Thermospheric density estimation using SLR observations to very low Earth orbiters

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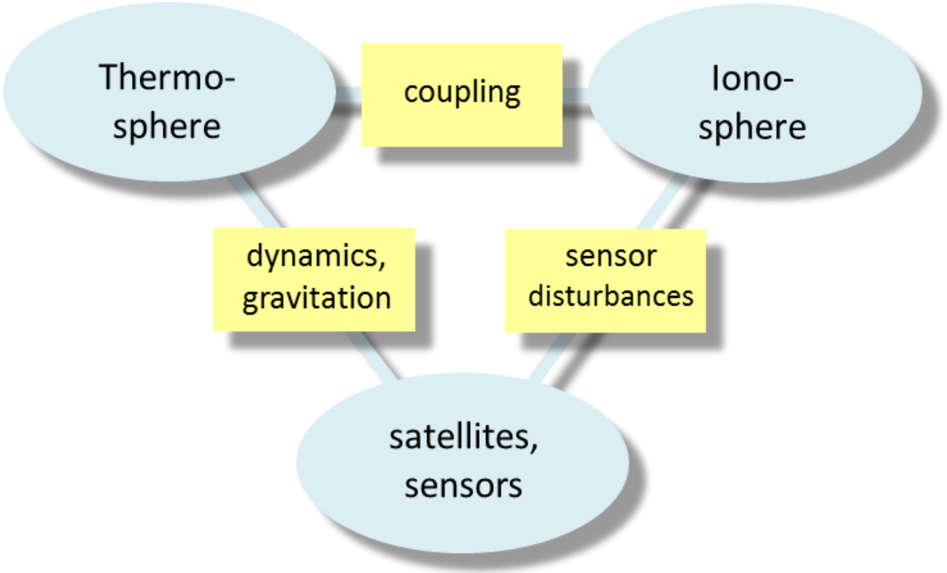
Introduction

INSIGHT project: Interactions of Low-orbiting Satellites with the Surrounding Ionosphere and Thermosphere

IAPG-TUM München; DGFI-TUM München; GFZ Potsdam; IfE, University Hannover

Main objectives of the project:

- investigate the thermosphere dynamics at low orbits,
- address the ionosphere – thermosphere coupling,
- study the interactions of thermosphere and ionosphere with sensor systems of geodetic space missions.



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DGFI-TUM contributions to INSIGHT:

- **Sensitivity analysis of SLR observations to thermospheric models**
- **Estimation of thermospheric parameters from SLR observations**
- **Combined estimation including non-spherical satellites such as GOCE and SWARM**
- **Assimilation of electron density measurements into a thermosphere- ionosphere coupling model**

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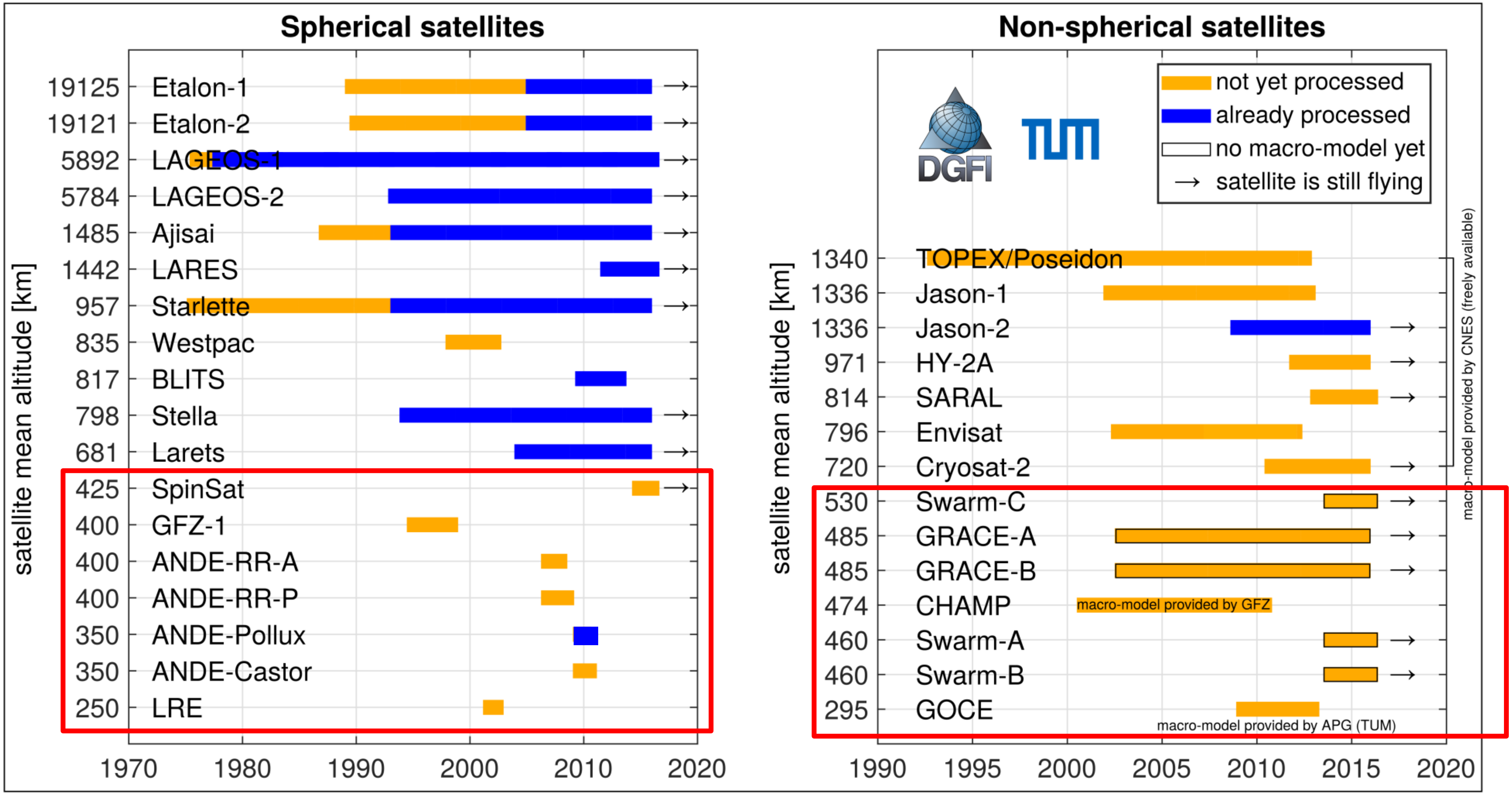
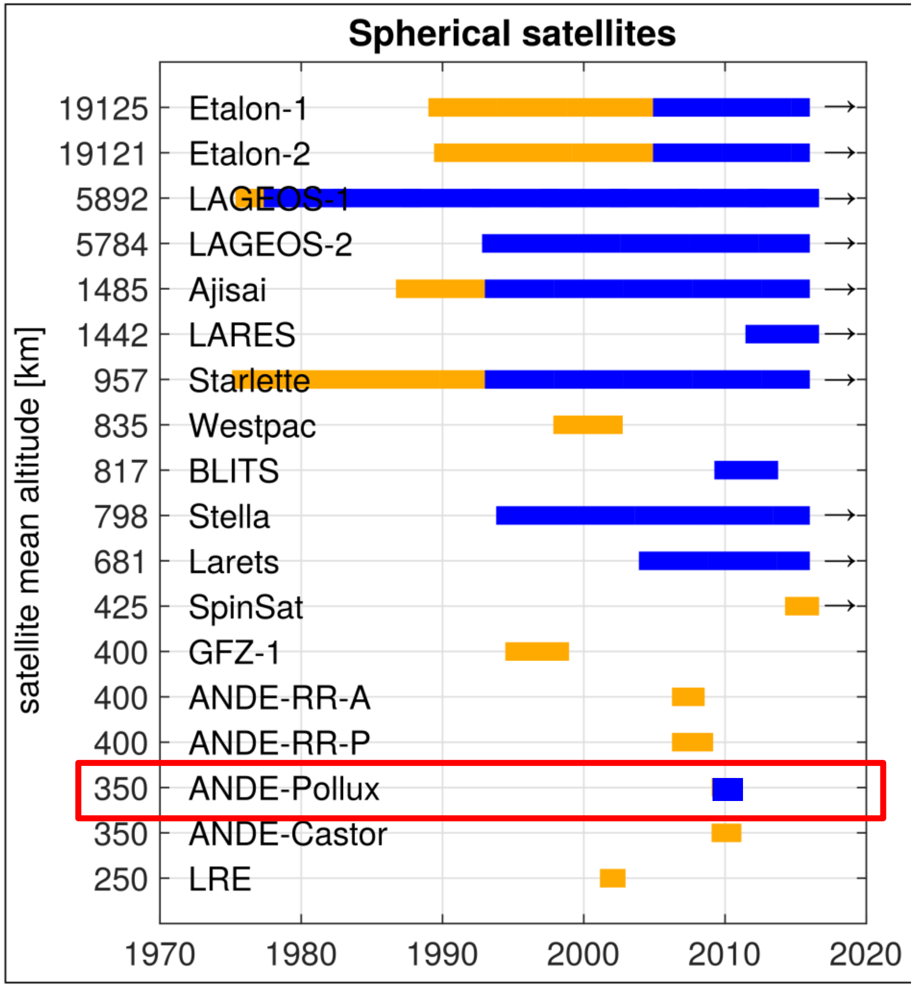
Available/processed SLR observations



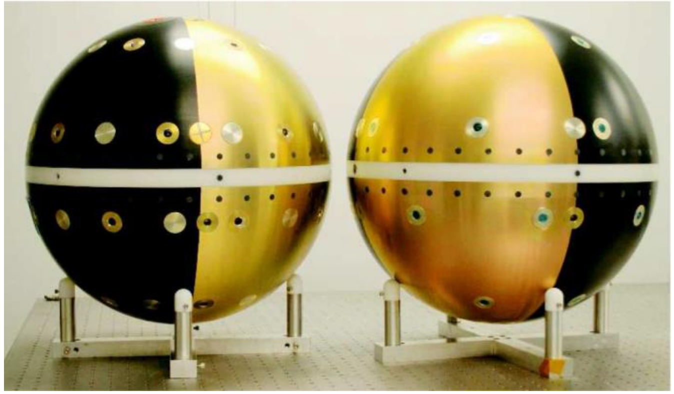
- LEO satellites are hard to observe (fast rotation of telescopes necessary)
- Spherical satellites have very short mission duration (few months to 1-2 years)

Available/processed SLR observations



- ➢ Processed period for ANDE-Pollux: 49 days (3.5-day arcs)

Atmospheric Neutral Density Experiment (ANDE)



The ANDE spheres Castor (left) and Pollux (right)

Characteristics of ANDE-Pollux (P):

- Spherical
- Altitude ≈ 350 km
- Inclination ≈ 51.6 degree
- Mass ≈ 27.442 kg
- Center of mass offset ≈ 223.98 mm
- Mission duration (lifetime) from July 2009 to March 2010

Equation of motion of LEO satellites

Direct Gravitational acceleration | Indirect Gravitational acceleration | Non-Gravitational acceleration

$$\ddot{\boldsymbol{r}}_{\text{sat}}(t) = \underbrace{\boldsymbol{a}_{\text{KEP}}(t) + \boldsymbol{a}_{\text{GE}}(t) + \boldsymbol{a}_{\text{GM}}(t) + \boldsymbol{a}_{\text{GS}}(t)}_{\boldsymbol{a}_{\text{DG}}(t)} + \underbrace{\boldsymbol{a}_{\text{GT}}(t) + \boldsymbol{a}_{\text{GNT}}(t)}_{\boldsymbol{a}_{\text{IG}}(t)} + \boldsymbol{a}_{\text{NG}}(t)$$

$\boldsymbol{a}_{\text{DG}}$ = direct gravitational acceleration

$\boldsymbol{a}_{\text{KEP}}$ = gravitational acceleration caused by the point-concentrated mass of the Earth (Stokes coefficient $C_{0,0}$)

$\boldsymbol{a}_{\text{GE}}$ = gravitational acceleration caused by the Earth (Stokes coefficients $C_{n,m}, S_{n,m}$ with $n, m \in \mathbb{N}^{+}$ and $m < n$)

$\boldsymbol{a}_{\text{GM}}$ = gravitational acceleration caused by the Moon

$\boldsymbol{a}_{GS}$ = gravitational acceleration caused by the Sun and other planets

$\boldsymbol{a}_{\text{IG}}$ = indirect gravitational acceleration (indirect effect on the satellite via the Earth)

$\boldsymbol{a}_{\text{GT}}$ = gravitational acceleration caused by mass variations due to solid Earth and ocean tides

$\boldsymbol{a}_{\text{GNT}}$ = acceleration caused by mass variations due to non-tidal loading effects (e.g., atmospheric, hydrological, oceanic)

$\boldsymbol{a}_{\text{NG}}$ = non-gravitational acceleration

Equation of motion of LEO satellites

Direct Gravitational acceleration

Indirect Gravitational acceleration

Non-Gravitational acceleration

$$\ddot{\boldsymbol{r}}_{\mathrm{sat}}(t) = \underbrace{\boldsymbol{a}_{\mathrm{KEP}}(t) + \boldsymbol{a}_{\mathrm{GE}}(t) + \boldsymbol{a}_{\mathrm{GM}}(t) + \boldsymbol{a}_{\mathrm{GS}}(t)}_{\boldsymbol{a}_{\mathrm{DG}}(t)} + \underbrace{\boldsymbol{a}_{\mathrm{GT}}(t) + \boldsymbol{a}_{\mathrm{GNT}}(t)}_{\boldsymbol{a}_{\mathrm{IG}}(t)} + \boldsymbol{a}_{\mathrm{NG}}(t)$$

According to Ciufolini (1987) and Lucchesi (2001; 2002) the **non-gravitational acceleration** $\boldsymbol{a}_{\mathrm{NG}}$ can be split into:

- **radiation parts** (direct solar radiation pressure, Earth albedo, satellite eclipses, Poynting-Robertson effect, Yarkovski-Rubincam effect (anisotropic thermal radiation), Yarkovski-Schach effect (infrared radiation)),
- **drag-like parts** (**atmospheric drag**, solar wind, interplanetary dust),
- **other parts** (e.g., Earth magnetic field, relativistic effect).

For (spherical) LEO satellites the **atmospheric drag perturbing acceleration** $\boldsymbol{a}_{\boldsymbol{D}}$ is the **largest one** and, thus, the **main error source** in LEO satellite POD.

Refined aerodynamic perturbation modeling

- ANDE-P → spherical satellite → only drag forces (no side/lift forces)

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

$\hat{\boldsymbol{u}}_D = \frac{\boldsymbol{v}_{rel}}{\lVert \boldsymbol{v}_{rel} \rVert}$	drag unit vector
$\boldsymbol{v}_{rel}$	relative velocity of the satellite w.r.t. the thermosphere
C_D	thermospheric drag coefficient, describing the interaction of the atmosphere with the satellite surface
ρ	integrated thermospheric (neutral) density
A_{eff}	effective satellite cross-section area interacting with the atmosphere
m	satellite mass

Refined aerodynamic perturbation modeling

- ANDE-P → spherical satellite → only drag forces (no side/lift forces)

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

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ρ	integrated thermospheric (neutral) density
A_{eff}	effective satellite cross-section area interacting with the atmosphere
m	satellite mass
f_s	Lagrange scaling factor → this parameter is estimated!

- **How does the estimated scaling parameter be interpreted?**

Refined aerodynamic perturbation modeling

- ANDE-P → spherical satellite → only drag forces (no side/lift forces)

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

To which of the terms in the equation above the scaling factor can be associated?

- The **area-to-mass relation** A_{eff}/m is for spherical satellites usually the most accurate parameter.
- The uncertainties in the **thermospheric density** and the **drag coefficient** C_D are significant under all conditions of solar and geomagnetic activity and at all latitudes and themospheric altitudes.
- At altitudes below 350 km it is assumed that the thermospheric density **is the least accurate parameter**.
- **Thus, we assume the scaling parameter f_s is accociated with ρ.**

Computation of the thermospheric density ρ

"hot" atomic oxygen and ionospheric atomic oxygen ions O+ (to be considered at altitudes > 500 km)

- Implemented thermospheric models

Thermospheric model	Reference	thermospheric constituents (k)
DTM2013	(Bruinsma et al., 2008)	H, He, O, N2, O2, Ar
JB2008	(Bowman et al., 2008)	H, He, O, N2, O2, Ar
CIRA86	(Hedin et al., 1988)	H, He, N, O, N2, O2, Ar
NRLMSISE00	(Picone et al., 2002)	H, He, N, O, N2, O2, Ar, anomalous oxygen

- Implemented horizontal wind model: HWM14 (Drob et al., 2015)

Computation of the drag coefficient C_D

Assumption 1 → **Free molecular flow**: no inter-molecular collisions at satellite altitudes > 150 km (based on the Knudsen number)

Assumption 2 → **Sentman's GSI model**: interaction between gas and satellite surface at altitudes < 500 km

Assumption 3 → Satellite surface is covered with a layer of absorbed atomic oxygen → **fully diffuse reflection** of the gas particles with **full accomodation** ($\alpha = 1$; explanation on next slide)

Assumption 4 → **Thermal flow**: incident flow at satellite surface is superposition of random thermal molecule velocity (Maxwell-Boltzmann distribution) and bulk velocity (v_{rel})

Assumption 5 → **Maxwell-Boltzmann velocity** of re-emitted particles

Assumption 6 → $\boldsymbol{T_w = 300\ K}$

Computation of physically-based drag coefficient C_D

- Based on the assumptions, C_D can be computed according to

$$C_{D,k}^{(sp)} = \frac{4s_k^4 + 4s_k^2 - 1}{2s_k^4}\mathrm{erf}(s_k) + \frac{2s_k^2 + 1}{\sqrt{\pi}s_k^3}e^{-s_k^2} + \frac{2\sqrt{\pi}}{3 4s_k}\sqrt{\frac{T_w}{T_\infty}}$$

Key parameter 1 → Molecular speed ratio $\boldsymbol{s_k = \frac{v_{rel}}{v_{m,k}}}$ with $v_{m,k} = \sqrt{\frac{2RT_\infty}{m_k}}$ (most probable molecular velocity for k'th constituent with atomic mass m_k (using gas kinetic theory; Maxwell-Boltzmann)

Key parameter 2 → Satellite relative velocity w.r.t. thermosphere $\boldsymbol{v_{rel} = v_{sat} - \omega_e \times x_{sat} - v_{wind}}$

Key parameter 3 → Energy accommodation coefficient $\boldsymbol{\alpha = \frac{E_i - E_r}{E_i - E_w}}$ which quantifies the amount of energy exchange between gas and surface

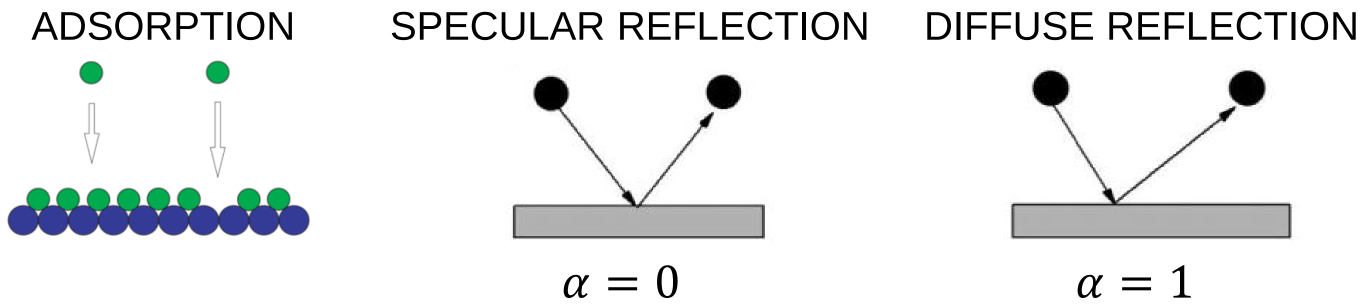
Key parameter 4 →

Computation of physically-based drag coefficient C_D (3/3)

- Based on the assumptions, C_D can be computed according to

$$C_{D,k}^{(sp)} = \frac{4s_k^4 + 4s_k^2 - 1}{2s_k^4}\operatorname{erf}(s_k) + \frac{2s_k^2 + 1}{\sqrt{\pi}s_k^3}e^{-s_k^2} + \frac{2\sqrt{\pi}}{34s_k}\sqrt{\frac{T_w}{T_\infty}}$$

Key parameter 1 →



Key parameter 2 →

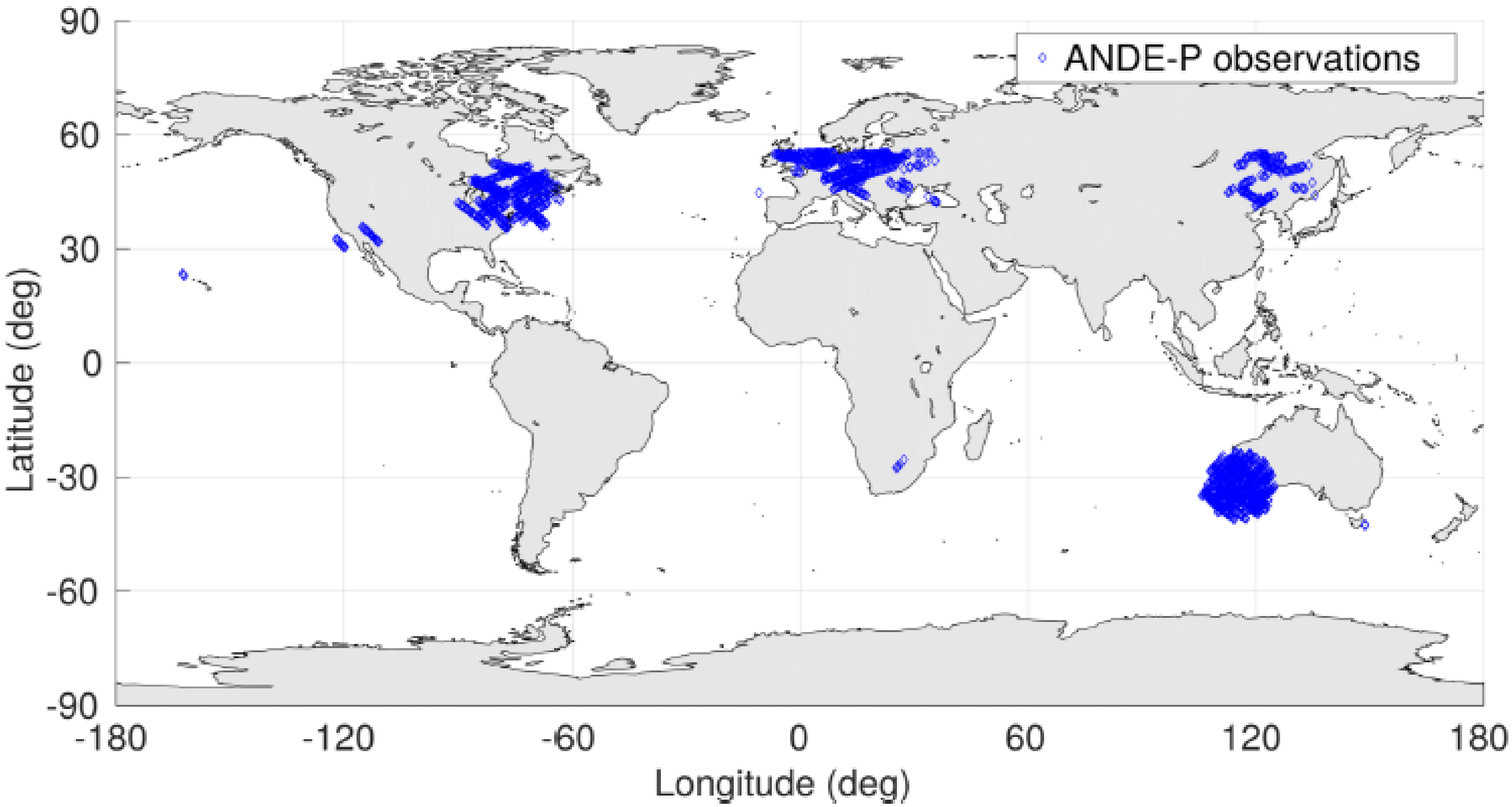
E_i, E_r, E_w → kinetic energies of incident, reflected and re-emitted molecules with temperature of the surface (wall)

Key parameter 3 → Energy accommodation coefficient $\boldsymbol{\alpha = \frac{E_i - E_r}{E_i - E_w}}$ which quantifies the amount of energy exchange between gas and surface

Key parameter 4 → Satellite surface and thermospheric temperatures $\boldsymbol{T_w}$ and $\boldsymbol{T_\infty}$

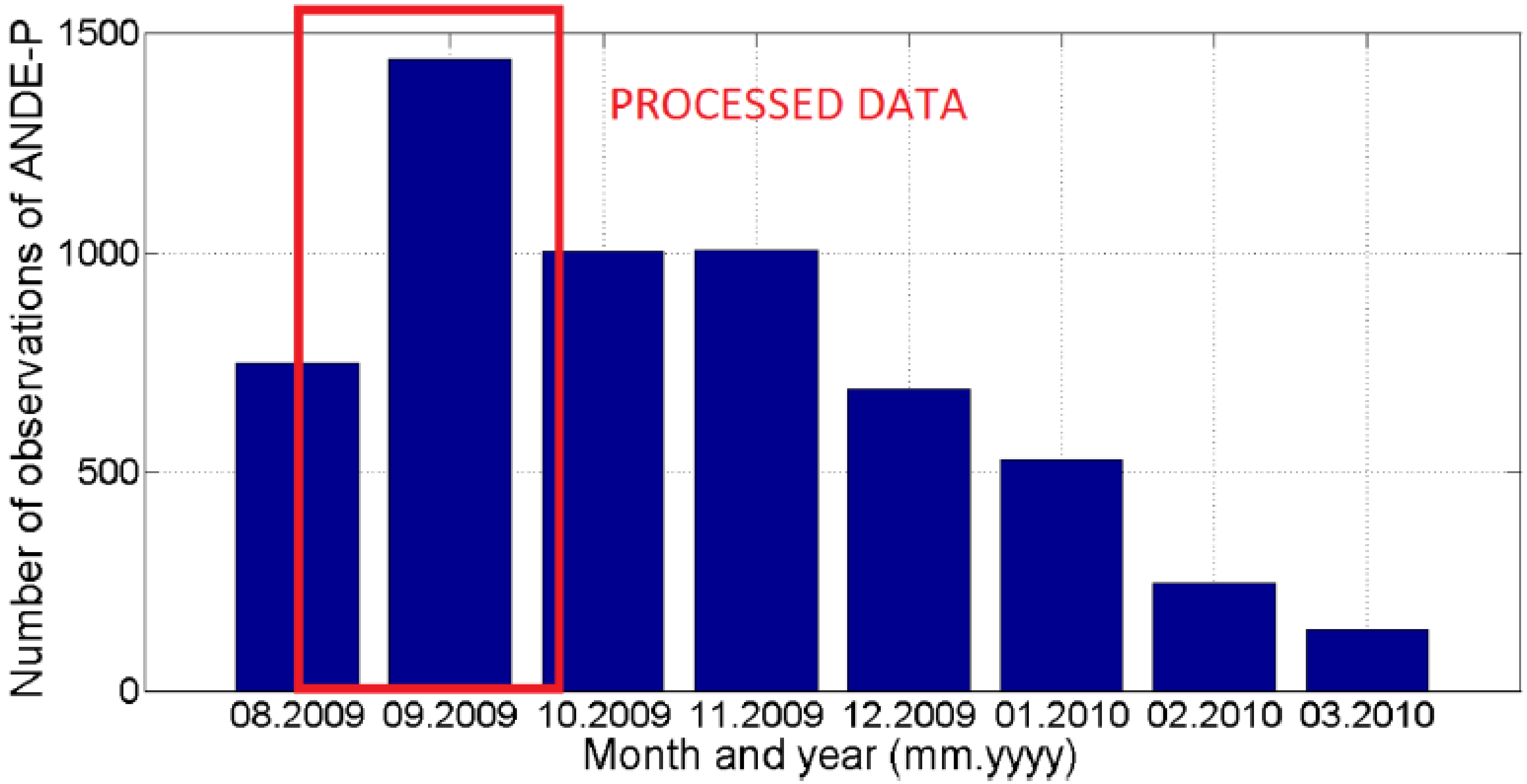
ANDE-Pollux observations

- ❑ Geographic distribution

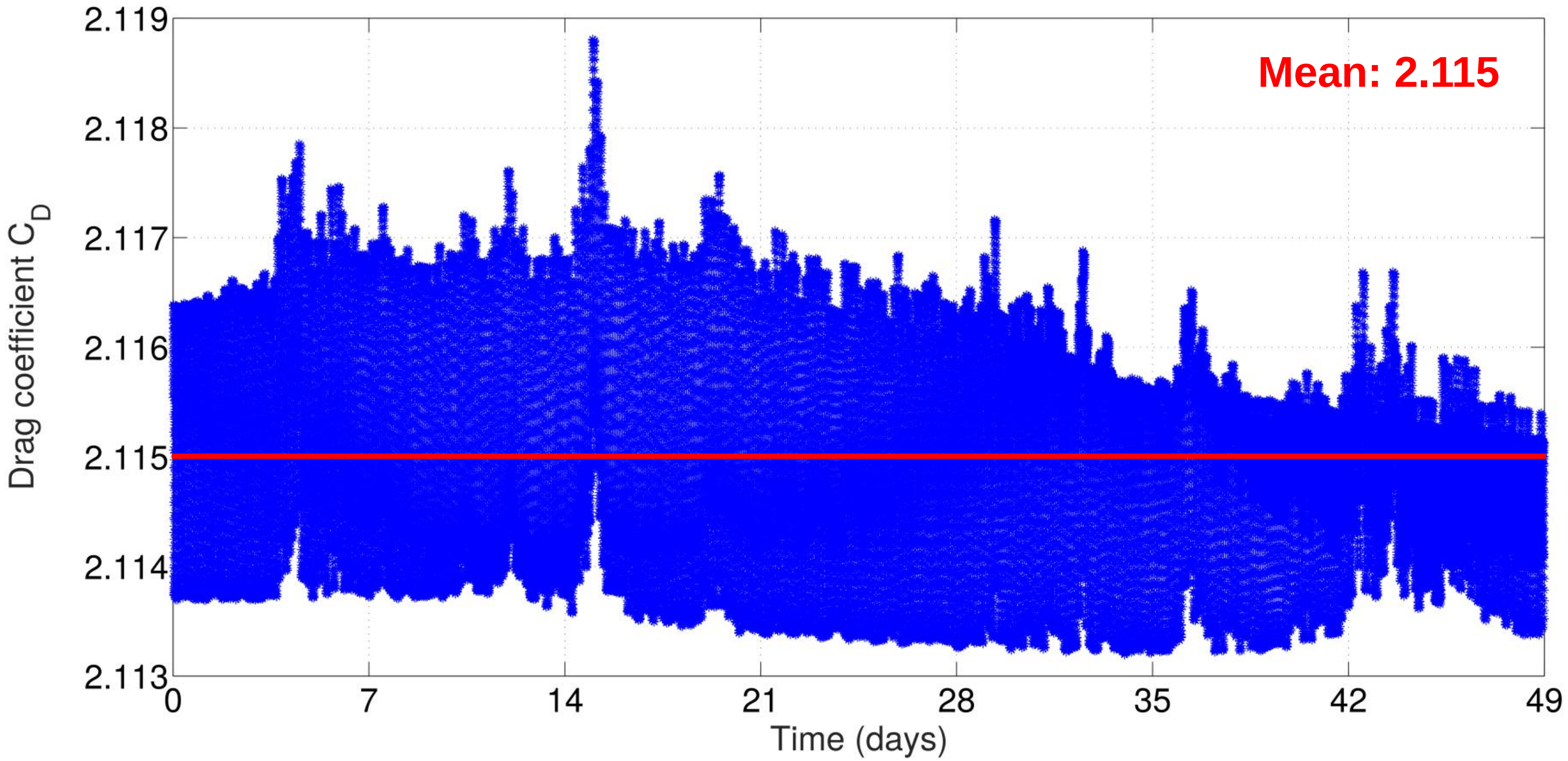


ANDE-Pollux observations

- Temporal distribution: 49 days from end of August to beginning of October 2009



Physically modeled C_D for ANDE-Pollux



- *From Nicholas* et al. (2007), we get $C_D = 2.1123 \pm 0.00763$ based on different assumptions and different thermospheric model (thermospheric temperature); comparable with the average value from above

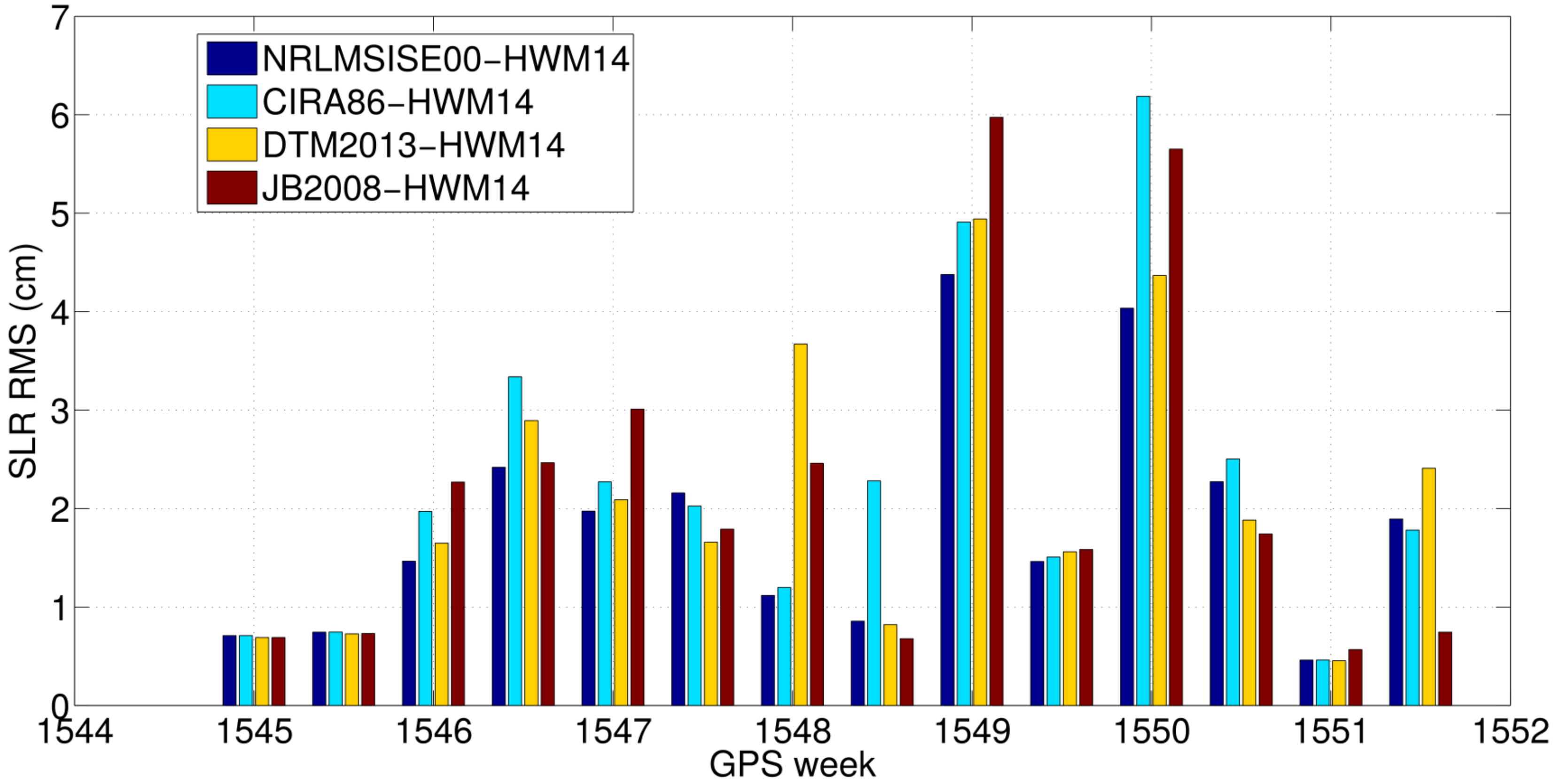
ANDE-Pollux solution setup

- General dynamic models: IERS Conventions 2010

Estimated parameters	Temporal resolution
Keplerian elements	One set per arc (initial epoch)
Solar radiation pressure coefficient	One per arc
Albedo coefficient	One per arc
Empirical coefficients (CPRs)	One set per arc (sin/cos; along-/cross-track)
Lagrange scaling coefficients	Four per day (6-hour resolution; along-tr.)

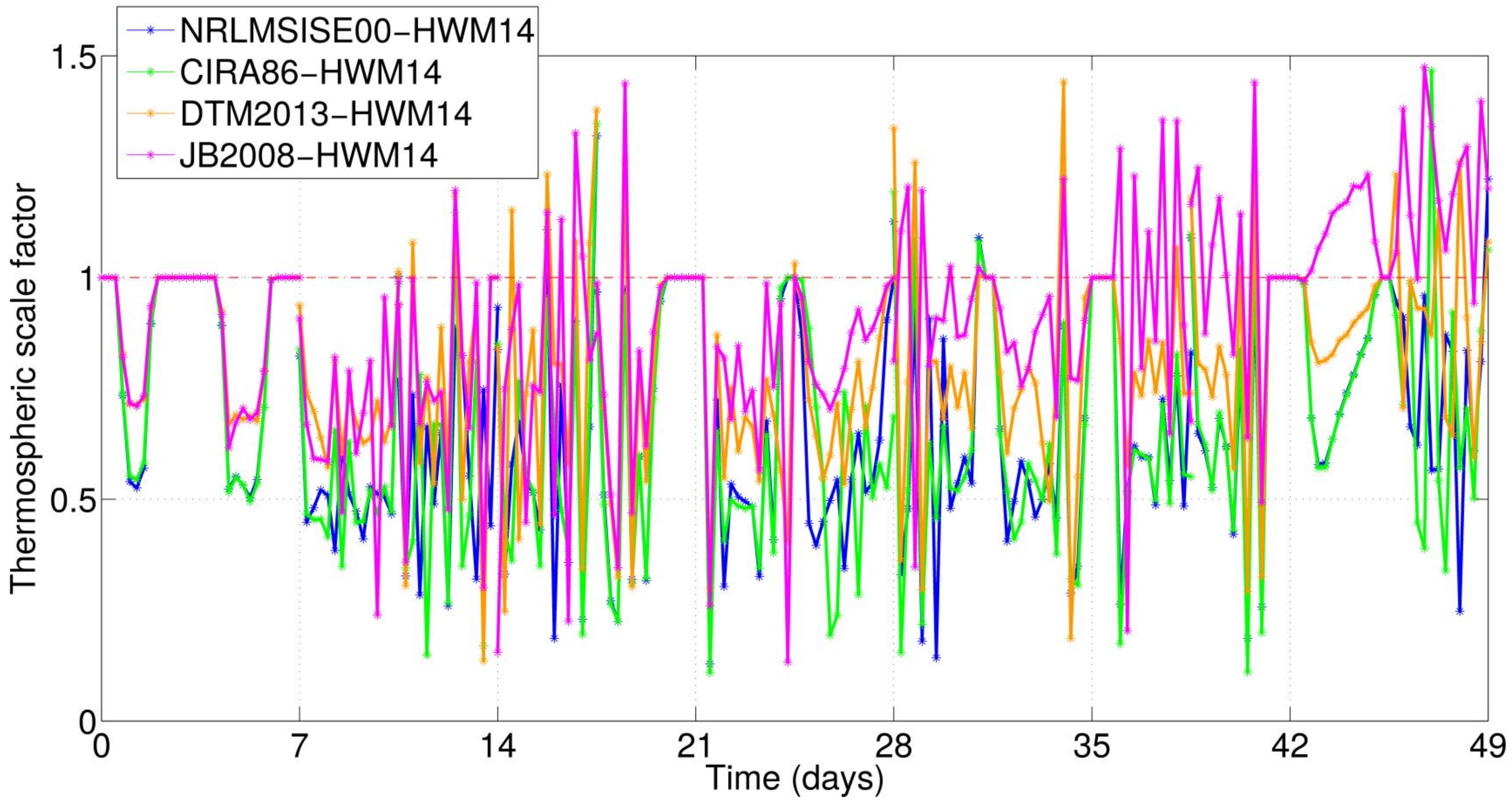
Integrated sensitivity on thermospheric models

- Impact of thermospheric models on SLR orbit computation (RMS of observation residuals)



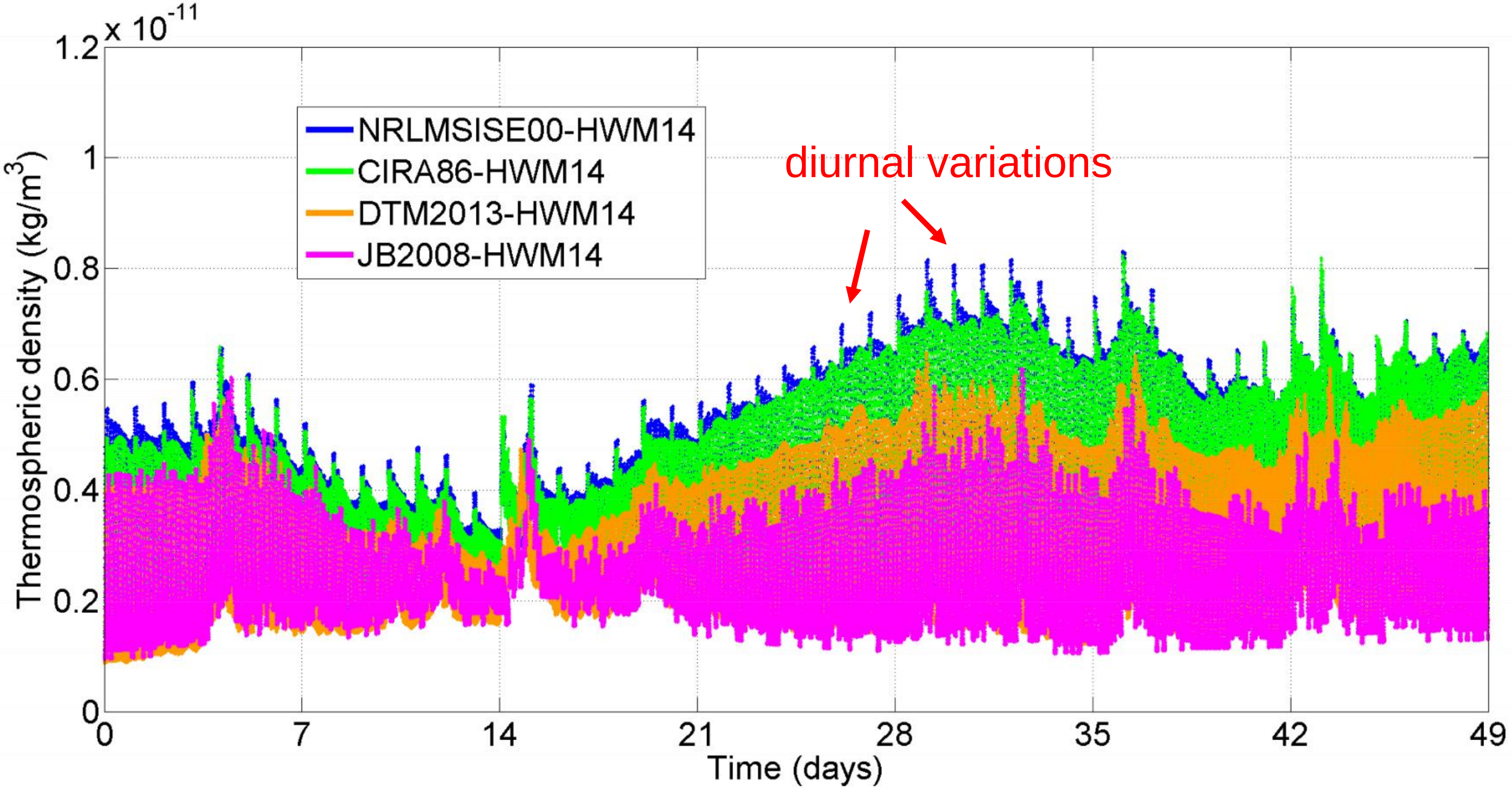
- Mostly low impact on orbit variance factors since estimated scaling coefficients compensate differences in thermospheric models
- Variance factors hard to compare since outlier detection is done separately for each solution setup

Estimated Lagrange scaling coefficients f_s



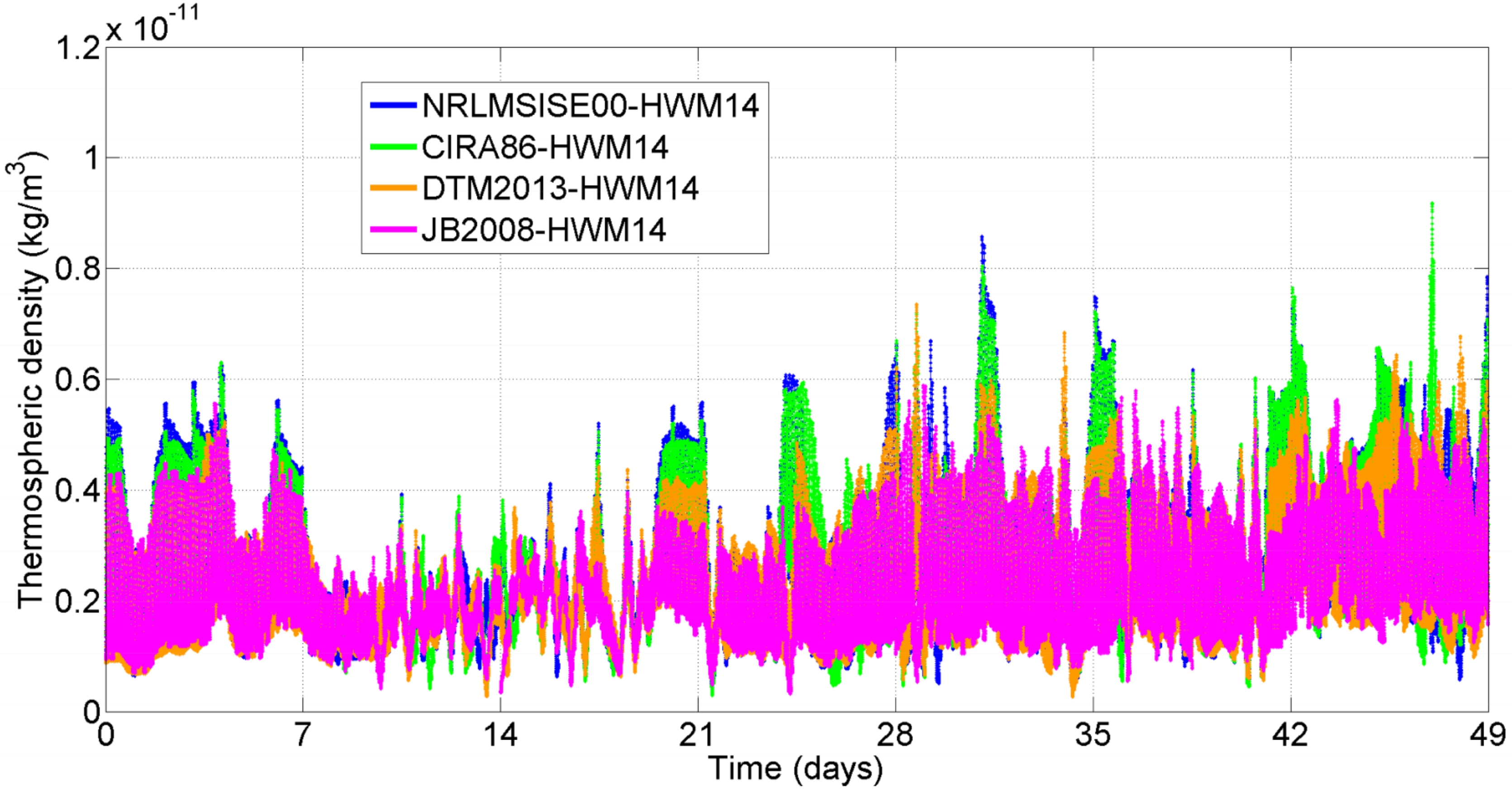
- If the scaling coefficient is equal to 1 no SLR observations were available
- NRLMSISE00 and CIRA86 agree very well; more recent models show offset (especially at the end of the time series)

Modeled thermospheric densities ρ



- JB2008 shows in general the lowest density distribution values
- Large offset of JB2008 w.r.t. CIRA86 and NRLMSISE00; smaller offset w.r.t DTM2013

Scaled thermospheric densities $f_s \cdot \rho$



- In general, CIRA86 and NRLMSISE00 are scaled to more recent models
- No offset change for JB2008 and DTM2013
- Density variations of JB2008 and DTM2013 are reduced

Summary

- Refined aerodynamic perturbation modeling in DGFI-TUM's POD software package allows us to estimate integrated absolute thermospheric densities by considering:
  - GSI-models of Schamberg and Sentman
  - thermospheric models CIRA86, NRLMSISE00, JB2008 and DTM2013
  - horizontal wind model HWM2014
  - estimation of Lagrange scaling factors in any temporal resolution (currently 6h)
- Setup of the software package for the processing of 49 days of ANDE-Pollux SLR observations to perform a sensitivity analysis to the thermospheric density variations
- SLR observations are sensitive to different thermospheric densities
- CIRA86 and NRLMSISE00 are scaled towards the more recent models JB2008 and DTM2013

Acknowledgement:
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Thanks for your attention