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A comparison of scale factors for the thermospheric density from satellite laser ranging and accelerometer measurements

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Introduction and Motivation

- The knowledge of the thermospheric density is of crucial importance not only for **precise orbit determination** (POD) of **low Earth orbiting** (LEO) satellites at altitudes below 1,000 km, but also for **re-entry predictions** and **satellite maneuvers**, as well as for **geo-scientific applications** such as remote sensing, and satellite gravimetry.
- Several **empirical thermospheric models**, such as NRLMSISE-00 or JB 2008, provide the thermospheric density among other parameters.
- Since these models are based on **different input data sets**, they can give quite different results, especially for **strong space weather events**.
- Since LEOs are sensitive to **atmospheric drag**, appropriate **on-board instrumentation** (accelerometers, trackers, reflectors, etc.) can be used to derive density information.
- As satellites above 550 km are usually not equipped with accelerometers, the question arises if **SLR measurements** to LEO satellites provide a **suitable complement** to accelerometer measurements to obtain thermospheric density information?

Procedure

- We distinguish between:
  - **1st Approach** utilizes the POD of LEO satellites to estimate scale factors of the thermospheric density from SLR tracking measurements
  - **2nd Approach** consists in the calculation of scale factors of the thermospheric density from the evaluation of the aerodynamic acceleration using satellite accelerometer (ACC) measurements
- In the equation of motion of a LEO satellite the aerodynamic acceleration is defined as

$$\boldsymbol{a}_{\text{aero}} = -\frac{1}{2}\frac{A_{\text{ref}}}{m}\,\boldsymbol{c}_{\text{aero}}\,\rho_{\text{M}}\,v_{\text{rel}}^2$$

with $\boldsymbol{c}_{\text{aero}}$ = force coefficient vector depending on geometry and orientation of the satellite, $\boldsymbol{A}_{\text{ref}}$ = effective cross-section of the satellite interacting with the atmosphere, m = total satellite mass, ρ_M = thermospheric density (NRLMSISE-00), v_{rel} = velocity of the satellite relative to the atmosphere.

Thermospheric density and selected satellite missions

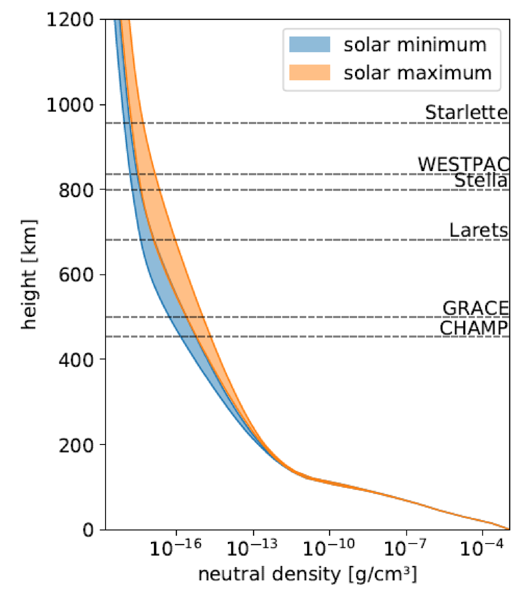

Figure 1: Sketch of the thermospheric density calculated from the NRLMSISE-00 model as a function of height.

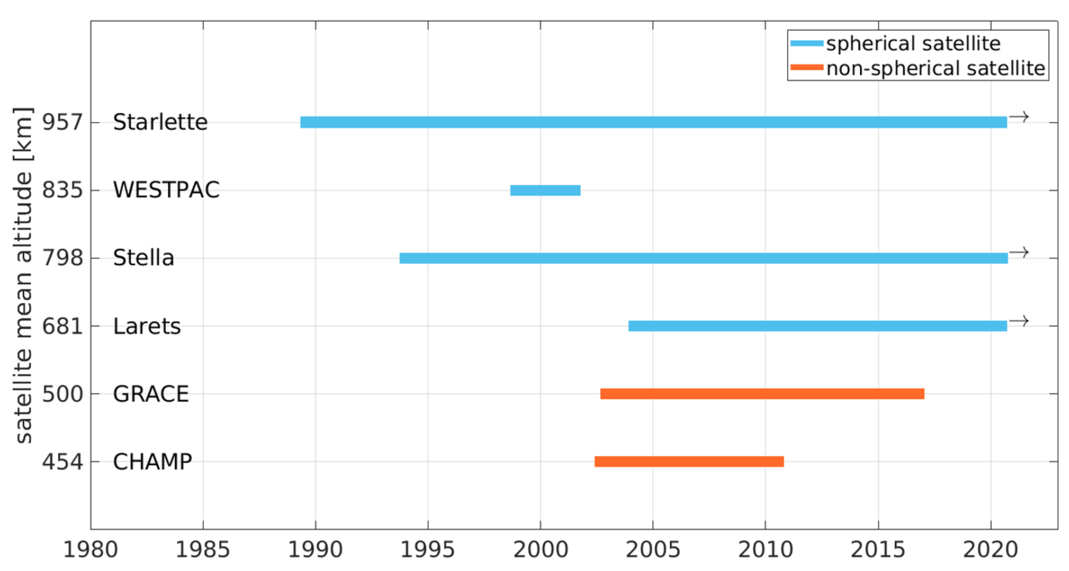

Figure 2: Lifetimes and mean altitudes of the satellite missions Starlette, WESTPAC, Stella, Larets, GRACE and CHAMP used in our study. An arrow indicates that the corresponding satellite is still in orbit and in use.

Procedure (cont.)

- The 1st approach is typically applied to **spherical** LEO satellites
- In this case, the **drag acceleration** $\boldsymbol{a}_{\text{aero}} \approx \boldsymbol{a}_{\text{drag}}$ reads

$$\boldsymbol{a}_{\text{drag}} = -\frac{1}{2}\,f_{\text{s,SLR}}\,\frac{A_{\text{ref}}}{m}\,C_{\text{D}}\,\rho_{\text{M}}\,v_{\text{rel}}^2\,\boldsymbol{x}$$

- with $\boldsymbol{x}$ = along-track unit vector, C_{D} = dimensionless aerodynamic drag coefficient.
- The **scale factor** $f_{\text{s,SLR}}$ **estimated** from **SLR** has to be interpreted as the mean value resulting from the integration along the orbit during a time interval of 12 hours
- In the 2nd approach, **space-borne accelerometry** was used to provide in-situ thermospheric density data along the satellite orbit with a high temporal resolution, e.g., of 10 seconds for GRACE.
- By solving the equation of the aerodynamic acceleration for the density $\rho_{\text{M}} = \rho_{\text{ACC}}$ we obtain the thermospheric density and finally the **scale factor** $f_{\text{s,ACC}}$ from **ACC**

$$\rho_{\text{ACC}} = \frac{-2\cdot m\cdot \boldsymbol{x}^T\boldsymbol{a}_{\text{aero}}}{A_{\text{ref}}\cdot \boldsymbol{x}^T\boldsymbol{c}_{\text{aero}}\cdot v_{\text{rel}}^2} \qquad f_{\text{s,ACC}} = \frac{\rho_{\text{ACC}}}{\rho_{\text{M}}}$$

Results

- Figure 3 shows the **estimated scale factors** after smoothing with a 10-day moving average filter to remove noise
- It can be seen that the estimated scale factor time series from SLR and ACC data **agree very well**
- This indicates to what extent the NRLMSISE-00 **model density values differ** from the measured thermospheric densities derived from SLR and ACC measurements
- To relate the filtered scale factor time series to the **solar activity**, the top panel in Fig. 3 depicts the time series of the 10-day averaged **F10.7 index**

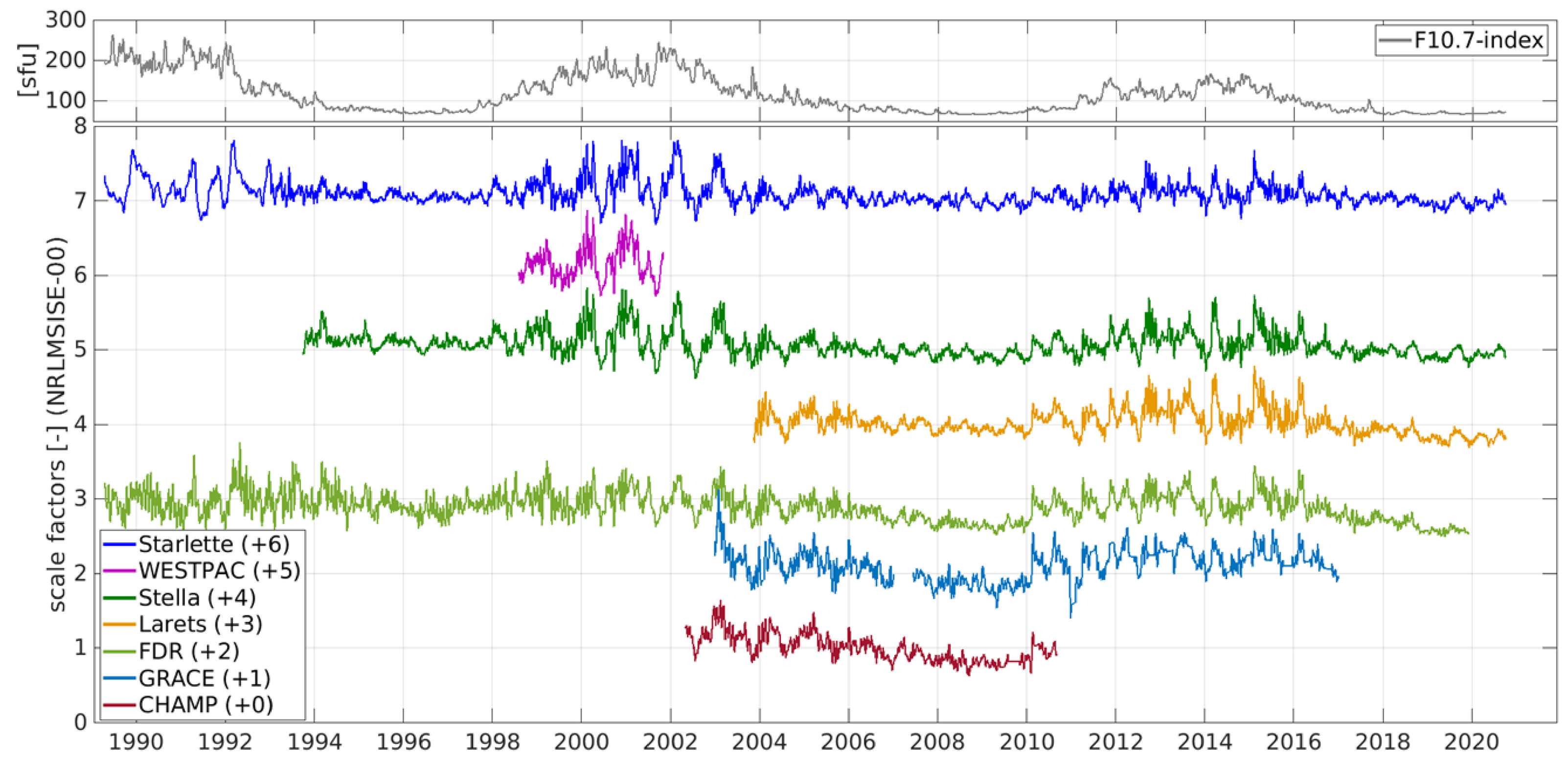

Figure 3: Time series of filtered scale factors $f_{\text{s,SLR}}$ of the thermospheric density from SLR using DGFI-TUM's software package DOGS-OC, $f_{\text{s,ACC}}$ of the ACC measurements and of the fitted density ratios (FDR) in an average altitude of 575 km by Emmert et al. (2021) globally (bottom panel) compared to the F10.7 solar activity index (top panel). The scale factor time series are shifted against each other by +1 according to their mean altitude to make them more distinguishable. Note, to assess the reliability and quality of the estimated scale factors $f_{\text{s,SLR}}$, PODs have also been performed by using IGG's SLR software package GROOPS

Results (cont.)

- Table 1 lists the **mean values** and **standard deviations** for the scale factor time series for **low solar activity** (**LSA**, period from 1.1.2006 to 3.9.2010) and **high solar activity** (**HSA**, period from 1.1.2011 to 31.12.2016)
- In case of **LSA** the **scale factors increase** in general **with increasing satellite altitude**, whereas during **HSA** the **scale factors decrease** with **increasing altitude**
- Hence, on average, the NRLMSISE-00 model **overestimates** the thermospheric density at **LSA** and must be down-scaled using the estimated scale factors, while the model **underestimates** the thermospheric density at **HSA** and must be up-scaled

Solar activity	Statistics	Starlette	Stella	Larets	FDR	GRACE	CHAMP
LSA	Mean	1.01	0.96	0.99	0.74	0.95	0.89
	STD	0.07	0.08	0.09	0.12	0.16	0.11
HSA	Mean	1.10	1.12	1.12	0.96	1.20	-
	STD	0.12	0.17	0.19	0.16	0.16	-

Table 1: Mean values and standard deviations (STD) of the estimated scale factors for various satellite altitudes from SLR measurements and from GRACE and CHAMP accelerometer measurements.

- Table 2 shows the **correlation coefficients** between each pair of the scale factor time series shown in Fig. 3 regarding to overlapping time intervals

Table 2: Correlations between the different scale factor time series from Fig. 3
- *Largest values of the SLR-only, accelerometer-only and mixed SLR-accelerometer correlations (yellow circles)*
- *Correlations decrease with increasing height difference (red box)*

	Starlette	WESTPAC	Stella	Larets	FDR	GRACE	CHAMP
Starlette	1	0.96	0.90	0.86	0.73	0.71	0.70
WESTPAC	0.96	1	0.98	—	0.83	—	—
Stella	0.90	**0.98**	1	0.93	0.84	0.77	0.75
Larets	0.86	—	0.93	1	0.93	0.81	0.74
FDR	0.73	0.83	0.84	0.93	1	0.89	0.92
GRACE	0.71	—	0.77	**0.81**	0.89	1	0.89
CHAMP	0.70	—	0.75	0.74	0.92	**0.89**	1

Conclusions

- For the first time, we have compared scale factors of the thermospheric density derived from SLR and ACC measurements
- Correlations of 0.7 to 0.8 are obtained between the estimated scale factors from SLR and ACC measurements depending on the height
- The mean values of the estimated scale factors of the thermospheric density provided by the NRLMSISE-00 model for various satellite altitudes as obtained from our analysis of SLR measurements to 4 satellites at mean altitudes of 681 to 957 km and from GRACE and CHAMP ACC measurements are 0.89 to 1.01 at LSA and 1.10 to 1.20 at HSA
- SLR measurements to LEO satellites are a very well suited complement to ACC measurements to obtain information on the thermospheric density.

Publications (selected)

- Zeitler et al. (2021). Scale factors of the thermospheric density - a comparison of SLR and accelerometer solutions. Journal of Geophysical Research: Space Physics, 126, e2021JA029708, doi: 10.1029/2021JA029708
- Vielberg et al. (2018): Comparison of Accelerometer Data Calibration Methods Used in Thermospheric Neutral Density Estimation. Ann. Geophys., 36 (3), 761–779, doi: 10.5194/angeo-36-761-2018
- Emmert et al. (2021): A Globally Averaged Thermospheric Density Data Set Derived From Two-Line Orbital Element Sets and Special Perturbations State Vectors. Journal of Geophysical Research: Space Physics, 126 (8), e2021JA029455, doi: 10.1029/2021JA029455.

DFG Deutsche Forschungsgemeinschaft

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