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Using SLR observations to Low Earth Orbiting satellites to scale neutral thermospheric density values

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Motivation

Atmospheric drag is the major non-gravitational perturbation acting on Low Earth Orbiting (LEO) satellites at altitudes up to about 1000 km. The drag depends, among other parameters, on the **neutral density of thermosphere** that is usually provided by empirical and physical models.

Empirical models have been derived since 1961 using such observations as mass spectrometer, incoherent scatter radar, orbital data (satellite acceleration from precise orbit determination), accelerometer data from CHAMP, GRACE, GOCE and Swarm missions.

Knowledge on the density of the Earth's thermosphere and exosphere is a prerequisite for planning satellite missions, precise orbit determination (POD), orbit and re-entry prediction, collision avoidance of artificial satellites orbiting the Earth at altitudes below 1000 km.

This poster shows the capability to calibrate thermospheric density values **using Satellite Laser Ranging (SLR) observations** of LEO satellites at altitudes between 248 and 425 km. In particular, time series of scaling factors of the thermospheric density provided by **five empirical models** (CIRA86, NRLMSISE00, JB2008, DTM2013, and CH-Therm-2018) derived using SLR observations to three 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 are presented (see Fig. 2 and 3).

The method used – orbit analysis approach

Atmospheric drag $\boldsymbol{a}_D$ is the major non-gravitational perturbation acting on LEO satellites and significantly depends on the thermospheric neutral density ρ:

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

where $\frac{A_{\text{ref}}}{m}$ is the ratio of the effective cross-sectional area of the satellite to its mass (known),

- C_D is the dimensionless **drag coefficient** (is analytically computed using a gas-Surface interaction model, physical assumptions, and key parameters),
- ρ is the **thermospheric neutral density** (based on the prior mentioned models),
- v_{rel} is the relative velocity of the satellite w.r.t. the atmosphere (computed from POD using Horizontal Wind Model 2014 (HWM14)),
- $\hat{\boldsymbol{u}}_D$ is the drag unit vector (computed from POD).

The scaling factor f_s scales the thermospheric density values computed from different empirical models and **is estimated** from the analysis of SLR observations to spherical LEO satellites.

Our approach is based on a **reduced-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. (2018), more results are discussed in Rudenko et al. (2018).

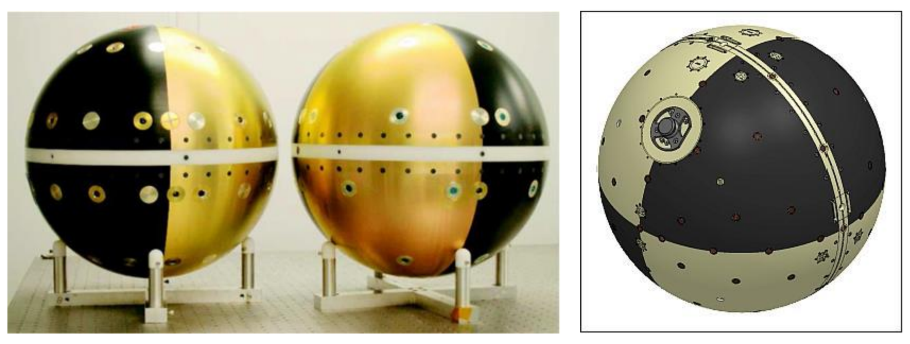
Parameters estimated at each orbital arc:

- initial state vector,
- one scaling factor of the solar radiation pressure perturbing acceleration,
- one scaling factor of the Earth albedo and infrared radiation pressure perturbing acceleration,
- one scaling factor of the empirical accelerations in along- and cross-track direction (sine- and cosine-term),
- multiple scaling factors f_s of the thermospheric neutral density values (e.g., every 6/12 h).

Satellites used and their main characteristics

In order to obtain reliable scaling factors, SLR observations to LEOs with a **spherical shape** (for details see Tab. 1) are used in the following analysis.

Figure 1:
left: "Atmospheric Neutral Density Experiment-2" (ANDE-2) Pollux (P) and Castor (C),
right: "Special Purpose Inexpensive Satellite" (SpinSat),
image credit: NRL.



Satellite name	Diameter [m]	Mass [kg]	A_{ref} / m [m^2 / kg]	CoM [m]	Drag coefficient [-]	Initial altitude [km]	Inc. [deg.]
ANDE-P	0.483	27.442	0.00667	0.224	2.115 ± 0.002	350	51.6
ANDE-C	0.483	47.450	0.00386	0.225	2.115 ± 0.002	350	51.6
SpinSat	0.558	52.650	0.00465	0.264	2.126 ± 0.002	425	51.6

Table 1: Parameters of the satellites used in this study.

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Results: estimated scaling factors of thermospheric density values

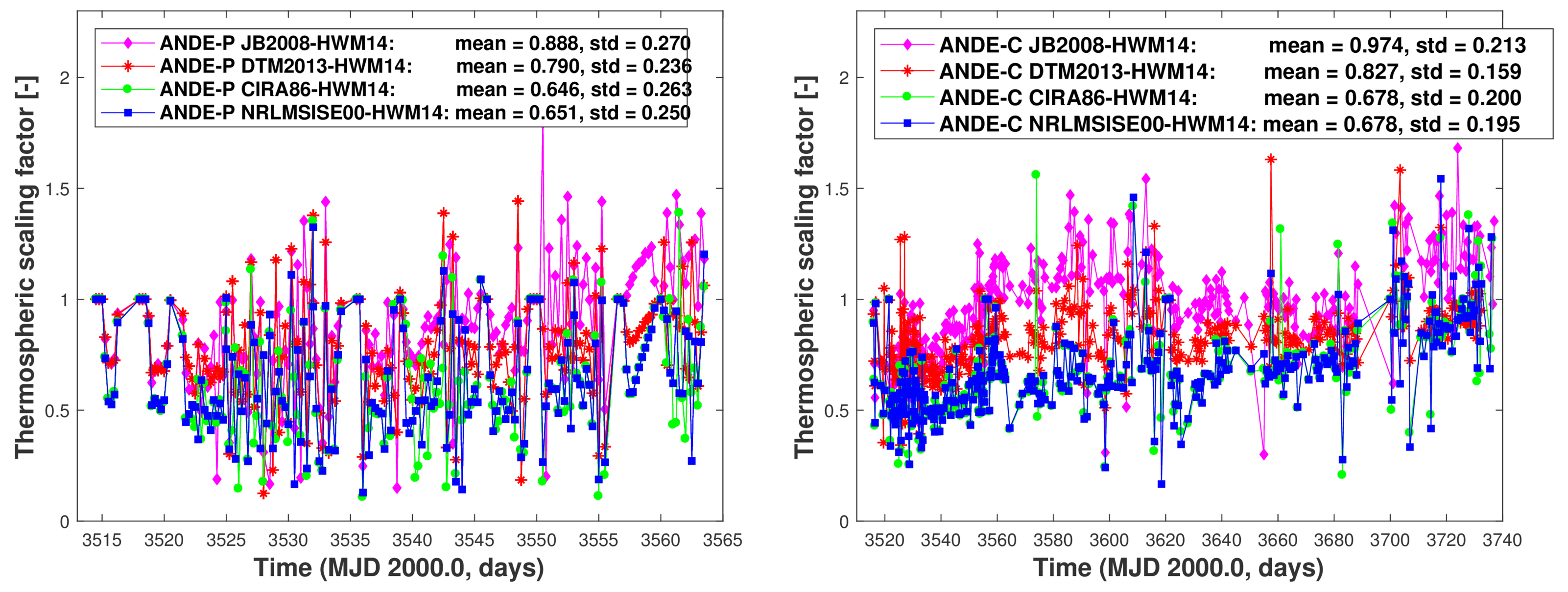

Figure 2: Scaling factor f_s estimated from SLR observations to ANDE-P from 16 August 2009 to 3 October 2009 (left) and to ANDE-C from 16 August 2009 to 26 March 2010 (right), modified from Rudenko et al., 2018. The ANDE-C data analysis indicates a trend.

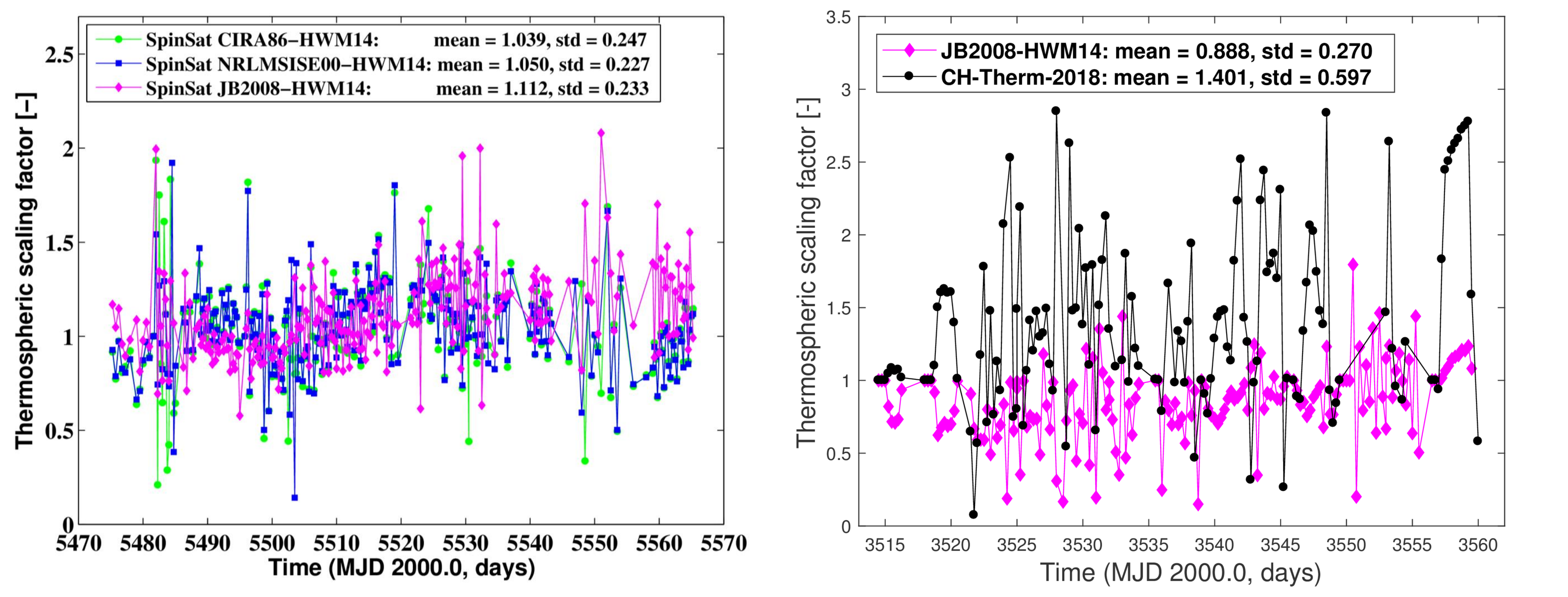

Figure 3: Scaling factor f_s estimated from SLR observations to SpinSat from 29 December 2014 to 29 March 2015 (left) and to ANDE-P from 16 August 2009 to 30 September 2009 (right), modified from Rudenko et al., 2018.

Summary

The mean values and standard deviations of the thermospheric density scaling factors of each thermospheric model (the wind model HWM14 is included) estimated using SLR observations to each of the three satellites at the given time spans are summarized in Tab. 2.

Thermospheric model	ANDE-P 16.08.09 – 03.10.09, low solar activity 248 < h < 369 km	ANDE-C 16.08.09 – 26.03.10, low solar activity 297 < h < 350 km	SpinSat 29.12.14 – 29.03.15, 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	—	—

Table 2: Mean values and standard deviations of the estimated thermospheric density scaling factors.

Conclusions and outlook

- **SLR observations are sensitive** to variations in the thermospheric density.
- **Time series of scaling factors of thermospheric density values** provided by five empirical models (CIRA86, NRLMSISE00, JB2008, DTM2013, and CH-Therm-2018 (Xiong et al., 2018)) have been derived using SLR observations to three spherical LEO satellites (ANDE-P, ANDE-C, and SpinSat) at periods of low (August 2009 to March 2010) and high (January to March 2015) solar activity.
- The scaling factors of thermospheric density derived from SLR observations of satellites **ANDE-P and ANDE-C agree well** within the standard deviations for the overlapping period.
- Scaling factors of CIRA86, NRLMSISE00, and JB2008 models **change depending on the level of solar activity**. These models overestimate the thermospheric density values at periods of low solar activity and slightly underestimate them at periods of high solar activity.
- **The CH-Therm-2018 model** underestimates the thermospheric density and provides the largest scatter of estimated scaling coefficients among the model tested.
- These satellites are difficult to track due to their high angular velocity. Therefore, we stress an **importance of dense tracking of such satellites** in the future to get reliable results.

References

- Panzetta F., Bloßfeld M., Erdogan E., Rudenko S., Schmidt M., Müller H. (2018) ***Towards thermospheric density estimation from SLR observations of LEO satellites - A case study with ANDE-Pollux satellite***, J Geodesy, DOI:10.1007/s00190-018-1165-8.
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- Xiong C., Lühr H., Schmidt M., Bloßfeld M., Rudenko S. (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.