2.5)

* GEO.

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[168] ESA LVC 2004.

[169] Accuracy of some data must be doubted.

[170] Wade 2007.

They may be categorized into small, medium and heavy launchers depending either on payload mass or lift-off mass. No stringent classification is established.

For further considerations, a new launch vehicle classification that depends on delivered payload mass is introduced:

- **Small** launchers:	Up to 2 t into LEO	**17** available in 2004
- **Medium** launchers:	2 t to 8 t into LEO	**19** available in 2004
- **Large** launchers:	More than 8 t into LEO	**16** available in 2004

Criterion is the LEO payload capacity as given in the ESA launch vehicle catalogue, independent of the orbital inclination and LEO altitude.

Table 4-2 can be further extended by the launch vehicles of **Table 4-3** that entered service after 2004 or are expected to do so in the next few years.

Table 4-3: Various Launchers in Development (2007)[171]

Name	Country	m_0 [t]	m_p [t]	
			LEO	GTO
Falcon 1*	USA	27	0.57	
Falcon 1e	USA	39	0.72	
Vega	EUR	137	1.5	
Angara 1.1	RUS	149	2.0	
Angara 1.2	RUS	171	3.7	
Falcon 9	USA	324	9.9	5.1
K-1	USA	382	4.6	
Angara-A3	RUS	480	14.6	2.4
Angara-A5	RUS	773	24.5	6.6
Falcon 9 Heavy	USA	885	27.5	12
Ares I	USA	907	25	
Ares V	USA	3 350	130	

* Declared operational in March 2007.

Though some launch vehicles are restricted to certain institutions, the number of available launch vehicles is high compared to the number of available payloads. Some space transportation systems explicitly offer dual- or multi-launch capability, further reducing the total number of required launches.

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[171] Kyle 2007, SpaceX 2007, Khrunichev 2005, RpK 2007, ESA 2007, NASA 2007.

A) Performance

The technical data of most transportation systems is well known. The ratio of payload mass m_p and total launch or lift-off mass m_0 is a common value for launch vehicle performance.

Average payload mass ratio of the existing launchers previously presented in Table 4-2 is

- for LEO: **2.1 %** (Small: 1.2 %, Medium: 2.1 %, Large: 3.1 %)
- for GTO: **1.0 %** (Small: 0.5 %, Medium: 0.8 %, Large: 1.3 %)

Payload mass ratio, and with it performance, increases with launch vehicle size.

Figure 4-7 and **Figure 4-8** graphically illustrate the launch mass and payload capacities of the vehicles presented in Table 4-2 and Table 4-3 (white symbols represent vehicles in development).

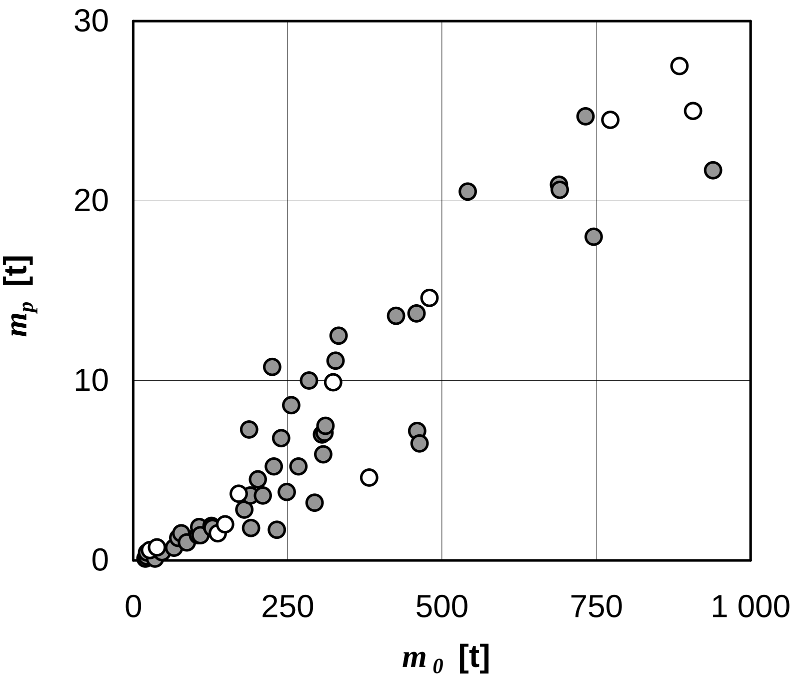

Figure 4-7: Launch Vehicle Payload Capacity – LEO[172]
(Grey: Available Vehicles (2004), White: Vehicles in Development (2007))

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[172] ESA LVC 2004, Kyle 2007, SpaceX 2007, Khrunichev 2005, RpK 2007, ESA 2007, NASA 2007.

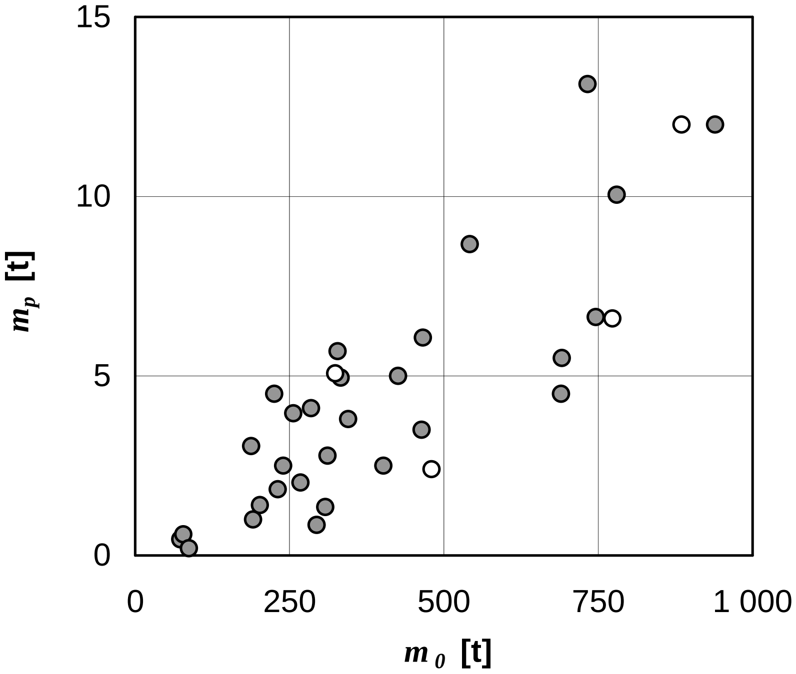

Figure 4-8: Launch Vehicle Payload Capacity – GTO[173]
(Grey: Available Vehicles (2004), White: Vehicles in Development (2007))

B) Launch Preparation Time

Space missions are planned with a long lead time. Detailed mission planning and preparation, beginning prior to the formal launch vehicle ordering, requires lead times of typically between 1 and 2 years.

C) Reliability

Current space transportation technology requires highest performance at lowest weight. Therefore, generous safety margins for stressed technical components are not applicable.

Additional to failures caused by material stress and loads, other reasons for launch failures include software glitches, electronic failures, combination of rare events, information gaps, assembly failures, and many more.

Figure 4-9 shows that the annual average launch reliability $P_{ave,yr}$ of space transportation systems increased a lot in the early days of spaceflight due to the learning effect, and seems to remain roughly at the same level since the late 1970s.

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[173] ESA LVC 2004, Kyle 2007, SpaceX 2007, Khrunichev 2005, RpK 2007, ESA 2007, NASA 2007.

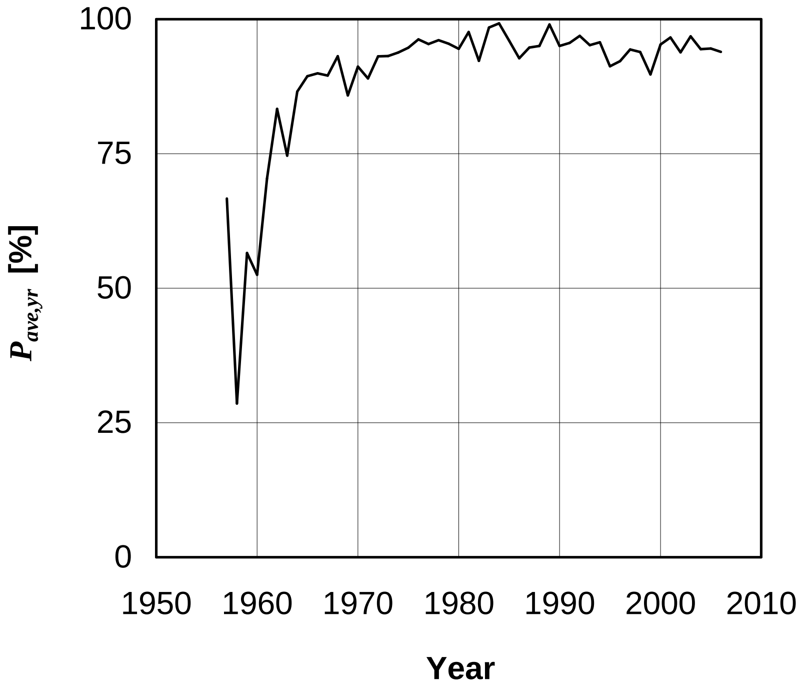

Figure 4-9: Annual Orbital Launch Success Rate

Most failures are not subject to wrong computations, but are caused by an unpredicted chain of random events. Launch failures must be characterized as singularities, but with a high number due to the enormous complexity and operational demands of space transportation systems.

4.1.1.2.3 Launch Costs[174]

Basically all available launch systems were developed with public funding. Exceptions are Pegasus and Minotaur of OSC (use of existing missile components) and Falcon 1 of SpaceX (additional funding by NASA COTS). For decades now, there are simultaneous activities for completely private funded launch vehicles, none of them yet successful.

The further use of the word “costs” is not stringent and not exactly correct. Actually, for the most part, it specifies prices that are charged by the contractor.

A) Development Costs

The cost numbers for launch vehicle development C_{dev} vary depending on source. Numbers of **Table 4-4** may serve as a guideline for orders of magnitude.

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[174] To be exact, launch costs (or transportation costs) are transportation prices charged by the launch service contractor.

Table 4-4: Space Transportation System Development Costs[175]

System	C_{dev} [G $]
Ariane 1	2
Ariane 5	8

The ratio of investment I and annual turnover T for a launch vehicle should be as low as possible for economically sound operations. Simplified, turnover for launch operators is the product of the number of launches per year n and the charged launch prices P, and investments are equal to development costs C_{dev}.

$$\frac{I}{T} = \frac{C_{dev}}{n \cdot P_{lau}} \qquad (4.1)$$

With launch prices of 180 M $[175] and current launch rates of 5 per year, the annual ratio for Ariane 5 is close to 10. Considering that the profit is only a fraction of the turnover, profitability is very difficult to achieve.[176]

This has two consequences:

- Private launch providers have to rely on vehicles that were developed with public support – this way, development costs have little effect on actual launch prices and profitability.
- Public development of new launch vehicles must end in economic disaster. This is done for political reasons only.

B) Specific Transportation Costs

Transportation costs are usually given as specific costs related to payload mass. Hence they are given by the total cost (or charged price) of a launch C_{tr} relative to the available payload mass m_p.

$$c_{tr} = \frac{C_{tr}}{m_p} \qquad (4.2)$$

The launch price is mostly independent of the public funded development costs. Usually, only recurring costs such as operational and vehicle costs are regarded.

Fixed prices are uncommon. Launch prices are a matter of negotiation for the most part. Approximate specific costs are shown in **Figure 4-10** for LEO and GTO. Specific transportation costs decrease with launcher size due to increasing launcher per-

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[175] Wade 2007.

[176] This means: If the revenues *were* the profits, Ariane 5 was profitable within 10 years. If profits are only 10 % of the revenues, it takes 100 years, not even considering interest rates.

formance.

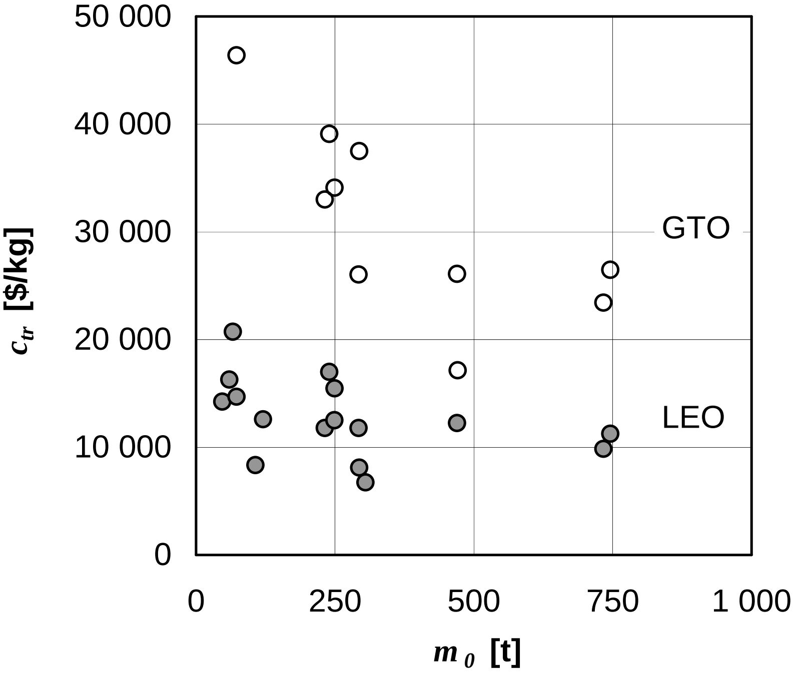

Figure 4-10: Specific Transportation Costs[177]

Specific costs for LEO, GTO and solar escape are available from current examples, as seen in **Table 4-5**. The numbers are for large launch vehicles. As already mentioned, specific costs of small launchers are higher.

Table 4-5: Current Specific Transportation Costs

Destination	Vehicle	Payload	c_{tr} [$/kg]
LEO	Ariane 5[177]	ATV	9 000
GTO		ComSats	18 000
GEO			36 000
Lunar Surface	Saturn V[178]	?*	100 000
Solar Escape	Atlas 5[179]	New Horizons[180]	430 000
Lunar Return	Saturn V[178]	Apollo Crew	2 200 000

* Estimated surface payload mass for descent with CSM+LM mass.

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[177] Wade 2007.
[178] Griffin 2007.
[179] Space News 12/12/2005b.
[180] Space.com 19/01/2006.

The lower limit of manned spaceflight costs can be derived with the current price for a Soyuz taxi seat to the ISS that is given as 30 to 40 M $.[181] Dividing NASA's official US-STS launch cost number of 450 M $[182] by the number of crew (that is seven) results in a price about twice that of the Soyuz seat.

The *actual* cost of one Soyuz seat cannot be determined due to missing cost data.

4.1.1.2.4 Summary of Present Space Transportation Situation

Of the dozens of launch vehicle families and sub-configurations developed since the 1950s, about 50 types are currently in service. Except for Pegasus and US-STS, they are multi-staged, vertically launched, expendable rockets.

The exclusive use of rockets for transportation results in high launch acceleration, extreme noise, vibrations, restrictions of payload mass and volume, and long lead times. These systems are extremely expensive and reliability is significantly lower than 100 %. Important characteristics of these transportation systems are:

- Annual orbital launch rate: About 60 launches
- Annual failure rate: Between 2 and 8 %
- Launch prices LEO: 10 000 to 20 000 $/kg
- Launch prices GTO: 20 000 to 40 000 $/kg
- Launch prices beyond: Considerably more
- Launch price LEO (human): 30 million $/pax

Future cheap space transportation is often seen as the key for extended spaceflight activities. A detailed analysis of the performance and cost limits of future space transportation systems gives a clear statement on potential cost reductions.

4.1.1.3 Future Space Transportation Systems

As was shown in chapter 2.1, predictions of the future are unreliable. But an analysis based on mathematical equations and physics allows conclusions on *performance* of future space transportation systems.

The *cost* situation of these vehicles can then be roughly estimated with simple considerations. This gives an idea if the efforts for space transportation will change in the foreseeable future.

Two types of transportation systems are analyzed:

- Conventional, impulse based systems
- Alternative, exotic systems

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[181] Space Adventures 2007.
[182] NASA KSC 2007.

4.1.1.3.1 Physical Performance Limits of Conventional Transportation

Conventional transportation includes all launch systems that use impulse based chemical propulsion, mainly rocket engines, but also air breathing engines and more exotic propulsion types such as nuclear and electric engines. The physical limits are easily derived with the rocket equation.

4.1.1.3.1.1. The Rocket Equation (Tsiolkovsky Equation)

As mentioned in chapter 2.2.2, the rocket equation was derived by Konstantin Eduardovich Tsiolkovsky in 1897 and published in 1903. Its basic form is

$$v_{id} = c \cdot \ell n \frac{m_0}{m_f} \quad . \qquad (4.3)$$

Derived from the principle of conservation of momentum, it specifies the achievable velocity of a rocket under idealized working conditions v_{id} with the effective exhaust velocity c of the rocket engine and the ratio of rocket launch mass m_0 and final mass m_f.[183]

The final mass m_f is the launch mass minus the consumed propellant mass m_{pr},

$$m_f = m_0 - m_{pr} \quad , \qquad (4.4)$$

and the launch mass m_0 is the sum of consumed propellant mass m_{pr},[184] payload mass m_p, and the remaining net mass m_{net} of the rocket itself,[185]

$$m_0 = m_{net} + m_{pr} + m_p \quad . \qquad (4.5)$$

With this, and with introduction of the payload mass ratio m_p/m_0,

$$\frac{m_p}{m_0} = \left(1 + \frac{m_{net}}{m_{pr}}\right) e^{-v_{id}/c} - \frac{m_{net}}{m_{pr}} \qquad (4.6)$$

is obtained from equation (4.3). This payload mass ratio specifies the performance of a rocket, along with its reciprocal, the Growth Factor G, which specifies the launch mass (and with it the size) of the rocket required to deliver a given payload mass.

$$G = \frac{m_0}{m_p} \qquad (4.7)$$

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[183] Ruppe 1966.

[184] Total propellant mass is, of course, higher than consumed propellant mass.

[185] This includes the wet structural mass with gases and lubricants as well as propellant residues.

Analogue, for a rocket with n subsequent (or tandem) stages instead of one stage, the total velocity consists of the velocity increments of each stage i,

$$v_{id} = \sum_{i=1}^{n} v_{id,i} \quad , \tag{4.8}$$

with payload mass of stage i equal to initial mass of stage $i+1$,

$$m_{p,i} = m_{0,i+1} \quad . \tag{4.9}$$

Therefore,

$$\frac{m_p}{m_0} = \prod_{i=1}^{n} \left[\left(1 + \frac{m_{net,i}}{m_{pr,i}} \right) e^{-v_{id,i}/c_i} - \frac{m_{net,i}}{m_{pr,i}} \right] \tag{4.10}$$

is obtained. It is valid for tandem staging as well as for parallel staging.[186] Though parallel staging is quite popular at present, it has a lower performance than tandem staging because more useless structural mass (booster support structure, hull of empty core stage tankage) is carried for a longer time during ascent.[187]

This equation is further referred to as the engineering form of the Tsiolkovsky Equation. It specifies the maximum achievable performance of any vehicle propelled by impulse based engines, depending only on a few parameters.[188]

Introducing the required velocity Δv of a proposed mission, for example ascent to LEO, v_{id} must meet at least the velocity requirement,

$$v_{id} \geq \Delta v \quad . \tag{4.11}$$

The ratio of the vehicle's net mass m_{net} to the consumed propellant mass m_{pr} is further referred to as structural design factor k_{net},

$$k_{net} = \frac{m_{net}}{m_{pr}} \quad . \tag{4.12}$$

Therefore, only three parameters define the performance of a launch vehicle:

- Δv: The mission's velocity requirement
- c: The engine's exhaust velocity (linked to specific impulse I_{sp})
- k_{net}: The vehicle's structural design factor

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[186] In case of parallel staging, the figures of boosters and core stage must be combined as one virtual first stage, with the core stage subsequent to booster separation as a virtual second stage.

[187] Lösch 1995.

[188] Exact, figures are only obtained by trajectory calculations. The accuracy is sufficient for the following considerations, though.

Table 4-6 represents the optimistic lower limit of values for present launch vehicles.

Table 4-6: Assumed Parameter Values for the Tsiolkovsky Equation

	Parameter	**Value**
Velocity Requirement including losses [m/s]	Δv	9 200
Average Specific Impulse [s]	I_{sp}	390*
Structural Design Factor	k_{net}	0.1

* Average value for all stages during ascent from sea level to vacuum.

Assuming these values for the parameters, the engineering form of the Tsiolkovsky Equation defines the maximum payload of present launch vehicles depending on the velocity requirement, as seen in **Figure 4-11** for single stage (SSTO) and two stage to orbit (TSTO) space transportation systems.

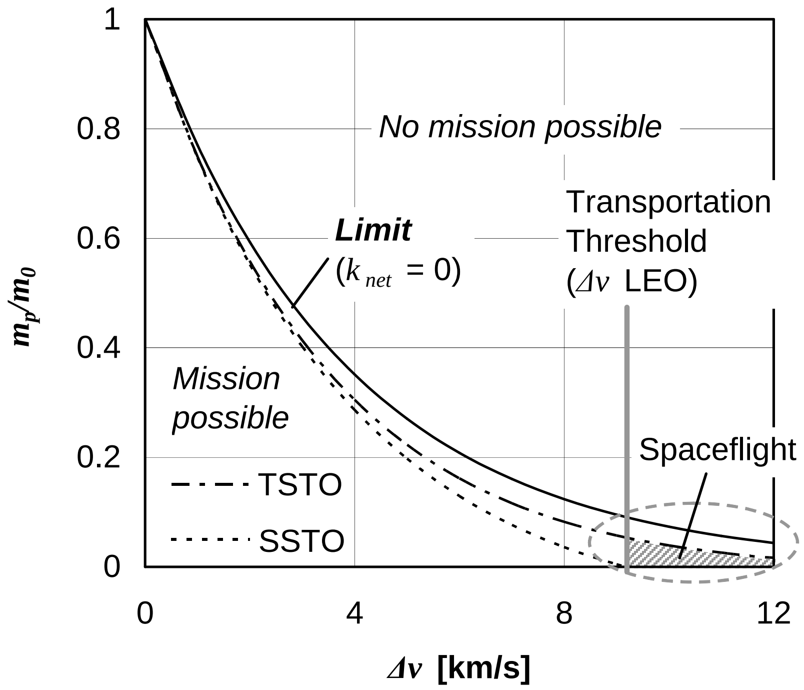

Figure 4-11: Payload Ratio as of Tsiolkovsky

The limit is situated where k_{net} equals zero, meaning that the launch vehicle itself weighs nothing. The area above the limit requires launch vehicles with negative mass.

The Space Transportation Threshold is visible as the minimum velocity requirement for LEO.

The exact value of each of the mentioned three parameters Δv, c and k_{net} depends on numerous side conditions and factors:

- Mission design for Δv
- Engine performance for c
- Vehicle design for k_{net}

The subsequent analysis of the three parameters specifies the achievable limit of each parameter value and thus gives a clear answer to the maximum performance that can be expected of conventional space transportation systems in the future.

4.1.1.3.1.2. Parameter Δv: Mission Design

The required velocity Δv that the launcher has to deliver consists of the final circular velocity of the requested orbit v_{cir} and the additional velocity efforts for the according losses Δv_{loss} during ascent. The vehicle might have an inertial velocity Δv_0 at launch.

$$\Delta v = v_{cir} + \Delta v_{loss} - \Delta v_0 \qquad (4.13)$$

A) Circular Velocity v_{cir}

For the reference orbit at 300 km, v_{cir} is physically given as approximately 7.73 km/s.

B) Velocity Losses Δv_{loss}

Δv_{loss} consists of numerous losses, including gravity losses during ascent Δv_{gra}, the drag losses at atmospheric flight Δv_D, and additional minor losses occurring for vehicle control, Δv_{con}.

$$\Delta v_{loss} = \Delta v_{gra} + \Delta v_D + \Delta v_{con} \qquad (4.14)$$

Losses during staging are low and therefore neglected for further considerations.

Gravity losses occur during the whole ascent period of ballistic systems because of the continuous deceleration of the vehicle due to the force of gravity. With a duration of the ascent Δt_{asc}, they can be given as

$$\Delta v_{gra} = g_0 \Delta t_{asc} k_{gra} \;, \qquad (4.15)$$

with the factor $k_{gra} < 1$ that depends on the trajectory.[189]

Minimum values for Δv_{gra} within acceptable acceleration boundaries are about 1 600 m/s.

Atmospheric drag depends on air density ρ, vehicle speed v, aerodynamic drag coef-

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[189] Ruppe 1966.

ficient c_D, reference area A, mass m and duration t.

$$\Delta v_D = \int \frac{\rho}{2} v^2 c_D \frac{A}{m} dt \qquad (4.16)$$

Drag velocity losses for large ballistic vehicles are in the order of 200 m/s.[190]

The control losses, including engine swivel for guidance and control as well as engine power-up prior to launch, are almost negligible. They are in the range of 10 to 30 m/s.

Winged launch vehicles with aircraft-like launch trajectories do not offer advances in velocity requirements: The gravitational losses are lower than for ballistic systems, but the higher drag (larger drag area, induced drag due to created lift) results in a higher total velocity requirement.

C) Initial Velocity Δv_0

There are many proposals to increase the initial launch velocity Δv_0. Significant increases by technical means can only be realized using technical systems that resemble additional vehicle stages, basically resulting in a launcher with $n+1$ stages. The only natural increase is the effect of Earth's rotation, with Earth's radius r_E, time for Earth's rotation period t_E, and the latitude of the launch place φ.

$$\Delta v_0 = \frac{2\pi}{t_E} r_E \cos(\phi) \qquad (4.17)$$

This effect has a maximum of about 460 m/s at equatorial launch sites.

D) Results

The resulting minimum velocity requirements are presented in **Table 4-7**.

Table 4-7: Optimized Velocity Requirements [km/s]

Parameter	Name	Value
Circular Velocity	v_{cir}	7.73
Velocity Losses	Δv_{loss}	1.81
Initial Velocity	Δv_0	0.46
Resulting Minimum Requirement	Δv	**9.08**
Realistic Minimum Requirement	Δv	9.20

A value of 9.1 km/s is extremely optimistic. Non-equatorial launch sites, higher orbital inclinations, and increasing orbital altitudes result in substantial velocity requirement

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[190] Ruppe 1966.

increases. Under realistic assumptions, the minimum LEO requirement must be seen as 9.2 km/s.

4.1.1.3.1.3. Parameter c: Engine Performance

Resulting from the effective exhaust velocity c and Earth's standard acceleration of gravity g_0, engine performance is commonly given as specific impulse I_{sp}.

$$I_{sp} = \frac{c}{g_0} \qquad (4.18)$$

Due to external atmospheric pressure, the maximum impulse is achieved in vacuum, and is considerably less at sea level. Focus is on liquid propellant engines. Solid and hybrid rocket engines have significantly lower specific impulse than liquid rocket engines and are therefore not discussed.

A) Historic Rocket Engine Performance Development

Increases in engine performance are often seen as a key development for future launch vehicles. But performance of chemical engines seems to have reached a maximum in the 1970s, as seen in **Figure 4-12** and **Figure 4-13**.

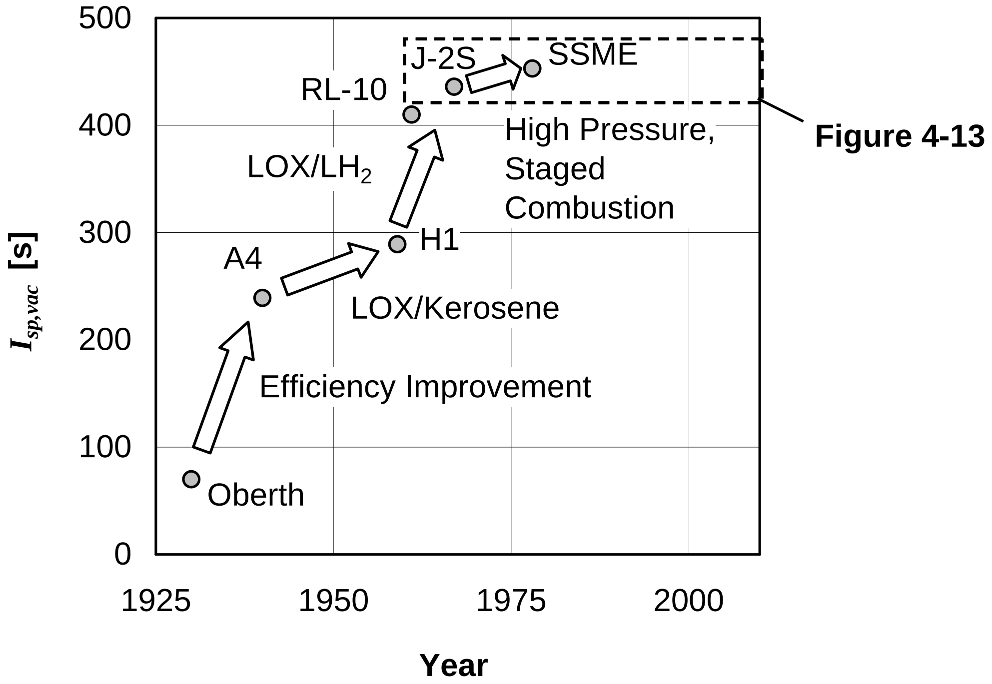

Figure 4-12: Development of Liquid Engine Specific Impulse[191]

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[191] Schmucker et al. 2007.

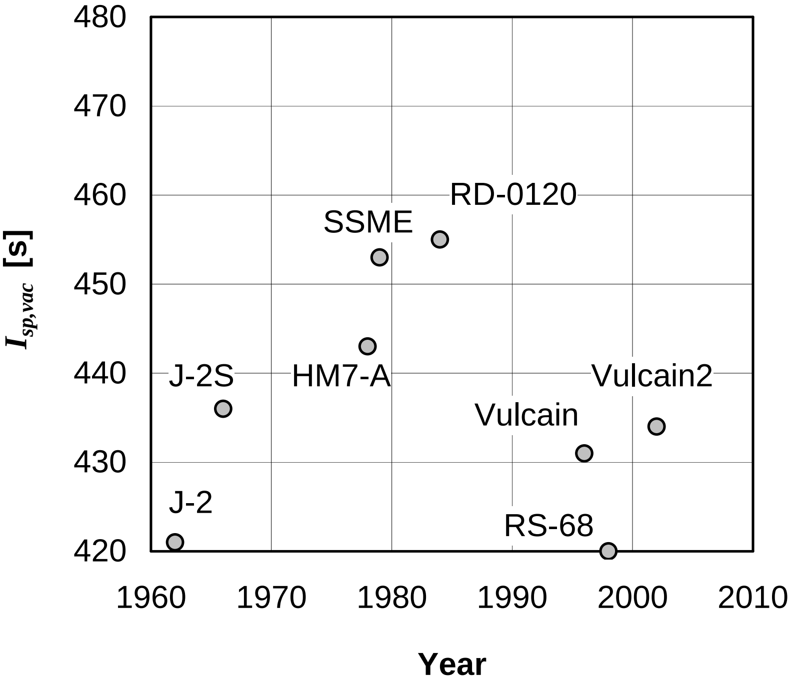

Figure 4-13: Development of LOX/LH₂ Engine Specific Impulse[192]

B) Future Rocket Engine Performance Range

The Zeuner-Wantzel equation gives the exhaust velocity of the one dimensional equilibrium c_{ODE}, with the universal gas constant R, gas molecular weight m_{mol} and specific heat ratio γ, combustion chamber temperature T_c, and pressure ratio p_e/p_c.[193]

$$c_{ODE} = \sqrt{2 \frac{R}{m_{mol}} \frac{\gamma}{\gamma - 1} T_c \left[1 - \left(\frac{p_e}{p_c} \right)^{\gamma - 1/\gamma} \right]} \tag{4.19}$$

But it is important to know that, with

$$h_c = 2 \frac{R}{m_{mol}} \frac{\gamma}{\gamma - 1} T_c \ , \tag{4.20}$$

the combustion chamber enthalpy h_c is decisive! The other parameters depend upon each other and are useful for computations only.

For a given propellant combination (oxidizer and fuel), the exhaust velocity c mainly depends on the nozzle area ratio A_e/A_t that is related with p_e, propellant mixture ratio r_{OF}, and combustion chamber pressure p_c. Variations of those parameters give in-

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[192] Schmucker et al. 2007.
[193] Ruppe 1966, Cornelisse et al. 1979.

sights concerning the potential for future improvement of engine performance.

The exemplary engine used for computations is the liquid oxygen/hydrogen Space Shuttle Main Engine (SSME) with exemplary data as of **Table 4-8** (data differs depending on source). Performance losses due to efficiency factors are not regarded.

Table 4-8: Exemplary SSME Data[194]

Parameter	Value
A_e/A_t	77.5
r_{OF}	6
p_c [bar]	204.1

Increase of the nozzle area ratio seems to have a grave impact on engine performance, as is seen in **Figure 4-14**. But realization is difficult: A nozzle diameter increase by a factor of 4 leads to a performance increase of 4 %, but with a nozzle diameter that grows to almost 10 m, with increased probability of nozzle flow separation.[195]

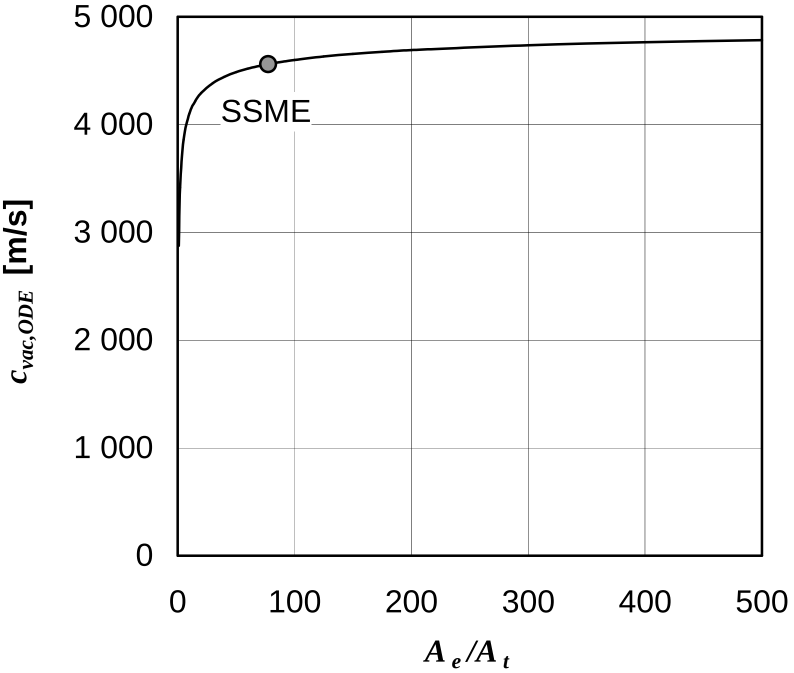

Figure 4-14: Influence of Nozzle Area Ratio on Engine Performance[196]

Figure 4-15 and **Figure 4-16** are drawn in the same scale as Figure 4-14 to illustrate the even lower impact on performance that parameter variations of r_{OF} and p_c have.

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[194] Wade 2007.

[195] Due to ambient pressure during operations at sea level. (NASA MSFC 1974)

[196] Computations were done using Gordon McBride as of NASA SP-273.

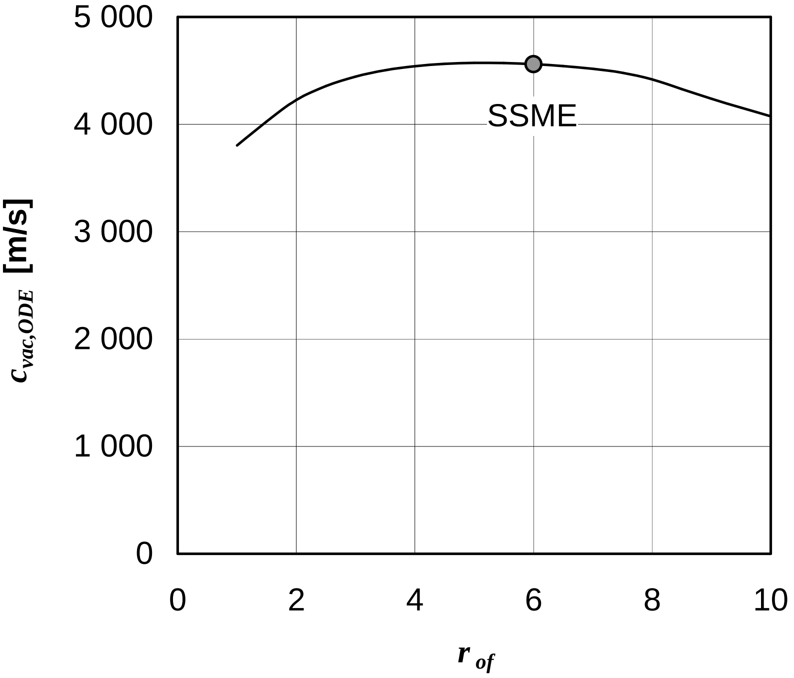

Figure 4-15: Influence of Propellant Mixture Ratio on Engine Performance[197]

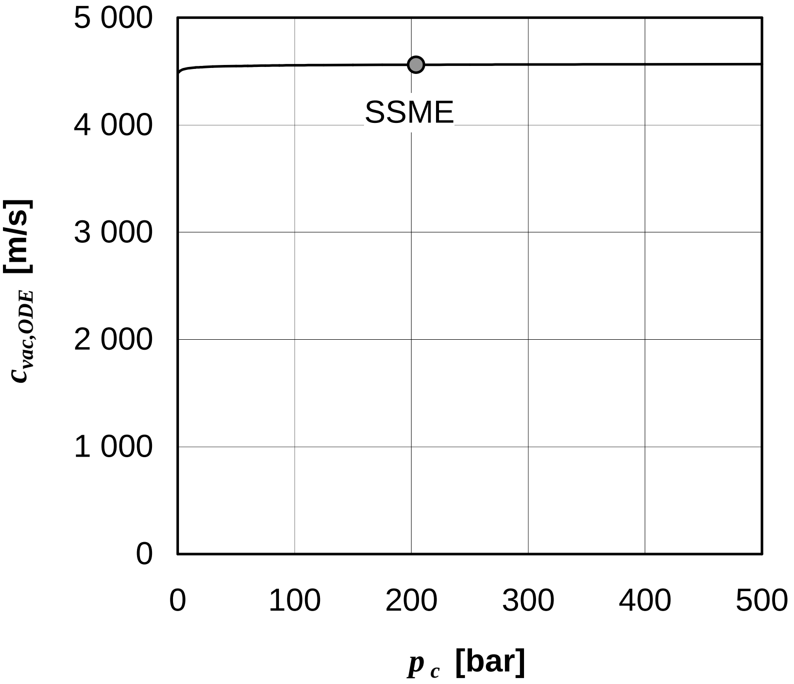

Figure 4-16: Influence of Combustion Chamber Pressure on Engine Performance[197]

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[197] Computations were done using Gordon McBride as of NASA SP-273.

Other propellants than liquid hydrogen and liquid oxygen may deliver higher performance values[198], for example use of fluorine instead of oxygen. The potential increase of specific impulse is only by a few percent, which may be important for missions on the limit, but is insignificant for the current needs of space transportation.

The theoretical impulse $I_{sp,vac}$ for an SSME computed from data of Table 4-8 is 465 s. A common value in literature for the SSME is 453 s.[199] The difference between the computed theoretical value and the actual value is a result of losses and efficiency factors. Thus, the SSME developed in the 1970s already achieves technical efficiency factors close to 100 %, as seen in **Table 4-9**.

Table 4-9: I_{sp}-Efficiency[200]

	$I_{sp,vac}$ [s]	Efficiency [%]	Comments
Energetic SSME Value	ca. 630		Without physical losses
Max. ODE-Flow	513		p_c, A_e/A_t approaching infinity
SSME ODE-Flow	465	**100**	SSME parameter values
Actual SSME Value	453	**97.4**	Actual performance

Neither other propellants nor improved efficiency factors or optimization of relevant parameters can significantly increase engine performance in theory – only an increase in area ratio seems to significantly increase the specific impulse.

In reality, even large area ratios are not feasible due to two reasons:

- Engineering factors (mass and dimension of the engine)
- Nozzle flow separation (for non-vacuum use)

An optimistic future liquid engine performance increase of 5 % is assumed for further considerations. In reality, though, engine performance is unlikely to increase.

C) Air Breathing Engines

Air breathing engines, especially ramjets and scramjets, are often seen as the key to reduce transportation costs of future space transportation systems, thus changing the future ratio of spaceflight efforts and benefits. The need to carry the oxidizer with the launch vehicle is eliminated. For a given propellant flow, and thus a given propellant mass m_{pr} and mission time t, the thrust F of air breathing engines seems to be much higher:

Rocket engine thrust F_{roc} is a product of mass flow and effective exhaust velocity c.[201]

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[198] Cornelisse et al. 1979.

[199] Wade 2007.

[200] ODE-Flow computations (Gordon McBride as of NASA SP-273) comprise the Carnot efficiency. Therefore, the given ODE-Flow I_{sp} is the maximum achievable value.

[201] Ruppe 1966.

$$F_{roc} = \dot{m}_{pr,roc} c_{roc} \tag{4.21}$$

For air breathing propulsion, thrust F_{abp} is the combined mass flow of air (oxidizer) and carried propellant (fuel) minus the inlet impulse of the air resulting from the velocity v of the vehicle.

$$F_{abp} = \left(\dot{m}_a + \dot{m}_{pr,abp}\right) c_{abp} - \dot{m}_a v \tag{4.22}$$

For identical propellant mass flow $\dot{m}_{pr}$, thrust of the air breathing engine is much higher because of the high ratio of air flow against propellant mass flow.

$$\frac{F_{abp}}{F_{roc}} = \frac{\dot{m}_a}{\dot{m}_{pr}} \frac{c_{abp} - v}{c_{roc}} + \frac{c_{abp}}{c_{roc}} \tag{4.23}$$

In other words: The air breathing engine achieves the same thrust as the rocket engine with less on-board propellants, resulting in a nominal high I_{sp} value, and making it attractive for launcher applications.

But the high I_{sp} for these engines is a calculated figure, because it is based on the fuel mass flow only while I_{sp} for rocket engines is based on the total propellant flow.

And there are other, even more decisive drawbacks of air breathing stages:

- **Minimum velocity for operation of ramjets and scramjets**
  Additional engines to reach ignition speed are required, increasing vehicle mass and size.
- **High speed operation in atmosphere**
  High heat loads on the vehicle's structure at high velocities.
- **Optimal operating conditions vary with Mach number**
  Performance is limited by decrease of thrust with increase of speed and drag for given inlet size.
- **Limited maximum velocity**
  While drag increases with speed, performance of ramjets and scramjets decreases, limiting achievable velocities to roughly 2 km/s.

Even if air breathing vehicles could be realized in the way they are proposed in studies, their performance cannot meet that of comparable rocket propelled first stages, as presented in **Figure 4-17**. With about 110 t mass subsequent to first stage separation, the Sea Launch Zenit-3SL vehicle has a similar mass to the proposed Horus upper stage of Sänger II. Delta IV M has a high performance hydrogen first stage remotely comparable to Sänger II, while the winged US-STS – after booster separation – is similar to the Horus configuration, except for the external tank.

The performance of the proposed Sänger II air breathing, winged first stage is considerably less than that of existing rocket's first stages.

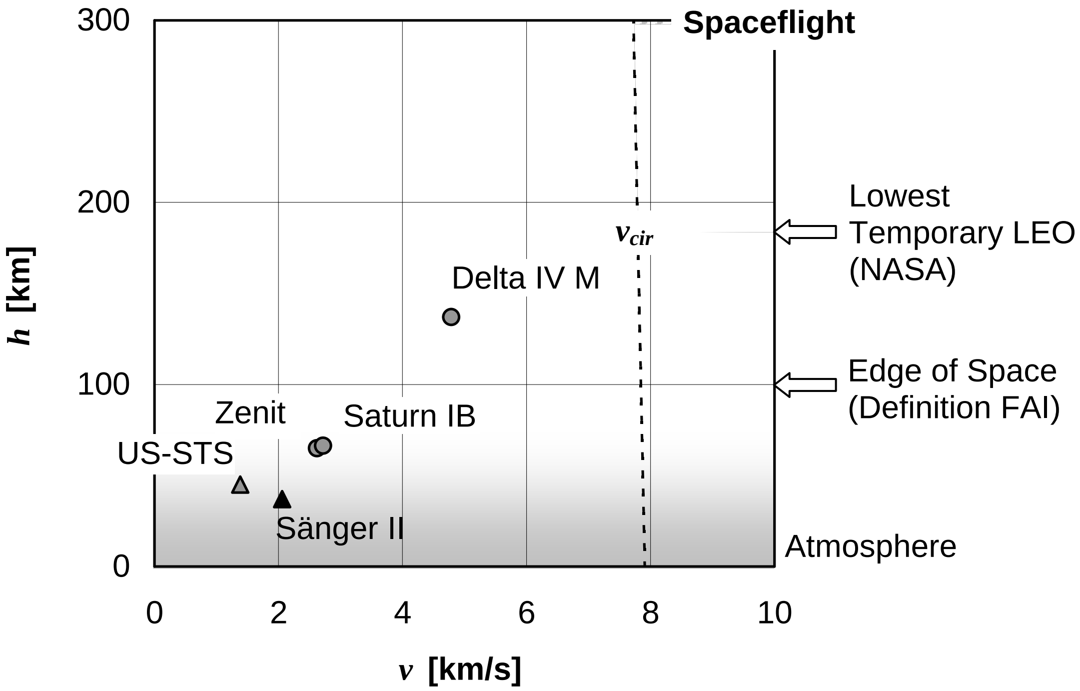

Figure 4-17: Stage Separation of Comparable Air Breathing and Rocket Propelled First Stages[202]

Air breathing vehicles are not a promising way to increase launch vehicle performance. High performance is only achieved in theory, and even that performance is negligible compared to the remaining ascent the rocket upper stage has to cover.

D) Electric Propulsion

Though electrical engines such as ion thrusters and plasma thrusters achieve high specific impulses of several thousand seconds, their thrust in the range of a few Newton is far too low to lift a launch vehicle from the ground.

E) Nuclear Propulsion

There were several proposals over the years for nuclear propelled space transportation systems and stages. Static firing tests were done for the U.S. NERVA engine project in the 1960s, but the program was cancelled soon.

There are four known ways of nuclear power production:[203]

• Radioisotope:	Insufficient energies
• **Nuclear fission**:	**Applicable**
• Nuclear fusion:	Not yet applicable

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[202] Koelle et al. 1989, Boeing 2007, IFC Kaiser 1999, Boeing 2003, Haussler 1966.

[203] Ruppe 1980.

- Disintegration of matter: Not yet realized

There are two types of propulsion:

- Electrical nuclear propulsion: Nuclear reactor powers electric engine. Must be discarded for launch vehicles because of low thrust levels.
- Thermal nuclear propulsion: Fluid is heated by nuclear reactor expanded by nozzle similar to chemical propulsion. The only applicable method.

Using hydrogen as a working fluid, and assuming realistic values for maximum reactor temperature, chamber pressure and efficiency factors, the maximum energy content of the fluid is 12.5 kWh/kg, resulting in a maximum realistic $c_{vac,del}$ of 8 200 m/s[204] or lower.[205]

Even if an increase of the specific impulse with present or future technologies was possible, there are other restrictions that complicate the use of thermal nuclear propulsion:

- Estimated engine mass is at least 15 % of the created thrust,[204,205] thus exceeding the mass ratio k_{net} of present chemical propelled launchers simply by engine mass alone.
- Additional mass penalties, such as large hydrogen tank, sufficient radiation shielding, additional safety installations, …
- High hazardous potential in case of failure.

Thus, nuclear propulsion is currently not an option for launch vehicles.

E) Conclusions

Air breathing engines and electric and nuclear propulsion are not an option. Chemical rocket engine impulse is at a limit and cannot increase by more than 5 %.

4.1.1.3.1.4. Parameter k_{net}: Vehicle Design

A low structural mass ratio m_{net}/m_{pr} or k_{net} is essential for space transportation systems. Even assuming a weightless rocket without any mass, final payload mass is only a small fraction of the propellant mass that is required to reach orbit. An increase of net mass quickly reduces payload mass to zero.

A) Current Situation

Structural factors of realized rocket stages have a great variety. A trend concerning propellant density, stage type (lower or upper stage) and stage size is visible, though. **Figure 4-18** presents a selection of realized stages.[206] The mass ratio is given with-

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[204] Ruppe 1980.

[205] Ruppe 1967.

[206] Schmucker Chr. 1999.

out engine mass m_{en} and is considerably higher if engines are included.

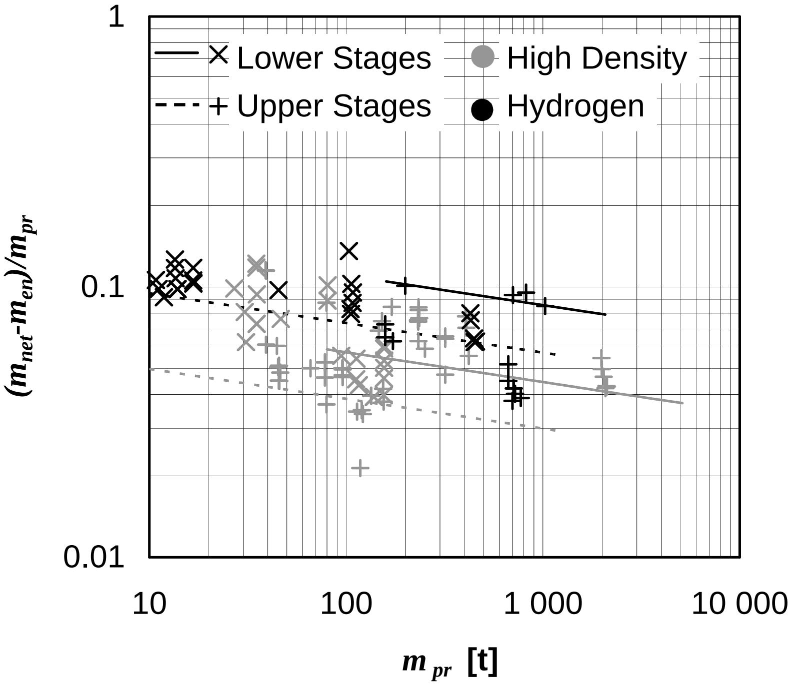

Figure 4-18: Mass Ratios of Rocket Stages[207]

Average mass ratios of about 0.1, including engine mass, are optimistic.

B) Usual Approach for Future Launch Vehicles

Many studies and proposals seem to use a specific net mass approach: The Tsiolkovsky Equation is used to calculate a launcher's final mass.

$$m_f = m_0 e^{-\Delta v/c} \quad (4.24)$$

By subtraction of the launcher's desired payload mass, the tolerated maximum net mass results. This value is then given as the expected net mass of the vehicle.

$$m_{net} = m_f - m_p \quad (4.25)$$

C) Mass Increase During Development

The vehicle net mass m_{net} and, with it, the mass ratio k_{net} are difficult to predict. Though various methods for mass prediction exist, they are similar to cost prediction methods: Both usually underestimate the true value.

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[207] Schmucker Chr. 1999.

The net mass that is predicted at early development phase is usually exceeded. Mass increase is a common reason for program cancellation.

D) Prospects

Accurate net mass prediction is quite impossible. Significant future net mass decreases cannot be expected, as is visible by the historic development of structural masses presented in **Figure 4-19**.

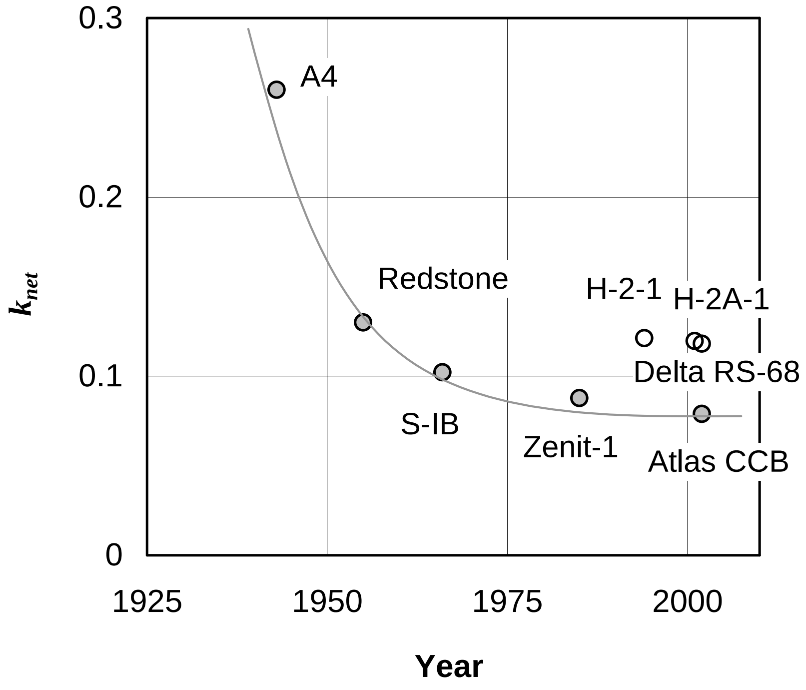

Figure 4-19: Development of First Stage Structural Mass Ratio[208]
(Grey: High Density Propellants, White: Hydrogen)

For further considerations, a very optimistic average value of 0.08 for k_{net} of future launch vehicles is assumed.

4.1.1.3.1.5. Conclusions for Future Launch Vehicle Performance

Performance of chemical rockets is close to the technical and physical limits due to decades of research and development activities. No significant advances in performance and mass can be expected in the future:

- Δv Given, no reduction possible
- c At technical and physical limit
- k_{net} At technical limit, no significant reduction possible

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[208] Wade 2007.

Nevertheless, it is assumed that – somehow – the parameter values of future launch vehicles might change to the identified theoretical optima. These values, along with the previously identified *present* values, are presented in **Table 4-10**.

Table 4-10: Optimistic Present and Future Values of Tsiolkovsky Parameters for Expendable Two Stage Systems

Parameter	Present	Future
Δv	9.2	9.1
I_{sp}	390	409.5
k_{net}	0.1	0.08
m_p/m_0 (LEO)	0.05	0.07

The resulting modified Tsiolkovsky payload ratio diagram with present and future parameters is seen in **Figure 4-20**.

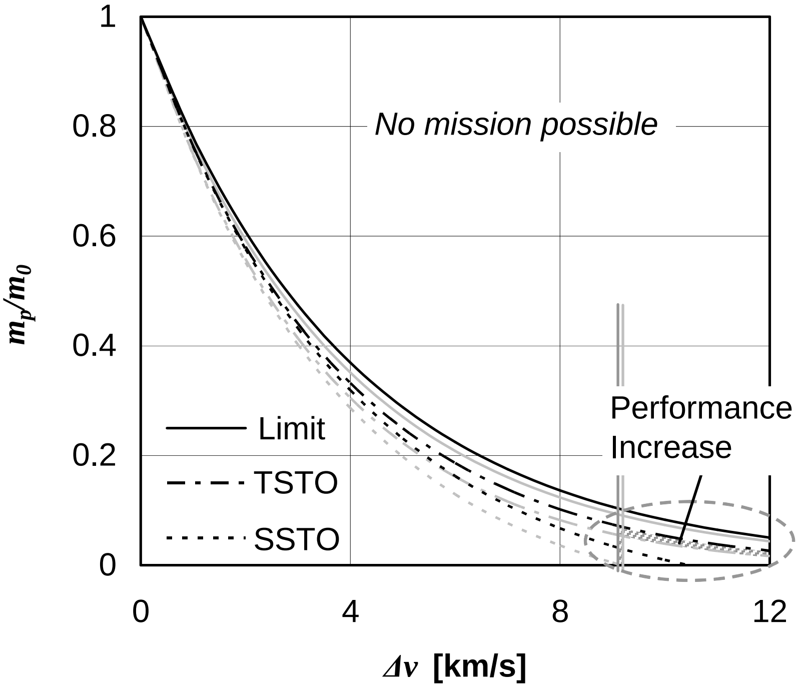

Figure 4-20: Optimistic Payload Ratio of Future Launch Vehicles

Combining all extremely optimistic assumptions for future developments, there is a given physical and technical upper payload ratio limit of 7 % for future expendable two stage launch vehicles.[209]

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[209] Performance of SSTO is worse in any case. Compared to TSTO, three stage vehicle performance is lower for LEO (Schmucker Chr. 1999), but higher for escape missions. Launchers with more than three stages suffer under high k_{net}. The optimum solution for LEO is TSTO. (Schmucker Chr. 1999)

4.1.1.3.1.6. Performance of Reusable Systems

Reusable space transportation systems are often seen as a means to offer cheap access to space. Performance issues are addressed first, cost issues follow later.

The prerequisites for reusable systems differ from expendable systems, affecting each of the three Tsiolkovsky parameters.

A) Impact on Δv

If a vehicle is to be reusable, it must return to Earth. In the reference case of LEO transportation, this requires a velocity impulse worth at least 2 % of v_{cir} to commence LEO deorbit.[210]

Winged vehicles can land without further velocity requirements. Ballistic vehicles require propelled braking and landing maneuvers for soft landing, requiring a combined additional velocity requirement of approximately 800 m/s, adding up to more than 10 % of v_{cir} for LEO return.

Additional mission velocity requirements for orbital maneuvering and attitude control are neglected.

B) Impact on c

Reusability has no impact on engine performance.

C) Impact on k_{net}

Reusable systems require numerous subsystem additions that increase net mass:

- Orbital attitude and altitude control system
- Deorbit engines
- Deorbit propellant and tanks
- Reinforced structures (reentry and landing loads)
- Heat shield
- Wings or parachutes and descent engines
- Landing gear or airbags
- …

Minimum effect on the net mass is estimated as a factor of 2 for ballistic systems, while winged systems receive a higher penalty factor of 3 due to landing gear, wing structure, large area heat shield, higher dynamic pressure loads (requiring stronger structures) and additional aerodynamic control surfaces.

Figure 4-21 shows the influence of increasing k_{net} on the payload ratio of two staged space transportation systems.

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[210] Ruppe 1966.

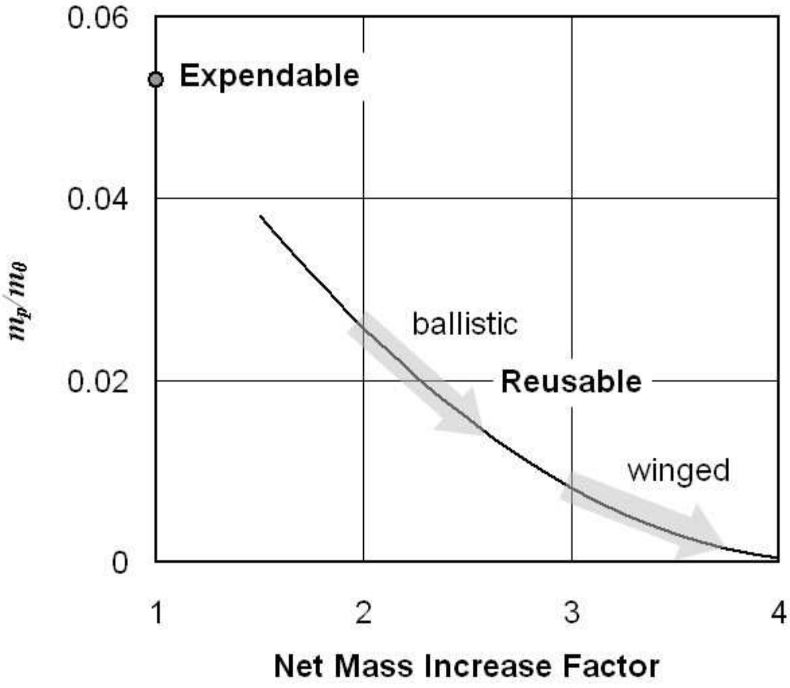

Figure 4-21: Influence of k_{net} on Payload Ratio of Two Staged Vehicles

D) Summary

The identified parameter penalties are summarized in **Table 4-11**. The parameters of expendable systems increase by the presented factor if the system is reusable. Resulting Growth factors G vary depending on assumed engine impulse, basic velocity requirement and basic structural mass ratio, thus two cases are presented: Present technology and future technology (see Table 4-10).

Table 4-11: Penalty Factors for Reusable Two Stage Systems[211]

Affected Parameter		**Penalty Factor**	
		Ballistic	**Winged**
Δv		1.1	1.02
c		1	1
k_{net}		2	3
G	Present	3.7	8.1
	Future	2.4	3.2

---

[211] The values are very sensitive. A penalty factor of 4 instead of 3 for k_{net} of winged systems increases the penalty factor of G for present systems from 8.1 to 479. The reason is simple: G is the reciprocal of the payload mass ratio. If payload mass approaches zero, the Growth factor approaches infinity, and with it the penalty compared to expendable systems.

As can be seen, performance of reusable systems is significantly worse than that of expendable systems.[212] This must be remembered for later cost analysis.

4.1.1.3.2 The Promises of Exotic Space Transportation Systems

Some proposals for future space transportation systems do not rely on conventional impulse based propulsion, and thus eliminate the restrictions of the Tsiolkovsky Equation.

A) On Surface Acceleration

Numerous concepts propose that payloads should be accelerated to circular velocity on Earth's surface and then thrown to orbit. Acceleration is done by various means, including chemical cannons, electromagnetic guns and other proposals.

The power P required for acceleration depends on payload mass m_p, acceleration distance l_{lau}, maximum acceleration a and efficiency factors η. See **Figure 4-22**.

$$P = \frac{m_p \Delta v^3}{4 \cdot l_{lau} \cdot \eta} \qquad (4.26)$$

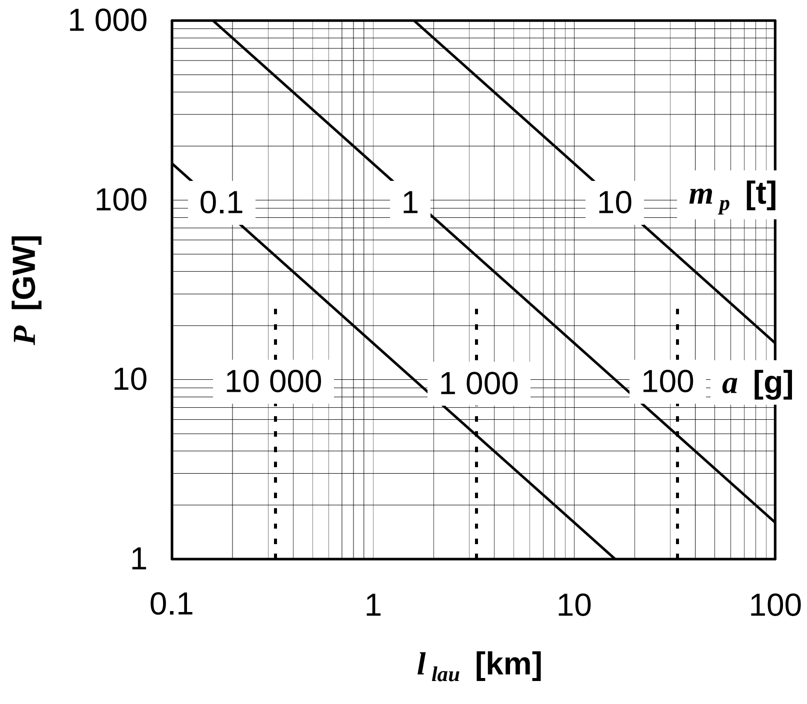

Figure 4-22: Surface Acceleration Power Requirements

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[212] There are more negative aspects of reusable systems, such as the short production timeframe and small production numbers, resulting in loss of competence within a few years. This is contrary to expendable systems that are produced continuously.

The payload is released within Earth's atmosphere, thus experiencing dynamic pressure q, with exit velocity v and air density ρ:

$$q = \frac{\rho}{2} v^2 \qquad (4.27)$$

Assuming 8 km/s exit velocity at sea level, the payload experiences pressure in the order of 40 MPa. At leaving the accelerator, this results in deceleration of numerous 10 000 g, which in turn increases the initial velocity requirement to more than 8 km/s.

Additional problematic aspects are extreme heating due to air friction and the additional subsystems that are required for final injection into orbit.[213]

B) Space Elevator

A cable or ribbon links an equatorial site on Earth's surface with a space station in GEO. Payloads are transported along the cable similar to an elevator.

Available materials do not have sufficient tension length for the required cable. The required tension length can be reduced by a varied cable diameter,[214] but adequate materials (carbon nanotubes, …) can only be produced in laboratory scale.

The dynamic characteristics and loads, induced by wind force, atmospheric turbulences and tidal forces, are difficult to predict. Furthermore, the actual installation of the system – if it was available today – is practically not feasible.

C) Conclusion

The existing concepts for exotic launch systems are not feasible for various reasons and must be discarded.

4.1.1.3.3 Future Costs of Space Transportation

Significant space transportation cost reduction is often seen as essential for future spaceflight (see chapter 2.3).

As will be demonstrated, costs are difficult to define even for existing launch vehicles. Future costs prediction is even more problematic, but simple approaches at least allow a statement concerning the expected order of magnitude for future costs.

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[213] Orbit injection requires directed thrust. This requires engines, propellants and an attitude control system. This again requires power supply, guidance and control, engine compartment, …

[214] Ruppe 1980.

4.1.1.3.3.1. The Problem of Cost Definition

Quantitative cost analysis is extremely difficult. The views of what has to be included in “costs” differ widely. To give an example of daily life:

When car owners are asked for the cost of traveling a kilometer with their car, the answers will vary, depending if – and how – they consider factors such as current fuel prices, taxes, resale value, eventual repairs, and many more. But the answers of the car owners are roughly in the same order of magnitude.[215]

The situation of launch costs is similar. Cost numbers vary depending on source and method of calculation. This makes exact and reliable quantitative statements about launch costs nearly impossible, but the order of magnitude can be stated.

An exemplary cost analysis of Saturn V and US-STS further illustrates the cost definition problem.

A) Total Launch Costs

NASA states the average cost to launch a Space Shuttle $C_{tr,STS}$ as <u>450 M $</u>.[216]

But NASA’s 2007 budget $C_{ann,STS}$ for the US-STS is 4 G $, and planned launch rate $n_{ann,\,STS}$ was 4 launches. With

$$C_{tr} = \frac{C_{ann,STS}}{n_{ann,STS}} \quad , \qquad (4.28)$$

$C_{tr,STS}$ can also be seen as <u>1 000 M $</u>.

The recurring cost of a Saturn V launch $C_{tr,SatV}$ was stated by NASA administrator Michael Griffin as 325 M $, equal to about 1 100 M $ in Fiscal Year (FY) 2000 $.[217] This complies to an applied inflation factor of 3.38.

It is assumed that the GDP Deflator or GDP Price Index was used to calculate this number.[218] If that was the case, the year 1972 comes close to the applied inflation factor.[219] Converting the 1 100 M $ number from FY 2000 to FY 2007 $, a Saturn V launch would be <u>1 230 M $</u> according to the current NASA administrator.

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[215] Many thanks to Gerhard Thiele of ESA for this analogy.
[216] NASA KSC 2007.
[217] Griffin 2007.
[218] Bell 2007b.
[219] 1971-2000: Factor 3.52; 1972-2000: Factor 3.36; 1973-2000: Factor 3.22.

But the number increases assuming that the given Saturn V cost is not a 1972 number, but an average cost value of all launches, resulting at least in the year 1970 or earlier as basic year for the 325 M $ number.

Then applying the NASA New Start Index (NNSI) instead of the GDP Deflator, Saturn V launch costs increase to 1 910 M $ in FY 2007 $.[220]

Therefore – applying *only official numbers* – there is a launch cost range for US-STS and Saturn V in FY 2007 $ as seen in **Table 4-12**.

Table 4-12: Range of Saturn V and US-STS Launch Costs [FY 2007, M $]

C_{tr}	Saturn V	US-STS
Minimum	1 230	450
Maximum	1 910	1 000

B) Specific Transportation Costs

Two payloads can be assumed for Saturn V: The commonly accepted 125 t in LEO for the three stage configuration,[221] and the heaviest payload transported to LEO, that is Skylab, launched by the two stage configuration and weighing 88.5 t.[222]

The heaviest payload of the US-STS so far seems to have been the Chandra X-Ray Observatory at STS-93 in 1999 with a payload mass of 22.75 t.[221] The reference maximum cargo to orbit capacity of the US-STS is 28.8 t.[223]

Again, applying *official numbers*, there is a wide range of payload capacity, as seen in **Table 4-13**.

Table 4-13: Range of Saturn V and US-STS Payload Mass [t]

m_p	Saturn V	US-STS
Minimum	89	22.8
Maximum	125	28.8

This results in specific transportation costs c_{tr} between 10 000 and 21 000 $/kg for Saturn V and between 16 000 and 44 000 $/kg for Shuttle. In **Figure 4-23**, the specific costs are visible as gradients.

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[220] NASA JSC 2007c.
[221] NASA 2007.
[222] NASA MSFC 1973.
[223] NASA Shuttle 2005.

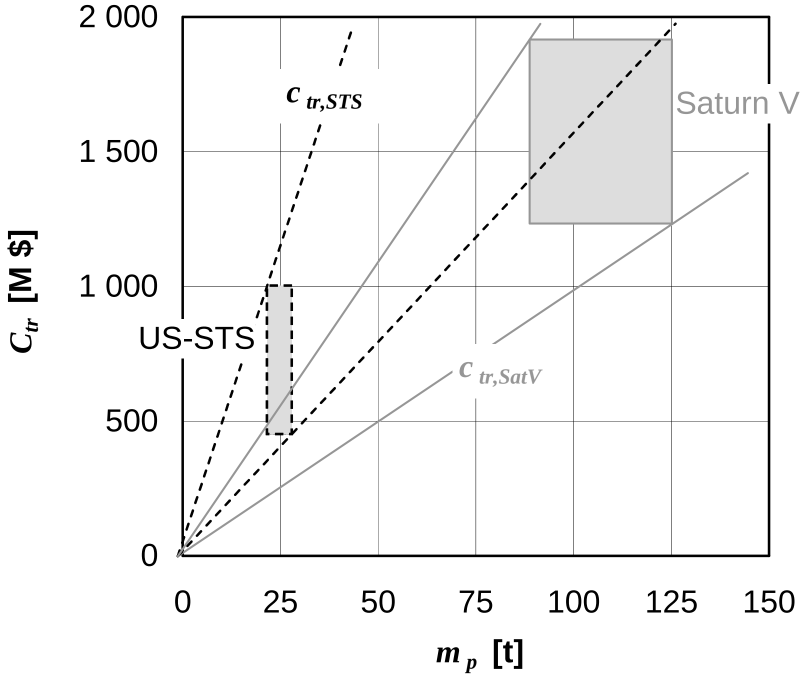

Figure 4-23: Specific Transportation Costs – Saturn V and US-STS

C) Conclusion

Exact transportation cost numbers are impossible to identify, even relying on official numbers of past and present systems. But qualitative statements resulting from simple considerations seem valid: In the given case, it can be stated that specific transportation costs of the US-STS are about twice that of Saturn V.

If cost analysis of existing vehicles with given numbers is unclear, exact prediction of future costs must be even more unreliable. But trends can be identified. One often cited way to reduce future costs is reusability of launch vehicles.

4.1.1.3.3.2. Cost Reduction by Reusable Systems

Reusability is often seen as a way to reduce transportation costs. A common argument is that an aircraft is not thrown away after a transatlantic flight, too.[224]

But two independent approaches clearly show that reusability is not a means to reduce specific space transportation costs: Cost correlation approach and energy correlation approach.

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[224] This comparison is wrong: An aircraft is refurbished and refueled as it arrives at its destination. It then returns in the same way as it arrived. A launch vehicle can neither be refueled and refurbished in orbit, nor is Earth return the same as launch to orbit. Air traffic would be quite different if intercontinental distances were twice as far as they are, and if the airliners were not refueled at their destination.

A) Cost Correlation Approach

To estimate the effect of reusability on launchers, simple considerations are sufficient. Launch costs for a vehicle C_{tr} within a program can be written as

$$C_{tr} = \frac{C_{dev} + C_{veh} n_{veh}}{n} + C_{l/o} \ , \tag{4.29}$$

with invested development costs C_{dev}, total number of launches n at the program, vehicle costs C_{veh}, number of vehicles used for the program n_{veh}, and the launch operation costs $C_{l/o}$ for each launch.

If the vehicle is reusable, it also has to perform more or less complex maneuvers in space that require additional ground support staff and result in additional mission costs C_{mis}, and the vehicle must be recovered and eventually refurbished for the costs $C_{r/r}$, resulting in

$$C_{tr} = \frac{C_{dev} + C_{veh} n_{veh}}{n} + C_{l/o} + C_{mis} + C_{r/r} \ . \tag{4.30}$$

To better estimate the respective cost values, this equation is written as

$$C_{tr} = C_{veh} \left[\left(\frac{C_{dev}}{nC_{veh}} + \frac{n_{veh}}{n} \right) + \frac{C_{l/o}}{C_{veh}} \left(1 + \frac{C_{mis}}{C_{l/o}} + \frac{C_{r/r}}{C_{l/o}} \right) \right] \ , \tag{4.31}$$

with numerous cost ratios that are easier to assume than absolute values.

To compare the costs of a program using reusable launch vehicles (RLV) and expendable launch vehicles (ELV), a program scenario of 1 000 launches is assumed.

The ELV program has a development cost about 100 times that of construction cost of a single vehicle; launch and operation costs are a third of the vehicle costs, while no further costs for mission operation or recovery and refurbishment incur.

Costs of the RLV program are normalized against the ELV program. The whole program is done by a single vehicle, with vehicle costs 20 % higher than the ELV, and development costs one third higher. Launch and operation costs are expected to remain the same, while additional mission costs 10 % of the launch costs are added, as well as recovery and refurbishment on the scale of one third of the launch costs. All parameters and their values are presented in **Table 4-14**.

Table 4-14: Estimated Launch Cost Parameter Situation

Parameter	Expendable	Reusable*
C_{veh}	1	1.2
C_{dev}/C_{veh}	100	1.3
n	1 000	
n_{veh}/n	1	0
$C_{l/o}/C_{veh}$	0.3	1
$C_{mis}/C_{l/o}$	0	0.1
$C_{r/r}/C_{l/o}$	0	0.3

* Normalized against Expendable.

For these parameters, equation (4.31) gives the results of **Table 4-15**. Because the RLV costs were normalized against the ELV costs, the numbers mean that an RLV launch is less than half the cost of an ELV launch. Excluding development costs, the RLV performs even better with only one third the cost of an ELV launch.

Table 4-15: Transportation Costs of Expendable and Reusable Systems

	$C_{tr,exp}$	$C_{tr,reu}$	$C_{tr,reu}/C_{tr,exp}$
without development	1.33	0.46	**0.34**
including development	1.43	0.62	**0.43**

Now, an engineering perspective is included in the considerations. The total transportation cost per launch that was calculated above does not take into account each vehicle's actual performance concerning delivered payload mass.

The previous calculations were based on similar sized vehicles. For further considerations, both ELV and RLV systems consist of two stages. The specific payload costs c_{tr} of any vehicle are defined as transportation costs per payload mass.

$$c_{tr} = \frac{C_{tr}}{m_p} \tag{4.32}$$

Introducing the Growth Factor G into the equation, the specific costs are

$$c_{tr} = \frac{C_{tr}}{m_0} G \tag{4.33}$$

with launch mass m_0. Assuming the similar vehicle size, the launch mass of both the RLV and ELV is considered equal, resulting in a specific cost ratio of

$$\frac{c_{tr,reu}}{c_{tr,exp}} = \frac{C_{tr,reu}}{C_{tr,exp}} \frac{G_{reu}}{G_{exp}} \quad . \qquad (4.34)$$

This leads to a conclusion regarding the specific transportation costs of reusable vehicles compared to expendable vehicles.

In chapter 4.1.1.3.1.6, the minimum performance penalties for reusable systems were identified. The resulting minimum Growth Factor ratio for ballistic systems with optimistic assumptions for future technology parameters was:

$$\frac{G_{reu}}{G_{exp}} = 2.4 \qquad (4.35)$$

For winged systems, the Growth Factor ratio was 3.2.

Both Growth Factor ratios are combined with the cost ratios of reusable systems compared to expendable systems that were presented in Table 4-15, respectively 0.34 without and 0.43 including development costs. Results for eventual future vehicles are shown in **Table 4-16**. The ELV is considered as ballistic.

Table 4-16: Specific Transportation Cost of Reusable Launch Vehicle Compared to Expendable Launch Vehicle (Future Limit)

		Ballistic	**Winged**
$c_{tr,reu}/c_{tr,exp}$	without development	0.83	1.10
	including development	1.04	1.38

This means that, <u>even at most optimistic assumptions for future launch vehicles</u>, the cost of delivering 1 kg of payload into LEO for a reusable *ballistic* system is expected to be in the same order as for an expendable system. For a *winged* reusable system, the cost is higher because of the poor payload mass ratio. This is clearly visible assuming the previously identified <u>present</u> performance parameters for **Table 4-17**:

Table 4-17: Specific Transportation Cost of Reusable Launch Vehicle Compared to Expendable Launch Vehicle (Present)

		Ballistic	**Winged**
$c_{tr,reu}/c_{tr,exp}$	without development	1.27	2.79
	including development	1.60	3.50

Remember, these considerations were done assuming:

- High end engines
- Structural mass ratios at the absolute lower limit

- Mass penalties for reusable systems at the lower limit
- Program of 1 000 launches
- All 1 000 launches with one reusable vehicle
- No launch failure – reliability of 100 %!

B) Energy Correlation Approach

A different, somewhat naïve approach is the correlation of official numbers for launch costs C_{tr}, payload mass m_p and kinetic energy requirements of orbital vehicles to receive the specific cost per invested kinetic energy c_{kin} for reusable and expendable vehicles:

$$c_{kin} = \frac{C_{tr}}{\frac{1}{2} m_p \, \Delta v^2} \tag{4.36}$$

The results in **Table 4-18** show similar numbers for both orbital and suborbital reusable systems, with significantly lower costs for the expendable system.

Table 4-18: Specific Kinetic Energy Costs

	Name	**C_{tr} [M \$]**	**m_p [t]**	**Δv [km/s]**	**c_{kin} [\$/kJ]**
Reusable	US-STS	450	23	9.2	**0.46**
	Space-ShipTwo[225]	1.2	1.2	2.0	**0.50**
Expendable	Ariane 5	180	19	9.2	**0.22**

C) Conclusion

The result of both approaches is the same: Reusable systems cannot reduce transportation costs. Reusability is not the key for extensive space transportation and cannot reduce the efforts and costs of the transportation threshold.

4.1.1.3.3.3. Estimating the Lower Limit of Transportation Costs

Many complex approaches try to predict the lower limit of space transportation costs. But simple, naïve approaches that simplify space transportation to a strictly energetic problem can also give an idea of the achievable lower limit of transportation costs.

A) Propellant Energy Approach

Basic data for a day's journey by car, an intercontinental flight and an orbital launch are presented in **Table 4-19**.

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[225] Scaled Composites' SpaceShipTwo offers room for 8 persons (2 pilots and 6 passengers) with 6 customers paying a total 1.2 M $ per flight (Virgin Galactic 2007). For each person, 150 kg including supportive elements (seats, life support, …) are assumed, resulting in a payload of 1.2 t.

Table 4-19: Assumed Basic Vehicle Data

	Car	**Aircraft**	**Rocket**
Vehicle Type	Compact Car	A330-200	Soyuz TMA
Exemplary Route	Munich Hamburg	Munich Cape Town	Baikonur LEO
Propellants	Gasoline	Kerosene	Kerosene (Oxygen)
Fuel Density [kg/l]	0.74	0.81	0.81
Heating Value [MJ/kg]	43.5	42.8	42.8
Travel Distance [km]	1 000	9 000	-
Travel Duration [h]	9	11	0.2
Spent Fuel [kg]*	59.2	80 000	4 x 11 500, 28 900, 6 200
Av. Engine Power [kW]	78	2 x 37 500	
Crew/Passengers	4	323	3
Final Mass [kg]	1 500	150 000	7 200
Payload Mass [kg]	400	34 000	2 300**

* Without oxidizer.
** Progress cargo ship.

The used amount of energy for the given route is roughly the product of the heating value H_i and the fuel mass.

$$E = H_i \cdot m_{fu} \qquad (4.37)$$

For automobile and aircraft, the product of average engine power P_{ave} and duration t confirms the numbers.

$$E = P_{ave} \cdot t \qquad (4.38)$$

The results are presented in **Table 4-20**. Though surprisingly the total energetic requirement of the orbital launch is similar to the intercontinental flight, the number of passengers and the delivered payload mass widely differ.

The results show that, if the costs for space travel would solely depend on the energy requirements, the costs for one astronaut can not decrease to less than 100 times the cost of an intercontinental flight (because the energy requirement *per person* is 100 times higher!). Analogue, the specific payload cost limit is at least 15 times higher than worldwide air mail costs.

Table 4-20: Rounded Results of the Energetic Cost Approach

	Distance Drive	**Interconti-nental Flight**	**Orbital Launch**
Energy requirement			
Total [kWh]	720	960 000	970 000
per Person [kWh]	180	3 000	323 000
per Final Mass [kWh/kg]	0.5	6.4	135
per Payload Mass [kWh/kg]	1.8	28	420*
Normalized to Aircraft			
Total	0.00075	1	1
per Person	0.06	1	**100**
per Final Mass	0.075	1	20
per Payload Mass	0.065	1	**15***

* Progress.

At current prices of roughly 1 000 $ for an intercontinental flight and 15 $/kg for air mail, this would mean 100 000 $ per astronaut or 225 $ per kg – a reduction by the factor of 300 (manned) and 50 (unmanned) respectively.

Remember, these considerations take no cost factors beyond propellant energy into account. The true lower cost limit must be significantly higher due to unregarded factors for spaceflight (vehicle requirements, flight frequency, …). A better, more comprehensive approach is the use of kinetic energy as a factor.

B) Kinetic Energy Approach

The kinetic energy E_{kin} of an object is defined as:

$$E_{kin} = \frac{1}{2} m \cdot v^2 \qquad (4.39)$$

For further considerations, the mass of the object is seen as constant and identical for each way of transportation – an assumption that favors spaceflight because it does not address the considerable propellant amounts and additional equipment (payload fairing, orbital control system, …) that must be accelerated besides the payload.

Figure 4-24 shows typical kinetic energies for various velocities of an object with the mass of 1 kg.

The kinetic energy of 1 kg in LEO seems high with roughly 30 MJ. But this is less than 10 kWh, equivalent to the amount of energy required to light 15 average bulbs over 10 hours for electricity costs of roughly 1 $, which in turn seems low.

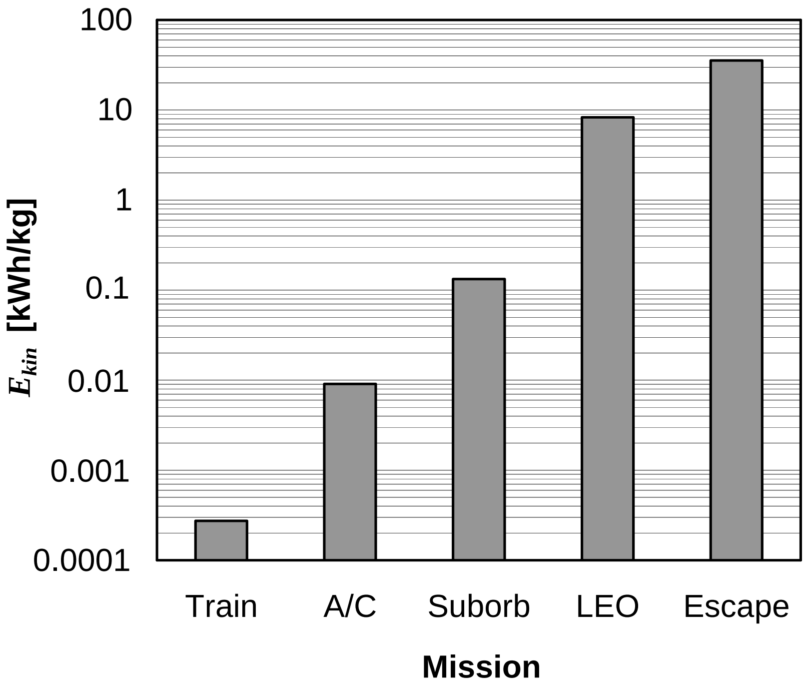

Figure 4-24: Kinetic Energies of Various Velocities for 1 kg

Again normalized against air transportation, expected transportation costs are extrapolated in **Table 4-21**.

Table 4-21: Transportation Costs by Kinetic Energy Considerations

Class	Vehicle	v [km/h]	E_{kin} [kWh/kg]	E_{kin}*
Train		160	0.0003	0.03
Aircraft	B-747	920	0.009	1
Suborbital	SpaceShipOne	3 518	0.13..	14.6
LEO	Soyuz	27 828	8.3	**915**
Escape	New Horizons	57 600	35.6	3 920

* Normalized.

This approach shows that energetic efforts are almost a thousand times higher for a LEO launch vehicle than for an aircraft. With the current worldwide air mail cost of about 15 $/kg, the current launch costs of about 15 000 $/kg are pretty well met. From the kinetic energy approach, ways of cost reduction do not seem possible.

C) Conclusion

The two approaches were optimistic and did not take specific engineering requirements of spaceflight into account. The propellant approach states a lower cost limit at 225 $/kg for LEO, and the kinetic approach mirrors present launch costs.

The approaches can only give a vague idea of the achievable order of magnitude of the lower limit of space transportation costs, but it is doubtful if the existing correlation of velocity requirement and cost (or price), as seen in **Figure 4-25** with offered prices for one passenger c_{pax}, can somehow be changed some day.[226]

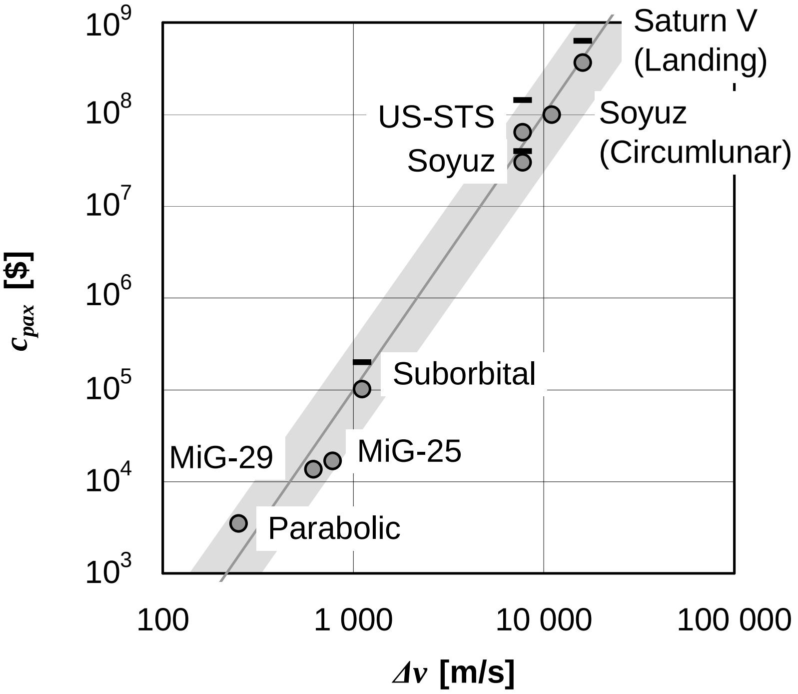

Figure 4-25: Correlation of Requirements and Costs[227]

Therefore, significant cost reduction down to the order of current air transportation costs seems impossible. A reduction by the factor of 2 is the very best that can be expected for the future, but it is more probable that the costs remain constant.

4.1.1.3.4 Consequences for Future Transportation Efforts

As identified by other studies,[228] new launch vehicles will not change the current space transportation situation due to physical and technical constraints:

- Engine performance is at the physical limit
- Structural mass has approached a minimum (barely above zero)
- Future exotic transportation systems are infeasible
- Future cost, even disregarding physical, technical and economical restraints,

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[226] As the line in Figure 4-25 shows, there is an empirical correlation of velocity requirement and passenger costs (that are, in fact, prices!) of $c_{pax} = \Delta v \cdot k$, with $k = 10^{-4}$ \$s/m. An interpretation with the Tsiolkovsky rocket equation seems not possible. This might be due to varying characteristics of the presented data points: Reusable and expendable vehicles, air breathing and rocket engines, use of price numbers instead of costs, increasing mass requirements for higher velocities, …

[227] Zero G 2007, Virgin Galactic 2007, Space Adventures 2007, RusAdventures 2007, NASA 2007.

[228] Schmucker Chr. 1999.

cannot be significantly reduced
- Reusability is not a way to reduce costs

The future situation of space transportation must be expected to remain at the same level as the present situation, regarding performance as well as costs.

The efforts and costs of the transportation segment will remain very high for the foreseeable future. Significant reductions are hardly possible.

4.1.2 The Hardware and Operations Segment

Any payload that is launched to space has an intended mission. The majority of missions can be viewed independently of transportation, as illustrated in **Figure 4-26**.

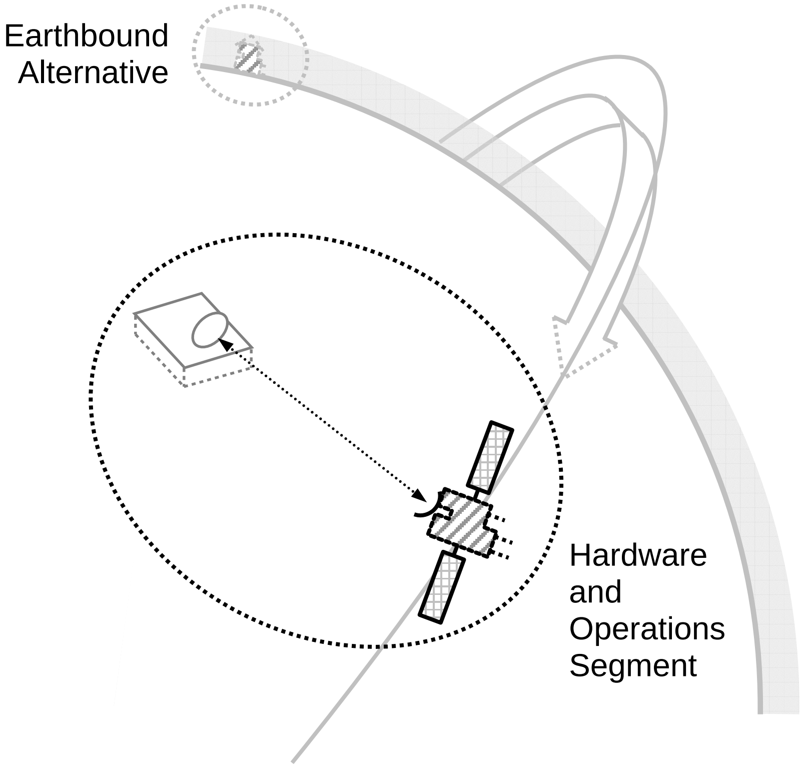

Figure 4-26: The Hardware and Operations Segment

The launch restrictions previously identified for any payload are disregarded in this chapter. Focus is on the difficulties and restrictions that the characteristics of space itself impose on the hardware, and the way they complicate any kind of operations in space (and on other celestial bodies). Both combined enable activities in space.

Similar to transportation, the restrictions are physical and technical, and therefore they can be clearly identified. Again, costs are not as easily defined, but a raw estimation is possible.

Analogue to the transportation chapter, a short introduction on activities in space gives an idea of the requirements of hardware and operations. This is followed by a detailed view on the space environment, by the resulting consequences for hardware and operations, and then, by a look on the present and future cost situation.

As will be seen, space hardware and operations will remain demanding and extremely expensive.

4.1.2.1 Activities in Space

From 1957 on, man made objects quickly advanced throughout the solar system, as illustrated in **Figure 4-27**. The Voyager 1 space probe, launched in 1977, currently is the most distant man made object with about 15.4 billion km in July 2007.[229] The range of human activities is still limited, though.

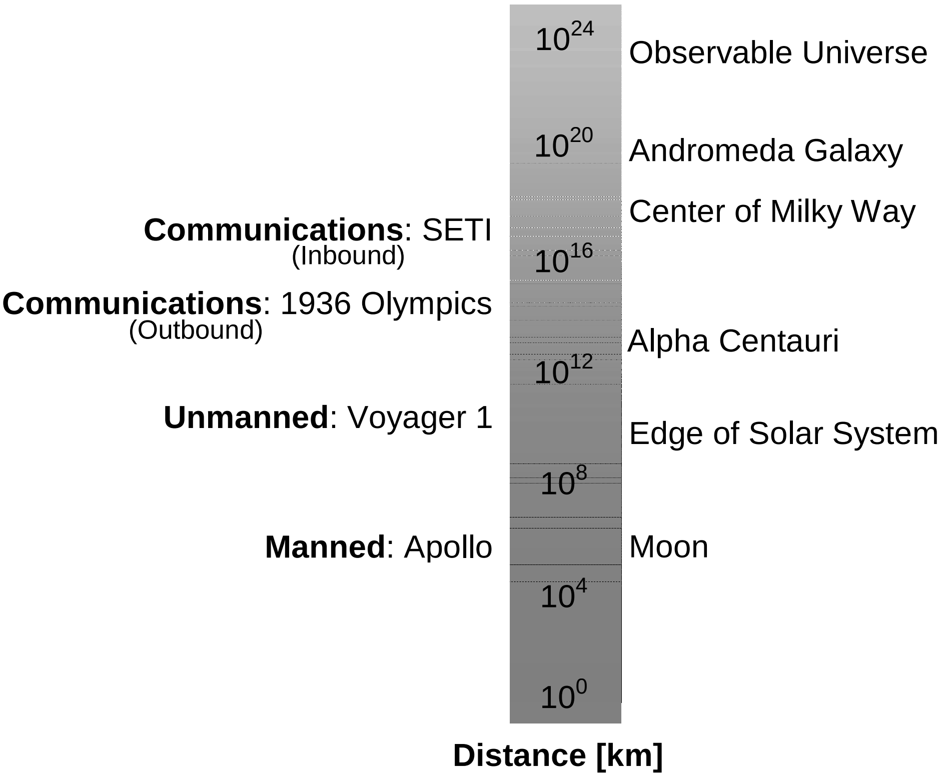

Figure 4-27: Range of Communications, Unmanned and Manned Spaceflight

Up to now, the most distant manned spaceflight missions were the Apollo lunar missions. Since 1972, no human has left LEO. The most distant interaction of humanity with other objects could be seen as the Search for Extraterrestrial Intelligence (SETI) project. It scans for artificial radio signals as far as about 30 000 light years away.

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[229] NASA JPL 2007a.

Table 4-22 shows the currently most distant target successfully reached by nations with a noteworthy space program, combined with the respective mission's launch date. The farthest distance to Earth during mission operations is presented. Only missions with indigenous launcher *and* spacecraft are listed.

Table 4-22: Various National Missions[230]

Mission	Country	Target	Launch	Max. Distance [km]
Voyager 1	USA	Grand Tour	1977	> 15 400 000 000
Mars 2	SU	Mars	1971	360 000 000
Hayabusa	J	Asteroid	2003	350 000 000
Giotto	EUR	Comet	1985	214 000 000
Rosetta*	EUR	Comet	2004	1 000 000 000
Chang'e-1	PRC	Moon	2007	380 000
METSAT	IND	GEO	2002	36 000
Diademe 2	FRA	LEO	1967	1 733
Prospero	UK	LEO	1971	1 403

* Mission en route.

These distances are illustrated in **Figure 4-28**. It should be mentioned that until October 2007, no Chinese or Indian spacecraft has left Earth orbit.

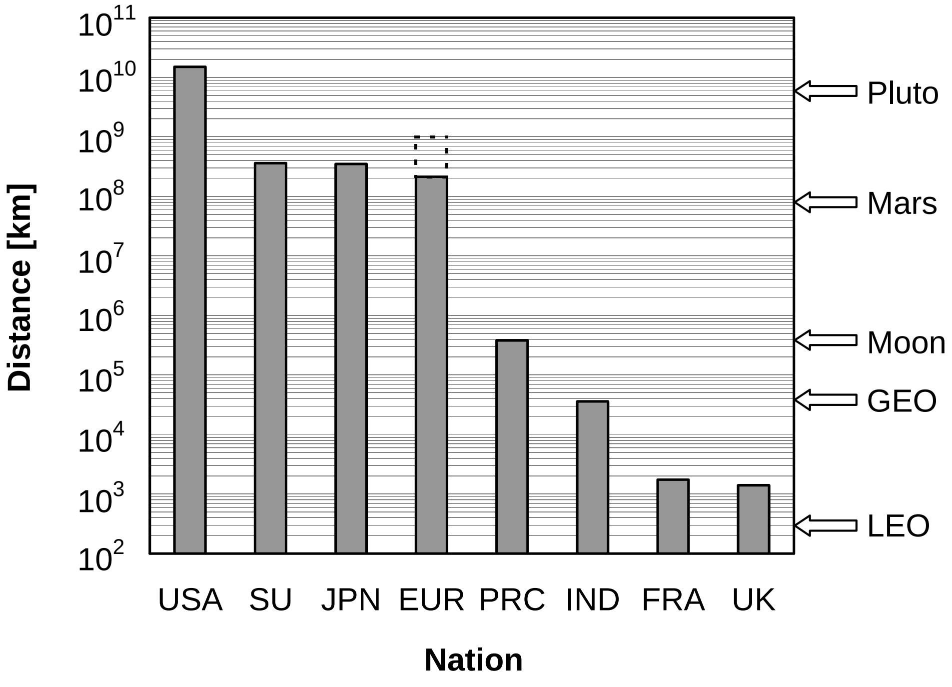

Figure 4-28: Most Distant Missions by Nation[230]

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[230] ESA 2007, NASA 2007, Wade 2007.

Analogue to the destinations of space transportation, space activities may be performed in LEO, GEO and other Earth orbits, in deep space, in orbits of other celestial bodies, and upon their surface.

In general, two categories are differentiated:

- Manned activities
- Unmanned activities

Assets and drawbacks of manned and unmanned activities should be considered for each activity. But for further considerations, this issue is factored out, and a brief overview will only state essential characteristics. Wherever human presence is required, it will be done – the debates about human spaceflight completely miss the issues of benefits of and motivation for spaceflight![231]

4.1.2.1.1 Unmanned Systems

Advance into space of unmanned vehicles is presented in **Figure 4-29**.

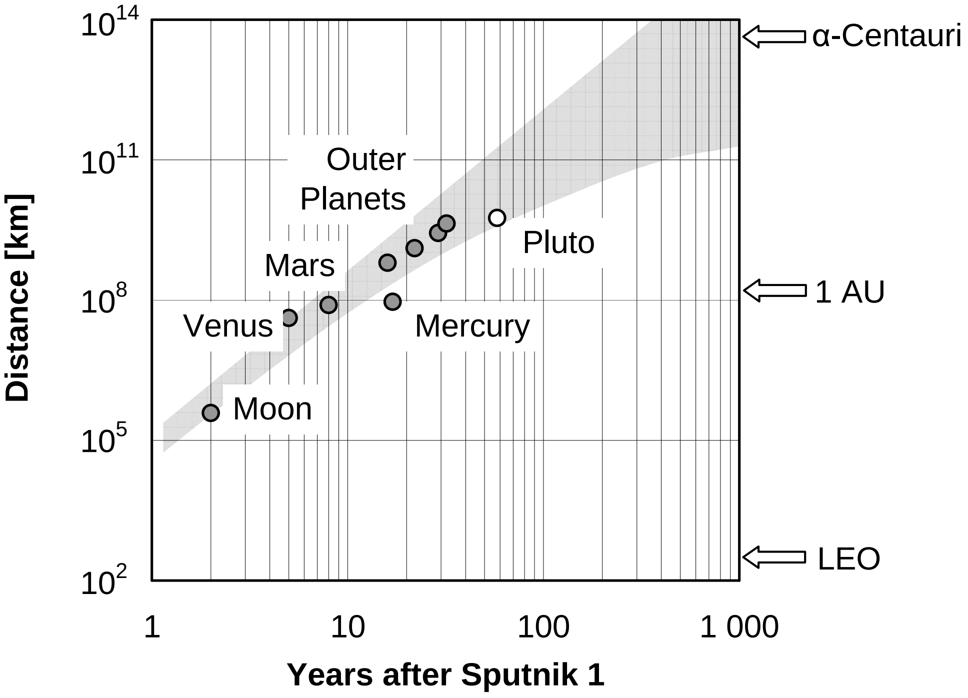

Figure 4-29: Advance into Space – Unmanned

Categories of unmanned systems are:

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[231] Actually, manned activities are negligible: Only 5 % of all orbital launches were manned (see Table 4-1), and less than 15 % of the annual U.S. spaceflight expenditures are currently spent for manned activities (about half of NASA's budget compared to total U.S. government space budgets, see chapter 8.7.6).

- Remote-Controlled: Instructions are executed directly – direct link between human and remote controlled activity.
- Automated: Pre-programmed activities are remotely activated.
- Autonomous (artificial intelligence): Fully automated, own decisions, but human surveillance is still required.

The communication lag due to maximum speed of light communications requires an increase of autonomy with spacecraft distance.[232] For earthbound controllers, remote controlled activities close to real time are only possible in LEO.

This leads to characteristic basic requirements for unmanned space systems:

- Autonomous internal supply (power, …)
- Total automation/robotics
- System diagnosis for error detection
- Sufficient environment sensors
- Redundancy as far as possible
- Extensive pre-planning (no tests with subsequent corrections under real operational conditions possible)

4.1.2.1.2 Manned Systems

Human presence is required for large scale construction work, but also to fulfill missions that have human presence as an objective, for example medical research or footprint missions to Moon or Mars. The attributes of humans instead of robots could be required for numerous reasons:

- Flexibility
- Perceptual capacity and processing of information
- Agility
- Dexterity
- Ability of decision-making for unpredicted tasks, problem solving, discovery of new phenomena and effects, …
- Adaptation to new situations and information
- Recognition of complex relations and structures

This and other reasons make manned systems preferable for tasks of:

- Recovery, maintenance, repair, overhaul, integration, construction
- Context in society (Humans as explorers, scientists, decision makers, …)
- Humans as subject of research

Characteristic requirements and attributes of manned systems are:

- Extreme reliability of the supportive technical systems

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[232] For Mars, one way signal travel time is between 5 to 20 minutes, depending on constellation.

- Relatively independent of terrestrial remote control
- Return to Earth
- Limited mission duration
- Life support system

Advance into space of manned vehicles is presented in **Figure 4-30**, in the same scale as the advance of unmanned vehicles in Figure 4-29.

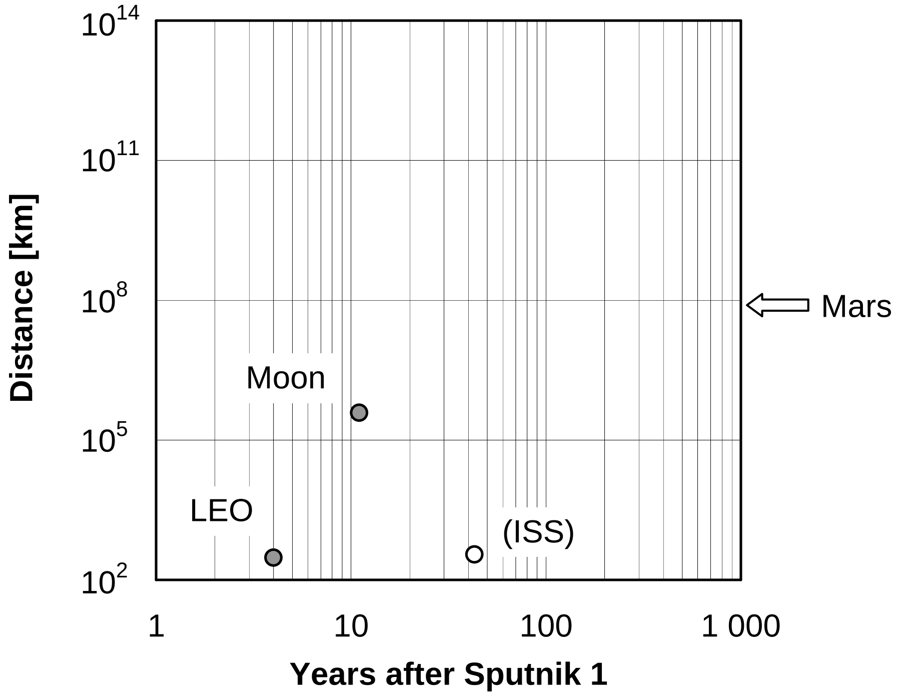

Figure 4-30: Advance into Space – Manned

The ECLSS (Environmental Control and Life Support System), often referred to as life support system, is currently the limiting factor of manned mission duration. ECLSS may be divided into open-loop and closed-loop systems. Open-loop ECLSS are the current standard in manned spaceflight. Resources that are recovered from the produced waste are not sufficient for total crew supply, thus requiring a steady flow of outside resources. Closed-loop systems are not yet available and very difficult to realize.[233]

Figure 4-31 presents the development of manned mission duration since Gagarin's historical flight. Grey circles represent the mission duration of the applied space vehicle or station, ranging from launch to abandonment by the last crew. Black triangles represent the longest manned mission aboard the space vehicle, ranging from launch to return of the astronaut/cosmonaut.

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[233] Even on Earth – without size, mass and energy restrictions –, closed-loop systems are not yet realized. The large scale experiment "Biosphere 2" that was done in the 1990s in Arizona to proof the feasibility of closed-loop systems failed.

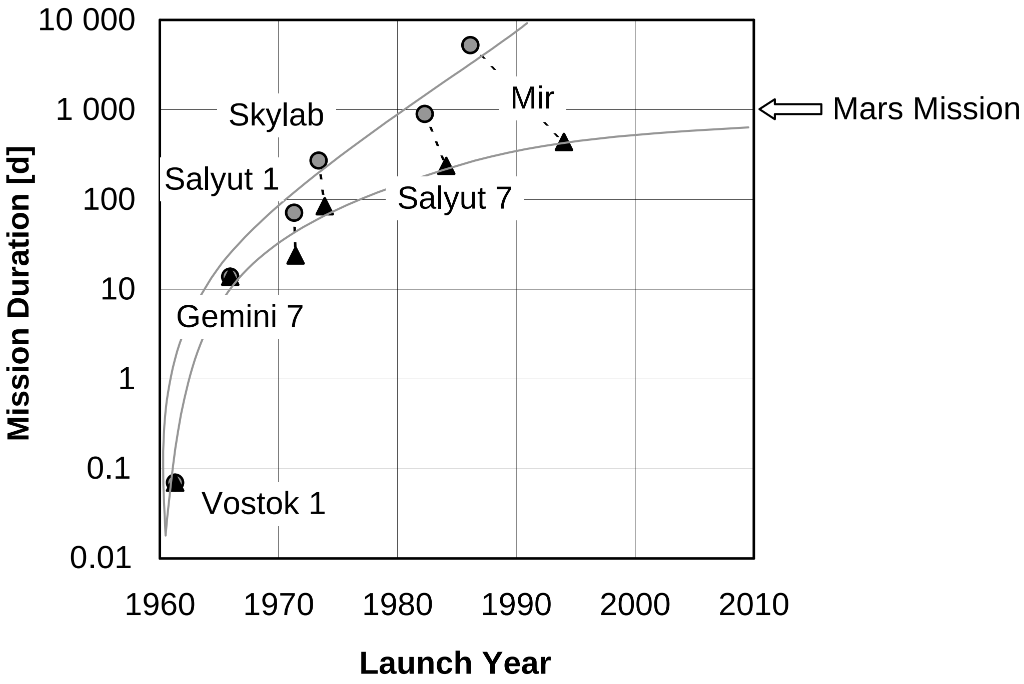

Figure 4-31: Development of Manned Mission Duration[234]
(Grey: Vehicle Mission Duration, Black: Longest Manned Expedition)

Manned activities are seen as more expensive primarily due to the significant mass increase compared to unmanned activities. As mentioned in chapter 4.1.1.1.2, the minimum mass requirement for one astronaut is approximately 1.5 t for short term missions.

4.1.2.2 A View on the Space Environment

“Space” has unique characteristics that significantly differ from Earth’s that must be mastered by spaceflight and could be utilized for space activities, including:

- Weightlessness (or various gravitational forces at other celestial bodies)
- Temperature
- Vacuum (or atmosphere at other planets)
- Radiation
- Distance to Earth
- Unlimited Space
- Small Particles (micrometeoroids, dust)

Most of these characteristics are independent of orbital altitude, and are also true for suborbital operations, deep space, lunar surface, and other accessible locations. The characteristics must be mastered to enable any activity in space.

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[234] Wade 2007.

Unique environmental characteristics do not automatically result in extensive utilization, as can be seen at some of Earth's environments presented in **Table 4-23**.

Table 4-23: Fundamental Differences of Earth and Space (Environmental Conditions)

Topic	Earth			Space
	Temperate Latitudes	**Antarctica**	**Deep Sea**	**LEO**
v_{min} [km/h]	-	-	-	**28 000**
Radiation	low	low	-	**high**
External Pressure [bar]	1	1	> 100	**~ 0**
Oxygen	available	available	bonded	**-**
Consumables	all	water	limited	**-**
Temperature [℃]	-15 – +30	-47 – +4 [235]	4	**-129 – +93**[236]
Period T_{max} to T_{min}	ca. 6 months	ca. 6 months	-	**45 minutes**
Transportation [$/kg]	< 0.05	ca. 2 – 5	< 10	**> 10 000**
Technical support required for survival	no	yes	yes	**yes**
Colonized	yes	no	no	**no**
Manned Laboratories	numerous	several	-	**one**
Expeditions	perpetually	perpetually	rare	**very rare**

Though mastering the conditions at Earth's poles or in the deep sea is easy compared to space, especially concerning manned operations, there are no extensive activities in Earth's extreme environments.

Adding the transportation threshold to the picture, the situation for space worsens even more. Compared to LEO, the ocean bed and the poles are easy to reach and do not have considerable transportation restrictions. That simplifies the efforts for construction, service and resupply of local infrastructures. But up to now, no one seriously considered a perpetually manned deep sea research station.

A closer view on each of the characteristic aspects of the space environment gives a better understanding of the challenges of space activities.

4.1.2.2.1 Weightlessness and Low Gravity

For any orbital and deep space operations, a state of microgravity can be assumed, resulting in new challenges for technical operations. Different gravity levels on other celestial bodies offer some challenges, too.

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[235] AWI 2004.

[236] NASA STS-116 2006a.

Manned missions impose additional efforts due to the significant impact of varied gravity on the human body.

A) Microgravity

This aspect is influenced or modified by the spacecraft itself, with spacecraft mass, gravitational gradients, vibrations of technical devices, accelerations due to attitude control, and other aspects.

Newton's third law of motion, the law of reciprocal actions, is of major importance for activities in microgravity. Each force F applied on (and within!) a spacecraft creates an equal reaction force,

$$\vec{F}_{A\rightarrow B} = -\vec{F}_{B\rightarrow A} \quad . \qquad (4.40)$$

Operations that include any kind of force application require constant and exact attitude control.

This includes low force operations like solar array deployment, movement within spacecraft (manned or robotic), and many more. This principle is especially important for high force operations, such as mining operations on small asteroids.

The advantage of practically non-existent structural loads for any type of technical devices is neutralized by the yet inevitable high accelerations during launch. Only deployable structures like solar arrays may benefit from microgravity conditions on a structural view. Nonetheless, once deployed, these array structures must be stiff enough to confine oscillation.

Another side effect is the absence of free convection in microgravity.[237] Technical devices used in pressurized spacecraft cannot use free convection for cooling or heating purposes. Forced convection is required for most applications. This is also true for breathing organisms to avoid suffocation.

The general effects of microgravity on organisms are known,[238] but not yet fully understood. Effects include:

- Space motion sickness
- Cardiovascular deconditioning
- Loss of muscle strength and mass
- Amyotrophia
- Osteoporosis
- Skin aging

---

[237] To be exact, the grade and direction of convection depends on the local quality of microgravity, but it is seen as absent to simplify considerations.

[238] NASA IIST 2007.

To counter these effects, rigorous training on various devices is required for astronauts and cosmonauts in space, creating induced vibrations and oscillations that interfere with the microgravity environment desired for scientific experiments. Some studies even propose the use of centrifuges to create artificial gravity during manned long duration missions.[239]

B) Low Gravity

The gravity force on other celestial bodies depends on their mass. Because Earth is the most massive celestial body with a solid surface in our solar system, all expected activities on non-Earth surfaces (especially Moon, Mars and asteroids) will take place in lower gravity. Other than microgravity, low gravity probably has a minor impact on technical devices and structures. The gravity of minor asteroids is low enough that it can almost be seen as microgravity.

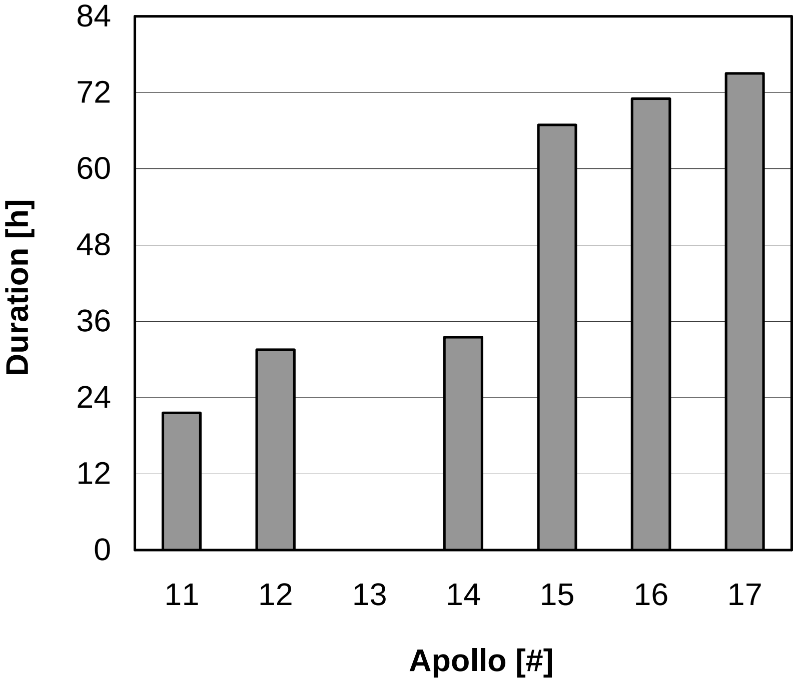

Figure 4-32: Apollo Lunar Surface Hours[240]

The impact of low gravity on the human body is widely unknown. The only experiences were gained during the six successful Apollo lunar landings, as seen in **Figure 4-32**. Average surface stay duration was 49 h 56 m, maximum surface stay duration was 75 h with Apollo 17, and total accumulated surface man hours were 599 h 8 m.[240] The fact that microgravity effects on the human body are not yet fully understood – although each ISS expedition crew member spends about 7 times more

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[239] This shows a kind of schizophrenia that manned spaceflight suffers from: On the one hand, microgravity is desired for scientific reasons, on the other hand microgravity is battled for health reasons.

[240] NASA Apollo 2006.

hours in microgravity than all Apollo astronauts combined on lunar surface – must lead to the conclusion that practically nothing is known about the biological hazards of long duration low gravity exposure.

Contrary to microgravity, scientific experiments in low gravity are quite insensitive to human presence.

4.1.2.2.2 Temperature

From an engineering perspective, the quick successive temperature changes in most space environments and the high temperature gradients between lighted and shadowed parts of an object are at least as challenging as the extreme absolute temperatures. This leads to very high stresses for materials. **Table 4-24** shows approximate values for environmental temperatures.

Table 4-24: Temperatures

Location	T_{min} [°C]	T_{max} [°C]	Period T_{min} to T_{max}
Earth: Temperate	-15	+30	6 months
Earth: Antarctica[241]	-47	+4	6 months
Earth: Desert	±0	+50	12 hours
LEO[242]	-129	+93	45 minutes
Moon[243]	-233	+123	2 weeks
Mars[244]	-87	-5	12 months
Deep Space	-270	-270	-

Details like exact position and partial shadow effects are not considered; the table only serves as a rough guide.

Figure 4-33 gives a better understanding of the challenge, graphically illustrating the temperature ranges.

The thermal expansion of materials poses a remarkable technical problem. Expansion rate depends on the material, but also on the phase: Gas expands more than liquids, liquids more than solid materials. The term for one-dimensional thermal expansion of solid materials is

$$\Delta l = l_0 \; \alpha \; \Delta T \quad , \tag{4.41}$$

with initial length l_0, temperature difference ΔT and thermal expansion coefficient α.

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[241] AWI 2004.
[242] NASA STS-116 2006a.
[243] NASA Fact 2007.
[244] NASA Fact 2007.

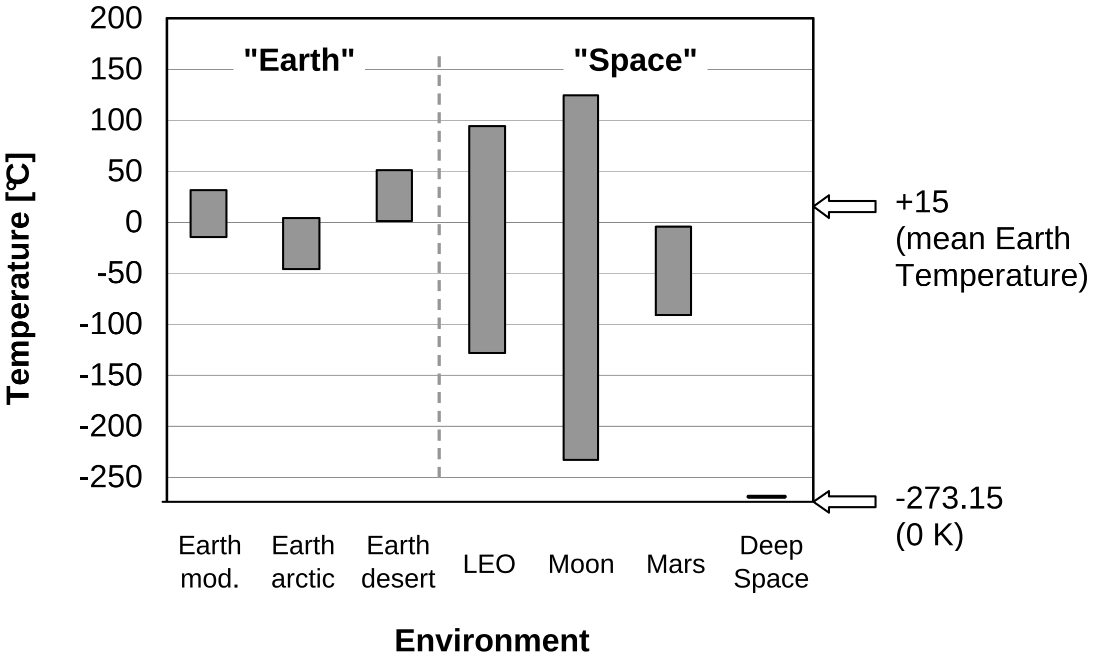

Figure 4-33: Temperature Ranges of Various Environments[245]

Additionally, the extreme temperatures require thermal conditioning not only for sensitive electronics, but also especially for manned missions.

4.1.2.2.3 Vacuum

Vacuum has a significant effect on materials:[246]

- Outgassing of materials
- Recondensing of outgassed materials on critical surfaces
- Change of material properties
- Galling, pitting, and cold welding of metals

This alone limits the range of applicable materials for any kind of space hardware. The effects increase with exposure duration.

Another aspect is the lubrication of moving parts that is almost impossible for vacuum conditions, complicating any applications that require fast moving and rotating parts.

Vacuum also prohibits heat exchange by convection. Thus, space systems that have to release surplus heat to enable a constant internal temperature level[247] can only do this by means of radiation.

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[245] AWI 2004, NASA Fact 2007, NASA STS-116 2006a.
[246] Griffin et al. 2004.
[247] This primarily affects manned systems.

4.1.2.2.4 Radiation

The harsh radiation environment of space cannot be underestimated in its dangerous effects on living organisms and sensitive electronics, as well as its negative effects on material properties. The only positive aspect is the potential use of solar electromagnetic radiation for heating and power generation.

Radiation is generally divided into non-ionizing and ionizing radiation.

Non-ionizing radiations include optical radiations (ultraviolet, visible and infrared – and lasers), static and time-varying electric and magnetic fields and radiofrequency (including microwave) radiation.[248] They must be considered under technical and health aspects.

Major technical aspects are degradation of various materials under optical radiation and the sensitivity of computers and other high end electronics.

Ionizing space radiation is generally divided into solar wind, solar cosmic rays produced by solar particle events (SPE), and galactic cosmic radiation (GCR).[249]

GCR, solar wind and SPE differ in duration and intensity. GCR and solar wind are continuous radiations depending in strength on the 11-year solar activity cycle. GCR intensity can increase from maximum to minimum solar activity by the factor of 2.5. SPEs are directed fluxes of highly energetic particles created at solar flares.[249] Solar wind and SPEs are effective only within our solar system. The GCR dominates in interstellar space.

Earth's atmosphere and magnetic field absorb or deflect most of the aggressive, potentially hazardous solar and cosmic radiation. LEO is still considered to be within Earth's magnetic field. But the lack of both an atmosphere and a noteworthy magnetic field on the Moon and other celestial bodies is the reason that hardware and crew are exposed to increased cosmic and solar radiation on other planetary surfaces. GCR exposure on planetary surfaces is about half of deep space operations exposure due to the bulk shielding of the planetary body itself.

Radiation is seen as the major health risk for manned long term space exploration. The mission duration accounts for the required radiation protection. As Apollo demonstrated, short term missions do not necessarily require massive radiation protection. But for long duration missions, safe havens for protection against SPEs are required as well as SPE emergency mission procedures. The shielding against the continuous flux of GCR also has to meet high standards.

The definitions of maximum radiation doses for astronauts are higher than general public guidelines by an order of magnitude, as presented in **Table 4-25**.

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[248] ICNIRP 2007.
[249] Eckart 1999.

Table 4-25: Ionizing Radiation Exposure Limits [Sievert/year]

Organization	effective	BFO	Eye	Skin
German Radiation Protection Ordinance[250]	0.02	0.05	0.15	0.5
EU Council Directive[251]	0.05		0.15	0.5
ESA[252]		0.5	1	3
NASA[253]		0.5	2	3

If a SPE is created by a solar flare, the crew has a few hours at best – depending on distance from the sun – to reach a radiation shelter against the highly energetic SPE. These events occur intermittently and unpredictably a few times during a solar cycle and may last up to one week.[254] The radiation doses of a SPE can reach more than 1 Sv. Extensive shielding is required, resulting in significant mass increase. The risk of SPEs also complicates EVA operations in space and on planetary surfaces. If no mobile shelters are available, the crew must stay close to a stationary shelter that can be reached within the given lead time.

Only very few values about radiation intensity in space are found in literature, and most of the sources differ significantly. Thus, it must be assumed that the intensity and effects of radiation in the space environment are not yet well understood. But it is a fact that any part of the space environment is subject to significantly higher radiation than Earth's surface. Therefore, radiation must be seen as a hazardous restriction to any kind of space activity, requiring special procedures and equipment, for manned as well as unmanned missions.

4.1.2.2.5 Distance to Earth

The physical distance to Earth and Earth's surface has many assets, but also one major drawback from an engineering perspective.

The distance to Earth's surface enables many activities where earthbound alternatives are very complex and costly or do not exist at all. The distance allows a good, global overview of Earth itself, enabling remote sensing, surveillance and reconnaissance, and many other types of activities.[255]

But this natural distance to Earth also has a negative side. Every technical device must be maintained, repaired and overhauled to extend its service life. The distance

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[250] BMU 2001.
[251] EU 1996.
[252] ESA HMM 2004.
[253] NASA JSC 2006.
[254] Eckart 1999.
[255] Most of the social and cultural justifications of spaceflight rely on the distance to Earth and the departure of mankind to the unknown, as stated in the famous science fiction series Star Trek: "To boldly go where no man has gone before".

combined with the efforts of transportation prohibits maintenance, thus resulting in a very high reliability requirement.

Therefore, once launched, an object must be viewed as isolated without the chance of repair. The recent failure of the Chinese communications satellite Sinosat 2 provides an excellent example. Launched on October 29, 2006 from the Xichang space center on a Long March 3B booster, the five ton satellite reached its transfer orbit, but the antennas and the 100 ft solar arrays failed to deploy. The Chinese government finally had to acknowledge the loss of the satellite on November 28, resulting in a complete failure of the 190 M $ mission (500 M $ in Western terms).[256]

In addition, the communications delay for greater distances must be considered. Real time communication becomes difficult at Lunar distance (2.5 s envelope delay) and impossible at Mars (from about 10 to more than 40 minutes).

4.1.2.2.6 Unlimited Space

Though Earth still offers remote areas with vast space available for structures of any kind, deep space really is infinite. There are no limiting restrictions.

Of course, the number of GEO slots for example is limited, as is the lunar surface and the theoretical number of objects in LEO. The statement is only aimed at theoretical restrictions of object size and dispersion.

But there also is another aspect of unlimited space: Basically unlimited resources!

4.1.2.2.7 Small Particles

There are two categories of hazardous small particles: Those with high relative velocities (micrometeoroids) and those with relative velocities approaching zero (dust).

A) Micrometeoroids

In space, the impact of a small particle releases great amounts of energy due to the commonly high relative velocities in the order of several km/s.

$$E_{kin} = \frac{1}{2} m\, v^2 \tag{4.42}$$

Without protective atmosphere that dissipates the particles by frictional heating, either shielding is required, or the possible impact effects must be taken into account.

Surface operations on other celestial bodies and in low orbits reduce the general deep space impact probability roughly by half due to planetary bulk shielding.

Impact probability depends on particle size, object surface area, object velocity, flight

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[256] AW&ST Nov 27 2006.

direction, object location, and present or past nearby other celestial bodies (planets, moons, asteroids, planetary rings, comets, …).

B) Dust

Not only the Moon, but also Mars and asteroids are covered with very fine dust. Due to extreme aridness, the particles do not stick together. This fine dust easily adheres electrostatically to every object surface.[257] This is a special problem for optical devices and sensors, but also for bearings and moving parts of machines.

There may also be a health effect of dust contaminated manned installations.

4.1.2.3 Consequences for Hardware and Operations

The unique environmental aspects of space result in fundamental differences for any hardware and operations in space and on Earth.

4.1.2.3.1 Hardware for Space

Space infrastructures have more in common with machines than with buildings. Following assembly, functionality must be proven on Earth, and only then the infrastructure is transported to its destined place. It has a design life cycle and cannot be recycled or refurbished (except for minor components, e.g. Hubble, ISS).

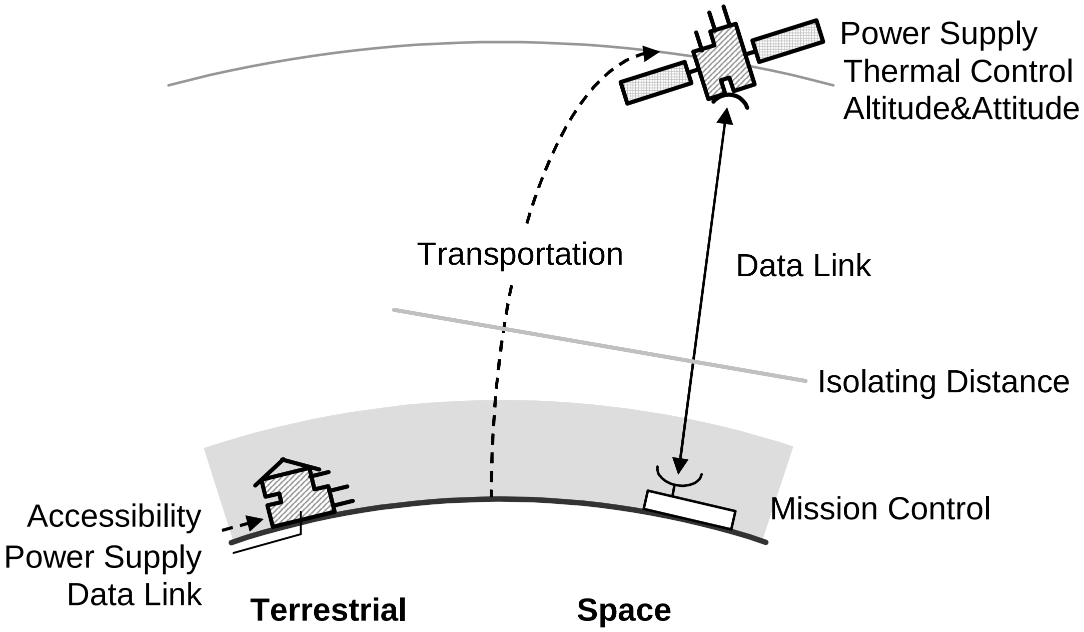

Figure 4-34: Differences of Terrestrial and Space Applications

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[257] Eckart 1999.

Some of the additional components and features that are essential for most types of space hardware are visualized in **Figure 4-34**. A few exemplary topics and their different treatment on Earth and in space regarding hardware are presented in **Table 4-26**.

Table 4-26: Fundamental Differences of Earth and Space – Hardware[258]

Topic	Earth	Space
Required Orientation	Surface	Attitude Control System
Required Location	Surface	Orbit Control System
Thermal Control	Passive	Active
Cooling Method	Convection	Radiation
Surveillance	Sporadic	Permanent
Ground Support	No	Indispensable
Maintenance	Regular	Impossible
Return to Earth	-	Challenging
Structure	Sufficient	Extreme Lightweight
Power Supply	External	Internal
Accessibility	Simple	Challenging to Impossible

Detailed views on terrestrial and space hardware offer even more insights to the high requirements of space. Three categories are analyzed:

- Unmanned
- Manned
- Combined

4.1.2.3.1.1. Unmanned

Unmanned vehicles, such as satellites and probes, must be independent of external supplies and work autonomously. Distant probes and rovers are handicapped by long transmission durations, thus making real time remote control and interference by ground control impossible. Some vehicles on Earth have similar exploration tasks.

A) Underwater Robot: DEPTHX Diving Robot

DEPTHX is an acronym for Deep Phreatic Thermal Explorer, an autonomous underwater vehicle capable of taking samples from up to 1 000 m water depth. In early 2007, it was used to explore underwater sinkholes in Mexico.

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[258] These differences are for the predominant characteristics and type of objects, and exceptions are possible. For better understanding: A nuclear power plant on Earth also requires complicated active cooling systems. But a calculator on Earth does not – in space, it does.

B) Comparison with Analogue Space Vehicles

Table 4-27 reveals key differences of autonomous vehicles for Earth and space operations. DEPTHX is compared to modern planetary probes.

Table 4-27: Autonomous Reconnaissance Devices

	DEPTHX	**MESSENGER**	**New Horizons**
Exploration Target	Underwater	Mercury	Pluto
Operation Distance to Earth/Sea Level [km]	< 1[259]	> 90 000 000	> 5 000 000 000[260]
Total Mass [kg]	1 300[259]	1 100[261]	478[262]
Av. Diameter [m]	2.13[259]	1.85[263]	2.5[260]
Electrical Power [kW]		0.45[263]	0.2[260]
Mean Temperature [℃]	4	< 450[261]	-269
External Pressure [bar]	< 100	0	0
Radiation Dose	negligible	extreme	high
Total Mission Duration	hours	7.5+ yr[261]	10+ yr[262]
Travel Time	hours	6.5 yr[261]	9.5 yr[262]
Data Collection	hours	1+ yr[261]	ca. 1 yr[262]
Costs [M $]	**5**[264]	ca. 360	**700**[262]
Reusability	yes	no	no

4.1.2.3.1.2. Manned

Some terrestrial facilities are similar to manned space stations or lunar bases in numerous ways: They must be autonomous for a long period of time, and they must ensure survival of humans in a hostile environment. Polar and underwater research stations are good choices for comparison.

A) Underwater Laboratory: Aquarius

The Aquarius station is managed by the American National Oceanic and Atmospheric Administration (NOAA). It was constructed 1986-87 and deployed at the U.S. Virgin Islands in 1988. It was later recovered, refurbished and redeployed two times, and is currently located at the Florida Keys at an average water depth of 15 m.[265] Since 2001, Aquarius is also used as a training station for astronauts with the NASA Extreme Environment Mission Operations (NEEMO) missions.[265]

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[259] Stone Aerospace 2007a.
[260] Space News 12/12/2005b.
[261] NASA JHUAPL 2007.
[262] Space.com 19/01/2006.
[263] Wikipedia 2007.
[264] Astrobiology.com 01/06/2007.
[265] NOAA 2007.

B) Polar Station: Neumayer III

The German research station Neumayer III, located at Atka Bay in Antarctica, is managed by the Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI). It is currently under construction and will start operations in February 2009. It represents the third generation of the German Neumayer stations.[266]

C) Comparison with ISS

At first view, both Aquarius and Neumayer III seem to have some similarities to space stations. But **Table 4-28** clarifies the differences in requirements between manned infrastructures on Earth and in space.

Table 4-28: Extreme Environment Laboratories

	Aquarius[267]	**Neumayer III**[266]	**ISS**[268]
Location	Underwater	Antarctica	Space
Avg. Altitude	-15 m	100 m	350 km
Geographic Location	Florida Keys	Atka Bay	51.6° LEO
Total Mass [t]	116+82*	2 300	186/419.6**
Habitable Surface [m^2]	37	1 650	
Habitable Volume [m^3]	74		425/935**
Standard Crew	6	11	3/6**
Maximum Crew	6	40	6/9**
Av. Mission Duration	10 days	9 months	6 months
Electrical Power [kW]		140+190	26/110**
Temperature Range [°C]	+20 – +30	-47 – +4[269]	-129 – +93[270]
External Pressure [bar]	2.5	1	0
Radiation Dose	Negligible	Negligible	High
Deployment duration [a]	< 1	2	12
Construction Costs [M $]		**25.2**[271]	ca. **100 000**
Operating Costs per Day and Crew Member [$]	1 700	hundreds	millions
Predicted Life Cycle after Completion [a]		25-30	> 5

* Baseplate and habitat. Numbers differ within source.
** June 2006 (actual)/December 2010 (planned).

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[266] AWI 2007.
[267] NOAA 2007.
[268] NASA HQ 2006a.
[269] AWI 2004.
[270] NASA STS-116 2006a.
[271] In €: 21 million. (AWI 2006)

Though the ISS project seems incomparable to Aquarius and Neumayer III, especially concerning technical efforts and costs, it must be compared to the other laboratories due to their common goal of scientific research. From a rational perspective, the benefits of the three facilities should be proportional to the required efforts.

4.1.2.3.1.3. Combined

Because of their terms of accessibility, some facilities are manned in their earthbound version, but only man-tended or unmanned in their space version. Best examples are telescopes. The objectives are similar, but the technical requirements are very different for Earth and space.

A) Existing Ground Telescope: Keck Observatory

The W.M. Keck Observatory consists of two telescopes built in 1993 and 1996 at Mauna Kea, Hawaii. Each has a mirror diameter of 10 m and is equipped with adaptive optics to reduce atmospheric turbulence blurring. The distance between both telescopes is 85 m.[272] The Keck telescopes currently have the 3rd largest telescope diameters in the world.

B) Planned Ground Telescope: European Extremely Large Telescope

At December 2006, ESO gave green light for a detailed study of the European Extremely Large Telescope (E-ELT) to start construction within three years. The telescope will be over 100 times more sensitive than the Keck telescopes.[273]

C) Flying Telescope: SOFIA

In 1996, DLR and NASA agreed on a Stratospheric Observatory for Infrared Astronomy (SOFIA). The 2.5 m telescope is located aboard a Boeing 747 and will operate at altitudes above the major atmospheric influences. First flight tests began in 2007.

D) Comparison with Space Telescopes

Total cost of the Hubble Space Telescope (HST) is given as 1.5 G $.[274] But, adjusted for inflation and measured according to the same accounting methods as the JWST, HST is estimated at a total cost of 7 to 8 G $.[275] Anyway, HST is considered NASA's most successful scientific mission, generating almost 7 000 scientific papers during 800 000 observations from 1990 to early 2007.[276]

Space telescopes are more expensive than ground telescopes by at least an order of magnitude, and they are extremely sensitive to malfunctions, thus limiting their service life.

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[272] Wikipedia 2007.
[273] ESO 2007.
[274] Wade 2007.
[275] Space News 20-2007a.
[276] Space News 17-2007b.

But it is questionable if the current and next generation of terrestrial telescopes and their instruments would have reached their level of performance and quality if the HST was never developed and deployed. Space telescopes are cutting-edge technology, and they might be a catalyst for high tech developments for Earth applications – a role that many space applications share.

The costs and performance of space telescopes compared to the mentioned observatories on Earth are presented in **Table 4-29**.

Table 4-29: Various Observatories

	Keck[277]	**E-ELT**[278]	**SOFIA**[277]	**HST**[279]	**JWST**[280]
Full Name	W.M. Keck Observatory	European Extremely Large Telescope	Stratospheric Observatory for Infrared Astronomy	Hubble Space Telescope	James Webb Space Telescope
Location	Hawaii	Chile?	Aircraft	LEO	L2
Height above sl/ Av. Distance [km]	4.1	2.6	12	590	1 500 000
Wavelength	Optical, Near-IR	Optical, Near-IR	IR	Optical, Near-IR, UV	IR
Mirror Type	2 x Mosaic	Mosaic	Single	Single	Mosaic
Diameter [m]	2 x 10	42	2.5	2.4	6.5
Resolution [arcsec]	0.04 to 0.4	0.001 to 0.6		0.05	
First Light [Year]	1993/96	2017	2009	1990	2013
Costs [M $]	**2 x 100**	**1 000**[281]	**700**[282]	**1 500**	**4 500**

4.1.2.3.2 Operations in Space

The operation is closely linked to the hardware: Requested operations dictate hardware design, and given hardware limits executable operations.

4.1.2.3.2.1. Difference to Terrestrial Operations

Operations in space are more difficult to realize than on Earth. Simple tasks require tremendous efforts. Three simple examples may illustrate the fundamental difference between terrestrial and space based activities:

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[277] Wikipedia 2007.
[278] ESO 2007.
[279] Wade 2007.
[280] Space News 21/11/2005.
[281] In €: 800 million. (ESO 2007)
[282] Space News 23-2007.

- Refueling and Maintenance
- Thermal Measurements
- Conducting Scientific Experiments

A) Refueling and Maintenance

The capability to refuel an object and change parts of hardware in space is complicated enough that a 300 million $ technology demonstration mission of the U.S. Defense Advanced Research Projects Agency (DARPA), presented in **Table 4-30**, had to verify the feasibility.

Table 4-30: Orbital Express Data[283]

Mission Name	Orbital Express
Initiator	DARPA
Mission Launch	March 2007
Mission Duration	4 months
Preparation Time	Years
Costs	300 M $

On Earth, refueling an object is a matter of minutes, as is change of hardware. Cost is about zero.[284]

B) Thermal Measurements

In space, the simple experiment of measuring the increase of temperature on a black plate's surface due to sunlight irradiation requires a full grown satellite mission with reliable attitude control, qualified sensors, telemetry, ground control, … – enough efforts for years of work.

The same experiment on Earth requires few minutes for one student with a thermometer at a sunny day.

C) Conducting Scientific Experiments

On Earth, a scientific experiment is assembled and then conducted, usually by the initiator of the experiment, sometimes by lab assistants.

For space, an experiment is assembled, tested numerous times over many years, and then it is conducted in an orbital laboratory by an astronaut who attended years of training for days of actual work, as seen in **Table 4-31**.

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[283] AW&ST Jul 18 2007.

[284] The reason that space servicing is expensive is not just because it is *unmanned* and autonomous and therefore complicated: The *manned* US-STS Hubble servicing missions are estimated at 1 G $ each (unmanned Hubble servicing missions were discarded by NASA for being even more expensive).

Table 4-31: Conducting Scientific Experiments on Earth and in Space

	Earth	**Space**
Number of Experiment Cycles	Arbitrary	Many on Earth, One in Space
Personnel	Lab Assistant/Scientist	Astronaut
Required Education/ Training	Secondary	Advanced University Degree, Flight Training, Survival Training, Mission Specific Training, …
Modifications of Hardware	Always Possible	Restricted, Frozen Design

D) Conclusion

Space significantly increases the required efforts for any activity, no matter how simple it may seem. In space, everything is extremely complicated.

4.1.2.3.2.2. Complexity of Manned Operations

The requirements, the complexity, the efforts and the costs of manned operations increase with the type of activity that is performed by the astronaut, as seen in **Figure 4-35**.

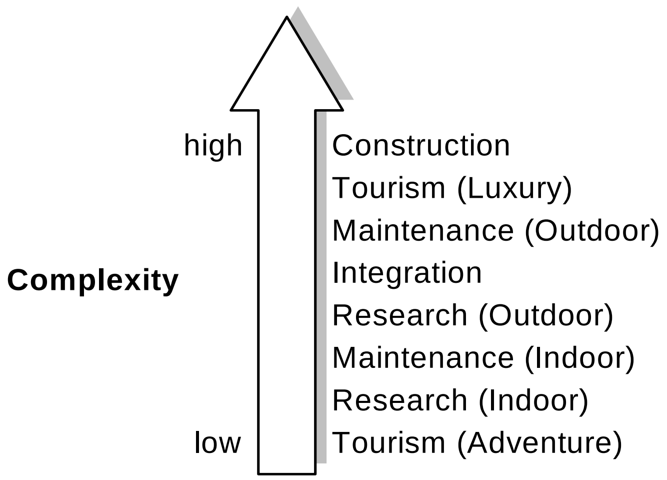

Figure 4-35: Complexity of Manned Operations

Simple space tourism has the lowest requirement: The person sits in the spacecraft and looks out the window. The activities become more and more challenging with the complexity of required operations.

Integration, maintenance and construction activities that are performed by astronauts are extremely difficult due to numerous reasons. One of them is the astronaut suit required for each outdoor space activity that significantly reduces the astronaut's freedom of movement, field of vision, and endurance. It is stated that the ISS construction spacewalks have been compared to "hanging a shelf while wearing roller skates and two pairs of ski gloves with all your tools, screws and materials tethered to your body so they don't drop".[285]

This has not only to do with weightlessness, but with the nature of space operations. Proposed lunar base construction activities may be characterized in a similar way: Four persons are expected to build a perfect house (or an aircraft – space infrastructure has more in common with complex machines!) in the desert, wearing the same ski gloves and heavy suits, using as much in situ material (sand) as possible, living in a small container, and being supplied by one small truck every six months.

4.1.2.4 Financial Aspects of Hardware and Operations

Costs for a space mission can be divided into three major parts:

- Transportation into space, including launch vehicle and launch operations
- The hardware itself, including development, construction, and qualification
- Operation of the hardware during the mission

Transportation costs were examined in chapter 4.1.1.3.3. The remaining costs of a mission must be assigned to the hardware and operation segment.

4.1.2.4.1 Present Cost Situation

Similar to transportation costs, exact cost numbers for hardware and operations are difficult to define.

Statements concerning operation costs are a lot more difficult than statements about space hardware costs.

A) Hardware

Lightweight structures and the required materials (titanium, …) are often blamed for the high costs of space hardware. But development, quality assurance, and, for the most part, the required support systems and actual instruments are the decisive cost drivers of hardware.

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[285] NASA HQ 2006a.

Each piece of space hardware basically is a prototype, specifically designed for the intended mission. The harsh space environment sets high requirements for hardware, and thus increases hardware costs. Structural cost, and therefore the influence of lightweight structures, is only a small part of total costs, as seen in **Figure 4-36**.

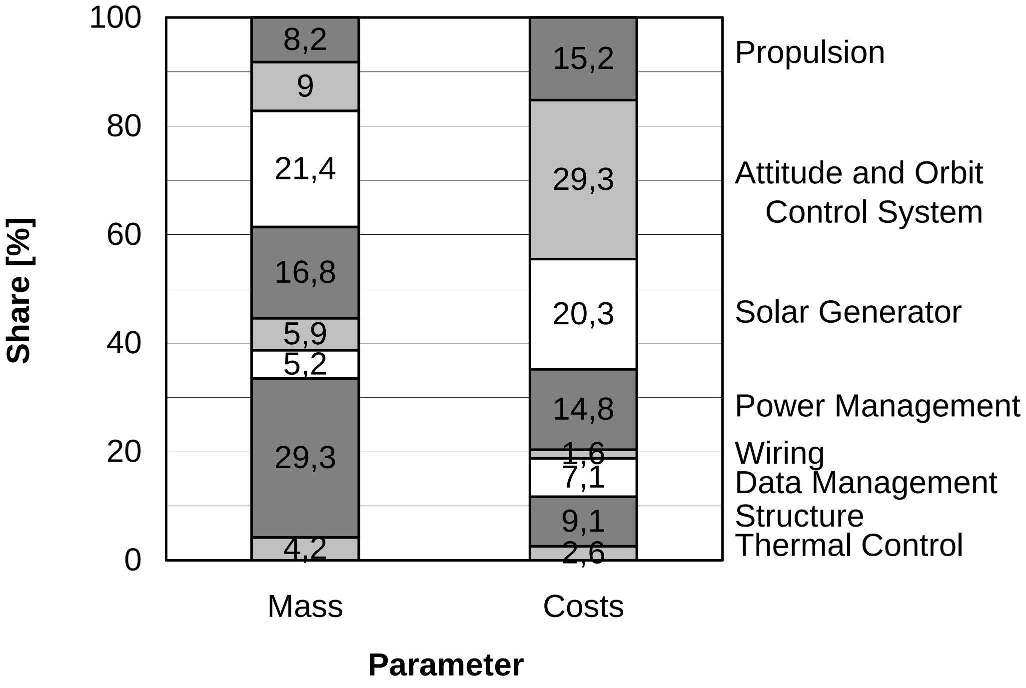

Figure 4-36: Satellite Platform Mass and Cost Breakdown[286]

Assuming that lightweight structures are used anyway, as it has always been done in the spaceflight sector, there should be a rough correlation between mass of the hardware that is used in space – which is nothing else than payload mass m_p –, and cost of the hardware used in space C_p. This correlation results in specific space hardware costs c_p.

$$c_p = \frac{C_p}{m_p} \qquad (4.43)$$

With this, total cost for heavier space payloads is generally higher than for smaller and lighter payloads, which is true for most missions, for example:

- Keyhole spy satellite – Quickbird imaging satellite
- ISS – Skylab
- Mars Science Laboratory – Mars Pathfinder

Actually, there is a correlation between mass and costs, as can be seen in **Figure**

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[286] Quirmbach 2001.

4-37 with some selected examples.

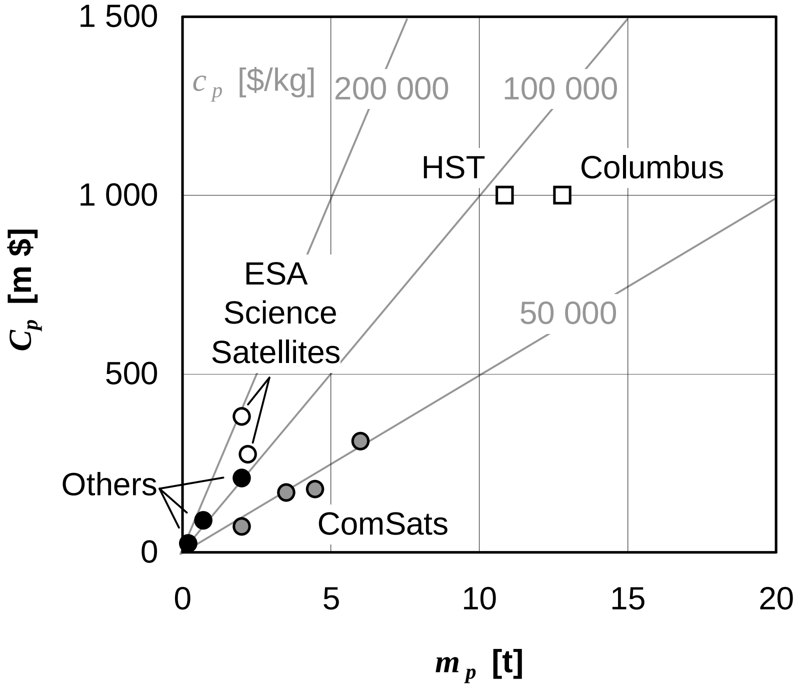

Figure 4-37: Correlation of Space Hardware Mass and Cost[287]

Specific hardware costs c_p are between 50 000 to more than 200 000 $/kg.

The lower limit of 50 000 $/kg seems to be subject to the standardization of ComSat platforms, but the given satellite masses probably include the apogee motor with propellants for GEO injection. That means that the actual satellite hardware mass is only roughly 50 % of the given mass, thus doubling the specific hardware costs.

Total hardware size and mass do not play a significant role for c_p. Two extremes may illustrate this:

- The total costs of the ISS are about 100 G $, including launch costs.[288] Total mass, once finished with a total of roughly 30 US-STS flights, will be 420 t.[289] The official NASA US-STS launch cost is 0.5 G $.[290] Launch costs of other ISS partners might add up to less than 5 G $.
- The picosatellite MOVE (Munich Orbital Verification Experiment) that is cur-

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[287] Reliable data is very hard to find. When a value is actually published, it is hard to say if the given value includes development, launch support, insurances, operating support, software updates, and many other factors. The same is true for the given hardware mass: It could include propellants for altitude and attitude control as well as for orbit insertion, which increases mass of GEO satellites by a factor of 2. But the general order of magnitude, as seen in the figure, remains the same.

[288] ESA ISS 2005.

[289] NASA HQ 2006a.

[290] NASA KSC 2007.

rently built at the Institute of Astronautics of the Technical University of Munich is estimated at roughly 200 000 $. Satellite mass is one kilogram.[291]

The resulting specific costs are similar, as is seen in **Table 4-32**.

Table 4-32: Specific Hardware Cost Comparison

Hardware	m_p [kg]	c_p [$/kg]
ISS	420 000	190 000
MOVE	1	200 000

For the ISS, the individual payload masses add up to the total ISS mass referred to as m_p.

There seems to be an effect on c_p depending on intended mission type: Commercial communication satellites have the lowest specific costs, followed by scientific probes and satellites (including manned installations), and then, most expensive, military hardware. Verification is difficult, though, because no reliable data is available.

B) Operation

Operational costs are high due to required ground control, mission staff, operators, and more.

Both manned and unmanned activities require large scale surveillance and support activities on the ground. Approximately 16 000 people alone in the USA contribute to NASA's Space Shuttle program and thus are required for the program and its launches,[292] but also unmanned scientific missions such as NASA's Cassini probe, launched in 1997 and in orbit around Saturn since 2004, require permanent surveillance and ground crews ranging from 100 to 300 persons during the entire mission.[293]

Simplified, total operation costs C_o consist of the time of operation t_o, meaning mission duration, and the costs of operation c_o,

$$C_o = c_o \cdot t_o \qquad (4.44)$$

c_o mirrors the complexity of the operations: The more complex the operation, the more manpower is required, resulting in a higher value of c_o. Exact values for c_o cannot be determined due to missing reliable data.

The costs for hardware and operations $C_{h\&o}$ of any given mission are therefore given as the sum of total hardware costs and total operation costs,

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[291] Czech, personal conversation.
[292] NASA STS-116 2006b.
[293] Muscettola et al. 1998.

$$C_{h\&o} = C_p + C_o \ . \qquad (4.45)$$

4.1.2.4.2 Future Cost Outlook

The current cost drivers for space hardware will not change in the foreseeable future:

- Low production numbers
- Highest quality levels
- Very specific requirements
- System autonomy and high complexity
- Resistance against the hostile space environment
- Lightweight structures

Though lightweight structures are included as a factor, they are of minor importance – space hardware is <u>not</u> expensive because it requires lightweight structures!

Operational costs will not change either. Even with present levels of automation, continuous surveillance of spacecraft systems is a must.[294] This requires ground stations, a global network of communication facilities, and large numbers of ground workforce (operators, support staff, technicians, …).

Therefore, hardware operation costs for any activity in space, manned or unmanned, must be expected to remain at continuously high levels.

4.1.2.5 Consequences for Activities in Space

The space environment is extremely hostile, not only for life forms, but also for machines. Its characteristics complicate activities, but they also offer unique chances. Therefore, only activities in space that make use of at least one of the special aspects of the space environment are sensible. Spaceflight should

- utilize at least one characteristic aspect of space,
- accept and master the other aspects.

<u>*Any*</u> activities in space are always linked to higher efforts than on Earth. That means that they will always be more expensive than identical terrestrial alternatives.

Hardware and operations costs will remain at present levels because the characteristic cost drivers of space will not change in the future.

The efforts and costs of the hardware and operations segment will remain <u>extremely high</u> for the foreseeable future, and significant reductions are hardly possible.

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[294] The Soviet Union lost contact to numerous planetary probes because it had no global space communication network, thus prohibiting continuous surveillance.

4.2 The Motivation

The definition of motivation seems to be more the task of a sociologist than that of an engineer. But the inevitable minimum efforts that were presented in the previous chapters require a good reason.

At first, three acting elements of society are introduced and their basic interests are identified. This is followed by a view on their economic potential and willingness to spend money, and then, on the consequences of the results concerning spaceflight.

The following considerations may perhaps seem naïve to sociologists and economists, but they are sufficient for further analysis.

4.2.1 The Three Elements of Society

Society can be seen as the sum of individuals, supplemented by the two non-personal institutions state and industry.[295] In one way or another, both institutions must serve the interests of the individuals in the end.

With that assumption, society consists of three elements that interact with each other, as illustrated in **Figure 4-38**:

- Individual (households)
- Industry (companies)
- Government (state, public)

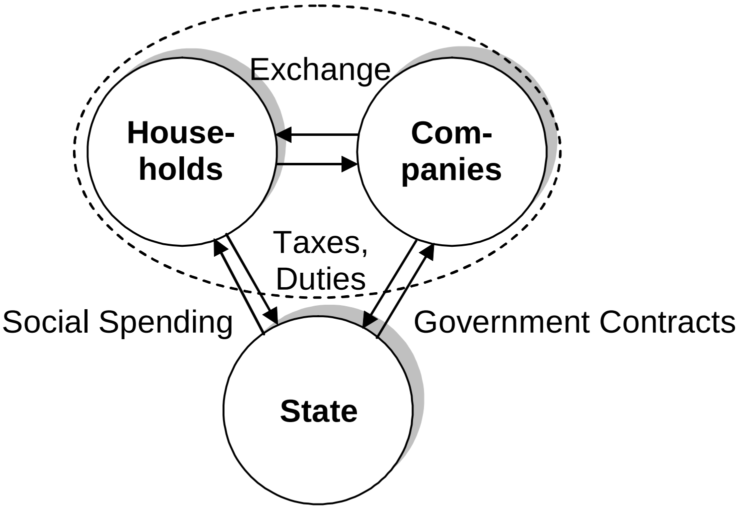

Figure 4-38: Interaction of Individuals, Companies and the State

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[295] The classification is arbitrary and could as well include other elements or institutions, such as churches, unions, all of humanity, special interest groups, and many others. But as will be seen, especially in the context of spaceflight, limitation on the three selected elements is absolutely sufficient.

Each element has different specific interests, potentials, capabilities and duties. They can serve either as a user or as a provider. The finances basically originate from private households. A key question for spaceflight (as well as for other areas) is:

How can spaceflight make positive contributions for individuals, companies and the state?

The basic dictum must be at least preservation or increase of the present situation of all of the three elements.

4.2.2 Interests of the Three Elements

The different interests emerge with a closer look onto each element.

4.2.2.1 Individuals

Society is composed of individuals, each of them a personality with individual attributes, interests, goals, desires, potentials and capabilities. This leads to individual consequences of action. Individuals do not form a homogenous community with identical attributes.

The basic goal of every activity of an individual is advantage and personal benefit.[296] The individual is motivated to act in a way that its present individual situation is improved or, at least, consolidated. The egoism of the individual is a suited natural attribute to achieve this improvement.

The urge to improve the individual situation is the source of the efforts and commitment that are the fundamental drivers to advance the whole society, with the mechanisms of economy and free market as a good example.[297]

Individual interests and desires can be classified hierarchically according to their urgency. Existential needs, such as food, clothes or sexuality, are the most basic. These are followed by physical safety, including security of body, family and property. Next step are idealistic needs like friendship and love. At the end of the hierarchy are esteem and self actualization. This Hierarchy of Human Needs, as seen in **Figure 4-39**, was first developed by Abraham Maslow (1908 – 1970).[298]

The lower the need is situated, the more important is its satisfaction! The need for food is more powerful than the need for self actualization! Therefore, motivation of individuals must be judged by the affected type of need.

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[296] Even idealistic goals like climbing Mount Everest have personal benefits: To achieve a personal, pre-set goal (and, perhaps, to be admired by others). With this, the personal benefit of an idealistic goal is satisfaction of the need of self actualization as well as self esteem. The same is true for altruism: The actors themselves feel better by doing selfless deeds.

[297] Laws are supposed to limit the negative effects of these mechanisms, but this is a topic that belongs to the element “state”.

[298] Brockhaus 1979.

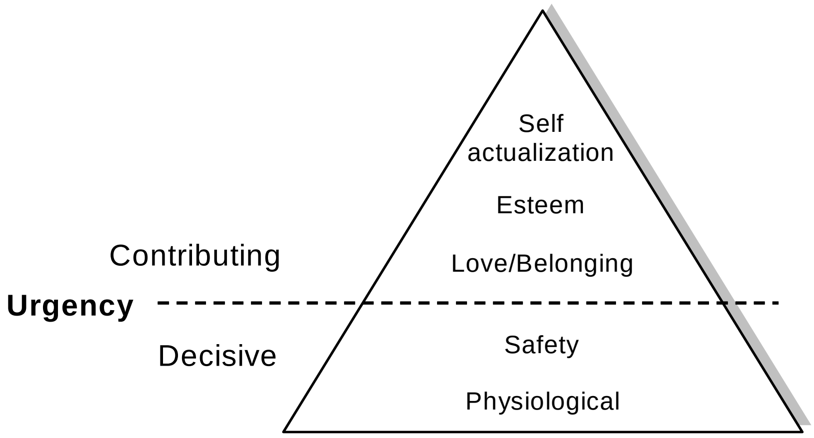

Figure 4-39: Maslow's Hierarchy of Human Needs

Spaceflight itself is situated at the upper level of the hierarchy (fun, adventure and personal interest complies with self actualization), but it can certainly contribute to the satisfaction of needs in lower levels. For individuals, the decisive question is:

How can spaceflight help to satisfy individual human needs and improve the situation of individuals, and how much is the individual able and willing to pay for it?

4.2.2.2 Companies

The one and only purpose of a company is business: Creating profits by selling products, services or information to individuals, the government and public sector, or other companies, as seen in **Figure 4-40**. The actual contents of these offers are completely unimportant as long as they are in demand. Individuals offer their workforce to companies and create these offers for a service (wages) in return.

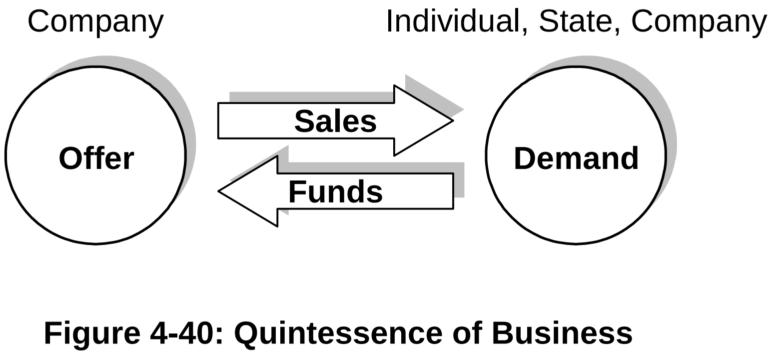

Figure 4-40: Quintessence of Business

The satisfaction of the needs of paying customers is the decisive point of every offer. Companies lack these special needs except of improvement of their own situation.

As a dominating characteristic, every company tries to maximize its profits. Products and services are just necessary means for that end. The number of employees, environmental protection and other factors are not part of the initial business.

Spaceflight itself has no special meaning for companies. Only increase of revenues, profit maximization and advantages over rivals (technical and strategic) are of importance. For the industry, the decisive question is:

How can spaceflight contribute to increase the profits of companies?

4.2.2.3 State and Public Sector

It is the national duty of a state to protect its citizens and their basic resources, and to increase the common standard of living. The state must ensure peace and liberty, economic prosperity, protection of the natural environment, and existence of a satisfying social and cultural environment for its citizens – to use one word, the state has to guarantee and increase *safety*, in all facets of life: Health, wealth, integrity, … .

Additional, it has to reduce social inequities and internal and external political tensions. The duties of the state concern sovereignty, future conservation and standard of living – the needs of the majority of its individual citizens should be satisfied.

These national duties are subjective, though. The representatives of the state – the politicians in the government – are individuals that are motivated by other personal needs and interests (reelection, corruption, personal interests, …).

The state is financed only by its individuals and companies. Public action quite often counteracts the individual pursuit of advantage because of the state's social duties. Inequities are equaled and advantages are limited by regulations and taxes. Tax allowances and subsidies are counterproductive to the limitation of advantages. For the government, the decisive question is:

How can spaceflight support the government and the state to effectively execute national duties?

4.2.3 Financial and Economic Orders of Magnitude

For its realization, spaceflight has to be financed. Nothing is realized without sufficient funding – the intention alone is insufficient.

Before the three elements of society are analyzed concerning their potential for funding space activities, a view on the current state of spaceflight funding and on general financial expenditures is recommended. **Table 4-33** presents some general economic data.

Table 4-33: Various Basic Economic Data (ca. 2005)

Economic Parameter	Germany	USA	World
Gross Domestic Product [G $][299]	2 782	12 455	44 385
Employees [million][300]	41	150	
Public Spending Ratio [%][301]	45.6	34.5	
Defense Budget [G $][302]	35.1 (2003)	466 (2004)	950 (2004)
Bituminous Coal Subsidy [G €][301]	1.6		
Bit. Coal Mining Employees[301]	38 500		
Annual Reunification Costs [G €][303]	ca. 100	-	-
War in Afghanistan (annual) [G $][304]		90	

These numbers must be compared to space related economic data presented in **Table 4-34**.

Table 4-34: Space Related Economic Data

Economic Parameter	Number
Visible U.S. Space Budgets* [G $] (2007)[305]	35.4
Total U.S. Government Space Budgets [G $] (2007)[306]	62.6
U.S. NASA Budget [G $] (2007)[305]	16.7
European ESA Budget (2006) [G €]	2.9
German DLR Budget [G €] (2007)[307]	0.8
Indian ISRO Budget [G $] (2007)[308]	0.9
Space Industry Employees Germany (2005)[309]	5 300
Total Aerospace Industry Employees Germany (2005)[309]	81 300

* Combining NASA, NOAA, MDA and USAF overt space related budget requests.

Comparing the numbers, the true scale and meaning of spaceflight becomes visible. Spaceflight turnover is insignificant compared to the Gross Domestic Product (GDP), and effects of spaceflight funding on the GDP are therefore not traceable, as exemplary presented for Germany in **Figure 4-41**.

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[299] World Bank 2006.
[300] ILO 2007.
[301] Globus 1994-2007.
[302] Global Security 2007.
[303] Spiegel Nr. 15 2004.
[304] ARD 31/10/2006.
[305] Space News 6-2007.
[306] Space Foundation 2008.
[307] DLR 2007.
[308] Space News 9-2007b.
[309] BDLI 2007.

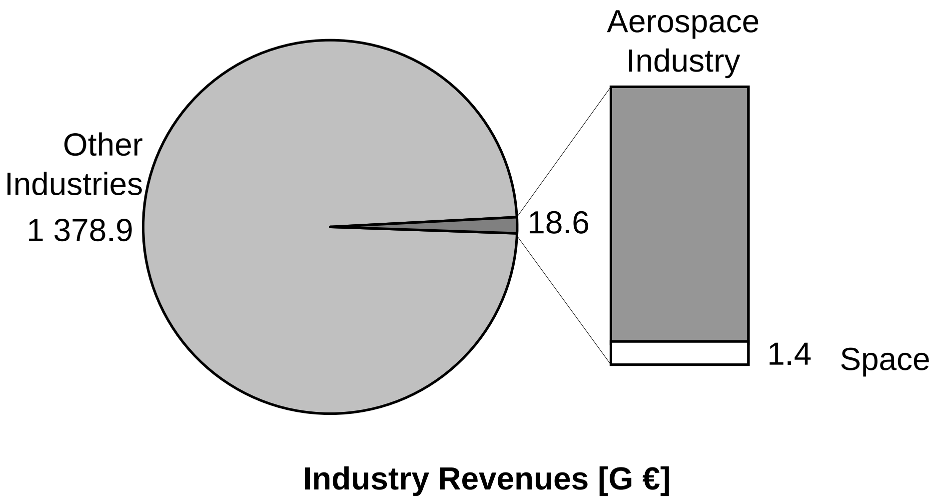

Figure 4-41: Share of Aerospace and Space Industry Revenues on Total Industry Revenue (Germany 2005/06)[310]

The same is true for the employment situation, as presented in **Figure 4-42**. Considering that Germany is a leading industrial nation, the worldwide economical meaning of the space industry is expected to be even less.

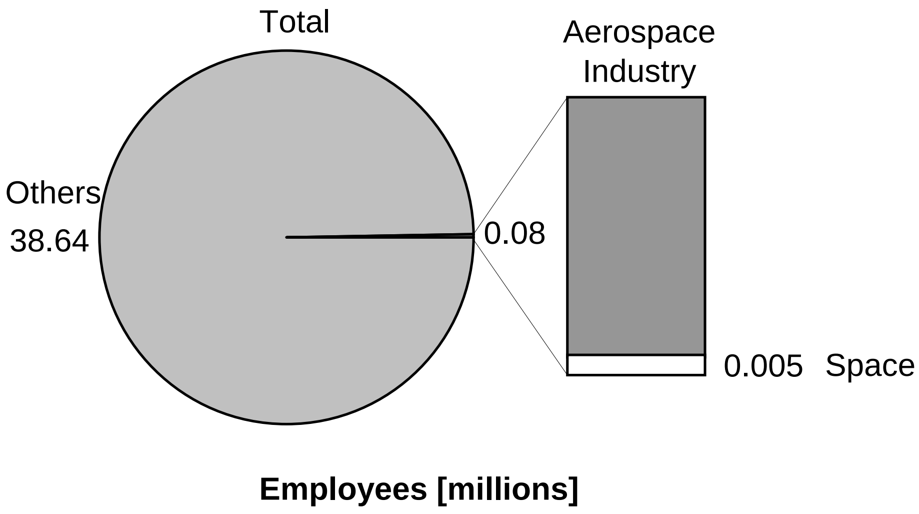

Figure 4-42: Share of Aerospace and Space Employees on Total Employees (Germany 2005)[311]

This is of course true for other specialized areas, for example bituminous coal mining, but the meaning of the space industry is too often significantly overestimated.

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[310] World Bank 2006, BDLI 2007.

[311] BDLI 2007, destatis 2007.

Comparing expenditures and project costs of **Table 4-35** with space related costs of **Table 4-36** leads to another insight:

Table 4-35: Various Financial Orders of Magnitude[312]

	Concerned	[G $]	Funding
Trade Volume (2005)	Germany	1 745	Private
Turnover (2005)	ExxonMobil	340	Private
F-35 Total Life Cycle[313]	USA	299[314]	Public
777 Program (2007-16)	Boeing	184	Private
Corporate Merger (2000)	AOL/Time Warner	164	Private
Profits by Tourism (2005)	USA	82	Private
Trademark Value (2006)	Microsoft	62	
Corporate Acquisition (2005)	Procter&Gamble/Gilette	61	Private
F-35 Program (2007-16)	USA	45	Public
Private Equity Transaction	RJR Nabisco	25	Private
Artificial Island (2007)	The Palm Jumeirah	12	Private/Public
Gotthard Base Tunnel (2015)	Switzerland	6.4	Public
High Speed Rail Line (2006)	Nuremberg – Munich	4.3	Private/Public
Coal Power Plant (2010)	BoA 2/3	2.6	Private
Skyscraper (2004)	Taipei 101	1.6	Private

Table 4-36: Typical Space Related Costs

Program	Costs [G $]
Mercury[315]	1.9
Gemini[315]	5.1
Apollo[315]	105
Skylab[315]	12
US-STS (launch)	1
Ariane 5 (development)[316]	8
Ariane 5 (launch)[316]	0.18
ISS[317]	100

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[312] Globus 1994-2007, AW&ST Apr 23 2007.

[313] AW&ST Sep 17 2007b.

[314] In early 2008, some reports mentioned that the cost is expected to increase to 1 000 G $.

[315] Griffin 2007. These numbers in FY 2000 $ stated by NASA Administrator Griffin are criticized of being only two thirds of the real values due to application of a wrong inflation index. (Bell 2007b)

[316] Wade 2007.

[317] ESA ISS 2005.

In general, financial means are virtually unlimited. If there is a sufficient reason, hundreds of billions of dollars are available for one project. Therefore, spaceflight activities are not subject to a general limitation of financial means.[318]

The bottleneck lies in a good justification to use these financial means for spaceflight. Whatever their order of magnitude, spaceflight activities can be funded – as long as there is sufficient conviction by the spending authority to do this.[319]

4.2.4 Economic Potential of the Three Elements of Society

In chapter 4.2.1, the three elements and their interests were identified. The previous chapter showed that there is no noteworthy limitation of financial means for large projects. Therefore, each element is now analyzed for its potential financial contributions for spaceflight.

4.2.4.1 Individuals (Households)

Individuals are subject to rigid financial restrictions. The major part of expenditures is fix, being required either for taxes and duties or to satisfy existential needs (food, …).

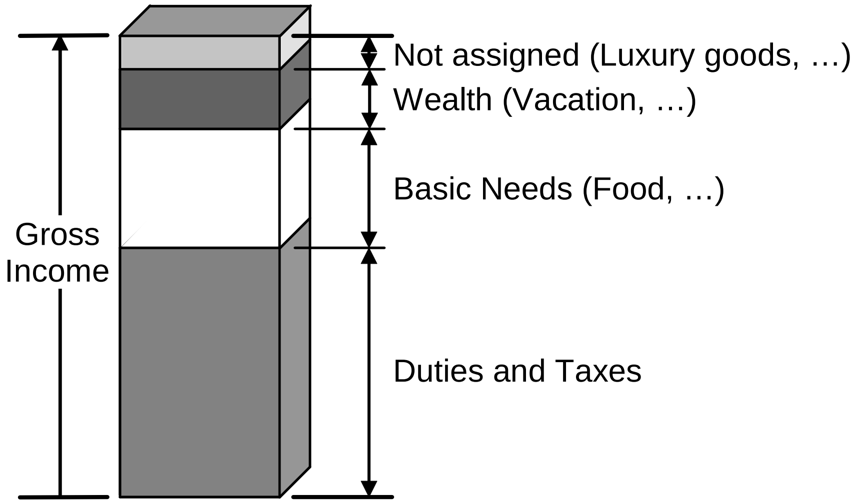

Figure 4-43: Financial Structure of the Individual

The potential for personal spaceflight expenditures is the small financial amount available for personal luxuries as seen in **Figure 4-43**. Other areas of an individual's assets are accessed only if spaceflight can decrease the total amount of required

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[318] The total costs of the Apollo program, taking inflation into account, are in the same order of magnitude as the financial help that, since 1991, is annually transferred from the Western part of Germany to the Eastern part (Puttkamer 1992, Spiegel Nr. 15 2004, Griffin 2007) – in other words: **Germany could have financed one Apollo program each year.**

[319] Actually, the world's total GDP could be seen as the upper limit.

spending, or the investment has a potential positive return.

Available financial means of an individual are a fraction of the total income. Statistical real and Gross National Incomes (GNI) per capita are:

- Average real income per capita in the U.S. (2005):[320] 25 036 $/year
- Average GNI per capita in the U.S. (Atlas method, 2005):[321] 43 560 $/year
- Average GNI per capita in the World (Atlas method, 2005):[321] 7 011 $/year

If its needs are satisfied in an effective and comprehensible way, the individual is willing to spend money. This is also true for the individual's approval of the application of taxes.

This significantly limits the potential contribution of a single individual to spaceflight. The given combined spaceflight threshold is too high – meaning too expensive – for a single individual.[322]

Individuals can fund spaceflight activities only either via industrial products and services or with taxes, leaving only industry and state as potential firsthand actors.

4.2.4.2 Industry (Companies)

Spaceflight plays a role for companies only if it creates or supports successful business, meaning profits as benefits. Potential Customers are individuals, the public sector (the state), or other companies. In the end, the customer demand is decisive, whether natural or artificially generated.

What is actually used for economic activities is of no further relevance. Spaceflight has no special meaning compared to other topics.

Economic operations require sufficient sales, turnover and marketing. Two parameters are of fundamental importance:

- Potential market size, meaning the number and quality of the customers
- Achievable market share, meaning the percentage of customers that can be addressed

Profitability is only given if, over time, the expenditures are lower than the revenues.[323]

Figure 4-44 illustrates the simplified flow of commercial business.

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[320] DeNavs-Walt et al. 2005.

[321] World Bank 2007.

[322] It is highly unlikely that the few persons who have sufficient funds spend billions of dollars on space projects just for personal fun.

[323] The same is true for the state, by the way, but this is often discarded.

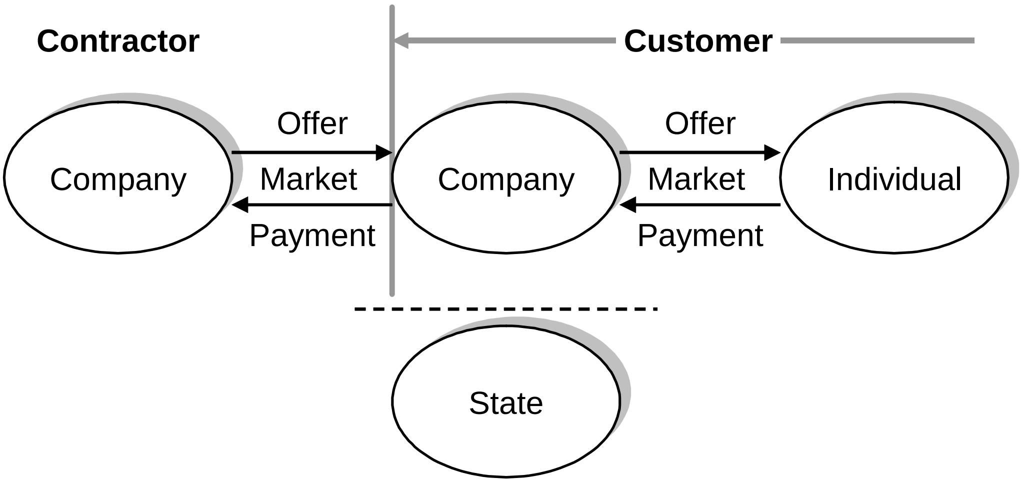

Figure 4-44: Commercial Business Flow

The following considerations are from an engineering point of view and should not be seen as part of economical sciences.

Simplified, profits are turnover minus costs.

$$P = T - C \qquad (4.46)$$

A project begins at t = 0 with an investment I. For spaceflight, the high costs lead to high investments at project start. Therefore, interest rates r should be included in the considerations.

The first real business that produces turnover T starts at $t = t_{bu}$. Basic company costs are C_0, and additional business costs at turnover production are the product of a constant parameter k_{bu} and the turnover T.

At the time t, the parameters of interest are:

Investment costs $I\left(1+r\right)^t$ (simplified: $I\left(1+r\,t\right)$) (4.47)

Business costs $t\,C_0 + T\left(t-\Delta t_{bu}\right)k_{bu}$ (4.48)

Revenues $T\left(t-t_{bu}\right)$ (4.49)

These considerations of business development are graphically shown in **Figure 4-45**.

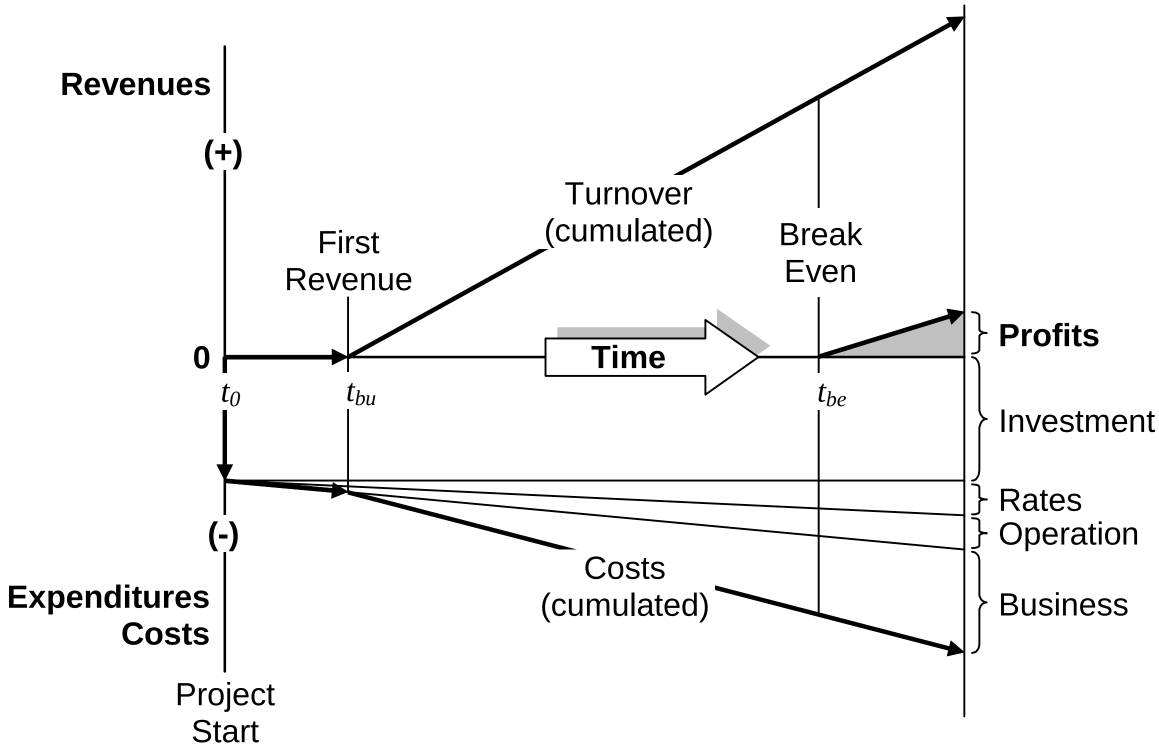

Figure 4-45: Exemplary Business Development with Revenues, Costs and Profits

A sensible business has a break even point t_{be}. This is when the total revenues surpass the total costs. At this point of time, profits are created.

$$t_{be} = \frac{I + T\left(1 - k_{bu}\right) t_{bu}}{T\left(1 - k_{bu}\right) - r\, I - C_0} \tag{4.50}$$

Disregarding t_{bu}, the break even point is

$$t_{be} = \frac{I}{T\left(1 - k_{bu}\right) - r\, I - C_0} \tag{4.51}$$

or

$$t_{be} = \frac{I}{T} \; \frac{1}{1 - k_{bu} - \frac{r\, I}{T} - \frac{C_0}{T}} \;, \tag{4.52}$$

with the ratios of investments to turnover I/T and basic costs to turnover C_0/T as decisive factors. Without a healthy ratio, profitable business is impossible.

Complex spaceflight projects are characterized by high investments and comparatively low profits. The launcher business, for example, requires billions of dollars for launcher development with profit margins of some millions. Companies will only invest in the spaceflight sector if either the basic investments are paid by the state (e.g. satellite launch vehicle development), or if a huge market seems available while the operating costs are low.

An additional difference between private and governmental companies must be mentioned: For private companies, the sales revenues must be higher than the expenditures on the long term – a break even point must be reached within a reasonable timeframe. State owned enterprises and institutions are in a different situation: The majority of the costs is burdened by the state, and only a fraction of the costs must be earned, distorting the need of profitability presented above.

Private companies will only support spaceflight activities if profits are expected. If this is the case, and the business seems to be sound, even very high initial investments are accepted. The amount of available financial means is virtually unlimited.

4.2.4.3 State (Government)

The income of the state, meaning duties and taxes, is usually quite constant and foreseeable.

Public support is not limited exclusively to spaceflight, nor is it limited to research and development funding – for example, jet propellant is free of tax even today. Various examples for public development support are:

- Nuclear power generation
- Civil aviation
- Computers

The state can have either a restricting or a supporting influence. Restricting measures include laws and prescriptions. Supportive means promotion and funding.

Promotional support means governmental efforts and contracts on national and international levels to sell products and services, and financial support includes:

- Absorption of losses
- Funding of investments
- Absorption of operational costs
- Provision of existing facilities
- Public contracts
- Tax incentives
- Subsidies

Massive support of the industry by the state is privatization of the profits with socialization of the costs.

The influence of the state on the business flow is illustrated in **Figure 4-46**.

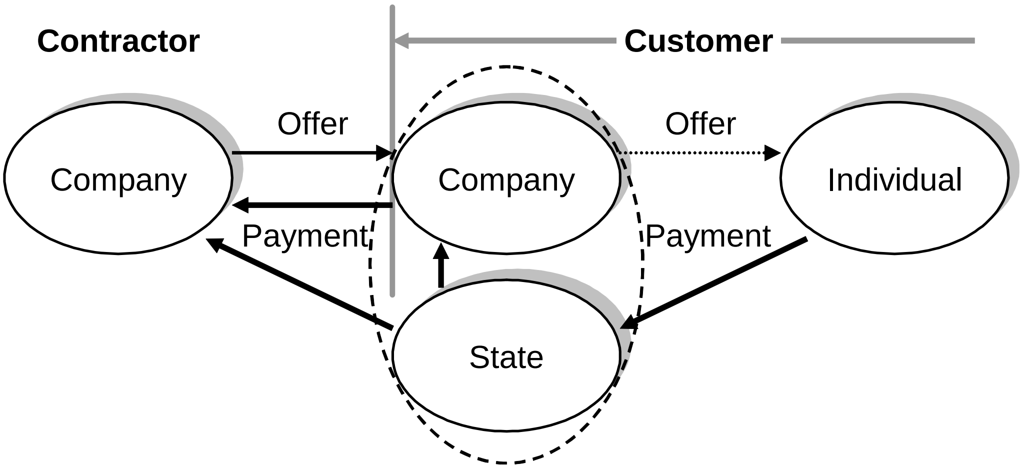

Figure 4-46: Public Influence on Commercial Business Flow

The often cited global effect on economy by public support of industries is usually negligible. The field of industry that is supported is a fraction of the economy. The amount of support is a fraction of the field. The strengthening effect is a fraction of the support. This is especially true for space and aerospace (see chapter 4.2.3).

Massive public support of industries without regard to realistic backflow leads to collapse (Soviet Union, …).

Public engagement for space activities is done by military or intelligence institutions (partially classified) and by space agencies (visible).

National space agencies have various objectives:

- Representation
- Research and development
- Coordination of national science and research and development activities

A major difference to industrial activities is the lack of commercial interests. This allows research in areas without any commercial benefits. With the exception of NASA, the financial order of magnitude of an average national space agency is similar to a large university.

The European Space Agency (ESA) has a special position as supranational agency. Additional objectives are:

- Policy – European unification
- Bundling of similar national interests and activities
- Realization of large programs

- Participation in space activities for small nations

ESA is dominated by strong national interests (jobs, industrial policy, regional return, …). These interests are often counterproductive for spaceflight, resulting in increases in cost and complexity as well as decisions for solely political motivated programs without actual space related benefits.

The government's financial means depend on the according national economy. For industrial nations, they are high, but anyway, they are limited.

4.2.5 Five Categories of Motivation and Three Elements of Society

The insights about financial means and interests of the three elements are now set into context with the previously (chapter 2.4) identified historical driving factors of spaceflight.

These driving factors, being nothing else than categories of motivation, were:

- Adventure, fun and personal interest
- National security
- Politics
- Science and research
- Commercialization

The three identified elements of society have different financial means available:

- **Individual**: Insufficient for spaceflight (only via industry and state)
- **Industry**: Virtually unlimited
- **State**: High, but limited

This is the key for spaceflight activities. Combining the elements with the types of motivation regarding their identified interests, as in **Table 4-37**, it becomes clear when – and by whom – spaceflight is financed, and with that, when space activities are *realized*.

Table 4-37: Identified Motivation and Available Financial Means

	Individual	**State**	**Industry**
Adventure, fun, …	(X)	-	-
National security	X	**X**	-
Politics	(X)	**X**	-
Science and research	(X)	(X)	-
Commercialization	(X)	-	**X**
Financial means	-	X	X

For the individual, only national security touches one of Maslow's basic needs – safety – and is therefore in the interest of every single individual. Every other motivation depends on higher needs and varying personal interests, and is therefore not true for every single individual, especially concerning spaceflight. Though individuals cannot finance spaceflight on their own, this must be considered by state and companies because both are financed by the individual – as taxpayer and customer.

For the state, politics and all of the motives that were attributed to it is of primary interest. The same is true for national security, which is part of its national duties. Some nations also see supporting science and research as an important part of their national duties.

For the industry, the only important motivation is commercialization, meaning profits.

In the past, space related activities were extensively financed during two periods: One was the breakthrough of rocketry before and during World War II, and the other was in the 1950s and 1960s, further refining performance and reliability of launch vehicles (in majority by missile development), and achieving the major milestones of spaceflight. **Figure 4-47** shows NASA's expenses over the years from 1958 to estimated 2007 with various inflation indices, further backing this statement.

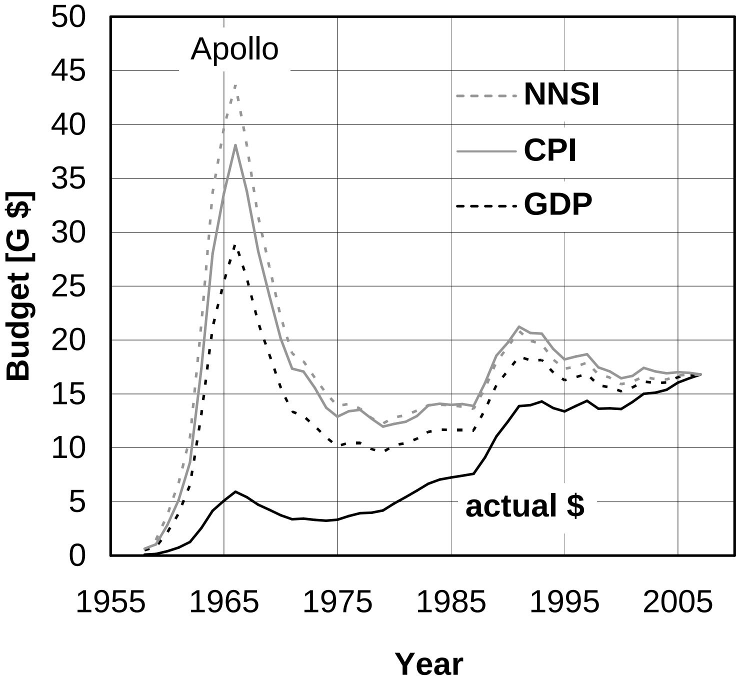

Figure 4-47: Annual NASA Budgets[324,325]

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[324] NASA Budget Info 2007, Wikipedia 2007a, US GPO 2004, US DoL 2007, NASA JSC 2007c.

[325] The significant variation in numbers, depending on the applied inflation factor, again underlines the problem of clear statements regarding actual costs.

Both times, the state financed the developments. Both times, the government was motivated to do this, at first for military/security purposes, then for political reasons.

Throughout history, the aspect of potential conflicts, and thus “national security”, was always of central importance for technological advances and developments, and this was also true for rocketry and spaceflight. As the old proverb goes: "πόλεμος πάντων μὲν πατήρ ἐστι."[326]

Politics are a major driver for spaceflight development, but only if spaceflight supports the objective set by politics. That may be the reason why, for example, the science oriented NASA budget declined after Apollo and is still far from the levels of the 1960s, while the main purpose of public space agencies such as NASA can be seen as science and research. This means that science and research is not sufficient on its own. Remember, these agencies’ funding is only a small percentage of the total global space related budgets (see Figure 2-11).

Adventure and personal fun, incited by the deeply rooted human fascination for space, are significant drivers for the spaceflight engagement of the individual. But the means of an individual are not sufficient to master the challenges of spaceflight; this can only be done by the state or large corporations. But if enough individuals are interested *and* are poised to pay for them, companies might offer spaceflight activities for profit.

Spaceflight must therefore find topics and applications that may offer either sustained advancement of the goals of politics, help the state to fulfill its national duties, or give corporations the opportunity to make profits.

4.2.6 Consequences for Future Realization of Spaceflight

Financial means must be seen as an equivalent for work and, therefore, for activities.

Activities are bound to motivation. If the motivation is sufficient, and the financial means exist, only then will spaceflight activities be realized.

The previous chapters identified industry and state as potential financiers of spaceflight.

- **Industry**
  Individuals spend money willingly if their individual needs are satisfied. Companies invest money to make profits, and the profits are generated by individuals. Thus, companies work as catalytic converters to bundle and satisfy the interests of individuals.

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[326] “War is the father of all.” Heraclitus, about 540 – 480 B.C. By the way, the original meaning is closer to “contest” than to “war”.

- **State**
  Public funding is available for projects that are meant to support the state in carrying out its national duties.

Financial means of the state are high, but limited. Financial means of the industry are practically unlimited – but only when profits are in sight.

4.3 Important Interactions of the Considered Aspects

At first, the relation of space transportation and the payload side (hardware&operations) under the identified restrictions and requirements is analyzed, leading to a new evaluation of space transportation. Then, the combined interaction of efforts with motivation and benefits is reviewed to derive the evaluation method and categorization of the subsequent analysis of spaceflight topics.

4.3.1 The Efforts – Transportation and Hardware&Operations

Analysis of the interaction under the previous results leads to interesting insights:

A) Common View of the Role of Space Transportation

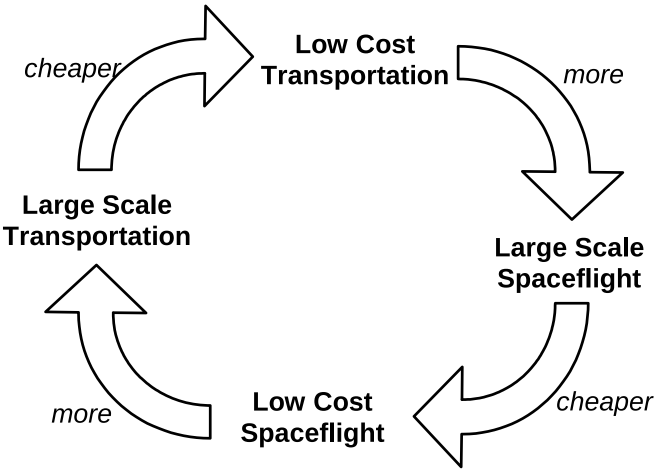

Figure 4-48: "Munchhausen Circle" of Spaceflight Costs

The high transportation costs are usually seen as the limiting factor for spaceflight activities. **Figure 4-48** illustrates the current view of the effects of transportation cost reduction on spaceflight activities: Once transportation costs are lowered, space activities will increase, thus requiring more transportation and further lowering the costs. This argumentation bears a close resemblance to the story of the Baron of Munchhausen, who escapes from a swamp by pulling himself out by his own hair.

Increase of activities may lower *specific* costs, but it will always increase *total* costs.

B) Actual Mission Cost Distribution

Total cost of a mission or a program C_{tot} consists of more than the transportation costs C_{tr}. Transportation is only a fraction k_{tr} of the total cost,

$$k_{tr} = \frac{C_{tr}}{C_{tot}} \quad . \tag{4.53}$$

Table 4-38 presents various known total mission costs and transportation costs.

Table 4-38: Program Costs and Transportation Costs

Program	C_{tot} [M $]	C_{tr} [M $]	k_{tr}
Apollo	105 000[327]	15 000*	0.14
Skylab	12 000[327]	1 100[327]	0.09
New Horizons	700[328]	205[329]	0.29
Phoenix	417[330]	65**	0.16
MSL	1 753[331]	200	0.11
LRO	600[332]	136[333]	0.23
WorldView I	ca. 500[334]	65**	0.13

* 15 Saturn I/IB a 120 M $, 12 Saturn V a 1 100 M $.[327]
** In August 2007, Delta II prices are said to have pushed past the 65 M $ mark.[335]

As can be seen, transportation costs are only a small fraction of total mission costs. One reason is that for most space missions, the hardware is a prototype that is developed from scratch with high costs, while launchers are available systems.[336]

With fractions of only <u>10 % to 30 % of total mission cost</u>,[337] space transportation is secondary! The hardware and operations segment with high costs for payload hardware and operations is decisive for space mission costs, not the transportation![338]

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[327] Griffin 2007.
[328] Space.com 19/01/2006.
[329] Space News 12/12/2005b.
[330] AW&ST Jun 11 2007.
[331] AW&ST Apr 9 2007a.
[332] AW&ST Apr 17 2006.
[333] NASA GSFC 2007b.
[334] AW&ST Sep 17 2007a.
[335] Space News 32-2007a.
[336] Some might argue that Apollo program cost also included launcher development – that is certainly not the case for the other exemplary programs.
[337] Preliminary analysis indicates that the fraction is even lower for military space programs.
[338] This view is not common in spaceflight circles. As an example: D. E. Koelle stated in a lecture at the Technical University Munich on May 8, 2008 that transportation was 80 % of total Apollo cost.

Mastering the space environment characteristics and ensuring reliable operation in space are the true cost drivers. Transportation costs are secondary. Therefore, the Spaceflight Threshold must be illustrated as in **Figure 4-49**.

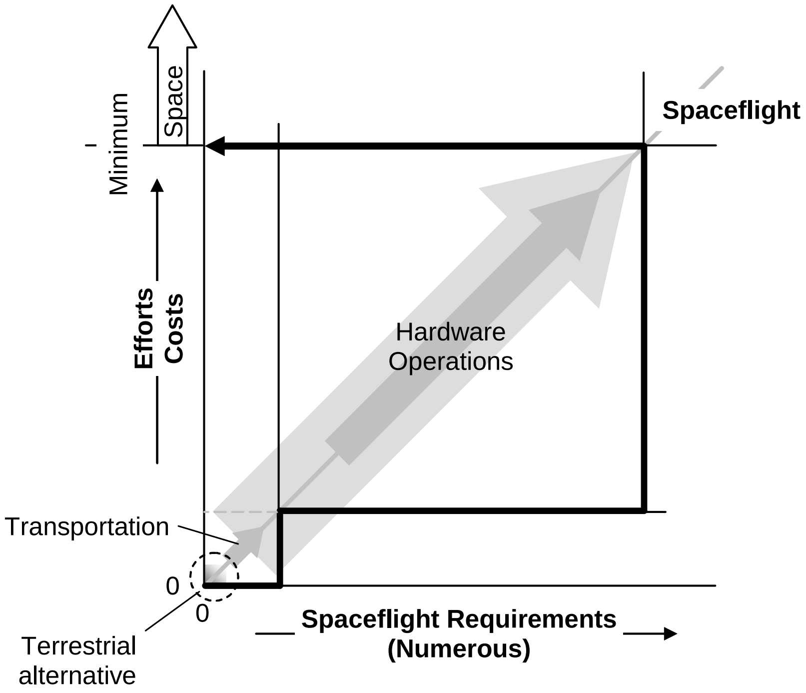

Figure 4-49: The Spaceflight Threshold – Quantitative Illustration

C) Relation of Transportation Costs and Payload Costs

The costs of hardware and operations are subject to the characteristics of space, and not to the high transportation costs! The common belief that low transportation costs will also reduce the payload costs cannot be substantiated. This is made clear on two statements:

- **"Cheap transportation allows low quality standards, thus reducing costs."**
  Wrong: Cars, printing machines, excavators, computers, and any other complex machines that are produced in Europe and exported to Australia are thoroughly checked and qualified before they are delivered, even though transportation is quite inexpensive and they could be easily returned to Europe for repair. Products must be absolutely reliable. The same would be true for cheap space transportation.

- **"Cheap transportation allows high mass, thus reducing costs."**
  Wrong: Increasing size of payloads could even result in higher costs. The U.S. House Science & Technology Committee was told by 'scientists' in

spring 2007 that “forcing NASA’s Science Mission Directorate to use [Atlas 5 and Delta IV instead of Delta 2] would tempt programs to build bigger, more expensive spacecraft than strictly necessary”.[339] Besides, the lightweight construction of payloads is not a significant cost driver, as was previously shown in chapter 4.1.2.4.1.

D) Actual Effects of Transportation Cost Reduction

Space transportation costs are roughly a quarter to one tenth of total mission costs. Payload costs are not affected by transportation costs. That means that, even assuming cost free space transportation, mission cost would be reduced only by 10 to 30 % at best.

E) Available Payloads

Now, even assuming cost free space transportation, the cost of spaceflight remains at a very high level, and the number of actual missions will not increase. Expensive space hardware and mission operations are decisive.

Early considerations for the US-STS program showed the dilemma: If transportation costs would have been as low as projected, NASA would not have had enough missions and payloads to achieve the projected launch rates of several dozen shuttle launches per year.[340,341]

F) Conclusion

As will be seen later, lower transportation costs turn out to be supportive for some space applications. But in general, low transportation costs are not the key to extended spaceflight activities.

Concentration only on transportation cost reduction is not a successful way to enable extensive spaceflight.

4.3.2 Evaluation Method – Interaction of Efforts, Benefits and Motivation

The interaction of efforts, benefits and motivation regarding spaceflight was already outlined in chapter 3.2:

- Benefits are created by any activity that is done in space.
- The creation of these benefits requires efforts.
- These efforts must be measured against the created benefits.
- If the benefits are higher than the efforts, motivation to actually do the activ-

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[339] Space News 24-2007a.

[340] Easterbrook 1980.

[341] Heinz Hermann Koelle said about potential utilization of the Saturn V launch vehicle: “We had produced the Saturn V, with up to four units a year, but there were no payloads. Developing a payload of this size takes six to seven years and lots of money.” (Marsiske 2005)

ity in space exists.

The efforts that are required for any space activity were identified in detail in chapter 4.1. It was shown that the efforts – and costs – are very high, and will remain so in the future.

The relevant interest groups (companies and government), their basic motivations, and their potential to mount the mentioned efforts were identified in chapter 4.2.

Based on these insights, every imaginable topic that could make use of spaceflight is now analyzed in the following chapters for its potential to create benefits. This is done under the following aspects:

A) Earthbound Alternatives

The foe of every spaceflight activity is its analogous terrestrial counterpart. Transportation efforts on Earth are negligible compared to space launches, and the operational requirements on Earth are well known, understood, and – for the most part – easily mastered, thus always resulting in lower efforts and costs. Therefore, equivalent earthbound alternatives are usually preferred.

Even if the aspect of transportation was negligible due to a sudden breakthrough of technology, the hardware and operations segment still remains as a threshold, as seen in **Table 4-39**. This is equivalent to the modern capabilities of terrestrial transportation that never resulted in a colonization of Antarctica or the Deep Sea.

Table 4-39: Fundamental General Differences of Earth and Space

	Earth	**Space**
Minimum Duration of Preparation and Training	-	Years
Ways of Transportation	Afoot, horse, car, truck, train, aircraft, helicopter, ship, …	Rocket
Minimum Transportation Costs	-	Tremendous
Maintenance, Repair, Overhaul	Common practice	Almost nonexistent
Power Availability	Abundant	Self-supply
Environment	Accustomed	Hostile
Basic Character of Installations	Building	Machine
Return to Earth	-	Extremely difficult

The proposed activity is done in space *only* if the proposed benefit cannot be achieved on Earth due to the unique attributes of the space environment. If there is a terrestrial alternative with acceptable results, then the motivation for the earthbound solution is higher, as illustrated in **Figure 4-50**, and the space activity will not be realized.

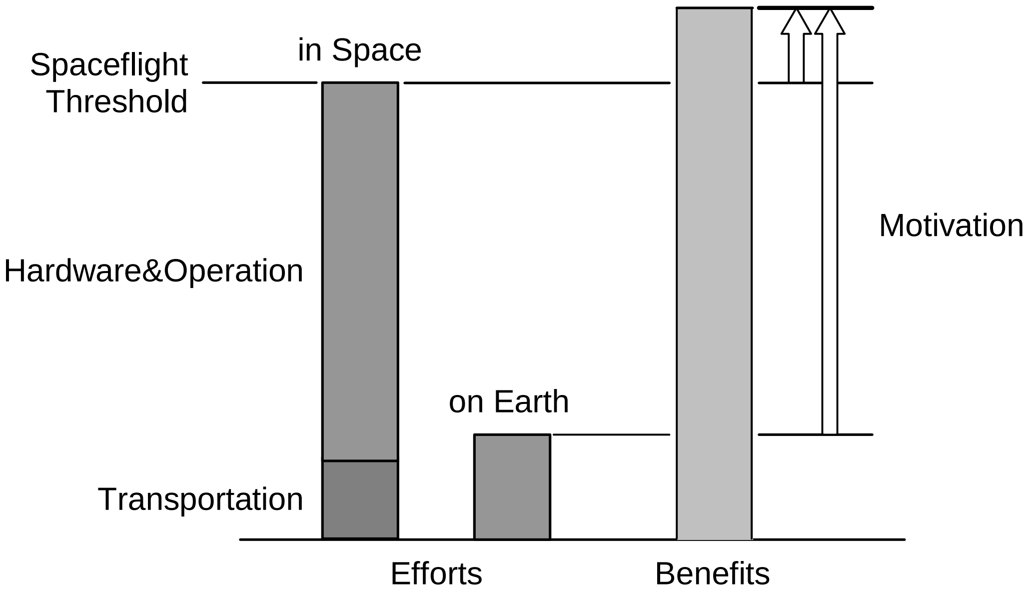

Figure 4-50: Earthbound Alternatives to Spaceflight Activities

If expected space transportation costs alone are higher than the total costs on Earth, the proposed spaceflight activity must be instantly ruled out.

B) Concentration on Benefits

For many years now, perhaps since the era of Apollo, there is a concentration on the wrong aspects. The eye of the spaceflight community lies on the first aspect, the transportation, with operation and hardware following a long way behind. But what is actually to be achieved with spaceflight activities is too often ignored.

The identification of *adequate benefits* must be the focus of all space related considerations.

C) Quantification of Efforts and Benefits

As previously mentioned, the efforts for any space activity must be weighed against the expected benefits. The required efforts are easily quantified based on technical analysis – regarding the technical feasibility –, and based on cost estimations considering past and present experiences.

Benefits are not as easy to quantify. Though there are many topics that can clearly be analyzed for economical value, other topics may create benefits that cannot be measured in quantities – commercial ventures can easily be quantified with a cost-benefit calculation, but reliable tools to estimate immaterial values are non-existent.

The greatest difficulty lies in the characterization of the benefits concerning social and cultural aspects. Each individual has different views of these benefits. These benefits are currently in the focus of the public debate about spaceflight.

Benefits that are unintentionally or peripherally created must be considered separately, and special focus must lie on topics that may eventually create benefits by reducing the risk and effects of potentially catastrophic events.

D) Classification of Potentially Beneficial Spaceflight Topics

For further analysis, all spaceflight related topics are therefore classified into four categories, as seen in **Figure 4-51**.

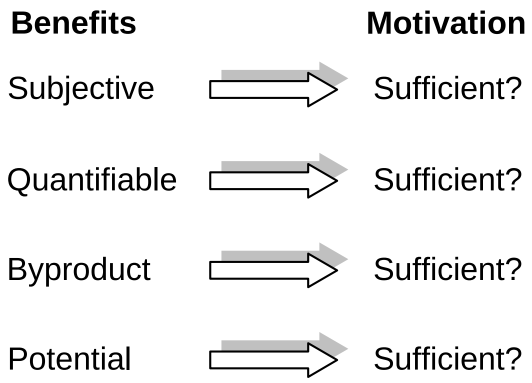

Figure 4-51: Classification of Spaceflight Topics

According to the expected type of benefits, these categories include:

- Topics that do not create quantifiable, material benefits but subjective ones – philosophic, social and cultural topics
- Topics that can be quantified in costs and profits – commercial topics
- Topics that may create peripheral benefits as a byproduct – spin-off and technology transfer
- Topics that may pay off not initially, but have the potential to do so some day (or never!) – topics of prevention and security

Some of the space related topics that will be addressed are difficult to classify. Some topics overlap with each other and could be classified into various categories. The classification is not flawless, but it presents a reasonable outline for analysis.

4.4 Summary of Results

Space efforts are very high and seemingly cannot be reduced in the foreseeable future. But even reducing the costs by half would not significantly change the big picture. Though transportation costs are very high, the decisive costs are created by the hardware that is required for any activity in space due to requirements that are dictated by the characteristics of the space environment. Additional operating costs depend on mission duration and other factors. They are significant for long duration space activities, but else, they can be neglected for simplification. Therefore, the efforts for spaceflight, measured in specific costs, can be stated as in **Table 4-40**, which comply with the lower limits of present costs that were identified in the previous chapters.

Table 4-40: Efforts for Spaceflight

	Destination	**Cost [$/kg]**
Transportation	LEO	10 000
	GTO	20 000
	GEO	35 000
	Beyond	Considerably more
Hardware	Anywhere in space	50 000

Of the three defined elements of society, only the state (to be more specific: the current government) and private companies (or “industry”) have the sufficient means to realize spaceflight, though in the end, both are financed by individuals in the role of taxpayer or customer. Therefore, the primary interests (motivation!) of government and companies are decisive – but only if their motivation is in line with the interest of individuals (votes for the government and market for the companies!).

Under the aspects of given efforts and required motivation, a large variety of topics concerning spaceflight can now be analyzed. These topics are classified in four categories, depending on the type of benefits that they might create. These four categories of benefits are further referred to as *subjective*, *quantifiable, byproducts* and *potential*, and are analyzed in detail in the next four paragraphs.

5. Subjective Benefits

Most justifications of spaceflight, especially human spaceflight, regard topics that directly touch society and human individuals. The resulting benefits exist, but they cannot be quantified in an economic sense, as is illustrated in **Figure 5-1**. They are subject to varying personal judgment, thus complicating a neutral statement. Most of them can also be referred to as trans-utilitarian benefits.[342]

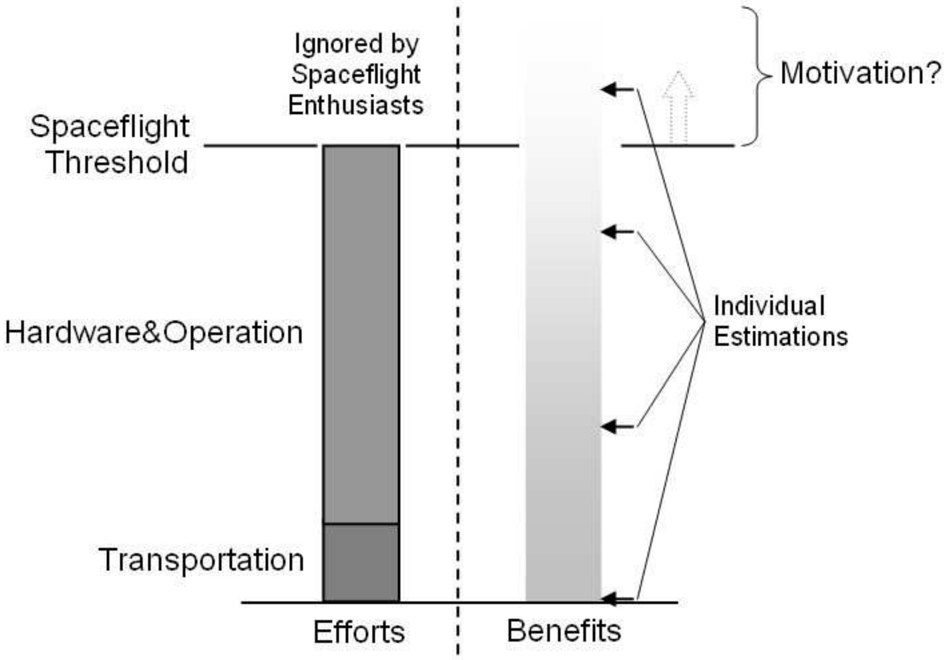

Figure 5-1: The Benefits of Social, Cultural and Philosophic Topics

Quantitative comparison of efforts and benefits for a clear result is impossible for this category of benefits. This rules out profit oriented companies for realization, and leaves the state as a primary actor.

The focus of literature clearly lies on this category of benefits. The efforts are usually ruled out, resulting in the simple equation

$$M = B \quad . \qquad (5.1)$$

This means that (for this category) benefits B and motivation M are usually seen as equivalent, and thus motivation of the state to finance *any* type of space activities would be given.

With this view, the demanded spaceflight lacks a clearly defined objective: Some top-

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[342] Gethmann et al. 1993, Gethmann 2006.

ics demand a huge increase of spaceflight, others vaguely ask for a human presence in space, and still others see any type of spaceflight as sufficient.

And this leads to another effect: If the efforts are ignored and no objectives are specified, then everybody can join in the conversation because no expertise on spaceflight is required. This is not true for the other categories of benefits.

But the efforts cannot be ruled out – they do not vanish by wishful thinking. Therefore, each of the following topics is analyzed for the quality of its justification. In the end, a qualitative statement concerning the obligation of the state to finance spaceflight justified by the sum of subjective benefits is given.

Addressed topics regarding subjective benefits are:

- Effects on the human society
  - Space as the driving force of civilization
  - Utilization for political propaganda
  - Technical overcoming of war
  - A new species of mankind
- Effects on the human individual
  - Media and spaceflight
  - Influence on the cultural sector (arts)
  - Active support of education
- Spaceflight as a personal challenge
- The need to explore just because
- Spaceflight as a modern age monument
- National promotion of spaceflight
  - Economical aspects
  - National prestige
- Science and research
- The search for life

With that, most space related topics that might touch social, philosophic and cultural questions for mankind should be covered.

5.1 Effects on the Human Society

Spaceflight is present in the awareness of society, and could therefore play a supportive role for certain social aspects.

5.1.1 Space – The Driving Force of Civilization?

Since ancient times, humanity was inspired by:

- The marvels of the night sky,

- The wish to fly,
- The desire to reach the stars,
- The urge to enter alien spheres (esotericism).

This motivation is deeply anchored in the human spirit. It is the wish for:

- Escaping mundane restrictions,
- Conquering new worlds,
- Reaching the heavens, the realm of the gods, and becoming equal.

Earliest cultures constructed monuments such as Stonehenge that are linked with astronomy. The heavens were of major importance for Babylonians, Egyptians, Greeks, and most other ancient cultures. After all, they were seen as the place where the gods came from, and where they still resided – by some, this is seen today as an indication that the ancient "gods", in fact, were extraterrestrial visitors.[343]

The orientation towards the marvels of the sky, day and night, and the unraveling of their meaning, may well have been a trigger for the development of human spirit and science. But though the heavens – space – thus have a special standing, they are but one of many topics responsible for human development.

Spaceflight emerged as the way to make the old dream of conquering space come true. Thus, the journey into space without any regard to utilization or benefits was in the focus for a long time, even at its period of realization. Today's discussion about the justification of spaceflight is rather born out of necessity than out of real interest; the fascinating, adventurous aspect still remains strong in our society, with the majority of mankind impressed by the sheer thought of spaceflight.

This potential direct impact of spaceflight onto human society and its individuals is therefore often used to justify space activities. But this effect must not be overestimated: Major parts of society have no interest in and/or understanding of spaceflight, and thus the mere existence of this benefit must be questioned. [344]

No special objective is required for this topic. The current activities can be seen as compliant, resulting in annual efforts of several billion dollars.

Spaceflight in the context of this justification is not a means to satisfy any basic needs of individuals. And only to potentially impress and entertain an unknown share of our society is not a sufficient reason to justify national expenditures of several billion dollars a year.

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[343] Däniken 2003.

[344] Not everybody is impressed of spaceflight achievements. Pablo Picasso's comment on the Apollo lunar landing: "It means nothing to me. I have no opinion about it, and I don't care." The New York Times, July 21, 1969

Table 5-1: Evaluation of "Driving Force of Civilization"

Topic		Space as Driving Force of Civilization
Objective		Any type of spaceflight
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 1 000 000 000 $
Benefit & Motivation	Social, Cultural	Crossing the borders
Result	Quality of Justification	**Overestimated**
Comment		No interest of major parts of public

5.1.2 Utilization for Political Propaganda

Selective distribution of filtered information – propaganda – is a common political tool to improve one's situation and gain influence on people without directly confronting a rival. This may include concentration on problems or negative actions of the other side, positive presentation of the own side, and directed disinformation.

Compared to terrestrial communication methods, satellite communications are difficult to suppress and independent of geographic conditions as well as physical presence. Satellite radio and television programs can reach virtually everybody everywhere on Earth, and thus are excellent tools for propaganda.

As examples, Western satellite television in East Europe during the Cold War could be named, but also the French satellite "Symphonie", launched in 1974 with a transponder directed to Canada, as well as the worldwide broadcasting of news channels, including CNN International and Al Jazeera.

This requires communication satellites with efforts of several hundred million dollars, which are done anyway for commercial purposes.

Table 5-2: Evaluation of "Political Propaganda"

Topic		Utilization for Political Propaganda
Objective		ComSat
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $
Benefit & Motivation	Social, Cultural	Political support
Result	Quality of Justification	**Doubtful**
Comment		Anyway done for commercial reasons

5.1.3 Technical Overcoming of War

Spaceflight is complex and expensive. A single nation can hardly afford huge space projects like large space stations or manned Mars expeditions. The expected costs of hundreds of billions of dollar would be roughly comparable to the costs of a war in magnitude (see Table 8-20 for costs). This analogy was first considered by Eugen Sänger in the 1950s, and he concluded that space programs might be a sensible alternative to the efforts of war.[345]

This approach is that of a spaceflight enthusiast, and regrettably cannot be transferred to the larger part of the population. The alternative to war is *no war*, and not another expensive endeavor. The reasons for a war are not influenced by spaceflight alternatives, and no additional financial means become available by avoidance of military action.

The hopes of the early 1990s, that more financial support was available for astronautics with the end of the Cold War, were not fulfilled: The U.S. expenditures for defense are now higher than ever before. The enormous expenditures of the Soviet Union for armament in the 1970s and 1980s were one reason for its collapse, and therefore probably contribute to inflation and economic depression in general. The consequences for large scale spaceflight expenditures might be similar.

Besides that, space has become just another potential theater of war, with numerous military satellites in orbit and potential temporary use of space for strategic missile attacks.

For these reasons, this argument for spaceflight must be discarded.

Table 5-3: Evaluation of “Overcoming of War”

Topic		Technical Overcoming of War
Objective		Extensive spaceflight
Technical Feasibility		Feasible
Effort	Costs	Several 100 000 000 000 $ per year
Benefit & Motivation	Social, Cultural	Peace
Result	Quality of Justification	**Wrong**
Comment		No defense spending decrease after Cold War, space as a new battleground

5.1.4 A New Species of Mankind

The effect of spaceflight on the human way of thinking has two facets. On the one

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[345] Sänger 1958.

hand:

- Dawn of a new age
- Departure towards a new dimension
- Mastery of modern technology
- Perpetual progress and unlimited technical abilities

On the other hand:

- Realization of limitations and insignificance of humans in cosmic dimensions
- Realization of vulnerability of humanity, nature and Earth itself

This ambivalence is the reason for the hope that, with spaceflight, humans are educated towards increased responsibility and awareness, with a continuous advance in technology, society and morality. This new species of humanity is sometimes referred to as "homo astronauticus". The lasting global impression that was made by the famous images of an Earthrise above the lunar horizon during the Apollo program, as seen in **Figure 5-2**, might have been a first glimpse.[346]

Figure 5-2: First Earthrise Color Photograph by Apollo 8[347]

But this change of attitude would take many generations to develop. Human attitude did not change noticeably for thousands of years. Only in some parts of specific cultures first changes of a positive development can be identified, and the development of a new attitude is not necessarily positive.

The first steps of mankind into space are occasionally compared to the evolutionary step of the first animals that once left the water and began their conquest of the land.

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[346] Walter 2002; see also a letter by Ernst Stuhlinger from 1970 (Zito 1971, Nasa Watch 2008).
[347] NASA History 2006.

This is substantially wrong for a simple reason: For those animals, survival was easy because the environment already offered supplies such as food. Orbital and deep space offers absolutely nothing, and planetary surfaces are bare of easily accessible supplies. The potential to support life must first be artificially created at tremendous efforts – huge space stations will significantly exceed the cost of the ISS, requiring trillions of dollars and more. This certainly creates no motivation for the government to launch extensive human space programs.

The creation of a new species of mankind actually was the driving force behind the research of Konstantin Tsiolkovsky that led to his development of the rocket equation: Mastering the technologies of spaceflight, mankind should conquer space to ensure its survival, and, combined with selective reproduction and liquidation of the inferior forms of life (including most animals and plants, but also parts of humanity), to set the prerequisites to become a dominating, immortal species.[348,349]

Also, other previous ideas to create a new species of mankind with an improved attitude failed, with Soviet communism as the best example.

Thus, this argument for spaceflight must be discarded.

Table 5-4: Evaluation of "New Species of Mankind"

Topic		New Species of Mankind
Objective		Extensive manned spaceflight
Technical Feasibility		Very Challenging
Effort	Costs	Several 1 000 000 000 000 $
Benefit & Motivation	Social, Cultural	Better behavior of humanity
Result	Quality of Justification	**Wrong**
Comment		Basic human attitude the same for millennia, topic not exclusive for spaceflight

5.2 Effects on the Human Individual

From a cultural and social perspective, human beings are:

- Receiving beings (reception and procession of information)
- Generating beings (creation and self-actualization)

They are still lead by archetypical instincts, emotions and needs: Fear, curiosity, safety and security, self-actualization. Spaceflight may help to satisfy these needs in

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[348] Hagemeister 2006.

[349] It is suspected that Hermann Oberth might have entertained thoughts in a similar direction at his later years.

several aspects.

5.2.1 Media Coverage of Spaceflight

Television, newspapers, magazines, and the internet let us participate at spaceflight activities that are presented as colorful spectacles: Mars Exploration Rovers, Space Shuttle launches, ISS construction, Hubble images, … .

This virtual participation can satisfy archetypical instincts like admiration of noise and fire with the perceptible power of a rocket launch, the discovery of new worlds, identification with modern heroes, adventure, touching the final frontier, and so on. This may be another explanation of the phenomenon that everybody, in a certain way, seems fascinated by spaceflight.

But spaceflight is not the only topic that inspires humans with awe. Other events have the same effect, some of them even more intensive – for example sport events or rock concerts. There are ideas to present spaceflight in a similar manner to spark public interest in spaceflight by ways of presentation similar to these events.[350] But there is a decisive difference. The majority of other successful events is characterized by several aspects that spaceflight misses:

- Competition
- Creation of a feeling of togetherness (a kind of team spirit)
- Comprehension (understanding of the events)
- Identification with the participants

To give two examples:

- Motor sports would be uninteresting if only one car was participating, the "event" was watched without any co-spectators, and no one ever had the opportunity to drive a car himself.
- Football games would be uninteresting if only one team was playing without opponents in an otherwise empty stadium, no other teams existed, the rules were incomprehensible, and no one ever played football himself.

Competition was a major factor in the early days of the Space Race between the USA and the USSR, and Apollo created an intensive common feeling of suspense and team spirit.[351] But without drama and suspense, public interest rapidly declines. Only the drama of Apollo 13 again aroused great public interest for a short time before the last Apollo missions were cancelled. In a similar manner, this is true for the tragedies of Challenger and Columbia.

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[350] Space News 1-2007.

[351] The (relative) isolation of the U.S. space program might be a side effect: With too much international cooperation, it would not remain a truly American program, losing support throughout the American population.

The mechanisms at work are the same as for movies or sport events. But these events are privately funded – spaceflight requires public funding that is orders of magnitudes higher than common types of entertainment.

As a further aspect, spaceflight cannot be repeated in various different ways with unexpected twists to create a level of suspense for the spectator – quite contrary, precise repetition of exactly planned and exercised processes is essential for spaceflight.

The scientific and technical contents of any field are of minor importance for the public, because the majority neither has the capability to understand the real meaning, nor is it interested in it. The same is true for the mastery of technical challenges or the potential impacts of scientific discoveries: For the current goals of actual spaceflight, there simply is no public interest because people's daily lives are not visibly affected.[352]

How often spaceflight is covered in the news may be used as a guideline for public interest.[353] But if an increase in number is used to justify the activities, then spaceflight is used to justify spaceflight – meaning that spaceflight should be done because spaceflight is in the news, and this is not a clean argumentation.[354]

Media coverage alone is a poor argument for public funded space activities.

Table 5-5: Evaluation of "Media Coverage"

Topic		Media Coverage of Spaceflight
Objective		Preferably manned spaceflight
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 1 000 000 000 $
Benefit & Motivation	Social, Cultural	Interest in spaceflight
Result	Quality of Justification	**Poor**
Comment		Spaceflight is used to justify spaceflight

5.2.2 Potential Influence on the Cultural Sector (Arts)

Though this list may be disputed, the cultural sector with focus on arts includes:

- Cultural heritage (museums, archives, …)

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[352] Spaceflight is present in our daily lives, but the use of a car navigation system usually does not spark interest in the launch of a navigation satellite.

[353] Pagel 2006.

[354] Though the following analogy is flawed, too, this would mean that skyscrapers should be constructed with public funds, just to be spectacularly blown up when they are finished, because their collapse guarantees news coverage.

- Literature (books, libraries, press, …)
- Music[355]
- Visual arts (theater, photography, painting, …)
- Films and videos
- Television and radio

The field of astronautics influences many aspects of this sector in various ways, and therefore it is part of cultural activities. But it is only one field among many others.

In **Table 5-6**, numbers of the German space and cultural sectors are presented to get an idea of their relative meaning.

Table 5-6: Cultural and Space Sectors in Germany in Numbers (2005)

	Cultural	**Space**
Employees[356]		5 300
Total Number of Museums[357]	6 155	
Public Expenditures [G €]	8.0[357]	0.76[358]
Annual Museum Visitors [Millions][357]	101.4	

As can be seen, there are more museums in Germany than employees in the space sector, and the public expenditures for cultural support are more than ten times those for the space sector.

Regarding the insignificance of spaceflight compared to the whole cultural sector, it could be concluded that the fraction of the cultural sector that is actually influenced by spaceflight is perhaps larger than the space sector itself.

Table 5-7: Evaluation of "Influence on Cultural Sector (Arts)"

Topic		Potential Influence on the Cultural Sector
Objective		Any type of spaceflight
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 1 000 000 000 $
Benefit & Motivation	Social, Cultural	Public presence of spaceflight
Result	Quality of Justification	**Wrong**
Comment		Influence on arts is independent of actual realization

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[355] Hungarian composer Peter Eötvös' violin concerto "Seven" was inspired by the Columbia tragedy.

[356] BDLI 2007.

[357] Globus 1994-2007.

[358] in 2007. (DLR 2007)

But culture and the arts were influenced by thoughts of spaceflight without regard of its actual realization. This is proven by a wide range of examples for space related works that were created long before Sputnik 1, ranging from Jules Verne to the character of Buck Rogers. Thus, this argument for spaceflight must be discarded.

5.2.3 Active Support of Education

Education, in this context meaning the mediation of knowledge, is a decisive factor for future development, and is therefore one of the most important national duties.

Developing countries suffer on bad infrastructural conditions and insufficient local educational capabilities. Spaceflight is ideally suited to solve some of these problems, for example by use of communication satellites to give lessons in remote areas via telecommunication.

Early considerations date back to the 1970s, but realization of the concepts seems to be tough.

Table 5-8: Evaluation of "Active Support of Education"

Topic		Active Support of Education
Objective		ComSat
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $
Benefit & Motivation	Social, Cultural	Education
Result	Quality of Justification	**Moderate**
Comment		Exists on small scale, tough realization

5.3 Spaceflight as a Personal Challenge

Spaceflight is often seen as a challenge, and its mastery as a cultural duty of mankind – the often cited "Final Frontier" that mankind encounters. The natural urge of men to reach borders and cross them is seen as justification for astronautics, especially for human spaceflight. Advocates of this theory refer to great adventures in history, such as Amundsen reaching the South Pole or Hillary's first climb of Mount Everest, but this also includes today's adventurers who seek to master Everest or other challenges.

But these ventures were based on the personal ambition of individuals who were subject to Maslow's highest layer of Human Needs: Self actualization.[359]

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[359] Though millions may have been thrilled of his ascent to Everest, it probably was not Hillary's primary motive to entertain others. But the interest of other people in his venture certainly increased his

Mountain climbing and similar activities can be performed by single men largely on their own expenditures, and thus it is done extensively, as seen in **Figure 5-3**.

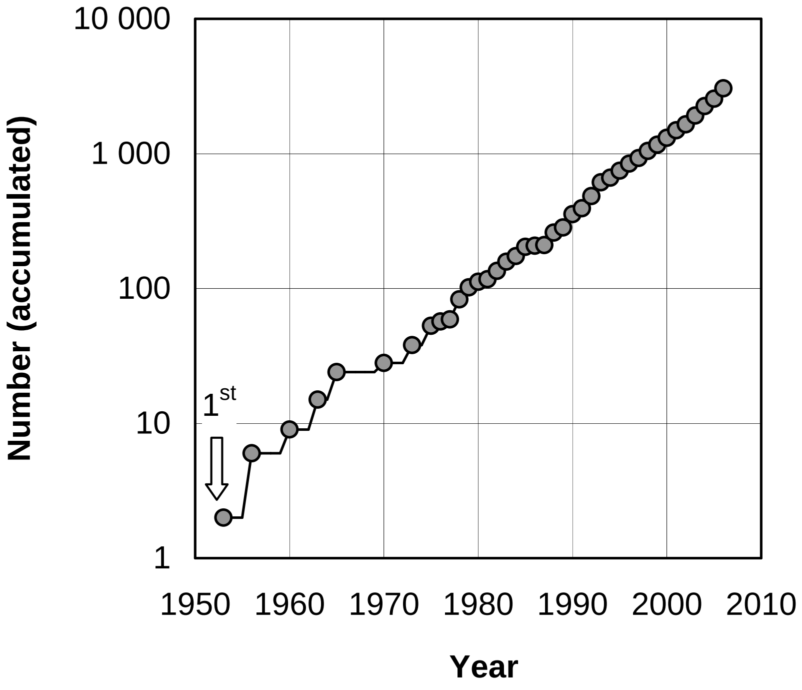

Figure 5-3: Total Mount Everest Ascents[360]

Spaceflight is a tremendous quest with efforts that are greater by several orders of magnitude. The motivation of self actualization for one individual is questionable when it is based on massive public funding. But if somebody has the means to do spaceflight on his own, without public funding, he should not be hindered.[361]

Table 5-9: Evaluation of "Personal Challenge"

Topic		Spaceflight as a Personal Challenge
Objective		Manned spaceflight
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 1 000 000 000 $
Benefit & Motivation	Social, Cultural	Self actualization
Result	Quality of Justification	**Questionable**
Comment		Realization not feasible for a single individual

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self esteem – according to Maslow, a need situated on a similar level as self actualization.

[360] Jurgalski et al. 2007.

[361] Space tourism is a task for companies, not individuals. These companies expect *quantifiable* profits. Thus, space tourism is analyzed later in chapter 6.3.2.

5.4 “Because It Is There” – Exploration

There seems to be a desire for exploration that is deeply rooted in the human mind. This is perhaps best seen in a quote attributed to George Mallory who disappeared in 1924 at an attempt to make the first ascent of Mount Everest. When he was asked why he wanted to climb Everest, he said: “Because it is there.”

Innumerous studies, essays and editorials exploit this ancient human desire as the driving factor for spaceflight, especially for manned exploration.

A) Thoughts on the Origin of the Desire for Exploration

The basic urge in humanity to explore might be rooted in the natural force of life to spread, to conquer new – and perhaps better – natural habitats.

But space has a very special position in the potential directions of exploration. The interest in the deep sea or newly discovered cave systems is considerably less, and has always been.

The inherent fascination of space could be born out of the human urge to go *up*, to reach altitudes that were previously inaccessible. There is no similar urge to go *down*. This is manifested in religious beliefs (the heavens are the realm of the gods, whereas hell is subterraneous), legends (story of Icarus), or even hierarchic matters (to move up to the executive suite located on the top floor). By the way, if asked, most people would instinctively prefer sitting in a space capsule to a small submarine. But this vague feeling alone is insufficient to justify spaceflight expenditures, especially if others are seated into space capsules, and not the taxpayer himself.

B) Often Cited Historical Parallels: Christopher Columbus, Lewis and Clark

The achievements of great explorers of the past are often compared to the current situation of spaceflight. Probably the most strained comparisons, at least in the U.S. dominated part of publications, are Christopher Columbus and Lewis and Clark. These parallels are fundamentally wrong, though.

Columbus wanted to discover a new trade route to India. That, and the prospect to exploit any lands that might be discovered on the way, were the reason his expedition was funded by Ferdinand and Isabella of Spain. Scientific exploration was never an objective of his journey, including the myth that Columbus wanted to proof that the Earth was a sphere. This was never doubted at his times.[362,363]

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[362] Encarta 2007, Odell et al. 1962-63.

[363] Columbus probably had never tried his journey had he known the real distance to Japan. He greatly underestimated Earth’s circumference and the size of Asia: Instead of 19.000 km, he assumed that Japan was only about 4.000 km away from the Canary Islands (Encarta 2007, Odell et al. 1962-63). Many thanks to Wolfgang Seboldt of DLR for sparking these considerations.

Meriwether Lewis and William Clark led the first North American overland expedition to the Pacific coast from 1804 to 1806,[364] but not for the commonly stated scientific exploration goals. Thomas Jefferson stated the objective of the expedition in a letter to Lewis as follows:

> "The object of your mission is to explore the Missouri river, & such principal stream of it as by it's course and communication with the waters of the Pacific ocean whether the Columbia, Oregon, Colorado or any other river may offer the most direct & practicable water communication across this continent for the purposes of commerce."[365]

Jefferson also justifies the need to get to know the people that are discovered on the expedition solely by potential future trade.[366] Scientific goals are almost nonexistent. The whole expedition was funded only for commercial reasons.

C) True Exploration: Trieste

The diving expedition of Jacques Piccard and Don Walsh to the Pacific Ocean's Challenger Deep in the Mariana Trench in 1960 is much closer to space exploration. The depth of 10 912 m that they reached with their bathyscaphe "Trieste" is still unsurpassed.[367] Compared to spaceflight, the efforts were less by orders of magnitude. But the motives, objectives and results of the expedition were similar to those of present space exploration proposals. Piccard and Walsh were not motivated by trade and commerce, but by science, adventure, and probably personal fame.

D) Conclusion

First exploration is a motive only for adventurers,[368] and these do not have sufficient financial means for spaceflight. The known space environment that is in reach with current technology does not support trade and commerce: There is no trade partner in space, and promising commercial aspects of space are rare, as will be seen in chapter 6.

In this context, the argument that we must explore now to develop new vehicles that can be utilized for commerce is also wrong. Columbus began his journey with ships that were available. He did not develop new ships to cross the ocean, and the ships he used were common trading vessels, not special ships for exploration.[367]

The fascination of the unknown and the wish to explore are insufficient to justify the high expenditures required for spaceflight. In the past, costly "exploration" expeditions were funded by governments only in expectation of trade and commerce.

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[364] Brockhaus 1979.

[365] Library of Congress 2006.

[366] Library of Congress 2006.

[367] Brockhaus 1979.

[368] As was previously identified, the decisive motivation for Apollo was not exploration.

Table 5-10: Evaluation of “Exploration”

Topic		“Because It Is There” – Exploration
Objective		Primarily manned expeditions beyond Earth
Technical Feasibility		Feasible (done in the past)
Effort	Costs	Several 100 000 000 000 $
Benefit & Motivation	Social, Cultural	Insights
Result	Quality of Justification	**Insufficient**
Comment		Historic large scale exploration only funded for trade and commerce

5.5 Spaceflight as a Modern Age Monument

Magnificent architectural monuments like the Egyptian Pyramids, medieval cathedrals or the Great Wall of China are often compared to the Apollo Lunar Landing. All are considered great engineering projects of the past, more or less lacking immediate visible benefits, but being a source of inspiration for the following generations for hundreds or even thousands of years – they are monuments for eternity.

The comparison of Apollo and other space projects to these terrestrial projects is problematic. The Apollo program was strictly politically motivated, while terrestrial monuments were realized either due to religious reasons, or very practical motives, like satisfying the people (Colosseum of Rome) or the need of defense (Great Wall of China). These strong reasons are not evident for proposed space missions such as a human Mars landing.

Table 5-11: Great Projects of Mankind

Topic	**Pyramids**[369]	**Cathedrals**[370]	**Apollo**[371]
Workforce	30 000	1 000	300 000
Part of Population [%]	2 (Nation)	3 (City)	0.2 (Nation)
Part of GDP [%]	7	10	< 1
Time to Accomplishment [a]	30	100	10
Resulting man-years	1 000 000	100 000	3 000 000

By the way, Apollo has required a considerably smaller part of population for a considerably smaller period than the construction of the Great Pyramid or a medieval ca-

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[369] Wastlhuber, personal conversation.

[370] The numbers must be seen as rough estimations. Orders of magnitude should be correct.

[371] Brockhaus 1979.

thedral had, thus having a smaller impact on economy, as is seen in **Table 5-11**: It was not as hard to cope with as was the construction of the ancient monuments.

But the main difference lies in the nature of space programs. Architectural monuments are solid testimonials of their great realization efforts. They can be visited, they can be seen, touched, and most of them even entered. Space activities are not enduring for the public. Though traces of Apollo still are on the Moon and will be for a long time, they cannot be seen or visited by everyone. Only launch pads and assembly buildings still exist – similar to the stone pits used for the pyramids.

If ever humans will frequently visit the Moon, the Apollo relics on the lunar surface certainly will be important landmarks. But for the foreseeable future, Apollo 11 will remain invisible for humans on Earth.

This makes Apollo similar to other elusive expeditionary firsts, such as Magellan’s first circumnavigation of the world, but it has nothing in common with cathedrals or pyramids.

Table 5-12: Evaluation of “Modern Age Monument”

Topic		Spaceflight as a Modern Age Monument
Objective		Large scale (human) space programs
Technical Feasibility		Feasible (done in the past)
Effort	Costs	Several 100 000 000 000 $
Benefit & Motivation	Social, Cultural	Inspiration and admiration of future generations; tourist attraction
Result	Quality of Justification	**Wrong**
Comment		Unlike historic monuments, spaceflight is elusive

5.6 National Promotion of Spaceflight

In this context, national promotion covers activities that a state is not bound to do as a national duty, but that the state could be motivated to support for strategic reasons: To increase its reputation in the eyes of its citizens as well as in the eyes of other nations. Spaceflight can hereby be exchanged with any other sector.

5.6.1 Economical Aspects

There are repeated campaigns and proposals since the 1970s, especially from industrial lobbyists and associations, to support spaceflight for economical reasons. The requests grow in intensity whenever a weariness in governmental funding morality becomes visible. This phenomenon is not restricted to spaceflight, but is visible in every other discipline.

It is argued that the government is bound to fund the high tech sector of astronautics for future conservation and creation of jobs, to acquire international contracts, and to preserve international competitiveness. This funding is sometimes seen as start up financing until spaceflight is self-supportive, similar to nuclear energy, for example.

But spaceflight depends on public support now for more than 50 years, still without a significant share of economy – this cannot be declared as start up financing anymore.

And the meaning of the spaceflight sector compared to the total national economy is insignificant. For example, doubling NASA's budget of 2005 from 15.7 G $[372] to 31.4 G $ would have had a hardly measurable impact of 0.1 % on the total U.S. GDP of 12 455.1 G $[373] (see also chapter 4.2.3 for respective numbers for Germany).

Investments in spaceflight are sometimes seen as a proof for a nation's potential.[374] But space activities are not an indicator for economic power, wealth, and potential of a country, as is illustrated in **Figure 5-4**.

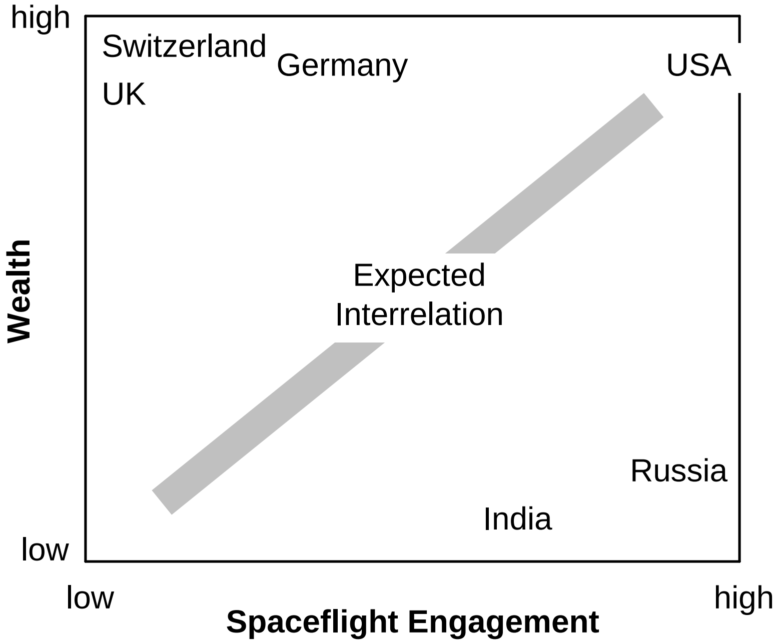

Figure 5-4: Interrelation of Spaceflight Engagement and Wealth

A wealthy society has the potential to engage in spaceflight activities, and it should do so. But for poor societies, extensive spaceflight activities could accelerate their

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[372] Wikipedia 2007a.

[373] World Bank 2006.

[374] A German federal minister of research once said: "Wer Raumfahrt kann, kann auch alles andere [*Who can do spaceflight can do everything else*]." (Schmucker, personal conversation)

bankruptcy and lead to disaster (as happened with the Soviet Union).

Table 5-13: Evaluation of “National Economical Aspects”

Topic		National Economical Aspects
Objective		Any type of spaceflight
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $ and more
Benefit & Motivation	Social, Cultural	Subsidization of national economy
Result	Quality of Justification	**Insignificant**
Comment		Impact on GDP insignificant

5.6.2 Spaceflight for National Prestige

Aside from the national security aspect, national prestige as part of politics can be seen as an important driving force of spaceflight development in the 20th century. Advance into space was seen as a way to demonstrate the superiority of a nation or a political system.

Between the USA and the USSR, this force lost a lot of intensity with the success of Apollo 11 and the Soviet Union’s clear loss of the Space Race. It finally disappeared with the collapse of the Soviet Union in 1990. For the established industrial nations, spaceflight is not a new and exciting challenge anymore.

For ambitious, upcoming nations like China and India, this political justification for spaceflight activities still remains important and is accordingly persecuted, and perhaps, in time it will again rise as a major driving force of spaceflight.

Table 5-14: Evaluation of “National Prestige”

Topic		National Prestige
Objective		Any type of spaceflight
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $ and more
Benefit & Motivation	Social, Cultural	Increase of self confidence and national pride
Result	Quality of Justification	**Variable**
Comment		Significant in 1960s for USA, SU; now important for developing countries

5.7 Science and Research

The sensible position of science and research within the four categories of spaceflight benefits proves to be difficult. Science may change human attitudes and influence culture and society (chapter 5), may generate unexpected byproducts (chapter 7), may have quantifiable commercial value (chapter 6), and without doubt it is important for the future of mankind (chapter 8). But the genuine value of space science and research is almost impossible to identify, and therefore it is addressed here, within the category of subjective benefits.

Science and research are part of human culture and a pillar of civilization and wealth, and thus without doubt a national duty. But the type, scale and number of scientific activities will always be subject to discussion.

Commercial science and research activities are not further analyzed here because they are part of a corporation's activities to ensure future competitiveness. The costs are transferred to the product prizes and paid by the customers. This shifts the focus on governmental science activities that have no imminent financial return flow in mind. Here, space science must compete with other, non space related areas of science and research.

The focus lies on scientific missions in space and their results, but the peripheral effects of space related, public funded research on education should not be underestimated. As an example, in the period of 1989 to 2002, the German hypersonic and space transportation program "Sänger" alone generated 618 seminar papers, 472 diploma theses, 251 doctoral theses and 13 state doctorates.[375]

A) Type and Frequency of Missions Beyond Earth Orbit

Scientific missions to other celestial bodies are rare, but they are positioned at the heart of "space science" if it is taken at its literal meaning: The gain of knowledge about the universe beyond Earth that is only enabled by spaceflight.

The cost increases not only with the number of scientific instruments (equal to mass increase!), but also with the distance of the vehicle's destination, and with the mission's primary objective. Requirements increase with flyby, impact, orbit, landing, on site mobility and sample return.[376]

Figure 5-5 and **Figure 5-6** present the number of missions to various targets beyond Earth orbit from 1957 to December 2006. Mission success is given if the primary goal is accomplished; spacecraft currently en route (Rosetta – Comet, Messenger – Mercury, New Horizons – Pluto) are counted as success.

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[375] Högenauer 2006.

[376] Sample collection at flyby (e.g. NASA's „Stardust" mission) is less demanding than in situ surface sample collection.

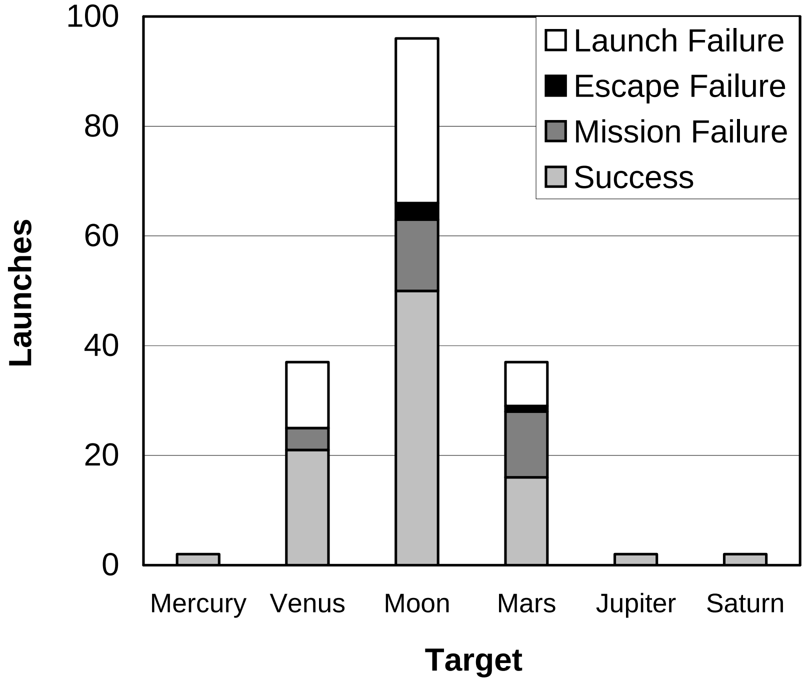

Figure 5-5: Missions Beyond Earth Orbit by Primary Target (1)

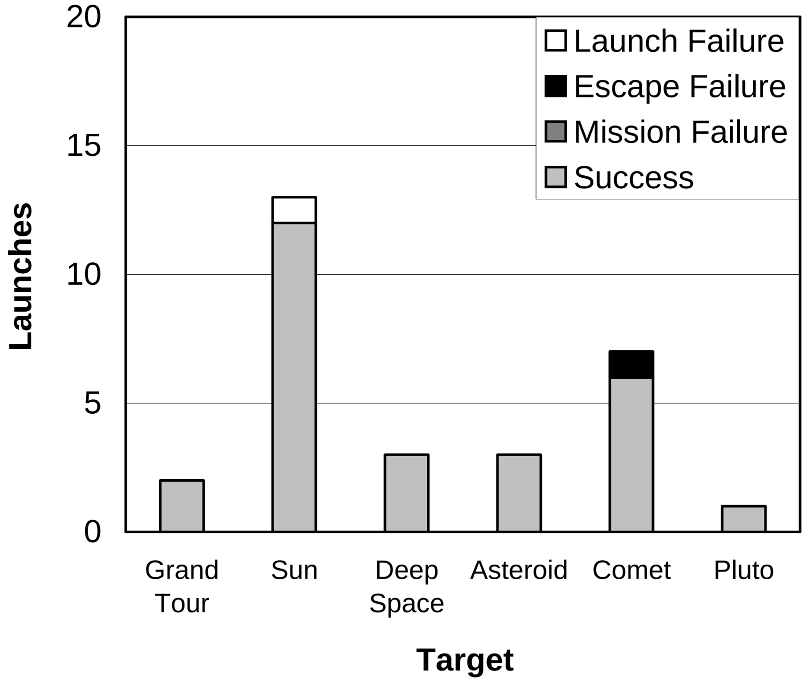

Figure 5-6: Missions Beyond Earth Orbit by Primary Target (2)

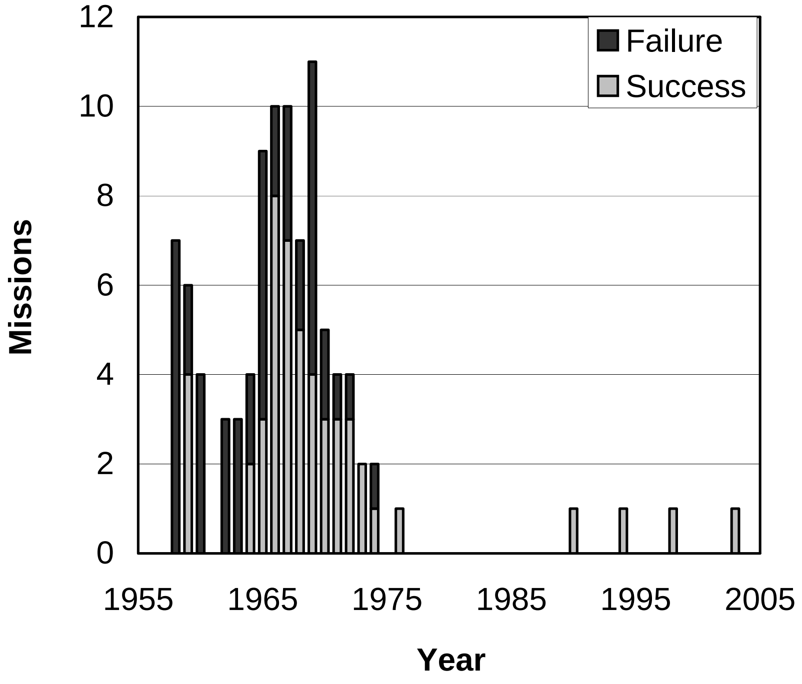

Figure 5-7: Missions to the Moon

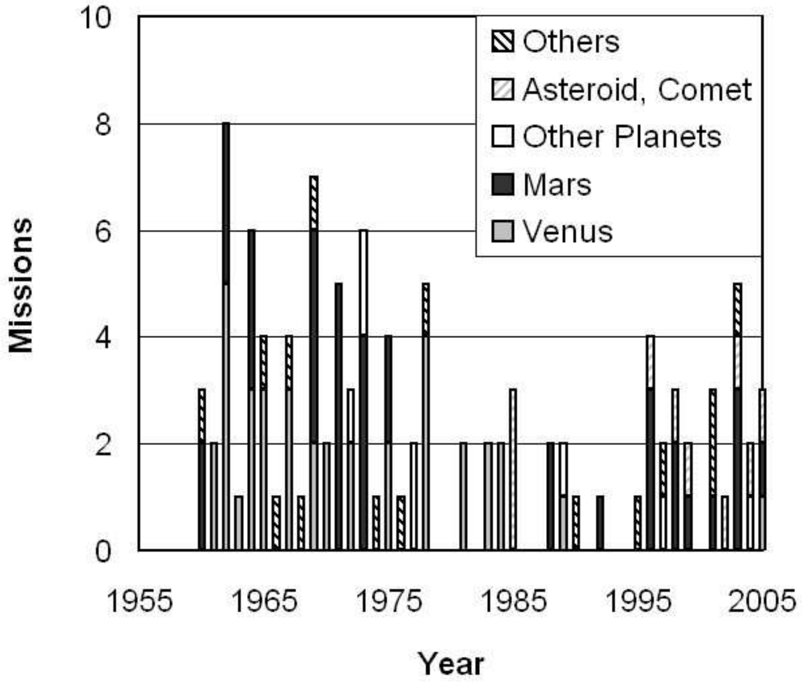

Figure 5-8: Missions Launched Beyond the Moon

Figure 5-7 and **Figure 5-8** reveal that scientific missions are subject to trends:

- The lunar missions ended with the Apollo program in the early 1970s, with only four missions in the following thirty years. Interest was renewed in the early 2000s, with numerous missions awaiting launch between 2007 and 2010.
- For twenty years, Mars was unimportant with only three intended missions. Interest was renewed in the 1990s.
- Since the mid 1980s, only two missions were sent to Venus.
- Aside of three probes that were sent to Halley's comet in 1985, asteroids and comets were discovered as scientific objects in the 1990s, with an almost annual frequency of missions.

Various recent and planned missions are presented in **Table 5-15**.

Table 5-15: Various Present and Future Science Missions

Name	Destination	Launch	Costs [M $]
Venus Express (ESA)	Venus	2005	264[377]
New Horizons (NASA)	Pluto	2006	700[378]
Phoenix (NASA)	Mars	2007	417[379]
MSL (NASA)	Mars	2009	1 753[380]
ExoMars (ESA)	Mars	2011	708[381]
BepiColombo (ESA/JAXA)	Mercury	2013	798[382]
JWST (NASA)	L2	2013	ca. 4 500[383]

The costs of space science missions are in the order of magnitude of at least several hundred million dollars.

B) Areas of Scientific Research

The main fields of science in space are:

- Astrophysics
- Physical experiments
- Medical topics
- Biology
- Geology
- Chemistry
- Meteorology

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[377] In €: 220 million. (ESA Info Note 1/2005)
[378] Space.com 19/01/2006.
[379] AW&ST Jun 11 2007.
[380] AW&ST Apr 9 2007a.
[381] In €: 600 million. (Space News 12/12/2005a)
[382] In €: 665 million. (Space News 9-2007a)
[383] Space News 21/11/2005.

Past scientific activities could be categorized in the following way:

- Research of space environment effects (e.g. ISS),
- Distant observation (space telescopes),
- On site activity (flyby, orbit, impact, landing, return).

The range of objects of scientific value seems as large as the potential methods of their research. But from a distant view, the number of different mission scenarios decreases. The scientific value of each mission and its discoveries is high for the involved scientific community of course, but the public is hard to convince that, for example, each new Mars lander mission to analyze Martian rock composition and measure wind speeds is different from its precursors.

C) The Use of "Space" as Keyword

There is another problematic aspect that the space science community should be aware of. The words "space" and "spaceflight" open doors to research funding that remain closed for many other disciplines.

To give an example:

- If anybody requested that a remote desert on Earth should be charted by land survey teams to increase accuracy of existing maps from three meters to one meter, no one would be interested in this endeavor, let alone finance it.
- If the survey should be done via satellite, funding seems not probable, but at least possible.
- If the Moon was to be charted with one meter resolution by an orbiter, as proposed by the German space agency DLR, public funding of the mission, expected to be 300 to 400 M €, has good prospects.[384]

This effect may be good for spaceflight, but it brings with it a large responsibility for the proposal of such missions. The proponents should be well aware of the funding levels that are required for their scientific goals.

Spectacular new missions that return comprehensible results to the public may have even better chances to receive funding. To give an example: Everybody understands the primary objective of the New Horizons Pluto flyby mission: To finally visit the last of the classical nine planets. But objectives such as high resolution measurement of solar flare effects on the tail of Jupiter's magnetic field will be incomprehensible for the majority of the public. Temporary concentration on spectacular, comprehensible missions may enhance the advertising effect for spaceflight that too many past and present science missions seem to lack.

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[384] Spiegel Online 28/02/2007.

D) Consequences and Proposals

The general scientific value of spaceflight is very high, as is demonstrated every year by numerous discoveries. The present scale of funding should not be decreased.

But an increase in funding, resulting in an increased scale of activities, is unlikely as long as the backflow of investments is not clearly present, or as long as scientific use and benefits remain mysterious for the public. The often repeated phrase "to better understand processes on Earth" may be true, but the real benefit too often is expansion of knowledge without a practical purpose for the public that pays the bills. That means high efforts for the benefit of a few scientists.

The present flow of benefits from space science is outlined in **Figure 5-9**.

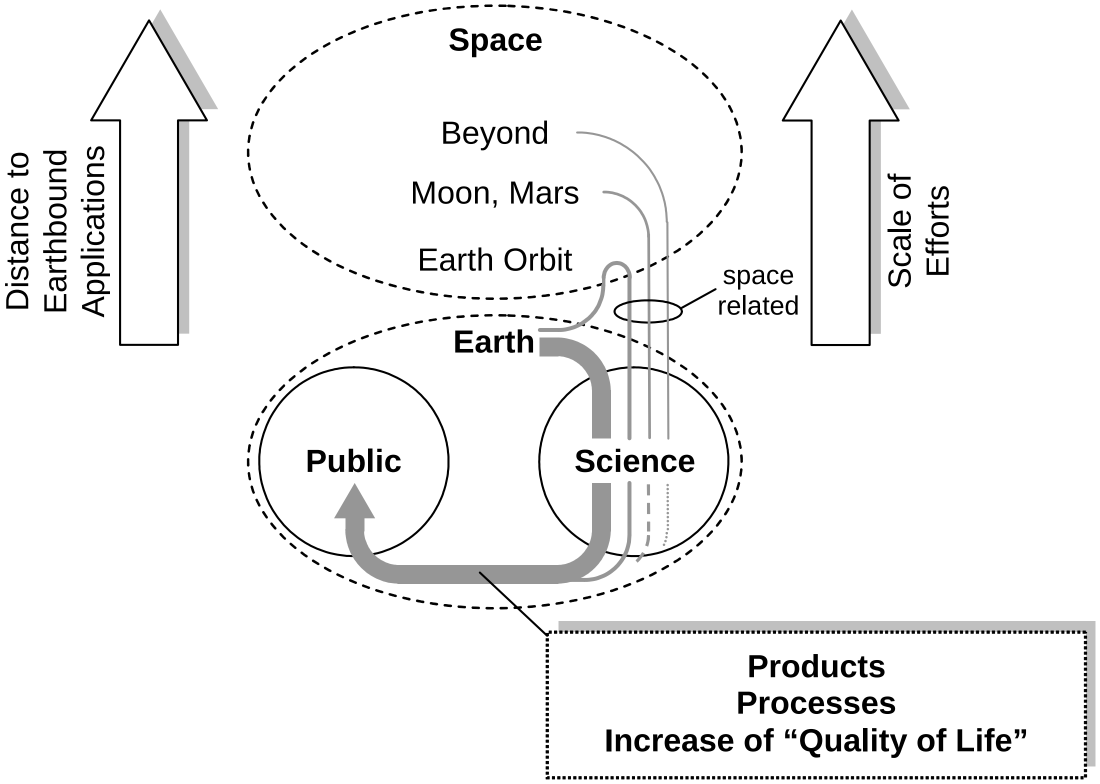

Figure 5-9: Flow of Scientific Insights and Benefits

A partial disorientation of science and research – and with it, the basic problem – becomes visible in the planned utilization of the ISS. NASA is entitled to use about 22 experiment racks in the station (twelve in Destiny module, five in Columbus module and a like amount in Kibo module). After years of preparation and construction of the station, half of them are still unfilled, with NASA offering use of them free of charge to outside users.[385,386]

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[385] AW&ST Jul 2 2007.

Another fact that must be considered for future science missions, aside of the costs, is the high risk of spaceflight, especially for manned missions. The loss of orbiter Columbia in 2003 at its return from a scientific research mission seems to have led to a new aspect in the view of manned science missions, as was written in the February 2007 edition of *Nature* magazine:

> "Just as disturbing was the banality for which the astronauts had died. Columbia had been on a mission to conduct some small experiments in microgravity, including a promotional test for a fragrance company. Until it ended in tragedy, the mission barely made local headlines in Houston. "We believed this was not an adequate vision to justify the risk of putting astronauts into space," [investigation board member John Logsdon] says. The board recommended a re-examination of NASA's entire rationale for human spaceflight."[387]

Space sciences are one scientific discipline among many others. Science by the means of spaceflight must be measured against these other disciplines. The nature of spaceflight activities requires higher funding levels than most earthbound sciences. This must always be considered for future activities, to justify financial support, but also to ensure responsible selection of scientific mission proposals. A few other science disciplines, for example particle physics, are in a similar situation, but the space community should not point to them as a justification.

Nonetheless, as was mentioned, science and research is part of national duties, and if a state is able to finance space science, it should do so on a certain scale, with a certain percentage of its gross domestic product.

Table 5-16: Evaluation of "Science and Research"

Topic		Science and Research
Objective		Various types of spaceflight
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $ and more
Benefit & Motivation	Social, Cultural	New insights and knowledge
Result	Quality of Justification	**Sufficient**
Comment		Significance of various topics for the taxpayer varies considerably

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[386] A McDonnell Douglas TV commercial of 1988 vividly shows the change of attitude towards the space station. While a manned laboratory orbiting Earth is shown and Russian radio communications are heard, a voice says: „Right now, miles above the Earth in a manned space station, experiments are being conducted that could cure major diseases, new and valuable metal alloys are being created, and new scientific data that could literally change the course of history are being collected every minute. Shouldn't we be there, too? – America needs the space station… now."

[387] Brumfiel 2007.

5.8 The Search for Life

Of all space related scientific discoveries, the proof of existence of extraterrestrial life would probably have the most significant social, philosophical and cultural impact on humanity, as well as immense scientific value.

5.8.1 Defining Life

The ideas of a clear definition of life, and with it, the identification of necessary prerequisites of celestial bodies to sustain life, are controversial.

At present, liquid water, carbon and oxygen are generally seen as prerequisites for existence of even primitive forms of life, though there also seems to be a possibility that primitive life that is based on silicate may exist.[388]

Carbon based life seems to be the only way, though, due to the unique characteristics of carbon based chemistry.[389] Furthermore, the metabolism of silica based life forms would have to get rid of the solid silicon oxide waste products instead of gaseous carbon dioxide – and this seems impossible.

Some groups propose that life may exist in any aqueous environment (e.g. aerosols in Venus atmosphere), and that even exotic solvents (e.g. liquid methane or nitrogen) may harbor life.[390]

The latter view of possible “weird life”[390] would drastically increase the chance that life is discovered elsewhere in the universe, in our galaxy, and possibly in our own solar system, but this remains questionable.

Anyway, the fundamental basics of life itself still remain completely unknown.

5.8.2 In Our Solar System

Through the centuries, it was obvious that life existed not only somewhere in the universe, but close by, in our own cosmic neighborhood.[391] As an example, at the end of the 19th century, the novels “*Auf zwei Planeten*” (*On Two Planets*) of Kurd Lasswitz[392] and “*The War of the Worlds*” of H. G. Wells depicted an invasion of Martians – at that time a quite imaginable threat. And up to the first flyby of Mars by Mariner 4 in 1965, it was seriously speculated that vegetation was the reason for the seasonal shifts of Mars’ color.[393]

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[388] Walter 2001.
[389] Walter 2002.
[390] NRC 2007.
[391] Walter 2001.
[392] Lasswitz 1969.
[393] Braun 1968.

The ever cloud covered Venus was another potential candidate for life, until the first probes discovered the infernal conditions on its surface; the myth of the inhabited Mars was destroyed in a similar way with the first close-up pictures that were reminiscent of the lunar surface, but showed no signs of life.

The insight that life could not exist in the hostile environments of all the other celestial bodies of our solar system settled down for a brief period, and the focus of the search shifted towards more distant targets. But new discoveries of life at hostile places on Earth, for example at the black smokers in the deep sea, renewed the conviction that primitive organisms could have survived on Mars, Titan, Europa, Enceladus, and perhaps elsewhere.

In-depth analysis of the quest for extraterrestrial life shall not be further discussed here. But the transformation of scientific chains of evidence into chains of speculation is remarkable and must be mentioned. Today, the question is not if life could have originated in other places than Earth. The question now is *if it survived* somewhere, as if it was clear that creation of life takes place everywhere.[394] This change of attitude is illustrated for Mars in **Figure 5-10**.

At present, no year passes without news about “new evidence for possible life” in our solar system. Just to name a few:

- Eventual bacteria fossils in Mars meteorite on Earth (1996)
- Methane on Mars (2004)
- Rocks once “drenched in water” on Mars (2004)
- Possible remains of frozen ocean on Mars (2005)
- Complex carbon molecules in Titan’s upper atmosphere (2005)
- Liquid water geysers on Enceladus (2005)
- Landslides or gullies on Mars (2006)
- Bright-toned silica soil on Mars (2007)

Since Friedrich Wöhler’s artificial synthesis of urea in 1828, it was clear that organic compounds had nothing to do with life. The same is true for the Miller-Urey-experiment of 1953 that produced amino acids out of water, methane, ammonia and hydrogen. But during the last years, the mere existence of water or organic compounds on other celestial bodies became a most probable sign for life. This is not very supportive for the case of spaceflight because of several reasons:

- Water must not necessarily mean life – hydrogen is abundant in the universe, and it reacts with oxygen regardless of existence or creation of life,
- The public gets bored by basically the same news again and again,
- These announcements will soon be ignored by the public,
- It sounds too much like a lame excuse for the taxpayer,
- If the public finds out that – hypothetically and just as an example – the

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[394] With this assumption, life must have existed on Venus earlier than on Earth: The preconditions for life must have been better closer to the sun in early times, and the impact event that created Earth’s Moon must have added to the time difference in favor of Venus.

landslides on Mars are a result of fine dust and have nothing to do with water, the credibility and the funding of future missions will suffer.

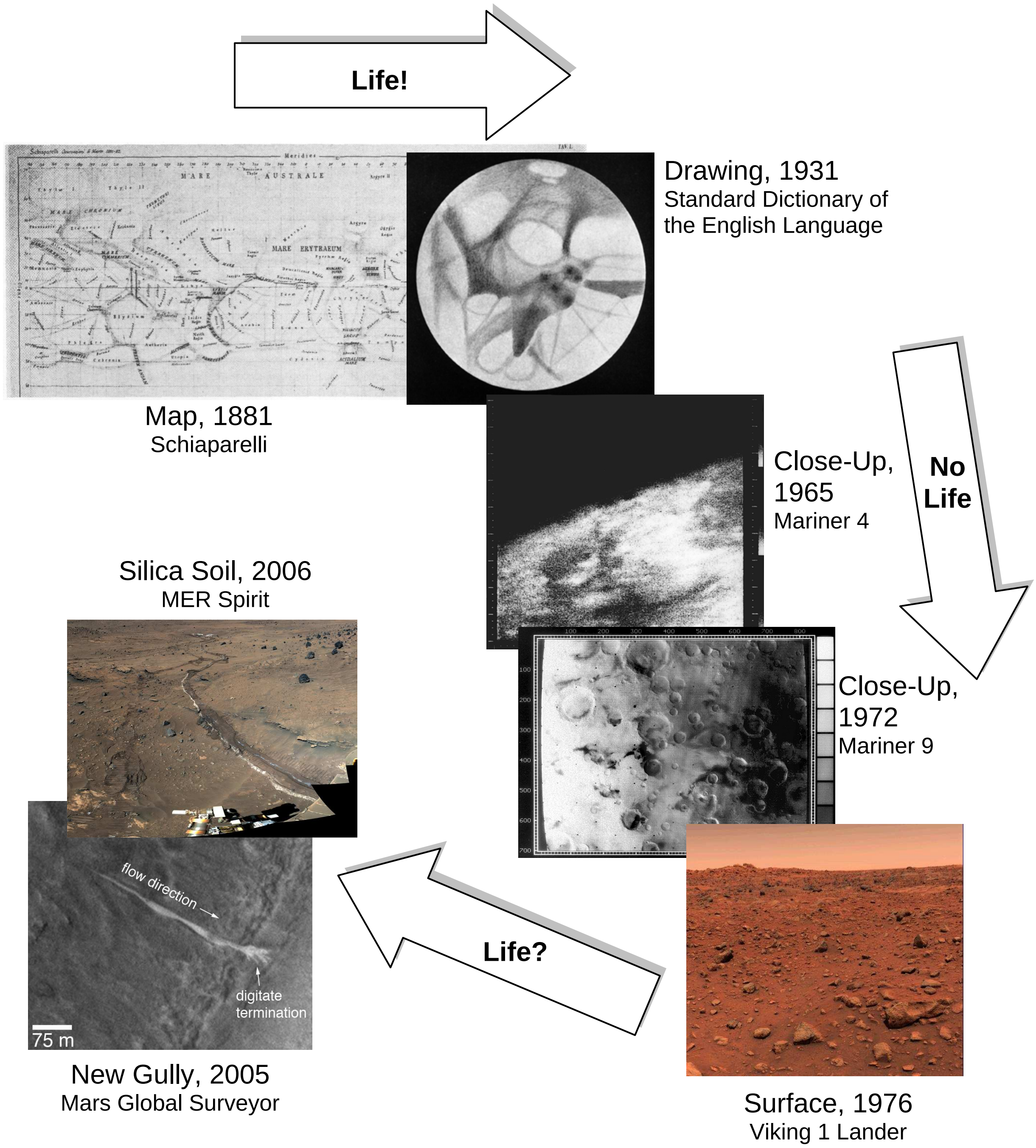

Figure 5-10: Images of Mars and Expected Life[395]

Missions – manned or unmanned – that can give clear answers should be preferred to missions that will sell another chain of speculation as “possible evidence”.

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[395] Walter 2001, Exploring Mars 2007, NASA GSFC 2007c, NASA JPL 2007b.

5.8.3 Somewhere Else

Due to the lack of adequate means, the search for extra solar life hitherto concentrates on radio signals of possibly artificial origin. These signals could only be emitted by extraterrestrial intelligences (ETIs), thus limiting the search to highly developed alien civilizations.

There are means to consider the chances that life exists elsewhere in our galaxy or in the universe, for example the Drake Equation, the Weak Anthropic Principle and the Fermi Paradox.[396] But they are of theoretical nature and can only give statistical answers, and they also concentrate on ETIs and not on life itself.

The increasing sensitivity of instruments and new search methods led to the first discovery of an extrasolar planet, 51 Pegasi b, announced in 1995. The number of confirmed exoplanets since increased exponentially, as seen in **Figure 5-11**.[397]

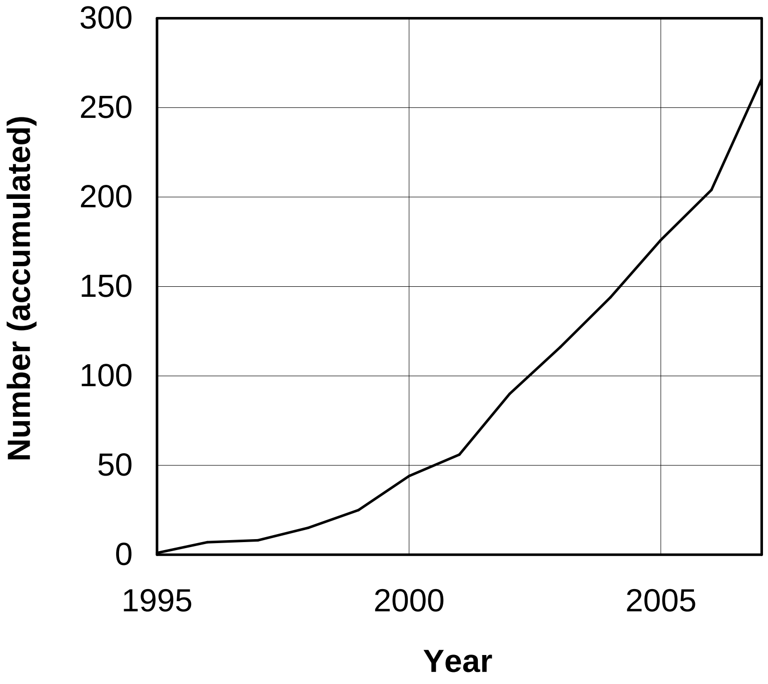

Figure 5-11: Total Number of Confirmed Extrasolar Planets[398]

This leads to the conclusion that detection methods may soon be sensitive enough that they might allow to discover humid, Earth like planets with moderate surface temperatures and oxygen rich atmospheres, thus providing evidence for alien life (at least carbon based life, see chapter 5.8.1). This will probably be impossible without

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[396] Walter 2001.

[397] Likewise, about ten new planetary bodies with diameters of roughly 1 000 km and more were detected in the outer regions of our own solar system between the years 2000 and 2005 alone. (Delsanti et al. 2006)

[398] Schneider 2008.

space based methods of detection.

The sensitivity of instruments to detect and directly observe this type of planets may be achieved some day. The chances of success are completely unknown, though, but the list of factors P_i that result in the probability of existence of habitable planets P_{hab} is very long.

$$P_{hab} = \prod P_i \qquad (5.2)$$

These probabilities include factors concerning

- the star (size, stability, solar wind intensity, …),
- the neighborhood (stable planetary, stable stellar, …),
- the planet's satellites (stabilization by large moon, its early creation, …),
- asteroid impact frequency,
- … .

Every single probability is smaller than 1, and if the unknown number of factors approaches infinity, the probability of creation of a habitable planet approaches zero.

5.8.4 Prospects

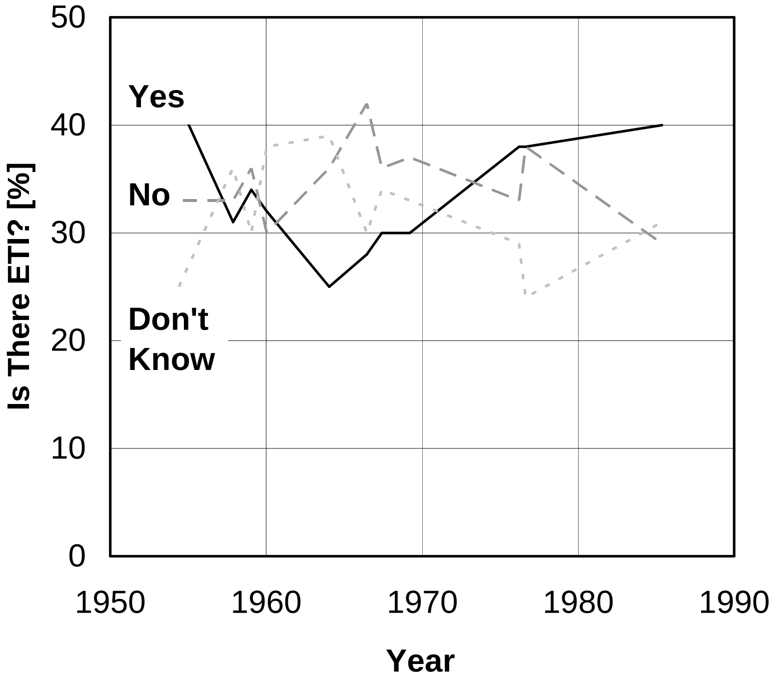

Figure 5-12: Believe in Existence of Extraterrestrial Intelligence[399]

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[399] Allensbach 1985.

The belief that life on Earth is not unique is widely spread. With the launch of Sputnik and the early days of spaceflight, belief in extraterrestrial life dropped for some years, as seen in **Figure 5-12**. Presented are results of various polls in Germany, concerning the question if intelligent life exists somewhere else in the universe.

Today, the search for traces of life in our solar system is at least as intense as the search for signs of life in other solar systems, and it is a driving force of science missions and a good argument for funding. The question for extraterrestrial life can probably only be answered by means of spaceflight. And if the quest for life is successful some day, this will have a great impact on society.

But the search has another effect, no matter if successful or not: If life was discovered, we would try to go there and study it. If the search remains yet unsuccessful, we will try harder and extend our reach to find something. Either way, spaceflight as a tool is indispensable, and it will avail from the search for life.

Table 5-17: Evaluation of "Search for Life"

Topic		Search for Life
Objective		In situ research (robotic and human), sample return, sensitive space telescopes, …
Technical Feasibility		Challenging
Effort	Costs	Several 100 000 000 $ and much more
Benefit & Motivation	Social, Cultural	Answers on fundamental questions
Result	Quality of Justification	**Significant**
Comment		Can only be done with spaceflight

5.9 Conclusion

All of the topics presented in this chapter are "soft", and, for the major part, missing plans for actual realization. Most of the topics have the focus on *distance to Earth* in common, and they are supportive for any type of spaceflight activities (with special emphasis on exploration). They try to justify any kind of engagement in spaceflight. Today, by the mentioned equivalent of benefits and motivation, these topics are used as main arguments for governmental spaceflight funding.

But there is a huge gap between the number and scale of ideas, visions, and proposals on the one side, and actual realization on the other side. It must be concluded that it is much easier to imagine or envision spaceflight than to make it reality. As soon as real engineering – with required efforts! – comes into play, the visions disappear.

As was stated in the beginning of this chapter, subjective benefits are subject to personal judgment and interests. But the number of individuals who are actually interested in spaceflight is lower than expected by most spaceflight enthusiasts, and more important, the needs that are addressed are too weak to fundamentally justify more engagement by the state.

For a few topics, though, companies could serve as a means to realize spaceflight, if a sufficient number of individuals is willing to pay for it – for example “personal challenge”, leading to space tourism. This leads to quantifiable benefits (profits!), and is therefore further considered in chapter 6.

Scientific topics can be quantified in a way of results, papers, doctorates, and so on, but the majority of the philosophical, cultural and social reasons for space exploration and exploitation remain on the spiritual side, lacking an indigenous force for realization. They can only support the justification of the existing activities, but they are not strong enough to launch new, large scale activities on their own, and justify the huge efforts and expenditures. As a result, spaceflight might create philosophical, cultural and social benefits as a byproduct – benefits that cannot be measured in quantities.

The sum of justifications seems strong enough to require public engagement in spaceflight to a certain percentage of the available gross domestic product. This seems to explain the present scale of scientifically oriented civil spaceflight activities.

But future visions for spaceflight activities are only transferred to reality if they are funded, and they are only funded if they create substantial value for those who fund them.

Spaceflight that is solely done to create subjective benefits requires public funding. This is due to the “soft”, trans-utilitarian character of these benefits. They can justify limited national (and international) space activities, but are not strong enough to motivate a state to significantly increase its current expenditures for space. The efforts for spaceflight will remain at the same level. Thus, the scale of spaceflight that is motivated by subjective benefits will also remain at the current level for the foreseeable future.

6. Quantifiable Benefits

Commercial applications are crucial for spaceflight development. Their benefits can be clearly quantified as revenues. If they are feasible, if there are no political restrictions, and if profits are expected, then industry will develop the applications.

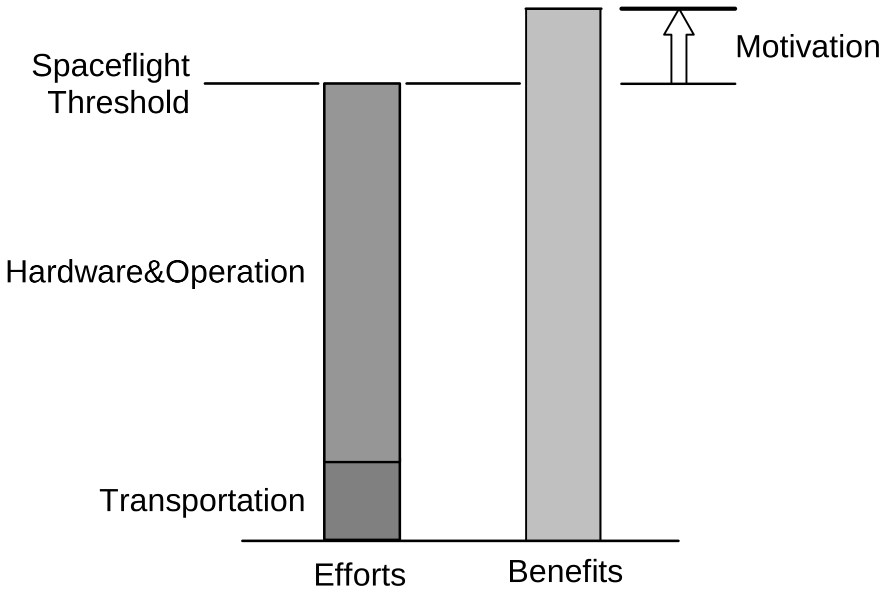

Figure 6-1: The Benefits of Commercial Topics

For the following topics, the identified evaluation method can easily be applied:

$$M = B - E \ . \qquad (6.1)$$

If the benefits B in form of revenues outweigh the efforts E or expenditures, as seen in **Figure 6-1**, motivation M is given, and investments will be made. The prime actors are companies, the state is secondary and might contribute with start up financing. Nonetheless, motivation is only given if, in the long term, profits can be expected.

The following topics are analyzed:

- Commercial aspects of current activities
    - Launch vehicles and satellite transportation services
    - Launch sites
    - Earth satellite applications
    - Insurance
- Future enhancement of current activities
    - Services in space

  - Providing space infrastructures
  - Privatization of science missions
- Applications for the “entertainment society”
  - The astronaut experience
  - Space tourism
  - Space burial
  - Advertising
- Resources, materials and products
  - Resource mining and extraction
  - Production and manufacturing
- Energetic and environmental tasks
  - Power generation in space
  - Waste Disposal
  - Illumination and other space mirror applications

With this, the known commercial aspects of spaceflight should be covered.

6.1 Commercial Aspects of Current Activities

Public funding still dominates numerous current spaceflight activities. But private companies have taken hold in some areas, for example space transportation or satellite applications. An analysis of the economic chances to take hold in this existing market of current spaceflight activities is required to judge the potential for further investments in this direction, and to verify the evaluation approach.

The activities are classified into space transportation services, allocation of launch sites, Earth satellite applications, and a brief look on the insurance business.

6.1.1 Launch Vehicles and Satellite Transportation Services

Space transportation’s technical aspects and financial orders of magnitude were already addressed. A successive view of the present market situation is required to understand the actual commercial aspects and future potential of current space transportation.

Though space transportation and launch services are always seen as the major part (and major barrier) of spaceflight, **Figure 6-2** underlines the minor role of transportation that was previously identified in chapter 4.3.1.

Space transportation revenues are negligible compared to satellite manufacturing and satellite services as well as ground equipment. In 2005, launch service revenues were a mere 3.4 % of the total world satellite industry revenues of 88.8 G $.[400]

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[400] SIA 2006.

The exact meaning of the fields “Satellite Services” and “Ground Equipment” are explained later in chapter 6.1.3.1.

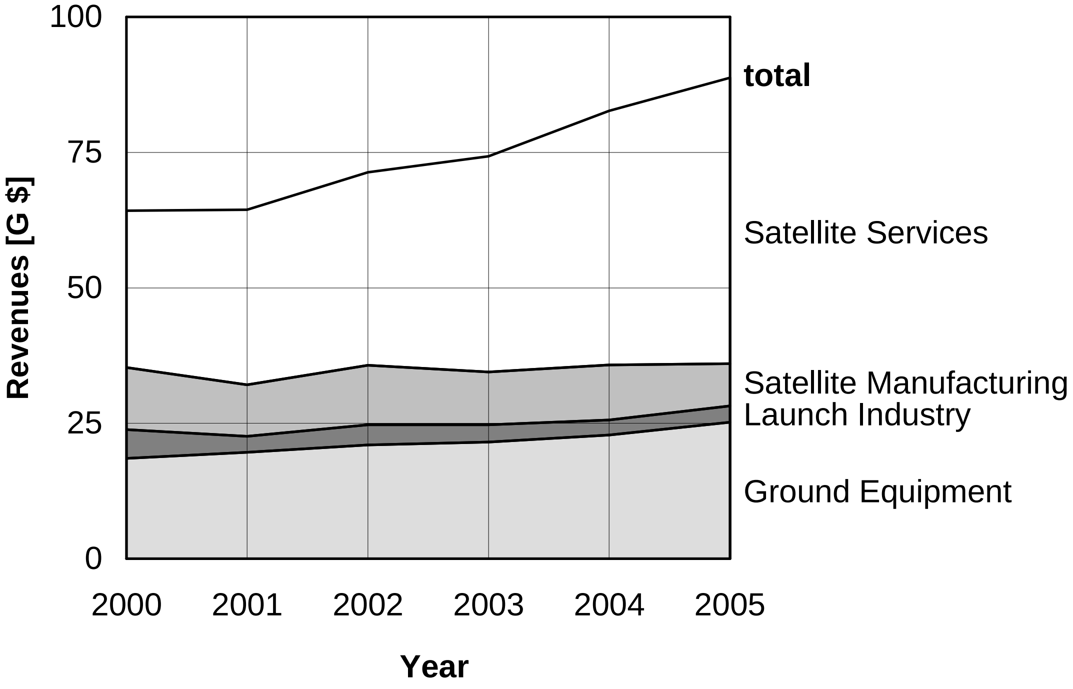

Figure 6-2: World Satellite Industry Revenues[401]

A) Launch Rates

The total available market for space launches is estimated with a look at the launch rate development over the last years. For economical analysis, average present launch rates are important. Average orbital launch rate, as seen in **Figure 6-3**, is about 60 per year.

Supplemental numbers for important space transportation systems are presented in the following Figures:

Figure 6-4 presents the launch log of the European Ariane 5, besides the Proton and the Sea Launch Zenit-3SL currently one of the most important large satellite launch vehicles.

In **Figure 6-5**, the long year record of the U.S. Delta family of launch vehicles is presented. The repeating changes in annual launch frequencies should be noticed.

The launch log of the Pegasus launch vehicle is presented in **Figure 6-6**. The low annual launch numbers are characteristic for small space transportation systems.

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[401] SIA 2006.

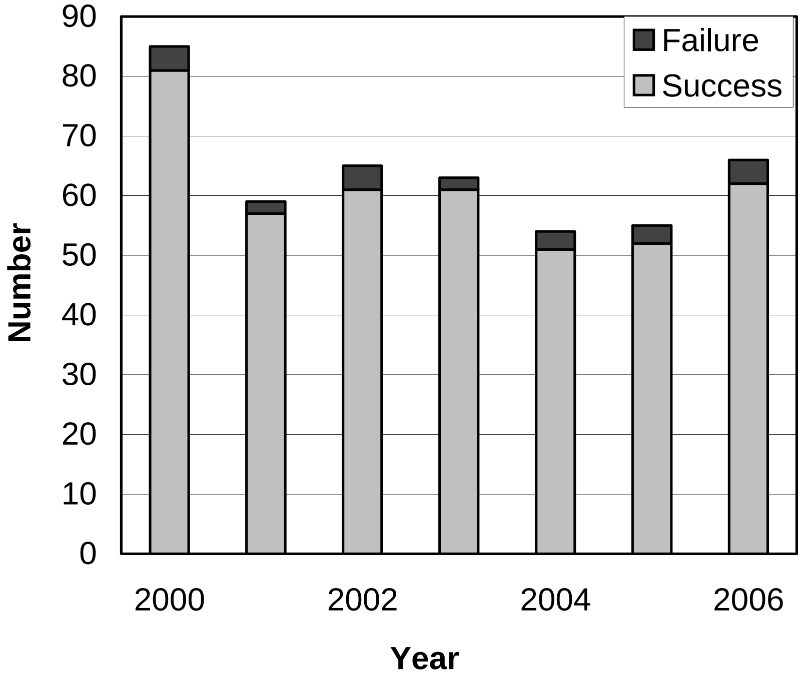

Figure 6-3: Recent Space Launch Activities

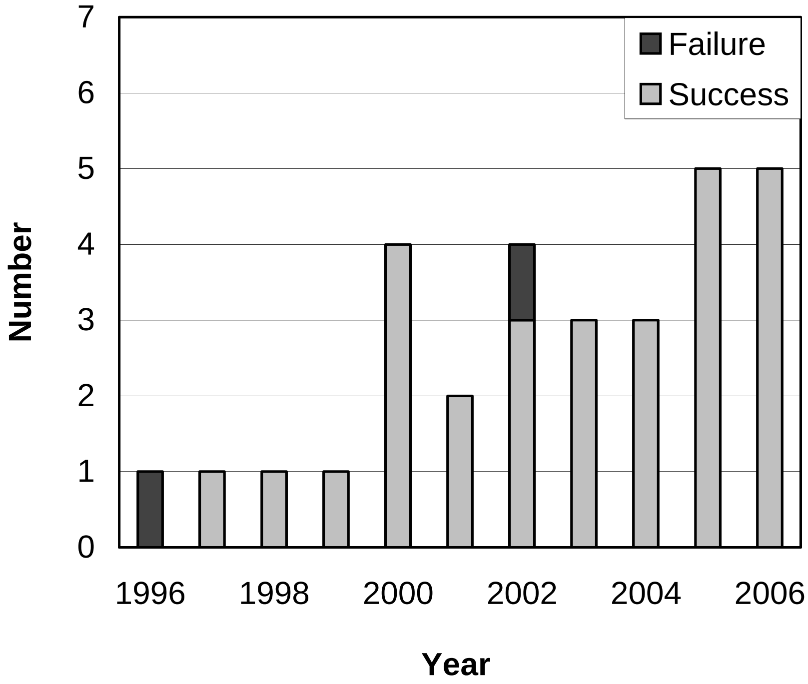

Figure 6-4: Ariane 5 Launch Log

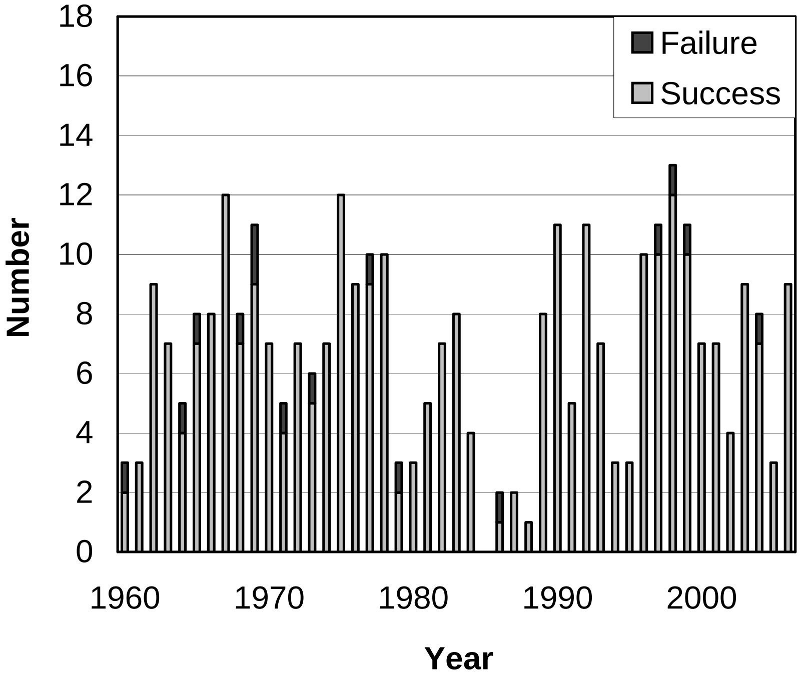

Figure 6-5: Delta Launch Log

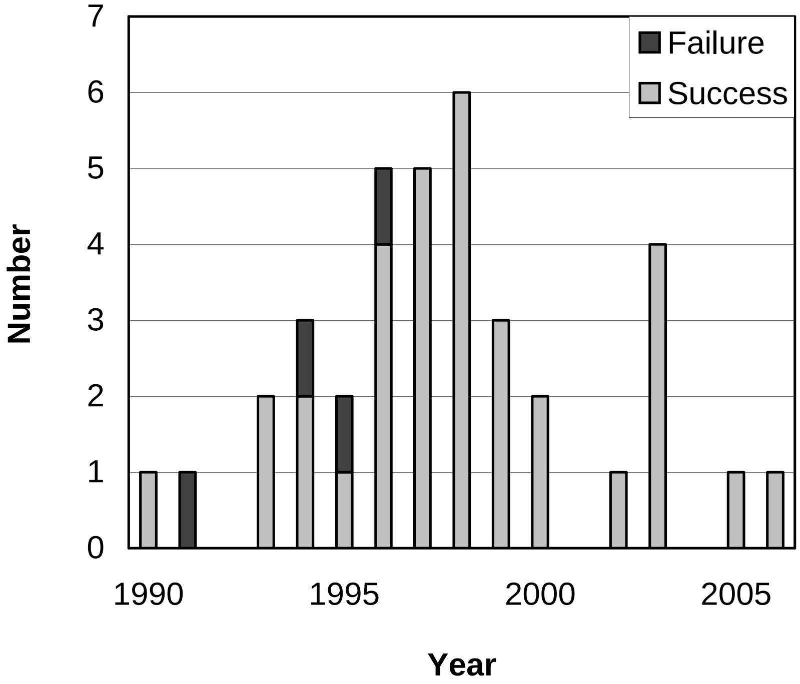

Figure 6-6: Pegasus Launch Log

B) Launch Prices

Depending on the source of information and type of transportation system, orbital launch prices for unmanned systems range from less than 10 M $ to about 200 M $ per launch. For further considerations, an average of 100 M $ is assumed.

C) Market Volume

A simple equation allows estimation of the current annual launch market volume, with average launch frequency n_{lau} and estimated average launch price P_{lau}:

$$T_{lau,ave} = n_{lau,ave} \cdot P_{lau,ave} \qquad (6.2)$$

With the previously identified numbers, the resulting average launch market turnover $T_{lau,ave}$ per year would be 6 G $.

Figure 6-7 shows the share of commercial and governmental launches over the last years. It shows that about two thirds of the launches are done by national institutions or governments with sensitive payloads. Most of these payloads are legally bound to be launched with governmental launchers. It is optimistic to assume that half of the launches are unrestricted and might be done by private companies, reducing the available annual launch market to 3 G $, which is consistent with the numbers of the satellite industry association presented earlier in Figure 6-2.

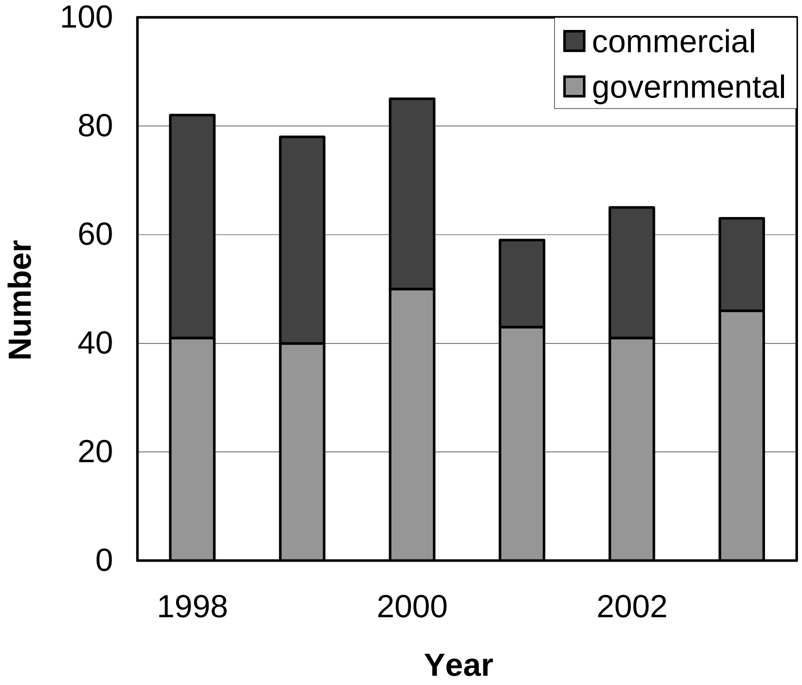

Figure 6-7: Governmental and Commercial Launches[402]

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[402] Futron 2003.

D) Supply and Demand

At present, the supply (the number of available launch vehicles) is quite high compared to the demand (the number of actual launches). Available launchers of the year 2004, already presented in Table 4-2, are categorized into three classes:

Small:	Up to 2 t LEO payload capacity
Medium:	2 – 8 t LEO payload capacity
Large:	More than 8 t LEO payload capacity

In **Figure 6-8**, the launches of the year 2004 are assigned to the according launcher classes, revealing supply and demand of each class.[403]

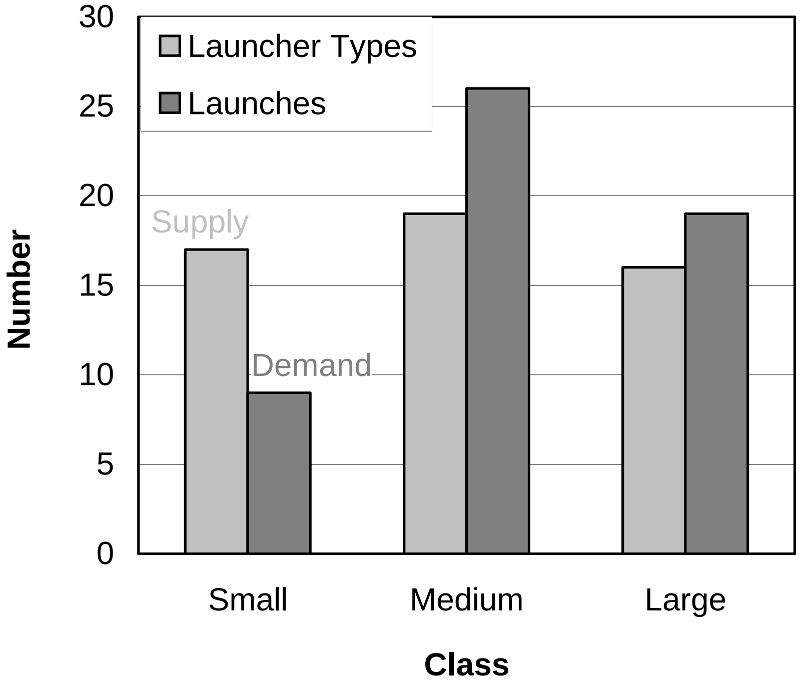

Figure 6-8: Supply and Demand of Launchers (2004)[404]

In 2004, the number of available small launch vehicle types was twice as high as the number that was actually launched. The numbers of medium and large missions were slightly higher than the number of offered launch vehicle types.

For the years 2005 and 2006, as shown in **Figure 6-9** and **Figure 6-10**, a similar pattern is visible.

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[403] Some launch vehicles that are not commercially available (e.g. China, Israel) are also included.
[404] ESA LVC 2004.

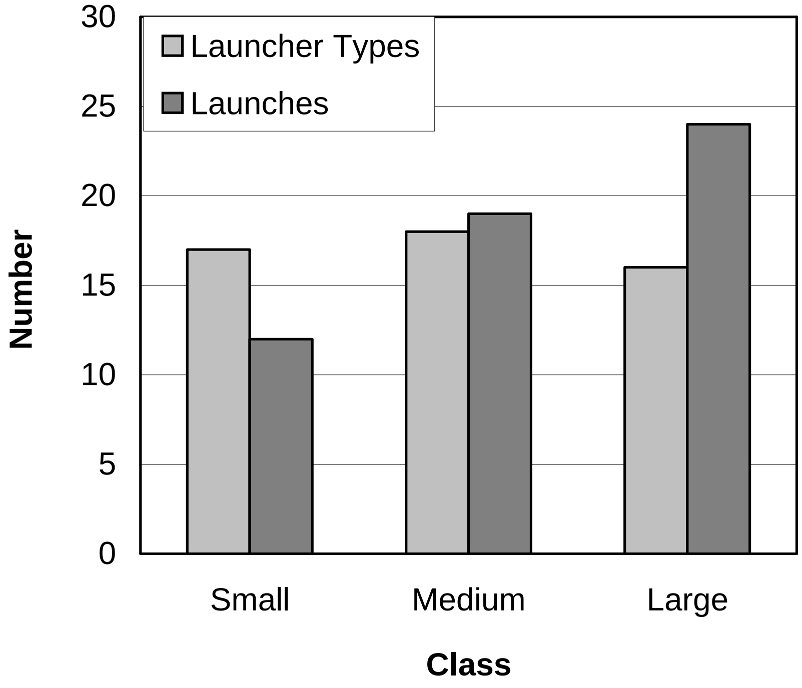

Figure 6-9: Supply and Demand of Launchers (2005)[405]

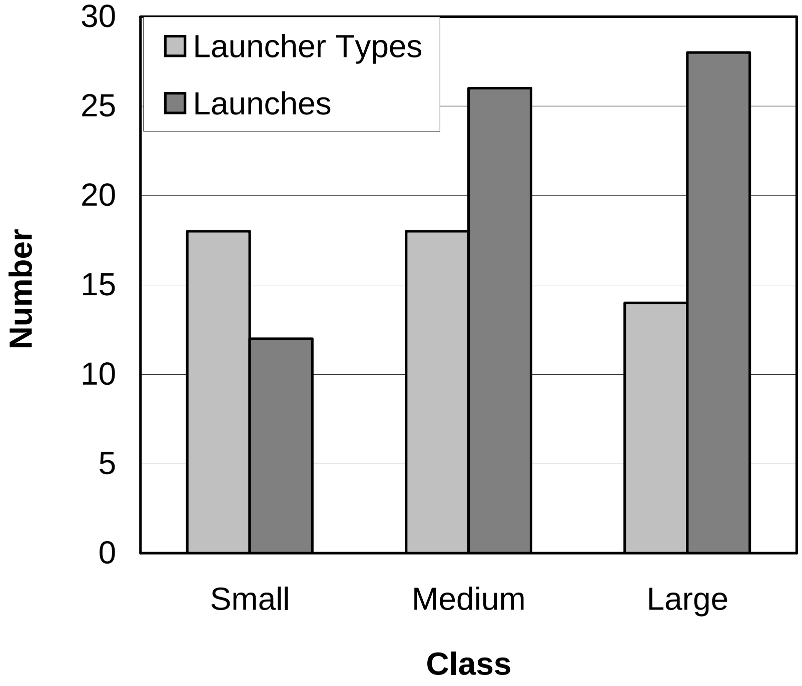

Figure 6-10: Supply and Demand of Launchers (2006)[405]

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[405] ESA LVC 2004.

A future increase of small vehicle launch rates is unlikely because of the higher specific launch costs compared to large vehicles.

The number of available launch vehicles changes over the years, as seen in the previous figures, because new vehicles are introduced and old vehicles are decommissioned.

E) Results

The average number of orbital launches over the last years remains constant with about 60 per year. This leads to the assumption that these rates will also remain constant for the near future.

The exact numbers may change with the definitions of launcher class, availability, and launcher type, but it is clear that there is a significant oversupply of launchers compared to payloads, especially of small launchers of less than 2 t into LEO.

Development costs of launch vehicles are high, exceeding launch prices by one or two orders of magnitude (see chapter 4.1.1.2.3). Even assuming significant market shares, a newly developed launch vehicle will not be profitable for a very long time.

A simple computation may illustrate this, with launch class market share $s_{lau,class}$, annual launch rate of the vehicle class $n_{lau,ave,class}$, charged price per launch P_{lau}, and true launch cost for the company C_{lau}. This creates annual profit P_{ann}.

$$P_{ann} = s_{lau,class} \cdot n_{lau,ave,class} \cdot \left(P_{lau} - C_{lau} \right) \qquad (\ 6.3\ )$$

If rates are neglected, real profit is achieved at the year t, when the sum of the annual profits exceeds the vehicle development costs C_{dev} (assuming constant launch rates and market shares), leading to

$$t \geq \frac{C_{dev}}{P_{ann}} \ . \qquad (\ 6.4\ )$$

Annual launch rates for a specific vehicle must be expected as constantly low. Small launchers will have more difficulties to achieve economic operations than large launchers due to the smaller number of annual launches. The option of launching multiple small payloads on one large rocket further decreases the need for new small launchers. Without massive public financial support during development, new launch vehicles are not a promising way to commercial success, and new small launch vehicles even less.

Table 6-1: Evaluation of "Launch Vehicles and Satellite Transportation"

Topic		Launch Vehicles and Satellite Transportation
Objective		Same as topic
Technical Feasibility		Feasible (currently done)
Effort	Costs	Development: Several 1 000 000 000 $ Launch: Several 10 000 000 $
Benefit	Revenues	Slightly higher than launch costs
Motivation	Profits	Only if development is excluded
Result	Commercial Attractiveness	**Low** (Medium to High)
Comment		Depends on public funding of development. Existing mature market

6.1.2 Launch Sites

Launch operation costs of existing conventional launch systems are about one third of the total launch costs. Thus, commercial operation of launch sites is a topic.

Table 6-2 presents various current orbital launch sites with their latitude. The lower the latitude, the higher the velocity gain due to Earth rotation, resulting in higher available payload mass.

Table 6-2: Various Worldwide Orbital Launch Sites[406]

Name	Nation	Latitude [°]
Baikonur	RUS/KAS	46.0
Barents Sea (Mobile)	RUS/INT	69.2
Cape Canaveral	USA	28.5
Edwards (Mobile)	USA	34.5
Jiuquan	PRC	41.2
Kagoshima	JPN	31.1
Kourou	EUR	5.1
Plesetsk	RUS	62.5
Odyssey (Mobile)	USA/INT	0
Sriharikota	IND	13.4
Taiyuan	PRC	37.3
Vandenberg	USA	34.5
Xichang	PRC	28.1

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[406] Wade 2007.

Mobile launch sites of Table 6-2 are Delta III class submarines for Volna, L-1011 Stargazer aircraft for Pegasus, and Odyssey platform for Zenit-3SL.

Construction costs for launch sites are high, exemplary 344 M $ for one Soyuz launch pad in Kourou without any operational additions.[407] Launch operations are usually performed by the launch contractor himself, for example Arianespace or United Launch Alliance. Enhanced commercial business is therefore not expected.

Table 6-3: Evaluation of "Launch Sites"

Topic		Launch Sites
Objective		Offering orbital launch sites
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $
Benefit	Revenues	Several 10 000 000 $ per launch
Motivation	Profits	Eventually
Result	Commercial Attractiveness	**Low**
Comment		Saturated market, politics, …

6.1.3 Earth Satellite Applications

Earth satellites currently offer the most important commercial applications of spaceflight. Depending on their primary mission, commercial satellites are divided into three categories:

- **Communication**
  Data relay satellites
- **Earth Observation**
  Images at visible and invisible part of the spectrum
- **Navigation**
  Global positioning via satellite signals

The categories can be combined for specific applications. **Figure 6-11** shows the satellites on orbit as of July 2007 in regard to their primary mission. Only satellites that are partially or completely used for commercial purposes[408] are presented. "Other" mission types include, for example, the inflatable habitat demonstrators of Bigelow Aerospace.

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[407] AW&ST Mar 5 2007.

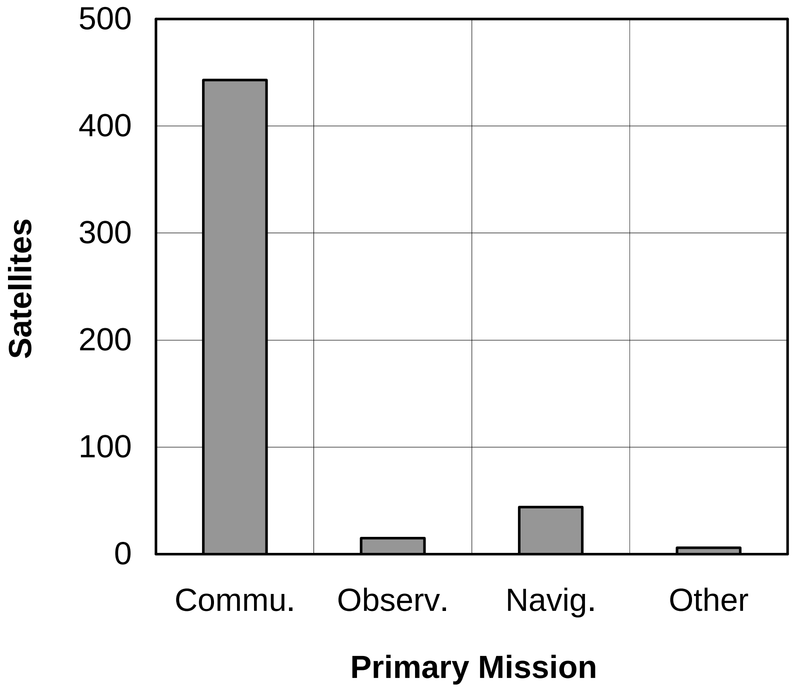

Figure 6-11: Primary Missions of Commercial Earth Satellites[408]

6.1.3.1 General Characteristics

A view on commercial aspects and available satellite orbits is helpful for further considerations, before the three satellite categories are analyzed in detail.

A) Commercial Aspects

A satellite system consists of two segments:

- Space segment
- Ground segment

The satellite in space is always supported by a ground segment. There are no completely autonomous satellites.

The ground segment consists of a number of ground stations, transmitters, and receivers. Primarily, they are used for satellite control. But the ground segment also includes the users or customers of the satellite mission, as seen in **Figure 6-12**.

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[408] UCS 2007.

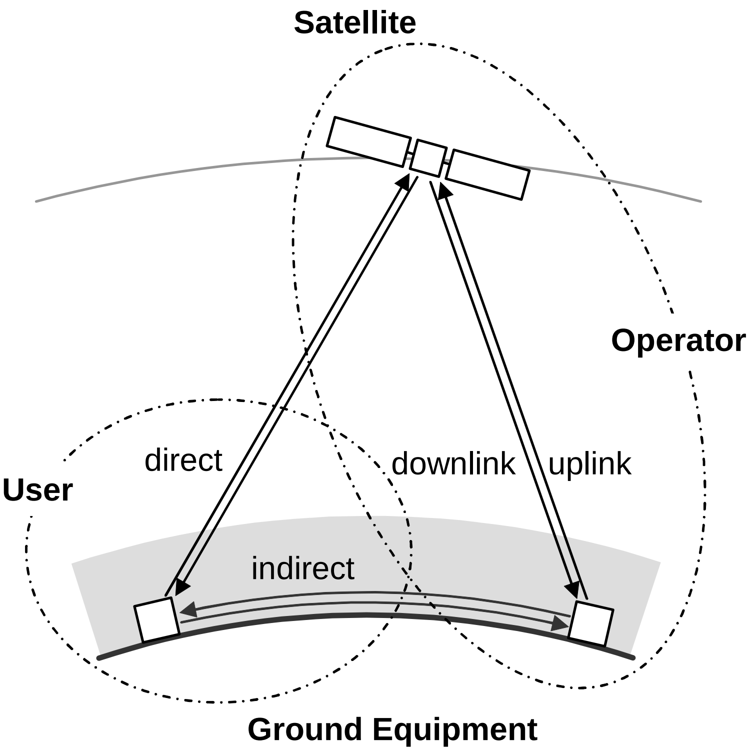

Figure 6-12: Commercial Elements of Satellite Systems

Satellites are used to receive or create data that is then sent to Earth. Either the data is received at one or several ground stations and then relayed to the end user, or the user is in direct contact with the satellite, as seen in **Figure 6-13**.

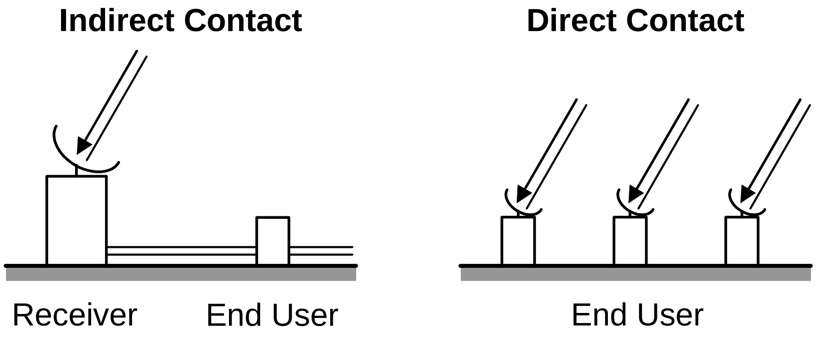

Figure 6-13: Types of Satellite Utilization

The commercial field of satellite systems can be divided into:

- Ground Equipment

- Launch Industry
- Satellite Manufacturing
- Satellite Services

Ground Equipment includes ground control stations, but also any devices that are required by the end user to use the satellite system service, for example satellite phones or dishes for TV reception.

The launch industry is required to place the satellite into orbit. This topic was covered in chapter 6.1.1.

Satellite Manufacturing is the production of the satellite itself, including subsystems.

Satellite Services means services that are created by the satellite systems, and can be commercially offered to create revenues, for example Digital Broadcasting Services (DBS) or Digital Audio Radio Services (DARS).

The total revenues of each segment were already presented in Figure 6-2. The service itself is becoming ever more important with almost two thirds of revenues, as is seen in **Figure 6-14**. Ground equipment is almost one third of revenues, with satellite manufacturing and launch services at almost negligible percentage.

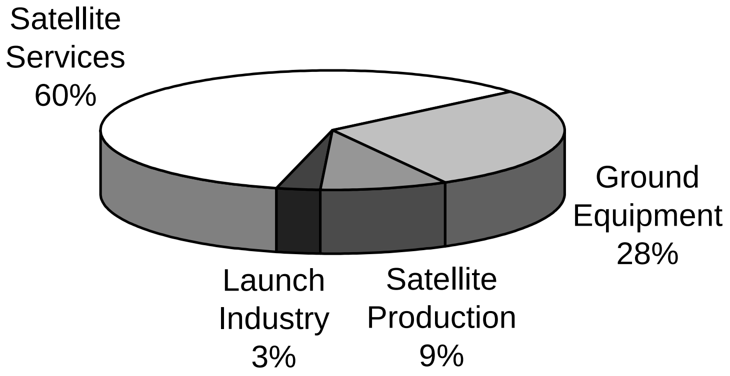

Figure 6-14: Percentages of the Satellite Industry Revenues (2005)[409]

The figure also states that the financial volume of satellite manufacturing (hardware) is about three times that of the launch service division (transportation). This is in accordance with the results of chapter 4: The basic hardware cost of ComSats is roughly 50 000 $/kg, with specific transportation costs to GTO of about 18 000 $/kg.

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[409] SIA 2006.

For commercial activities, the annual profits created by the satellite services must be considerably higher than the annual costs, as illustrated in **Figure 6-15**. The end user devices (that were included in “Ground Equipment”) usually are not part of a satellite operator’s business.

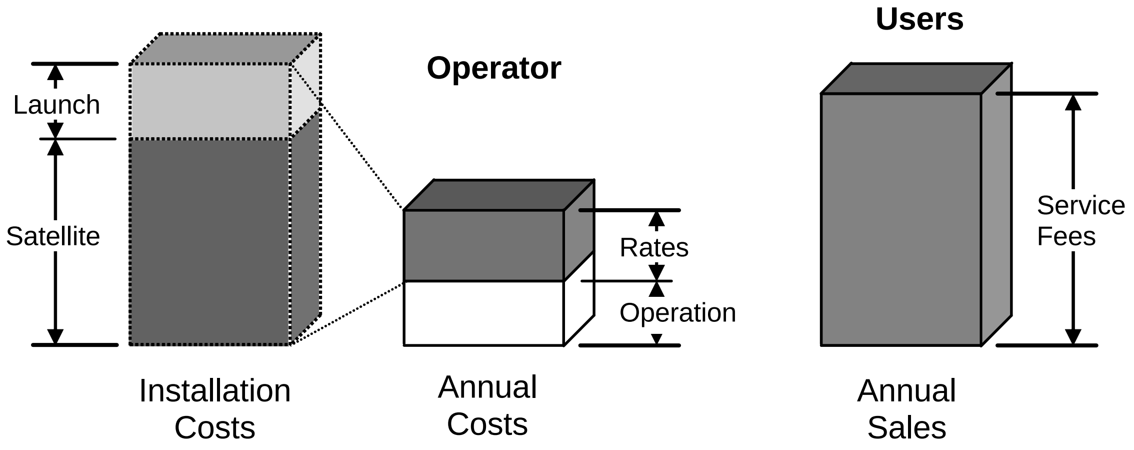

Figure 6-15: Commercially Financed Satellite Operations

B) Satellite Orbits

There are four different types of Earth orbits that are of various importance:

- **GEO**
  Altitude ca. 36 000 km, 24 h orbit time, thus stationary relative to Earth’s surface, continuous maneuvers for station keeping required. Typical location of communication and weather satellites.
- **MEO**
  Altitude between LEO and GEO. Typical location of navigation satellites.
- **LEO**
  Typical altitude between 200 and 2 000 km, orbit time about 90 minutes. Typical location of observation satellites.
- **Elliptic**
  Highly elliptical orbits, satellites spend majority of time over designated area. Location suited for various satellite mission types.

6.1.3.2 Communication

Satellites can be used as data relays. This includes relaying phone calls or internet traffic, but also broadcasting radio and television signals. Satellites used for these applications are referred to as communication satellites. The first serious proposal of this space application was made by Arthur C. Clarke in 1945.[410]

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[410] Feuerbacher et al. 2006.

A) Characteristics

Due to its characteristics, communication via satellite has various assets and drawbacks.

Assets:

- Distance between communicating partners is secondary
- Stationary mounted antenna for GEO satellites
- Quick and simple access for participants
- No large infrastructural preparations required (no laying of cables)
- Comparatively simple installation
- Low atmospheric interference (for certain ranges of the spectrum)
- Simple linking of distant areas

Drawbacks:

- Signal envelope delays
- Tracing of antenna required for LEO and MEO satellites
- Significant reduction of signal strength
- Limited data rates
- High initial installation costs
- Free line of sight to satellite required (for most ranges of the spectrum)

Because of their different distance to Earth, signal delays are low for LEO satellites and high for GEO satellites. Speed of light c limits the minimum signal delay t_{min} to the signal's travel time to the satellite and back, if signal processing delays are not regarded. Satellite distance is s_{sat}.

$$t_{min} = 2\frac{s_{sat}}{c} \qquad (6.5)$$

Optical or laser communication links are significantly affected by atmospheric and weather effects. Optical inter-satellite links are possible, but for further considerations, only microwave communication is regarded.

The limitation of satellite data transfer rates has two main reasons: Limitation of available bandwidth and available transmitter power. For communication links with noise N, as is the case in all microwave satellite communications, the maximum error-free channel capacity C is given by the Shannon-Hartley theorem.[411] As mentioned, it also depends on signal strength at the receiver S and available bandwidth B.

$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right) \qquad (6.6)$$

---

[411] Griffin et al. 2004, Schmucker et al. 2006.

External noise is usually negligible at frequencies above 200 MHz, and internal noise is approximately $1.6 \cdot 10^{-21}\,B$.[412] Satellite communication frequencies are in the area of several GHz.[413]

Signal strength at receiver S is identical to received signal power, and depends on transmitter power P_{tx}, frequency f, speed of light c, distance s between receiver and transmitter, area of the antennas A, efficiency factors η of the antennas, and atmospheric losses η_{atm}.[414] This is illustrated in **Figure 6-16**.

$$S = P_{tx} \cdot \left(\frac{f}{c\ s} \right)^2 \cdot A_{tx} \cdot \eta_{tx} \cdot A_{rx} \cdot \eta_{rx} \cdot \eta_{atm} \qquad (6.7)$$

The allocation of the radio spectrum frequencies is managed by the International Telecommunication Union.

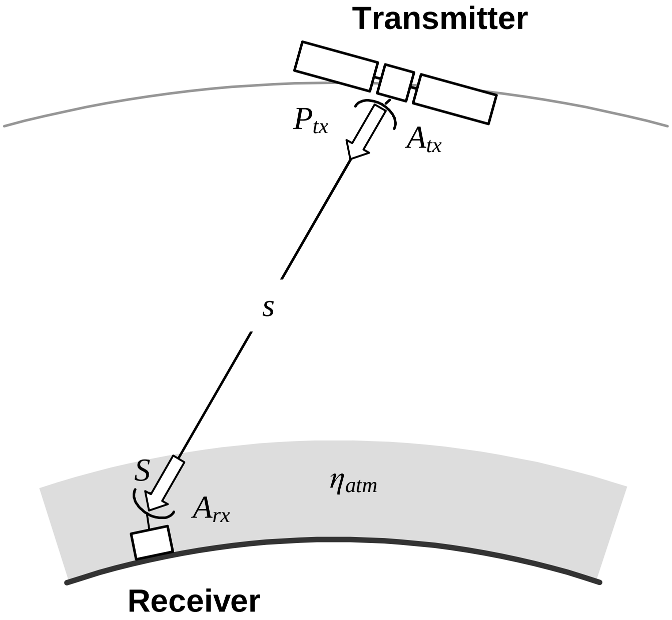

Figure 6-16: Satellite Data Transmission

Bandwidth limitation is a physical problem, but power limitation is primarily an engineering problem. Thus, the available power on new geostationary communication satellite platforms increased over the years, as seen in **Figure 6-17**.

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[412] Ruppe 1967.
[413] Griffin et al. 2004.
[414] Schmucker et al. 2006.

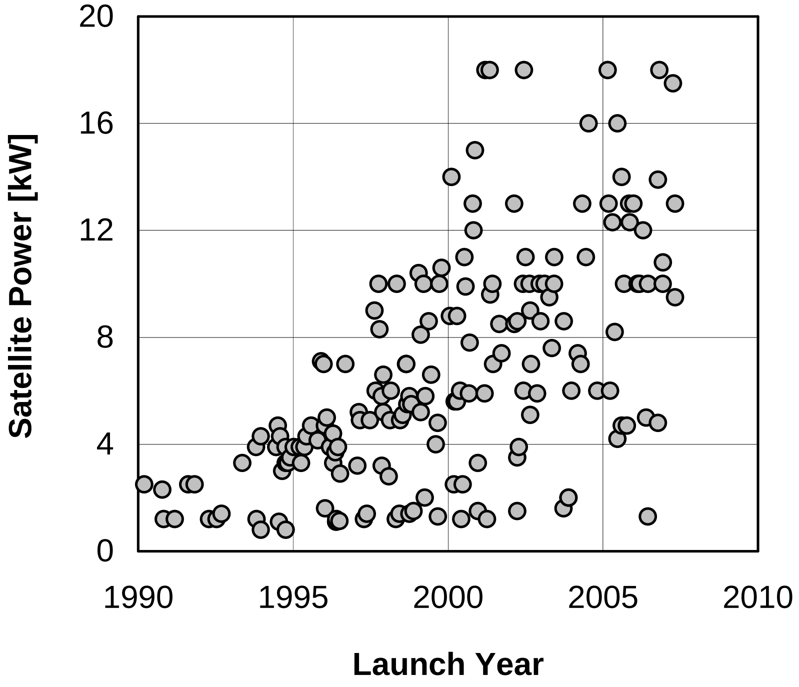

Figure 6-17: Development of GEO Communication Satellite Power[415]

Available power is then distributed to several transmitters or transponders on the satellite. Though the total available power increased over the years, and various methods for data rate increase were applied (data compression, noise reduction, …), the total data transfer rate of satellites remains limited.

Lifetime of communication satellites is limited to about 15 – 20 years due to solar cell degradation and limited propellants for altitude and attitude control. Number of available slots for GEO satellites is also limited, not only for collision avoidance, but also because of interference effects with transponders of adjacent satellites.

Satellite services are generally divided into Mobile Satellite Services (MSS), Fixed Satellite Services (FSS) and Digital Broadcasting Services (DBS). FSS and MSS are characterized by the nature of the user devices: MSS serves mobile phones and moving objects such as aircraft, while FSS is primarily intended for data relay from and to fixed positions.

B) Current Situation

For decades now, communication satellites are the backbone of commercial satellite applications. In **Figure 6-18**, it is visible that more than half of the total operating satellite fleet is used for commercial communication purposes.[416]

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[415] UCS 2007.

[416] These numbers include satellites that are not exclusively used for commercial applications, as well as satellites that are not solely used for communication purposes.

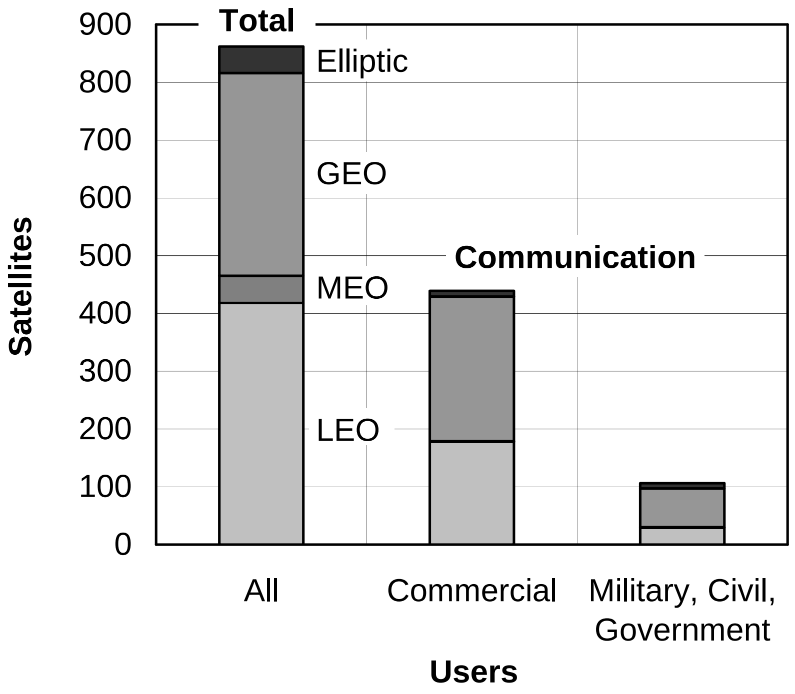

Figure 6-18: Number of Operational Satellites: Communication[417]

Revenues of communication satellite operators are in the order of a few billion $ per year. **Table 6-4** presents revenue numbers of leading FSS operators.

Table 6-4: Top Fixed Satellite Service Operators[418]

Satellite Service Operator	Location	Revenue [M $]		Satellites
		2006	2005	
Intelsat	Bermuda	2 100	2 030	51
SES	Luxembourg	1 900	1 720	36
Eutelsat	France	1 050	885	23
Telesat	Canada	411	407.3	7
JSAT Corp.	Japan	326	373	8
Star One SA	Brazil	195.8	164.5	5
SingTel Optus	Australia	191.8	165.7	4
Loral Skynet	United States	164	152	5

With a total 1.2 billion $ in 2006, the globally generated revenues of MSS business are considerably less than FSS.[419] The majority of revenues – about 80 % – is gen-

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[417] UCS 2007.
[418] Space News 25-2007.
[419] Space News 12-2007.

erated in DBS.[420]

C) Terrestrial Alternatives

Cable links are the primary competitor for FSS. Optical fibers significantly increased the capacities of terrestrial cable networks, as seen in **Table 6-5**.

Table 6-5: Various Data Transfer Rates and Capacities (2005)[421]

Connection	Bandwidth [Gbit/s]
Cable Capacity London – New York	320
Maximum Workload	153
Total Transatlantic Cable Capacity	3 000
Maximum Workload	750
Average Communication Satellite	1 – 10

The majority of MSS is rivaled by terrestrial wireless communications. Satellite phone services such as Globalstar and Iridium now have low market shares compared to terrestrial services (GSM and UMTS) that are offered by cellular phones.

D) Consequences

There are attractive earthbound alternatives that threaten the satellite communication business, but for various applications, such as broadcasting of television signals or data links to remote areas, the position of satellite services remains strong.

Significant increases in market share cannot be expected, as well as significant losses. The volume of the commercial satellite communications business probably remains at a slow increase for the foreseeable future.

Table 6-6: Evaluation of "Communication Satellites"

Topic		Communication Satellites
Objective		Same as topic
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $ per satellite
Benefit	Revenues	Several 100 000 000 $ per satellite
Motivation	Profits	Yes
Result	Commercial Attractiveness	**Medium to High**
Comment		Existing market

---

[420] Whalen 2005.
[421] Schmucker et al. 2006.

6.1.3.3 Earth Observation

Their distance to Earth and their field of view makes satellites attractive as platforms for observations in various wavelengths. Only monitoring for commercial purposes is considered in this chapter.

A) Characteristics

Earth observation by satellite has various characteristics:

- Global overview
- Continuous, non-discrete data
- Coverage of remote areas
- Limited resolution
- Atmospheric influences (depending on wavelength)
- Large amounts of data
- Continuous or periodic area observation (depending on orbit)

Of potential interest for observation are:

- Geologic relief and deeper layers
- Biosphere
- Hydrosphere
- Cryosphere
- Atmosphere
- Man made objects

The potential wavelength for observation is limited by Earth's atmosphere. Transparency is given roughly between 300 nm to 2 µm and 2 cm to 10 m.[422] Early satellites concentrated their observations on the visible spectrum of light.

Depending on the orbital altitude of the satellite, the size of the observed section increases, and data resolution decreases. Current maximum resolution of commercial satellites is about 50 cm. For military and governmental applications, resolution is probably better roughly by an order of magnitude.

The high amount of data that is created by modern satellites, combined with comparatively low data transfer rates, makes real time analysis of footage almost impossible. Only low resolution global views and selected small areas can be monitored close to real time.

The object of interest is surveyed either passively or actively. Passive surveys register reflected radiation or rays that are emitted by the object, whereas active survey uses artificial illumination by the satellite, as illustrated in **Figure 6-19**.

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[422] Brockhaus 1979.

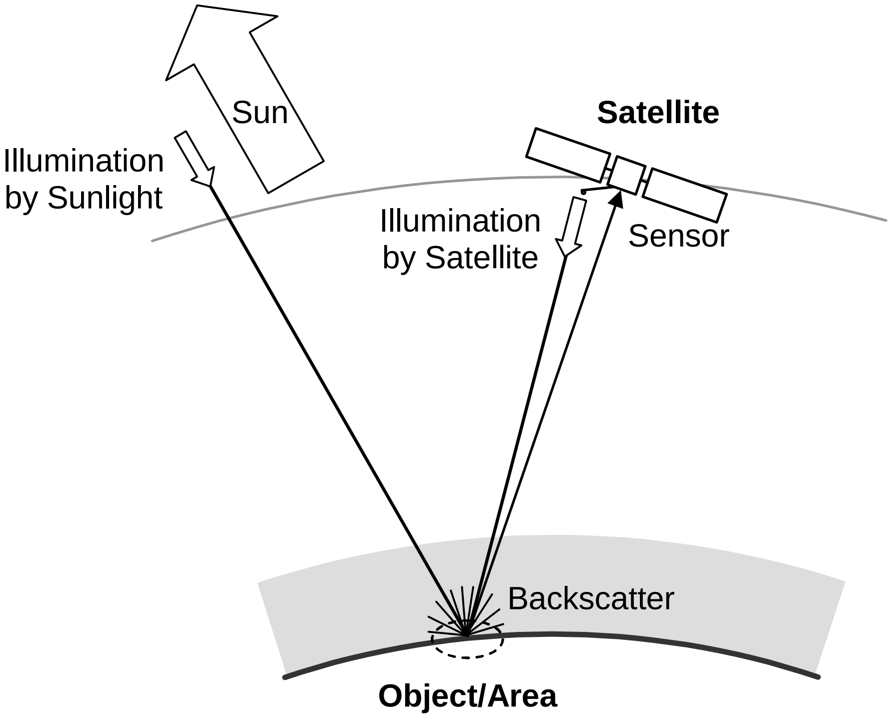

Figure 6-19: Passive and Active Observation Systems

Another important characteristic is linked to the orbital altitude. GEO satellites always have the same area in observation, but the distance of 36 000 km significantly reduces maximum resolution.

LEO satellites continuously cover different small sections of Earth due to a small field of view at altitudes as low as 200 km, and due to velocities of almost 8 km/s relative to Earth's surface. Orbit inclination limits the observable part of Earth to the according latitude. The higher the inclination of the satellite orbit, the more percentage of Earth's surface can be monitored. Only polar orbits enable monitoring of the whole planet.

B) Current Situation

While the number of operational observation satellites for military, civil and governmental purposes is still considerable, the number of observation satellites for commercial activities is very low, as seen in **Figure 6-20**. This is a strong indication for a difficult market situation.

All commercial observation satellites are located in LEO. The majority of other Earth observation satellites is positioned in LEO, too, with a few in GEO and a negligible amount in elliptic orbits.

The total worldwide market of satellite observation data was expected to increase to

2 G $ in 2008, but these expectations probably will not be met.[423]

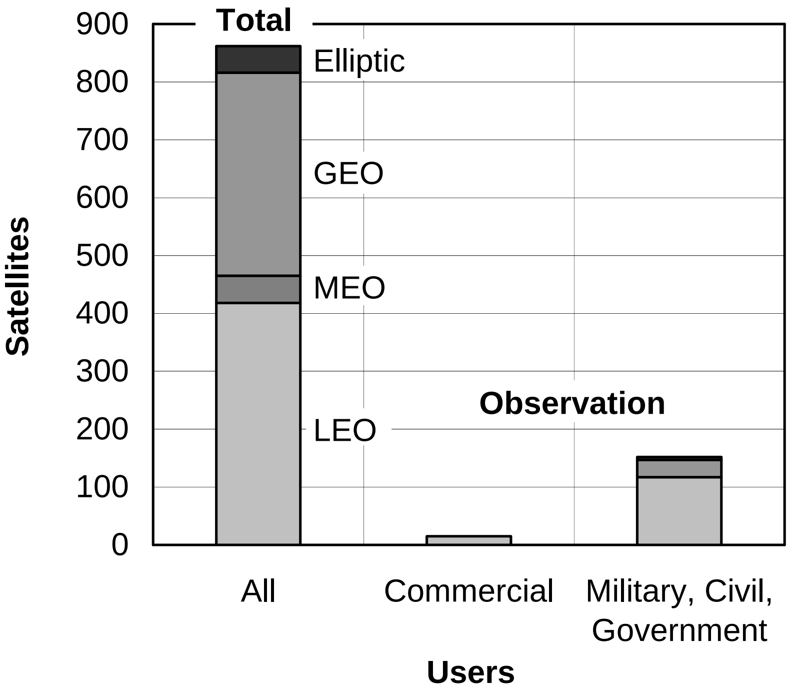

Figure 6-20: Number of Operational Satellites: Earth Observation[424]

The total annual revenue of the Earth observation market $R_{obs,ann}$ is a result of the potential amount of annually sold images or data blocks of an area n_{img}, charged price P_{img}, Earth surface area A_E, image size A_{img}, and correctional factors for the utilizable part of Earth's surface k_{sur} (0.3)[425] and areas of commercial interest k_{com} (< 1).

$$R_{obs,ann} = n_{img}\ P_{img}\ k_{sur}\ k_{com}\ \frac{A_E}{A_{img}} \qquad (6.8)$$

Image sizes range from 25 km² to 10 000 km².[426] Prices vary, ranging from 5 mile²/$ to 200 mile²/$, with other offers at 105 $ per image,[426] depending on resolution, wavelength, and date. This results in a range of 10 to 390 $ for a 5 000 km² image.

Even assuming that k_{com} is 1, and 10 images of the same area are sold annually at an average price of 200 $ for 5 000 km², the resulting total annual revenue is slightly more than 60 M $. This is far from the projected market in the range of a few billion $.[427] The market is therefore not self-supporting and is probably funded by

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[423] VDI 03/08/2007.

[424] UCS 2007.

[425] Satellite imagery of oceans, polar areas and deserts, for example, is a niche product for a very small number of customers, primarily for research applications. Ocean surfaces alone cover 70 % of Earth's surface. Therefore, the value of 0.3 is optimistic.

[426] Digital Globe 2007.

[427] VDI 03/08/2007.

public contracts.

C) Terrestrial Alternatives

Large area observations can only be done with a dense network of numerous gauging stations, but these offer local values only. Installation, maintenance and operation is expensive and complex, especially in remote areas and on oceans.

Selected areas can be observed by aircraft or balloons. Though optical resolution might be better, this has the drawbacks of violation of foreign airspace and potential interception in sensitive cases.

For global data acquisition, there are no sufficient terrestrial alternatives to space.

D) Consequences

Though the market for geodetic data was assumed as large, it is insignificant at a closer look, and other methods of observation further reduce the commercial need of geodetic satellite data.[428]

But Geographic Information Systems (GIS) that cover the whole globe, such as Google Earth and NASA World Wind, require large amounts of imagery. The growing public awareness level of these products, combined with innovative and easily accessible data sets, could perhaps lead to a growing, stable Earth observation satellite data market.

Table 6-7: Evaluation of "Observation Satellites"

Topic		Observation Satellites
Objective		Same as topic
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $ per satellite
Benefit	Revenues	Several 100 000 000 $ per satellite
Motivation	Profits	Eventually
Result	Commercial Attractiveness	**Medium**
Comment		Success depends on public customers. Existing market

---

[428] To calculate the optimum routes for mail delivery of the Deutsche Post mail service, available geodetic satellite data was not sufficient. Thus, the mailmen were equipped with GPS devices to acquire exact data of mailbox locations – satellite navigation solved a problem that Earth observation was not capable to solve. (VDI 03/08/2007)

6.1.3.4 Navigation

The sky was used for navigation since ancient times. But though the U.S. Navy tested rudimentary satellite navigation (that was based on the Doppler effect) as early as 1964,[429] the true capabilities of serious applications were not recognized. Satellite navigation, as it is used today, was never anticipated.

A) Characteristics

Modern satellite navigation works as illustrated in **Figure 6-21**:

- Permanent satellite tracking by ground stations
- Computation of orbit parameters
- Successive transmission of parameters to satellite
- Continuous calibration of orbit and time parameters and correction factors
- Satellite sends orbit parameter, time and correction factor
- Computation of satellite distance by the receiver via sent parameters
- Distance to and position of satellites define position of receiver[430]

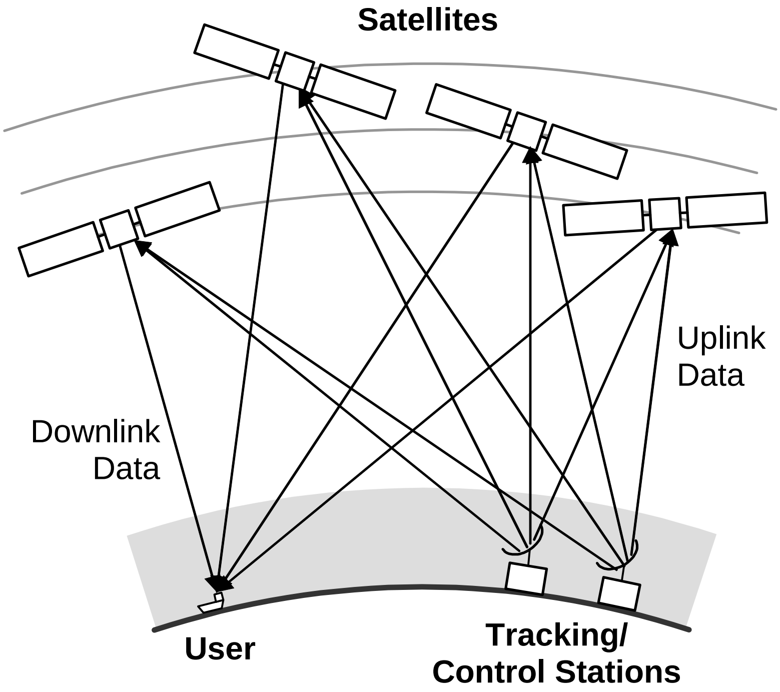

Figure 6-21: Satellite Navigation

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[429] Braun 1968.

[430] Accuracy is only as good as the data quality of the actual satellite position.

A high number of satellites in view, extremely precise satellite clocks, and a high quality of orbit parameter measurements increase the accuracy of navigation.

As seen in **Figure 6-22**, satellite navigation systems are another good example for the worldwide imitation of the U.S. space program.

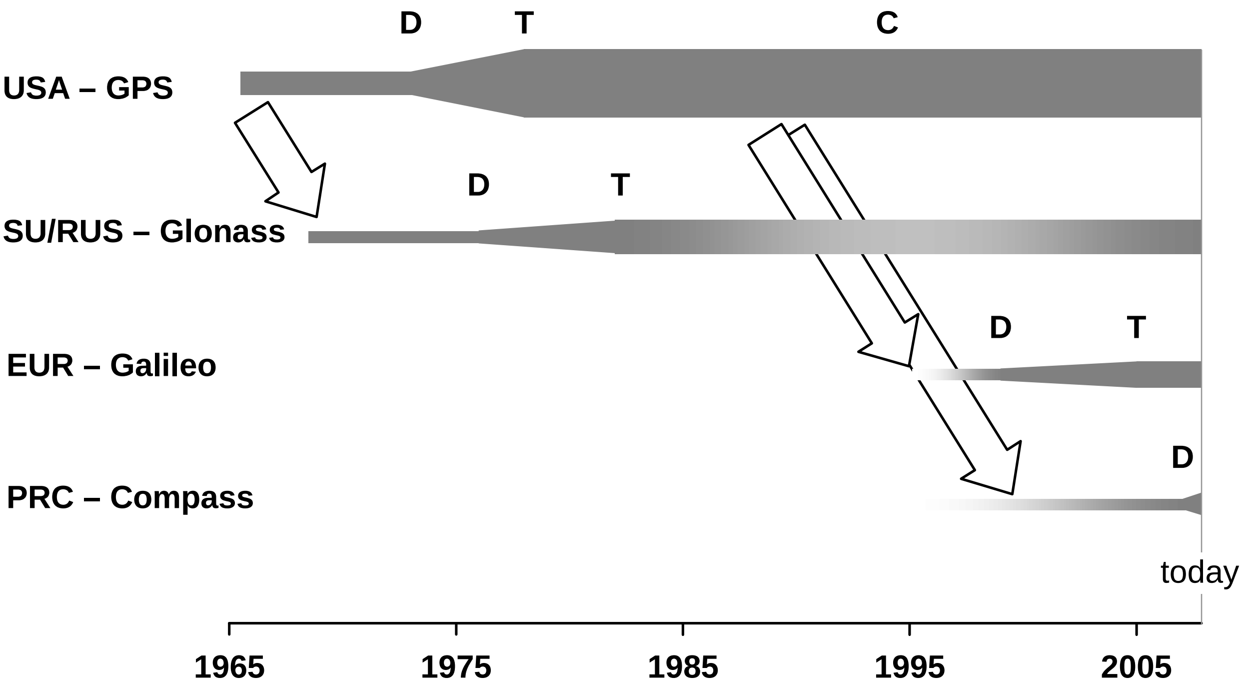

Figure 6-22: Development of Satellite Navigation Systems
(D: Development Start, T: Test Satellite, C: Completion)

Currently, there are two operational active satellite navigation systems, with two more announced for the near future, as seen in **Table 6-8**.

Nominal specifications of the system accuracy must be regarded with caution. Considering that present nominal accuracies are not met, the accuracy of future systems must be expected as lower than specified.[431]

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[431] Car navigation systems often assume a wrong street as starting position. The system swaps to the right street after some seconds of driving. Thus the assumption of low actual accuracy.

Table 6-8: Satellite Navigation Systems

	GPS	**Glonass**	**Galileo***	**Compass***
Nation	USA	RUS	EUR	PRC
Start of Installation		1982[432]	2009*[433]	2007[434]
Start of Operation	1995[435]	1996[435]	2012*[435]	2008*[435]
Satellite Generation	2R (3)[436]	M (K)[437]		
Orbital Planes	6[436]	3[437]	3*[433]	
Satellites – nominal	24+5[437]	24+0*[437]	27+3*[433]	30+5*[434]
Satellites – actual**	29+1	12+7	0+1	0+4
Satellite Mass [t]	2[436]	1.4[436]	0.7*[433]	2.2[436]
Standard Accuracy [m]	16/6*/2*[435]	57[435]	4*[435]	10*[435]
Max. Accuracy [m]	10[438]		1*[438]	
Installation Costs [M $]	ca. 6 000[436]		4 680*[439]	
Operation Costs [M $/a]	750[436]		264*[440]	
Investor	DoD	Government	EU	Government

* Planned.
** April 2007.

The significantly higher accuracy of the planned navigation systems compared to the two existing systems is illustrated in **Figure 6-23**.

B) Current Situation

Figure 6-24 presents the number of navigation satellites compared to the whole operational Earth satellite fleet.

Though the number of satellites is small compared to the communication sector, the created revenues are considerably higher. The European Union states the annual growth of the worldwide market for related products and services as 25 %, with 3 billion satellite receivers in service in 2020, and an expected market volume of 400 G € in 2025.[441]

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[432] Space Daily 21/05/2007.
[433] ESA 2007.
[434] Aerospace America 5/2007.
[435] Spiegel Nr. 10 2007.
[436] Wade 2007.
[437] Space Daily 30/04/2007.
[438] Space Daily 18/09/2007.
[439] In €: 3 900 million. (Aerospace America 5/2007)
[440] In €: 220 million. (Aerospace America 5/2007)
[441] EU 2006.

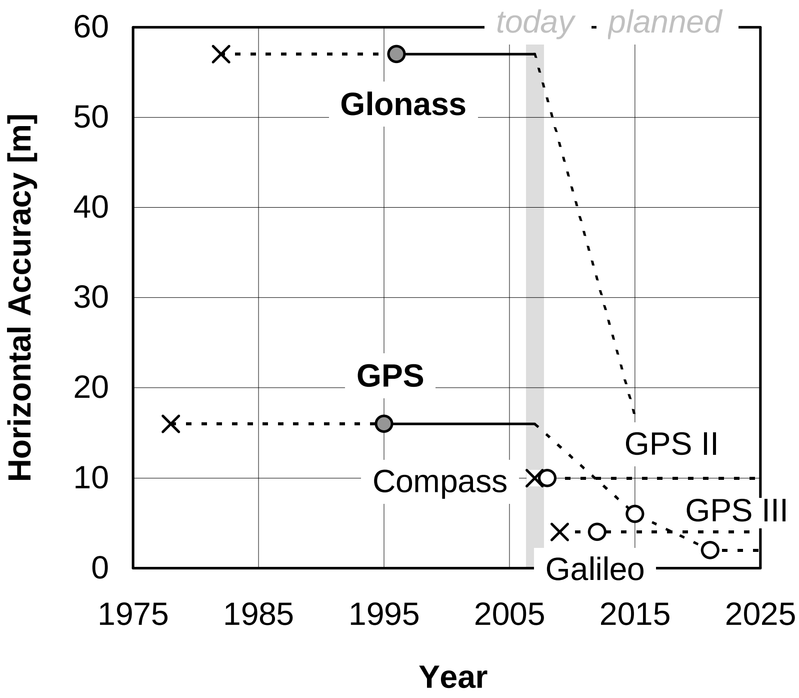

Figure 6-23: Current and Planned Accuracy of Satellite Navigation Systems[442]
(Cross: Beginning of Installation, Grey: Actual, White: Planned)

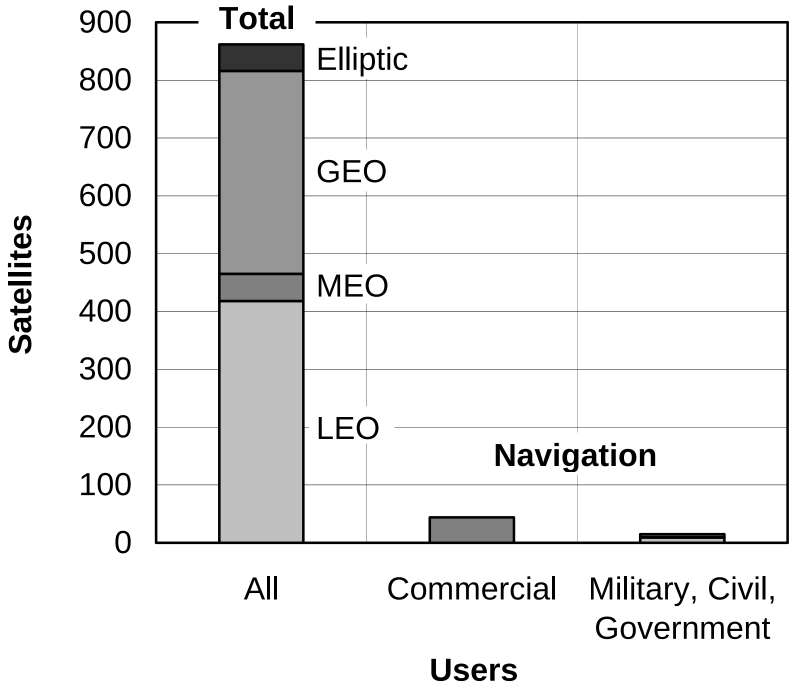

Figure 6-24: Number of Operational Satellites: Navigation[443]

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[442] Spiegel Nr. 10 2007.
[443] UCS 2007.

The U.S. Global Positioning System (GPS) and the Russian Глобальная Навигационная Спутниковая Система, or Global Navigation Satellite System (ГЛОНАСС or GLONASS), both offer their basic service for free.

C) Terrestrial Alternatives

There are no comparable terrestrial alternatives for global navigation. Terrestrial stations can be used to increase accuracy, as is the case for the Differential Global Positioning System (DGPS). Terrestrial wireless communication systems could be used for navigation, too, but this is not an option for remote areas.

D) Consequences

GPS and GLONASS basic signals are free of charge, as are the planned open service signals of Galileo. Thus, offering a product on an existing market where the same product is already available for free is not a way to commercial success.

Galileo development and deployment was subject to serious delays during the times of public private partnership, and resulted in the retreat of the industrial side from the project in 2007. Galileo installation is now funded by the European Union alone, which gives a clear indication of expected profits (and motivation) from the industry side.[444]

Though Galileo is still seen as a European program of strategic importance, a cost relation hints that the motivation is not really given: The projected Galileo installation cost of 3.9 G € that will offer benefits for all of Europe is only slightly more than twice the projected cost of the planned maglev train connection between Munich's central station and airport. But still, funding of Galileo is debated.[445]

The market for related ground segment products (receivers), though, seems healthy, with 13 million mobile navigation systems sold in Europe alone in 2006 that created revenues of 4.7 billion €, and an estimated increase to 20 million sells in 2007.[446] But as long as the corresponding signals are for free, no profits of the space segment can be expected.

Galileo may still make profits in the way that European governments are committed to contracts for the use of costly national services, such as police or military applications. While this would amortize the system costs, the taxpayer would have to pay twice: Once for system installation and once for system utilization.

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[444] The strategic argument that only Galileo guarantees signal delivery because GPS signals might be degraded in times of crisis is invalid. On September 18, 2007, the White House announced that the capability of signal degradation (Selective Availability) will not be present in the GPS III satellite generation. (White House 18/09/2007)

[445] Civil navigation is a topic concerning traffic. If the ministries of transportation of the EU member states were prompted to spend only a half percent of their annual budget on Galileo, the system was financed within a few years.

[446] FAZ 16/03/2007.

Table 6-9: Evaluation of "Navigation Satellites"

Topic		Navigation Satellites
Objective		Same as topic
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 1 000 000 000 $ per system
Benefit	Revenues	None*
Motivation	Profits	Negative*
Result	Commercial Attractiveness	**Low**
Comment		Only ground segment can be profitable

* For satellite operator.

6.1.3.5 Combinations

New ways of utilization with new types of benefits emerge by combining the three major types of satellite applications. A few examples are:

- Agriculture: Selective fertilizing and optimized harvesting with navigation and observation
- Transportation: Significant reduction of traffic jams with communication and navigation[447]
- Disaster management: Survey of damages and coordination of rescuers with observation, communication and navigation
- …

The combination of services may result in potential applications that are not yet discovered.

6.1.3.6 Comparing the Fields of Satellite Applications

The close view on communication, observation and navigation leads to conclusions about the current situation and future potentials of satellite applications.

Table 6-10 lists a summary of satellite applications. Positive aspects are marked as bold. By coincidence, each field of applications has the same number of four positive aspects.

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[447] According to an ADAC report from 03.03.2000, traffic jams in Germany annually waste 12 G liters of gasoline, and create an economic damage of more than 100 G $. Many thanks to Dr. Olaf Przybilski of TU Dresden and Dr. Christian Gritzner of DLR for these numbers.

Table 6-10: Potentials of Satellite Applications

Aspect	Communication	Earth Observation	Navigation
Commercial Applications	**yes**	few	ground segment
Ways of Application	depleted	limited	**great potential**
Large Scale	**yes**	no	**yes**
Terrestrial Alternatives	strong	**very limited**	**limited**
Future Growth	no	**yes**	**yes**
Self Financed	**yes**	rather no	no
Governmental Support	**little**	significant	significant
National Duty	no	**yes**	rather yes
Scientific Significance	low	**high**	medium

Though significant growths in the space segment of satellite application markets are not expected, commercial satellites currently are a very important, major application of spaceflight.

6.1.4 Insurance

Two types of perils must be distinguished: Risk of property and risk of liability.

A) Property Risk

- Before launch: Thermal stress and mechanical damage at production, transport, integration, …
- At launch: Launch failure, off-nominal parameters (acceleration, noise, pressure, vibration, temperature), orbit injection failure, …
- Before operation: Mechanical failure (deployment of solar arrays, communication dish, …), electronic failure, …
- At operation: Internal (hardware, software, …) and external (micrometeoroids, space debris, …) failure sources.

B) Liability Risk

- Damage on Earth: Launcher and payload. Launch sites usually are governmental property and are not insured.
- Damage in space: Law of negligence. For space debris collisions, the origin of small debris particles is difficult to identify.

Currently, annual orbital satellite insurance rates are often less than 1.8 % of the insured value, and launch insurance premiums are down to less than 14 %, depending on various factors.[448]

Though governmental launches usually are not insured, space insurance currently is a profitable business.[448]

Table 6-11: Evaluation of “Insurance”

Topic		Insurance
Objective		Insurance of launches and satellites
Technical Feasibility		-
Effort	Costs	Several 100 000 000 $ per year
Benefit	Revenues	About 1 000 000 000 $ per year
Motivation	Profits	Yes
Result	Commercial Attractiveness	**Medium to high**
Comment		Existing market

6.2 Future Enhancement of Current Activities

Commercial business could be enhanced to other activities in the future, providing customers in space with services or hardware. Some of these activities are currently performed by governmental institutions, others are in demonstration or development phase and might be of commercial interest in the near future.

6.2.1 Services in Space

This includes all services beyond current satellite transportation.

6.2.1.1 Supplying Space Stations

Planned decommissioning of the US-STS fleet in 2010 leaves a gap in ISS supply capabilities. Combined with prospects of the first private orbital space station deployments, various companies launched initiatives to deliver supplies to these orbital outposts.

With exception of the US-STS, supply missions are unmanned to increase payload mass and reduce costs. Examples are Russian Progress, European ATV, and Japanese HTV, as seen in **Table 6-12**.

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[448] Space News 26-2007.

Table 6-12: Unmanned Governmental Supply Vehicles

Name	Agency	m_p [t]
Progress	Roskosmos	2.3
ATV	ESA	8.3
HTV	JAXA	6.0

Under the Commercial Orbital Transportation Services (COTS) program, NASA agreed in August 2006 to support development of the private transfer vehicles Dragon from SpaceX and K-1 from RocketplaneKistler (RpK) with almost 500 M $.

For the timeframe of 2010-15, NASA identified a shortage of supply delivery to the ISS of 48.8 t (79.6 t with packing factor).[449] Assuming a payload mass of 3 t for each flight, this would be 27 flights for 80 t of cargo within five years. If no other missions are offered, development costs and operational costs of privately funded new vehicles must be amortized with these 27 missions.

Regarding the current four annual flights of Progress, five flights per year seem realistic for the proposed vehicles. But considering previous experiences, the goals of COTS seem very optimistic: ATV and HTV development each cost roughly one billion dollar, took about ten years, and will launch at best once a year.[450]

Supply of ISS and other future stations maybe is a commercial option, but with very high technical and financial hurdles.

Table 6-13: Evaluation of "Supplying Space Stations"

Topic		Supplying Space Stations
Objective		Cargo transfer vehicle
Technical Feasibility		Feasible (currently done)
Effort	Costs	Development: Several 1 000 000 000 $ Launch: Several 10 000 000 $
Benefit	Revenues	Slightly higher than launch costs
Motivation	Profits	Only if development is excluded
Result	Commercial Attractiveness	**Low** (Medium)
Comment		Depends on public funding of development. Few flights expected

6.2.1.2 On Orbit Maintenance, Repair, Overhaul

Minor hardware defects might have a huge impact on space missions. Failure of a

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[449] Gerstenmaier 2007.
[450] Bell 2007a.

simple solar array deployment mechanism endangers the whole mission, and attitude control fuel depletion is a restricting factor of mission duration. In such cases, maintenance, repair and overhaul (MRO) services would be desirable.

Some minor maintenance tasks might be done unmanned, as was demonstrated by the USAF's Orbital Express mission in 2007, including refuel and simple mechanical tasks.[451] More complicated tasks require manned missions.

Potential services are:

- Integration
- Repair
- Refuel
- Maintenance
- Recovery and return

The high mission requirements, especially for manned missions, result in high costs. For profitable servicing missions, the mission itself must be less expensive than the payload that is to be serviced, else a new payload could be launched as well:

$$C_{tot,MRO} < C_p + C_{tr} \qquad (6.9)$$

The fact that a complete mission – including transportation, hardware and operation – must be financed to save the hardware part of another mission prohibits economically sound manned MRO space missions for the foreseeable future, even though the specific space hardware costs are extremely high. Multiple MROs during one mission might offer a solution, though.

Table 6-14: Evaluation of "On Orbit MRO"

Topic		On Orbit Maintenance, Repair, Overhaul
Objective		Complex robotics or manned flights
Technical Feasibility		Feasible (demonstrated)
Effort	Costs	Many 100 000 000 $
Benefit	Revenues	Several 100 000 000 $
Motivation	Profits	Negative
Result	Commercial Attractiveness	**Low**
Comment		One complex mission to save one mission

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[451] AW&ST Jul 18 2007.

6.2.1.3 Orbital Trajectory Modification

Change of orbital inclination or increase of orbital altitude of a spacecraft might be required because of residual atmospheric drag or failed orbit injection. This would require an autonomous propulsion stage with docking capabilities.

During the 1970s, it was intended to raise the orbit of the U.S. Skylab space station with a Teleoperator Retrieval System (TRS) that should be launched by the Shuttle. The project was cancelled in December 1978 because of Skylab malfunctions, rapid Skylab orbital altitude decrease, and development delays of TRS and US-STS.[452]

At present, the customer situation seems to be insufficient for commercially profitable operations.

Table 6-15: Evaluation of "Orbital Trajectory Modification"

Topic		Orbital Trajectory Modification
Objective		Space tug
Technical Feasibility		Feasible (demonstrated)
Effort	Costs	Several 100 000 000 $
Benefit	Revenues	Several 100 000 000 $
Motivation	Profits	Eventually
Result	Commercial Attractiveness	**Low**
Comment		Insufficient market

6.2.1.4 Disposal of Orbital Debris

Space debris might be defined as any artificial object in space without active altitude and attitude control system. This is a growing problem for any orbital operations.

Due to its high relative velocity, even an impact of small orbital debris particles on satellites and manned installations may have disastrous consequences. Known collisions of satellites with space debris include:

- French spy satellite "Cerise", collision on July 24, 1996 with part of an Ariane rocket stage that was launched in 1986. Loss of stabilizer equipment (partial failure).[453]
- Russian communication satellite "Ekspress AM11", collision on March 29, 2006 with "space garbage". Satellite was removed to disposal orbit (total failure).[454]

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[452] Ruppe 1980.
[453] Spiegel Online 06/06/2006.
[454] Space Daily 17/04/2006.

The total number of orbital debris increases, not only because of continuous new space missions, but also because of debris particle collisions resulting in decrease of their size and increase of their number.[455]

To reduce the number of debris, there are prescriptions for the staging of rockets and satellite separation to create as few debris particles as possible. Unintended events can significantly increase the number of particles in orbit, for example explosive malfunctions of upper stages.

North American Aerospace Defense Command (NORAD) currently tracks more than 12 000 objects with a diameter larger than 0.1 m in Earth orbit, as seen in **Figure 6-25**. The sudden increase in early 2007 is due to a successful Chinese anti satellite weapon test that destroyed a defunct weather satellite at about 800 km LEO.

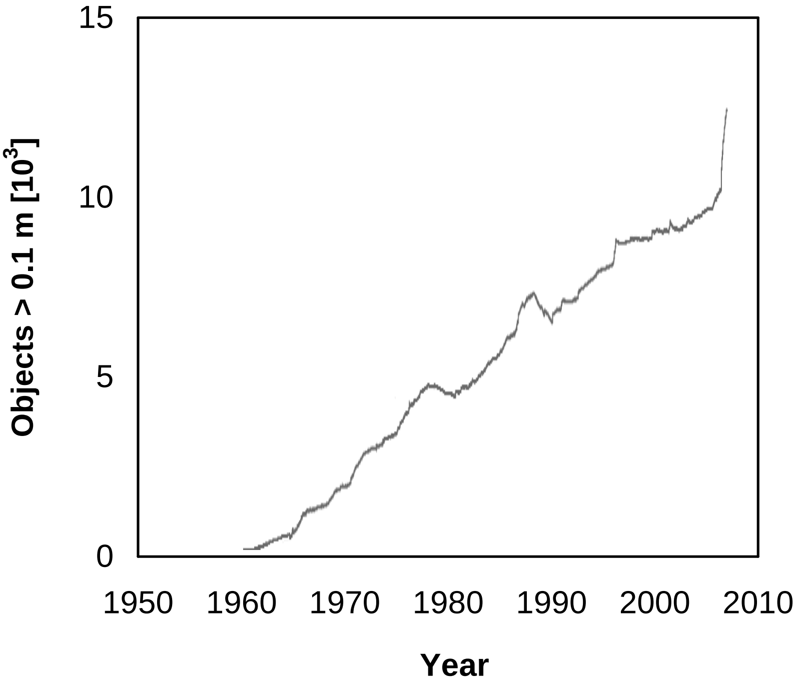

Figure 6-25: Historical Growth of Space Debris[456]

Active measures to reduce orbital debris numbers and to dispose used upper stages or inactive satellites are required on a long term. Various ways have been proposed so far, but the missing industrial activities lead to the conclusion that either orbital debris disposal is not imminent, or, more probable, the question who has to pay for debris removal is unsolved.

In the future, when this question is solved, a sufficient market might emerge.

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[455] Spiegel Online 06/06/2006.
[456] CelesTrak 2007.

Table 6-16: Evaluation of "Disposal of Orbital Debris"

Topic		Disposal of Orbital Debris
Objective		Space tug*, …
Technical Feasibility		Feasible (demonstrated)*
Effort	Costs	Several 100 000 000 $
Benefit	Revenues	-
Motivation	Profits	Negative
Result	Commercial Attractiveness	**None**
Comment		No paying customer identified

* For large debris (satellites, rocket stages, …). Situation for smaller debris unclear.

6.2.2 Providing Space Infrastructures

Infrastructure similar to the ISS could be developed and installed to support current activities in space and offer new applications. This might include manned laboratories and other support structures. Tourism offers are considered in a later chapter.

6.2.2.1 Earth Orbit

Various types of platforms to perform research and other activities in space could be provided by private companies instead of national institutions. Today, platforms like ISS are financed by the state, as is seen in **Figure 6-26**.

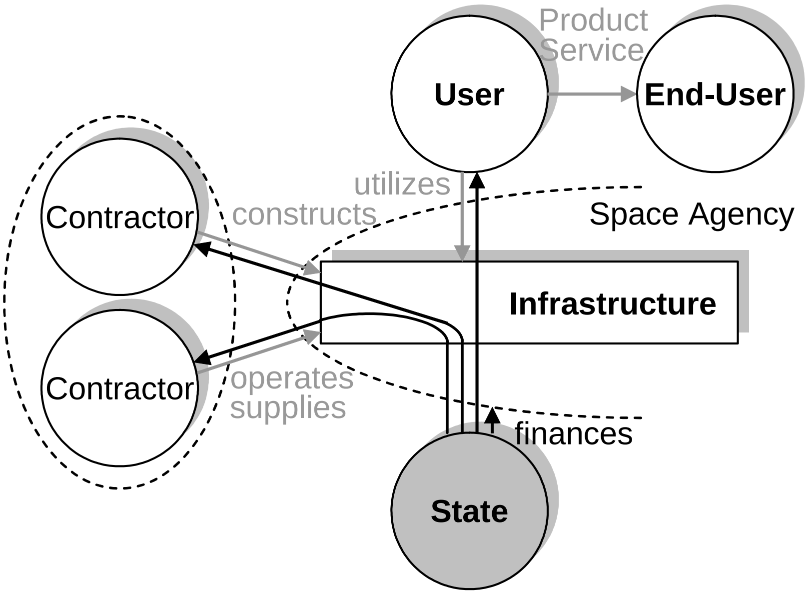

Figure 6-26: Public Funded Space Infrastructure

For a commercial infrastructure, no public funding is needed at all, as is illustrated in **Figure 6-27**.

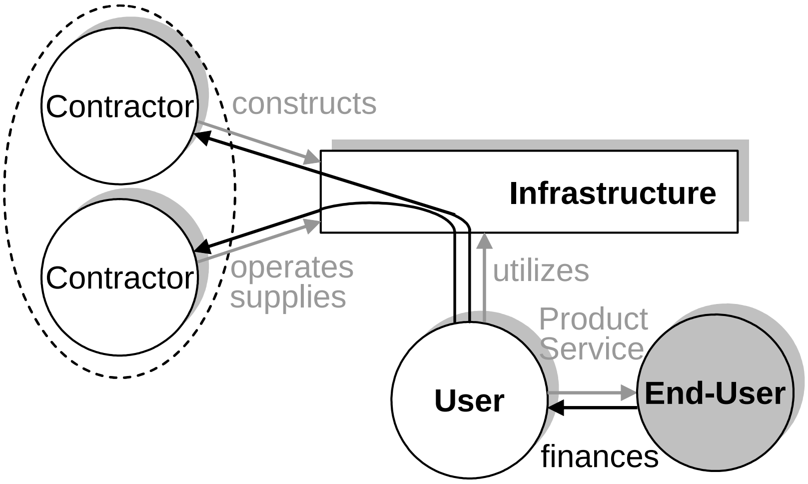

Figure 6-27: Commercial Space Infrastructure

Further considerations are about infrastructures that are primarily used for science and research applications, meaning an enhancement of current activities. These structures could be unmanned, man-tended or permanently manned.

In addition, a special type of infrastructure for satellite support applications is analyzed.

A) Unmanned Systems

These are mandatory for long term research and high quality microgravity. An example for a previous system is the European EURECA platform.

EURECA was developed for transportation by the US-STS and was placed in orbit on 31 July 1992 by mission STS-46. It was retrieved 10 months later by US-STS Orbiter Endeavour.[457]

Though the system was operated successfully, no private contracts followed, and without further public funded missions, the program was canceled. Thus, current demand seems not to be sufficient for this type of systems.

B) Man-tended Systems

Similar to unmanned systems, but with brief tending periods by astronauts. One part of ESA’s Columbus laboratory was planned as Man Tended Free Flyer (MTFF). The

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[457] NASA GSFC 2003.

program was canceled for financial reasons. Similar to unmanned systems, market demand seems to be too weak.

C) Permanently Manned Systems

There were several orbital laboratories since the early 1970s, including the large Skylab and Mir, but also the small Soviet Salyut and Almaz series stations. **Figure 6-28** presents past and present stations.

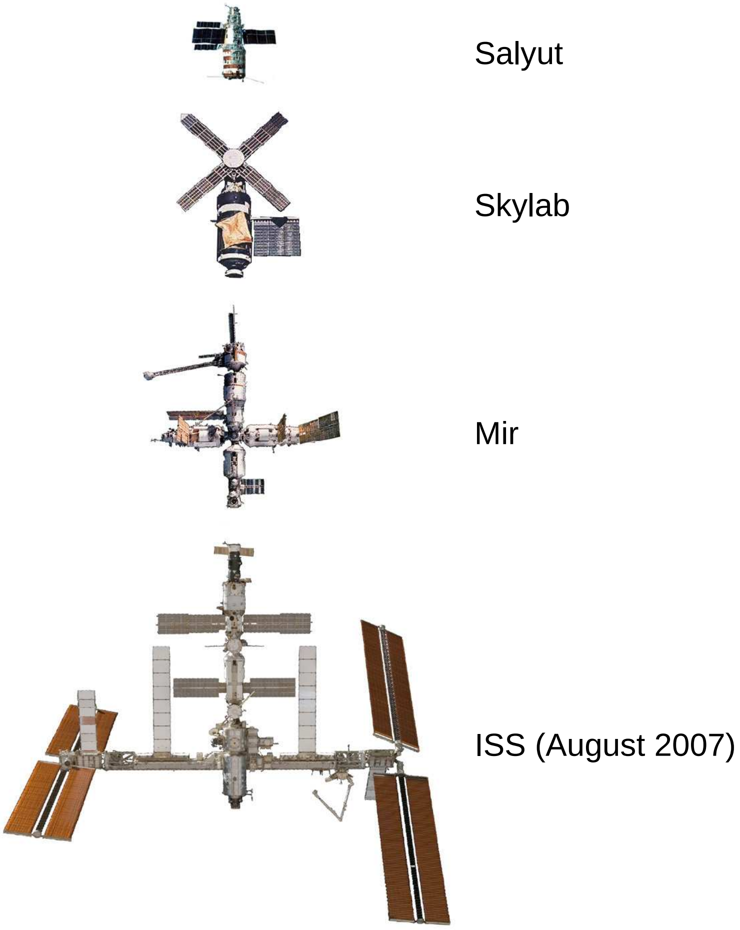

Figure 6-28: Space Station Overview (True to Scale)

The ISS program shows the enormous complexity of space stations: Initiated in 1984 by U.S. President Ronald Reagan, it will be finally completed in 2010 at a cost of more than 100 G $.[458]

Stations larger than ISS are similar to space hotels, with expected costs of several hundred to thousand billion dollars (see chapter 6.3.2.2 for detailed information). It is often ignored that these objects have nothing to do with houses on Earth. They are highly complex machines, vaguely comparable with aircraft, but not with buildings.

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[458] ESA ISS 2005.

Small inflatable stations, as proposed by Bigelow Aerospace,[459] could be offered to other nations for rent. The national prestige that comes with an astronaut in space might be sufficient for the high expenditures that have to be charged. Nations that have no excellent relationships to Russia and USA might take this offer to launch their first astronauts to a space station. But even then, the expected number of customers would be a few dozen at best.

Therefore, these stations are only interesting in combination with space tourism, as will be seen later.

Table 6-17: Evaluation of "Research Stations – LEO"

Topic		Research Stations – LEO
Objective		Small Stations
Technical Feasibility		Feasible (done in the past)
Effort	Costs	Several 1 000 000 000 $
Benefit	Revenues	Several 100 000 000 $
Motivation	Profits	Negative
Result	Commercial Attractiveness	**Low**
Comment		Only with additional use for tourism

D) Satellite Supply Structure (SSS)

Orbital slots are limited, especially at geostationary positions. Currently, more than 400 operational satellites are located in LEO between 200 and 900 km, with additional 350 in or close to GEO.[460]

Large truss structures could increase the limited number of geostationary orbital slots. "Sub-Satellites" would dock permanently with the structure in GEO. Attitude control and power supply is offered by the structure.

This proposal is problematic due to numerous reasons:

- Interference of communications that have similar frequencies
- Complex SSS deployment (similar to ISS, but in GEO!)
- High total SSS mass compared to single GEO satellites
- Maintenance requirements (similar to ISS)
- High risk of automated sub-satellite docking procedure

Risk and costs would be considerably higher than for present single GEO satellites, with the additional problem of communications interference. SSS is not an option.

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[459] AW&ST Apr 9 2007b, Space News 15-2007.
[460] UCS 2007.

6.2.2.2 Destinations Beyond Earth Orbit

Infrastructure in lunar orbit, on lunar surface and at other locations is linked to considerably higher transportation costs.[461] Currently, only federal space agencies could be named as potential customers. But for various reasons (politics, risk management, …), utilization of private infrastructure for missions to destinations beyond Earth orbit – manned and unmanned – is out of question for them.

Table 6-18: Evaluation of "Research Stations – Beyond LEO"

Topic		Research Stations – Beyond LEO
Objective		Lunar orbit station, lunar base, …
Technical Feasibility		Very Challenging
Effort	Costs	Several 100 000 000 000 $
Benefit	Revenues	-
Motivation	Profits	Negative
Result	Commercial Attractiveness	**None**
Comment		No customer identified

6.2.3 Privatization of Science Missions

Table 5-15 listed some current space science programs. Though the costs in the order of several hundred millions of dollars are subject to more than just hardware, it is interesting to compare the cost and key facts of public funded probes to that of private funded satellites, as in **Table 6-19**. Under certain prerequisites, competitive business with transportation and infrastructures seems possible; perhaps, the same is also true for this domain of public space activities.

It should be noted that expected mission life of commercial satellites is considerably longer than that of science probes, while development time, and thus the costs, are considerably less.

If science missions and the respective platforms for the instruments were subject to a free market, significant cost reductions for space agencies and profits for private companies might be possible, because this part of space activities is a major victim of the present mechanisms of space business (see chapter 9.2).

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[461] With the numbers of Table 4-5 and the supply requirement of 7 kg per day and person (NASA HQ 2006a), and taking into account the additional masses and costs of the lander and the container, the annual basic supply cost for a three man lunar outpost is several G $.

Table 6-19: Key Facts of Selected Probes and Satellites

	Phoenix[462]	**LRO**[463]	**Thor 5**[464]	**WorldView I**[465]
Subject	Mars Lander	Lunar Observation	Communication	Earth Observation
Funding	**Public**	**Public**	**Private**	**Private/Public**
Gross Mass [kg]	524*	1 846 (949**)	2 450	2 500
Mission Live [a]	0.75+0.25	1+	15	7.25
Power Supply [kW]		0.8	4.3	3.2
Key Features	1 m Excavation	0.5 m Resolution Imagery	24 Ku-Band Transponders	0.45 m Resolution Imagery
Development [a]	4[466]	4	2	3
Launch Year	2007	2008	2007	2007
Mission Cost [M $]	**417**	**600**[467]	**201.7**	ca. **500**[468]

* On surface.
** Dry mass.

Cost reduction for the agencies could lead to additional missions that in turn further reduce costs. Venus Express and Mars Express clearly showed that cost reduction is possible using common elements for science missions.

Perhaps, additional cost savings are possible with development contracts that are combined with advertising campaigns: Zeiss, developing optical instruments for planetary probes, or General Motors, developing rover components, could use their activities for advertising purposes.

Table 6-20: Evaluation of "Privatization of Science Missions"

Topic		Privatization of Science Missions
Objective		Satellites, planetary probes
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $
Benefit	Revenues	Several 100 000 000 $
Motivation	Profits	Eventually
Result	Commercial Attractiveness	**Interesting**
Comment		Depends on politics, science community

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[462] AW&ST Jun 11 2007.
[463] NASA GSFC 2007b.
[464] Space News 17-2007a, Telenor 2007.
[465] Digital Globe 2007a.
[466] NASA News 05-141.
[467] AW&ST Apr 17 2006.
[468] AW&ST Sep 17 2007a.

6.3 Applications for the “Entertainment Society”

Self-actualization has a high standing in today’s societies. These societies are often called “post-industrial”, though this designation is misleading, because no society ever relied more on industrial capacities than that of the 21st century. The designation “Entertainment Society” is probably more accurate. Huge financial potential lies in the markets of these “Entertainment Societies”.

The utilization of space to satisfy the needs of individuals can be either indirect (via media, science fiction, movies, advertising, …) or direct (space tourism).

The adventurous aspect is certainly a decisive motivation for individual participation and presents a return to the ancient motivation of science fiction and spaceflight.

6.3.1 The Astronaut Experience

To experience the thrill of spaceflight without actual participation is mentioned for completeness. Aside of the inexplicable fascination of astronautics, another motivation to take part in space related activities might be the feeling to have participated in something very special, and to tell others about it – a kind of showmanship. Currently, there are numerous offers of various types, for example:

- Rocket launch VIP tickets (including preparations, tours of companies, plants, institutions, … prior to launch)
- Astronaut training (neutral buoyancy facility/water tank, centrifuge, Soyuz simulator, …)
- Parabolic flights

The majority of the offered activities takes place in Russia, but is marketed by the U.S. company Space Adventures. Costs range from several 1 000 $ to several 10 000 $, depending on the booked package. The economic effect for space agencies is insignificant. But profits are made, and the advertising effect for spaceflight is certainly positive and should not be neglected.

Table 6-21: Evaluation of “The Astronaut Experience”

Topic		The Astronaut Experience
Objective		Same as topic
Technical Feasibility		-
Effort	Costs	- (done anyway)
Benefit	Revenues	Several 10 000 $
Motivation	Profits	Yes
Result	Commercial Attractiveness	**Insignificant**
Comment		Not a real spaceflight topic

6.3.2 Space Tourism

In the public view, space tourism covers suborbital flights, orbital flights, and limited stays at places in Earth orbit and beyond (including a safe return to Earth!). It is currently seen as a potential initiator of large scale spaceflight activities, and as a means to drastically reduce transportation costs.[469]

There were numerous announcements of commercial spacecraft as well as space stations in the past years that are to be used for space tourism. Some are presented in **Table 6-22**.

Table 6-22: Various Space Tourism Projects

Company	Name	Topic	Initiator	(Former) Company	Target Date
Virgin Galactic	SpaceShipTwo	Suborbital	Richard Branson	Virgin Group	2009
Bigelow Aerospace	Sundancer	Space Station	Robert Bigelow	Budget Suites	2010
SpaceX	Dragon	Orbital	Elon Musk	PayPal	2010
Armadillo Aerospace	-	Suborbital	John Carmack	id Software	
SpaceDev	-	Suborbital, Orbital	James Benson	Compusearch, ImageFast	2010
Blue Origin	New Shepard	Suborbital	Jeff Bezos	Amazon	
XCOR Aerospace	Xerus	Suborbital	Jeff Greason	Intel	2010

Tourism is the least requiring manned space activity (see chapter 4.1.2.1.2).

In the subsequent paragraphs, analysis is done by the following steps:

- Overview of current offers and prices (parabolic, suborbital, orbital, lunar)
- Estimation of future offers and prices (space hotels)
- Common market estimations and real situation
- Additional remarks
- Conclusions for space tourism

6.3.2.1 Overview of Current Space Tourism Offers

Suborbital flights are marketed as spaceflights to attract a large number of customers, though their maximum velocity is only a small fraction of that of orbital flights (see chapter 3.1.3). These flights are nothing else than high speed parabolic flights,

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[469] Fawkes 2006.

so normal parabolic flights must be included in the following considerations, too.

The major reasons for space tourism activities seem to be the experience of weightlessness and the distant view of Earth.

A) Parabolic Flights

A modified airliner flies a parabolic trajectory to simulate microgravity for a brief period. In the case of ESA, the 25 s microgravity phase of its Airbus A300 Zero-G is framed by injection and pull out phases of 20 s that induce an increased force of 1.8 g.[470] This is repeated about 30 times, depending on the campaign.

Qualified aircraft are currently in use at ESA (Airbus A300 Zero-G), NASA (McDonnell Douglas C-9B), Roskosmos (Ilyushin IL-76 MDK), and at the U.S. company Zero Gravity Corporation (Boeing 727-200 G Force One).[471] Tourist offers are primarily made by the private Zero Gravity Corporation for about 3 500 $ per person and flight.

B) Suborbital Flights

The majority of announced space tourism projects focuses on this category. Compared to parabolic flights, the duration of the microgravity phase is longer because of a peak altitude of more than 100 km. **Figure 6-29** shows a rough calculation.

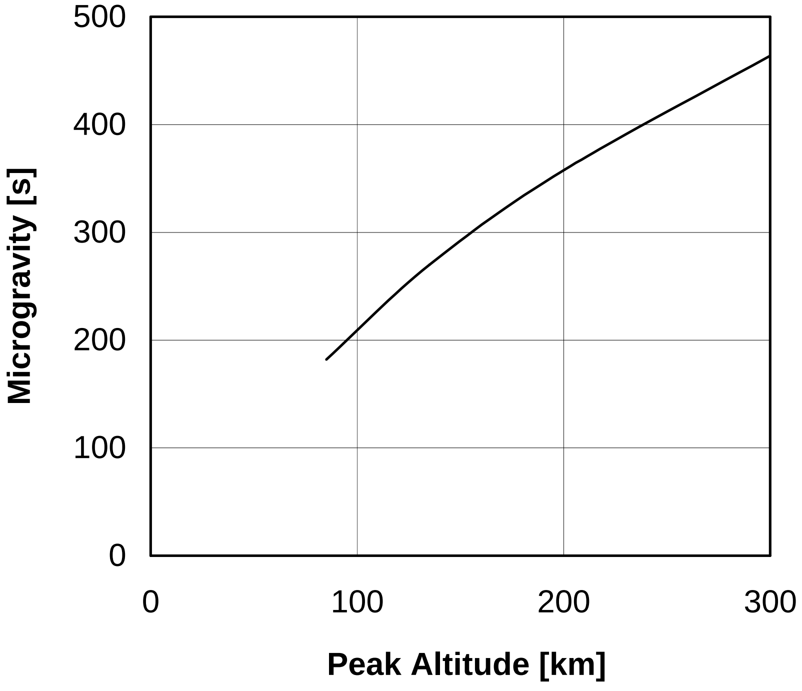

Figure 6-29: Microgravity Period at Suborbital Flights

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[470] ESA A300 Zero-G.

[471] ESA A300 Zero-G, NASA JSC 2007b, Zero G 2007.

Suborbital flights offer extended weightlessness durations, and Earth's curvature is visible under a black sky. According to FAI definition of space, suborbital flights reaching altitudes of more than 100 km are considered spaceflights.[472] Therefore, participants of these flights are officially regarded as astronauts.

Though the engineering achievement is impressive, these flights are no real spaceflights (velocity considerably lower than orbital velocity, see chapter 3.1.3)!

The announcement of the first X-Prize in 1996, offering a 10 million $ reward for the first private suborbital 100 km flight, triggered development activities for numerous vehicles.

After a first successful test flight in June 2004, Scaled Composites finally won the X-Prize in October 2004 with their famous SpaceShipOne, a hybrid rocket engine powered vehicle released from a carrier aircraft at high altitudes.[473]

For safety and regulation reasons, the flights of SpaceShipOne were done with mass dummies, though two passengers could have accompanied the pilot. The success of SpaceShipOne lead to the design of a larger SpaceShipTwo that will carry 8 people instead of 3. At current plans, this vehicle will be used by the company Virgin Galactic to carry out commercial flights for paying customers at 200 000 $ per passenger starting in 2009.[474]

These developments resulted in the general assumption that comparatively low rewards could trigger a self contained development of a private spaceflight industry that never had any success in the past 50 years. Parallels to the 10 million $ X-Prize can be seen in the 50 million $ America's Space Prize for orbital flights[475] as well as in NASA's Commercial Orbital Transportation Services (COTS) effort.

Various current suborbital flight tourism projects are presented in **Table 6-23**.

Table 6-23: Various Suborbital Space Tourism Projects

Company	Name	Price [$/pax]	Customer Projection	Target Date
Virgin Galactic[476]	SpaceShipTwo	200 000	50 000 pax/10a	2009
Rocketplane Kistler[477]	Rocketplane XP	250 000		2008
EADS Astrium[478]	-	> 200 000	15 000 pax/a	2012
XCOR Aerospace[479]	Xerus	102 000		2010+

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[472] FAI 2006.
[473] Scaled Composites 2006.
[474] Virgin Galactic 2007.
[475] Bigelow 2007.
[476] Space News 45-2006.
[477] RpK 2007.
[478] Space Daily 13/06/2007.
[479] Space Adventures 2007.

Suborbital space tourism has some problematic aspects. The experience of weightlessness requires a large cabin volume to enable simultaneous free floating of the paying customers, and large cabins result in increased mass. The transition phase between microgravity and reentry loads must be considered, too. All passengers must have returned to their seats to safely endure the high reentry loads.

Finally, it should be reminded that, though it is always referred to as the backbone of future space tourism, until now no tourist ever participated in a suborbital flight, and that suborbital has nothing to do with orbital spaceflight.

C) Orbital Flights

Due to the limited Soyuz orbital service life of approximately 180 days, the Soyuz lifeboat docked at the ISS is replaced twice a year. During these so called taxi missions, the third seat of the Soyuz is offered for sale by the Russian space agency to reduce initial mission costs. National space agencies make use of this offer as well as other spaceflight participants, also referred to as space tourists. The U.S. company Space Adventures currently offers Soyuz taxi seats for 30 to 40 million $.[480]

As of October 2007, five persons participated on such a mission including a week’s stay onboard the ISS: Dennis Tito, Mark Shuttleworth, Greg Olsen, Anousheh Ansari and Charles Simonyi. They are often referred to as the first space tourists. But they were not the first non-professionals in space as seen in **Figure 6-30**.

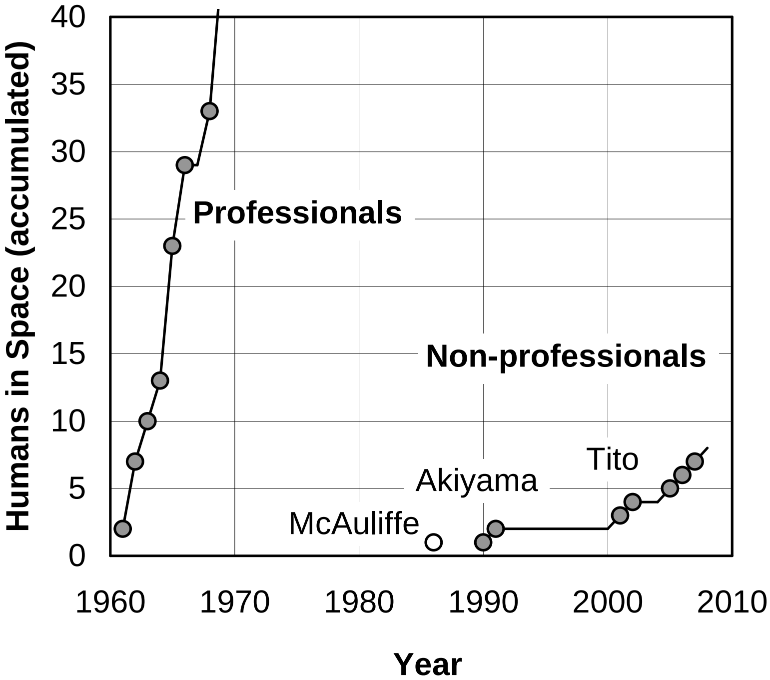

Figure 6-30: Professionals and Non-Professionals in Space

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[480] Space Adventures 2007.

Christa McAuliffe, a teacher by profession, never reached space. She was part of the crew of the ill-fated Challenger launch in 1986.[481] Japanese Tohiro Akiyama visited Mir in 1990 as a journalist.[482] His flight was paid by the Japanese television network he was working for. The British astronaut Helen Sharman of 1991 is also sometimes referred to as a non-professional because her flight was financed by British companies.

The previously mentioned America's Space Prize sponsored by Robert T. Bigelow tries to ignite the orbital tourism market by offering an award of 50 million $: A reusable vehicle must carry 5 persons to a 400 km LEO twice within 60 days before the year 2010.[483]

D) Lunar Mission

In August 2005, Space Adventures – the company that managed the flights of Tito, Shuttleworth, Olsen, Ansari and Simonyi – announced that it offers circumlunar flights for 100 million $ per person, beginning as early as 2008. Meanwhile, the timeframe slipped to 2011 to 2012. The flights would use a modified Soyuz capsule with additional hardware elements.[484] A similar plan was proposed earlier in 2004 by Constellation Services International, Inc..[485]

The realization of these projects must be questioned: The Soviet circumlunar and lunar landing projects of the 1960s were failures despite tremendous governmental efforts, and the current Russian space industry capacities seem not to exceed those of the Soviet Union of the 1960s.

6.3.2.2 Space Hotels

A special infrastructure is required in space for long duration stays. The ISS is sufficient for the current space tourist frequency of less than one per year. But the ever anticipated booming space tourism market resulted in plans for space hotels that are larger than ISS. 100 guests and more is a typical size, comparable to Wernher von Braun's space station concept of the 1950s.

There are two potential categories of clients:

- **Adventure**
  Also regarded as non-professional astronauts, identical with today's spaceflight participants. The hard living conditions of professional astronauts are desired. Similar to mountain climbers in a base camp.

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[481] McAuliffe's backup candidate, Barbara Morgan, finally launched into space aboard Endeavour in August 2007 at STS-118 as an astronaut, being selected by NASA as a mission specialist in 1998.

[482] Wade 2007.

[483] Bigelow 2007.

[484] Space Adventures 2007.

[485] CSI 2007.

- **Luxury**
  The extraordinary price must include all kinds of luxury, resulting in an according space hotel layout. Similar to tourists on a cruise ship.

Depending on the expected type of clients, different assumptions and cost computations are required.

A) Adventure Type

This type of hotel is comparable to the Bigelow Aerospace proposal of April 2007 that intends to offer three large human outposts in LEO by 2015.[486] A crew of three, rotating twice a year, is responsible for housekeeping, while there is room for 12 guests at four week intervals. The minimum daily supply requirement per person is comparable to ISS astronauts with approximately 7 kg per day.[487] Further parameters are given in **Table 6-24**.

Table 6-24: Cost Computation of Space Hotel – Adventure Type

Parameter	Value
Location	LEO
max. Guests	12
Personnel	3
Guest Stay Duration [d]	28
Life Cycle [a]	10
Average Utilization [%]	80
Transportation Costs [$/kg]	10 000
Infrastructure Costs [$/kg]	50 000
Transportation per Person [$/pax]	30 M
Rates [%]	0
Ground Control Costs [$/d]	1 M

While Bigelow Aerospace offers the four week stay for an astronaut (including transportation) at 14.9 M $,[488] the computed result for an adventure type hotel is 11.6 M $ without transportation, and 41.6 M $ including flight costs.[489]

B) Luxury Type

The significantly increased mass requirements for a luxury client result in significant cost increase. The client is offered spacious quarters, entertainment facilities and increased supplies of 12 kg per day.

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[486] AW&ST Apr 9 2007b, Space News 15-2007.

[487] NASA HQ 2006a.

[488] Space News 15-2007.

[489] The order of magnitude is important, not the exact number. Computation details are therefore not further discussed here. Computations were validated with ISS numbers (see next page).

Aside of the guests, service personnel as well as station maintenance workers must stay at the hotel. Housekeeping experiences with the ISS and the high personnel requirements of hotels and cruise ships lead to the assumption of at least 0.3 to 0.5 persons per guest. Other assumed parameters are presented in **Table 6-25**.

Table 6-25: Cost Computation of Space Hotel – Luxury Type

Parameter	Value
Location	LEO
max. Guests	100
Personnel	30
Guest Stay Duration [d]	7
Life Cycle [a]	10
Average Utilization [%]	80
Transportation Costs [$/kg]	10 000
Infrastructure Costs [$/kg]	50 000
Transportation per Person [$/pax]	30 M
Rates [%]	0
Ground Control Costs [$/d]	1 M

The resulting vacation costs of 34.7 M $ per person and week, including flight, seem acceptable. But this number must be seen in context with more than 40 000 guests that are required within 10 years, and with total program costs of 1 450 G $.

C) Resulting Conclusion

The projected costs significantly depend on the specific transportation costs for the guests. The specific infrastructure costs are of minor influence. Considering the results of chapter 4.3.1 – that hardware and operation are the true space cost drivers –, this might be an indication that the hardware and operations segment costs are assumed as too low. Reliable predictions are not possible without detailed analyses.

A view on the ISS program reveals the challenges of space station construction programs. The costs exploded, the scale decreased, and completion is far behind the original schedule. Computed with the same method as both hotels, the ISS program costs would be 56.8 G $, which is substantially lower than the real ISS program costs of more than 100 G €.[490]

An adventure type hotel seems to be at the limit of commercial feasibility. Severe cost increases during realization must be expected.

The luxury space hotel is larger and more expensive than any previous spaceflight activities by an order of magnitude. Realization seems impossible.

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[490] ESA ISS 2005.

And a fact that is often ignored must be considered for both hotel types: There are no hotels at the South Pole or on the highest mountain peaks. Public interest does not justify the expenses and efforts. Why should a space hotel do?

6.3.2.3 Estimation of the Potential Space Tourism Market

Most estimations see the space tourism market as the key to extended spaceflight activities. Even a small share of the current world tourism revenues of 680 G $ (2005)[491] would be sufficient for extended space tourism activities.

A) Current Numbers and Common Predictions

Parabolic

Parabolic flights are commercially offered for 3 500 $ per person in the USA.[492] Other opportunities are available in Russia and in Europe, but are primarily limited to research institutions. The number of potential clients is quite high.

Suborbital

Current predictions are controversial. EADS estimates 15 000 customers per year by 2020[493] (resulting in 2 500 to 3 750 annual flights), similar to a study by The Futron Corporation that forecasts 15 700 passengers in the year 2021 alone.[494] Another study by Futron predicts a total suborbital launch vehicle market of 852 flights through 2020.[495]

The price of suborbital space rides is similar to that of luxury cars. Thus, the number of potential clients might be similar. The global demand for cars that are priced at 250 000 € and more is 2 500, and the total number of potential customers is estimated at 80 000[496] – all of them so called High Net Worth Individuals (HNWI) that have more than 30 M $ of liquid means. In 2007, this number increased to 94 970.[497]

Optimistic estimates state the total number of millionaires worldwide as potential customers, which is 9.5 million.[497]

The most promising candidate to offer suborbital rides, Virgin Galactic, had more than 200 booked customers[498] with total deposits of more than 20 M $ in mid 2007, with interest of over 80 000 people from 120 countries.[499]

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[491] UNWTO 2006.
[492] Zero G 2007.
[493] Space Daily 13/06/2007.
[494] Futron 2002.
[495] Space Foundation 2006.
[496] SZ 03/03/2007.
[497] Globus 1994-2007.
[498] Space News 27-2007.
[499] Space Daily 12/07/2007.

Orbital

Prices for orbital rides to the ISS increased from 20 M $ to between 30 and 40 M $ in 2007.[500] The potential market is seen as growing, with more than 50 passengers annually from 2020 on.[501]

None of the orbital space tourists yet was a billionaire.

Circumlunar and Others

Flights are offered by Space Adventures for 100 M $.[500] This would be a simple circumlunar flyby on a free return trajectory.

B) Real Situation

Sufficient numbers of clients are a prerequisite for the successful commercial development of space tourism. Aside of the financial side, the clients must have sufficient physical capabilities, and they must have the motivation to spend their money on space tourism – the perspective of space enthusiasts on this subject is irrelevant!

As already mentioned, the average price offers for flights currently are:[502]

- 3 500 $ parabolic
- 100 000 $ – 200 000 $ suborbital
- 30 000 000 $ – 40 000 000 $ orbital
- 100 000 000 $ circumlunar

Sufficient income and assets are required to spend money on the currently expensive space tourism offers. **Table 6-26** shows exemplary numbers.

Table 6-26: Number of Millionaires and Billionaires Worldwide (2007)

Type	Number
Millionaires[503]	9 500 000
High Net Worth Individuals (> 30 M $)[503]	94 970
Billionaires[504]	946
Billionaires with more than 10 G $[504]	67

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[500] Space Adventures 2007.
[501] Futron 2002.
[502] Zero G 2007, Virgin Galactic 2007, Space Adventures 2007.
[503] Globus 1994-2007.
[504] Forbes 2007.

Consumer acceptance is given when the fortune of the consumer is significantly higher than the flight cost. Estimated fortunes of Tito and Shuttleworth were 200 respectively 600 million $, that is a factor of 10 to 30 related to the cost of their spaceflight of 20 M $ then. But Tito certainly was more motivated to do his space trip than the average citizen is. The actual factor is probably much higher.

A survey of the German Allensbach institute of 2004 that is presented in **Figure 6-31** gives a clue to the average motivation. The questions were: "Would you like to fly into space and orbit Earth? If yes, how much money are you willing to spend for such a journey?"

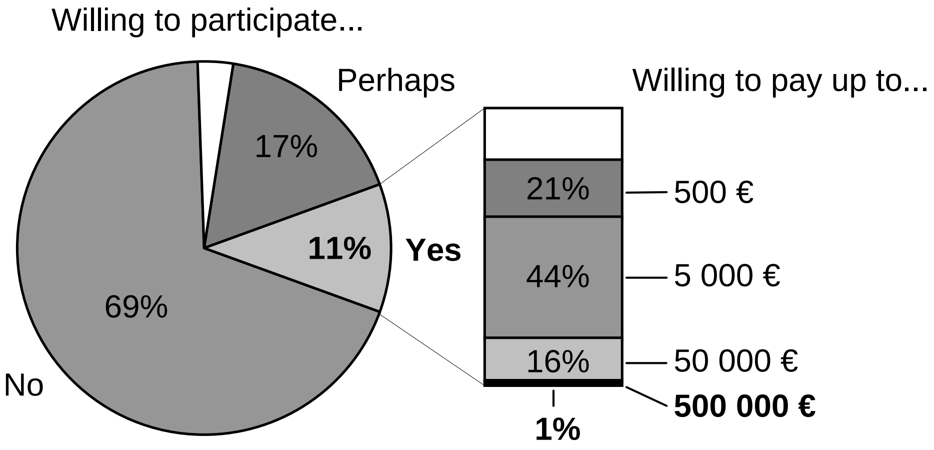

Figure 6-31: Motivation – Potential Space Tourists[505]

Another restricting factor is physical health. Because most potential customers are of advanced age (the average billionaire is 62 years old[506]), physical problems may further limit the number of clients.[507]

With these limitations, an estimation of the real number of potential customers is possible:

- **Limitation 1**: Even space enthusiasts do not pay more than 1/10 of their fortune for space tourism.
- **Limitation 2**: Of the whole population, 11 % are interested in space tourism. This includes the enthusiasts.
- **Limitation 3**: Only 1 % of them is actually willing to pay the prices (in the range of suborbital flights).

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[505] GEO Wissen Nr. 33 2004.

[506] Forbes 2007.

[507] It should be noted that age has another negative influence on market size: Elder people are less adventuresome than young persons, and are not as interested in exciting experiences.

Not regarded are limitations due to physical and mental problems.

Combined with the numbers of Table 6-26 (that can be seen in the figure as grey symbols), the resulting number of potential space tourism customers is illustrated in **Figure 6-32**.

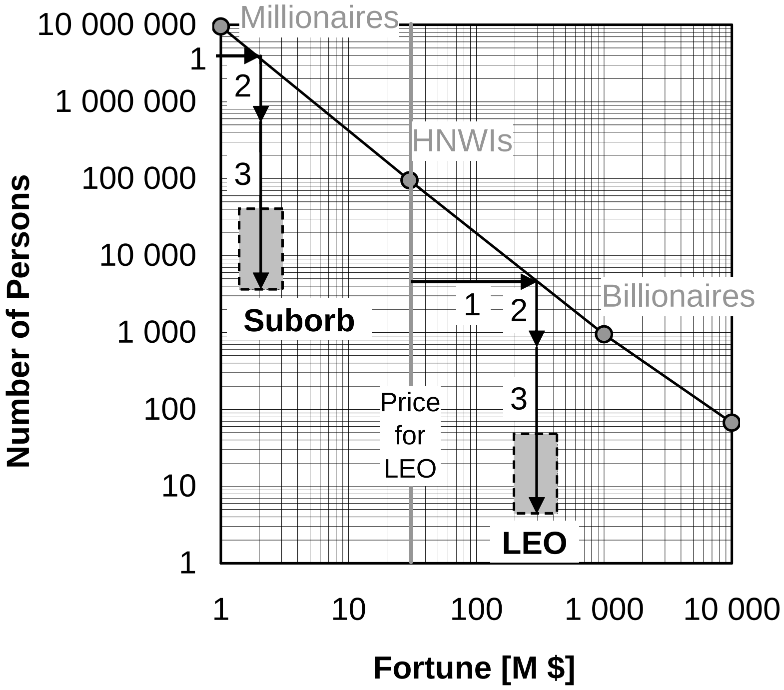

Figure 6-32: Potential Space Tourists Worldwide[508]

Even assuming that the range of actual customers could be up to ten times more than those resulting from Limitations 1 to 3, estimations for the total (not annual!) space tourism market are:

- 4 000 to 40 000 for suborbital tourism,
- 5 to 50 for orbital tourism,
- 1 to 10 for circumlunar tourism.

These resulting numbers are considerably lower than other current projections.

Another disregarded commercial risk are accidents. It must be assumed that the tourism offers will be cancelled at first massive loss of life, similar to Zeppelin and Concorde; and the reliability of space vehicles is comparatively low.

C) Current Acceptance of Similar Offers

There are other offers comparable to space tourism, as can be seen in **Table 6-27**.

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[508] Globus 1994-2007, Forbes 2007.

Table 6-27: Other Tourism Adventure Offers

Type	Price [$/pax]
MiG-29 Flight[509]	13 700
MiG-25 High Altitude Flight (+25 000 m)[509]	16 870
Dive to the Titanic (-4 000 m)[510]	40 000

Though these offers are considerably less expensive and less dangerous than suborbital or orbital rides, there are not enough customers for large scale business operations.

6.3.2.4 Additional Remarks

There are two main objectives for a potential space tourist: To view the Earth from above the atmosphere, and to experience weightlessness. Weightlessness can be achieved with various means. Specific cost for a second of microgravity (µg) differs significantly, depending on the selected type of “space tourism”, as presented in **Table 6-28**.

Table 6-28: Specific Cost of One Second of Weightlessness

Type of Flight	Total µg Duration	Costs [$]	Maximum Acceleration [g]	Specific µg Costs [$/s]
Parabolic	15 x 25 s	3 500	2	10
Suborbital	>200 s	200 000	5	1 000
Orbital	ca. 8 d	30 000 000	5	40
Circumlunar	10 d	100 000 000	9	115

The suborbital second of microgravity is a hundred times more expensive than that of normal parabolic flights.

Expected launch masses m_0 of the vehicles[511] that are required for the different types of tourist spaceflights are presented in **Figure 6-33**, assuming a 10 t spacecraft mass. Compared to suborbital vehicles, the minimum sizes increase significantly, underlining the increasing challenges of orbital and lunar tourism compared to suborbital missions.

The lunar landing option (LL) does not consider a lunar orbit rendezvous maneuver, as was done by Apollo. Therefore, the estimated launch mass is considerably higher than Apollo’s 3 000 t.

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[509] RusAdventures 2007.
[510] Deep Ocean 2007.
[511] With presently available technology.

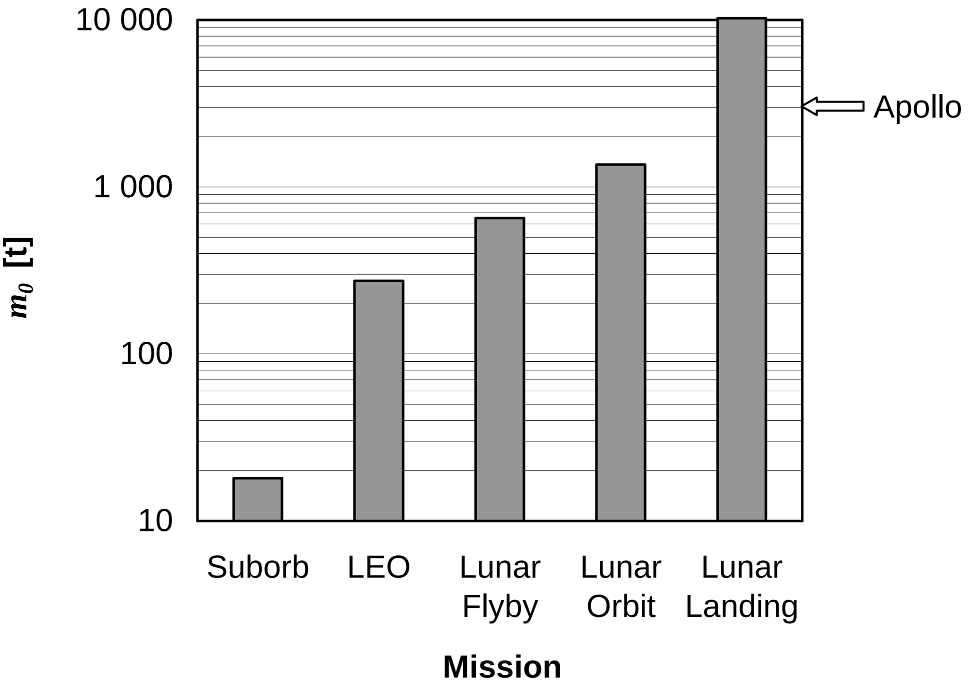

Figure 6-33: Launch Vehicle Mass Estimations

6.3.2.5 Conclusions

Though tourism is the manned spaceflight activity with the lowest requirements and technical challenges, the market for space tourism is not attractive. The suborbital tourism market is much smaller than generally anticipated. Orbital tourism is on the red line of commercial attractiveness even from an optimistic perspective. Circum-lunar tourism currently seems not feasible. Adventure class space hotels depend on cheap transportation, while luxury class space hotels are probably not feasible.

Total estimated customers for suborbital tourism are 4 000 to 40 000 for prices of 100 000 to 200 000 $ (which are expected to decrease after a few years).

Table 6-29: Evaluation of "Suborbital Tourism"

Topic		Suborbital Tourism
Objective		Suborbital "Spaceship"
Technical Feasibility		Feasible (demonstrated)
Effort	Costs	About 1 000 000 000 $
Benefit	Revenues	About 1 000 000 000 $
Motivation	Profits	Eventually
Result	Commercial Attractiveness	**Low to Medium**
Comment		High number of customers doubtful. Could be cancelled at first accident

Total estimated customers for orbital tourism are 5 to 50 for prices of 30 to 40 M $.

Table 6-30: Evaluation of “Orbital Tourism”

Topic		Orbital Tourism
Objective		Orbital manned flights
Technical Feasibility		Feasible
Effort	Costs	Several 1 000 000 000 $
Benefit	Revenues	Few 1 000 000 000 $
Motivation	Profits	Doubtful
Result	Commercial Attractiveness	**Low**
Comment		Without costs for station as destination

Total estimated customers for circumlunar tourism are 1 to 10 for prices of 100 M $.

Table 6-31: Evaluation of “Lunar Flyby Tourism”

Topic		Lunar Flyby Tourism
Objective		Manned circumlunar flight
Technical Feasibility		Challenging (done in the past)
Effort	Costs	Several 10 000 000 000 $
Benefit	Revenues	Less than 1 000 000 000 $
Motivation	Profits	Negative
Result	Commercial Attractiveness	**None**
Comment		USSR failed with realization

Adventure type hotels could be attractive for the offered cost of 14.6 M $ per person and week. However, the estimated cost is more than 40 M $, which could only work with more than 1 000 customers.

Table 6-32: Evaluation of “Space Hotel – Adventure”

Topic		Space Hotel – Adventure Type
Objective		Small space station
Technical Feasibility		Feasible (done in the past)
Effort	Costs	Several 10 000 000 000 $
Benefit	Revenues	Several 10 000 000 000 $
Motivation	Profits	Only at optimistic assumptions
Result	Commercial Attractiveness	**Doubtful**
Comment		Requires private and public customers

Luxury type hotels would be more than ten times the size of the ISS for more than ten times the cost. This is probably not feasible. Additionally, more than 40 000 guests are required.

Table 6-33: Evaluation of "Space Hotel – Luxury"

Topic		Space Hotel – Luxury Type
Objective		Very large space station
Technical Feasibility		Not Feasible
Effort	Costs	More than 1 000 000 000 000 $
Benefit	Revenues	Several 1 000 000 000 $
Motivation	Profits	Negative
Result	Commercial Attractiveness	**None**
Comment		Anyway not enough customers

Even significantly lower prices would not change the situation very much. Comparable tourist offers, such as diving expeditions to the wreck of the Titanic or MiG jet fighter flights, are already offered at significantly lower prices than space tourism rides, and they are not widely accepted.

6.3.3 Space Burial

At the following considerations, ethical aspects of burial in space are ruled out.

Since the first space burial mission "Celestis" in April 1997,[512] more than 300 burials of this kind have taken place on six missions, with another 300 on mission number seven due in October 2007.[513]

These "celestial burials" only carry a few grams of the cremated remains, either in orbit or on a suborbital mission. NASA even sent some of astronomer Eugene Shoemaker's remains to the Moon aboard Lunar Prospector in 1998. Meanwhile, even deep space missions are offered by a U.S. company, as seen in **Table 6-34**.

Up to 10 000 burials per year could be conducted each year by 2012.[514] Anyway, the number of "celestial burials" will double with the launch in fall 2007. Combined with the rising number of celebrities seemingly interested in the service, and considering that remains of famous people were already launched (Star Trek creator Gene Roddenberry, U.S. astronaut Gordon Cooper, Star Trek actor James Doohan, …),[515] the future market of space burials seems promising.

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[512] Wade 2007.
[513] Space Daily 12/06/2007.
[514] Space Daily 12/06/2007.
[515] FAZ 30/04/2007.

Table 6-34: Current Prices for Space Burial[516]

Destination	Cremated Remains		Price [$]	Ratio [$/g]
	Mass [g]	Participants		
(Suborbital)	1	1	495	495
	2	2	745	373
	7	1	995	142
	14	2	1 495	107
LEO	1	1	1 295	1 295
	2	2	1 945	973
	7	1	4 995	714
	14	2	7 495	535
Moon	1	1	12 500	12 500
	2	2	18 750	9 375
	7	1	44 995	6 428
	14	2	67 495	4 821
Deep Space	1	1	12 500	12 500
	2	2	18 750	9 375
	7	1	44 995	6 428
	14	2	67 495	4 821

Profits at current rates are supposedly high, considering that the lowest service offer for LEO of 535 $/g is about thirty to fifty times the average current LEO payload cost of 10 to 15 $/g. Even assuming a real payload fraction on the “burial vehicle” of only 10 %, with 90 % of the payload mass consisting of other masses like container or structural mass, the profit margin still seems very attractive.

Table 6-35: Evaluation of “Space Burial”

Topic		Space Burial
Objective		Space transportation
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 10 000 $/kg
Benefit	Revenues	Several 1 000 000 $/kg
Motivation	Profits	Yes
Result	Commercial Attractiveness	**High**
Comment		Growth market

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[516] Celestis 2007.

The service could be extended from increasing amounts of ashes up to “space mausoleums”, with the cryogenically stored remains of the customers on their way to other solar systems. The price that is charged for such services is, of course, secondary for the customer.

This application of spaceflight is technically feasible and economically sound, even with present technologies and costs.

6.3.4 Advertising

Advertising is very important for free economics. Aside of being a source of information for the potential customer, advertising is used to create attention – and spaceflight could contribute to this task.

Exemplary numbers of the advertising sector are presented in **Table 6-36**.

Table 6-36: Important Numbers of the Advertising Sector[517]

Criteria	Number
Expenditures for Advertising in the USA (1995)	88.9 G $
Expenditures for Advertising in Germany (1995)	22.0 G $
Expenditures for Advertising in Germany (2006)	30.1 G $

Potential applications include advertising campaigns with conventional space missions, as well as special, dedicated advertising missions.

6.3.4.1 Advertising at Current Space Missions

Today’s scientific and commercial missions could be used for advertisement purposes, as was already done in the past.

A) Rocket Branding

“Rocket Branding” was done on Russian Proton rockets in 1996 (“West in Space” for West cigarettes) and 2000 (“Pizza Hut”, at the launch that carried the ISS Zvezda service module). For both, the product brand was painted on the rocket. In 2001, brandings of this type were offered by the German company “Z New Media Solutions” for 1.2 M € per launch.[518]

This sort of advertising is only sensible when it reaches a large number of potential clients. The average number of rocket launch viewers is low, considering that most launches are not even shown on TV.

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[517] Globus 1994-2007.

[518] Z New Media 2007.

Other events – especially sport events – have a much better viewer and cost ratio. One 30 second TV spot during the 2005 Super Bowl was priced at 2.4 M $, but the Super Bowl was watched by more than 86 million viewers alone in the USA.[519]

Furthermore, even if companies would pay the price mentioned above for branding a rocket (in present U.S. dollars approximately 1.5 M $), it would only cover a small fraction of the current launch costs.

B) Product Placement

There are a few historical examples of product placement in space, including both Pepsi and Coca Cola with the Carbonated Beverage Dispenser Evaluation (CBDE) experiment at US-STS mission STS-51F in 1985. Coca Cola is said to have spent 0.75 M $ in the process.[520] There also were short commercial ads produced on Mir and the ISS. Pepsi is said to have paid 5 M $ for a TV spot aboard Mir station.

Other spectacular events are possible. For example, a golf ball was shot from the ISS during a spacewalk in November 2006 for an unknown sum paid by a Canadian company.

These events are financially negligible because the profits are only a fraction of the mission costs. But they can help to advertise spaceflight itself to the public and improve the public opinion about space. Additionally, though not much, they still improve the financial situation of space agencies.

6.3.4.2 Dedicated Advertising Missions

Aside of using standard space missions for advertising purposes, dedicated advertising missions are possible.

A) TV Shows in Space

There were some proposals to launch dedicated space missions similar to the “Big Brother” TV show concept, either to Mir (after being decommissioned), ISS, or a new space station. These TV shows should be financed with advertising profits.

Though the launch cost of a Soyuz is less than the production cost of major Hollywood films, the cost of the space station would probably be too high. Rental of existing space structures could make a globally broadcasted concept feasible, though. Technical feasibility was basically demonstrated with the IMAX movies at Shuttle missions and numerous live television links to LEO and even lunar surface.

B) Large Orbital Advertising Structures

Another proposal for space advertising is deployment of huge objects in orbit that

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[519] CNN 03/01/2006.

[520] Space.com 31/05/2001.

would be visible from Earth. For mass reasons, the object should consist of a pressure stabilized, extremely thin film. Basic realization of these objects was first proven by NASA with the 30 m diameter balloon “Echo 1A” in 1960.[521]

Because of residual atmospheric drag, the structure’s orbital altitude should be at least 500 km. Orbital stay duration would increase significantly with 1 000 km orbital altitude.

The impression of the visible size of the object seen from Earth’s surface $d_{vis,obj}$ is dominated by the impression of its visibility compared to the full Moon, $d_{vis,obj}/d_{vis,M}$. The average visible angle size of the Moon $d_{vis,M}$ can be computed as about 0.5 °.[522]

The actual diameter of the object d_{obj} depends on the orbital altitude h_{obj} and the requested visible size compared to the Moon, with lunar radius r_M and distance from Earth to Moon r_{E-M}.

$$d_{obj} = \frac{2\ r_M}{r_{E-M}} h_{obj} \frac{d_{vis,obj}}{d_{vis,M}} \qquad (6.10)$$

Thus, to appear the same size as the Moon, the object diameter must be more than 1 % of the orbital altitude.

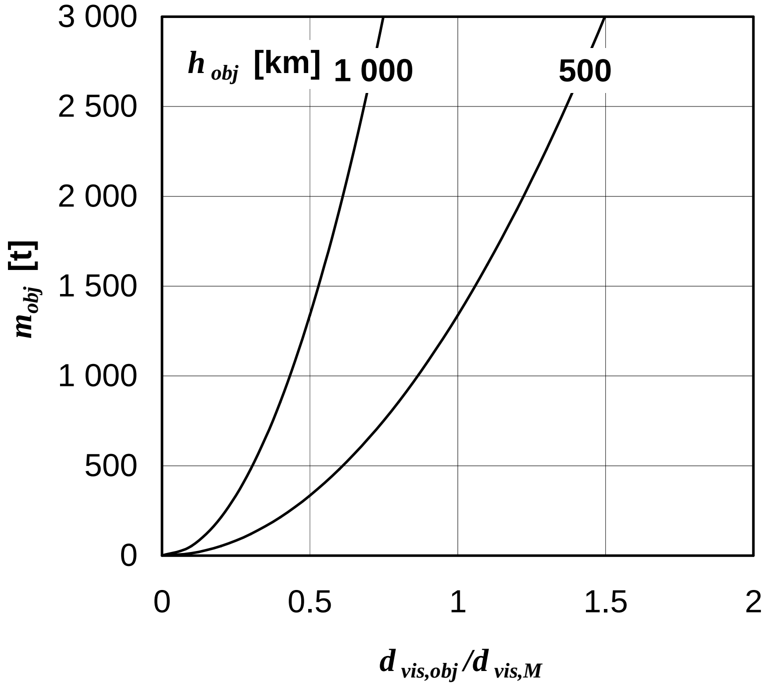

Figure 6-34: Mass and Size of Lens-shaped Orbital Advertising Object

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[521] Wade 2007.

[522] NASA GSFC 2007a.

For a lens-shaped object consisting of two circular films that are welded at the edge and are internally pressure stabilized, the mass m_{obj} is

$$m_{obj} = \left(2 \frac{r_M}{r_{E-M}} \right)^2 \pi \, \rho_{obj} \, s_{obj} \, h_{obj}^2 \left(\frac{d_{vis,obj}}{d_{vis,M}} \right)^2 , \qquad (6.11)$$

with the specific film density ρ_{obj}, and the film thickness s_{obj}. The pressure gas is not regarded. The expected mass of this object, depending on orbital altitude and visibility size, is presented in **Figure 6-34**. Assumed film thickness is 15 µm, film density is 1 390 kg/m³, both values being similar to the Mylar® film that was used for NASA's "Echo 1A" balloon.[523]

Aside of the object costs, the transportation costs are important. A seemingly Moon sized circular object in 500 km LEO would weigh about 1 340 t without pressure gas and attitude control. Current transportation costs would require minimum investments of about 14 G $ for transportation only.

Additional problems include high quality production of huge inflatable structures, expected damage by micrometeorites and space debris, outgassing, change of the object's shape resulting of loss of pressure at the end of the life cycle, and the disposal of the object.

But construction of a fragile object that consists of numerous cylinders ("sticks") instead of one huge lens could considerably reduce vulnerability and drive mass down to several 100 t. Due to the global attention and advertisement effect, the investment could be worthwhile, especially if transportation costs could be further reduced.

6.3.4.3 Conclusions

Product placement and rocket branding at current space missions are profitable, but insignificant for the sums that are required to finance spaceflight.

Table 6-37: Evaluation of "Advertising at Current Missions"

Topic		Advertising at Current Missions
Objective		Rocket branding, …
Technical Feasibility		Feasible (done in the past)
Effort	Costs	Several 10 000 $
Benefit	Revenues	About 1 000 000 $
Motivation	Profits	Yes
Result	Commercial Attractiveness	**Insignificant**
Comment		High profit margin for operator, but order of magnitude insignificant for spaceflight

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[523] Wade 2007, DuPont 2003.

For dedicated space missions, the situation is different. With utilization of existing space infrastructure, a dedicated international TV show in space might be interesting.

Table 6-38: Evaluation of "TV Show in Space"

Topic		TV Show in Space
Objective		Manned orbital flights
Technical Feasibility		Feasible (demonstrated)
Effort	Costs	More than 100 000 000 $
Benefit	Revenues	More than 100 000 000 $
Motivation	Profits	Probably
Result	Commercial Attractiveness	**Interesting**
Comment		Only with utilization of existing infrastructure

Though the advertising effect would probably be considerable, costs and technical challenges of constructing a visible advertising structure in space would be enormous.

Table 6-39: Evaluation of "Orbital Advertising Structure"

Topic		Large Orbital Advertising Structure
Objective		Same as topic
Technical Feasibility		Challenging
Effort	Costs	Several 1 000 000 000 $
Benefit	Revenues	?
Motivation	Profits	?
Result	Commercial Attractiveness	**Doubtful**
Comment		Advertising effect unknown

6.4 Resources, Materials and Products

Every aspect concerning resources and materials in space is considered, including mining, processing, and production in space and on other celestial bodies. Aspects of the space environment that are interesting for these tasks are:

- Practically unlimited resources
- Microgravity
- High vacuum

These aspects are positive or negative, strongly depending on the type of activity.

6.4.1 Resource Mining and Extraction

Though their number is not infinite, other solar system bodies – asteroids, comets, planets and moons – offer practically unlimited amounts of resources. As an example, the number of small asteroids with diameters between 1 and 3 km that are located in the asteroid belt is currently estimated as about 300 000.[524]

6.4.1.1 Situation on Earth

Though resources on Earth are factually limited, the amounts of most chemical elements and compounds are large enough to support human society for a very long time. The decisive factors for utilization are:

- Quality of enrichment
- Available amounts of sufficient enrichment
- Extraction costs
- Price on world market

Aside of the costs for mining and extraction, and eventual taxes and fees, terrestrial resources are basically cost free.

As a consequence, commercial mining and resource extraction is only done where the efforts to access existing deposits are low enough to create profits (except for a negligible amount of strategic materials).

6.4.1.2 Situation in Space

Proposals include small, singular missions and large scale mining activities. Processing and further utilization could be done on Earth or in space. Propellant production is one example for combined resource extraction and production activities.

A) Small Scale Activities

This is comparable to large scientific sample return missions with sample masses of several 100 kg. The high efforts and costs of such missions require extremely high value materials. Depending on the distance of the target object, and the expected purity or enrichment of the desired material, the cost increases dramatically.

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[524] Walter 2001.

The lowest prices of extraterrestrial materials are expected for locations that require the lowest efforts to reach. With present cost levels, this would be in the order of 1 000 000 $/kg for lunar and asteroid material return as a minimum (see Table 4-5). Though extremely high, the price is roughly in the same order as diamonds and could be attractive for jewelry. A problem, though, is clear identification of a piece of jewelry as a real Moon rock: If the true value of the stone is not immediately visible, public interest – and with it the price – might be too low.

There was a proposal of a company to finance an additional Apollo mission in the 1970s to return Moon rocks for jewelry uses. But NASA, as a non-profit organization, was not allowed to sell the flight.[525]

Table 6-40: Evaluation of "Resource Mining – Small"

Topic		Resource Mining – Small
Objective		Large sample return
Technical Feasibility		Challenging (demonstrated)
Effort	Costs	More than 1 000 000 $/kg
Benefit	Revenues	Perhaps 1 000 000 $/kg
Motivation	Profits	Eventually
Result	Commercial Attractiveness	**Low**
Comment		High primary investments, market unknown

B) Large Scale Activities

Construction of large, manned structures on the Moon or asteroids is required for mining operations.

Mining equipment is expected to have a high mass, especially considering the additional difficulties of mining operations in vacuum and at low gravity. The required infrastructure is considerably more complex than a space hotel, and must be located not in LEO, but on other celestial bodies. Therefore, construction costs are considerably higher than those for space hotels identified in chapter 6.3.2.2, resulting in the range of several thousands of G $.

Other restricting aspects of such activities are:

- Operational costs are expected to be in the same order of magnitude
- Complexity of operations is highest (see Figure 4-35)
- Adequate deposits are unknown, requiring extensive search pre-programs
- Utilization of in situ materials for construction is only possible after construction of sufficient production capacities (the produced goods must be high quality and space proof, further increasing costs)
- Returning large amounts of material to Earth is extremely demanding

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[525] Ruppe, Schmucker, personal conversation.

Large scale resource mining in space is not an option for the foreseeable future.

Table 6-41: Evaluation of "Resource Mining – Large"

Topic		Resource Mining – Large
Objective		Mining on Moon, Asteroid, …
Technical Feasibility		Not Feasible
Effort	Costs	Several 1 000 000 000 000 $
Benefit	Revenues	-
Motivation	Profits	-
Result	Commercial Attractiveness	**None**
Comment		Earth offers sufficient materials for less

C) Common Large Scale Proposal: Helium 3 on the Moon

The often proposed mining of Helium 3 on the Moon first requires functional fusion reactors on Earth that master the D-^{3}He fusion process that is even more demanding than D-D or D-T processes.[526] If this will ever be possible must be doubted from an engineering perspective.

One kg of ^{3}He could produce about 10^7 kWh usable electric energy on Earth.[527] At current energy costs of 0.17 €/kWh in Germany[528] (0.10 $/kWh in the U.S.[529]), and considering that generation costs are less than a third of the total costs, ^{3}He is currently worth less than 1 million $/kg – but lunar return costs of one Apollo mission are, at current cost levels, in the order of 2 million $/kg (see Table 4-5), not regarding the mining process costs that are expected to be even higher. See **Table 6-42**.

Table 6-42: Lunar ^{3}He Cost and Value Overview at Current Prices [M $/kg]

^{3}He Value	Transportation	Mining	Total ^{3}He Costs
1	2	4	6

Other problems are the actual enrichment of ^{3}He in lunar regolith, efficient extraction methods, actual processing and transportation and more. ^{3}He mining on the Moon is therefore not an option, nor will it be for a very long time, if ever.

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[526] Seboldt 2007.
[527] Ruppe 1991.
[528] Globus 1994-2007.
[529] US EIA 2007.

D) Propellant Production

Production of propellants from lunar regolith or Mars atmosphere seems comparatively simple on paper. But technical difficulties, including power supply, storage, impermeability, reliability and automation are still enormous. This is not a commercial option.

6.4.2 Production and Manufacturing

The idea of factories in space is not new. But up to now, production in space was done only on an experimental scale.

6.4.2.1 Attractive Space Attributes

Various physical processes are affected by Earth's gravity and atmosphere. These two factors are almost neutralized in space.

A) Microgravity and Weightlessness

Among the physical processes that are affected by gravity are thermal convection, sedimentation, solidification, and others.

The continuous acceleration of approximately 1 g or 9.80665 m/s² on Earth surface may be severely reduced by various means, as presented in **Table 6-43**. Though microgravity can be simulated on Earth for short durations, long duration periods are only achieved with space applications.

Table 6-43: Microgravity Quality and Duration

	Method	Acceleration [g]		Average Duration
		Minimum[530]	Maximum*	
Earth	Drop Tower	10^{-5}	1	5 – 10 s
	Parabolic Flight	10^{-4}	1.8	22 s
	Free Fall Capsule	10^{-2}	1	200 s
	Sounding Rocket[531]	10^{-3}	5	360 s
Space	US-STS Spacelab	10^{-4}	3	10 d
	ISS	10^{-3}	3 – 5	90 d
	Free Flyers	10^{-5}	3 – 5	unlimited

* Including mission preparation (launch, …), excluding impact.

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[530] Harr et al. 1990.

[531] Following the definition of chapter 3.1.3, sounding rockets are suborbital, and thus are not regarded as a space application.

A significant problem of large space structures is induced acceleration a_{ind} due to forced movement of any object that is not located in the structure's center of gravity.

$$a_{ind} = g_0 \frac{r_E^2}{r_E + h_{orb} + s} \cdot \left(\frac{1}{r_E + h_{orb}} - \frac{1}{r_E + h_{orb} + s} \right) \quad (6.12)$$

Theses accelerations depend on orbital altitude h_{orb} of the center of gravity, and distance s of the object from the orbital path of the structure's center of gravity, as illustrated in **Figure 6-35**.

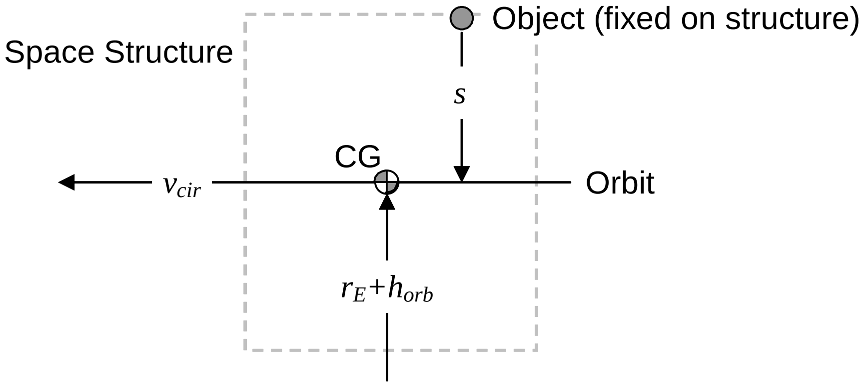

Figure 6-35: Acceleration Induced by Forced Motion

Therefore, the quality of microgravity in space barely exceeds 10^{-5} g.

Additional negative effects on microgravity result from:

- Other masses
- Atmospheric residual drag in LEO
- Internal forces (attitude control system, rotation, vibrations of onboard systems, human presence, …)

The long duration of the microgravity period has a neutralizing effect on the high costs of spaceflight: Dividing the total cost by effective microgravity duration, suborbital experiments are considerably more expensive than orbital options.[532]

B) High Vacuum

Residual atmospheric pressure in 300 km altitude is about $9 \cdot 10^{-11}$ bar, according to the 1976 U.S. Standard Atmosphere, but the real value may vary significantly due to solar activity and other reasons.[533] Between 10^{-9} to 10^{-11} bar for LEO is realistic.

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[532] Comparable to space tourism prices in Table 6-28 for one second of microgravity for one person.
[533] Griffin et al. 2004.

These values can further be reduced to a nearly perfect vacuum by the simple application of a shield, as shown in **Figure 6-36**.

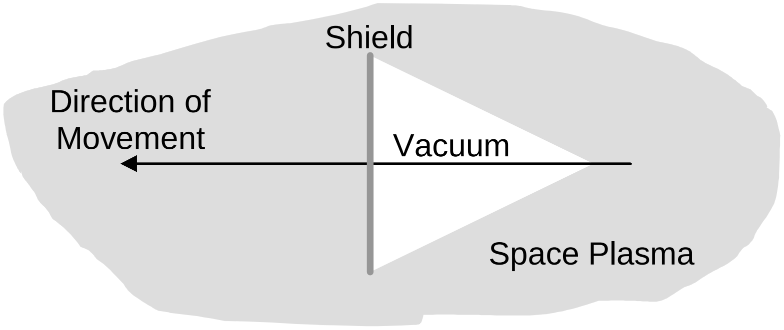

Figure 6-36: Perfect Vacuum by Means of Shielding

This could be of interest for exotic applications.

6.4.2.2 Utilization

There are numerous fields of interest, among them:

- Separation methods for pharmaceutical industries (electrophoresis, isoelectric focusing, …)
- Crystal growth (biotechnology, semiconductors, …)
- Manufacturing methods without containers
- Material sciences

Several unidentified types of utilization might exist.

6.4.2.3 Present State and Perspectives

The optimistic predictions of early spaceflight regarding factories in space have yet to come true. Two major barriers are:

- High round trip transportation costs compared to earthbound processes
- Significant technical problems at realization (experimental verification of functionality is insufficient for serial production)

The penalties of space production compared to production on Earth are illustrated in **Table 6-44** with the example of turbine blade manufacturing. The costs are normalized and shall only represent orders of magnitude. The higher efforts of space production become visible, especially considering recurring costs for large numbers of produced blades (new launcher, container, …).

Table 6-44: Exemplary Production in Space and on Earth
(Turbine Blade Manufacturing)

Required Steps	**Space**		**Earth**	
	Requires	**Costs***	**Requires**	**Costs***
Basic workpiece production	Factory (on Earth)	200	Factory	200
Transportation	Launcher	150	Truck	1
	Container with docking capability, altitude and attitude control, thermal control, power supply, …	300		
	Mission control	5		
Processing	Station (manned) with power supply, life support system, altitude and attitude control, …	5 000	Factory	200
	Astronaut time, supplies, mission control, …	30		
	Qualified machines	150		
Return	Return capsule with docking capability, control systems, heat shield, systems for landing, …	400	Truck	1
	Mission control	5		
Fine Machining	Machines	10	Machines	10
Quality Assurance	Test procedures	15	Test procedures	10
Total Costs		**6 265**		**422**

* Exemplary cost numbers in fictive currency to visualize orders of magnitude. Includes installations.

Production in space is too complex and costly to be a commercial option. But on an experimental scale, spaceflight may act as a catalyst for improved processes and production methods on Earth similar to spin-off and technology transfer.

Table 6-45: Evaluation of "Production and Manufacturing"

Topic		Production and Manufacturing
Objective		Transportation and return, station
Technical Feasibility		Feasible (demonstrated)
Effort	Costs	Several 10 000 000 000 $
Benefit	Revenues	?
Motivation	Profits	?
Result	Commercial Attractiveness	**None**
Comment		No products identified that require costly space production

6.5 Energetic and Environmental Tasks

Several tasks concern energy and power applications with their impact on Earth's environment. Aspects of the space environment that may contribute to better alternative solutions are:

- Distance to Earth
- Unlimited space
- Practically unlimited solar energy supply at constant rates

Energy and environment are decisive factors for the future development of mankind.

6.5.1 Power Generation in Space

The global energy market has an estimated volume of about 10 000 G $ per year, with roughly 30 % of this as electricity.[534]

Availability of applicable and storable energy is essential for human civilization. Often cited problems of terrestrial power generation include:

- Global warming (for fossil fuels)
- Depletion of ancient deposits (for fossil fuels)
- Radioactive waste production (for nuclear power generation)
- Insufficient efficiency factors (for regenerative energies)

Therefore, numerous proposals for space based power generation were made, mainly concentrating on Solar Power Satellites (SPS).

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[534] Schmucker et al. 2006.

6.5.1.1 Classification of Alternatives

Terrestrial supply of energy (electricity) can be divided into three parts:

- Generation
- Transmission
- Distribution

The basic costs are in the same order of magnitude for each part. One third of the customer's payment for electricity is in fact taxes and fees.[535] Thus, power generation costs effect only about one quarter of the final energy price, as is illustrated in **Figure 6-37**.

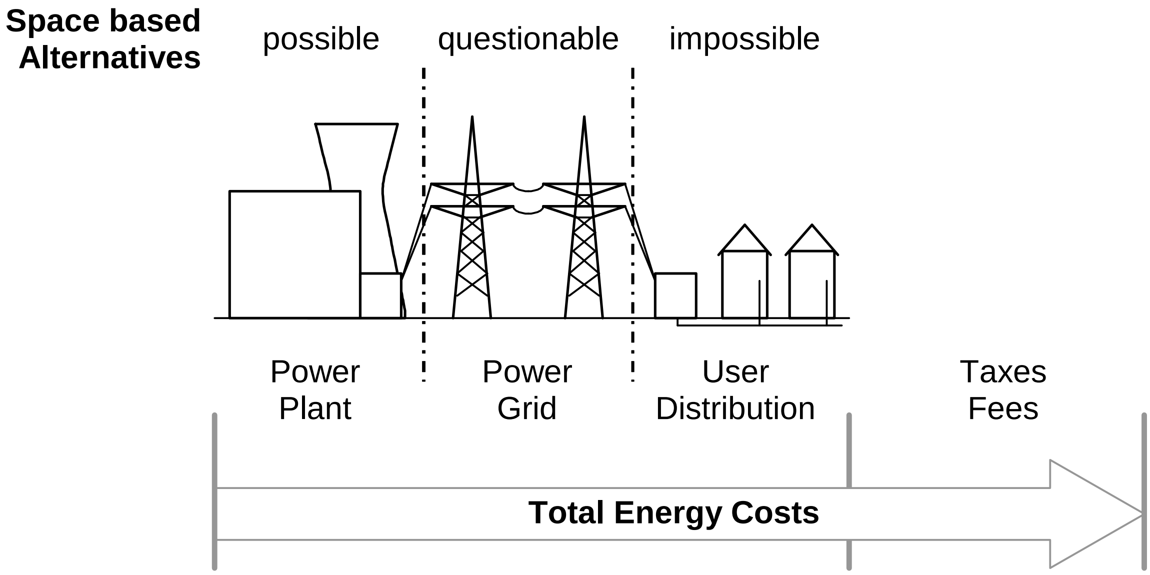

Figure 6-37: Terrestrial Energy Supply and Space Alternatives

There are several ways how spaceflight might contribute to terrestrial energy supply:

A) Fuel Mining in Space

The problems of fuel mining and extraction in space are the same as for other resources (see chapter 6.4.1.2).

Therefore, fuel mining (Helium 3, Uranium, Methane, …) in space is not an option for the foreseeable future.

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[535] Globus 1994-2007.

B) Fuel Production in Space

Energy sources available in space could be used to produce solid or liquid fuel that is then used in terrestrial power plants.

Though present power plant infrastructure could be used, the energy costs would increase significantly due to space transportation efforts and space capable fuel generation technologies (same problems as for space based production). This is also true for exotic fuels like antimatter.

Fuel production in space is not an option.

C) Terrestrial Power Generation and Energy Transportation via Space

Power is generated in a remote area on Earth and then transmitted to other areas via space. Reasons might be:

- High risk power plants (fusion, antimatter)
- Local availability of energy (solar: equator)
- Political and geographical barriers for power grid lines

As illustrated in **Figure 6-38**, the generated power is radiated to space by microwave or laser beams, where reflectors in GEO send them back to an Earth receiving station.

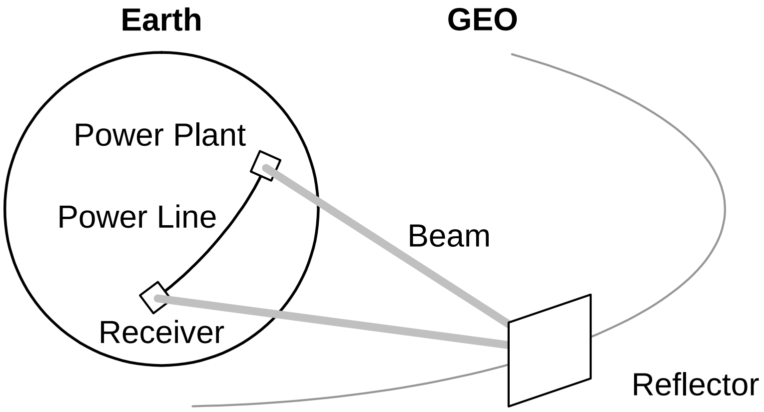

Figure 6-38: Energy Transportation via Space

High losses must be expected due to low efficiency factors. Reflector mass is expected in the order of several hundred tons. Numerous technical challenges remain to be solved (mirror attitude control, …). This is not a realistic alternative to power lines and pipelines.

Energy transportation via space is not an option.

D) Power Generation in Space and Energy Transportation to Earth

Power is generated by solar or nuclear means. Available locations are:

- Solar Synchronous Orbit (SSO. Special type of LEO)
- GEO
- Lagrange points
- Moon

Only GEO allows quasi-stationary power plants that stay above one terrestrial receiver. For all other locations, due to orbital characteristics, numerous receiver stations on Earth or additional reflectors in space are required for continuous power supply, as is illustrated in **Figure 6-39**.

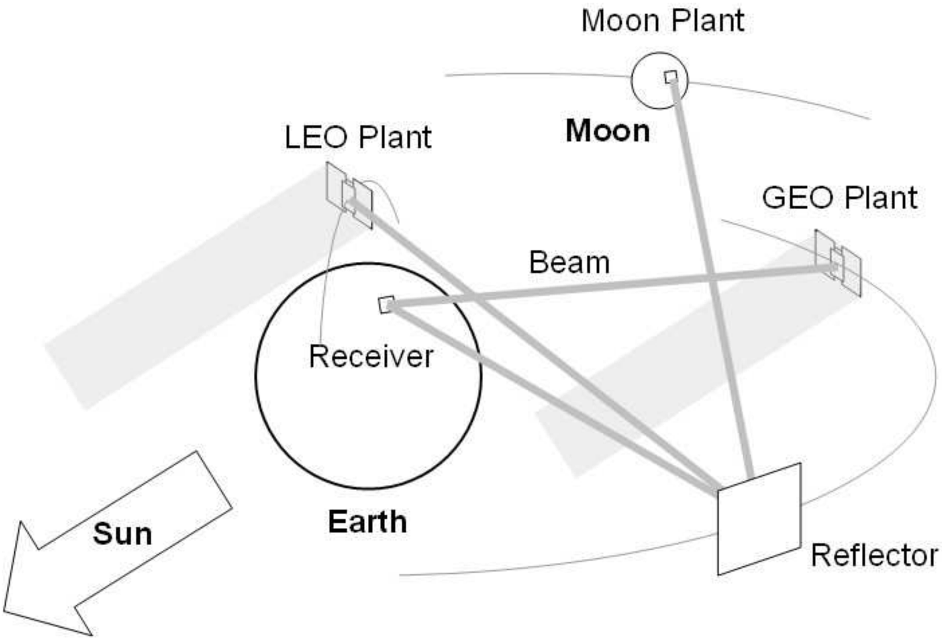

Figure 6-39: Available Power Plant Positions in Space

The maximum allowed cost of such an installation is limited by terrestrial alternatives: If the space based alternative is considerably more expensive, it will not be realized.

6.5.1.2 Solar Power Plants

There are many studies about solar power plants in space, also called Solar Power Satellites (SPS).

Characteristics of solar power in space are:

- Direct availability

- Constant power levels[536]
- Significantly higher energy density than on Earth

Average solar radiation flux values, considering daily and seasonal variations for Earth surface, are presented in **Table 6-46**.

Table 6-46: Average Solar Radiation Flux[537]

Parameter	Earth Surface		Space
	Tempered	Equator	
Intensity [kW/m²]	0.1	0.3	1.37
Energy Amount [kWh/m²]	876	2 628	12 000

Depending on the latitudinal location on Earth, the available solar energy flux in space is between 4 to 13 times higher than on Earth.

Problematic aspects of SPS are:

- Low total energy density – large area infrastructures required
- Energy transportation to Earth
- Shadow periods (depending on selected orbit)

As already mentioned, potential locations for SPS are GEO, LEO/SSO, Lagrange points and the Moon.

A) Geostationary Earth Orbit

The SPS is constructed in GEO or in LEO (with subsequent transfer to LEO using ion engines that are powered by the SPS itself, with the drawback of solar cell degradation when crossing Earth's radiation belt).

Basically, there are two power generation types:

- Solardynamic
- Photovoltaic

Solardynamic power generation is more efficient, but installed masses are higher than for photovoltaic power generation, as seen in **Table 6-47**. Masses per array area $m_{SPS/pow}/A_{SPS/pow}$ include supportive structures; presented efficiency factors are optimistic.

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[536] No day and night rhythm or cloud coverage. During the 11-year sun cycle, solar radiation levels at Earth's distance of 1 AU from the sun fluctuate at about 0.1 %, with singular peaks of 0.3 %. (NASA ARC 2003, NASA STS-107 2002)

[537] Seboldt 2004.

Table 6-47: Solar Power Generation Types[538]

Type		η [%]	$m_{SPS/pow}/A_{SPS/pow}$ [kg/m²]
Solardynamic		< 25	ca. 3.0
Photovoltaic	Crystalline	< 20	ca. 1.5
	Thin-Film	< 10	ca. 0.5

Power transformation efficiencies of **Table 6-47** are only one part of a chain of efficiency factors that reduce the total irradiated solar radiation flux power P_{sol} towards the real electrical power output on Earth P_{out}.

$$P_{out} = P_{sol} \cdot \prod \eta \tag{6.13}$$

The basic mode of operation of a GEO SPS with various influential efficiency factors is illustrated in **Figure 6-40**.

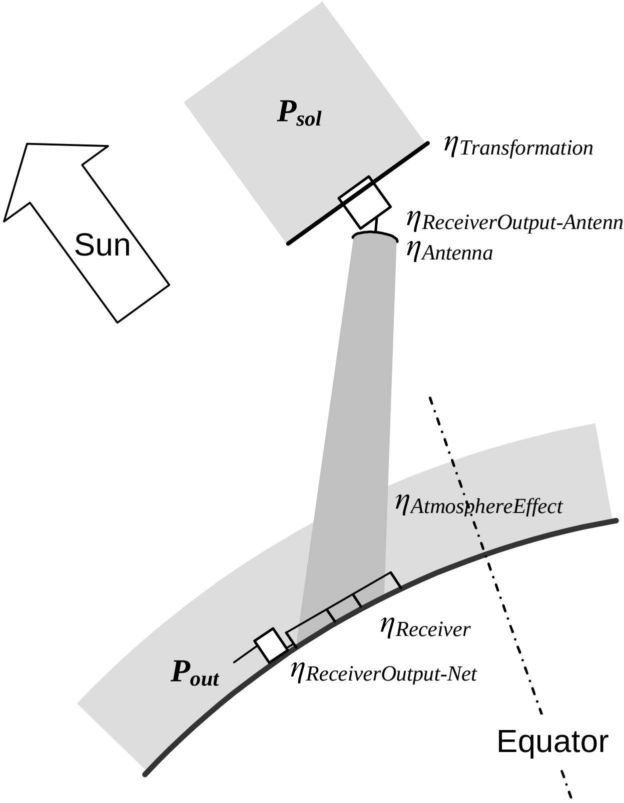

Figure 6-40: Mode of Operation and Efficiency Factors of a GEO SPS

In **Table 6-48**, average values for the most important additional efficiency factors are

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[538] Ruppe 1980, Seboldt 2004.

presented. They concern energy transportation from the SPS to the ground, and thus are independent of the type of power generation.

Table 6-48: Efficiency Factors for SPS[539]

Factor	η [%]
SPS Internal Conversion	88
SPS Antenna	97
Atmospheric Effects	99
Receiver	82
Receiver Internal Conversion	95

Total mass of a SPS m_{SPS} consists of antenna mass for power transfer $m_{SPS/ant}$, the converter that powers the antenna $m_{SPS/con}$, and, for the major part, of the elements that receive the solar power (e.g. solar arrays), $m_{SPS/pow}$.

$$m_{SPS} = m_{SPS/ant} + m_{SPS/con} + m_{SPS/pow} \tag{6.14}$$

Optimistically estimated for a large SPS, the mass of the antenna device and the converter is only 10 % of the receiver element array mass,

$$m_{SPS} = 1{,}1 \cdot m_{SPS/pow} \tag{6.15}$$

Combining this estimation with the values of Table 6-47 and Table 6-48, and with specific power input p_{sol} equivalent to the solar constant of 1.37 kW/m², conclusions on the specific effective terrestrial power output per SPS mass p_{out} can be made:

$$p_{out} = \frac{p_{sol} \cdot \prod \eta}{m_{SPS} / A_{SPS/pow}} \tag{6.16}$$

Table 6-49: Resulting SPS Data

Type		p_{out} [W/kg]
Solardynamic		68
Photovoltaic	Crystalline	109
	Thin-Film	164

The area requirement of the receiver or “rectenna” on Earth depends on the continuous exposure limit to microwave radiation which is assumed as an average 100 W/m².[540] Regarding efficiencies, this leads to a required area of 0.013 m² per Watt of terrestrial output, independent of power generation type.

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[539] Ruppe 1980.

[540] Seboldt 2004.

The specific numbers of **Table 6-49** can then be further used to estimate the costs for hardware, transportation and installation. For this, the following *extremely optimistic* numbers are assumed:

- Specific transportation costs are 1 000 \$/kg (construction in LEO!)
- Hardware costs are 3 000 \$/kg
- Installation costs are 2 000 \$/kg
- Operation time of the SPS is 20 years

Realistic assumptions would be significantly higher.

The resulting specific costs c_{energ} of one kWh terrestrial power output must be compared to current energy prices, as seen in **Table 6-50**. Average prices in the U.S. are 0.10 \$/kWh,[541] and 0.17 €/kWh in Germany[542] for the end user. For Germany, about 40 % are taxes and fees, and 60 % are costs that are equally shared between generation, transportation and distribution, as was already illustrated in Figure 6-37. This results in a current competitive energy cost of less than 0.04 €/kWh in Germany that would be substituted by 0.21 \$/kWh for SPS generated energy. The situation for the U.S. and the rest of the world is similar, if not worse due to lower local terrestrial energy costs. This means, SPS energy costs are at least 4 times higher than terrestrial!

Table 6-50: Energy Production Cost Comparison

Type		c_{energ} [\$/kWh]	
		Space (optimistic)	**Earth**
Solardynamic		0.50	ca. 0.05
Photovoltaic	Crystalline	0.31	
	Thin-Film	0.21	

Remember, the considerations above were made under the following assumptions:

- Extremely light SPS structural mass of 0.5 kg/m²
- Low mass penalty of 10 % for SPS antenna, cables, converter, …
- High efficiencies for solar power conversion
- LEO transportation costs of 1 000 \$/kg
- Costs of 3 000 \$/kg for space hardware
- Disregard of altitude and attitude control system
- Disregard of engines for transfer to GEO
- Disregard of terrestrial hardware costs (rectenna, …)
- Disregard of additional costs due to financing

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[541] US EIA 2007.

[542] Globus 1994-2007.

- Disregard of technical feasibility
- Disregard of numerous other economical and technical aspects

Using more realistic values for hardware and transportation costs, and still disregarding the technical challenges, computed SPS energy production costs rise by a factor of 15, meaning they are at least 60 times higher than terrestrial costs. Therefore, installation and operation of a solar power satellite is not an option.

B) Solar Synchronous Earth Orbit

Solar synchronous orbit (SSO) is a special LEO with high inclination. Expected costs for installation are the same as computed for the GEO SPS (installation in LEO was assumed!).

SSO, as any LEO, is not a stationary orbit, thus leading to additional problems. Either a stationary reflector in GEO is required (with additional efficiency losses), or numerous receiving stations must be installed around the world, combined with a complex, moveable SPS transmitter antenna.

Total SSO SPS performance is worse than GEO SPS performance.

C) Lagrange Points

The Lagrange points are not stationary relative to Earth surface. Problems are similar as for SSO, with additional ones resulting of higher distance to Earth.

D) Moon

Again, lunar surface is not stationary relative to Earth surface. Additional reflectors are required. Except for the lunar poles, there is a two week shadow period every month. Solar power plants on lunar surface are an even less attractive option than orbital plants.

6.5.1.3 Other Power Plant Types

Instead of solar power generation, other generation methods are possible. Only nuclear power seems sensible. The problem of energy transmission to Earth is the same as for SPS. But:

- Nuclear Fusion: No controlled fusion reaction yet. Probably too costly.
- Nuclear Fission: Nuclear fuel is heavy, supply with fuel rods costly. No alternative to terrestrial nuclear power plants.

Independent of power plant type, power generation in space is not an option.

6.5.1.4 Conclusion

The only sensible type of power generation in space – a geostationary solar power satellite – is commercially not competitive, even if its technical challenges and enormous investments are disregarded.

Table 6-51: Evaluation of "Power Generation in Space"

Topic		Power Generation in Space
Objective		Large solar power satellite
Technical Feasibility		Very Challenging
Effort	Costs	3.00 $/kWh
Benefit	Revenues	0.05 $/kWh
Motivation	Profits	Negative
Result	Commercial Attractiveness	**None**
Comment		Installation costs of several trillion $

6.5.2 Waste Disposal

The attributes of unlimited space and arbitrary distance to Earth make disposal of waste in space an attractive option. The high efforts of spaceflight reduce the materials worthwhile of space disposal to two categories:

- Toxic Waste
- Radioactive Waste

The idea of waste disposal in space, especially that of nuclear waste, is not new and was subject of numerous studies for many years.[543]

6.5.2.1 Characteristics of Eligible Waste Products

Toxic Waste is produced worldwide in large quantities. There is no common definition of toxic waste. It includes any kind of chemical as well as biological substances that are potentially harmful to living beings.

The disposal of radioactive or nuclear waste produced in nuclear power plants is a major topic of nuclear power production. The decisive nuclear waste is produced in form of spent fuel rods.

About 95 % of a fuel rod remain unchanged in the fission process. Not even 4 % of the spent fuel rod are actual waste consisting of highly active fission products.[544] Re-

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[543] Ruppe et al. 1979, Hayn et al. 1980, Schmucker 1982, DLR 1998.

[544] Brockhaus 1979.

processing of the fuel rods to segregate the high level waste (HLW) from the unspent fuel and reuse of the fuel is therefore sensible, especially considering the limited accessible uranium reserves on Earth.

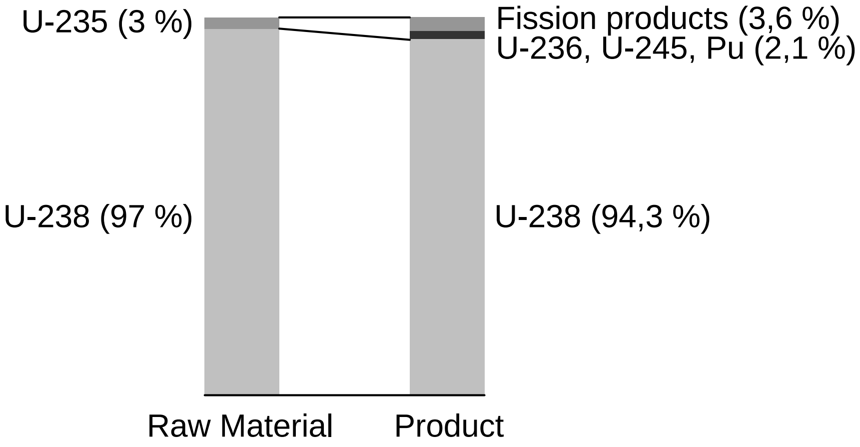

Figure 6-41: Exemplary Typical Nuclear Fuel Transformation

For the most common reactor type, the light water reactor, enriched Uranium of the type presented in **Figure 6-41** with about 3 % of U-235 is used as fuel.[545] Though the exact composition varies by a few percent,[546] the exemplary composition is sufficient for further considerations.[547]

Table 6-52: Quantities of Nuclear Waste

	Germany[548]	**USA**[549]	**Western World**[550]
Stored Spent Nuclear Fuel [t]		55 000	
Stored HLW [t]	26 145	15 000	
HLW Production per Year [t/a]			1 000

The worldwide nuclear power production increases steadily. Resulting HLW amounts are large, as seen in **Table 6-52**. For the whole world, an average HLW production of at least 2 000 t per year for the next 50 years seems realistic.

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[545] Brockhaus 1979.
[546] IK 1997.
[547] Persigehl, personal conversation.
[548] At end of 2004 (BFS 2007), assuming density of 15 t/m³.
[549] At end of 2005. (Macfarlane 2006)
[550] DLR 1998.

6.5.2.2 Methods of Disposal

A) On Earth

Toxic waste is usually combusted. Terrestrial deposition seems not to be an option.

Spent rods are usually recycled, and the HLW is deposited in deep geological repositories. Depending on the half-life of the waste components, it must be stored for thousands of years and longer.

B) In Space

There are various ways for waste disposal in space, as illustrated in **Figure 6-42**, some of them with the option of future waste recovery:

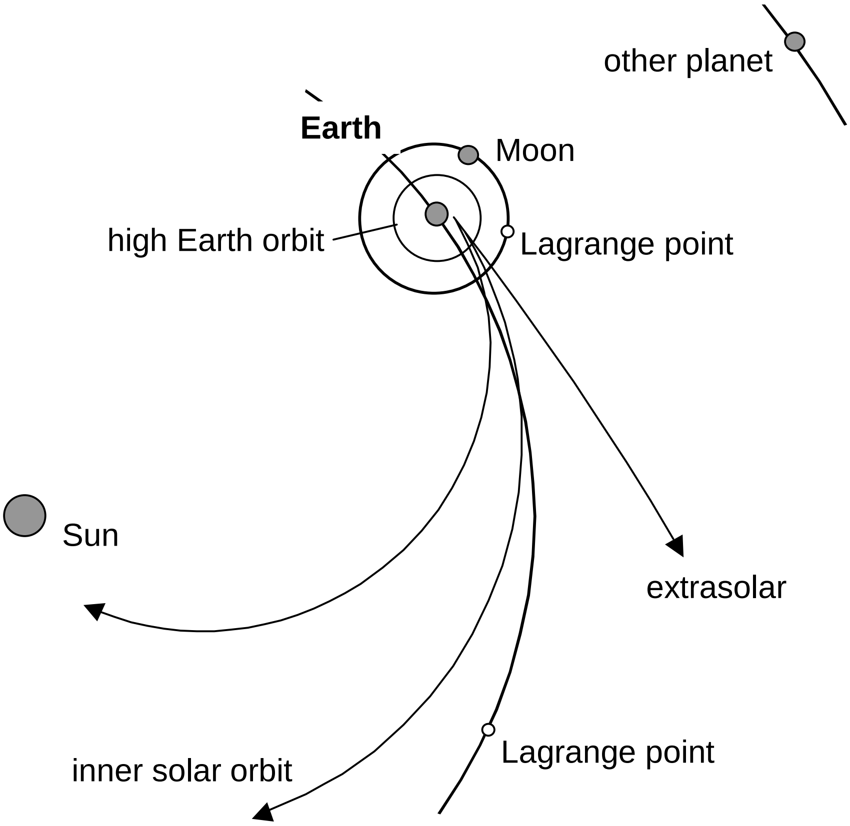

Figure 6-42: Various Available Locations for Waste Disposal in Space

- High Earth orbits (recoverable)
- Earth-Moon Lagrange points (recoverable)
- Lunar impact
- Earth-Sun Lagrange points (recoverable)
- Solar orbit

- Moon (recoverable)
- Other celestial bodies (partly recoverable)
- Extrasolar
- Sun

Velocity requirements increase from Earth orbit to sun disposal.

6.5.2.3 Cost and Profit Estimations

A) Toxic Waste

Transportation costs for space disposal are too expensive compared to toxic waste combustion costs. Space disposal is not an option for toxic waste.

B) Nuclear Waste

With given nuclear fuel rod mass m_{nuc} and resulting energy production E_{nuc}, specific nuclear energy production e_{nuc} is at best 1.2 · 10^6 kWh/kg.[551]

$$e_{nuc} = \frac{E_{nuc}}{m_{nuc}} \tag{6.17}$$

Resulting HLW mass m_{HLW} is the product of the previously assumed HLW fraction f_{HLW} of 3.6 % and the total nuclear fuel mass m_{nuc}.

$$m_{HLW} = m_{nuc} \cdot f_{HLW} \tag{6.18}$$

The specific energy production e_{HLW} per produced HLW thus is about 3 · 10^7 kWh/kg.

$$e_{HLW} = \frac{E_{nuc}}{m_{HLW}} \tag{6.19}$$

The specific cost for transportation of one kilogram of nuclear waste into LEO is

$$c_{tr,nuc} = k_{nuc} \cdot c_{tr} \quad . \tag{6.20}$$

Protective casing, heat shields and safety installations are assumed to increase mass of the transported waste by a factor k_{safe} of 10. This should be more than sufficient to ensure container integrity in case of launch failure.

For current costs and identified parameter values, a conservative transportation cost estimation to LEO of 100 000 $/kg of nuclear waste results. With

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[551] Brockhaus 1979.

$$c_{dis,nuc} = \frac{c_{tr,nuc}}{e_{nuc/HLW}} \,, \qquad (6.21)$$

the specific cost for LEO disposal $c_{dis,nuc}$ is 0.08 \$/kWh for unprocessed nuclear waste and 0.003 \$/kWh for HLW.

This means that the electricity tariff for nuclear generated power must increase by less than 0.01 \$/kWh to fully support LEO disposal of HLW at current space transportation costs – not regarding savings due to elimination of current costs of nuclear waste processing and disposal. The current average retail price of electricity is about 0.10 \$/kWh in the U.S.[552] and 0.17 €/kWh in Germany.[553]

The space disposal costs increase with the velocity requirements of the selected disposal targets, as seen in **Figure 6-43**.

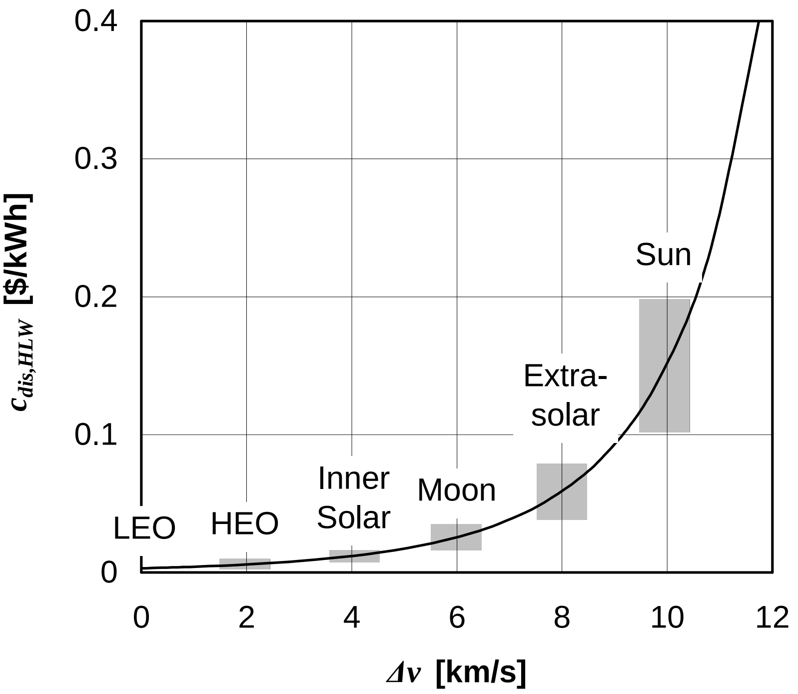

Figure 6-43: Additional Power Costs for Space Disposal

Nuclear high level waste disposal would be a commercially attractive, technically feasible way to significantly increase the scale of spaceflight activities, but only if payload container integrity can be guaranteed in case of launch failure.

Nonetheless, the public, and with it politics, are probably not very supportive of this proposal.

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[552] US EIA 2007.
[553] Globus 1994-2007.

Table 6-53: Evaluation of "Nuclear Waste Disposal"

Topic		Nuclear Waste Disposal
Objective		Transportation
Technical Feasibility		Feasible
Effort	Costs	About 100 000 \$/kg
Benefit	Revenues	More than 100 000 \$/kg
Motivation	Profits	Yes
Result	Commercial Attractiveness	**High**
Comment		Enables large scale spaceflight activities. Public and political support doubtful

6.5.3 Illumination and other Space Mirror Applications

Use of orbital mirrors for illumination is one of the oldest proposals for utilization of space. Considerations were already published in 1923 by Oberth. One of the applications he proposed was illumination of sea routes in the North Atlantic – he mentions potential avoidance of the Titanic disaster of 1912.[554,555]

A) Basic Considerations

Sun's diameter d_{sol} is 1.392 million km, with distance to Earth $s_{S\text{-}E}$ of 149.6 million km.[556] With

$$\varepsilon_{sol} = \arcsin \frac{d_{sol}}{s_{S-E}} \quad , \qquad (6.22)$$

this results in a visible angular size of the sun of 0.53 ° or 0.0093 rad at Earth's distance.

As illustrated in **Figure 6-44**, the size of the resulting focal spot on Earth's surface depends on mirror diameter d_{mir}, orbital altitude h_{orb} and mirror configuration.

The diameter (or semiminor axis) of the (elliptically) illuminated area d_{ill} depends on mirror distance s,

$$d_{ill} = \varepsilon_{sol} \cdot s \quad . \qquad (6.23)$$

Minimum focal spot size and, with it, maximum focal spot intensity, is logically

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[554] Oberth 1923.

[555] This was probably the first idea to use spaceflight for navigation and prevention.

[556] NASA GSFC 2007a.

achieved with the mirror in zenith of the target area,[557] resulting in

$$d_{ill,min} \approx 0{,}01 \cdot h_{orb} \quad . \tag{6.24}$$

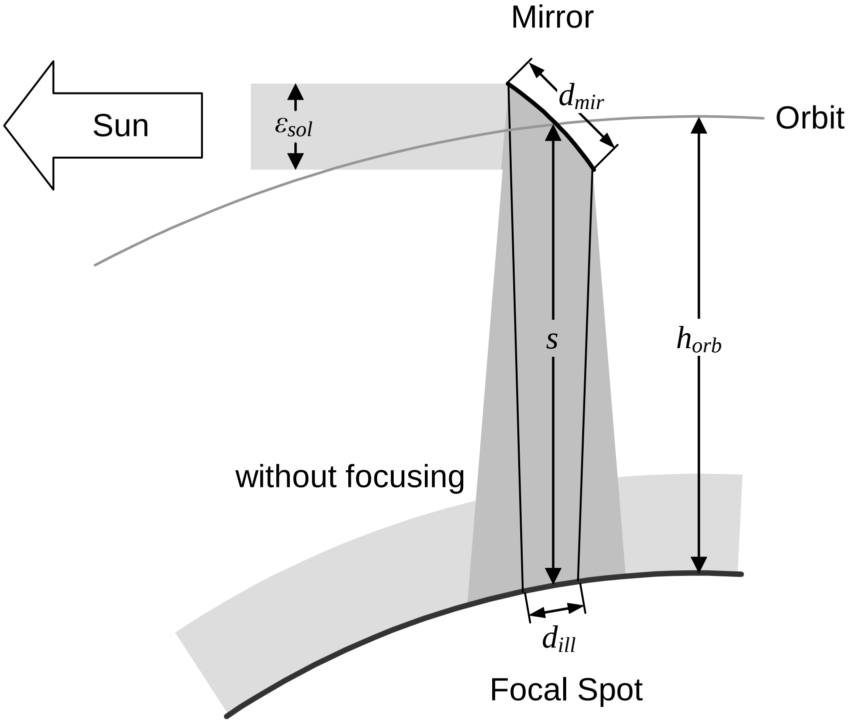

Figure 6-44: Space Mirror Parameters

The radiation power P_{ill} on Earth is subject to mirror efficiency factor η, effective mirror area A_{mir}, solar constant p_{sol} and the area ratio of mirror and focal spot:

$$P_{ill} = A_{mir} \, p_{sol} \eta \left(\frac{d_{mir}}{d_{ill,min}} \right)^2 \tag{6.25}$$

B) Illumination

Continuous illumination requires a geostationary position of the mirror at an altitude of about 36 000 km. This leads to minimum illumination spot diameter of about 360 km.

The light intensity or illuminance E_M of the full Moon is seen as adequate for illumination, which is about 1/400 000 of sunlight intensity.[558] With

$$A_{ill,min} \cdot E_M = A_{mir} \cdot E_{sol} \cdot \eta_{mir} \quad , \tag{6.26}$$

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[557] Ruppe 1970.

[558] NASA Science 2006.

resulting in

$$d_{mir} = \sqrt{d_{ill,min}^2 \frac{E_M}{E_{sol}} \frac{1}{\eta_{mir}}} \quad , \qquad (6.27)$$

and assuming a mirror efficiency of 90 %, the minimum mirror diameter for artificial moonlight is 600 m.

Using the material proposed for the advertising object in chapter 6.3.4.2 as reflector material, with thickness of 15 µm and density of 1 390 kg/m³, the reflector mass alone is 5.9 t. Total mirror mass is difficult to assume due to unknown technical issues such as required support structure or attitude control. 50 t is a very optimistic assumption, resulting in 1.5 to 2 G $ transportation costs to GEO at current prices, with additional costs for development and production.

As a comparison, Munich's city illumination has about 175 000 lamps that are active for 4 100 hours per year.[559] This results in annual energy costs of about 10 to 15 M € for illumination.

Though the illuminated area would be considerably larger than the area of one city, the costs of space mirrors are high. Application of mirrors in large areas with high population could possibly be commercially attractive, considering that the costs of a mirror could be spread on the whole affected illumination area. Further research is recommended, but more important, detailed research on mental and environmental effects of continuous illumination should be done.

Table 6-54: Evaluation of "Illumination"

Topic		Illumination
Objective		Space mirror
Technical Feasibility		Challenging
Effort	Costs	Several 1 000 000 000 $
Benefit	Revenues	Several 10 000 000 $ per city
Motivation	Profits	Eventually
Result	Commercial Attractiveness	**Low**
Comment		Public acceptance doubtful

C) Earthbound Solar Power Plant Illumination

Space mirrors could focus solar light towards terrestrial solar power plants, increasing power output and bridging night times. Due to the large minimum focal spot diameter, this would be sensible only for very large solar power plants of several thousand square kilometers. This might be a topic for the far future.

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[559] München 2004.

D) Other Applications

Other proposed applications of space mirrors are:

- Modification of weather and climate
- Military applications

Due to their nature, these applications are discussed in chapter 8.

6.6 Conclusion

It is important to remember that each space activity has a total mission cost C_{tot} consisting of transportation costs C_{tr} and the significantly higher hardware and operations segment costs $C_{h\&o}$.

$$C_{tot} = C_{h\&o} + C_{tr} \qquad (6.28)$$

$C_{h\&o}$ further consists of costs for operation C_o that are subject to mission duration and complexity, and of hardware or payload costs C_p that increase with payload mass m_p. For simplification, the factors are combined to a specific cost $c_{h\&o}$ that includes duration and complexity of the operation (see chapter 4.1.2.4). With this,

$$C_{h\&o} = m_p \cdot c_{h\&o} \ . \qquad (6.29)$$

Transportation costs are subject to payload mass m_p, specific transportation costs c_{tr}, and an optional factor k_{re} if the payload has to be returned to Earth.

$$C_{tr} = c_{tr} \cdot m_p \left(1 + k_{re}\right) \qquad (6.30)$$

Total space mission cost is therefore

$$C_{tot} = c_{h\&o} \cdot m_p + c_{tr} \cdot m_p \left(1 + k_{re}\right) \ . \qquad (6.31)$$

So, if $c_{h\&o}$ approaches zero because of low operational complexity and requirements, total mission costs roughly are

$$C_{tot} = c_{tr} \cdot m_p \left(1 + k_{re}\right) \ . \qquad (6.32)$$

Because c_{tr} is lower than $c_{h\&o}$, applications with this character are most promising. This is the case for simple waste disposal and space burial, for example.

When hardware and operations become more and more complex, c_{tr} gets insignificant, resulting in

$$C_{tot} = c_{h\&o} \cdot m_p \ . \qquad (6.33)$$

Thus, only extremely valuable products that do not require complex operations in space have a chance of commercial success. This is not the case for lunar ^{3}He, for example. For enduring services that have a low mass requirement, though, total cost is low, and is divided by the number of customers n and service duration t_o,

$$C_{user} = \frac{C_{tot}}{n_{user} \cdot t_o} \quad . \qquad (6.34)$$

This makes *services* in space for many users considerably more attractive than *products* – as is the case for satellite communication and navigation.

Any way, commercialization of space is extremely difficult. This result is consistent with the current scale of commercial space activities and the hesitant engagement of companies in space related fields of business that are not funded by public money.

Results of this chapter are:

- Launch business is a small part of space business with low profit margins.
- Current activities (launch business, satellites) will continue at roughly the same levels.
- Navigation stimulates the terrestrial market for user applications, but has no significant impact on the space development.
- The space tourism market is smaller than generally anticipated.
- Nuclear waste disposal and space burials are commercially sound concepts, but are subject to political and ethical aspects.
- All other future topics suffer on the high investment costs of spaceflight and the comparatively low financial return.

These results lead to another conclusion: It is the aspect “distance to Earth” that represents the key to commercial activities. All other previously identified space environment aspects (gravity, temperature, vacuum, radiation, unlimited space, small particles) contribute very little to nothing to successful commercialization of space – predominantly, they have a negative influence.

On Earth, commercial enterprises look for locations that promise the least additional costs and low restrictions to achieve a previously set goal. Examples are production lines that are moved from Europe to China. Space, in contrast, has higher requirements and hurdles than any earthbound environment.

To summarize this, successful commercial topics must be unique in a way that *only space* can offer an ultimate solution.

As long as no new, promising commercial space applications are revealed, increased commercial engagement in space activities cannot be expected. But identification of such an application will inevitably lead to extensive spaceflight activities.

7. Benefits as a Byproduct

An often cited justification of spaceflight lies in the terrestrial application of technologies, processes, services, and products that were originally developed for spaceflight. The common view concerning these byproducts, their actual significance, and the mechanisms leading to their creation are discussed in detail in this chapter.

Many of the topics that were considered in the previous chapter turned out to create byproducts of spaceflight, too. But due to their character, quantification of their actual value is impossible. For the byproducts that are analyzed in this chapter, quantification seems possible, though, as illustrated in **Figure 7-1**.

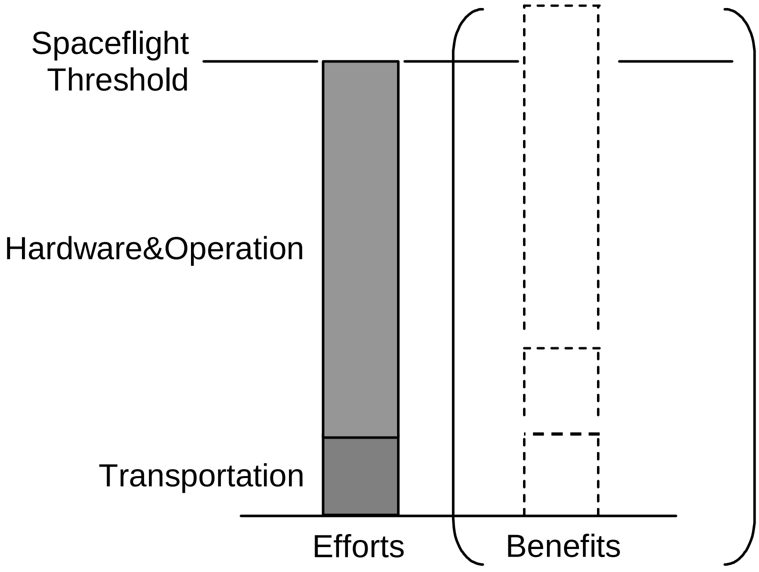

Figure 7-1: The Benefits That Come as a Byproduct

The main subject of this chapter is to give an answer to these questions: Is space related spin-off and technology transfer important enough to justify spaceflight on its own? If not, is a detailed cost benefit analysis required for each byproduct to make conclusions on expected future benefits?

Any type of spaceflight activities may randomly produce byproducts – no special mission objectives must be declared. Therefore, the following topics are considered for a global approach to spin-off and technology transfer:

- Common approach to the topic
  - Often cited spin-off examples
  - Present management of technology transfer
- Problematic aspects of spin-off and technology transfer
  - Spaceflight spin-off myths

  - Real spin-offs
  - Spin-off and technology transfer in other disciplines
  - Fundamental differences of spaceflight and other markets
  - Mechanisms of spin-off and technology transfer
- The role of spaceflight as a catalyst

With this, the actual role of spin-off and technology transfer for astronautics should be identified.

7.1 Common Approach

In general, spaceflight is seen as a pacemaker for technological research and development.[560] Solutions for the numerous problems and efforts of spaceflight activities might have a great range of applications on Earth. The process to do this is called technology transfer, while its actual application is called spin-off.

7.1.1 Often Cited Examples for Spin-Offs

Some of the most famous, commonly accepted spaceflight spin-off products are:

- Teflon
- Velcro
- Integrated Circuits
- Cordless power tools
- Quartz clocks
- Barcodes
- Space Pen

The total number and meaning of spaceflight spin-offs is often seen as enormous. Jesco von Puttkamer mentions that the backflow of the Apollo program was seven times higher than its investments, and for other space programs, the returns were up to ten times higher. A major part of these backflows must have been estimated as profits due to spin-off and technology transfer, because it is further stated that alone 259 out of many thousand spin-off applications of NASA space technology generated 22 G $ for the economy, and created, or saved, 353 000 jobs.[561]

7.1.2 Present Management of Technology Transfer

High technology sectors, especially astronautics, create countless technologies that

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[560] The Canadian documentary of Julian Jones, “How William Shatner Changed The World” (2005), even goes farther, naming the *fictional* spaceflights of the diverse “Star Trek” TV series and movies as vital inspiration for technologies such as cell phones, the software language “Basic”, and the modern iPod among others.

[561] Puttkamer 1992.

could be further used for other applications than previously intended.

There are public institutions – and some privately funded companies – that are commissioned to stimulate technology transfer activities, and support other companies in doing tech transfer. These institutions are numerous, and a selection is listed below.[562]

In Germany:

- Chambers of Industry and Commerce
- Technology transfer centers at various universities
- German Aerospace Agency (DLR)
- Helmholtz Society
- Steinbeis-Europa-Zentrum
- MST Aerospace
- ALROUND

In Europe:

- Spacelink Europe (MST Aerospace, Novespace, D'Appolonia, JRA Aerospace, …)
- ESINET
- ASLink
- T4Tech
- SME-Forum
- EuroTecBroker
- IRC
- CRAFT

In the USA:

- Technology Transfer Offices of the NASA Centers: Ames, Dryden, Glenn, Goddard, JPL, Johnson, Kennedy, Langley, Marshall, Stennis
- National Technology Transfer Network: National Technology Transfer Center (NTTC) and six Regional Technology Transfer Centers (RTTC): Far West, Mid Atlantic, Mid-Continent, Mid-West Great Lakes, Northeast, Southeast
- NASA Incubators: Ames Technology Commercialization Center, NASA Commercialization Center, Lewis Incubator for Technology, Emerging Technology Centers, UH-NASA Technology Commercialization Incubator, Florida/NASA Business Incubation Center, Hampton Roads Technology Incubator, BizTech, Mississippi Enterprise for Technology

These institutions are additionally supported by numerous public initiatives, for example SBIR and STTR in the U.S..[562]

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[562] Bahls 2005.

This means that spaceflight spin-off and technology transfer activities are intensely promoted all over the world to simplify the backflow of the funds that were previously invested in spaceflight.

7.2 Characteristics of Space Related Spin-Off and Technology Transfer

At a closer look, the situation of spin-off and technology transfer is different than usually presented:

7.2.1 Spaceflight Spin-Off Myths

Most of the so called spaceflight spin-offs emerge as myths at close examination.

- **Teflon**
  Teflon was accidentally discovered at the company DuPont in 1938. In the 1940s, it was used at various applications, including the Manhattan Project. Fluorine synthetics were further commercially developed and applied in the 1950s, and finally they were used for spaceflight in the 1960s.[563] **Figure 7-2** illustrates this interaction of different industrial branches.

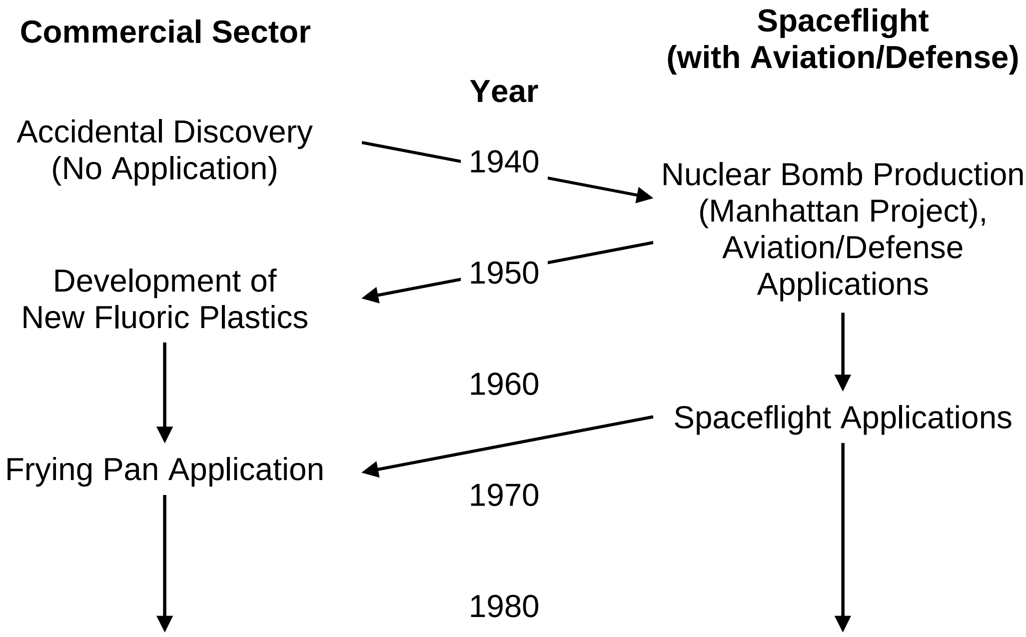

Figure 7-2: Interdisciplinary Development and Application of Teflon

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[563] Schmucker et al. 2006, NASA STI 2007.

- **Velcro**
  Velcro is a Swiss invention of the 1940s and was later used for the Apollo program.[564] Use for manned spaceflight continues until today.

- **Cordless Power Tools**
  Black & Decker presented the first cordless power tool in 1961. Later, Apollo astronauts used specifically designed tools on the Moon that were developed by the same company.[564]

- **Quartz Clocks**
  Quartz clocks date back to 1927. NASA partnered with a company in the late 1960s to develop highly accurate quartz clocks that also were commercially available for a time.[564]

- **Barcodes**
  The first barcode was developed in the U.S. by students in 1948 and patented in 1952.[565] A special type of barcode was later developed by NASA for inventory management of the space shuttle and other space related components.[564]

- **Space Pen**
  The so called "Space Pen" was developed in the mid 1960s by the Fisher Pen Company without any NASA money, but with the intent of selling it to NASA to increase its public sales. It was advertised as "Space Pen" and commercially available for a price of 1.98 $. Within a few years, NASA actually bought the pen and used it for Apollo and Skylab missions under the name of "Data Recording Pen".[566,567]

7.2.2 Real Spin-Offs

Nonetheless, there are actual spin-offs that were initially developed for spaceflight. But most of them are very specific, and the high number of technology transfer institutions that are required to generate the comparatively low number of applied processes and products shows how difficult creation of real spaceflight spin-offs is.

As an example, the annual NASA report about spin-offs and technology transfers of the year 2006 features 40 spin-offs in detail.[564] Among them are:

- **"SpaceStationSim" Interactive Video Game**
  NASA supported a software company in the development of a video game which puts the player in the position of "Chief Administrator", managing astronauts on the ISS as well as ISS construction and operation itself.[568]

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[564] NASA STI 2007.
[565] Wikipedia 2007.
[566] Day 2006.
[567] The Soviets used pencils.
[568] Interestingly enough, the currency used in the game is not dollars, but "international goodwill".

- **Anti-Icing Agent**
  For the aeronautical branch – not the astronautical! –, an anti-icing agent was developed that is either liquid or, when sprayed on a surface, solidifies to the consistency of sherbet for better adhesion. It is environmentally safe enough to be deemed "food grade".[569]

- **Provision of Satellite Imagery to "Lewis and Clark Geosystem"**
  In a collaborative initiative with other agencies, academia, and industry, an online collection of various resources was created that helps explain the route of explorers Lewis and Clark, and helps understanding their mission. NASA contributed imagery created by various sensing instruments.

- **Lightweight Thermal Insulation Sheets**
  Vaporized aluminum is deposited on thin plastic substrates to create a thin, flexible, thermal-reflective material. These sheets were already used to insulate Apollo lunar landing vehicles and the damaged part of Skylab, and are now in use as rescue blankets, blankets for marathon runners, outdoor gear, and more.

Over the years, some important contributions of the space sector to other important terrestrial products were often ignored. To present two examples:

- **Fuel Cell**
  This type of efficient energy storage was invented as early as 1839, but was advanced and applied in the space programs of the 1960s.[570]

- **Airbag**
  The gas generators for airbags or Supplemental Restraint Systems (SRS) combine insights and technologies originating in the space and defense technology sectors.[570]

Thus, there *are* successful terrestrial applications of space derived technologies.

7.2.3 Spin-Off and Technology Transfer in Other Disciplines

The importance of aviation, shipbuilding or other disciplines is not based on potential spin-offs. Technological advances in these fields that are applied on other fields are not regarded as justifications for their own activities.

Two examples illustrate this consideration: The Head Up Display (HUD) and Fly-by-Wire technology. By now, both are used not only in aircraft, but also in automobiles. But no one would ever claim that aviation is worthwhile because of these spin-offs.

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[569] It is ironic that NASA promotes, under the heading "Preventing Ice Before it Forms", an anti-icing agent created at NASA Ames Research Center, but still has foam insulation problems at its US-STS External Tank associated with icing (though, of course, the mechanisms at work differ significantly from those at airplane wings).

[570] Wagner 1996.

Spaceflight is the only engineering discipline that tries to justify itself with discovery of new technologies and potential spin-offs.

7.2.4 Fundamental Differences of Spaceflight and Other Markets

Successful spin-offs must have a sufficient market – they are useless if no one needs them. Spaceflight, similar to aviation and defense technologies, has specific characteristics that differ from the majority of other fields of technology, and therefore from other markets, as seen in **Table 7-1**.

Table 7-1: Characteristics of Sector-Specific Products and Technologies

Characteristic	Aerospace/ Defense	Civil Sector
Requirements	High	Low
Costs	High	Low
Dominant Factor	Availability	Cost
Quantities	Low	High
Processes	Reliable	Simple

This distance of spaceflight to other markets is further illustrated in **Figure 7-3**.

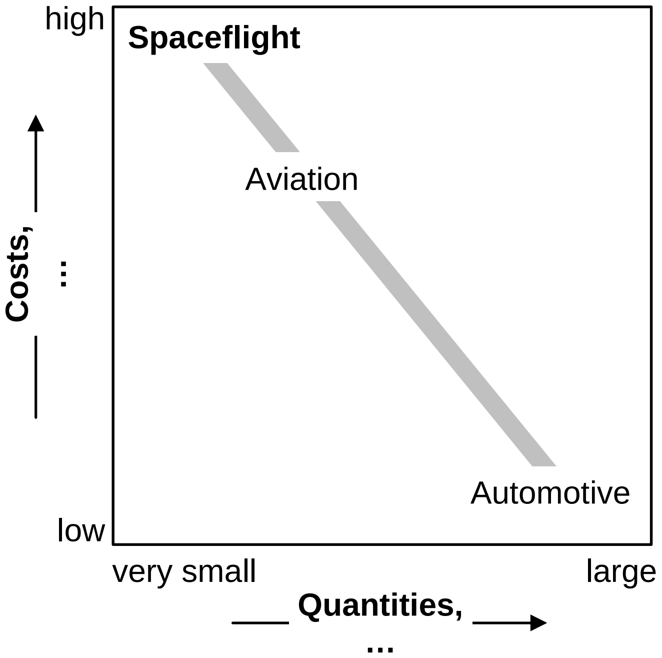

Figure 7-3: Spaceflight and Other Markets

Additionally, solutions and applications for spaceflight are very specific compared to other sectors, as illustrated in **Figure 7-4**.

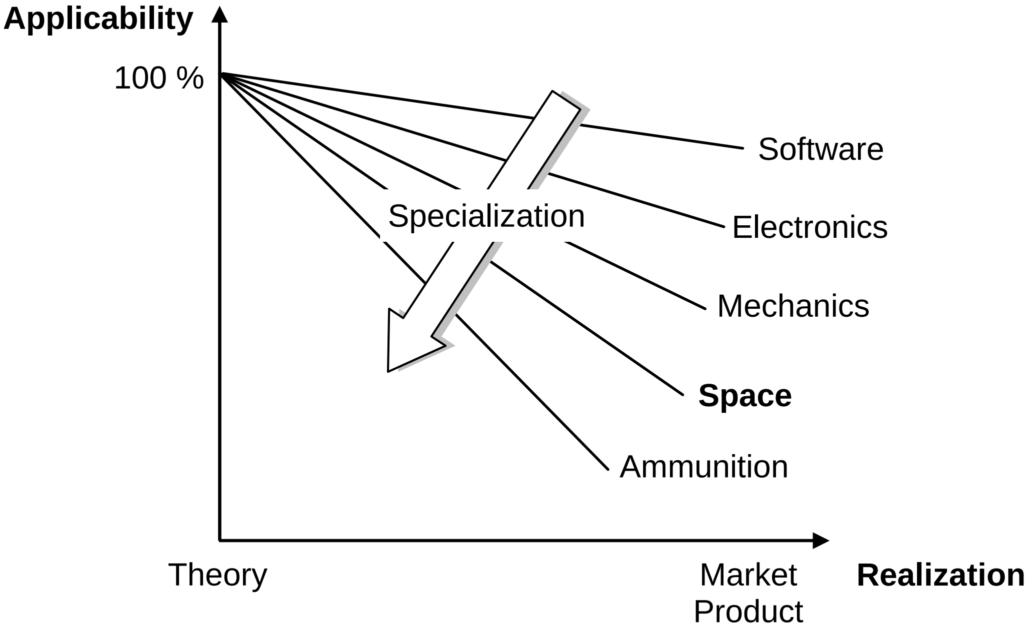

Figure 7-4: Applicability of Various Disciplines[571]

The market requirements dictate the specifications of products. Therefore, it is difficult to apply specific innovations of the spaceflight sector in the civil sector and vice versa. This significantly reduces the potential number of spaceflight spin-offs.

7.2.5 The Mechanism of Spin-Off and Technology Transfer

The fundamental process of problem solving is:

A *solution* is required for an existing *problem*.

For technology transfer, the process is reversed:

A *problem* is required for an existing *solution*.

Directed transfer of technology, and with it transfer of processes and products for potential use in other sectors, is extremely difficult due to this fundamentally different characteristic of the transfer process.

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[571] Illustration according to Th. Mayr, BDLI.

Technology transfer and technology advance usually show a certain pattern that is illustrated in **Figure 7-5**. It is not directed: The technologies and the resulting products of one sector are randomly seized by other sectors. The sector advances the technology for its own applications. From there, it bounces back or forth and is seized again by other sectors, or might return to previous sectors.

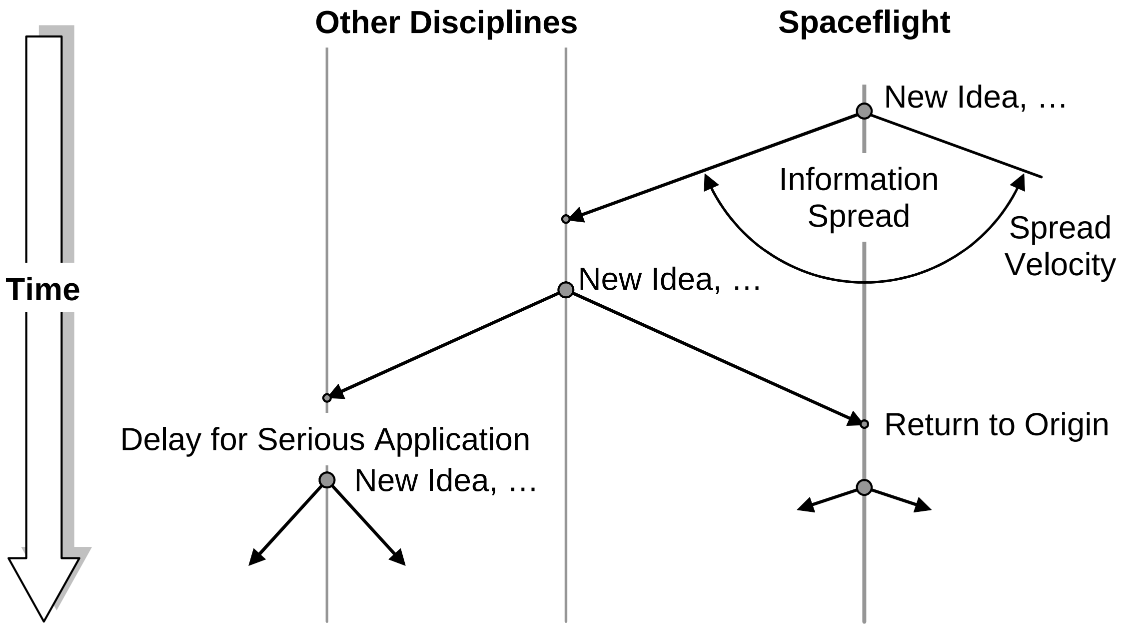

Figure 7-5: Spin-Off Mechanism

This process of bouncing has fundamental flaws for the high tech sectors of aerospace and defense, as is illustrated in **Figure 7-6**.

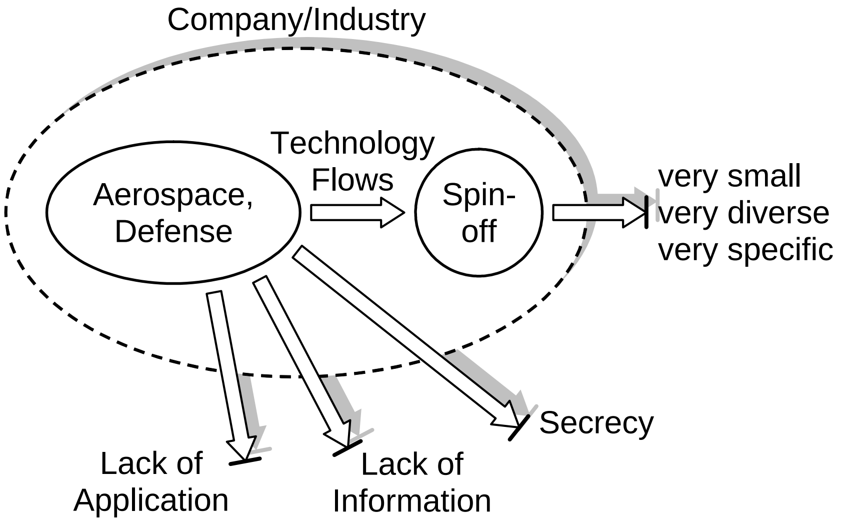

Figure 7-6: Barriers of Technology Transfer

These flaws are:

- By their very nature, there are lacks in the applicability of space technologies to terrestrial uses.
- The flow of information to other industries is problematic due to numerous reasons like, for example, basic philosophies.
- High tech industries are subject to increased secrecy, towards foreign companies (e.g. International Traffic in Arms Regulations), as well as in general terms.
- Spin-offs that are created within the same company, or even within the aerospace and defense sector, usually are very specific, have a small value of application, or are too diverse for the company to effectively market them.

But, if not as an origin of new products and technologies, spaceflight seems to play an important role as a catalyst for the advance of existing products and technologies.

7.3 The Role of Spaceflight as a Catalyst

All too often, astronautics are stated as origin of a technical development that, in reality, was a product of basic engineering that was later used for spaceflight applications, as is illustrated in **Figure 7-7**.

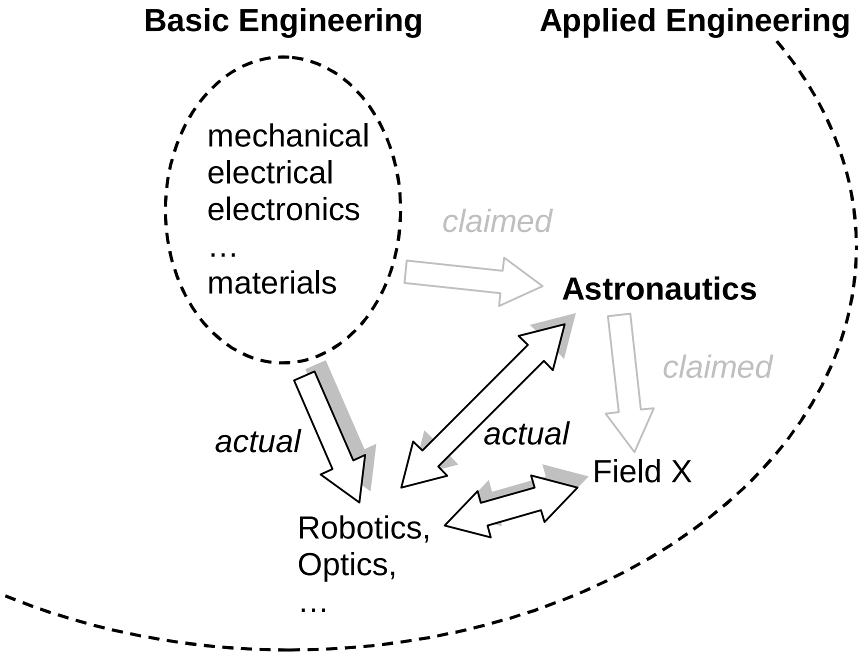

Figure 7-7: Flow of Technologies

Other areas of engineering do not claim that many technologies as inherent.[572]

But space applications can stimulate terrestrial developments, and they can bridge the gap until better suited terrestrial alternatives are available. Space telescopes and communication satellites may hereby serve as examples:

- Performance of the Hubble Space Telescope is soon surpassed by terrestrial telescopes.
- Communication satellites bridged the period to the development of intercontinental optical fiber cable networks.

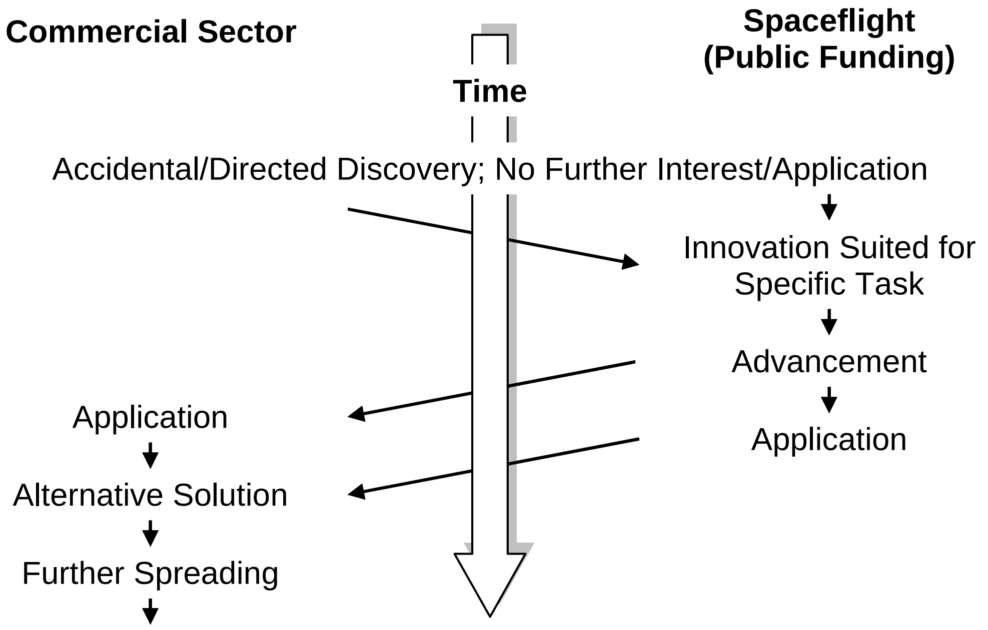

Figure 7-8: Interaction of Spaceflight and Commercial Sector

Innovations created by spin-off and technology transfer are not a predictable and enforceable process. But spaceflight may serve as a catalyst for further developments, as illustrated in **Figure 7-8**.

7.4 Results and Consequences

Considering previous experiences, and comparing the situation to other high tech disciplines, spaceflight does not have an extraordinary position that allows justifica-

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[572] The special standing of astronautics is also visible with the following example: No matter what a company (or institution or individual) develops (or produces) – if the product or process is used (or *could be* used) for space applications, it is seen as space technology! This includes drawer racks, screws, structures, interior design, heating elements, bearings, switches, furniture, … . But no one would ever claim to do automotive engineering just because he develops electric window controls, instrument panels, cables, seats or ashtrays for cars.

tion solely by spin-off and technology transfer. No field of technology can be justified only by the potential to create spin-offs. As was clearly stated by the head of the ESA Technology Transfer Programme Office:

> “Wir machen Raumfahrt nicht, um Technologietransfer zu betreiben [*We do not go into space to make technology transfer*].”[573]

The distance to Earth, and thus to terrestrial applications, is more a handicap than a chance for spaceflight spin-offs and technology transfer: For the most part, the solutions developed for space applications are too expensive or too specialized for sound terrestrial applications – they are too far away from the terrestrial needs.

But, due to its inherent extreme requirements, spaceflight has an important role as a catalyst for technological progress. This catalyst role is a byproduct that is created anyway at spaceflight activities – it can further back existing space programs, but it cannot justify spaceflight on its own.

Table 7-2: Evaluation of “Spin-off and Technology Transfer”

Topic		Spin-off and Technology Transfer
Objective		Any type of spaceflight
Technical Feasibility		Feasible (currently done)
Effort*	Costs	Several 1 000 000 000 $
Benefit & Motivation	Claimed	Processes, products, …
	Actual	Accelerated development
Result		Important catalytic effect, spaceflight done anyway for other reasons

* Done anyway.

It is no sufficient justification to engage in spaceflight activities <u>only</u> to potentially create byproducts, neither for companies nor for governments. But the byproducts that <u>are</u> created at national space engagements, and the catalytic effect of spaceflight for terrestrial applications both contribute to the relevance of a space program of leading industrial nations.

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[573] Frank M. Salzgeber, Acting Head of the Technology Transfer Programme Office of ESA, at a panel discussion at the Hannover Messe during the Space Transfer 08 Event, on April 23, 2008.

8. Potential Benefits

There are benefits with a low probability of occurrence, but once they occur, their impact is extremely high, and could even reach global scale. This is illustrated in **Figure 8-1**. In other words, spaceflight helps to create *potential* benefits.

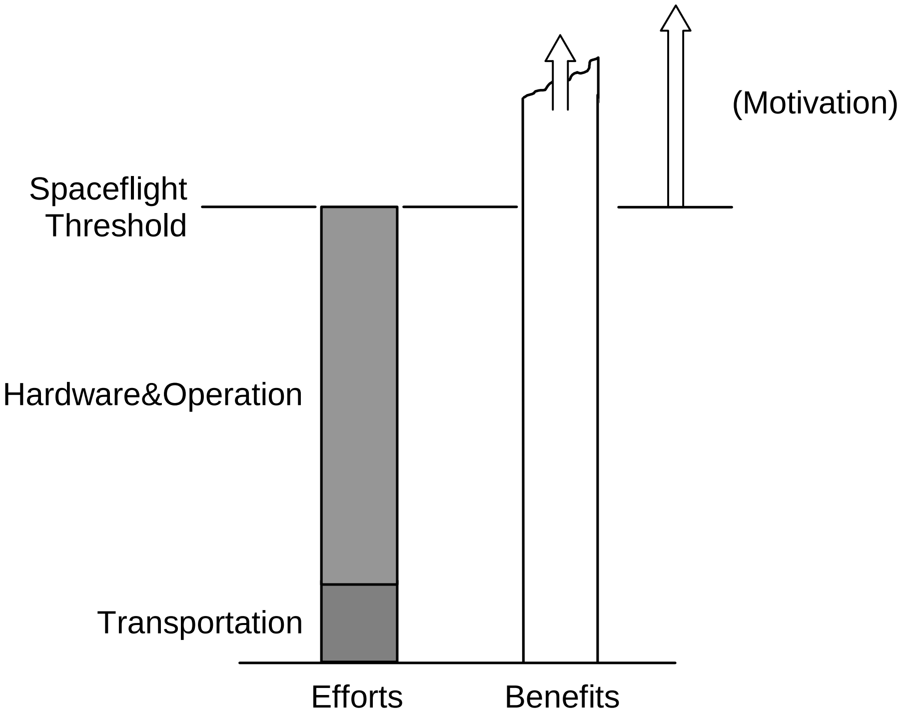

Figure 8-1: The Benefits of Topics Concerning Prevention, Security and Safety

The considered topics deal with threats that are difficult to estimate. The probability of occurrence seems low, but the potential negative effect might be high. Threat is hereby defined as a product of probability and effect.

$$Threat = Effect \times Probability \qquad (8.1)$$

The created benefit is reduction or neutralization of the expected threat and its consequences.

Some of these topics have the characteristic of an infinite zero problem, with effect approaching infinity and probability approaching zero. A clear and unambiguous classification of the actual threat is therefore impossible.

Spaceflight can have an influence the following topics by reducing either effect or probability. The considered threats are aimed at any individual, and their prevention is part of national duties, placing the state as prime actor for risk reduction.

Spaceflight might contribute to threat reduction with the following topics:

- Conservation by migration
  - Exodus to space
  - Interstellar travel
- Contributions against terrorism
- Natural disasters
  - General potential
  - Earthquakes
  - Tsunamis
  - Volcanoes
- Asteroid deflection
  - Threat situation
  - Deflection methods
  - “Test run”
- Weather and Climate
  - Weather prediction and control
  - Climate intervention and understanding
- An instrument of peacekeeping
  - Support at armed conflicts
  - Deterrence
  - Intelligence, surveillance, reconnaissance

With this, most potential contributions of spaceflight to stabilization and improvement of living conditions (on Earth) should be covered.

8.1 Conservation by Migration

Leaving our home planet – at least partially – would reduce the risk of extinction and ensure survival of life in the case of any catastrophic events on Earth. This exodus of life is often seen as mandatory by spaceflight enthusiasts.

8.1.1 Exodus to Space

Earth orbit, Lagrange points, Moon, and Mars are generally seen as most suitable destinations for the first human colonies in space. They would be a sufficient refuge in case of catastrophic events on Earth.

The minimum costs of a space hotel that were identified in chapter 6.3.2.2 lead to the assumption that space colonies will be even more costly. In **Figure 8-2**, the famous O’Neill habitats “Island One” and “Island Three” are shown,[574] with costs that were extrapolated from the previous space hotel cost results. As can be seen, the costs

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[574] Walter 2001.

are significantly higher than the world's current annual Gross Domestic Product (GDP).

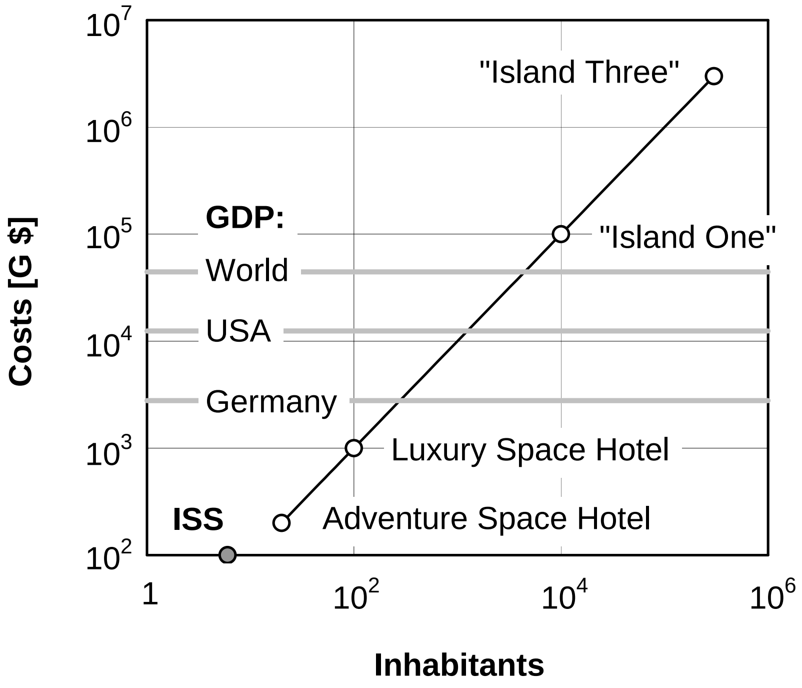

Figure 8-2: Extrapolated Costs of Space Colonies

There are several other aspects of construction and utilization of large space colonies that are yet unresolved and too often ignored:

- Tightness of large pressurized structures
- Balancing large artificial ecospheres
- Vulnerability to sabotage and terrorist attacks
- Construction of very large artificial structures (larger than anything on Earth!)
- Maintenance requirements
- Very long life cycle

A large scale exodus is so costly, and its feasibility with present technical means so questionable, that it cannot be expected for any foreseeable future.

8.1.2 Interstellar Travel

Interstellar travel is not necessarily required to ensure survival of the human civilization. As mentioned, colonies in our solar system are sufficient.[575] But for reasons of completeness, some considerations follow.

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[575] At least until our sun dies, which still takes the comfortable time of about 5 billion years.

A) Faster than Light Travel

According to the known laws of physics, traveling faster than light is impossible. A very good argument against faster than light travel is the tachyon pistol duel.[576]

The result of this experiment of thought is that every object that travels faster than light has the ability to violate causality: The laws of relativity state that, traveling faster than light, an object could appear at the target before it was launched, with catastrophic consequences for causality: In the tachyon pistol duel, person A is shot by person B *before* person A gives person B the reason to shoot at him.[577]

Therefore, faster than light travel must be discarded as impossible.

B) Slower than Light Travel

Achieving velocities of up to 10 % of the speed of light seems possible, at least in theory.[578] But realization must be questioned due to numerous engineering problems, at least with present technologies. The far future is unpredictable, but at least for the foreseeable future, neighbored solar systems are out of reach due to the high energy (and with it, propellant mass) requirements, as illustrated in **Figure 8-3**.

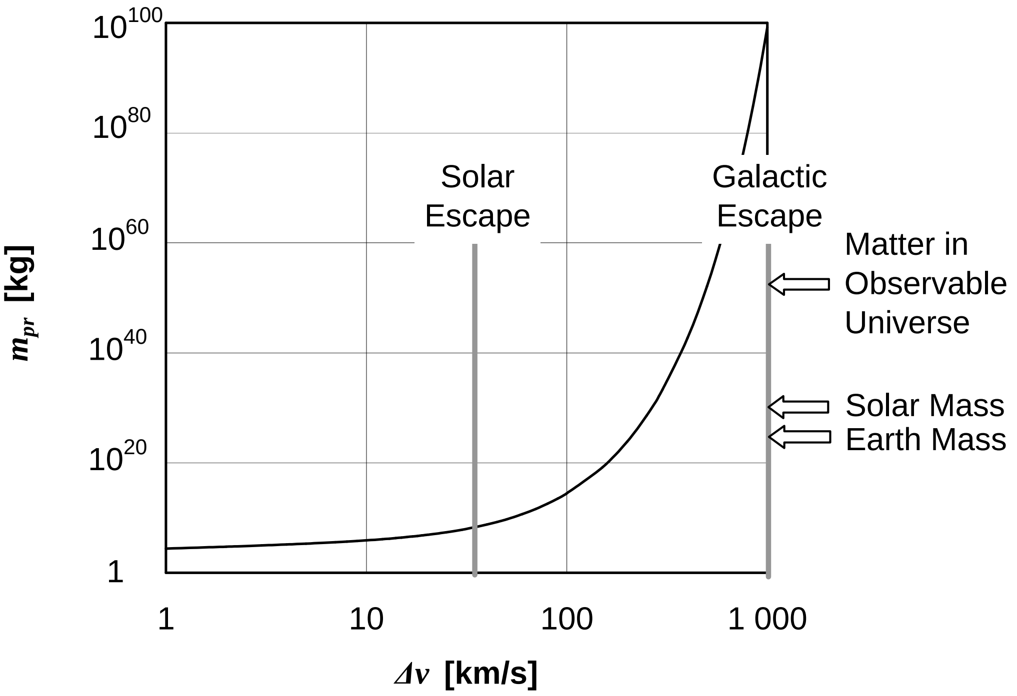

Figure 8-3: Propellant Mass Requirements for Present Technology
(Propellant Mass in LEO, Payload 100 t, No Structural Mass)

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[576] Throop 1996.
[577] Which is, by the way, a special case of prevention and a common excuse for starting a brawl (or a war). Tachyons are not necessarily involved.
[578] Walter 2001.

Additional to the problem of propulsion, there are several other factors that are very problematic for interstellar travel:

- Tightness of the spacecraft, boil-off losses and outgassing
- Interstellar radiation environment
- Expected high speed dust and micrometeoroid collisions
- Long time reliability of components
- …

Assuming that habitable planets usually generate intelligent life, Enrico Fermi's paradox[579] combined with our knowledge of exoplanets may help to give an answer to the general feasibility of interstellar travel in the future:

- Habitable exoplanets are never discovered: Even if interstellar travel might be possible, without suited destinations, it is never done anyway.
- Habitable exoplanets are discovered: There are suited destinations scattered throughout the galaxy, but we have never been visited by others – either interstellar travel is impossible, or we are alone.

Therefore, the probability of human interstellar travel in the future seems low.

8.1.3 Consequences

Currently, there is no immediate need for migration, and no commercial gain in construction of space colonies due to their astronomic costs (even ignoring their feasibility). Thus, efforts in this direction cannot be expected in the near future.

A good reason for colonies in the far future could be the inevitable coming of a new ice age on Earth in, say, about 80 000 years.[580] But it is impossible to say now what will be easier then, and less demanding: To fight against the consequences on Earth, or to emigrate to space.

Table 8-1: Evaluation of "Exodus to Space"

Topic		Exodus to Space
Objective		Same as topic
Technical Feasibility		Not Feasible
Effort	Costs	Several 100 000 000 000 000 $
Benefit	Effect	Sudden extinction of humanity on Earth
	Probability	Very improbable
	Threat	?
Resulting Motivation	Cost-Value Ratio	**None**

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[579] If there are ETI, they should have mastered interstellar travel and visited us by now.

[580] Walter 2002.

Table 8-2: Evaluation of “Interstellar Travel”

Topic		Interstellar Travel
Objective		Same as topic
Technical Feasibility		Not Feasible
Effort	Costs	-
Benefit	Effect	Extinction of humanity in solar system
	Probability	Zero
	Threat	None
Resulting Motivation	Cost-Value Ratio	**None**

8.2 Contributions Against Terrorism

Following the Cold War, terrorism seems to become a major threat to global stability and peace. Terrorism may manifest itself in directed attacks of organized groups, in less directed attacks of individuals, but also in the wake of collapsing states and orders. Various types of terrorism probably will be a threat for a long time to come.

A) Spaceflight as an Instrument for Terrorism

In theory, a spacecraft might be hijacked either firsthand or using ground control, and then used as a weapon. Application of dedicated military spacecraft (e.g. ICBMs) is possible, but civil sector launchers and spacecraft theoretically also have a high potential to inflict damage. Due to high security standards and very high requirements on qualification and manpower for effective use of a hijacked spacecraft, this scenario is extremely unlikely.

Thus, contrary to aviation, spaceflight cannot be directly applied for terrorist attacks.

Various rogue states could use spaceflight technology in form of ballistic missiles to deliver weapons of mass destruction. Considering the high requirements for reliability, and the expected retaliation strike of the attached state and its allies, this seems not very probable, though.

B) Spaceflight as an Instrument against Terrorism

In case of terrorism, threat may be defined as a product of potential terrorists’ motivation and their capabilities.[581]

$$Threat = Motivation \times Capability \qquad (8.2)$$

Spaceflight may support the identification and reduction of the factor “*capability*”:

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[581] Schmucker 2007.

- Reconnaissance to identify signatures of tests and development of nuclear, chemical and biological weapons[582]
- Identification of terrorist areas of retreat[582]
- On demand attacks on training camps or terrorist groups by the use of conventional armed long range ballistic missiles, similar to artillery or air support
- Support at detecting improvised explosive devices (IEDs)

Terrorist attacks with global effects, such as 9/11, occur only very sporadic, but continuous efforts with high expenditures are required to ensure permanent surveillance and defense readiness.

The continuous character of space based surveillance systems is well suited for these tasks, but sensor performance seems to be too weak yet for serious anti terror applications.

What is applicable today is tracking of suspected terrorists via satellite. This might be extended to other groups that are suspected of criminal intents. But these considerations quickly lead to ethic dimensions and are therefore not further discussed here.

Table 8-3: Evaluation of “Contributions Against Terrorism”

Topic		Contributions Against Terrorism
Objective		Reconnaissance, surveillance, attacks, …
Technical Feasibility		Challenging
Effort	Costs	Several 1 000 000 000 $
Benefit	Effect	Local: Loss of life Global: Economic damage
	Probability	Local: Low Global: Once up to now
	Threat	Local: Low Global: Very low
Resulting Motivation	Cost-Value Ratio	**Low**

8.3 Natural Disasters

Spaceflight can reduce the impact of natural disasters in various ways.

8.3.1 General Potential

Natural disasters have an increasing impact on human civilization. Growing population and colonization of high risk areas may contribute to increasing damage and

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[582] Hofschuster 2002.

death tolls.

There are two aspects where spaceflight could contribute:

- Prediction
- First aid and support

Long term predictions are comparatively worthless, short term predictions are decisive. Warnings of imminent natural disasters might not reduce the scale of damage, but they might save many lives. The potential of space based prediction methods must be analyzed for various types of disasters.

Once a natural disaster occurred, means of spaceflight might support rescue teams (satellite phones for rescue teams or orientation in remote areas[583]), and help to survey the scale, type and location of damages to infrastructure and terrain (for example warning of potential landslides in mountain regions in the wake of earthquakes or floods).

8.3.2 Earthquakes

Currently, there is no way to predict earthquakes with sufficient reliability. Short term predictions could significantly reduce the death tolls seen in **Table 8-4**.

A combination of local ground deformation and gas emissions seems to occur just before some earthquakes hit. With satellites that can monitor small movements of large areas, combined with in situ measurements, perhaps a kind of prediction could be developed. If successful, the spaceflight efforts would be negligible compared to the consequential benefits.

Table 8-4: Earthquakes and Consequences[584]

Location	Year	Magnitude	Deaths	Damage [G $]
Tangshan, PRC[585]	1976	8.2	up to 750 000	?
Cashmere, IND/PAK	2005	7.6	87 000	2
Kobe, JPN	1995	7.3	6 430	100
Niigata, JPN	2004	6.9	125	20
Los Angeles, USA	1994	6.7	32	21

The topic is not yet well understood. Extensive research is required.

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[583] Topography maps created with the Shuttle Radar Topography Mission (SRTM) in 2000 aided rescue teams in the wake of an earthquake in the remote Indian-Pakistani borderland. (Thiele 2007)

[584] NZZ 25/02/2006.

[585] Wikipedia 2007.

8.3.3 Tsunamis

The tsunami of late 2004 with estimated 220 000 fatalities and economic losses of about 15 G $[586] led to efforts for an early warning system in the Indian Ocean. Pressure sensors on the ocean floor register potential tsunami waves and transmit the data via satellite to threatened areas. Space based surveillance could also register movement of large ocean waves by radar.

Analysis of satellite images might help to define endangered coastal regions, and could give advice for safer future infrastructure development.

8.3.4 Volcanoes and Super-Volcanoes

The increasing subterranean pressure that obviously leads to volcanic eruptions seems to raise the level of the terrain surrounding the volcano. Radar satellites can easily measure these movements in remote areas with sparse vegetation.[587] The directions of lava flows and pyroclastic flows could also be predicted using satellite imagery.

The prediction and understanding of supervolcanic eruptions seems important because of their global impact. These eruptions occur ten times more often than comparable devastating asteroid impacts, leading to massive global effects.[588] Though these eruptions cannot be prevented, a warning would at least reduce the consequences.

8.3.5 Conclusion

Spaceflight can contribute to prediction and early warning of natural disasters and give support once the disasters occurred.

Table 8-5: Evaluation of "Natural Disasters"

Topic		Natural Disasters
Objective		Early warning satellites, ComSats, …
Technical Feasibility		Feasible (in part currently done)
Effort	Costs	Several 100 000 000 $
Benefit	Effect	Loss of life, economic losses
	Probability	High
	Threat	High
Resulting Motivation	Cost-Value Ratio	**High**

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[586] Swiss Re 2007.
[587] SZ 16/10/2007.
[588] Bindeman 2006.

8.4 Asteroid Deflection

Impact of large cosmic objects like asteroids or comets on Earth is a rare, but repeating event. Deflection of potentially dangerous objects may be recommended, depending on expected effects of impact.

Objects that have a perihelion of less than 1.3 AU are defined as Near Earth Objects (NEO), and those objects that potentially may pass Earth closer than 0.05 AU are defined as Potentially Hazardous Objects (PHO).[589] For simplification, all dangerous objects, including comets, are further referred to as asteroids or NEOs.

8.4.1 Threat Situation

Threat assessment can be seen as a combination of expected impact intensity (effect) and impact frequency (probability).

$$Threat = ImpactIntensity \times ImpactFrequency \quad (8.3)$$

A) Impact Intensity and Effects

Many examples of NEO impact events are known, not only on Earth, but also on other celestial bodies, as seen in **Table 8-6**, with object diameter d_{NEO}, impact crater diameter d_{cra}, released impact energy E_{imp} and area devastated by impact A_{imp}. The amounts of energy that are released at impact are remarkable.

Table 8-6: Various Impact Events[590]

Event	Location	Year	d_{NEO} [km]	d_{cra} [km]	E_{imp} [Mt TNT]	A_{imp} [km²]
Shoemaker	Jupiter	1994	2*	-	6 000 000	
Tunguska	Siberia	1908	0.06	-	12	2 200
Barringer	Arizona	50 k B.C.	0.05	1.2	2.5	1 500
Nördlinger Ries	Germany	15 m B.C.	1.5	24	100 000	350 000
Chicxulub	Mexico	65 m B.C.	10	180	200 000 000	global

* Largest fragment.

In general, objects with diameters of less than 50 m are not considered as threats, because they disintegrate in higher layers of Earth's atmosphere.[589] This size may only serve as a guideline, though, because even smaller objects may reach the surface and cause significant regional damage, dependent on object density, velocity, and entry angle.

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[589] NASA HQ 2006b.
[590] Wikipedia 2007.

Figure 8-4 gives a rough size and impact energy correlation of object diameter d_{NEO} and impact energy E_{imp} given in megatons TNT equivalent. For comparison: The Hiroshima nuclear bomb had a yield of about 0.015 Mt TNT.

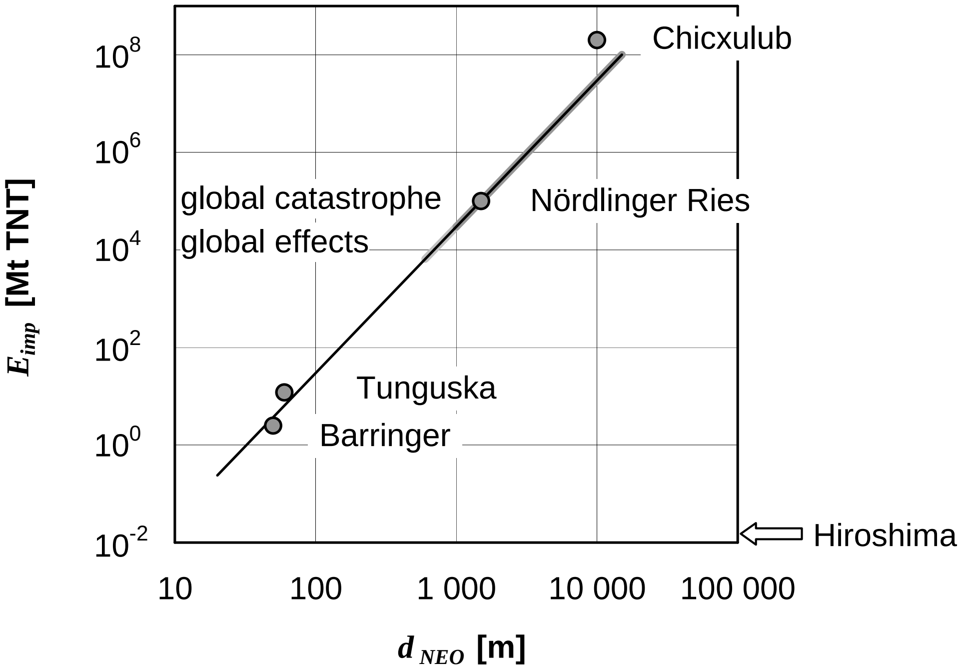

Figure 8-4: Asteroid Size and Destructiveness

The effects of a NEO impact on Earth depend not only on NEO size, but also on density and velocity of the object as well as impact angle and the character of the impact target area.[591] But a simple size and effect correlation is visible in Figure 8-4, with:

$$E_{imp}[Mt\ TNT] = 3 \cdot 10^{-5} \cdot d_{NEO}^3[m] \qquad (8.4)$$

Noticeable global effects occur from about 600 m NEO diameter upward, equivalent to an impact energy of roughly 10 000 Mt TNT, and a global catastrophe is expected from diameters of 1 km and more, resulting in expected fatalities of 1 billion and more, up to extinction of humanity.[592]

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[591] Collins et al. 2005.

[592] NASA HQ 2006b.

B) Impact Frequency

Average impact frequency correlates with the object diameter. Unlike impact energy, the frequency is only a statistical value, meaning that significant deviations from the statistical values must be expected. **Figure 8-5** presents the statistical correlation of object size and impact frequency.[593]

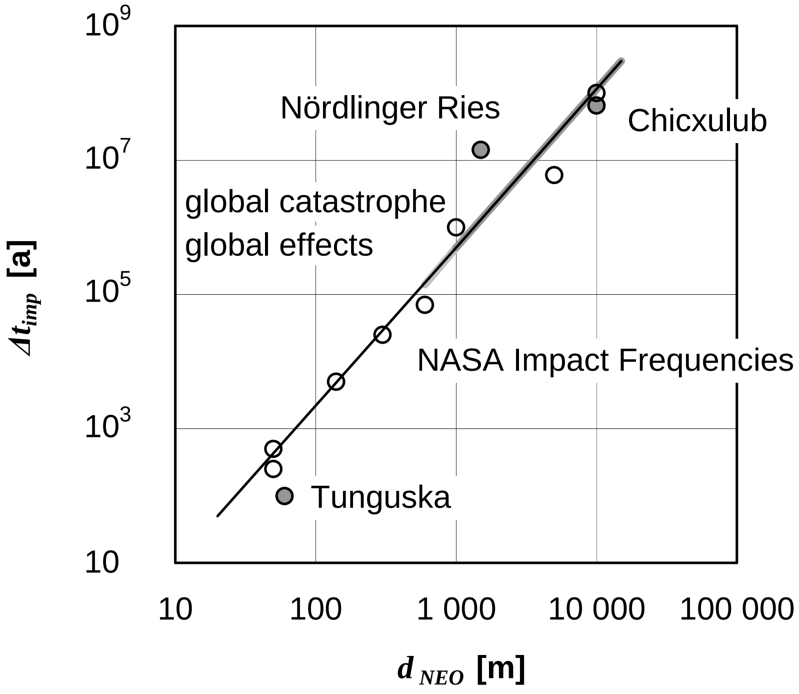

Figure 8-5: Asteroid Size and Impact Frequency[593]
(Grey: Actual Impacts, White: Statistical Impact Frequencies)

The line that is drawn as a correlation in Figure 8-5 reveals interesting facts: A Tunguska event is below the line, and thus is improbable to happen for some time, while an impact in the order of magnitude of Nördlinger Ries is statistically overdue.

C) Threat Situation

The statistical uncertainty of impact frequency leads to very uncertain statements about the actual threat situation.

Figure 8-6 illustrates the problem by showing the projected age of an asteroid deflection system, if the system should have (statistically) removed a threat only <u>once</u> since its installation.

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[593] NASA HQ 2006b.

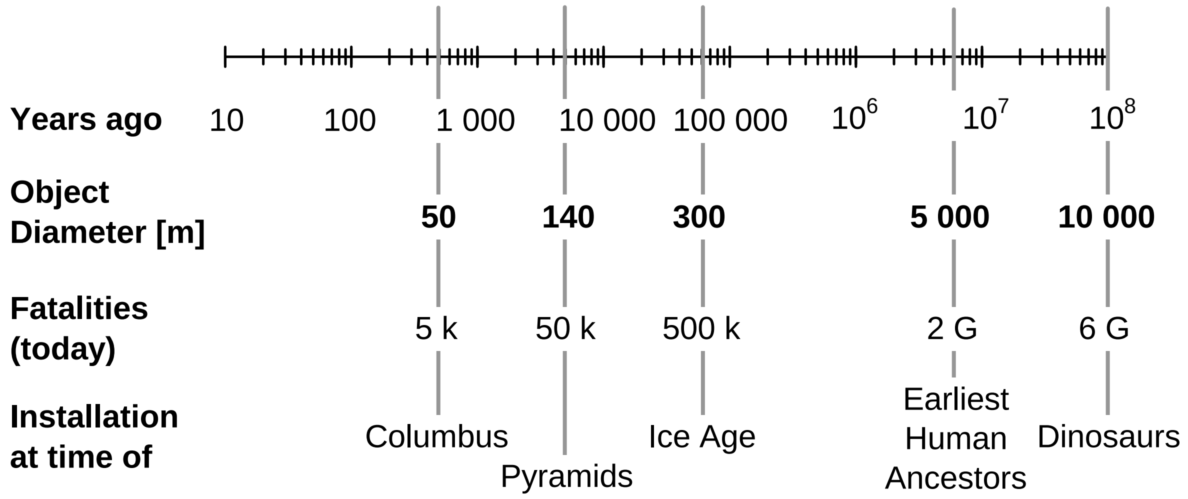

Figure 8-6: Required Deflection System Installation Date for One Statistical Threat Deflection[594]

It is not the question *if* a deflection system must be used some day. The question is *when* it has to be used.

8.4.2 Deflection Methods

The earlier the actions for course alteration are done, the less change of asteroid velocity Δv_{NEO} is required. There are various proposed ways of deflection, for example:

- Installation of chemical or ion propulsion system on the object. Requires very long lead time. Asteroid rotation might be a problem.
- Projectile impact. Eventually quite effective. Asteroid composition and resulting debris might be a problem.
- Nuclear device detonation on or close to surface. Eventually quite effective. Resulting debris might be a problem.
- Surface vaporization. Heating of surface, with thrust generated by evaporating gases. Requires high power levels and long duration.

The costs of installation of a deflection system must be expected at least in the order of several tens of billions of dollars. Similar to missile defense, the most problematic aspect might be a very short lead time before impact, requiring highest vigilance at all times.

If the object is discovered late, the engineering requirements are extremely high, though. In case that an incoming small asteroid of 50 m diameter and 20 km/s veloc-

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[594] NASA HQ 2006b.

ity should be deflected by a sideway 90° kinetic impact at lunar distance (384 400 km), with a kinetic missile stationed in L3 of the Earth-Moon system, the missile would have to hit the asteroid with a speed of about 1 500 km/s.[595] Ballistic missile defense is nothing compared to this (impossible?) task. Accordingly, the feasibility of deflecting large asteroids with current technology must be doubted.

8.4.3 "Test Run"

Deflection of an asteroid towards a terrestrial planet or moon, for example Mars, Venus, or Earth's Moon, would be an interesting task for two reasons:

- Feasibility and success of trajectory modification – and therefore of eventual deflection methods for PHOs – could be tested in reality
- Consequences of an actual impact could be observed

Though criticism must be expected due to eventual extinction of undiscovered life and other arguments, the gain of knowledge by a test run is high enough to further consider this type of space mission.

8.4.4 Perspectives

Even if there is an active asteroid deflection system installed, it is questionable if every threat could be detected in time for deflection. Large objects can be detected early with long lead time, but deflection is probably impossible. Small objects with low threat level can perhaps be deflected, but not detected.

Once a substantial threat is detected and successfully deflected, the system will be seen as great investment – if it is never used over thousands of years, it will be seen as useless waste of money.

Table 8-7: Evaluation of "Asteroid Deflection"

Topic		Asteroid Deflection
Objective		Space surveillance, large rockets, …
Technical Feasibility		Very Challenging
Effort	Costs	Several 10 000 000 000 $ and more
Benefit	Effect	Negligible to global devastation
	Probability	Low to about zero
	Threat	?
Resulting Motivation	Cost-Value Ratio	**?**

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[595] Maccone 2006.

8.5 Global Monitoring

Satellites can monitor Earth from space, using the continuous global coverage for various applications.

8.5.1 Search and Rescue

Satellites can be used to save lives not only in the wake of natural disasters, but also at other emergencies.

The international Search and Rescue Satellite-Aided Tracking System (COSPAS-SARSAT), consisting of U.S. NOAA satellites and Russian Cospas satellites, is credited with more than 20 300 rescues out of potentially life-jeopardizing emergencies worldwide between 1982 and 2006.[596]

Table 8-8: Evaluation of "Search and Rescue"

Topic		Search and Rescue
Objective		Observation and ComSats
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $
Benefit	Effect	Loss of life
	Probability	High
	Threat	High
Resulting Motivation	Cost-Value Ratio	**High**

8.5.2 Environment

Environmental satellites monitor Earth's

- Biosphere (flora and fauna),
- Hydrosphere (lakes, rivers, oceans, rainfall, …),
- Cryosphere (glaciers, polar ice, …),
- Atmosphere (clouds, winds, gas concentrations, …).

This allows numerous applications for environmental monitoring and protection. Among these applications are:

- Concentration of ozone
- Localization of waste oil dumping at sea
- Tracing of fish swarms

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[596] SpaceRef 15/01/2007.

- Monitoring of deforestation
- Ocean surface temperatures
- Pack ice localization
- Identification of imminent landslides
- Levels of air pollution
- …

Environmental monitoring by satellites is of increasing importance. The European Commission, for example, committed 1.2 G € to the first phase of its initiative for Global Monitoring for Environment and Security (GMES).[597] Aside of being a platform for environmental satellite data, GMES also includes development and operation of a series of monitoring satellites called Sentinel.

Being an objective of scientific and preventive character, the utilization of satellites to increase living conditions on Earth is a national duty and should be supported.

Table 8-9: Evaluation of "Environmental Monitoring"

Topic		Global Environmental Monitoring
Objective		Numerous observation satellites
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 1 000 000 000 $
Benefit	Effect	Loss of life, economic losses, …
	Probability	High
	Threat	High
Resulting Motivation	Cost-Value Ratio	**High**

8.6 Weather and Climate

Weather is a local phenomenon, occurring in short time spans. Climate is a global phenomenon, with extremely long timeframes.

8.6.1 Weather

Knowledge and prediction of weather has always been decisive for human development. Control of weather would have an even greater impact.

8.6.1.1 Prediction

Spaceflight can enable and support meteorology in two ways:

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[597] AW&ST Apr 30 2007.

- Direct monitoring of atmospheric and other phenomena
- Relay of terrestrial weather station data

Aside of local data, satellites allow measurements of reliable global average values.

Accuracy of weather predictions increased significantly by the use of satellite data. The reduction of negative meteorological effects by accurate prediction certainly is an important accomplishment of spaceflight.

Table 8-10: Evaluation of "Weather Prediction"

Topic		Weather Prediction
Objective		Observation and ComSats
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 100 000 000 $
Benefit	Effect	Economic losses, loss of life
	Probability	High
	Threat	High
Resulting Motivation	Cost-Value Ratio	**High**

8.6.1.2 Control

Directed manipulation of meteorological phenomena is a famous topic of science fiction.

A) Manipulation of Precipitation

Control of precipitation amounts would significantly increase the global standard of living in various ways, influencing the following aspects:

- Droughts
- Floods
- Harvest yields
- Famines
- Conflicts about humid territories

No serious, scientifically proven methods are known yet, especially of how means of spaceflight could actively influence precipitation. The use of space mirrors for directed solar irradiation, as well as huge sunshades, could perhaps be an option.

In any case, the gain would be huge enough for further serious research.

B) Redirection and Deflection of Cyclones

The fatalities and economic damages resulting from cyclones, especially tropical cyclones like hurricanes and typhoons, are enormous, as seen in **Table 8-11**.

Prevention of this type of disasters by the means of spaceflight would justify enormous investments.

Table 8-11: Impact of Cyclones

Name	Location	Year	Deaths	Economic Loss [G $]
unnamed[598]	BGD	1991	140 000	1.5
Katrina[599]	USA	2005	1 326	125
Tokage[598]	JPN	2004	100	6
Lothar[599]	EUR	1999	> 80	13

In theory, the course of hurricanes might be altered by heating the surface water of a close by ocean area by 2 ℃.[600] This might be achieved applying space mirrors or orbital microwave power plants, but the required amounts of energy E_{req} are extreme, with the amount of water to be heated V_{H2O}, the specific heat capacity of water c_{H2O} at about 4.19, density of water ρ_{H2O}, and a temperature increase ΔT:

$$E_{req} = V_{H2O} \cdot c_{H2O} \cdot \rho_{H2O} \cdot \Delta T \tag{8.5}$$

For an area of 10 000 km² that is to be heated to a depth of 2 m by 2 ℃, the amount of required energy is $8.4 \cdot 10^{16}$ J. This means that, for a limited timeframe of 2.5 days, a constant power input of almost 400 000 MW is required. That is the order of magnitude of the average power requirement of Germany.

The sun has major influence on the weather. With constant specific solar power input p_{sol} of 1.37 kW/m², and Earth's radius, the irradiated solar power on Earth can be compared with the world's total human energy consumption E_{tot}.

$$\frac{P_{tot}}{P_{sol}} = \frac{E_{tot,\Delta t}}{r_E^2 \cdot \pi \cdot p_{sol} \cdot \Delta t} \tag{8.6}$$

With 10 879 million tons of oil equivalent in 2006,[601] the annual energy consumption of human civilization is not even 0.01 % of the annually irradiated solar power. Thus, directed influence on the energies that affect our weather is far out of reach of human civilization. In the foreseeable future, weather modification remains impossible.

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[598] Schmucker et al. 2006.

[599] Swiss Re 2007.

[600] SZ 06/09/2005.

[601] Globus 1994-2007.

Table 8-12: Evaluation of “Weather Control”

Topic		Weather Control
Objective		Energy injection devices
Technical Feasibility		Not Feasible
Effort	Costs	-
Benefit	Effect	Loss of life, economic losses, …
	Probability	High
	Threat	High
Resulting Motivation	Cost-Value Ratio	**None**

8.6.2 Climate

Understanding of and human influence on the climate is a very contemporary issue.

8.6.2.1 Active Intervention

The current debate about global warming and human influence led to numerous proposals of how to stop global warming, for example shading Earth from sunlight by disintegration of a comet at L1,[602] or transportation of millions of tons of sulfur into the upper atmosphere.[603]

The technical and financial feasibility of such proposals is out of the question: The requirements are far too demanding. The order of magnitude of possible influence of human civilization compared to nature was illustrated with weather control in chapter 8.6.1.2. Weather is only a local phenomenon, and directed change of global climate is even more requiring.

Table 8-13: Evaluation of “Active Climate Intervention”

Topic		Active Climate Intervention
Objective		Sun shades, …
Technical Feasibility		Not Feasible
Effort	Costs	-
Benefit	Effect	Global warming
	Probability	High
	Threat	High
Resulting Motivation	Cost-Value Ratio	**None**

---

[602] Struck 2007.
[603] Crutzen 2006.

Proposed terraforming of Mars or Venus must be considered under this aspect: If the whole humanity, with combined forces, does not change Earth's climate in a way that is significant enough to be acknowledged by every scientist, will it ever be possible to significantly change the climate of another planet with considerably less efforts?

8.6.2.2 Understanding Climate Change

Due to its characteristics of monitoring and observation, only spaceflight can give detailed measurements and in-depth information of climate on a global scale, eventually resulting in a detailed understanding of climate change. Among major topics of importance are:

- Measurements of solar cycles and activity
- Planetary albedo definition
- Global atmospheric analyses
- Observation of other planets
- …

The climatic developments on other planets are of utter importance, and they can be observed by means of spaceflight. Recent measurements seem to indicate that global warming may not be limited to Earth alone, but also Mars,[604] Jupiter,[605] and even Neptune.[606] If verified, this might have a major impact on the understanding of Earth's current global warming.

A final, fundamental understanding of the mechanisms that drive Earth's climate will have one of two possible effects: Either the understanding of the mechanisms and reliable prediction of climate changes will result in directed and sensible counteractions, or climate change will be accepted as natural, and active intervention as out of reach for mankind. Either way, an understanding of climate is essential, and spaceflight might contribute significantly.

Table 8-14: Evaluation of "Understanding Climate"

Topic		Understanding Climate
Objective		Observation satellites, planetary probes
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 1 000 000 000 $
Benefit	Effect	Economic losses, loss of life, …
	Probability	High
	Threat	High
Resulting Motivation	Cost-Value Ratio	**High**

---

[604] Mars Daily 06/04/2007, Malin et al. 2001, NASA News 05-274.

[605] Space.com 04/05/2006.

[606] Hammel et al. 2007.

8.7 An Instrument of Peacekeeping

The military side of spaceflight – or “milspace” – is often either denied or discarded as unpleasant. But, as the following considerations will reveal, the part of spaceflight that is related to national security is commonly underestimated in several aspects.

Figure 8-7 presents the numbers of currently operational satellites that are labeled as military. It must be expected, though, that numerous other satellites labeled as governmental are used for intelligence, surveillance, reconnaissance (ISR) or other purposes.

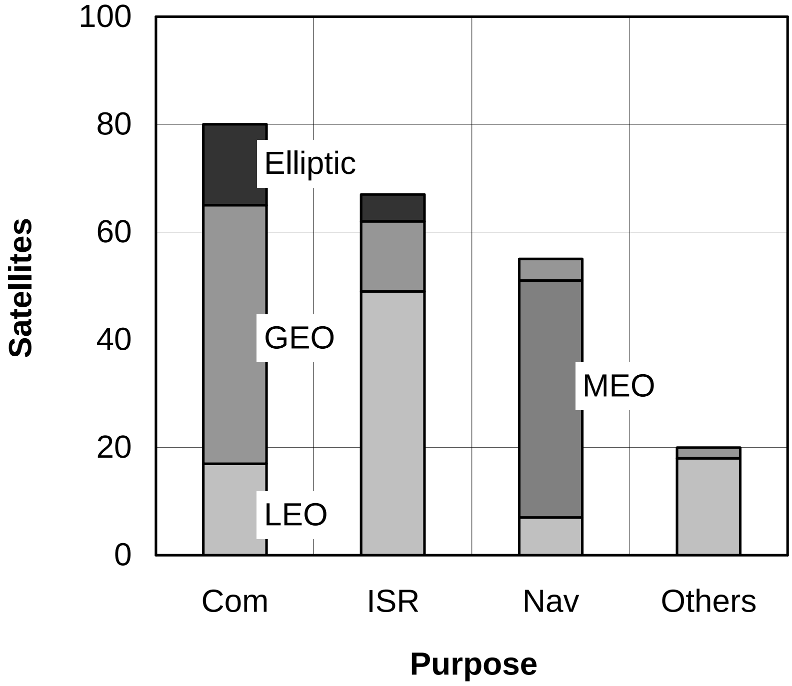

Figure 8-7: Operational Military Satellites[607]

Until the late 1970s – and probably longer –, about 50 % of all satellites launched by the Soviet Union were used for ISR purposes.[608]

The historical share of worldwide launches with military background on the total number of orbital and suborbital rocket launches, including missile tests, satellite missions, manned missions with military objectives, technology demonstrations and more, must be estimated as significantly more than 50 %, being probably in the range of two thirds or even more.

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[607] UCS 2007.
[608] Engel 1979.

8.7.1 Support at Armed Conflicts

This subchapter is unpleasant, but for reasons of completeness, every aspect of spaceflight must be mentioned.

In the case that prevention was not successful and open war erupts, astronautics can give effective support to warfare: Missiles, surveillance, C^3I (Command, Control, Communications, Intelligence), … .

Modern warfare is unthinkable without support from space or spaceflight technologies, and the effects of actually deployed and applied space related weaponry and defense measures effectively reduce civilian and military losses as well as collateral damage.

A) Increased Accuracy

As was first demonstrated in the Gulf War of 1991, GPS guided missiles and bombs allow selective destruction of targets with extremely high precision. Compared to the carpet bombing of World War II, strategically important targets can now be hit with considerably less collateral damage.

B) Reconnaissance

In case of armed conflicts, troop movements and strategic targets can be quickly identified via satellite at day and night (with optical, infrared, or radar), thus reducing the risk of striking vacant positions, or to identify movements of civil population in the theatre.

C) Real Time Communications

Satellite communications enable real time communication and decision making on a global scale. Troops in the field can be easily contacted and informed of new situations. This can be done without any in situ infrastructure construction efforts.

D) Combination: Network Centric Operations (NCO)

The military doctrine of NCO, formerly called network centric warfare, enables unprecedented coordinated use of military forces, supported by satellite communication and navigation. This will further reduce the number of casualties on both sides of an armed conflict.

It also enables unrestricted use of unmanned combat systems, including aerial and ground vehicles.

8.7.2 Historical Application of Missiles and Consequences

Space related technologies were first used in World War II, and since then, at various conflicts all over the world. Cruise missiles are hereby not regarded as space related technology.

Short Range Ballistic Missiles (SRBMs) were used in World War II (Germany: A4/V2), Yom Kippur War (Egypt: R-17), Afghanistan (Soviet Union: R-17), Iran-Iraq War (Iran: R-17, Iraq: mod. R-17), and Persian Gulf War (Iraq: mod. R-17).

The use of missiles probably had various impacts on the course of war, but, with one exception (Iran-Iraq), it actually never lead to military success.

- **World War II**
  From a military perspective, the V2 was insignificant. But the German expenditures for V2 serial production, not regarding its development, could have been used to produce either 23 000 V1, about 3 000 Type V Panther tanks, or about 2 000 Bf-109 aircraft, with an additional amount of 20 million liters of unused high grade propellants.[609] This might have had a significant impact on the course of war.

- **Yom Kippur War**
  The three Scud type missiles that were launched by Egypt in 1973 were insignificant in any way.

- **Afghanistan**
  A massive amount of about 2 000 missiles was used by Soviet forces in Afghanistan.[610] Though it seems that the military impact was insignificant, the large expenditures may have contributed to the Soviet decision for retreat.

- **Iran-Iraq War**
  In 1988, a maximum of 20 missiles per week was launched by Iraq towards Tehran within a period of four weeks, resulting in an exodus of the civil population.[610] Baghdad was also repeatedly attacked by Iran. This “War of the Cities” lead to a ceasefire.

- **Persian Gulf War**
  In 1991, Iraq launched several missiles towards Israel, without military effect. But this move might have strengthened the determination of the allied forces.

The use of (conventional) ballistic missiles has no impact on the military side. But in cases of massive use, the large expenditures for these weapon systems might reduce the duration of a war.

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[609] Schischka 2006.
[610] Schmucker 2007.

8.7.3 Deterrence

The actual use of weapons is only the ultimate choice. The preferred purpose of weapons – preferred by both sides! – is for intimidation.

During the Cold War, civil spaceflight was used as a means to demonstrate the power and superiority of the own nation and social system. Civil spaceflight thus can be used for "peaceful" enforcement of interests. While this scenario of a civil Space Race was an offset of the military developments in the background, an intensified effect is achieved by space related programs with obvious, straightforward military character.

A) Strategic Missiles

The origin of spaceflight lies in the application of rockets as a weapon. This is an inconvenient fact that cannot be denied.

The first known weapon application of rockets is disputed, but roughly estimated at the 13th century, probably by the Chinese against the Mongols in a battle in the year 1232.[611] The first extended range ballistic missile, the A4 or V2, was operational – and used – during the final months of World War II. Today, missiles combined with weapons of mass destruction are of special strategic importance, not for actual use, but as a threat, applying the theory of deterrence.

This was already stated by President Kennedy himself on December 5, 1962, at a secret meeting with his advisers:

> "I mean, with the Polaris submarines, with the planes we have, the navy's strategic force, and with the missiles we have, we have an awful lot of megatonnage to put on the Soviets [that is] sufficient to deter them from ever using nuclear weapons. […] Otherwise, what good are they? I don't – you can't use them as a first weapon yourself, so they're only good for deterring."[612]

The doctrine of mutual assured destruction guarantees the destruction of both defender *and* aggressor in case of war due to the range, speed and effect of modern nuclear missiles. A survival of the military command and the political leadership is improbable, further reducing the probability of starting a war. It is said that this principle avoided the Cold War from ever becoming "hot".[613,614]

B) Ballistic Missile Defense (BMD)

The same technology that enabled these offensive weapons now also allows active defense against these threats in form of missile defense.

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[611] Braun et al. 1979.

[612] Coleman 2006.

[613] Stuhlinger et al. 1994.

[614] Though deployed and in service for more than 50 years, until today not one human intentionally lost his live by a strategic missile (ICBM). No other type of weapon has this record.

Again, as with strategic missiles, there is a stabilizing effect:

- BMD activities of Western states render current activities of 3rd World countries on the field of ICBMs useless for the future: Once 3rd World states have developed and deployed ICBMs, there will already be a functional missile shield. Thus, ICBM development activities should be canceled now.
- All types of rockets and missiles have limited reliability. If adversary *A* has deployed missile defense, adversary *B* will not launch an attack because it could be intercepted, and he has to suffer the retaliation strike. Neither will adversary *A* launch an attack, because the retaliation strike of adversary *B* could still penetrate his missile shield that relies on interceptor missiles.

C) Anti Satellite Weapons

Anti satellite weapons are insignificant. Current missiles can only take out LEO satellites, and due to the 90 minutes orbital period of LEO combined with Earth's rotation, the synchronous elimination of multiple LEO satellites launched from one country is impossible. All navigation satellites and the majority of communication satellites are positioned in considerably higher orbits, and therefore almost impossible to reach for currently deployed ballistic missiles.

8.7.4 Intelligence, Surveillance, Reconnaissance (ISR)

Compared to surveillance aircraft, satellites are considerably less vulnerable. Continuous surveillance of military activities on Earth done by a network of reconnaissance satellites makes secret activities and surprises virtually impossible.

A) Past

In the early 1950s, the increasing abilities of air defense systems and the rumors of Soviet ICBM development led to the decision of the USA in 1956 to develop a photo reconnaissance satellite. Orbital injection was done by an Atlas upper stage that was explicitly developed for these purposes.[615] The satellite was first successfully launched under the name "Samos-2" in 1961, with an optical resolution of 6 m from 480 km altitude.[616] Photographic films were used that had to be recovered after the mission.

Kennedy was aware of Khrushchev's Berlin bluff of June/July 1961 only because Samos-2 discovered that the SS-7 and SS-8 ICBMs that the Soviets threatened to use were not yet deployed, but still under work at their test facilities.[616]

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[615] The upper stage became known as Agena. It was crucial for the Apollo program, because the first docking maneuvers in space were done with Agena stages at the Gemini program in the mid 1960s.

[616] Engel 1979.

This might have been an additional incentive for the Soviet Union's development of ISR satellites. Soon, photo reconnaissance satellites were frequently launched by both USA and USSR, and their photographs recovered after deorbit and return to Earth.[617]

B) Present and Future

Current commercial satellite imagery achieves image resolutions of 60 cm and less from 450 to 500 km LEO, with satellites the size of compact cars.[618]

The resolution of modern military surveillance satellites is classified, but the known dimensions (size of a school bus) and minimum orbital altitude (250 km) of the U.S. KH-11 Keyhole series satellites, and the fact that they are delivered in the same shipping containers as the Hubble Space Telescope,[619] allow exemplary conclusions for modern spy satellites, as seen in **Figure 8-8**.

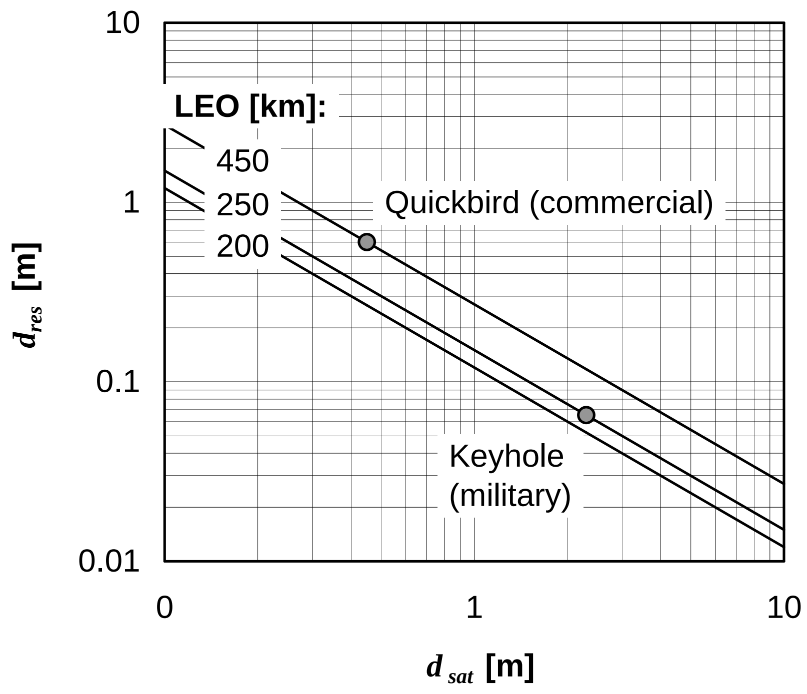

Figure 8-8: Optical Resolution of Modern Surveillance Satellites

Maximum optical resolution d_{res} depends on satellite lens diameter d_{sat}, orbital altitude h_{orb}, and wavelength λ, with $6 \cdot 10^{-7}$ m for the visible spectrum.[620]

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[617] Early Soviet reconnaissance satellites used a modified Vostok capsule as a return vehicle (Engel 1979) – the same device that safely brought Yuri Gagarin back to Earth in 1961.

[618] Digital Globe 2007.

[619] Wade 2007.

[620] Schmucker et al. 2006.

$$d_{res} = \lambda \frac{h_{orb}}{d_{sat}} \qquad (8.7)$$

This results in a theoretical optical resolution of 0.065 m for modern military satellites.

Figure 8-9 shows exemplary commercially available satellite imagery of military sites.

Figure 8-9: Satellite Imagery[621]

The resulting high quality images allow detailed and enduring surveillance of any kind of activity that might be linked with military aims, as well as reliable analysis of the potential threat. Combined with radar surveillance that is largely independent of weather influences and daylight, with infrared that allows identification of running engines and other details, and with eavesdropping satellites that identify increased traffic of communications, a flood of information should be available.

If this information is used wisely, there should be no more misinterpretations and surprises in the defense area.

C) Additional Note

The ground track of an ISR satellite can be used to identify areas of interest and the actual knowledge of the satellite's operator. Historic examples are:[622]

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[621] Digital Globe 2007, Google Earth 2007.

[622] Engel 1979.

- Soviet support of Indian troops at the Indo-Pakistani War of 1971
- Soviet knowledge (at least four days in advance) of the Arab surprise attack on Israel that started the Yom Kippur War in 1973

The frequent observation of certain remote areas by commercial satellite image companies that is easily identified, for example, with use of Google Earth, also hints at global areas of international interest, as seen in **Figure 8-10**.

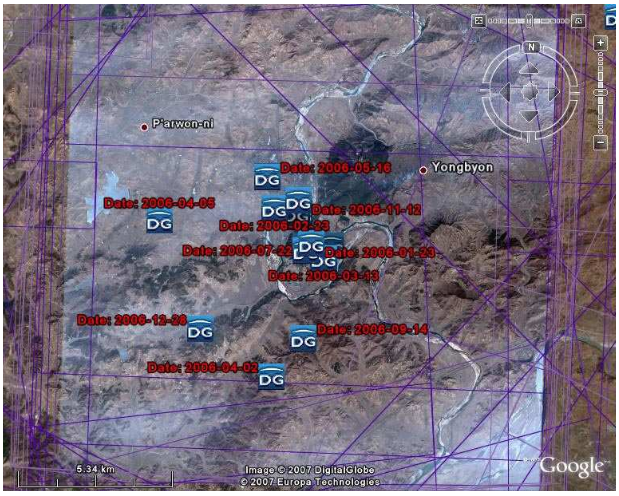

Figure 8-10: Frequently Photographed Areas[623]

8.7.5 Outlook

To give an example of the planned future utilization of space for defense purposes, various U.S. milspace programs are hereby presented:

- T-Sat: Highly secure communication links, first launch 2016, estimated life cycle cost of 16 G $[624]
- Space Radar: Next generation surveillance system, first launch 2016, estimated life cycle cost of 20-25 G $[624]
- GPS 3: Next generation navigation system, first launch 2014[625]
- …

Other studies and programs are:

- Conventional Global Strike: ICBMs armed with conventional warheads for global precision strikes within less than one hour
- Operationally Responsive Space: Launch of small satellites at demand

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[623] Digital Globe 2007, Google Earth 2007.
[624] Space News 32-2007b.
[625] Space News 36-2007.

within 24 hours
- Unmanned supply convoys guided by satellite
- Unmanned Combat Air Vehicles guided by satellite
- …

As seen in **Figure 8-11**, the huge data amounts of modern warfare require immense data transfer capabilities, momentarily surpassing the available capacities of the military services. During Operation Iraqi Freedom, 80% of used satellite communications were provided by the private sector.[626]

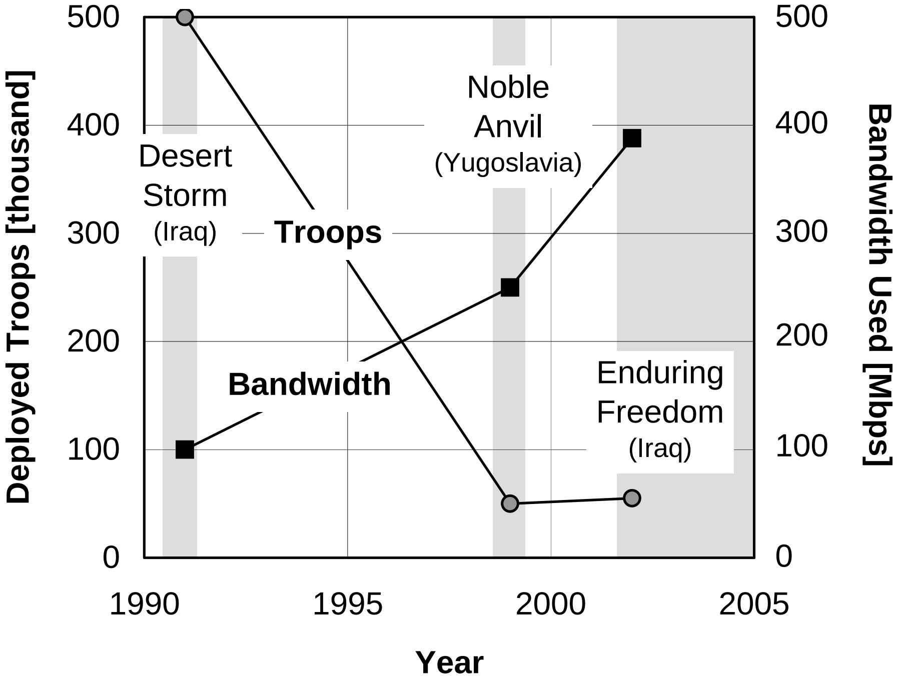

Figure 8-11: Military Satellite Communication Requirements[626]

In the far future, use of non-lethal weapons out of space might be possible, for example space mirrors that temporarily heat selected areas. International treaties limit deployment of weapons in space, though.

The role of space in the defense sector is getting ever more important, possibly establishing the asymmetric war as the dominating type of conflicts.

8.7.6 Financial Side

It is a fact that only the potential military application of spaceflight opened the door to space, with civil space programs as a mere byproduct. To underline this, **Table 8-15** presents various launch vehicles, their origin, and launches as of December 2007.

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[626] SIA 2004.

Table 8-15: Various Missile Derived Space Launch Vehicles[627]

Launcher (Family)	Country	Status	Developed as	in	Launches (Family)
Soyuz	RUS	Operational	ICBM (R-7)	1957	1 662
Atlas	USA	Operational	ICBM (Atlas A)	1957	326
Delta	USA	Operational	ICBM (Thor-Delta)	1957	581
Titan	USA	Decommissioned	ICBM (Titan 1)	1959	219
Cosmos 3M	RUS	Operational	IRBM (R-14)	1960	454
Dnepr	RUS	Operational	ICBM (R-36M)	1963	264
Proton	RUS	Operational	ICBM (UR-500)	1965	324
Rockot	RUS	Operational	ICBM (UR-100N)	1972	10

The defense sector continues to play an important role in spaceflight activities. This is mirrored by the annual expenses for defense in the space sector. **Table 8-16** confronts the requested U.S. civil space budget of 2007 with the **visible** military space budget.

Table 8-16: U.S. Space Related Budget Requests 2007 – Public and Defense Sectors [G $][628]

Sector	Institution	Space Related Budget Request	Total Request
Public	NASA	16.8	**20.5**
	NOAA	3.7	
Defense	USAF	5.5	**14.9**
	MDA	9.4	

There are no official numbers for the **actual** military space expenditures of respective U.S. institutions (MDA, NRO, CIA, Air Force, Army, Navy, …). But unofficial numbers give an idea of the actual situation:

- Total U.S. Government Space Budgets 2007: **62.6 G $**[629]
- Civil U.S. Government Space Budgets 2007: **17.7 G $**[629] (20.5 G $[628])
- (Department of Defense Space Budget 2007: 22.5 G $[629] (25.5 G $[630]))
- Total Military U.S. Space Budget 2007: **44.9 G $**[629]

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[627] Kyle 2007.
[628] Space News 6-2007.
[629] Space Foundation 2008.
[630] Shawcross 2006.

Including the unknown budgets within and aside of the Department of Defense (meaning CIA, NRO, …), milspace spending by far surpasses that of civil agencies NASA and NOAA combined. Similar priorities must be assumed for other nations than the USA. Thus, the national security sector is still the major force of spaceflight.

A side effect results from the extremely high milspace costs: The enormous spending on space related programs might well have been a contributing factor that the Soviet Union went bankrupt and the Cold War ended. Interestingly enough, this was unconsciously foreseen by President Kennedy in a meeting including Defense Secretary McNamara as early as December 5, 1962:

> Kennedy: "Well, there's no evidence that you can bankrupt a totalitarian [regime]. […] Their resources are still generous enough."
> McNamara: "Mr. President, I think there are problems –"
> Kennedy: "<u>The space program is the one that's going to…</u> [*laughter*]."[631]

8.7.7 Results and Consequences

Spaceflight has a truly global meaning in the applications of peacekeeping.

A) Results

The application of spaceflight for national security offered a new dimension of global surveillance and reaction:

- **ISR Satellites**
  Continuous surveillance of enemy territory, day and night, without offending national sovereignty, made concealed armament, political bluffs, and deployment of troops for surprise attacks impossible.

- **Communication Satellites**
  Instantaneous reports of troop movements, border violations, critical incidents and prevention of unintended consequences are possible. Instantaneous worldwide news coverage with all consequences is a byproduct.

- **Strategic Missiles**
  The knowledge of mutual assured destruction at any moment, without reliable defense, and the direct vulnerability of the political leadership itself contributed to a stabilizing effect.

Spaceflight disabled the concealment of preparatory military activities, and it also ended the strategic advantage of geographic distance. Suddenly, neither the two oceans that isolated the USA nor the vast expanses of the USSR had any special meaning in the age of ISR satellites, communication satellites, and strategic missiles.

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[631] Coleman 2006.

Support at current conflict helps to reduce losses both at one’s armed forces and the other’s civil population.

Table 8-17: Evaluation of “Support at Armed Conflicts”

Topic		Support at Armed Conflicts
Objective		Various satellites
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 10 000 000 000 $
Benefit	Effect	Loss of life
	Probability	High
	Threat	High
Resulting Motivation	Cost-Value Ratio	**High**

Deterrence was a major aspect during the Cold War and still plays an important role.

Table 8-18: Evaluation of “Deterrence”

Topic		Deterrence
Objective		ICBMs
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 10 000 000 000 $
Benefit	Effect	Large scale war: Massive loss of life, global economic losses
	Probability	Prior to spaceflight: Every few decades
	Threat	High
Resulting Motivation	Cost-Value Ratio	**Very High**

ISR is probably the most important aspect.

Table 8-19: Evaluation of “Intelligence, Surveillance, Reconnaissance”

Topic		Intelligence, Surveillance, Reconnaissance
Objective		ISR satellites
Technical Feasibility		Feasible (currently done)
Effort	Costs	Several 10 000 000 000 $
Benefit	Effect	Large scale war: Massive loss of life, global economic losses
	Probability	Prior to spaceflight: Every few decades
	Threat	High
Resulting Motivation	Cost-Value Ratio	**Very High**

B) Consequences

Since the beginning of the Space Age, no large scale war or global conflict erupted. This is mostly credited to the existence of nuclear weapons. But nuclear weapons without adequate means of delivery are not an essential threat for leading nations, and the additional aspects of military spaceflight have contributed much to the prevention of war.

Table 8-20 presents a selection of historic wars. Since World War II, there were only regional conflicts and asymmetric wars.

Table 8-20: Wars and Consequences

War	Year	Deaths [million]	Costs [G $]**
Mongol Conquests[632]	13th century	30*	
Thirty Years War[632]	1618-48	10*	
Napoleonic Wars[632]	1804-15	5*	
World War I[633]	1914-18	15*	
World War II[633]	1939-45	60*	
Korean War[634]	1950-53	0.04***	456***
Vietnam War[634]	1964-73	0.06***	518***
Iraq War (as of 9/2007)[632]	2003-?	0.004***	454***

* Rough estimations.
** Inflation-adjusted.
*** For USA only.

Astronautics certainly contributed both to the ending of symmetric wars and to the prevention of a hypothetic World War III. If wise use of space applications in the future could also support the prevention of asymmetric wars, then peacekeeping will continue to be the greatest achievement of spaceflight.

8.8 Conclusion

The topics of this chapter satisfy Maslow's decisive need for "safety", and thus are of direct importance for every single individual. Again, as in chapters 5 and 6, "distance to Earth" is the fundamental factor in most applications.

Results of this chapter are:

- Migration to space is not imminent, and no sufficient need to unlock the required funding is conceivable.

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[632] Wikipedia 2007.
[633] Leitenberg 2003.
[634] FAZ 31/10/2007.

- Spaceflight might support the fight against terrorism in various ways, though the actual threat of terrorism, seen in a greater context, is low.
- Spaceflight can support prediction of natural disasters, and plays a supportive role in aiding the victims.
- Only spaceflight offers the means for asteroid deflection, but it is completely unknown when this task is actually needed. It is not imminent.
- Spaceflight plays an important role in prediction and understanding of weather and climate, but active intervention is impossible due to technical limits.
- The understanding of climate (and its change) is of utter importance for the future direction of global economic and ecologic activities. Astronautics, with research of other planets as well as Earth, might well hold the key to this understanding.
- But the most important aspect is the commonly ignored role of military spaceflight.

The technology of spaceflight enables us to wage a war that may result in global devastation, but in the same way it is responsible for the longest period of global peace in recent history, meaning that no wars of *global* meaning[635] were fought since humanity mastered spaceflight.

In accordance with Newton’s law of force (see chapter 4.1.2.2.1), it is not possible to have one side of the medal without the other. While the technologies of spaceflight enable global devastation, they guarantee global security at the same time.

It is an uncomfortable fact that military spaceflight has dominated all space activities since their earliest days. But so far, the positive effects outbalance the negative undertone, and they will hopefully do so for the future.

Though it was never stated so clearly before in a work about benefits and motivation of spaceflight, this decisive insight was already intuitively felt by others. As it was perfectly formulated by James R. Asker in the Aviation Week Special Issue “50 Years of Spaceflight”:

> “If science and manned spaceflight are the glitzy celebrities at center stage and commercial satcom is the workaday stagehand, milspace is the writer-director, largely unseen, but knowing exactly who deserves credit for what in this grand production.”[636]

The global character of spaceflight enables both dangerous misuse, but also great beneficial applications for mankind. Identification and prevention of global perils for the safety of nations down to single individuals are essential for the preservation of our civilization, and spaceflight can – and does – contribute to this in unique ways.

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[635] Wars that involved leading nations of the world on both sides, doubtless with devastating results and far reaching global effects.

[636] AW&ST Mar 19/26 2007.

9. Additional Considerations

Prior to conclusions from the previous analyses and the summary of results, some additional considerations are done about spaceflight's historical development, its funding mechanisms, and the issue of technical understanding.

9.1 A New View of Spaceflight's Development

A final look into the past sheds a new light on the development of spaceflight. As a consequence, the true present role emerges, as well as the numerous coincidences that led to the development of astronautics as we know it today. But first, a brief look onto the unique historical circumstances.

9.1.1 A Very Special Constellation

Though spaceflight is extremely complex, it took a comparatively short span of time from the discovery of theoretical fundamentals to its greatest accomplishments, as illustrated in **Figure 9-1**.

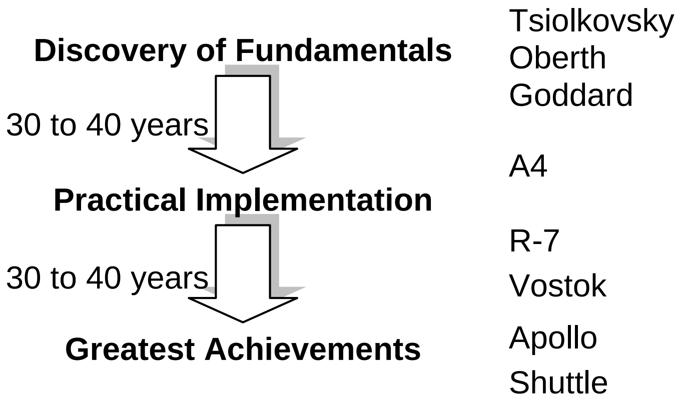

Figure 9-1: Pace of Spaceflight Development

Considerations about the mechanisms that drive technical developments give a perfect reason.

A) Useful Prerequisites for Technical Developments

It was stated in chapter 4.2.3 that every application is developed if only the demand is sufficient to justify the expenses. If the natural demand is insufficient – that means insufficient customers –, an artificial demand can be created.

The state is best suited to create this artificial demand. Assertive politicians with remarkable personality are required for this task.

The same kind of personality on the engineering side simplifies the technical development. Of course, a whole team of experts is required for large scale technical breakthroughs and realization, but a skilled and charismatic engineer and manager at the top simplifies interaction with the current customer (the politician) and potential future customers (the public) to support creation of an artificial demand.

Figure 9-2 illustrates these interactions.

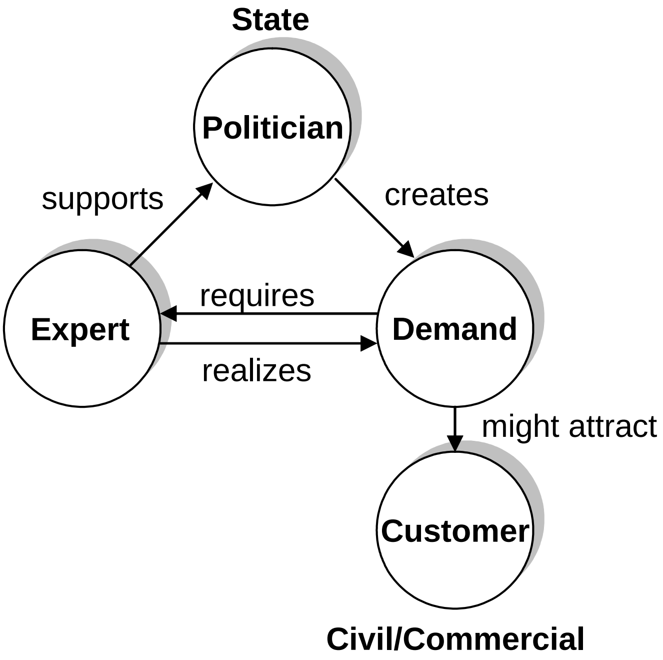

Figure 9-2: Interaction of Factors for Technical Development

B) Application of the Scheme on Spaceflight

The early situation of spaceflight fits perfectly into this scheme, with two of these constellations that even had an inciting effect on each other:[637]

- **USA**
  Politician J. F. Kennedy
  Engineer and manager W. von Braun
- **Soviet Union**
  Politician N. S. Khrushchev
  Engineer and manager S. P. Korolev

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[637] The ethical implications and motivations are not subject of the following considerations.

Neither Korolev nor Braun were appointed as head of the whole space program, but they were central figures for realization.[638]

The pace of spaceflight development slowed with the demise of the central actors, as seen in **Figure 9-3**.

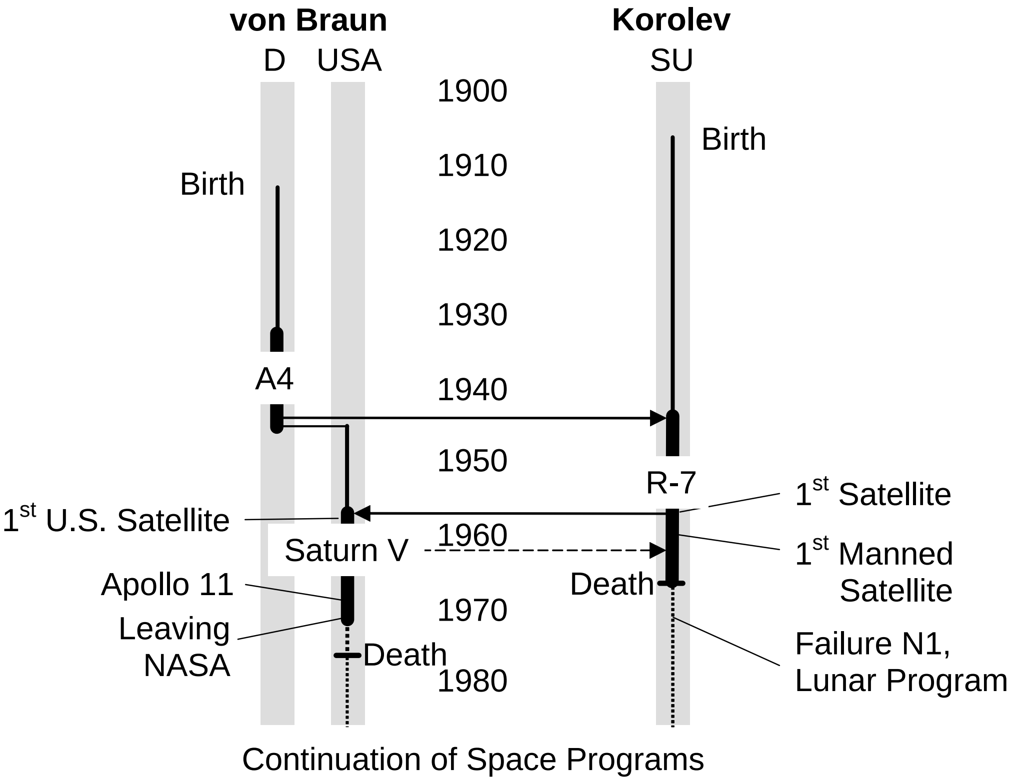

Figure 9-3: Influence on Space Program – von Braun and Korolev

Spaceflight did not manage to get a hold on commercial applications during these days. Until today, the attraction of potential customers and creation of a commercial demand for spaceflight was not very successful. Thus, the majority of spaceflight is still supported by the state.

It might be expected that extension of future activities would be easier if a similar version of this historical constellation repeats itself (hopefully in a peaceful way), and if the transition from artificial demand to actual demand is finally successful.

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[638] NASA Associate Administrator Robert C. Seamans Jr. and NASA Administrator James E. Webb had the idea of Braun running the whole Apollo program. Confronted with this idea, NASA Deputy Administrator Hugh L. Dryden said: “Well, if you and Jim want von Braun, that's fine with me. I'll take early retirement.” Braun was then appointed Saturn program leader. (Seamans 1996)

9.1.2 Spaceflight by Coincidence

Dealing with spaceflight's history, it becomes clear that the developments that finally climaxed with the Apollo program were quite improbable.

The efforts and the financial means for the development of spaceflight were enormous, as was previously illustrated several times. If only one link was missing in this unlikely chain of events, the motivation to develop rocket propulsion, and with it spaceflight, would have disappeared.[639]

Here are some fictive interruptions of the chain of events and their possible effects:

1. *Oberth resigns when his dissertation on rocket propulsion is rejected.*
   No results published, VfR never founded, Braun not interested in rocketry.
2. *Korolev does not survive his imprisonment in the gulag.*
   No Soviet missile successes, no Space Race, no U.S. spaceflight.
3. *World War I is a German success.*
   German military not interested in missiles, no rocket propulsion development.
4. *World War II is ends within one or two years.*
   German missile program is canceled, no rocket propulsion development.
5. *Wernher von Braun dies at the bombardment of Peenemünde in mid 1943.*
   Same as above.
6. *Nuclear weapons are not developed.*
   Missiles discarded as useless (V2 against London), no ICBM development.
7. *Wernher von Braun dies at his car accident in early 1945.*
   Successful U.S. space program improbable without Braun's assistance.
8. *Eisenhower permits an early orbital launch attempt by the Peenemünde team.*
   If successful: No Space Race triggered.
9. *The first launch of Vanguard in 1957 is successful.*
   Peenemünde team not reactivated, further U.S. successes questionable.
10. *The launch of Explorer 1 results in failure.*
    Same as above.
11. *Korolev is not successful in his efforts.*
    No Space Race triggered.

Of course, this is very speculative, and there are many more speculative assumptions that are not listed here.[640] But expected funding cuts due to missing motivation for spaceflight development – be it for political or military purposes – are reasonable.

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[639] Even if the means to develop the required technologies exist, it does not mean that these technologies are developed, and even less that they are applied. Many of Leonardo da Vinci's ideas took hundreds of years to realization, and there are countless other examples.

[640] For example, some believe that the Apollo Program would have been cancelled before the objective was achieved (e.g. at the Apollo 1 tragedy), had Lyndon B. Johnson not been determined to make the Moon part of the murdered president Kennedy's legacy. (Space News 20-2007b)

9.1.3 A World without Spaceflight

The results of the previous considerations lead to interesting mind games. If the chain of coincidences would never have launched the age of spaceflight, it can be speculated what the consequences would have been.

- *No spaceflight at all*
  The USA continue development of new aircraft for weapon delivery. The focus lies on supersonic bombers. Some basic research on rockets is made, but the technology turns out to be far too demanding for the expected results. The USSR tries to catch up on aircraft development and has no means or intention to begin missile development. Human spaceflight is seen as possible by some enthusiasts, but the expected costs are far too high for realization.
- *Cold War turns into Hot War*
  Though development of state-of-the-art anti aircraft missiles takes longer, and reconnaissance flights on enemy territory might be less risky, strategic air defense is handled by large numbers of interceptor aircraft. Thus, as before every large war in history, the exact abilities of the other side remain unknown. Defenses against nuclear retaliation strikes from enemy aircraft seem possible, deterrence loses its effect, and a crisis escalates into open war between West and East.

If the global peacekeeping effect of spaceflight is ignored, it is interesting to notice that our daily lives would not be that different. Among the more noticeable effects are:

- *The weather forecast is vague*
  Without weather satellites, meteorologists must rely solely on ground stations. Hurricanes, typhoons and cyclones and their paths might be difficult to predict, just as floods, blizzards and other phenomena.
- *No satellite navigation*
  Considering that satellite navigation is in use only for a comparatively short span of time, the actual effect is less than commonly expected.
- *Less environmental consciousness*
  The missing understanding of the fragility of Earth as seen from space, as well as the missing global survey of environmental effects, might have slowed environmental protection efforts.

Though it sounds strange, the situation is probably analogue to that of the cell phone: It has become an important part of our way of living, and without their cell phone, people feel something is missing. But until the mid 1990s, the portable phone was almost nonexistent, and no one missed it – daily life worked just fine without it.

9.2 Current Mechanisms of Spaceflight Funding

The following paragraph criticizes various aspects of the spaceflight community which result from matter of fact observations. Various items are not limited to spaceflight, but are also common in other fields – which is not a good excuse for the spaceflight sector to continue this way. No examples are mentioned, but they should be easy to find for the interested.

A) Reversal of Customer-Contractor-Risk-Principle

The basic idea of a free market has a contractor who offers a product, and a customer who pays for it. If the product is too expensive or otherwise not suited for the customer, he will not buy it. The risk lies at the contractor.

The spaceflight industry offers the idea for a product that does not yet exist. The state is contracted to buy the product and pays for its development, taking all the risks. The product usually grows more and more expensive, and the promised functionality is reduced. In the end, the state either cancels the project, or the industry delivers a product with huge time and cost overruns that are accepted by the state. Risk lies at the customer.

B) Ignorance

The customer – for example a politician not familiar with astronautics – is told what product is needed in the future. By coincidence, industry already has development plans for just this product that only need to be financed. Because the product looks great on paper, and the customer cannot judge its real value, funding is granted.

C) Cost Overruns

Once product development is granted, the cost *always* increases, independent of the direction of further actions:

- Current funding cuts increase total cost
  (extended development time, …)
- Current increase of funding increases total cost
  (future budgets are already granted, …)
- Project cancellation increases total cost
  (contract penalties, …)

D) Inertness of Large Companies

Large aerospace companies have a tendency to react slowly, and when they finally react, development costs for new programs are high. Small companies react quicker and produce results for less investments. Two examples are presented in **Table 9-1**.

Table 9-1: Comparable Space Programs of Small and Large Companies

Program Type	**Parameter**	**Company Size**	
		Small	**Large**
Suborbital Tourist Spaceplane	Company Name	Scaled Composites	EADS Astrium[641]
	Employees	250[642]	11 000
	Program Name	SpaceShipTwo	-
	Announcement	2004	2007
	First Flight Test*	2008	2012
	Passengers	6+2[643]	4+1
	Development Costs	**200 M $***[644]	**1 G €****
Space Transportation System	Company Name	SpaceX[645]	EADS Astrium***
	Employees	250	11 000
	Program Name	Falcon 1/9	Ariane 5
	Announcement	2002	1988[646]
	First Flight Test*	2006/2008**	1996[646]
	LEO Payload [t]	0.5/10**	16[646]
	Development Costs	**< 1 G $****	**8 G €**[646]

* Design, testing and construction of five SpaceShipTwo with two WhiteKnightTwo carrier aircraft.
** Planned.
*** Plus others.

But, compared to large corporations, the high requirements of space technology complicate engagements of small companies in this sector.

E) Importance of the Self Proposed Subject

By the submitter, the subject of the proposed program is always seen as more important than every other, thus needing immediate funding: “It might not be relevant yet, but definitely will be in the future, and should therefore be a national priority.”

F) Squeezing Money

Once a program is financed by public funds, endless minor modifications of the requirements lead to significant increase of program costs.

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[641] EADS 13/06/2007.
[642] Space News 24-2007b.
[643] Virgin Galactic 2007.
[644] AW&ST Aug 6 2007.
[645] SpaceX 2007.
[646] Wade 2007.

G) Responsibility for Cost Effectiveness

Once a contract is granted, it is of no interest for the contractor to be cost effective – additional funds are either granted, or the program is cancelled and termination funds are received.

The cost difference between Spacelab and Spacehab as seen in **Table 9-2** illustrates this: Spacehab was developed as a competitive piece of hardware that was to be rented to NASA. Spacelab was a granted governmental project.

Table 9-2: Cost Comparison: Spacelab and Spacehab

Name	Company	Contract Type	Costs [M $]
Spacehab	Spacehab Inc.	Commercial	70[647]
Spacelab	VFW-Fokker/ERNO/…	Governmental	ca. 700[648]
Columbus	EADS and subcontractors	Governmental	> 1 200[649]

Though Spacelab was only twice the size of Spacehab, costs were higher by a factor of 10. Columbus basically is a smaller Spacelab with 20 times the cost of Spacehab.

H) Starting From Scratch

The western space programs in particular rarely use existing components, structures or configurations. New generations of satellites, probes, or launch vehicles are usually designed completely from scratch.[650]

Numerous pre-programs and studies proceed a small scale demonstrator to proof basic feasibility. New launchers are designed following enduring configuration studies, though only one configuration is in use (this is similar to a car manufacturer each time considering the number of wheels on a new car).

Even if existing components are to be used for new applications, they must be heavily modified and improved. A good example is the J-2 engine of the Apollo era that is to be used for NASA's new Ares launch vehicles: It is improved that much that the derived J-2X engine essentially is a new engine, requiring a full test regimen and now being the pacing program item.[651]

The situation for privately financed space ventures seems to be different, though, as is seen for example with common communication satellite buses.

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[647] Wade 2007.

[648] In DM: 2.000 million. (Deutsches Museum 2007)

[649] In €: ca. 1.000 million.

[650] There are some exceptions, of course, for example the commonality of ESA's Mars Express and Venus Express probes.

[651] AW&ST Apr 16 2007.

9.3 The Understanding of Spaceflight Issues

A major drawback for spaceflight is the widespread lack of technical understanding and the false estimation of feasibility concerning announced programs, on the side of the general public as well as within the spaceflight community. Projects that are clearly not feasible are funded, resulting in program cancellation after enormous sums were spent, and thus undermining the trust of the public into further space activities.

The typical application sequence of the Tsiolkovsky Equation for future space transportation systems (see chapter 4.1.1.3.1.1) is a good example:

- Circular velocity is assumed as the velocity requirement Δv,
- Theoretical impulse in vacuum is assumed as engine performance c,
- A desired payload mass m_p is selected,
- Inserting these parameters into the equation delivers the required net mass of the launch vehicle.

9.3.1 Technical Issues

A lack of technical understanding can be seen on many occasions, not only in the media, but also by experts and even by renowned institutions.

A) Media and Public

Most space related reports and news in the media include errors that range from negligible to significant. Confusing kilometers with meters and billions with millions is quite common, but there are other errors, too. The announcement of the suborbital EADS tourist space plane for 2012 and its public release by news publisher Agence France-Presse (AFP)[652] is a good example:

- "…prepared to shoot tourists into suborbital orbit…"
- "…at a maximum speed of 3 G, or three times the force of gravity…"
- "…admire the earth globe against a cobalt sky with the sun and the moon side-by side in the background…"
- "…before the pilot hits the brakes at 4.5 G…"

Public misunderstanding and ignorance of facts and correlations that seem clear and simple for the space community is common. This must be kept in mind for any space related public outreach activities.

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[652] Space Daily 13/06/2007.

B) Experts

One famous example is the demand of a former NASA administrator to develop space transportation systems that should have a physically impossible payload mass ratio of 30 %.

Another example is an anecdote attributed to Wernher von Braun and Ed Heinemann:

> “Ed Heinemann of Douglas Aircraft was probably the greatest low-weight aircraft engineer that ever lived. He designed a single-stage-to-orbit launch vehicle in 1946, and relates the following story of a 1961 meeting with Braun:
>
> …I went to see Wernher Von Braun in Huntsville, Alabama, on a different matter…In the discussion that followed …. Wernher [was asked] <u>why he used a 26 percent structural weight fraction ratio</u> on the V-2.
>
> "Well," Von Braun said, "I built the structure strong enough to hold together, and frankly, it just came out that way."
>
> We (at Douglas) had differed from Wernher in our approach in that we worked backwards. <u>We began with a weight and designed components to remain within that weight. Wernher, on the other hand, designed the components and then arrived at a weight.</u> His circumstances were far different from ours, of course, since he was building a weapon which had to be very rugged. If there was a lesson in the [Douglas 1946] satellite project, it was that by starting out with a clean piece of paper and a different approach, suitable results could be achieved, regardless of what approach others might have taken to reach the same goal.”[653]

It is interesting that successful development *<u>on paper</u>* without a piece of hardware is put on a level with actual successful development, construction, deployment and *<u>operation</u>*. This approach underlines the distance to reality of most “experts”.

C) Institutions

Table 9-3 presents the official proposals of various aerospace companies for NASA’s X-33/Venture Star SSTO program in the 1990s.

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[653] Wade 2007.

Table 9-3: SSTO Proposals and US-STS Numbers[654]

	McDonnell	Lockheed	Rockwell	US-STS
m_0 [t]	1 088.6	991.6	907.2	**2 000**
m_{net} [t]	99.3	89.4	90.7	**269.4**
m_p [t]	20.4	26.7	19.1	**24.4**
m_{net}/m_{pr} [%]	10.25	10.21	11.37	**15.79**
m_p/m_0 [%]	1.87	2.69	2.11	**1.22**
T_{dev} [a]	5	5	5	**10**
C_{dev} [G $]	4 – 7	4.5 – 5	5 – 8	**ca. 40**
c_{tr} [$/kg]	< 2 200	< 2 200	< 2 200	**> 40 000**

Though the comparison with the numbers of the US-STS program should have exposed the infeasibility of the SSTO proposals, the program was funded for several years, spending almost 1 G $.[655]

D) Comment

Realization of topics that are physically and technically feasible, such as ballistic missile defense, is questioned by experts as unrealistic or infeasible. But topics that are far beyond our physical and technical abilities – and will be for any foreseeable future – are regarded in a way as if their realization is for sure and just a few years away:

- **Terraforming of Mars**
  Significantly changing the climate of other planets is seen as feasible. But even though the entire humanity, with all its industries, tries hard to change Earth's climate for decades now, the impact is small enough to keep alive a debate whether humanity has any influence at all.

- **The Moon as a Stepping Stone to Mars**
  Creating the capability to build and launch interplanetary space ships from the lunar surface is seen as feasible. But with the largest space program in history, the USA only achieved to keep two humans alive on the Moon for a maximum of three days.

- **Interstellar Travel**
  Sending a (manned?) spacecraft that has to operate continuously on a journey of several centuries or millennia in an extreme environment without any support from outside is seen as feasible. But even with continuous maintenance, repair and overhaul, and careful operation, some simple machines (historic cars, trains, …) on Earth can barely be hold in service for one century.

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[654] Schmucker et al. 2007.
[655] NASA 2007.

9.3.2 Program Size

The fact that the size and challenges of spaceflight programs, especially manned programs, are generally not understood either, is illustrated by two examples.

A) Chinese Space Program

The current Chinese space program is often referred to as very ambitious and respectable, with significant advances over the past years, a space station planned for the 2010s, and an expected manned lunar landing in the 2020s.

Table 9-4 compares the achievements of the early days of the U.S. and the Soviet space program with those of the Chinese program. The five years after the first manned orbital flight are regarded.

Table 9-4: Early U.S., Soviet and Chinese Space Programs

	USA (1962-66)	**SU (1961-65)**	**PRC (2003-07)**
Year of Reference	**1966**	**1965**	**2007**
First Manned Orbital Flight	1962	1961	2003
Orbital Launches within First 5 Years	348	149	35
Manned	14	8	2
Largest Launcher Available [t]	590	595	464
Largest Launcher in Development [t]	3 000	2 700	650*
Missions Beyond Earth Orbit	15	12	1

* Planned.

Combined with the fact that it is clearly based on Russian support, the space program of the PRC is significantly less advanced than the early U.S. and Soviet programs. Thus, achievements such as space stations and lunar landings cannot be expected in timeframes similar to those of the former USSR and the USA.

B) Vision for Space Exploration (VSE)

The VSE was announced in early 2004 in the wake of the loss of Orbiter Columbia. It proposes a return of the USA to the Moon within less than 20 years, using the Orion crew exploration vehicle and the shuttle derived Constellation program launch vehicles Ares I and Ares V.

The structure of the Apollo program and the renewed attempt of a U.S. lunar landing show significant differences. The Apollo program was achieved within 8 years, as seen in **Figure 9-4**. Orion/Constellation requires at least 16 years.

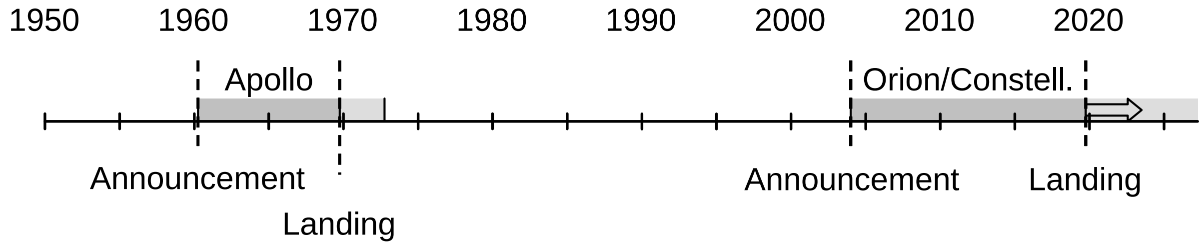

Figure 9-4: Timeframes of U.S. Lunar Landing Programs

The launch sequences of Apollo and the proposed Constellation program (as of February 2007) are illustrated in **Figure 9-5**.

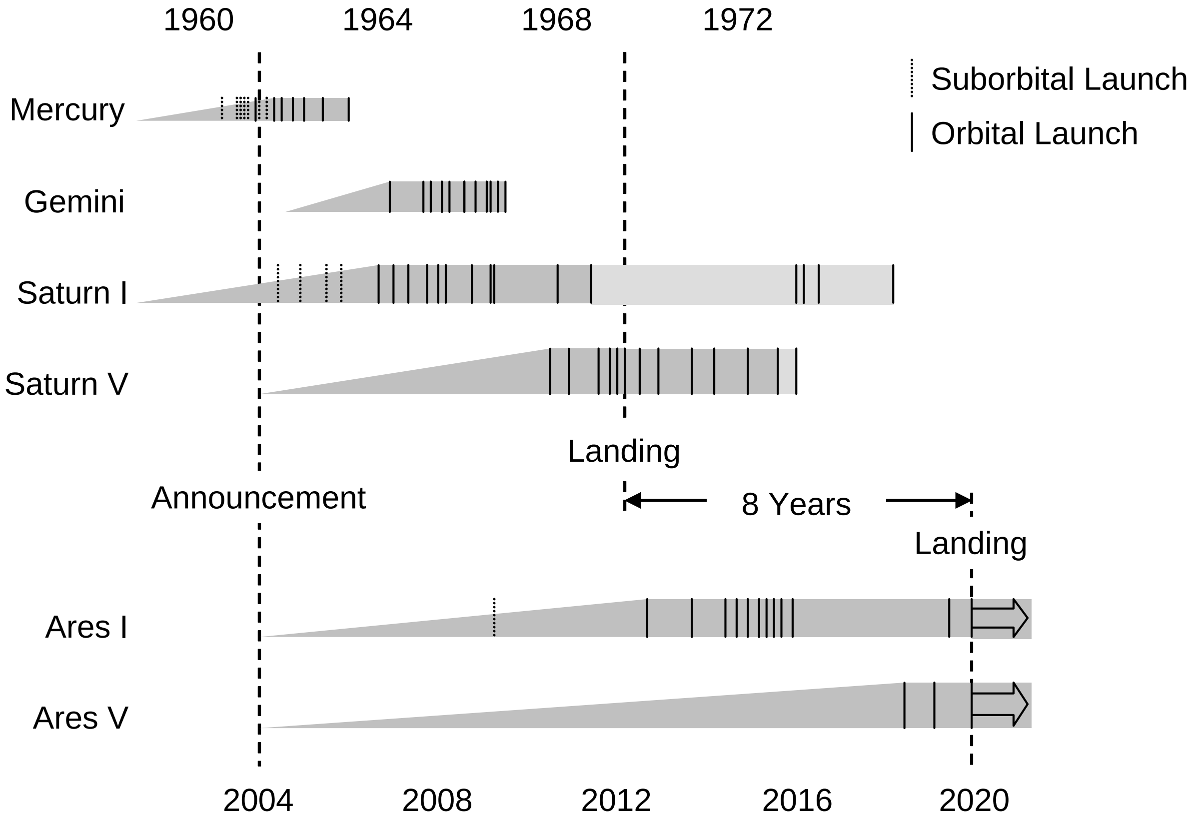

Figure 9-5: Launch Campaigns of U.S. Lunar Landing Programs[656,657]

The Apollo program had the lowest possible goal of a manned lunar landing: To send two humans to lunar surface and bring them back safely. As can be seen in **Table 9-5**, the new lunar program will offer considerably more at a considerably lower price,

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[656] Wikipedia 2007.

[657] The schedule is subject to continuous change, with launch dates slipping further back.

but at twice the time for realization.

Table 9-5: Apollo and Orion/Constellation

	Apollo	Orion/ Constellation
Initiated	1961	2004
Target Date	1969	2020
Time to First Landing [a]	8	16
Astronauts per Mission	3	4
on Lunar Surface	2	4
Maximum Stay Duration [d]	3	7 – 210
Launches per Mission	1	2
Program Costs [FY 2000, M $][658]	105	85*

* Until first landing in 2020.

That a considerably more ambitious program will be realized for a considerably lower price must be doubted.

C) Summary

In general, it seems that lessons taught by the problems of previous large space programs are all too often ignored, and the challenges of future programs are underestimated. There is a degradation of knowledge concerning spaceflight.

China will not set foot on the Moon within a few years, and India will not develop a reusable spaceplane, a task even the U.S. failed to fulfill.

9.3.3 Conclusion

The theoretical design of machines and components will always differ from real production regarding performance and cost. Not the theoretical design on paper, but the practical application and realization is the high art of engineering.

Only if the engineers propose physically and technically feasible programs, including realistic cost predictions, only then can large space programs be credible, only then will further funding be granted, and only then can spaceflight advance.

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[658] Griffin 2007.

10. Results

All of the previous comprehensive assessments lead to the following conclusions.

10.1 Final Conclusions

The four categories of benefits that were used to classify and analyze space activities were:

- Subjective benefits
- Quantifiable benefits
- Benefits as a byproduct
- Potential benefits

The benefits as a byproduct are created by any space activity – the required activities are not goal-oriented. This leaves a classification of three directions of spaceflight activities with fundamentally different motivation:

- ***Idealistic*** – primarily creating subjective benefits
- ***Commercial*** – primarily creating quantifiable benefits
- ***Preventive*** – primarily creating potential benefits

The characteristics of these directions of activities are listed in **Table 10-1**.

Table 10-1: Classification of Spaceflight Activities

Type of Requirements	Idealistic	Commercial	Preventive
Exemplary Topics	Science, Philosophy, …	Communication, Tourism, …	Peacekeeping, NEO Deflection, …
Exemplary Objectives	Planetary probe Mars landing, …	ComSat, Space station, …	ISR satellite, NEO tug, …
Declared Goal	Progress	Profits	Safety
Required Availability	Secondary	Secondary	Decisive
Consequence of Failed Mission*	None	Significant (Financial Losses)	Immense (High loss of life)
Required Reliability*	Low	High	Highest
Relevance of Costs	Medium	High	Low

* Unmanned systems.

In detail, the proposed new classification of spaceflight activities is:

A) Idealistic

This type of activities is used for many justifications of spaceflight. But the high requirements of spaceflight enable only large companies and national institutions to actually do spaceflight. Companies are not interested in idealistic motives, and the state has other, more urgent duties and tasks than spaceflight.

Some nations can afford this type of spaceflight activities, and will continue to do this, because the costs are negligible compared to the costs of other important tasks. For example, cutting the whole budget of NASA in 2007 and using it for social tasks would increase the U.S. federal spending on social programs from 1.581 trillion $ to 1.597 trillion $.[659] It is questionable if this difference would even be noticed.

There are parallels to museums, theaters or operas: Idealistic spaceflight activities will never be profitable. But they are a part of our culture, they inspire people, and leading nations of the world can afford them, and will continue to do so.

Though most of the considered topics are insufficient to justify spaceflight on their own, the sum of idealistic motivation is sufficient for the current scale of space activities.

Table 10-2: Examined Topics of Idealistic Spaceflight

Topic	Technical Feasibility	Quality of Justification
Space as Driving Force of Civilization	Feasible	Overestimated
Utilization for Political Propaganda	Feasible	Doubtful
Technical Overcoming of War	Feasible	Wrong
New Species of Mankind	Very Challenging	Wrong
Media Coverage of Spaceflight	Feasible	Poor
Potential Influence on the Cultural Sector	Feasible	Wrong
Active Support of Education	Feasible	Moderate
Spaceflight as a Personal Challenge	Feasible	Questionable
“Because It’s There” – Exploration	Feasible	Insufficient
Spaceflight as a Modern Age Monument	Feasible	Wrong
National Economical Aspects	Feasible	Insignificant
National Prestige	-	Variable
Science and Research	Feasible	**Sufficient**
Search for Life	Challenging	**Significant**

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[659] Brooks 2007.

B) Commercial

The commercial sector has virtually unlimited financial means at its disposal, as long as a higher return of investment is guaranteed. Some topics like communication satellites are already successfully exploited by commercial companies. Some other activities have a potential, but most have none.

Table 10-3: Examined Topics of Commercial Spaceflight

Topic	Technical Feasibility	Commercial Attractiveness
Launch Vehicles and Sat. Transportation	Feasible	Low (M/H)*
Launch Sites	Feasible	Low
Communication Satellites	Feasible	Medium to High
Observation Satellites	Feasible	Medium
Navigation Satellites	Feasible	Low
Insurance	-	Medium to High
Supplying Space Stations	Feasible	Low (M)*
On Orbit Maintenance, Repair, Overhaul	Feasible	Low
Orbital Trajectory Modification	Feasible	Low
Disposal of Orbital Debris	Partially Feasible	None
Research Stations – LEO	Feasible	Low
Research Stations – Beyond LEO	Very Challenging	None
Privatization of Science Missions	Feasible	**Interesting**
The Astronaut Experience	-	Insignificant
Suborbital Tourism	Feasible	Low to Medium
Orbital Tourism	Feasible	Low
Lunar Flyby Tourism	Challenging	None
Space Hotel – Adventure Type	Feasible	Doubtful
Space Hotel – Luxury Type	Not Feasible	None
Space Burial	Feasible	**High**
Advertising at Current Missions	Feasible	Insignificant
TV Show in Space	Feasible	**Interesting**
Large Orbital Advertising Structure	Challenging	Doubtful
Resource Mining – Small	Challenging	Low
Resource Mining – Large	Not Feasible	None
Production and Manufacturing	Feasible	None
Power Generation in Space	Very Challenging	None
Nuclear Waste Disposal	Feasible	**High**
Illumination	Challenging	Low

* With public funding at development phase: Medium to high (M/H), Medium (M).

C) Preventive

The means of spaceflight are able to avert great damage. The often ignored, but most important sector of spaceflight is in this category of activities: Military space.

By far, the major part of investments for space was done in this sector. And these investments seem to have paid off. Since the arrival of the space age, with uninterrupted reconnaissance and surveillance as well as the potential destruction of whole nations within minutes, the age of destructive, large scale symmetric wars ended.

Table 10-4: Examined Topics of Preventive Spaceflight

Topic	Technical Feasibility	Cost-Value Ratio
Exodus to Space	Not Feasible	None
Interstellar Travel	Not Feasible	None
Contributions Against Terrorism	Challenging	Low
Natural Disasters	Feasible	**High**
Asteroid Deflection	Very Challenging	?
Search and Rescue	Feasible	**High**
Global Environmental Monitoring	Feasible	**High**
Weather Prediction	Feasible	**High**
Weather Control	Not Feasible	None
Active Climate Intervention	Not Feasible	None
Understanding Climate	Feasible	**High**
Support at Armed Conflicts	Feasible	**High**
Deterrence	Feasible	**Very High**
Intelligence, Surveillance, Reconnaissance	Feasible	**Very High**

D) Distance to Earth is Decisive

Gravity (micro- or low gravity)
Temperature
Vacuum (or atmosphere of other planetary bodies)
Radiation
Distance to Earth
Unlimited Space (and resources)
Small Particles (micrometeoroids, dust)

Figure 10-1: The Decisive Aspect of Space

Of all previously identified aspects of the space environment, it is “Distance to Earth” that plays the only important role in the utilization of space.

It has a negative character only for the class of “benefits as a byproduct”. Looking back from here, this was one major reason for their dismissal as a sufficient justification for spaceflight.

E) Example

The new classification is further backed by an analysis of the 1962 quote of John F. Kennedy, illustrated in **Figure 10-2**. The politician sets the idealistic goal, preventive preparatory work in the background enabled the feasibility, and there is no commercial aspect, so the program was cancelled after the idealistic objective was achieved.

Preventive preparatory works enable

We choose to go to the Moon in this decade
the idealistic goal (to reach a distant place)

and do the other things,
that will be done together with other non-space goals

not because they are easy, but because they are hard
only for a political reason.
No commercial aspects!

Figure 10-2: Famous Kennedy Quote Under New Classification Aspects

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F) Required Changes in the View of Astronautics

Spaceflight suffers on the fact that many space advocates shut their eyes before reality. It must be accepted that:

- Space transportation will always remain expensive.
- Space transportation costs are not the dominating cost driver of spaceflight.
- Space hardware and operations will always be unreliable and expensive.
- Concentration on details will not change the big picture.
- The global meaning of current spaceflight is negligible in terms of expenditures, scientific results, spin-offs, economic effects.
- Military spaceflight always was, and still is the major part of space activities, concerning expenditures as well as benefits.
- Repeated revival of old ideas and concentration on infeasible proposals will not change the situation of spaceflight.
- ‘Preaching to the converted’ about spaceflight is irrelevant.
- Clear and understandable reasons for the public are required for extended spaceflight activities.

- The focus of activities should not lie on the reduction of efforts. Existing benefits must be communicated, and new potential benefits identified, both in compliance with the decisive aspect of motivation.

G) Predictions

Space transportation costs might one day decrease by a factor of 2 or more, but they will probably remain at the current levels. A decrease in transportation costs will not result in an increase of activities due to constant payload and operation costs.

Transportation is not the decisive factor. Mastering the environmental conditions for a rewarding task is decisive. Antarctica and the deep sea illustrate that low transportation costs play no role in colonization and utilization of a hostile environment.

Science and exploration missions will continue at the present level. A serious increase cannot be expected.

From a commercial point of view, there are some topics with large potential. Space burial and disposal of high level radioactive waste are the most promising. The potential of space tourism seems generally overestimated. Current commercial successes in space transportation, communication and Earth observation will continue. Navigation creates a huge market for the ground segment, but the space segment is commercially not viable and exists only due to public funding.

All topics of preventive character have great potential. Disaster management is done already, early warning might be possible some day. Asteroid deflection will be installed far in the future. The spending for military space will continue or even increase, as new potential space powers slowly emerge. This must not be seen as a threat, but quite to the contrary: Spaceflight as a chance for enduring peace.

10.2 Summary

Some of the gained insights might seem familiar, others might seem all new. Combined, they might contribute to the debate about spaceflight and its benefits.

Spaceflight cannot be compared to any other terrestrial discipline. Aside of the very demanding task of transportation from Earth to space, the activity in space must be enabled with very demanding hardware and operations. This creates a two-step threshold for any space activity.

The efforts required to overcome this threshold are enormous, and will always be due to physical and technical constraints: Neither space transportation nor space hardware and operations can ever become routine in the future. The costs of hardware and operations are considerably higher than those of space transportation, and will always be: To offer the *functionality in space* is the hard task.

Any task is only done if the expected benefits outweigh the efforts. For spaceflight, only government and large companies have sufficient means for realization. Companies are interested in profits, and governments in the contentment of their citizens.

Based on these insights, all imaginable types of activities that can be done in space must be analyzed under a cost-benefit ratio. This is complicated by the fact that many benefits are impossible to quantify.

In the analysis of space related activities, the *distance to Earth* was identified again and again as the decisive aspect of space. All other characteristics of space are more of a drawback than an asset.

Classification of expected benefits into four categories, combined with potential motivation, leads to the result for justifications of spaceflight illustrated in **Figure 10-3**.

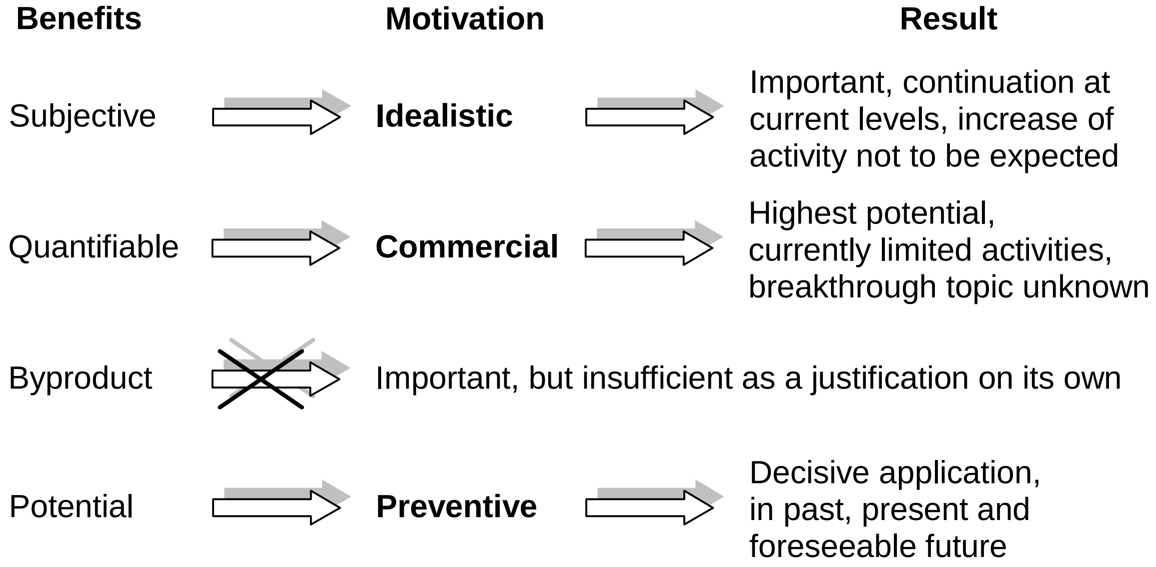

Figure 10-3: Justifications for Spaceflight Activities

Idealistic spaceflight tasks are performed by governments, and should be, but an increase in activities is not expected due to limited governmental funds and motivation.

Commercial spaceflight tasks are performed by companies, and financial means are virtually unlimited, but only if the revenues outweigh the investments. A promising, realistic commercial space venture is not yet identified due to the high investments required. But if it ever is, this would be the key to extensive spaceflight activities.

Preventive spaceflight tasks are performed by governments, and satisfy the most basic need of human individuals: The need for safety. Spaceflight offers unique ways to contribute to safety, ranging from the human individual to a global meaning. This was, is, and probably will be the most important motivation for spaceflight.

The combined insights demand a new phrase for “space<u>flight</u>” that shifts the focus from space *transportation* to *functionality and operations* in the space environment.

**“I have a hunch the most important reason we're going to space
is not known now.”**

Burt Rutan
1943 –
(Designer of SpaceShipOne)
Time, March 5, 2007

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