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Investigation of temporal change of thermosphere density scale factors derived from SLR observations to LEO 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.
- 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 mainly depends on the **density of the thermosphere** (see Eq. (1)), which is closely coupled to **the ionosphere** and, thus, to **space weather activity.**
- Precise knowledge on the density of the Earth's thermosphere is a prerequisite for planning of satellite missions, POD, orbit and re-entry prediction, collision avoidance of artificial satellites orbiting the Earth at altitudes below 1000 km.
- 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, **accelerometers** have provided thermospheric density with an unprecedented accuracy and resolution. At GFZ, the **empirical model CH-Therm-2018** (Xiong et al.) of the thermospheric density was developed from 9 years of **CHAMP acceleration measurements**. The model is based on 7 key parameters: height, solar flux, season, magnetic local time, geographic latitude and longitude,the magnetic activity represented by the solar wind merging electric field.

Satellite Laser Ranging (SLR) Observations

- Satellite Laser Ranging (SLR) is a geodetic **tracking technique** which can be used for LEO POD. It 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 **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 **spherical shape**.
- In our investigation, we use the satellites 'Atmospheric Neutral Density Experiment-2' (**ANDE-2**) **Pollux** (P) and **Castor** (C), as well as the 'Special Purpose Inexpensive Satellite' (**SpinSat**), see Fig. 2. The satellite radii are 0.483 m (ANDE-2) and 0.558 m (SpinSat).

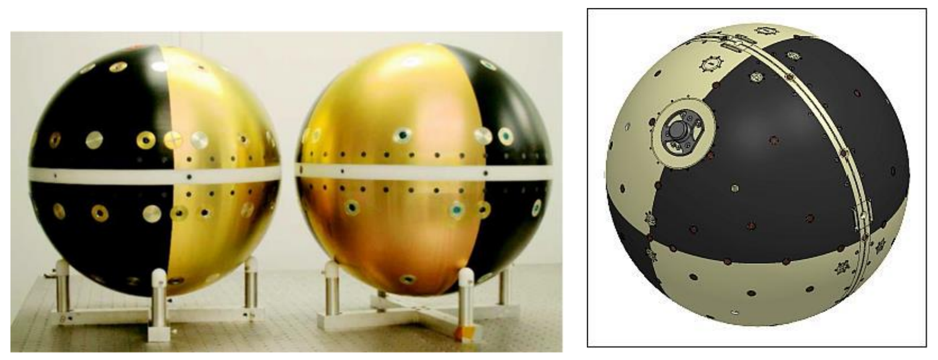

Figure 2: The ANDE-2 spherical micro-satellites Castor (left) and Pollux (middle), and SpinSat (right), image credit: NRL.

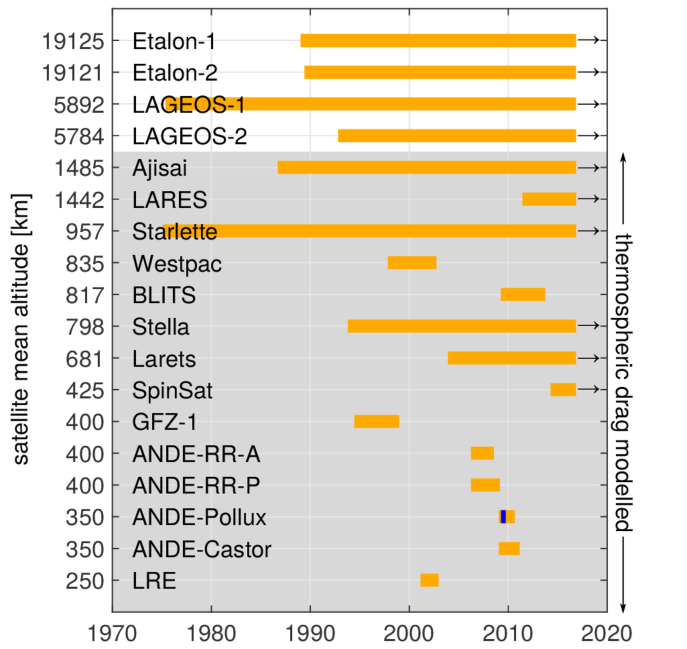

Figure 1: Mission lifetime and altitudes of spherical satellites usable for SLR applications.

Approach

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

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

where A_{ref} is the effective cross-sectional area of the satellite, m is the satellite mass, C_D is the dimensionless **drag coefficient** (analytically computed using a Gas-Surface Interaction model, physical assumptions and key parameters), ρ is the **thermospheric density**, v_{rel} is the satellite relative velocity w.r.t. atmosphere (computed from POD), $\hat{\boldsymbol{u}}_D$ is a unit vector.

- The **scale factor** f_s in Eq. (1) accounts for the different magnitude of the density values computed from different empirical models. We estimate the **scale factor** f_s according to Eq. (1) with a **temporal resolution** of **6-12 hours** depending on the amount of SLR observations available.
- 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., more results are discussed in Rudenko et al.

Results: estimated scale factors of thermospheric density

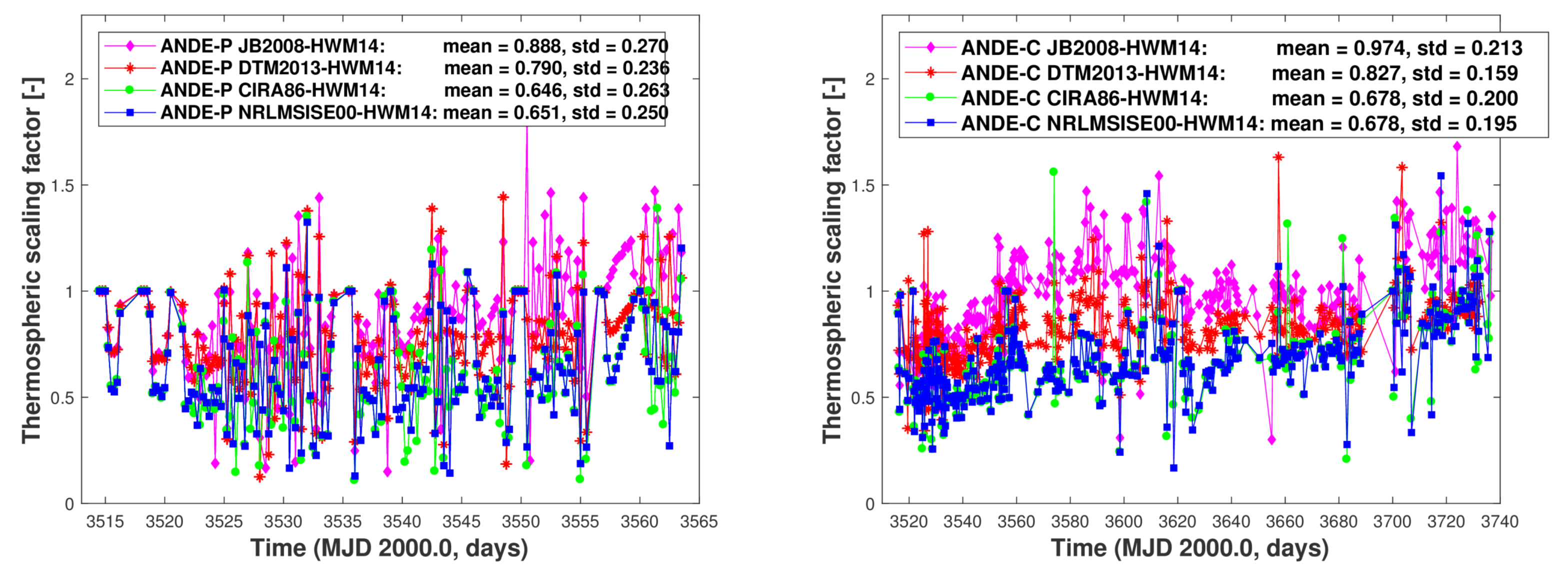

Figure 3: Scale factor f_s estimated from SLR measurements of ANDE-P from 16 August 2009 to 3 October 2009 (left) and ANDE-C from 16 August 2009 to 26 March 2010 (right). The ANDE-C data analysis indicates a trend.

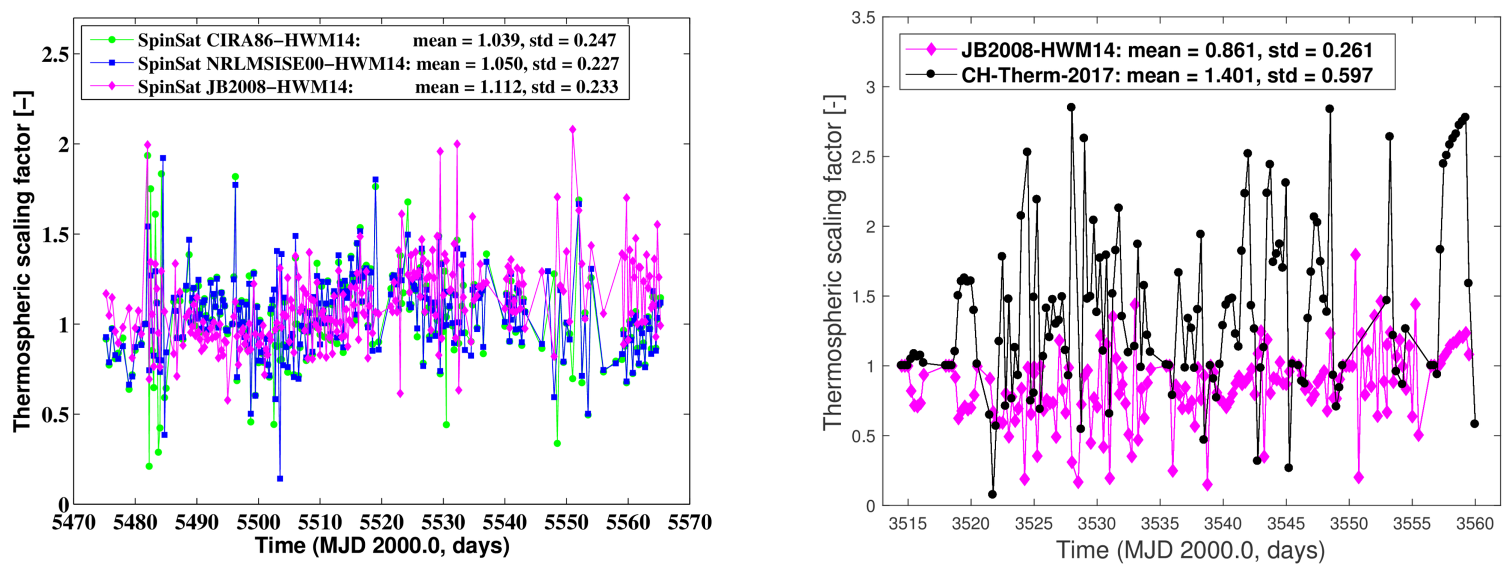

Figure 4: Scale factor f_s estimated from SLR measurements of Spinsat from 29 December 2014 to 29 March 2015 (left) and ANDE-P from 16 August 2009 to 30 September 2009 (right).

Summary

- Mean values and accuracies of the **scale factors** for 5 thermosphere model (the wind model HWM14 is included) estimated from SLR measurements to each of the three satellites at the given time periods:

Thermospheric model	ANDE-P 16.08.2009 – 03.10.2009, low solar activity, 248 < h < 369 km	ANDE-C 16.08.2009 – 26.03.2010, low solar activity, 297 < h < 350 km	SpinSat 29.12.2014 – 29.03.2015, high solar activity, 393 < h < 425 km
CIRA86	0.65 ± 0.26	0.68 ± 0.20	1.04 ± 0.25
NRLMSISE00	0.65 ± 0.25	0.68 ± 0.20	1.05 ± 0.23
JB2008	0.89 ± 0.27	0.97 ± 0.21	1.11 ± 0.23
DTM2013	0.79 ± 0.24	0.83 ± 0.16	---
CH-Therm-2018	1.40 ± 0.60	---	---

Conclusions and outlook

- **Time series of scale factors** provided for the 5 empirical models CIRA86, NRLMSISE00, JB2008, DTM2013, and CH-Therm-2018 have been derived using SLR observations to 3 the spherical LEO satellites ANDE-P, ANDE-C and Spinsat at the periods of low (August 2009 to March 2010) and high (January to March 2015) solar activity.
- DTM2013 provides the smallest **standard deviations** (0.16-0.24) of the estimated scale factors, while the largest standard deviations (0.60) are obtained for CH-Therm-2018.
- The scale factors derived from SLR observations to the two satellites ANDE-P and ANDE-C for the same (overlapping) period agree well within the standard deviations for the CIRA86, NRLMSISE00, JB2008, DTM2013 models.
- The scale factors for CIRA86, NRLMSISE00 and JB2008 change depending on the level of solar activity. These models overestimate the thermospheric density at low solar activity and slightly underestimate it at high solar activity.
- The CIRA86, NRLMSISE00, JB2008, DTM2013 models indicate trends in the scale factors estimated from ANDE-C data from August 2009 to March 2010.

References

- *Panzetta et al. Towards thermospheric density estimation from SLR observations of LEO satellites - A case study with ANDE-Pollux satellite*, Journal of Geodesy, in review.
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