Development of High-Precision Thermosphere Models for Improving Precise Orbit Determination of Low-Earth-Orbiting Satellites (TIPOD) – First Results

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Introduction and Motivation

- The motion of a satellite depends on gravitational and **non-gravitational** accelerations
- Modelling the **thermospheric drag** is a major challenge in precise orbit determination (POD) of low-Earth orbiting (LEO) satellites with altitudes below 1000 km – the thermospheric drag is directly related to the density of the thermosphere and is the largest non-gravitational acceleration for LEOs
- Contribution of the thermospheric drag for a LEO satellite at 200-350 km altitude: similar to J_2-term

Objectives

- Development of **high-precision thermosphere models** to **improve POD** of geo-scientific **LEO satellites**
- Composition of a set of observation techniques to determine appropriate **thermospheric key parameters** including a complete stochastic model
- Improving the knowledge of thermospheric density by extending the **empirical** model and calibrating model predictions by various observation techniques

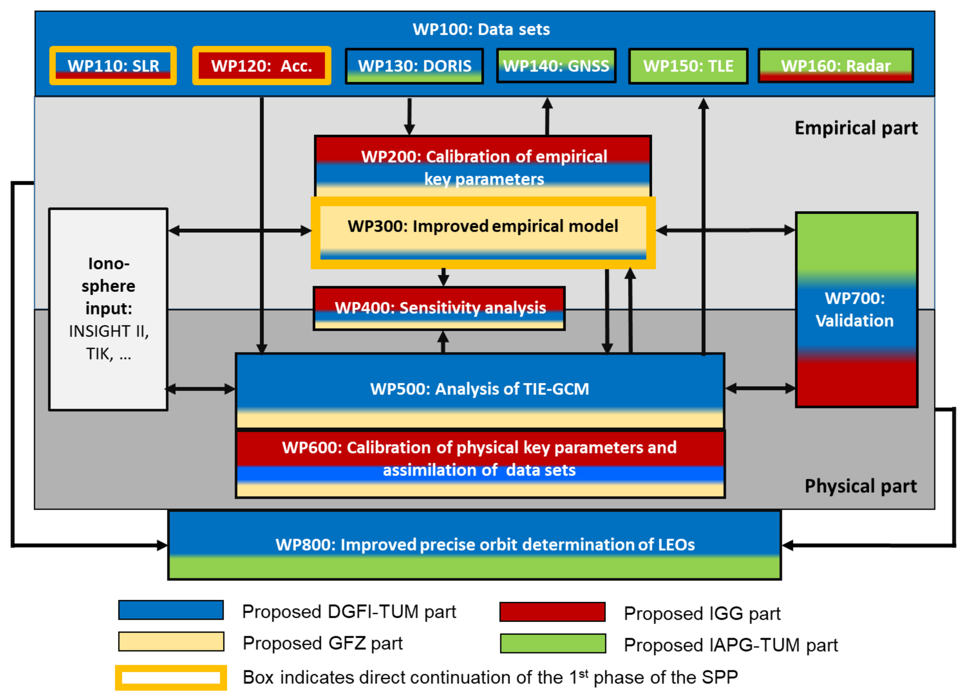
Used Thermospheric Density Models

- *Empirical Models*
  - COSPAR International Reference Atmosphere 86 (**CIRA86**)
  - **NRLMSISE00**
  - Jaccia-Bowman 2008 (**JB2008**)
  - Drag Temperature Model 2013 (**DTM2013**)
  - **CH-Therm 2018**; was developed by the GFZ partners during the Project INSIGHT of the 1st phase of SPP 1788 from CHAMP observations, [Xiong et al. (2018)]
- *Physical Model*
  - Thermosphere Ionosphere Electrodynamic General Circulation Model (**TIE-GCM**)

Internal and External Links

- TIPOD is a **continuation of** INSIGHT-I
- TIPOD results will be used for mutual validation with the outcome of other projects **within** and **external** to the SPP 1788 (**INSIGHT-II**, **TIK**)

Project Structure



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- The thermospheric density provided by the various models listed above **differs significantly** which shows the importance of further investigations
- Figure 1 shows **time series** of thermospheric density ρ for a fixed location from 4 empirical models around the 2015 St.Patrick Day

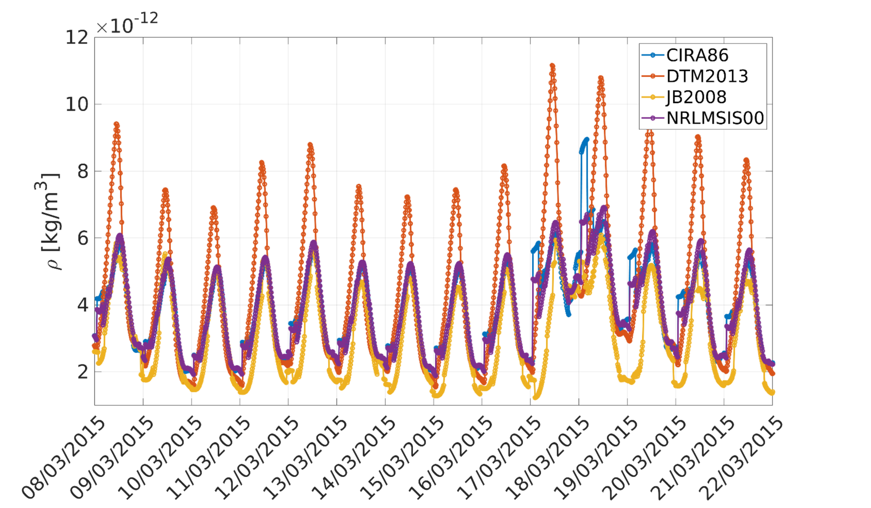

Figure 1: Time series of the above mentioned models for a fixed location (lon 5°, lat 15°) over a period of 15 days.

- It can be stated that the magnitude of the DTM2013 oscillation is significantly larger than the magnitude of the other 3 models
- Also important: the density change vs. the height
- Figure 2 illustrates a 2D plot of the density change along the height for the models (JB2008 and NRLMSISE00) for a quiet and a storm day (top) and the respective differences (bottom)

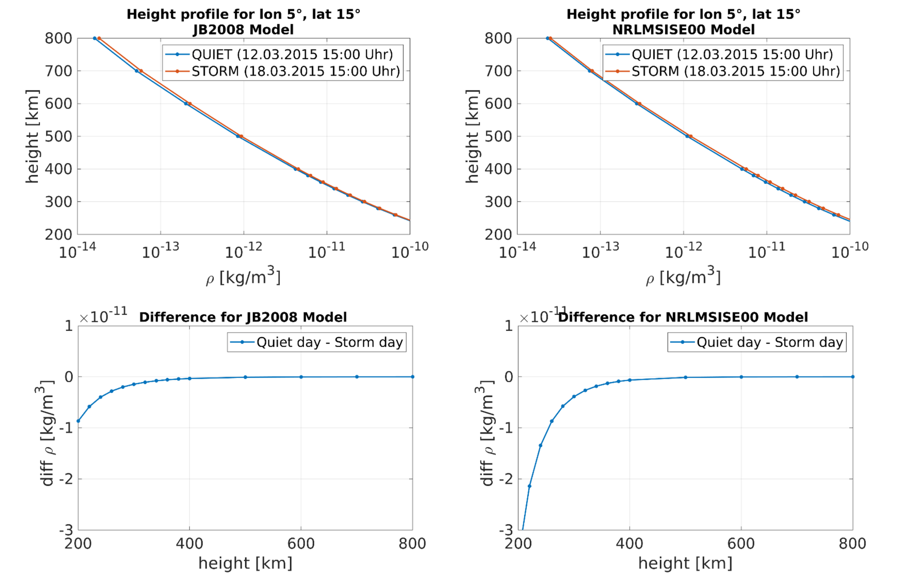

Figure 2: Representation of the density variation with height at a fixed location for a quiet and a storm day for JB2008 and NRLMSISE00 (top) and their differences (bottom).

- Next steps
- Accurate investigation of the height dependence of the thermospheric density
- Analysis of TIE-GCM (WP500)
- Assimilation of a scaled thermospheric density based on SLR observations into an empirical model (WP110)

IGG Bonn

- Figure 3 shows the performance of empirical and physical density models w.r.t. in-situ densities from CHAMP accelerometry (November storm 2003)

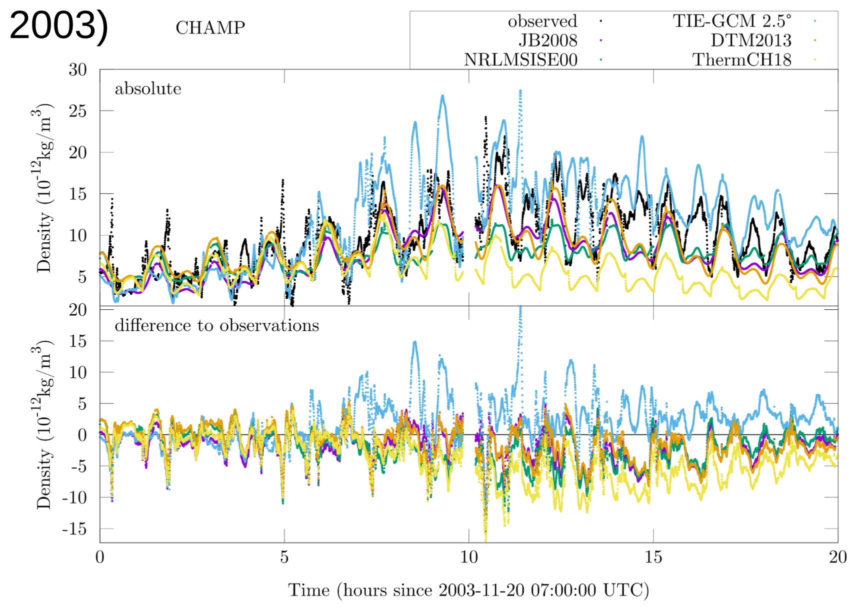

Figure 3: Performance of empirical and physical density models w.r.t. in-situ densities from CHAMP accelerometry.

- In the following table the corresponding statistics

Model $[10^{-12}\mathrm{kg/m^3}]$	Max	Mean	Median	Std
JB2008	12.82	-0.17	0.05	1.38
NRLMSISE00	15.54	0.77	1.16	1.83
TIE-GCM	20.56	0.22	-0.11	1.93
DTM2013	15.91	0.22	0.49	1.42
CH-Therm-2018	17.28	-0.80	-0.24	2.19

- Findings
- All models show larger deviations w.r.t the observations during the storm
- The empirical models, especially JB2008 and DTM2013, provide similar densities
- During the storm the densities derived from the physical model are larger than the observations most of the time whereas the densities from the empirical models are smaller
- Next steps
- Coupling TIE-GCM with PDAF (Parallel Data Assimilation Framework)
- Parameter sensitivity studies
- First experiments with assimilating an empirical model output in TIE-GCM

GFZ Potsdam

- At GFZ, the **empirical model CH-Therm-2018** of the thermospheric density has been developed by using 9 years (from August 2000 to July 2009) of **CHAMP observations** (satellite altitude from 460 to 310 km) within the project INSIGHT I
- The model is based on **7 key parameters**, namely height (***h***), solar flux (***P10.7***), season (***DoY***, day of year), magnetic local time (***mlt***), geographic latitude (***θ***) and longitude (***ϕ***), as well as the magnetic activity represented by the solar wind merging electric field (***Em***)
- Using multivariable least-square fitting for deriving the coefficient matrix.
- From the analyses of satellite laser ranging (SLR) observations of ANDE-P, ANDE-C and SpinSat for the time spans given in the table below, the following mean scaling factors of the thermospheric density provided by the CH-Therm-2018 model have been computed using the approach of Panzetta et al. (2018)

Satellite	Time span	Altitude [km]	Scaling factor
ANDE-P	16.08.2009 – 02.10.2009	349 - 323	0.970
ANDE-C	16.08.2009 – 06.02.2010	350 - 310	1.097
SpinSat	28.12.2014 – 29.03.2015	426 - 393	0.943

For more details see: IUGG-2019 General Assembly Poster presentation (JG05 p-358): Rudenko et al.: *Estimation of Scale Factors of Thermospheric Density Provided by Empirical Models Using SLR Observations to Low Earth Orbiting Satellites*

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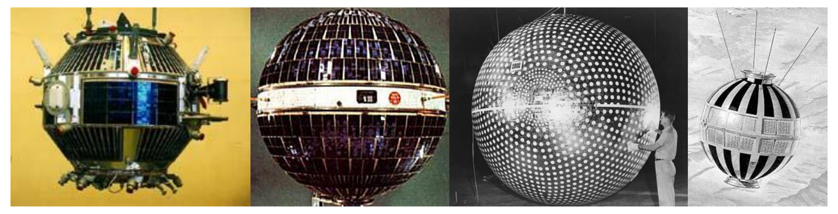
- We use **Two-Line Elements** (TLE, orbital element sets) of space debris objects to obtain **well-distributed but noisy** density estimates (complementary to the other sources of density estimates).
- Sets of **non-maneuvering debris objects** with constant cross-sectional areas (spheres) and calibrated ballistic coefficients are considered to **minimize the impact of drag model errors.**



- **Batch least-squares adjustment** is applied to obtain density estimates using **TLE-derived position vectors as pseudo-observations**. To this end, a reference density model is parameterized using piecewise **constant scaling factors** (= estimation parameters).
- In addition, **time-series data of the semi-major axis** is extracted from TLEs. This data is used to estimate **scale factors for a reference density model** by minimizing differences in the orbital decay.

References

- Panzetta et al. (2018): Towards thermospheric density estimation from SLR observations of LEO satellites: a case study with ANDE-Pollux satellite, J Geodesy, 93(3), 353-368, DOI:10.1007/s00190-018-1165-8
- Xiong et al. (2018): An empirical model of the thermospheric mass density derived from CHAMP satellite, Ann Geophys, 36(4):1141-1152, DOI:10.5194/angeo-36-1141-2018

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