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 abeude 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 1500 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) or the Cospar International Reference Atmosphere (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 time travel 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 DFGF 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.

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Model Approach
- For the LEO POD we model in our approach the atmospheric drag \(a_d\) as
  \[
  a_d = -\frac{1}{2} \mathbf{f}_d \cdot \frac{\rho_0}{\rho} \mathbf{V}_d \cdot \mathbf{V}_d \tag{1}
  \]
  where \(\mathbf{f}_d\) is the drag unit vector, \(\mathbf{V}_d\) is the effective cross-sectional area of the satellite, \(\mathbf{V}_d\) is the satellite mass, \(\rho_0\) is the dimensionless drag coefficient and \(\rho\) 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 (\(P_{10.7}\)), solar wind merging electric field (\(E_{\text{eff}}\)), magnetic local time (\(mL\)), geographic latitude (\(\varphi\)) and longitude (\(\lambda\)), as well as the magnetic activity represented by the solar wind merging electric field (\(E_{\text{eff}}\)).
- The model coefficients have been estimated by a multi-variate least-squares fit. The following box shows the different components of the model. Herein, \(H_0\) means the mass density scale height and \(\rho_0\) is the mass density at the reference height of 310 km.

\[
\begin{align*}
\rho &= f_s f_d f_{P_{10.7}} f_{E_{\text{eff}}} f_{mL} f_{\varphi} f_{\lambda} f_{H_0} f_{\rho_0} \tag{2} \\
1. \text{ Scaling factors (altitude and solar activity dependencies)} & \]
\[
\rho f_{P_{10.7}} f_{E_{\text{eff}}} f_{mL} f_{\varphi} f_{\lambda} f_{H_0} f_{\rho_0} \tag{2} \\
2. \text{ Harmonics (season, magnetic local time, geographic latitude and longitude dependencies)} & \]
\[
\rho f_{P_{10.7}} f_{E_{\text{eff}}} f_{mL} f_{\varphi} f_{\lambda} f_{H_0} f_{\rho_0} \tag{2} \\
3. \text{ Magnetic activity dependencies (solar wind merging electric field)} & \]
\[
\rho f_{P_{10.7}} f_{E_{\text{eff}}} f_{mL} f_{\varphi} f_{\lambda} f_{H_0} f_{\rho_0} \tag{2} \\
\]

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

Numerical Results
- 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.

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