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Estimation of scaling factors of thermospheric density provided by empirical models using SLR observations to Low Earth Orbiting satellites

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Introduction

The **neutral density of the thermosphere** is one of the key parameters used, in particular, to compute **atmospheric drag** acting on the Earth's orbiting satellites and objects at an altitude below 1000 km. Various **empirical and physical models** of the thermospheric neutral density have been developed since 1961. However, the thermospheric density computed using various up-to-date models significantly differs for the same time and positions (Figure 1).

A new method (Panzetta et al., 2018) has been developed at DGFI-TUM to estimate **scaling factors of the integrated thermospheric density** using Satellite Laser Ranging (SLR) observations to spherical Earth orbiting satellites, in combination with a full precise orbit determination. In this method, the total drag coefficient C_D (see Eq. 1) is computed using the Sentman model by averaging over all thermospheric species.

Using this approach, we have estimated scaling factors of the thermospheric density provided by the **CIRA86, NRLMSISE00, JB2008, DTM2013 and CH-Therm-2018** (Xiong et al., 2018) models using SLR observations to three spherical satellites. CH-Therm-2018 is based on 9-year accelerometer measurements from the CHAMP satellite from August 2000 to July 2009 when it flew at an altitude range between 460 and 310 km.

SLR observations used in this study: **ANDE-P** from 16 August 2009 to 3 October 2009**, ANDE-C** from 16 August 2009 to 26 March 2010 and **SpinSat** from 29 December 2014 to 29 March 2015, i.e. at the periods of low and high solar activity and the altitude range from 300 to 426 km.

Satellite Laser Ranging (SLR) observations

SLR is a geodetic **tracking technique** which can be used for Low Earth Orbiter (LEO) precise orbit determination (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 the **high measurement precision,** SLR observations are highly sensitive to any **perturbing acceleration** acting on the satellite.

To increase the accuracy of the estimated thermospheric density scaling factors, we use SLR observations to LEOs with a **spherical shape**, since, for such satellites, the errors of all parameters in Eq. (1) besides the thermospheric density are small. Therefore, for spherical satellites, the scaling factors are thermospheric density scaling factors.

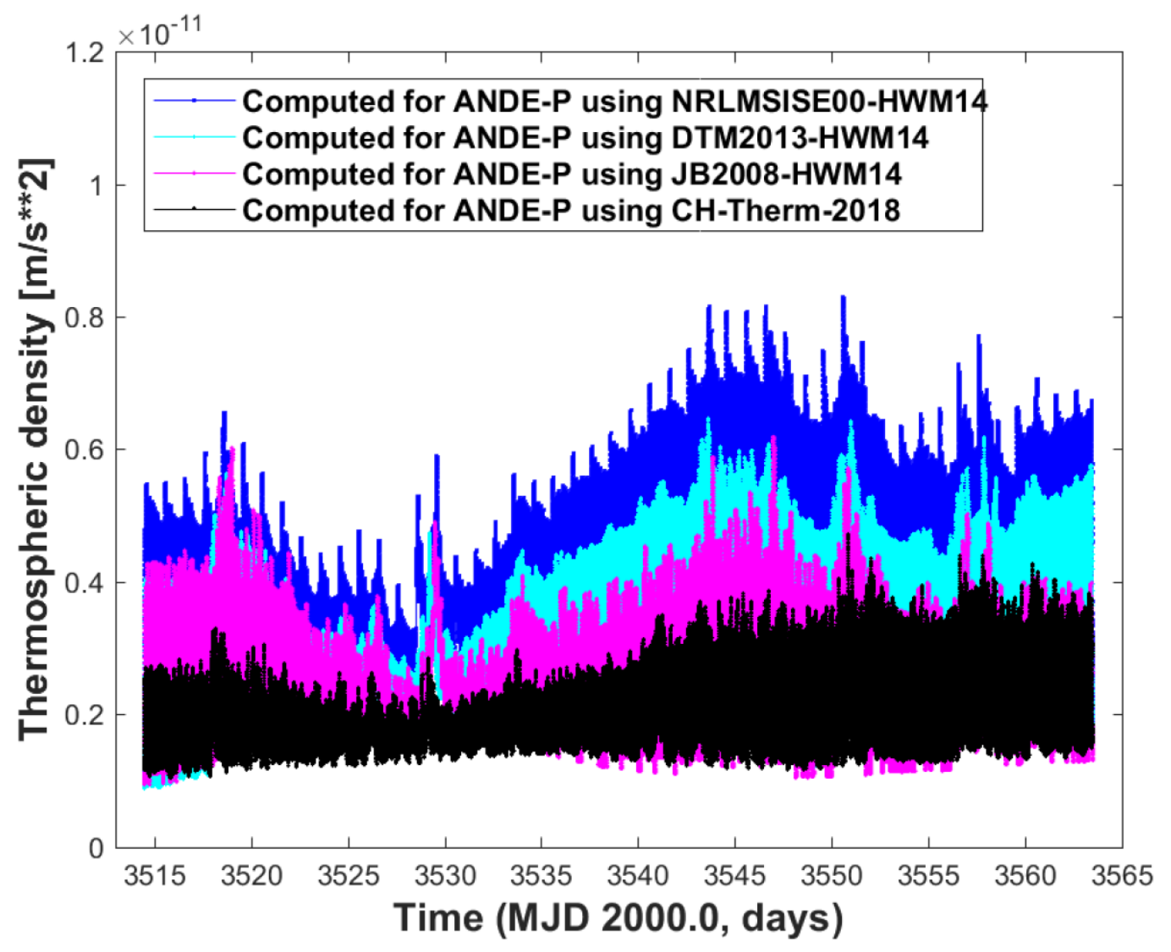

Figure 1: Thermospheric densities computed for ANDE-P using the NRLMSISE00, DTM2013, JB2008 and CH-Therm-2018 models.

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).

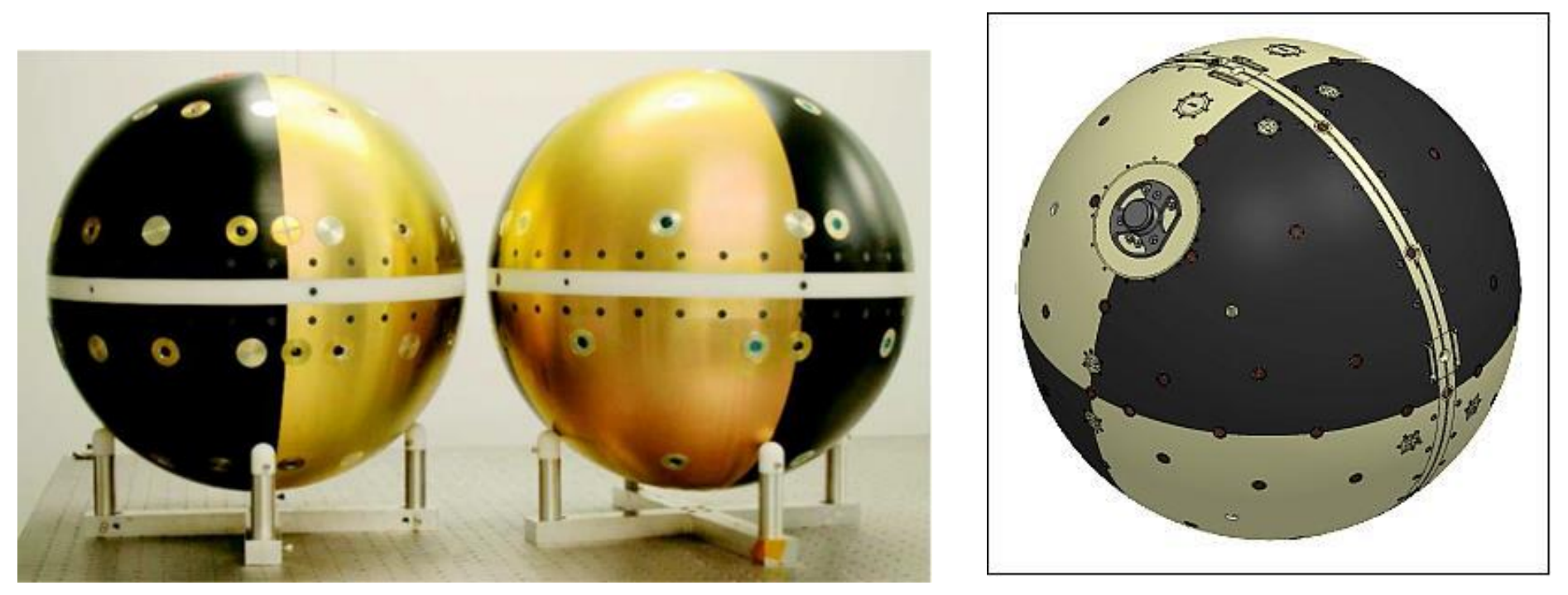

Figure 2: The ANDE-2 spherical micro-satellites Castor (left) and Pollux (middle), and SpinSat (right), image credit: NRL.

Approach

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

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

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 other key parameters), ρ is the **thermospheric density** at satellite position, v_{rel} is the satellite relative velocity w.r.t. atmosphere (computed from POD), and $\hat{\boldsymbol{u}}_D$ is a unit vector.

The **scaling factor** f_s in Eq. (1) accounts for the different magnitude of the density values computed from different empirical models. We estimate the **scaling 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. (2018), more results are discussed in Rudenko et al. (2018).

Results: estimated scaling factors of thermospheric density

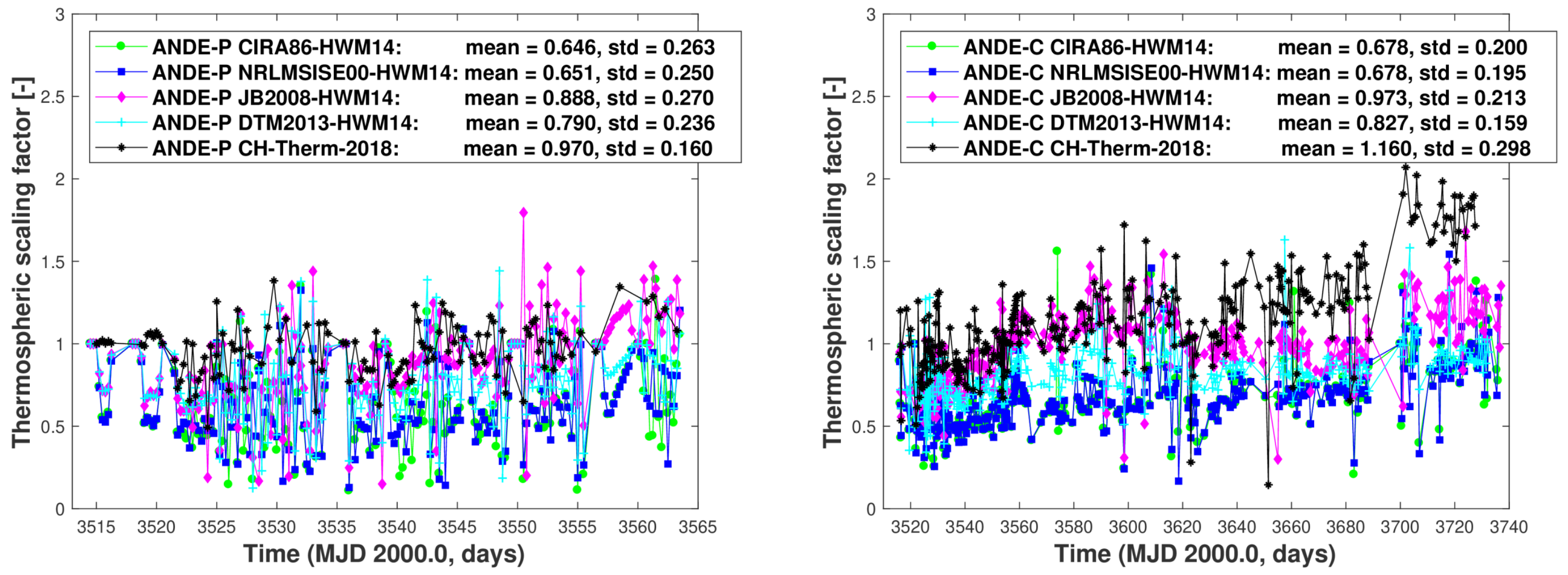

Figure 3: Scaling factor f_s estimated from SLR measurements of ANDE-P (left) and ANDE-C (right) for the time intervals given in Table 1 for the respective satellite. The ANDE-C data analysis indicates a trend.

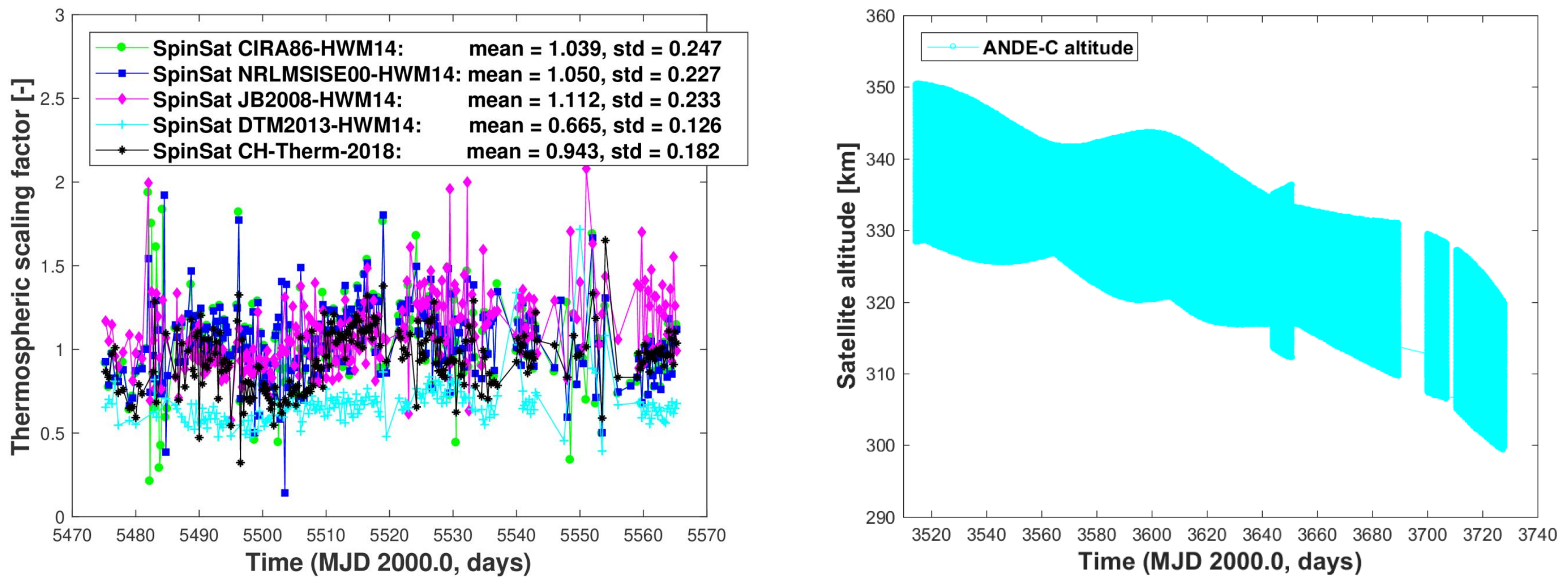

Figure 4: Scaling factor f_s estimated from SLR measurements of Spinsat (left) and ANDE-C altitude (right) for the time intervals given in Table 1 for the respective satellite. Gaps in the altitude and scaling factor time series are caused by the gaps in the observations not allowing to compute a reliable orbit at these time intervals.

Summary

- The mean values and accuracies of the **scaling factors** of thermospheric density of 5 models (with the horizontal wind model HWM14 included) estimated from SLR measurements to each of the three satellites at the time periods and the altitude h range specified are given in Table 1.

Table 1: Thermospheric density scaling factors computed using SLR observations for 5 models.

Thermospheric model	**ANDE-P** **16.08.2009 – 03.10.2009,** **low solar activity,** **323 < h < 349 km**	**ANDE-C** **16.08.2009 – 26.03.2010,** **low solar activity,** **300 < h < 350 km**	**SpinSat** **29.12.2014 – 29.03.2015,** **high solar activity,** **393 < h < 426 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	0.67 ± 0.13
CH-Therm-2018	0.97 ± 0.16	1.16 ± 0.30 (1.10 ± 0.23 until 06.02.2010)	0.94 ± 0.18

- **Time series of scaling factors** provided for the 5 empirical models CIRA86, NRLMSISE00, JB2008, DTM2013, and CH-Therm-2018 have been derived using SLR observations to three spherical LEO satellites ANDE-P, ANDE-C and Spinsat at the periods of low and high solar activity.
- The scaling 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 all five models.
- The scaling 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.
- All five models indicate **trends in the scaling factors estimated from ANDE-C data**.
- The thermospheric density provided by the **CH-Therm-2018 model fits rather good to SLR observations of three satellites**, since the thermospheric density of this model was scaled using the median scaling factor obtained using SLR data to ANDE-P in Xiong et al. (2018). The increased values of the scaling factors after 6 February 2010 (Fig. 3, right) are obtained at the ANDE-C altitude below 310 km (Fig. 4, right), i.e. below the validity altitude interval (310-460 km) of this model.

References

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Acknowledgement: This study was performed within the project INSIGHT funded by the German Research Foundation (DFG) in the framework of the Special Priority Programme (SPP) 1788 „Dynamic Earth".

The 27th IUGG General Assembly, July 8-18, 2019, Montréal, Québec, Canada