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Thermospheric density estimation from SLR observations of LEO satellites - a case study with the ANDE-Pollux satellite

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Perturbations due to the thermospheric density

The thermospheric neutral density plays a crucial role within the equation of motion of Earth orbiting satellites (Eq. (1)) since the drag acceleration $\boldsymbol{a_{drag}}$ is one of the largest non-gravitational perturbation and a function of the thermospheric density ρ_M:

$$\boldsymbol{a_{drag}} = -\frac{1}{2}\frac{A_{ref}}{m} C_D \rho_M v_{rel}^2 \boldsymbol{\hat{u}_D}, \quad (1)$$

where $\boldsymbol{\hat{u}_D}$ is the drag unit vector computed as $\boldsymbol{v_{rel}}/\|\boldsymbol{v_{rel}}\|$ with $\boldsymbol{v_{rel}}$ being the relative velocity of the satellite w.r.t. the thermosphere, A_{ref} is the effective cross-sectional area of the satellite interacting with the thermosphere, m is the satellite mass, and C_D is the dimensionless aerodynamic drag coefficient describing the interaction of the thermosphere with the satellite surface.

Usually, density estimations at high altitudes are based on accelerometer measurements of low Earth orbiting (LEO) satellites. The major limiting factor for the accuracy of those estimates are uncertainties in the complex satellite geometry (e.g. CHAMP) and the computation of the satellite-specific ballistic coefficient $(C_D \cdot A_{ref}/m)$. To overcome those problems, we use Satellite Laser Ranging (SLR) observations to a spherical satellite called Atmospheric Neutral Density Experiment - Pollux (ANDE-P) launched by the Naval Research Laboratory. This **passive** satellite was designed for thermospheric density estimation using SLR since it has

- a **spherical shape**,
- a **constant mass of 27.442 kg**,
- a **constant area of 48.26cm**,
- **30 optical retro-reflectors** (Fig. 1)
- and was orbiting the Earth between **August 2009 and March 2010** at
- an **altitude of about 350km**.

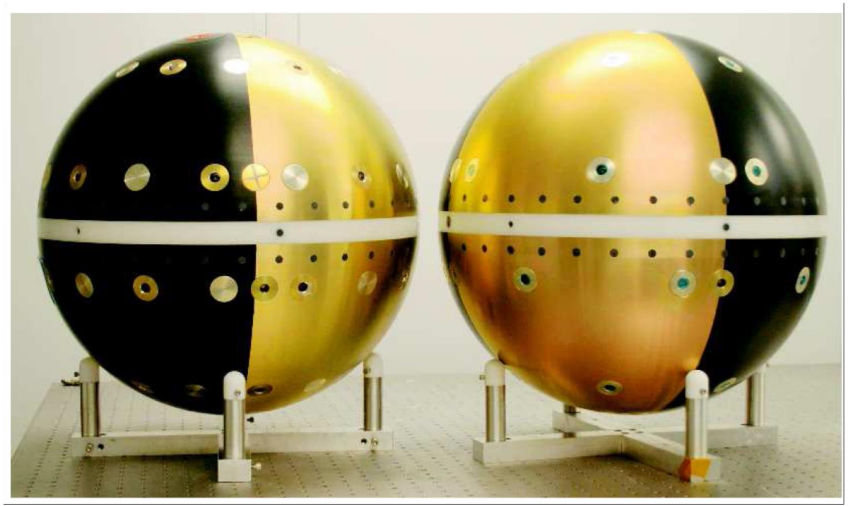

Fig. 1: The ANDE-2 spherical satellites Castor (left) and Pollux (right), image credit: NRL.

Due to the characteristics listed above, this type of LEO satellite is called `calibration' satellite. Such kind of SLR observations to satellites can be used to validate thermospheric models such as NRLMSISE-00, CIRA86, DTM2013 and JB2008 (see Fig. 2 and Tab. 2).

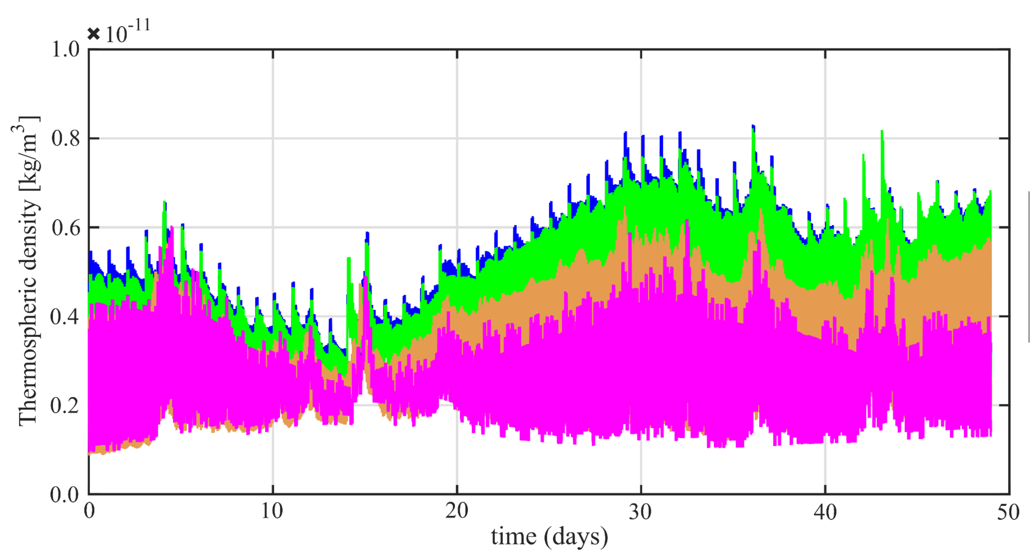

Fig. 2: Thermospheric densities of the models NRLMSISE-00 (blue), CIRA86 (green), DTM2013 (orange), and JB2008 (magenta) during the 49 days between August and October 2009.

since models show offsets, scale factors are estimated

ANDE-P solution setup

Within this experiment, we use the conventional dynamic models of the International Earth Rotation and Reference Systems Service (IERS; Petit and Luzum, 2010). Moreover, we test four different thermospheric models (Tab. 2), implemented in all solutions the most recent horizontal wind model HWM14 (Drob et al., 2015) and fixed station coordinates, Earth orientation parameters and gravity field parameters (Tab. 1). In total, we estimated 3.5 day arcs during 49 days between August and October 2009.

Tab. 1: Estimated parameters and their temporal resolution.

Estimated parameters	Temporal resolution
initial state vector	one set per arc (initial epoch)
solar radiation pressure scaling factor	one per arc
Albedo scaling factor	one per arc
empirical coefficients (CPRs)	one set per arc (sine/co-sine; along-/cross-track)
scaling coefficients (for drag acceleration)	for per day (6-hour resolution; along-track)

Tab. 2: Adopted empirical thermospheric models.

Thermospheric model	Reference
JB2008	Bowman et al. (2008)
DTM2013	Bruinsma (2015)
CIRA86	Hedin et al. (1988)
NRLMSISE-00	Picone et al. (2002)

Refined perturbation modeling

In Fig. 2, significant differences between the used thermospheric models are visible. In order to account for them, we refine Eq. (1) and estimate an additional scaling factor f_s for the drag acceleration (see also Tab. 1):

$$\boldsymbol{a_{drag}} = -\frac{1}{2}\frac{A_{ref}}{m} C_D \cdot f_s \cdot \rho_M v_{rel}^2 \boldsymbol{\hat{u}_D}, \quad (2)$$

Fig. 3 shows the estimated scaling factors in a 6-hour resolution during the investigated time interval. Due to the sparse global distribution of SLR observations to ANDE-P (only a few telescopes could observe this satellite), there are elements of the 3.5 day arcs where no scaling factor could be estimated at all (a priori value is equal to 1.0). In contrast to this, nearly all obtained scaling factors are smaller than 1.0. The JB2008 scaling factors are the closest to 1.0. The mean deviations between the scaling factors (Tab. 3) might be caused by different thermospheric densities shown in Fig. 2. Following Eq. (2), f_s compensates either for errors of the drag coefficient C_D, the modeled thermospheric density ρ_M or both together.

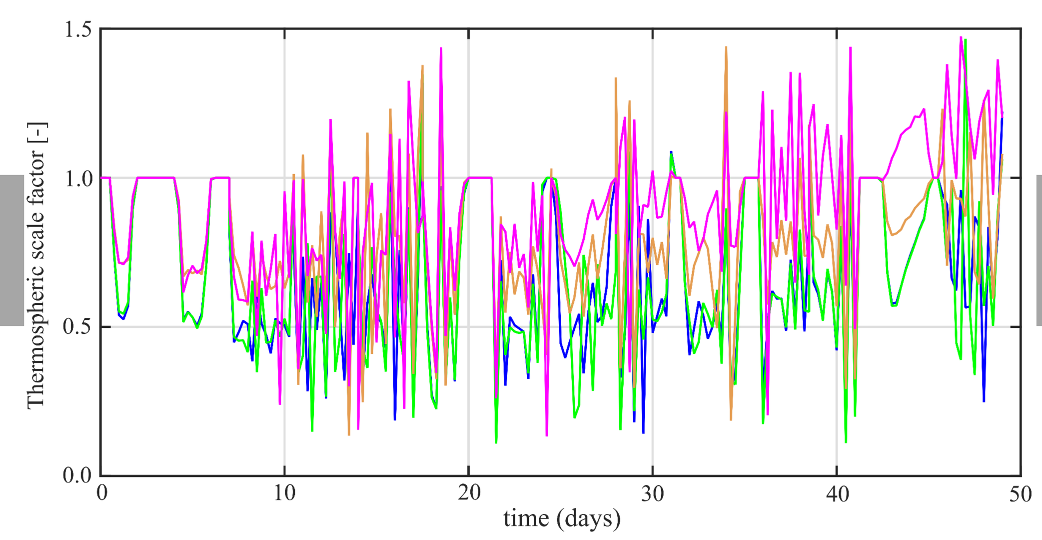

Fig. 3: Estimated scale factors of the different thermospheric models within the time interval of 49 days.

thermospheric densities agree well if scale factors are estimated

Results

The diagram depicted in Fig. 4 shows the possibilities to either analytically compute C_D and scale ρ_M (cases (A) and (B)) or to model ρ_M and scale C_D (case (C)). In this investigation, the thermospheric density is scaled by f_s since C_D is analytically computed on physical principles described in a gas-surface interaction (GSI) model. For a reliable interpretation of ρ_M, C_D, and f_s, it has to be considered:

- fundamental assumption: "free molecular flow"
- Sentman's model used as GSI model at altitudes lower than 550km
- thermal flow (superposition of Max-well-Boltzmann molecular velocity distribution and incident velocity)
- fully diffuse reflection of gas molecules
- Maxwell-Boltzmann velocity distribution of re-emitted particles
- Surface temperature of satellite $T_W = 300\text{K}$

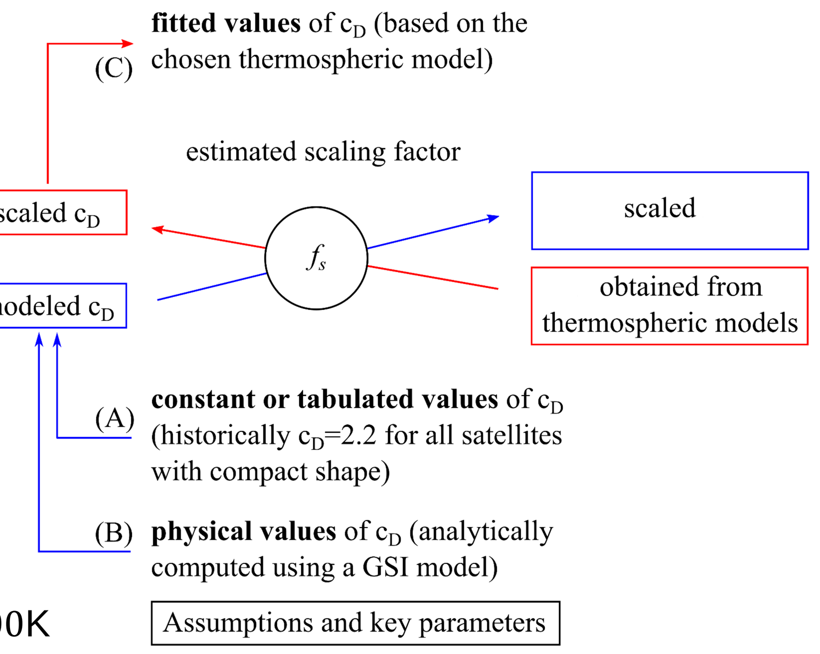

Fig. 4: Different possibilities to interpret the estimated scaling factor in the analysis.

The estimated scale factors show that JB2008 is the at least scaled model. In general CIRA86, NRLMSISE-00 and DTM2013 are scaled, to a larger or lower extent, towards JB2008 (Fig. 5). Finally, we conclude that thermospheric integral densities can be estimated (scaled) in a reasonable way using SLR observations to spherical satellites.

Tab. 3: RMS and mean values of the SLR orbit and the estimated scaling factors using four different thermospheric models.

Thermospheric model	SLR orbit RMS [cm]	RMS f_s [-]	mean f_s [-]
NRLMSISE-00	0.4004	0.74	0.70
CIRA86	0.4119	0.75	0.69
DTM2013	0.2939	0.85	0.82
JB2008	0.2662	0.93	0.90

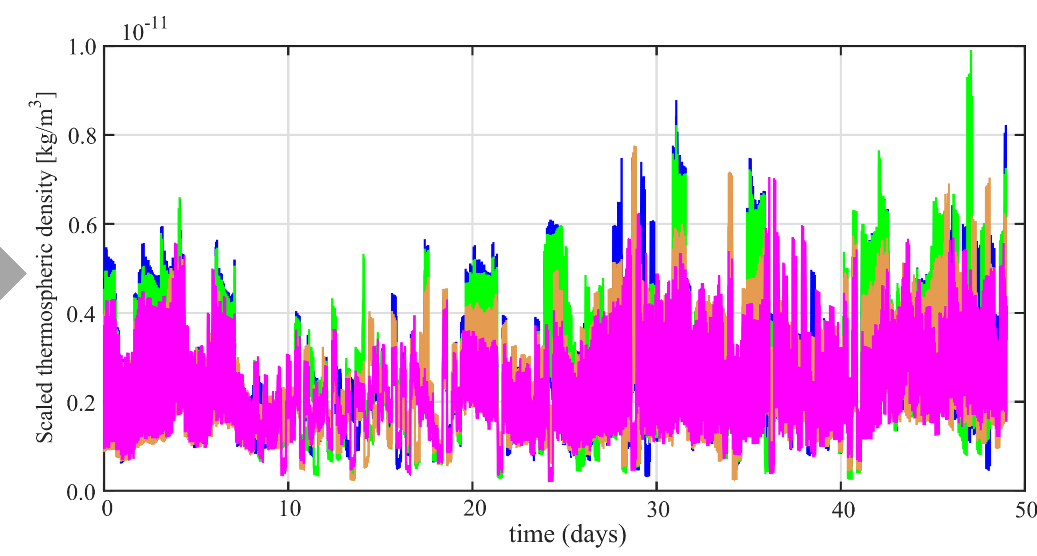

Fig. 5: Thermospheric total densities scaled using the 6-hourly estimated scale factors of the corresponding reference model.

For further details on this study, please see:

Panzetta F., Bloßfeld M., Erdogan E., Schmidt M., Müller H. (2017) **Absolute thermospheric density estimation from SLR observations of LEO satellites – A case study with ANDE-Pollux satellite.** J Geodesy, submitted

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