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Calibration of empirical thermospheric models by using laser observations to near-Earth orbiting spherical satellites

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Introduction

- The **non-gravitational acceleration** within the equation of motion of a satellite comprises **radiation parts** due to the direct solar radiation pressure and the Earth albedo pressure, **drag-like parts** due to the **atmospheric drag** and the solar wind pressure and **other parts,** e.g., related to the Earth's magnetic field and due to relativistic effects.
- For near-Earth or **Low-Earth Orbiting (LEO) satellites** – especially between altitudes of 80 km and 600 km – the atmospheric drag is the largest non-gravitational perturbation acceleration and, thus, the main error source in Precise Orbit Determination (POD) of LEO satellites.
- The drag is mainly depending on the **thermospheric density**, which is closely related to the **electron density** of the **ionosphere** and, thus, also to **space weather activity.**
- In the LEO POD the drag is presently described by models such as the **Jacchia-Bowman 2008** (JB2008) model or the **Cospar International Reference Atmosphere 1986** (CIRA86) model, which use globally defined space weather parameters such as the F10.7 index, etc.
- In the last decade, **accelerometer instruments** have provided thermospheric density data with an unprecedented accuracy and resolution. At GFZ, an **empirical model** of the thermospheric mass density has been developed by using 9 years of **CHAMP acceleration measurements**.

Satellite Laser Ranging

- Satellite Laser Ranging (SLR) is a geodetic **tracking technique** which can be used for the POD of LEO satellites.
- SLR provides highly accurate **travel time measurements** of laser pulses reflected at laser Retro-Reflector Arrays mounted on the satellite surface which have been emitted from telescopes on the Earth's surface.
- Due to the **high precision** SLR observations are highly sensitive to any **perturbing acceleration** acting on the satellite and, thus, to the atmospheric drag.
- In order to increase the accuracy of the estimated thermospheric density, we use in this investigation SLR observations to LEOs with a **simple spherical shape**. A list of spherical satellites is provided in Fig. 1
- Our approach is based on a **fully dynamic POD** of the selected spherical satellites using the DGFI Orbit and Geodetic parameter estimation Software (DOGS).
- All **a priori models** used in the POD are based on the recommendations of the IERS Conventions 2010.
- More details on the applied POD approach are given in Panzetta et al.: *Towards thermospheric density estimation from SLR observations of LEO satellites - A case study with ANDE-Pollux satellite*, submitted to Journal of Geodesy, in review.

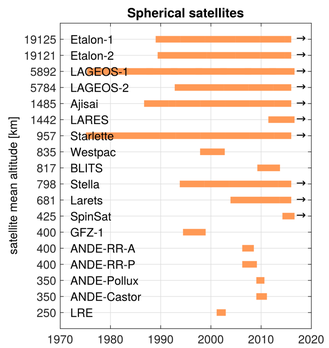

Figure 1: Mission lifetime and altitudes of spherical satellites usable for SLR applications.

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Model Approach

- For the LEO POD we model in our approach the **atmospheric drag** $\boldsymbol{a}_D$ as

$$\boldsymbol{a}_D = -\frac{1}{2} \cdot f_s \cdot \frac{A_{\mathrm{ref}}}{m}\, C_D\, \rho\, v_{\mathrm{rel}}^2\, \hat{\boldsymbol{u}}_D \qquad (1)$$

where $\hat{\boldsymbol{u}}_D$ is the drag unit vector, A_{ref} is the effective cross-sectional area of the satellite, m is the satellite mass, C_D is the dimensionless **drag coefficient** and ρ is the **thermospheric neutral density**.

- The **scale factor** f_s in Eq. (1) accounts for the different magnitude of the density values computed from different empirical models,
- Besides JB2008 and CIRA86 we – in particular – focus on GFZ's new empirical thermosphere model which has been developed by using 9 years of **CHAMP observations**. The model (see box below, Eq. (2)) is based on 7 **key parameters**, namely height (h), solar flux ($P10.7$), season (DoY), magnetic local time (mlt), geographic latitude (θ) and longitude (ϕ), as well as the magnetic activity represented by the solar wind merging electric field (E_m).
- The model coefficients have been estimated by a **multi-variate least-squares fit**. The following box shows the different components of the model. Herein, H_d means the mass density scale height and ρ_0 is the mass density at the reference height of 310 km.

Setup of the thermospheric density within the GFZ model

$$\rho = f_1(\rho_0, h, H_d) \cdot f_2(P10.7) \cdot f_3(DoY) \cdot f_4(mlt) \cdot f_5(\theta) \cdot f_6(\phi) \cdot f_7(E_m) \qquad (2)$$

1. Scaling factors (altitude and solar activity dependencies)

$$f_1(\rho_0, h, H_d) = \rho_0 \cdot e^{(-(h-310)/H_d)}$$

$$f_2(P10.7) = a_0 + a_1 \cdot (P10.7 - P10.7_{ref}) + a_2 \cdot (P10.7 - P10.7_{ref})^2$$

2. Harmonics (season, magnetic local time, geographic latitude and longitude dependences)

$$f_3(DoY) = 1 + \sum_{i=1}^{3} \{ b_1(i) \cdot \cos(\frac{i \cdot 2\pi \cdot DoY}{365.25}) + b_2(i) \cdot \sin(\frac{i \cdot 2\pi \cdot DoY}{365.25}) \}$$

$$f_4(mlt) = 1 + \sum_{j=1}^{4} \{ c_1(j) \cdot \cos(\frac{j \cdot 2\pi \cdot mlt}{24}) + c_2(i) \cdot \sin(\frac{j \cdot 2\pi \cdot mlt}{24}) \}$$

$$f_5(\theta) = 1 + \sum_{k=1}^{6} \{ d_1(k) \cdot \cos(\frac{k \cdot 2\pi \cdot \theta}{180}) + d_2(k) \cdot \sin(\frac{k \cdot 2\pi \cdot \theta}{180}) \}$$

$$f_6(\phi) = e_0 + \sum_{l=1}^{4} \{ g_1(l) \cdot \cos(\frac{l \cdot 2\pi \cdot \phi}{360}) + g_2(l) \cdot \sin(\frac{l \cdot 2\pi \cdot \phi}{360}) \}$$

3. Magnetic activity dependencies (solar wind merging electric field)

$$f_7(E_m) = m_0 + m_1 \cdot (E_m - E_{m_{ref}}) + m_2 \cdot (E_m - E_{m_{ref}})^2$$

- For the GFZ model we used tabulated values for the thermospheric density following the approach presented in Eq. (2).

Numerical Results

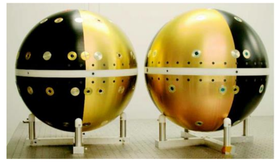

Figure 2: The ANDE-2 spherical micro-satellites Castor (left) and Pollux (right), image credit: NRL.

- In our investigations we use the two spherical satellites "**Atmospheric Neutral Density Experiment-2**" (ANDE-2) **Pollux** (P) and **Castor** (C); see Fig. 2 as well as the "**Special Purpose Inexpensive Satellite**" (SpinSat**)**.
- Figure 3 shows the rather sparse **spatial distribution** of the SLR observations to the ANDE-P satellite.
- We estimate the **scale factor** f_s according to Eq. (1) with a **temporal resolution** of **6 hours**.

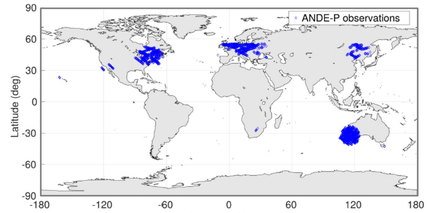

Figure 3: Ground track distribution of the SLR observations to ANDE-P during the processed data period of 46 days between August 16 and September 30, 2009.

- The two panels in Fig. 4 show the estimates of the scale factor f_s from ANDE-C (left) and SpinSat (right) SLR measurements by using **CIRA86**.

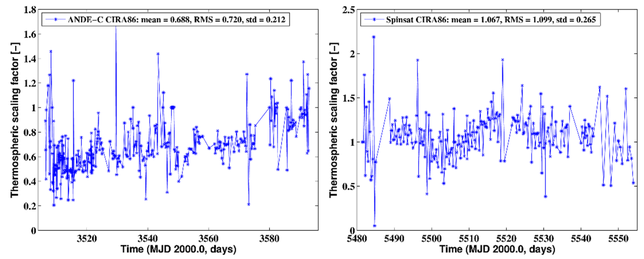

Figure 4: Estimates of the scale factor f_s from ANDE-C SLR measurements (left) and SpinSat SLR measurements (right). In the latter case the mean value of the estimates is larger, in the first case significantly less than 1.

- Figure 5 shows **preliminary results** for the GFZ model applied to ANDE-P SLR observations.
- Whereas the estimated scale factor values for the **JB2008** model are mostly less than 1 (**mean: 0.89**) the corres-ponding scale factor values for the **GFZ model** are larger than 1 (**mean: 1.47**).
- Future improvements in the procedure will be (1) an extended outlier detection procedure, (2) the use of the full GFZ model instead of tabulated density values and (3) the extension of the used gravity field model (EIGEN-6S) to degree and order 240.

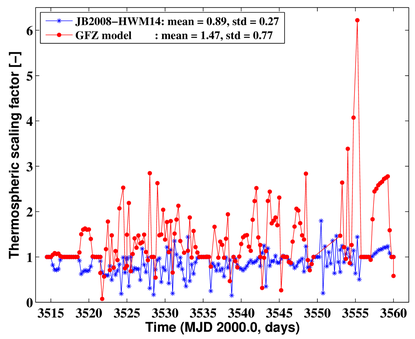

Figure 5: Estimated scale factors according to Eq. (1) from ANDE-P using JB2008 (blue) and the GFZ model (red) for the 46 days between August 16 and September 30, 2009.