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Earth rotation variations from geometric, gravimetric and altimetric observations and geophysical models

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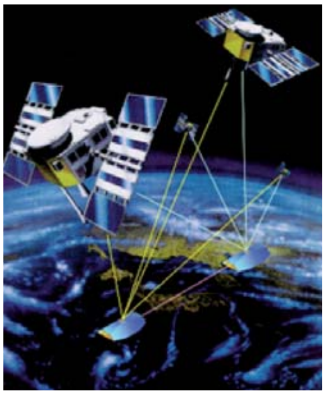

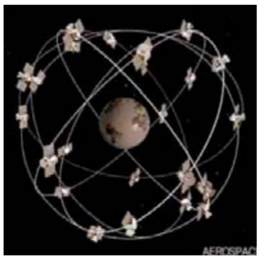

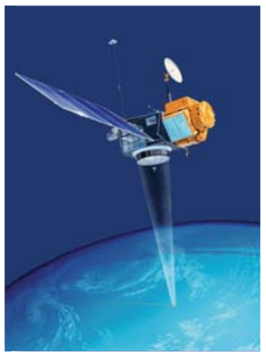

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1 Introduction

Observation techniques of the motion of the Earth's rotation axis with respect to the Earth’s surface (polar motion) and the angular velocity of the Earth (length of day) have been continuously improved over the last decades. While optical astrometry allowed for observations of polar motion with an accuracy of about one meter, modern space geodetic techniques such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Navigation Satellite Systems (GNSS) provide results at a millimeter level. However the geophysical interpretation of the time series in terms of contributions from particular geodynamic processes is a big challenge, since the observations reflect – according to the principle of superposition – the integral effect of the overall mass displacements and motions in the Earth system. Strictly speaking, geometric observations of polar motion reflect the motion of the Earth rotational axis with respect to the Terrestrial Reference Frame (TRF). Consequently systematic errors in TRF computations might appear as artificial signals in polar motion time series. Large efforts have been made in the assessment of mass transports in the atmosphere, oceans and continental hydrosphere in interdisciplinary research in order to improve physical understanding of geodynamic processes and their interactions. Therefore geophysical models as well as gravimetric and altimetric observations allow independent estimates of Earth rotation variations. The satellite Gravity and Climate Experiment (GRACE) allows to identify gravity field variations which are – according to the Newton's laws – caused by mass redistributions in the Earth system. Therefore these informations can be used to derive impacts on the Earth rotation. Furthermore satellite altimetry provides accurate information on sea level anomalies (SLA) which are caused by mass and volume changes of seawater. Since Earth rotation is solely affected by mass variations and motions the volume (steric) effect has to be reduced from the altimetric observations in order to infer oceanic contributions to Earth rotation variations. The steric effect is estimated from physical ocean parameters such as temperature and salinity changes in the oceans.

In this study specific individual contributions of global dynamic processes in the Earth system to Earth rotation variations are identified by means of a multitude of accurate geodetic space observations and geophysical models. As geodetic observations Earth rotation parameters from the geodetic space techniques VLBI, SLR and GNSS, time variable gravity field variations from the latest GRACE and/or Laser Geodynamics Satellite (LAGEOS) models as well as sea level anomalies from satellite altimetry reduced by the steric effect – determined from temperature and salinity fields of the world ocean – have been used. All these time series are compared with results from geophysical models for the atmosphere, oceans and continental hydrosphere and are investigated statistically.

2 Mathematical description of Earth rotation excitation mechanisms

The mathematical description of Earth rotation excitation mechanisms is derived from dynamic and geometric fundamentals of geophysics and geodesy. The dynamic of rotational motions of rigid bodies is treat in the theory of gyroscopes. This is an investigation field of physics in particular of mechanics. Whereas the definition and realisation of terrestrial and celestial reference systems within Earth rotation observations are performed belong to the investigation field of geodesy. This aspect is very important in order to find a mathematical formulation for the theory of Earth rotation.

The well known Euler-Liouville equation

$$\dot{\boldsymbol{I}}(t)\,\omega(t)+\boldsymbol{I}(t)\,\dot{\omega}(t)+\dot{\boldsymbol{h}}(t)+\omega(t)\times\boldsymbol{I}(t)\,\omega(t)+\omega(t)\times\boldsymbol{h}(t)=\boldsymbol{L}(t) \tag{2.1}$$

describes the rotational behavior of a non-rigid Earth model with respect to the Earth bounded reference system (e.g. Munk and Macdonald, 1960). In other words the equation of motion is based on the relationship between the instantaneous rotation axis ω(t) and the time variable inertia tensor **I**(t) of the Earth, the relative angular momentum **h**(t) as well as the external gravitational angular torque **L**(t). The mathematical description of Earth rotation excitation mechanisms can be found by solving the Euler-Liouville equation regarding the Earth rotation parameters (ERP) via the analytical approach, as pictured in the flowchart in Fig. 1. For investigations of polar motion and length of day variations the external gravitational angular torques induced from the Sun, Moon and planets have to be set equal zero since these torques are responsible for the orientation of the Earth in space. Which is described due precession – long wave precession of the Earth rotation axis around the pole of the ecliptic – and nutation – short periodic oscillations.

The analytical approach requires the linearization of the Euler-Liouville equation which can be achieved only by introducing the following assumptions:

- The figure of the Earth is axial-symmetric, i.e. $A=B=(A+B)/2$.
- The variable parts of the inertia tensor and the rotation vector are small, i.e. $|\Delta\mathbf{I}(t)| \ll C$ and $|\mathbf{m}(t)| \ll 1$.
- The relative angular momentum is small, i.e. $|\mathbf{h}(t)| \ll \Omega C$.

Thereby *A* and *B* are the equatorial moments of inertia of the Earth, *C* is the axial moment of inertia of the Earth, **m**(t) is the time variable part of the Earth rotation vector and Ω is the mean angular velocity of the Earth. In order to take the elasticity of the Earth into account further adoptions concerning tidal deformations, rotational deformations and motions as well as deformations due to loading effects are necessary. There exist several publications concerning the physical properties of the Earth proposing different adoptions, standards and models (e.g. Gross, 2008; Wahr, 2005). Consistent formulas regarding the conventions set up from the International Earth Rotation and Reference Systems Service (IERS) can be only obtained by taking into account that the ERPs are determined in the conventional tide free system (McCarthy and Petit, 2004). This implies the reduction not only of the time variable parts of the solid Earth tides but also of the permanent part in the linearized Euler-Liouville equation. The permanent tidal deformations of the solid Earth are geometrically described due to the flattening of the Earth. Their effect onto the gravity field of the Earth is given by the dynamical form-factor J_2 which is connected with the principal moments of inertia A, B and C. These constants have been determined at DGFI for the conventional tide free system (see Tab. 1). Time dependent tidal deformations have to be reduced in the time variable parts of the inertia tensor $\Delta\mathbf{I}(t)$. The rotation of the Earth induces deformations and motions which have to be taken into account in the equation of motion. These deformations depend on the constitution and properties of the Earth which can be either described by specific Love numbers or the complex Chandler frequency σ_0 as shown in Tab. 1, for more details see Gross (2008). According to Hough (1895) Earth rotation variations cause motions in the core of the Earth due to the fact that the core is completely decoupled from the Earth mantle. These motions have to be taken into account in the linearized Euler-Liouville equation. Furthermore the elasticity of the Earth is responsible for loading deformations of the Earth which are described by the loading Love numbers k_2' and $\Delta k_{an}'$ (Tab. 1). The latter takes into account the anelasticity of the Earth mantle.

Tab. 1: Recommended constants for the Earth model (conventional tide free system).

Parameter	**Value**	**Source**
Defining constants of the Earth model (conventional tide free system):		
Earth's equatorial radius a	6378136.3 m	Groten (2004)
Geocentric gravitational constant GM	$3.98004418 \cdot 10^{14}$ m^{3}s^{-2}	McCarthy a. Petit (2004)
Dynamical form-factor J_2	$1082.6267 \cdot 10^{-6}$	Groten (2004)
Mean angular velocity of the Earth Ω	$7.292115 \cdot 10^{-5}$ rad s^{-1}	McCarthy a. Petit (2004)
Physical Earth parameters:		
Constant of gravitation G	$6.673 \cdot 10^{-11}$ m^3 kg^{-1} s^{-2}	McCarthy a. Petit (2004)
Astronomical Earth's dynamical flattening H	$3.2737804 \cdot 10^{-3}$	Groten (2004)
$J_{2.2} = \sqrt{C_{2.2}^2 + S_{2.2}^2}$	$1815.5 \cdot 10^{-9}$	Groten (2004)
Love number k_2	0.298	Wahr (2005)
Love number $\Delta k_{ocn,l}$	0.043228	Dickman (2003)
Love number Δk_{an}	0.0125 + i 0.0036	Seitz (2004)
n_0 (change of the mean inertia tensor)	0.15505	Gross (2008)
Chandler freq. (period T_c / quality factor Q)	433 days / 179	Wilson a. Vicente (1990)
Load Love number k_2'	-0.308	McCarthy a. Petit (2004)
Load Love number $\Delta k_{an}'$	-0.011 + i 0.003	Wahr (2005)
α_3 (Core-mantle-coupling)	0.792	Mirriam (1980)
Derived Earth's constants (conventional tide free system)		
Equatorial moment of inertia A	$8.0095 \cdot 10^{37}$ kg m^{-2}	This study
Equatorial moment of inertia B	$8.0097 \cdot 10^{37}$ kg m^{-2}	This study
Axial moment of inertia C	$8.0359 \cdot 10^{37}$ kg m^{-2}	This study
Parameters of the Earth core		
Equatorial moment of inertia A_c	$9.1168 \cdot 10^{36}$ kg m^{-2}	Mathews et al. (1991)
Axial moment of inertia C_c	$9.1401 \cdot 10^{36}$ kg m^{-2}	Mathews et al. (1991)
Ellipticity ε_c	$2.546 \cdot 10^{-3}$	Mathews et al. (1991)

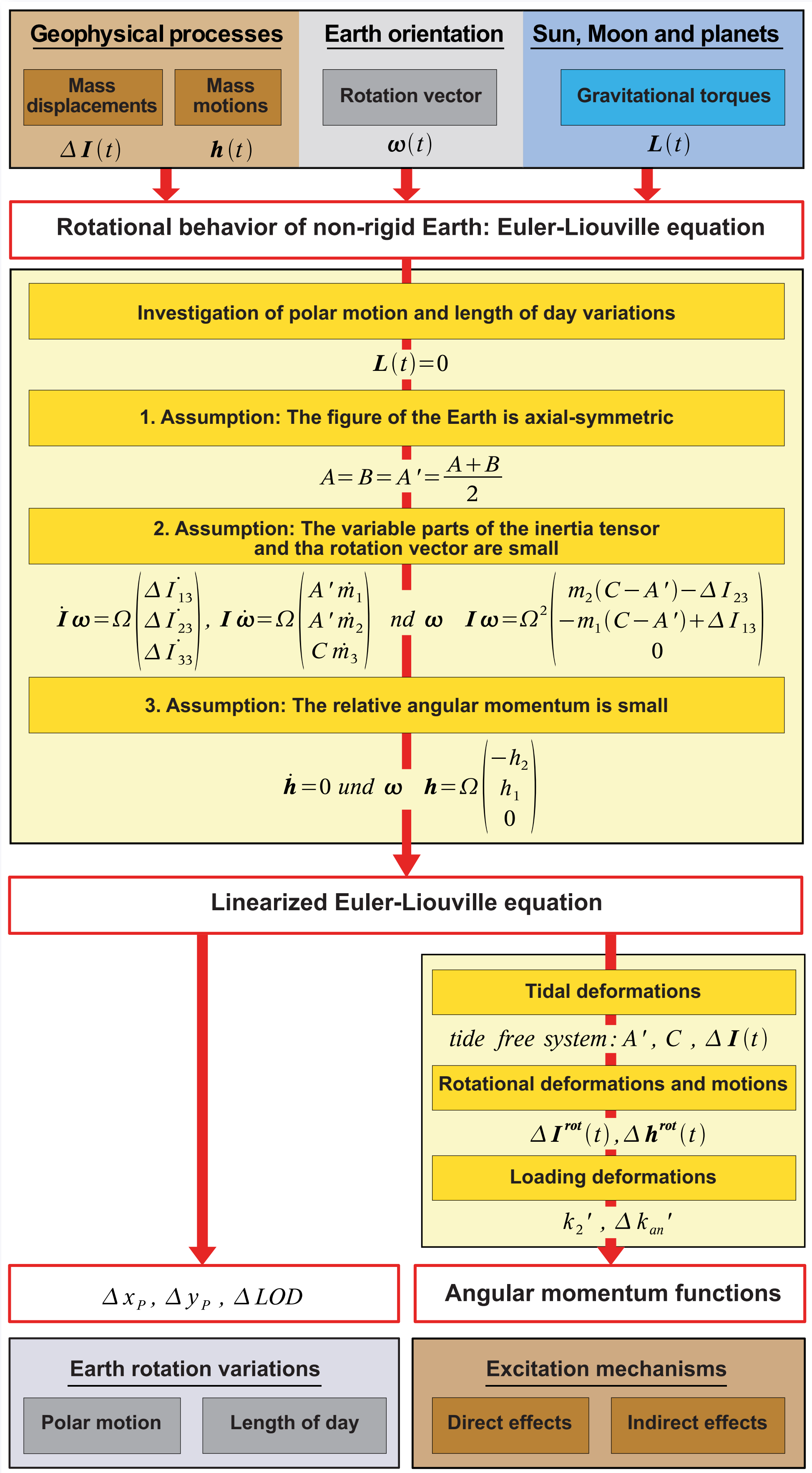

Fig. 1: Flowchart for the development of a mathematical description of Earth rotation excitation mechanisms – in from of angular momentum functions – from the Euler-Lioville equation.

The mathematical description of Earth rotation excitation mechanisms has been investigated. The following equations are recommended for angular momentum functions determinations consistent with ERP offered from the IERS:

$$\chi_1 = \frac{\Omega\left(1 + k_2^{'} + \Delta k_{an}^{'}\right)\Delta I_{13}(t) + h_1(t)}{(C - A_c + \varepsilon_c A_c)\sigma_0}, \tag{2.2}$$

$$\chi_2 = \frac{\Omega\left(1 + k_2^{'} + \Delta k_{an}^{'}\right)\Delta I_{23}(t) + h_2(t)}{(C - A_c + \varepsilon_c A_c)\sigma_0} \quad \text{and} \tag{2.3}$$

$$\chi_3 = \frac{\Omega\left(1 + \alpha_3\left(k_2^{'} + \Delta k_{an}^{'}\right)\right)\Delta I_{33}(t) + h_3(t)}{\Omega(C - C_c + \tilde{D})} \quad \text{with} \quad \tilde{D} = \frac{a^5\Omega^2}{3G}\left(n_0 + \frac{4}{3}\left(k_2 + \Delta k_{ocn,l} + \Delta k_{an}\right)\right). \tag{2.4}$$

3 Polar motion excitations from geodetic observations and geophysical models

Mass redistributions and motions in the Earth system cause changes in the Earth's rotation, geometry and gravity field and, visa versa, also impact geodetic space observation data of these quantities. In this section is explained how angular momentum functions can be derived for geodetic parameters such as Earth rotation parameters, second degree spherical harmonic coefficients and sea level anomalies as well as from geophysical modelling of the time variable inertia tensor of the Earth and the relative angular momentum.

Geometric space techniques such as VLBI, SLR and GNSS allow to detect accurately the motion of the Earth rotation axis with respect to the Earth's surface. Hence these geodetic observations reflect the integral effect of the overall redistribution and motion of masses within and exchanges between the individual subsystems of the Earth. The IERS offers in its EOP 05 C04 series estimations of polar motion. These daily time series can be transferred into the equatorial angular momentum functions according to Gross (1992) by

$$\chi_1 = x + \frac{2Q}{\frac{2\pi}{T_c}\left(1 + 4Q^2\right)}\left(\dot{x} + 2Q\dot{y}\right) \quad \text{and} \quad \chi_2 = -y + \frac{2Q}{\frac{2\pi}{T_c}\left(1 + 4Q^2\right)}\left(2Q\dot{x} - \dot{y}\right). \tag{3.1}$$

Time variable gravity field solutions provide informations about mass displacements in the Earth system. Therefore these observation data can be used to derive impacts of mass variations on the Earth rotation. Gravity field variations can be derived from LAGEOS 1&2 and/or from the satellite mission GRACE. Whereas the satellites LAGEOS 1&2 are only sensitive to low degree spherical harmonic coefficients the satellite mission GRACE is sensitive to spherical harmonic coefficients up to degree and order 100. Deduced equatorial angular momentum functions depend especially on the degree two spherical harmonic coefficients of the Earth gravity field according to the relation with respect to the principal moments of inertia of the Earth.

$$\Delta I_{13}(t) = -\frac{GM}{G} a^2 \sqrt{\frac{5}{3}} \Delta \bar{C}_{21}(t) \quad and \quad \Delta I_{23}(t) = -\frac{GM}{G} a^2 \sqrt{\frac{5}{3}} \Delta \bar{S}_{21}(t) \tag{3.2}$$

In these equations the normalized dimensionless Stokes coefficients $\Delta\bar{C}_{21}$ and $\Delta\bar{S}_{21}$ are applied.

There are three GRACE science processing centers, namely the Center for Space Research (CSR) and the Jet Propulsion Laboratory (JPL) in USA as well as the Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ) which determine monthly sets of gravity field coefficients. Published data sets are the so-called Level 2 GSM products which contain the geopotential coefficients of monthly static gravity fields that have been reduced by tidal effects (solid Earth, ocean and pole tides) as well as by non-tidal gravity signals of the atmosphere and oceans. The corresponding Level 2 GAC products contain the monthly mean geopotential coefficients of the applied atmospheric and non-tidal oceanic reductions which are derived from operational analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Ocean Model for Circulation and Tides (OMCT) (Thomas, 2002), respectively. Additionally Level 2 GAD products are offered which reflect the non-tidal oceanic part of gravity field variations modelled from atmospheric surface pressure and oceanic sea level pressure. An advantage of the different Level 2 products is that the integral mass effect on the Earth rotation as well as the mass effects from the oceans and the continental hydrosphere can be identified, as shown schematically in Fig. 2. The determination of the individual contributions requires the application of ocean and land masks, respectively in the space domain. Therefore equivalent water heights Δewh need to be calculated from the Stokes coefficients by a global spherical harmonic synthesis (GSHS) over a sphere with the mean Earth radius *a*:

$$\Delta ewh(\theta,\lambda) = \frac{R\rho_e}{3\rho_w} \sum_{n=0}^{N} \sum_{m=0}^{n} \frac{2n+1}{1+k_n} P_{nm}(\cos\theta)\left[\Delta\bar{C}_{nm}\cos m\lambda + \Delta\bar{S}_{nm}\cos m\lambda\right] \tag{3.3}$$

Here θ and λ denote the co-latitude and longitude of the computation point, $\rho_e = 5517$ kg m^{-3} is the mean density of the Earth, $\rho_w = 1000$ kg m^{-3} is the mean density of seawater and $P_{nm}(\cos\theta)$ is the associated Legendre polynomial of degree *n* and order *m*.

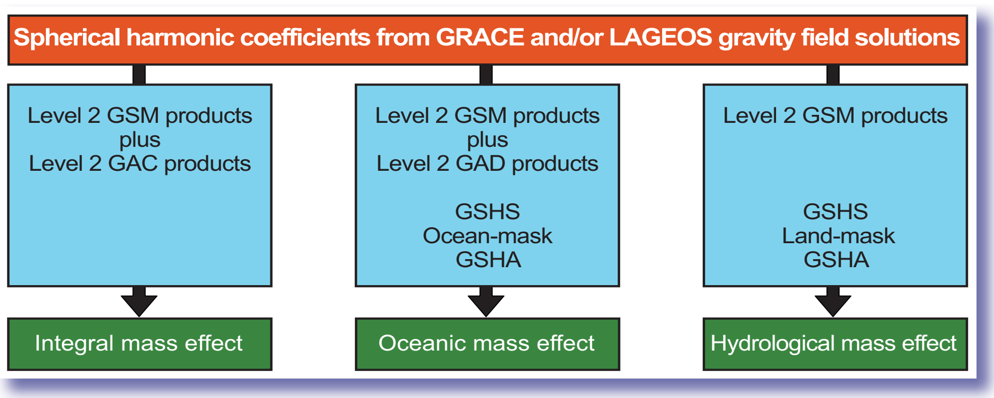

Fig. 2: Flowchart for the determination of the integral, oceanic and hydrological mass effect from time variable gravity field solutions.

A Gaussian filter with a radius of 500 km has to be applied in order to reduce the north-south oriented stripes in the space domain which are induced by systematic errors in the geopotential coefficients. Via the global spherical harmonical analysis (GSHA) the improved spherical harmonic coefficients are obtained, see Eq. (3.4) and (3.5). There are other institutions, namely the Institut für Geodäsie und Geoinformation (IGG) of the University of Bonn and the Groupe de Recherches de Géodésie Spatiale (GRGS) at the Centre National D'Études Spatiales (CNES) in France that provide GRACE gravity field solutions in the same data format. Furthermore the latter institution offers geopotential coefficients derived from only SLR observations to LAGEOS 1&2.

Sea level anomalies are cause by mass and volume changes of seawater. Therefore these geodetic parameters are sensitive to oceanic mass displacements and caused Earth rotation variations. In order to obtain the contribution of non-tidal oceanic mass variations to Earth rotation changes the sea level anomalies have to be reduced by the volume (steric) effect, as explained in Göttl and Seitz (2008). Sea level anomalies are provided from the french Archivage, Validation et Interprétation des données des Satellites Océanographiques (AVISO) archiving program as multi–mission solutions from the satellite missions such as Topex/Poseidon, Jason 1, ERS 1&2 and/or Envisat. The steric effect can be estimated from physical ocean parameters such as temperature and salinity changes in different depth layers of the ocean. Fofonoff and Millard (1983) give a detailed explanation about transient density anomalies using the equation of the state of seawater. Vertical integration of density anomalies within a water column yield steric sea level anomalies; for details see Chambers (2006). In this study we determined the steric effect from parameters of the World Ocean Atlas 2005 (WOA05) such as monthly three dimensional temperature and salinity fields based on objective analyses performed at the National Oceanographic Data Centre (NODC), see Antonov et al. (2006) and Locarnini et al. (2006). For comparisons we applied numerical corrections for the steric effect as provided from Ishii et al. (2006). After the reduction of the steric effect from the sea level anomalies the dimensionless normalized Stokes coefficients $\Delta\bar{C}_{21}$ and $\Delta\bar{S}_{21}$ can be obtained from the equivalent water heights by using the global spherical harmonic analysis:

$$\left.\begin{matrix}\Delta\bar{C}_{nm}^{ewh}\\ \Delta\bar{S}_{nm}^{ewh}\end{matrix}\right\} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\Delta ewh(\theta,\lambda)\bar{P}_{nm}(\cos\theta)\left\{\begin{matrix}\cos m\lambda\\ \sin m\lambda\end{matrix}\right\}\sin\theta\, d\theta\, d\lambda \tag{3.4}$$

$$\left.\begin{matrix}\Delta\bar{C}_{nm}\\ \Delta\bar{S}_{nm}\end{matrix}\right\} = \frac{3\rho_w}{R\rho_e}\cdot\frac{1+k_n}{2n+1}\left\{\begin{matrix}\Delta\bar{C}_{nm}^{ewh}\\ \Delta\bar{S}_{nm}^{ewh}\end{matrix}\right. \tag{3.5}$$

Afterwards these Stokes coefficients are converted into polar motion angular momentum functions by applying Eq. (3.2), (2.2) and (2.3).

Geophysical models for the atmosphere, oceans and the continental hydrosphere give information about mass displacements and motions in the corresponding subsystems of the Earth. The Global Geophysical Fluids Centre (GGFC) provides angular momentum time series (mass and motion terms) from the atmospheric reanalyses of the National Centers for Environmental Prediction (NCEP) and from the run kf049f of the ocean model ECCO (Estimating the Circulation and Climate of the Ocean), see Gross et al. (2003).

Furthermore the Special Bureau for Hydrology (SBH) of the GGFC offers monthly fields of global water storage variations from Global Land Data Assimilation Systems (GLDAS), one developed at the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre (CPC) and the other operated at the National Aeronautics and Space Administration (NASA), see Fan and Dool (2004) and Rodell et al. (2004). Furthermore monthly fields of surface water, groundwater and snow are available from the Land Dynamics (LaD) model (Milliy and Shmakin, 2002). In the framework of the DFG (Deutsche Forschungsgemeinschaft) research unit FOR584 "Earth Rotation and Global Dynamic Processes" angular momentum time series from operational atmospheric analysis of the ECMWF are available as well as from the ocean model OMCT.

Comparisons on the basis of polar motion angular momentum functions are performed for the integral mass effect as well as for specific individual effects, according to the concept shown in Fig. 3. The statistical investigations of all these time series shall improve our knowledge about existing uncertainty factors.

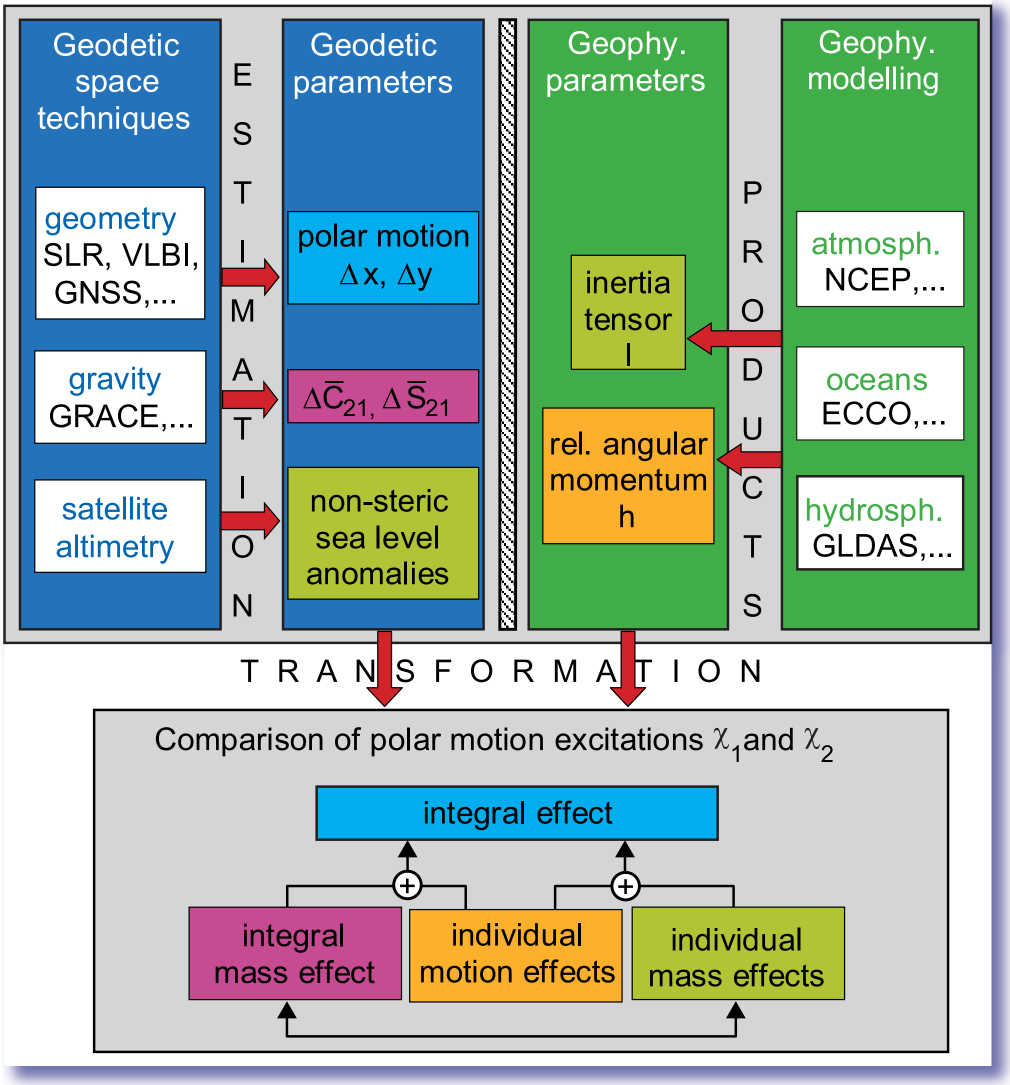

Fig. 3: Overview for possible comparisons of polar motion angular momentum functions determined from geodetic observations and geophysical models.

Fig. 4 displays polar motion angular momentum functions from mass variations of the atmosphere, oceans and continental hydrosphere. For the atmospheric mass effect only two geophysical model solutions are shown because currently the before mentioned geodetic observation data do not allow a separation of atmospheric mass variations. Both modelled signals are very similar and feature high correlation coefficients of 0.98 for χ_1 and 1 for χ_2 as well as low root mean square (RMS) differences of 1 mas. As will be seen later the dynamic processes of the atmosphere are better known than mass transports in other subsystems of the Earth. The oceanic mass effect can be identified by geophysical models as well as by gravimetric and altimetric observations, as described in topic 3. The signals show higher discrepancies than the modelled signals for the atmospheric effect. The RMS differences range from 3 to 9 mas for χ_1 and from 2 to 7 mas for χ_2. The maximum correlation coefficients occur of course between solutions derived from the same type of observation data, namely 0.80 for χ_1 and 0.90 for χ_2. The hydrological mass effect is determined from geophysical models and gravimetric observations. Especially in χ_2 significant discrepancies are obvious not only in the amplitude but also in the phase. The RMS differences range from 2 to 5 mas for χ_1 and from 4 to 9 mas for χ_2. The maximum correlation between modelled and observed signals show up with the hydrological model GLDAS^{CPC} 0.85 for χ_1 and 0.79 for χ_2. Consequently the mass effect from the continental hydrosphere is up to now the component with the largest uncertainty.

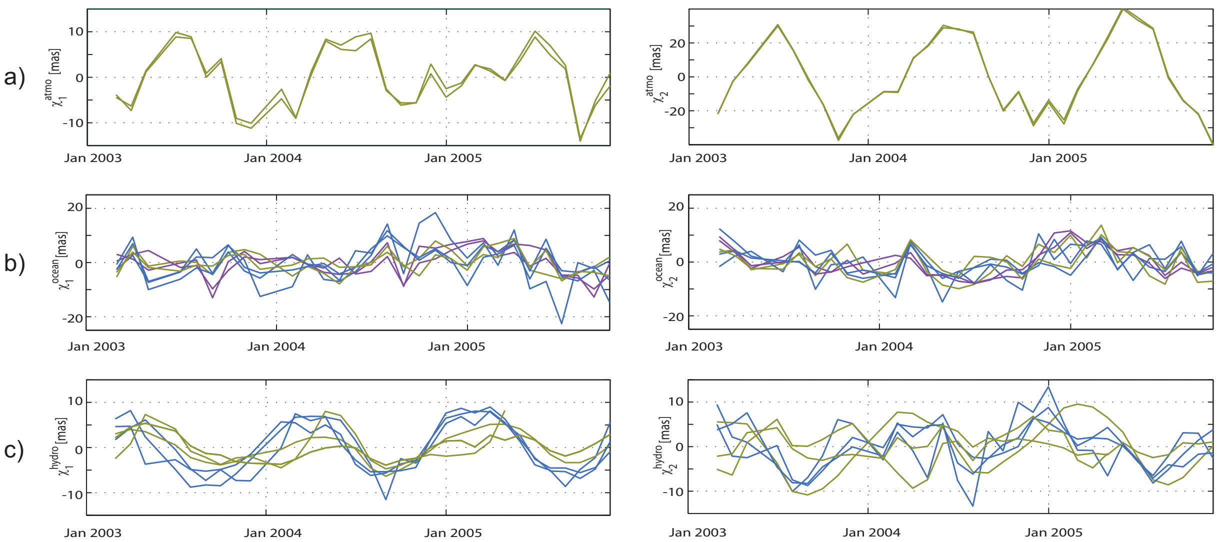

Fig. 4: Monthly time series of polar motion angular momentum functions for the mass effect from the atmosphere, oceans and continental hydrosphere (note the different scaling): Geophysical model results (green), gravimetric results (blue) and altimetric results (purple). (a) ECMWF, NCEP; (b) OMCT, ECCO, GFZ RL04, JPL RL04, ITG-Grace03, SLA with steric corrections from WOA05 and Ishii; (c) GLDAS^{CPC}, GLDAS^{NASA}, LaD, GFZ RL04, JPL RL04, ITG-Grace03.

Fig. 5 shows the polar motion angular momentum functions obtained from mass motions in the atmosphere and oceans. For each case two geophysical model solutions are shown for the motion effect because until now there exists no geodetic observations that allow to identify these phenomena. These time series confirm that the motion effects are smaller than the mass effects. The RMS differences for the atmospheric motion effect and the oceanic motion effect are equal, 4 mas for χ_1 and 3 mas for χ_2. The correlation coefficients for the atmospheric motion effect is 0.65 for χ_1 and 0.78 for χ_2. Whereas the correlation coefficients for the oceanic motion effect are slightly smaller 0.60 for χ_2. Thus the mass motions of the atmosphere are not better known than the ocean circulations.

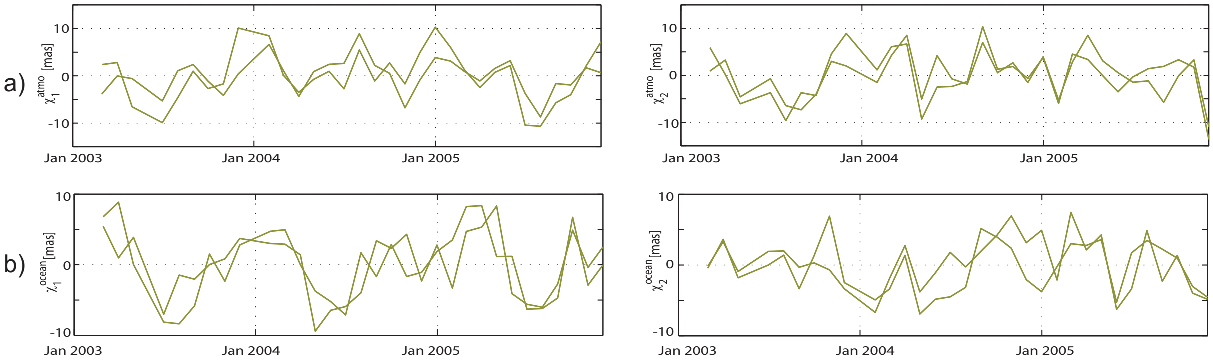

Fig. 5: Monthly time series of polar motion angular momentum functions for the motion effect from the atmosphere and oceans (note the different scaling): Only geophysical model results (green). (a) ECMWF, NCEP; (b) OMCT, ECCO.

Fig. 6 displays polar motion angular momentum functions from the overall mass displacements in the Earth system. The integral mass effect can be determined from the accurate geometric space observations by reducing the modelled motion effects from the atmosphere and oceans. Of course the models used for the reduction of the motion term from the so-called geometric excitations are not free of errors. Nevertheless the reduced geometric excitations seem to be a good reference for the integral mass effect. RMS differences and corresponding correlation coefficients are listed in Tab. 2 in the following topic. The statistical analysis reveals that the time series from combined atmospheric, oceanic and hydrological models show a higher agreement with the reduced geometric results than the single gravimetric solutions. Therefore in the following section a strategy is introduced to improve the polar motion angular momentum functions determined from time variable gravity field solutions.

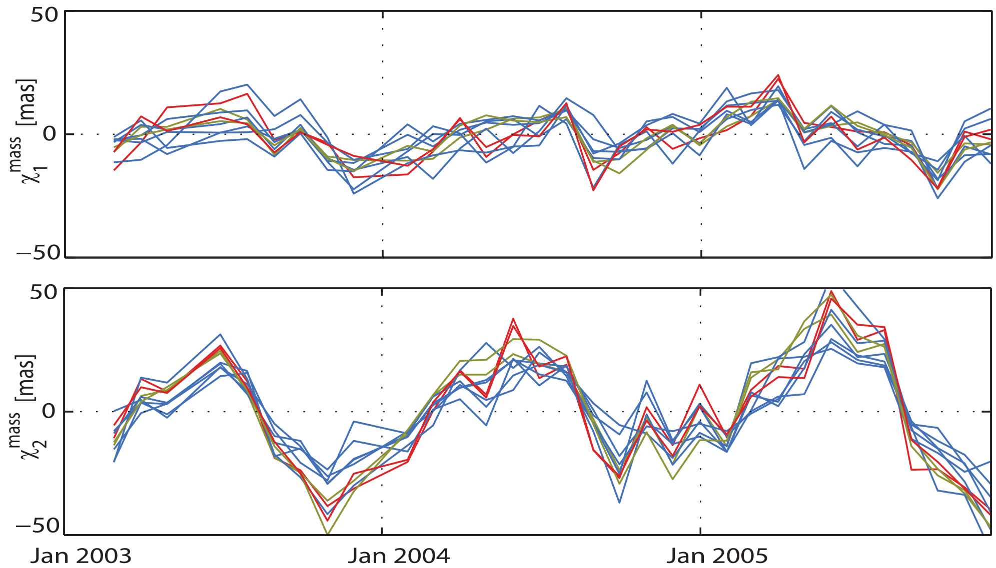

Fig. 6: Monthly time series of polar motion angular momentum functions for the integral mass effect: Geophysical model results from ECMWF plus OMCT plus GLDAS^{CPC} and NCEP plus ECCO plus GLDAS^{CPC} (green), gravimetric results from GFZ RL04, JPL RL04, CSR RL04, ITG-Grace03, GRGS(GRACE) and GRGS(SLR) (blue) and geometric results from the IERS ERP 05 C04 series reduced by modelled motion effects from ECMWF plus OMCT and NCEP plus ECCO (red).

4 Adjustment of gravimetric and altimetric data sets

The results gained from the previous data analysis are used to perform least square adjustments to estimate specific geophysical Earth rotation excitations. The motivation of such data combinations is in the reduction of systematic errors of data processing strategies, for example. Hence an adjusted set of gravimetric mass angular momentum functions χ_1 and χ_2 is computed from the individual solutions GFZ RL04, CSR RL04, JPL RL04, ITG-Grace03, GRGS(GRACE) and GRGS(SLR) which are shown in Fig. 6. The time series are weighted according to the RMS differences – Tab. 2 – with respect to the mean of the two reduced geometrical solutions for the integral mass effect. The adjusted time series show higher agreement with the geometric solutions than any of the individual gravimetric or modelled excitation series, as can be seen in Fig. 7. Not only the RMS differences of 5 mas for χ_1 and of 6 mas for χ_2 decreases but also the correlation coefficients of 0.86 for χ_1 and 0.97 for χ_2 gets higher (for comparison see Tab. 2). Reasons therefore could be that systematic errors in the GRACE data processing such as

- errors of the atmospheric and oceanic background models,
- shortfalls in the parametrization of the observation equations and
- omission error

are reduced due to the weighted adjustment of numerous gravimetric solutions.

Tab. 2: RMS differences and correlation coefficients with respect to the mean reduced geodetical results for the integral mass angular momentum functions.

χ_1	GFZ RL04	CSR RL04	JPL RL04	ITG-Grace 03	GRGS (GRACE)	GRGS (SLR)	ECMWF, OMCT, GLDAS^{CPC}	NCEP, ECCO, GLDAS^{CPC}
RMS [mas] differences	6	7	8	8	9	8	6	6
Correlation coefficients	0.71	0.71	0.61	0.62	0.65	0.62	0.77	0.80

χ_2	GFZ RL04	CSR RL04	JPL RL04	ITG-Grace 03	GRGS (GRACE)	GRGS (SLR)	ECMWF, OMCT, GLDAS^{CPC}	NCEP, ECCO, GLDAS^{CPC}
RMS [mas] differences	12	12	10	10	10	9	8	7
Correlation coefficients	0.94	0.89	0.96	0.93	0.91	0.94	0.95	0.95

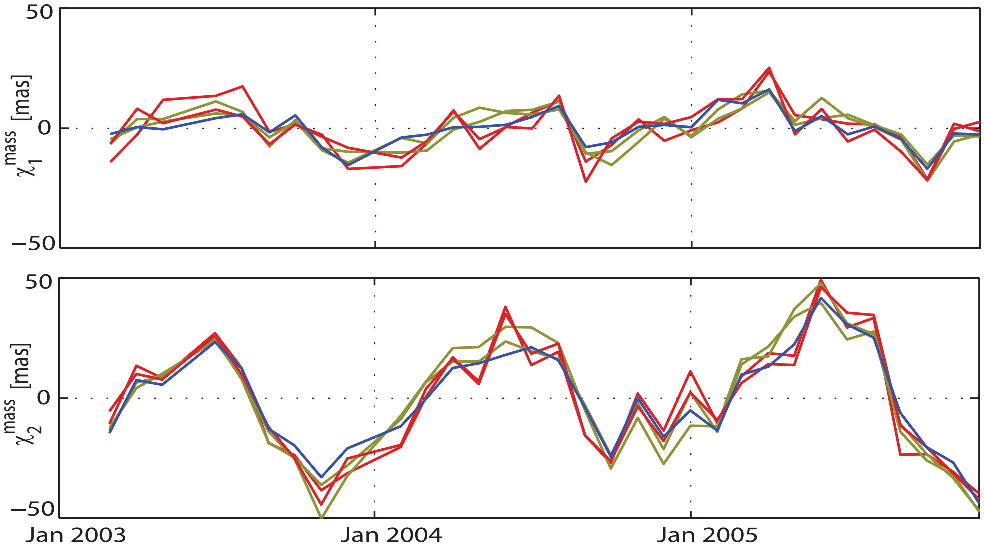

Fig. 7: Monthly time series of polar motion angular momentum functions for the integral mass effect: Geophysical model (green) and reduced geometric (red) results analogue to Fig. 6 and adjusted gravimetric results (blue).

Furthermore an adjusted set of oceanic mass angular momentum functions is determined from the individual gravimetric solutions JPL RL04 and ITG-Grace03 as well as from the altimetric solutions called WOA05 and Ishii according to the steric effect corrections. These time series – shown in Fig. 4 – are weighted according to the RMS differences with respect to the mean solution of the two ocean models ECCO and OMCT (Tab. 3). Again the adjusted time series – displayed in Fig. 8 – show a higher agreement with the model solutions than any of the individual gravimetric or altimetric time series. The RMS differences of 3 mas for χ_1 and χ_2 decrease and the correlation of 0.71 for χ_1 and 0.76 for χ_2 increase (see Tab. 3 for a comparison).

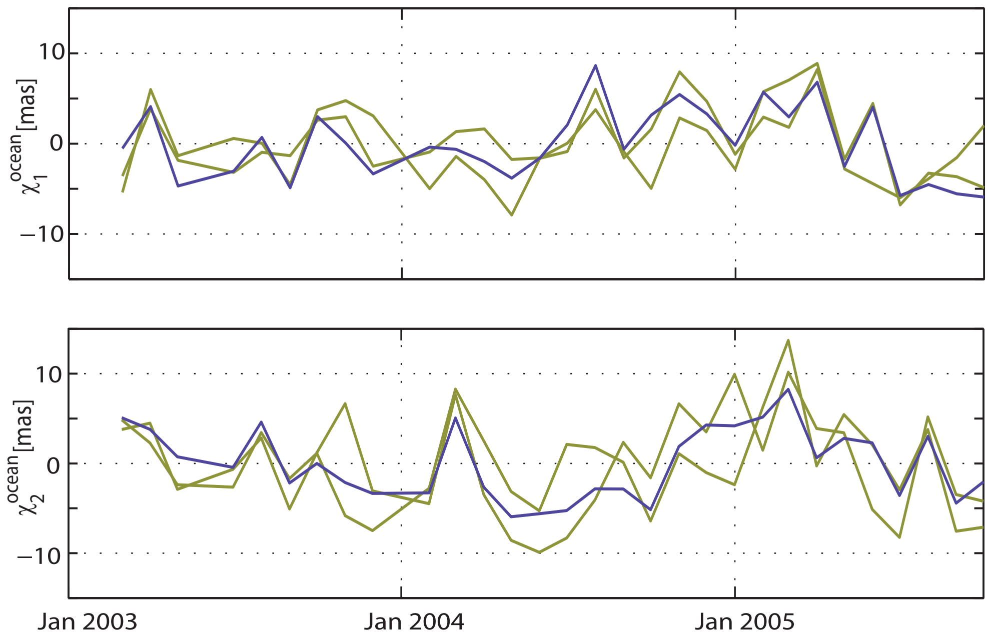

Fig. 8: Monthly time series of polar motion angular momentum functions for the oceanic mass effect: Geophysical model results analogue to Fig. 4 (green) and adjusted altimetric and gravimetric results (blue).

Tab. 3: RMS differences and correlation coefficients with respect to the mean ocean model results for the oceanic mass angular momentum functions.

χ_1	JPL RL04	ITG-Grace03	SLA reduced by steric effect from WOA05	SLA reduced by steric effect from Ishii
RMS [mas] differences	5	4	5	5
Correlation coefficients	0.55	0.56	0.43	0.49

χ_2	JPL RL04	ITG-Grace03	SLA reduced by steric effect from WOA05	SLA reduced by steric effect from Ishii
RMS [mas] differences	5	4	5	4
Correlation coefficients	0.65	0.58	0.54	0.66

5 Conclusions and outlook

In this study specific individual contributions of global dynamic processes in the Earth system to Earth rotation variations are identified by means of a multitude of accurate geodetic space observations and geophysical models. It has been shown that mass displacements of the atmosphere are better known than from other subsystems of the Earth. Whereas redistribution of masses in the continental hydrosphere has the largest uncertainty. In contrast mass motions of the atmosphere are not better known than ocean circulations. Furthermore it was found that a weighted adjustment of several gravimetric solutions for polar motion mass excitations significantly increase the agreement with geometrically determined excitations. In the same way a weighted adjustment of gravimetric and altimetric solutions for polar motion oceanic mass excitations improve the agreement with ocean models. Altogether it can be concluded that the combination of various geodetic space observations for Earth rotation determinations is very promising with respect to the identification of individual contributions of the subsystems of the Earth.

Foresight an adjusted set of polar motion excitations caused by mass variations in the continental hydrosphere shall be computed from individual solutions of the time variable gravity field. Until now, only the Gaussian filter has been applied for angular momentum function determinations from gravity field solutions. Therefore it shall be studied if other filter mechanisms show better results (e.g., correlated error filter, statistical filter). Furthermore a refined regression model will be set up which allows the separation of geophysical excitations of the individual components of the Earth system consistently from geometric, gravimetric and altimetric observations in one step. Therefore different data processing strategies of modern space-geodetic observation techniques have to be studied with respect to parameterizations, standards, models and assumptions in order to eliminate inconsistencies. Numerous excitation functions have to be calculated inclusive the corresponding variance-covariance information by applying the law of error propagation and/or the Monte-Carlo simulations. Finally the advantages of each geodetic observation technique shall be used within an adjustment to estimate improved individual excitation mechanisms of the Earth rotation. Each time series is build as the sum of excitation functions from the different components of the Earth system. Thus, the combination of geometric, gravimetric and altimetric time series allows basically the estimation of corrections to initial values of the excitation functions related to the different Earth system components (see Fig. 9).

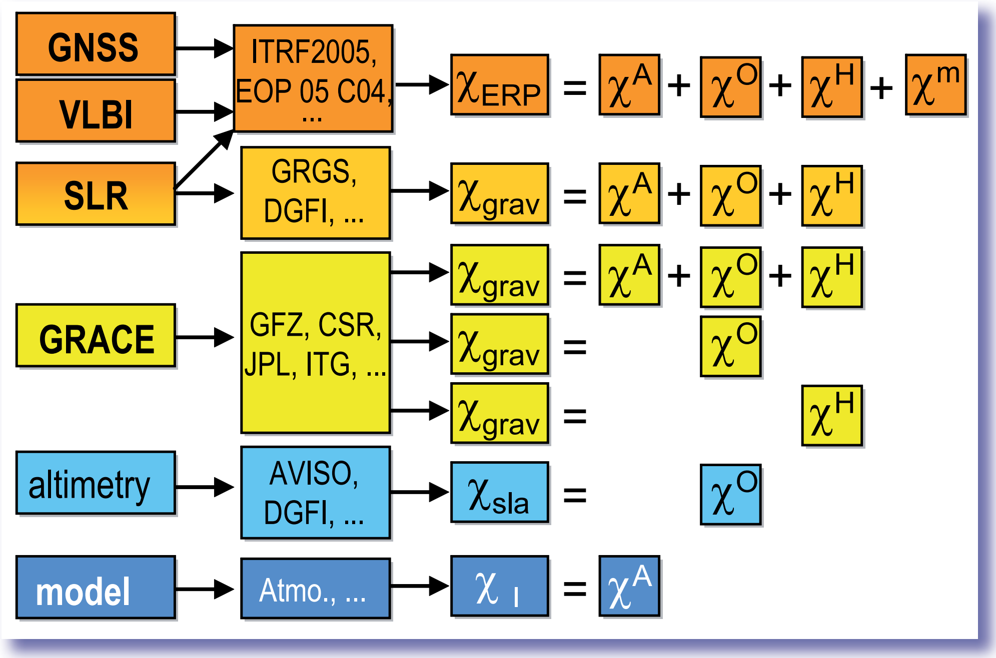

Fig. 9: Concept for the separation of Earth rotation variations from geodetic observations.

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