Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)
TUM School of Engineering and Design
Technische Universität München

TIPOD | DynamicEarth SPP 1788 | GFZ Helmholtz-Zentrum Potsdam | Universität Bonn | TUM

Development of High-Precision Thermosphere Models for Improving Precise Orbit Determination of Low-Earth-Orbiting Satellites (TIPOD) – Status Report

Michael Schmidt[1], Julian Zeitlhöfer[1], Lea Zeitler[1], Armin Corbin[2], Jürgen Kusche[2], Claudia Stolle[3*], Chao Xiong[3**], Urs Hugentobler[4], Christoph Bamann[4], Sergei Rudenko[1], Mathis Bloßfeld[1], Kristin Vielberg[2], Anno Löcher[2]

[1] Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM), Munich, Germany (mg.schmidt@tum.de), [2] Institute of Geodesy and Geoinformation (IGG), Bonn, Germany, [3*] now at Leibniz Institute of Atmospheric Physics at the University of Rostock (IAP), Kühlungsborn, Germany, [3**] Department of Space Physics, Electronic Information School, University of Wuhan, China, [4] Forschungseinrichtung Satellitengeodäsie, Technical University of Munich (FGS-TUM), Germany

Introduction and Motivation

- **Satellite motion** depends on gravitational and non-gravitational accelerations
- Modelling the **thermospheric drag** (largest non-gravitational acceleration) is a major challenge in **precise orbit determination** (POD) of **low-Earth orbiting** (LEO) **satellites** with altitudes below 1000 km
- The thermospheric drag is directly related to the **neutral density of the thermosphere**
- The thermospheric density is **physically coupled** to the electron density of the ionosphere

Objectives

- Development of **high-precision thermosphere models** to improve the POD of geoscientific LEO satellites
- Composition of a **set of observation techniques** (Satellite Laser Ranging (SLR), Accelerometer (ACC), DORIS, GNSS**,** Two Line Elements (TLE), Radar) to determine appropriate **thermospheric key parameters** including a complete stochastic model
- **Improving knowledge of thermosphere density** by extending the empirical model and calibrating model predictions by various observation techniques

Project Structure

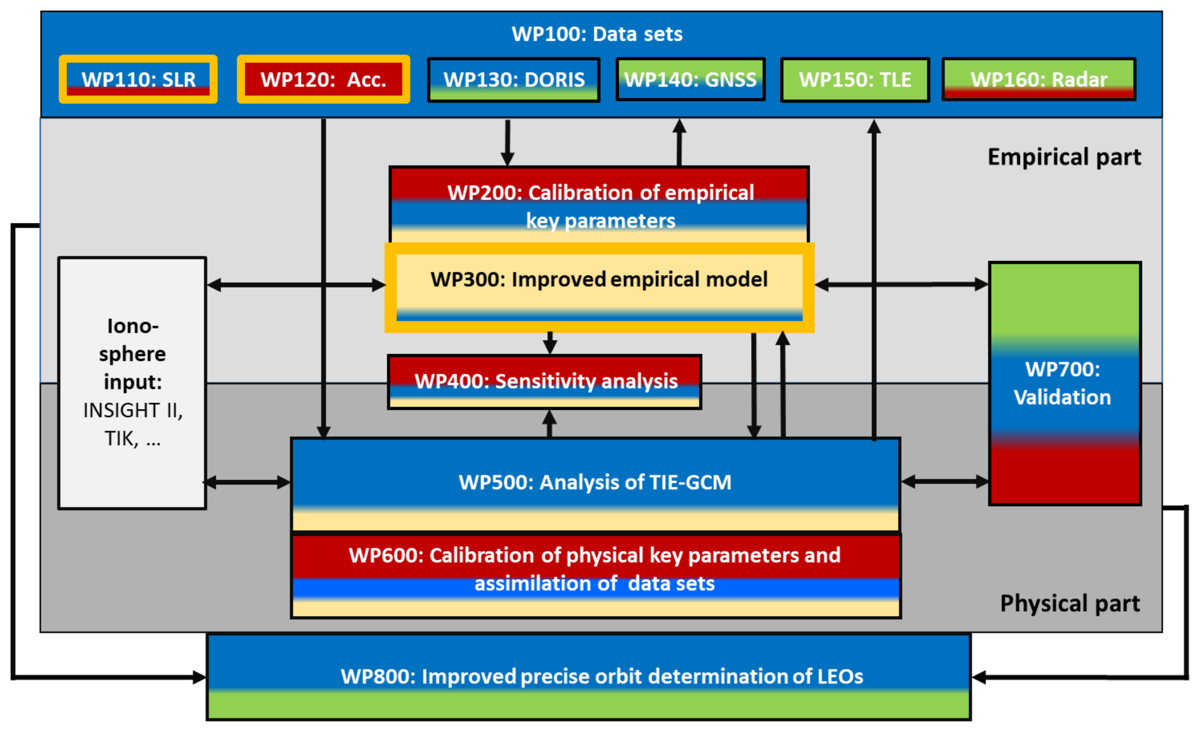

Figure 1: Flowchart of TIPOD as presented in the project proposal. It shows not only the work packages WP100 to WP800 of the 4 project partners visualized by different colors (DGFI-TUM: blue, IGG-Bonn: red, GFZ: beige and FGS-TUM: green), but also the relations to other projects funded either within the SPP (INSIGHT II) or externally (TIK).

- For various reasons, e.g., the Corona pandemic, both the **project duration** and the **project structure** had to be changed and adapted accordingly
- For example, in WP300 we replaced the empirical model CH-Therm-2018 with the empirical models **NRLMSISE-00** and **NRLMSIS 2.0** due to delays in the timing
- In WP100, we did not use the **DORIS observations** (WP130) and the **radar data** (WP160)
- As the project is still **ongoing**, we have not yet been able to complete the work in all WPs, e.g.,WP700 and WP800.

Contributions from DGFI-TUM

- Based on SLR (WP110) and ACC (WP120) we estimated in WP200 **scale factors** of various LEOs (Fig. 2) for the **thermospheric drag** computed by NRLMSISE-00 (see Zeitler et al. 2021)

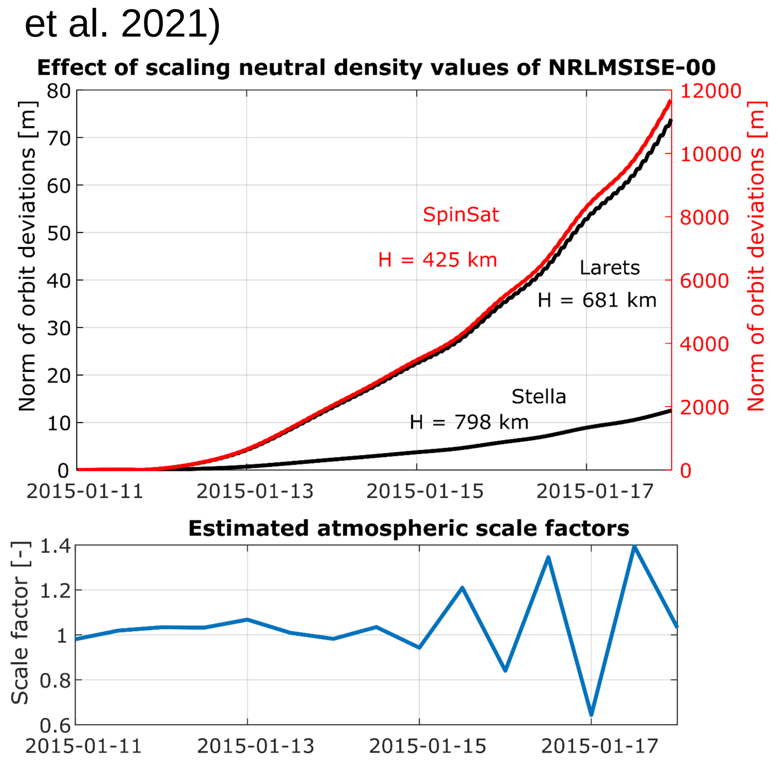

Figure 3: The norm of orbit deviations shown for 3 different satellites for a period of 1 week (top). The deviations are obtained when multiplying the neutral density values obtained from NRLMSISE-00 with the estimated scale factors (bottom).

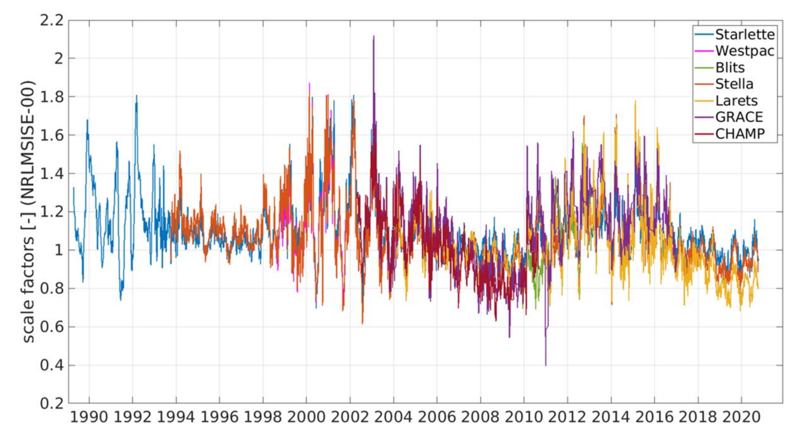

Figure 2: Time series of scale factors estimated from SLR and ACC. In this visualization we neglect all possible dependencies on the satellite orbits, e.g., the altitude

- In Fig. 3 we **compare** the results of 2 PODs: (1) setting the scale factors equal to 1, i.e., taking purely the NRLSISE-00 model and (2) considering the **estimated scale factors** from Fig. 2 to improve the thermospheric density values (WP800).

Table 1: The norm of orbit deviations in meters according to days after starting the 2 PODs.

	Stella	Larets	SpinSat
Day 1	0.05	0.29	46
Day 2	0.70	4.23	647
Day 3	2.17	13.00	2025
Day 4	3.74	22.52	3468
Day 5	5.83	34.85	5417
Day 6	8.92	52.78	8314
Day 7	12.52	73.90	11681

Contributions from GFZ / IAP

- Performance **check of different empirical and semi-empirical models** of the thermosphere, e.g., NRLMSIS, DTM13, and CH-Therm 2018 in **comparison with observations** (WP400)
- Provision of **model predictions** along satellite orbits to project partners (WP300)

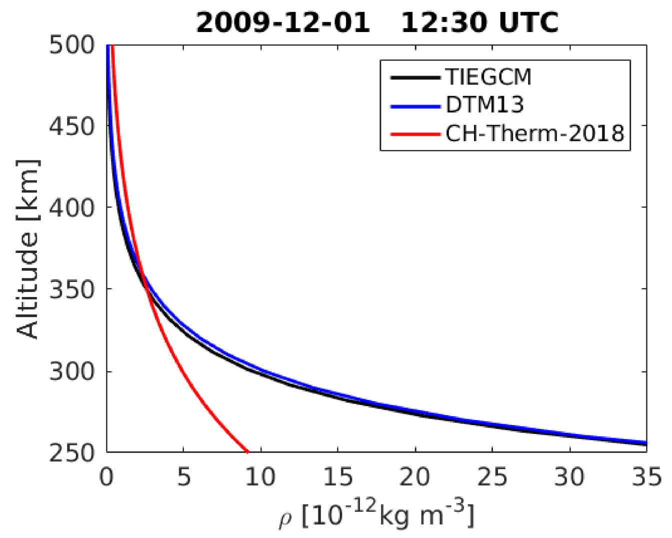

Figure 4: Variation of the thermospheric density with respect to the altitude of the empirical models DTM2013 and CH-Therm 2018 as well as the physical model TIE-GCM.

Contributions from FSG-TUM

- **Two approaches** for the determination of the ballistic coefficients from TLEs: (1) based on change of the semi-major axis over time, (2) based on an adjustment of the orbit model to TLE positions (WP150)
- Results computed from **spherical objects** with TLE on circular orbits below 1000 km available in 2016.
- TLE well suited to calibrate **long-term trend** of thermospheric density (WP700).

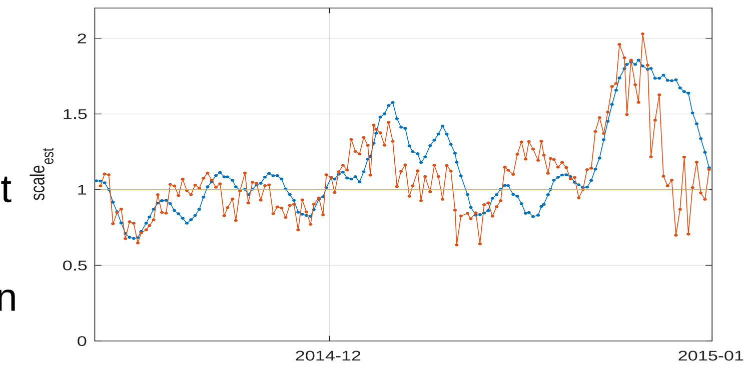

Figure 5: Density correction factors w.r.t. NRLMSISE-00 obtained for a TLE object at a height of 600 km using approach 1 (red) and 2 (blue). Approach 2 provides smoother results.

Contributions from IGG

- We published **accelerometer derived neutral mass** densities (WP120) onboard of the satellites CHAMP, GRACE-A, and SWARM-C (Vielberg et al., 2021)
- We contributed neutral densities derived from SLR POD (WP110) and accelerometer measurements (WP120) to the study by Zeitler et al. (2021) that investigates the comparison of scale factors (WP200)
- Based on the results of WP200, we **calibrated the NRLMSIS 2.0** model (WP300) using scale factors derived from CHAMP (see Corbin and Kusche, 2022)
- We investigated the **sensitivity** of the **physical model TIE-GCM** with respect to the indices F10.7 and Kp (WP400)
- We investigated **different setups** for the TIE-GCM model (WP500) and compared them with accelerometer derived densities (see Corbin and Kusche, 2022)
- We developed an **assimilative version of TIE-GCM** using the Parallel Data Assimilation Framework (P-DAF) (WP600)
- The developed software **is fast** since all ensemble members are computed in parallel and it is **easy to add new observation types**. In a first application (see Fig. 6) we assimilated neutral mass densities derived from CHAMP accelerometer using a new **two step approach** (see Corbin and Kusche, 2022)

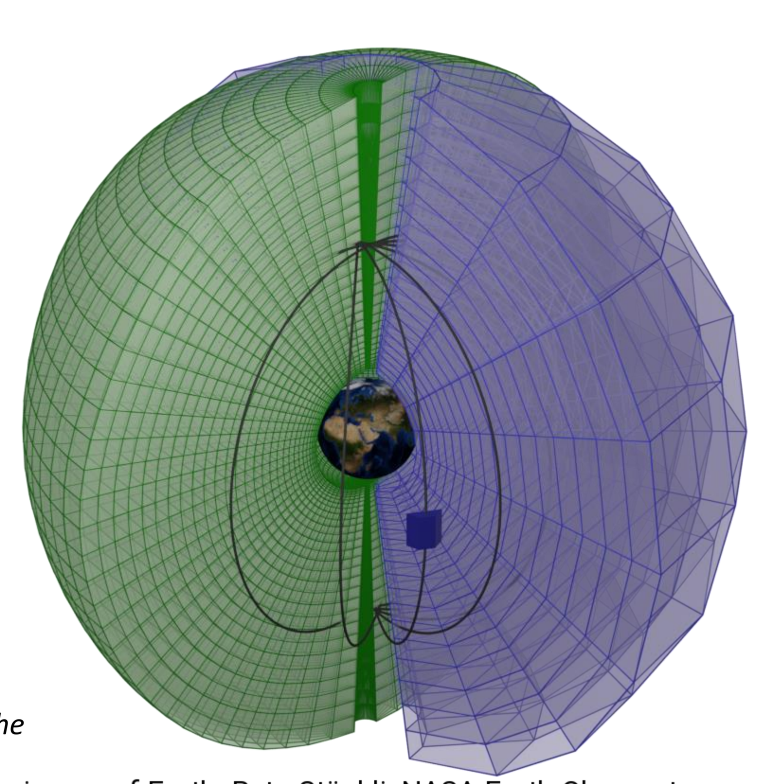

Figure 6: Illustration of the two-step approach. The along-track CHAMP observations (black curve) are used to calibrate the empirical NRLMSIS 2.0 model. Next, the calibrated model is evaluated on a global grid (blue grid) and then assimilated into the TIE-GCM model (green grid)

image of Earth: Reto Stöckli, NASA Earth Observatory

Further steps

- At DGFI-TUM the empirical model NRLMSISE-00 model will be transferred into a **multi-dimensional B-spline model** in order to **ingest the estimated scale factors** as shown in Fig. 3 and discussed in Zeitler et al. (2021)
- The **thermospheric models developed in TIPOD** on the basis of NRLMSISE-00, NRLMSIS 2.0 and TIE-GCM will be used in WP800 in the context of PODs of suitable satellites to assess the **potential for improvement** of these models.

Publications (selected)

- Corbin, A. and Kusche, J. Improving the estimation of thermospheric neutral density via two-step assimilation of in-situ neutral density into a numerical model, 11 May 2022, PREPRINT (Version 1) available at Research Square
- Vielberg et al TND-IGG RL01: Thermospheric neutral density from accelerometer measurements of GRACE-A, CHAMP and Swarm-C. data set. 2021 available at Pangea
- 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

DFG Deutsche Forschungsgemeinschaft

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