UNIVERSITY OF CHINESE ACADEMY OF SCIENCES
SHANGHAI ASTRONOMICAL OBSERVATORY

Thermospheric neutral density variations from LEO accelerometers and precise orbits

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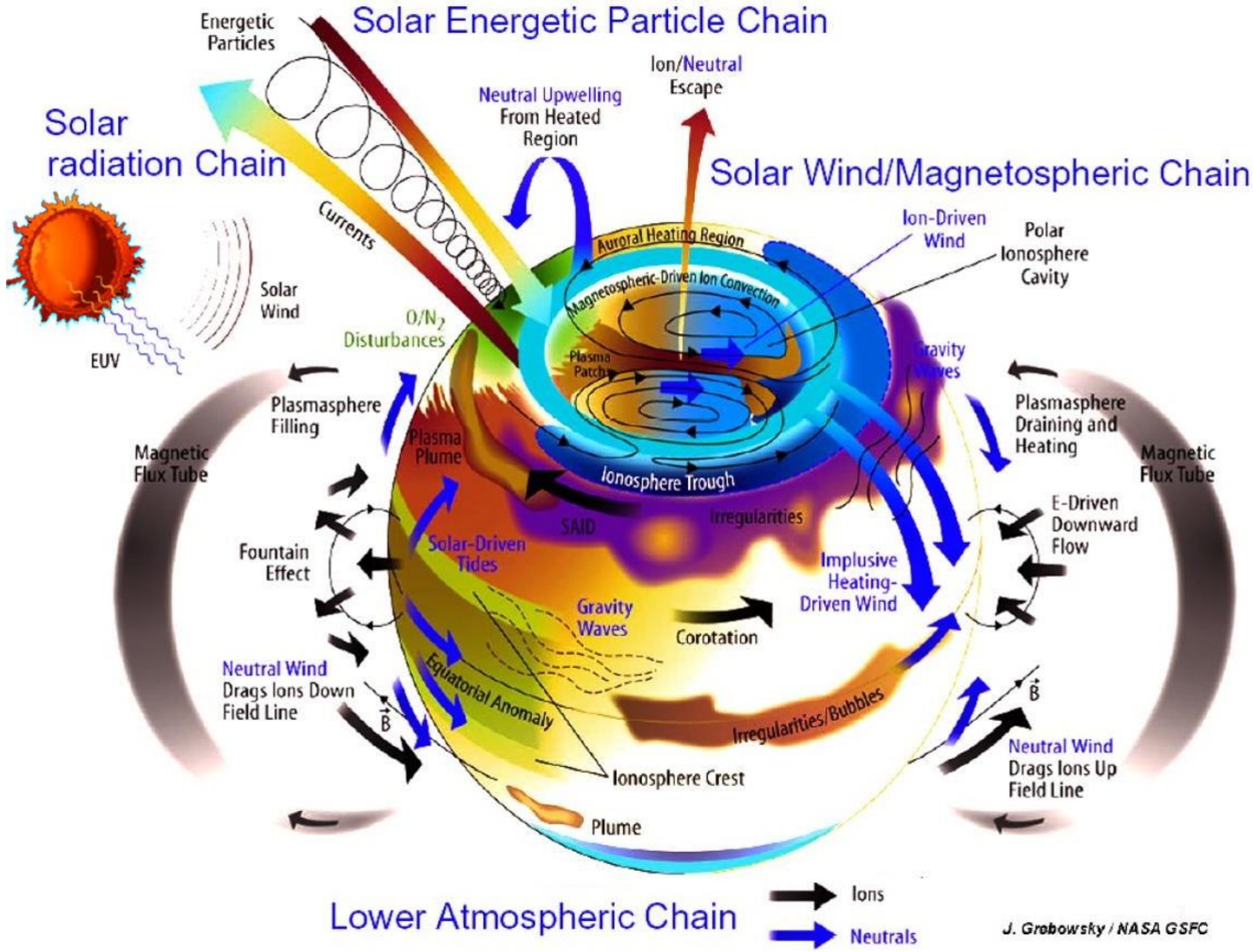
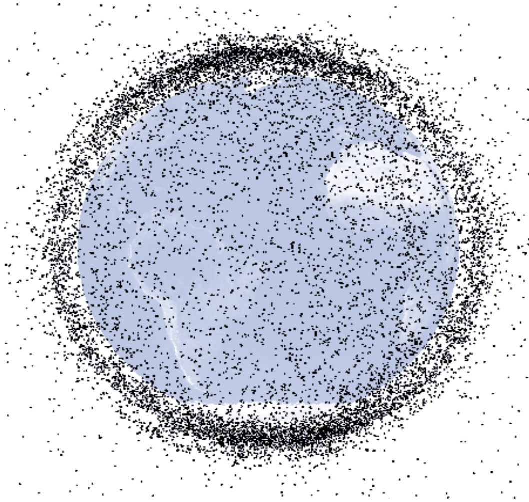
1. Introduction & Background

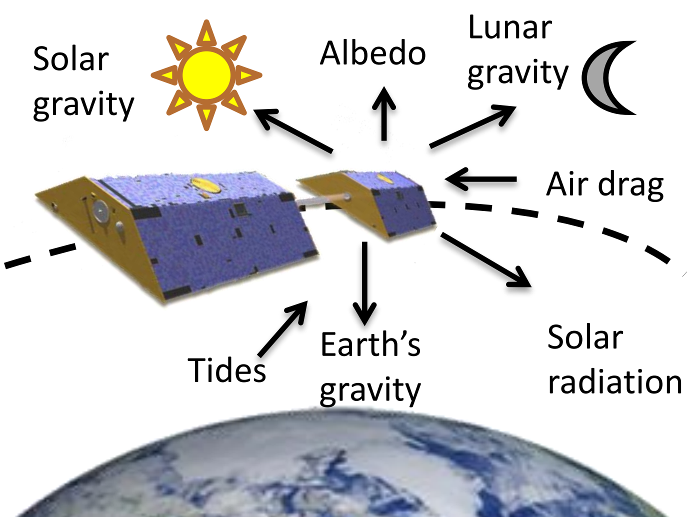
The thermosphere is highly ionized its geophysical processes are very complex due to the MIT coupling

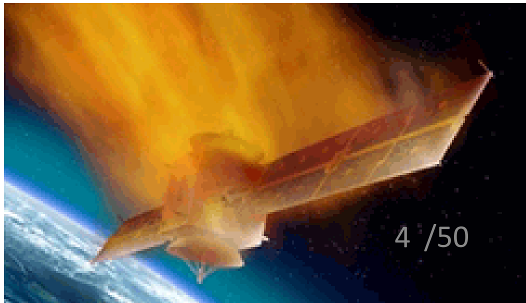


1. Introduction & Background

- Half of the world's active satellites (~1000) and about 20,000 inactive debris operate in LEO, where atmospheric drag produce orbital decay and perturbations.





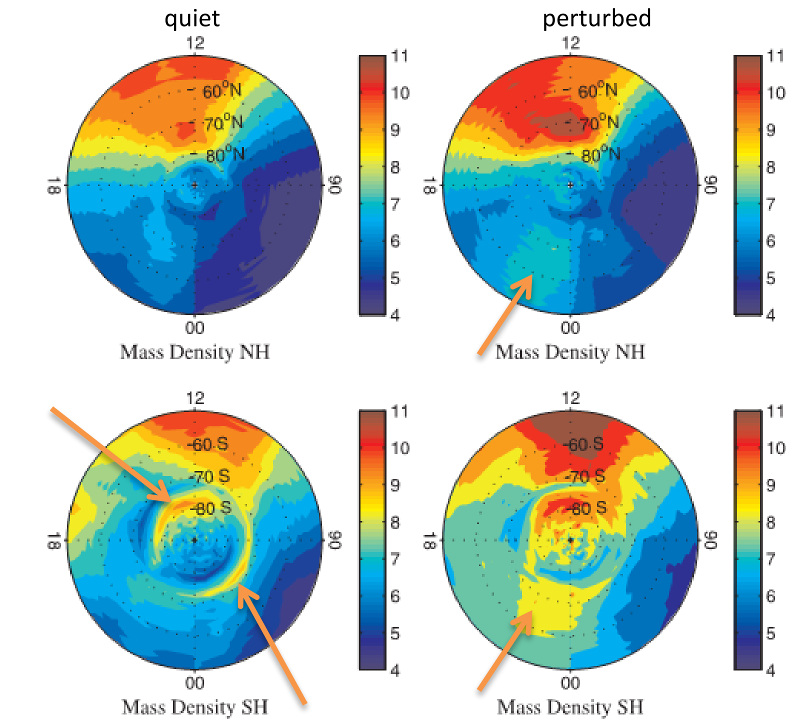


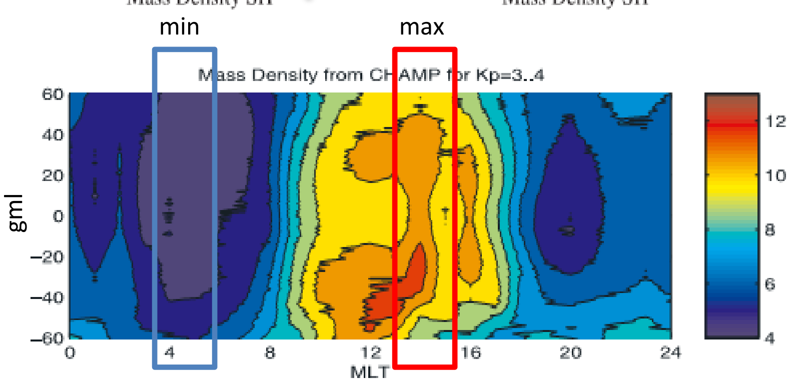
1. Introduction & Background

- **Thermospheric neutral density measurements and models are indispensable to study the MIT coupling and its physical processes.**
- **Accurate air-density models are essential for ephemeris prediction, orbital tracking and satellite guidance.**
- **Thermospheric neutral densities can be estimated from accelerometers and GNSS onboard LEO satellites.**

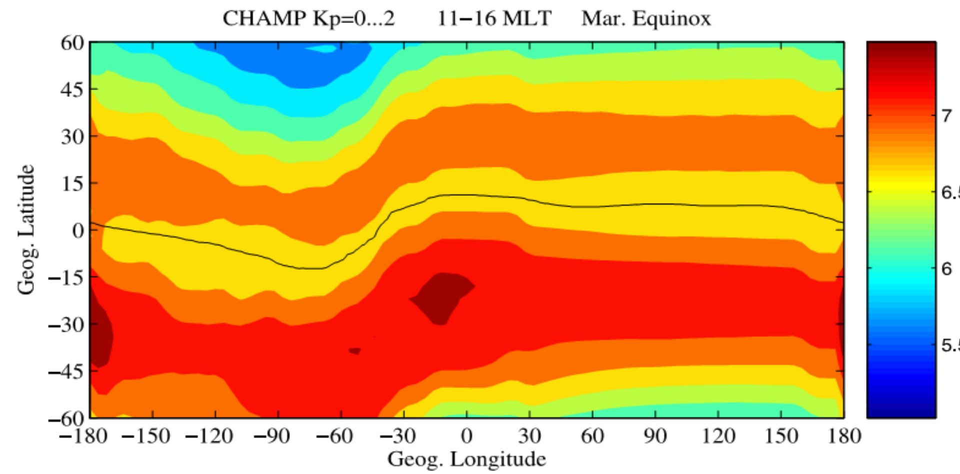
2. Progress, Problems & Motivation

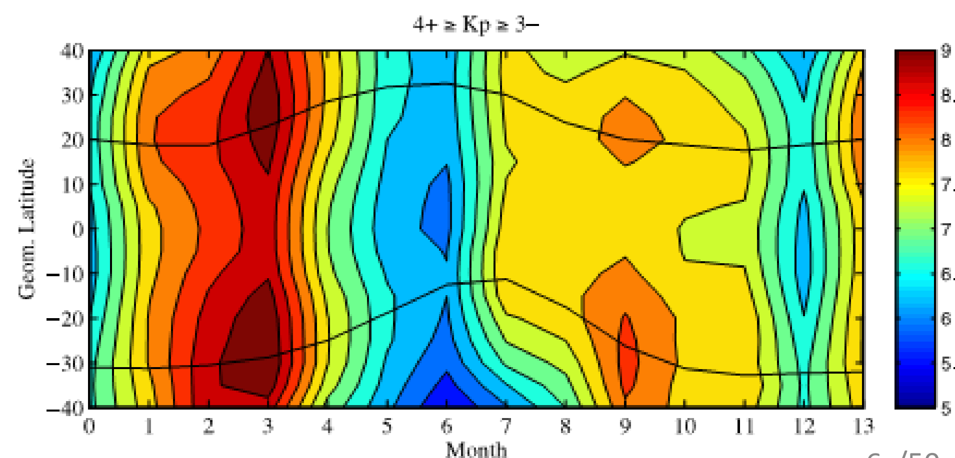
Global distribution of the thermospheric mass density





Equatorial mass anomaly (EMA)

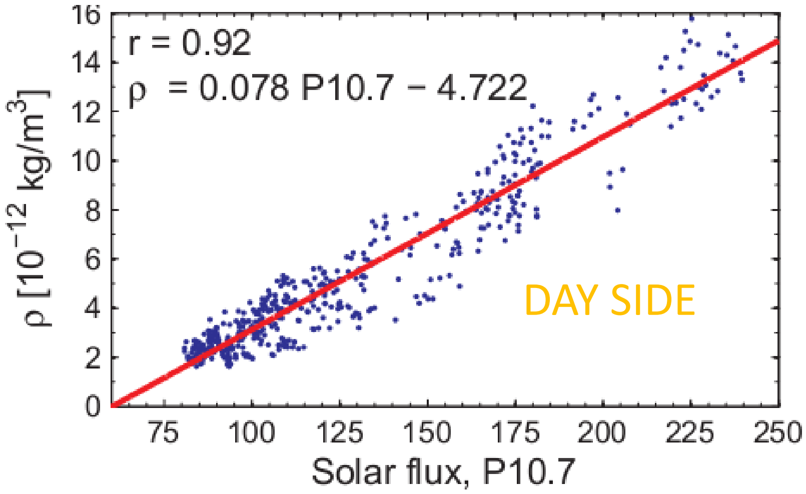


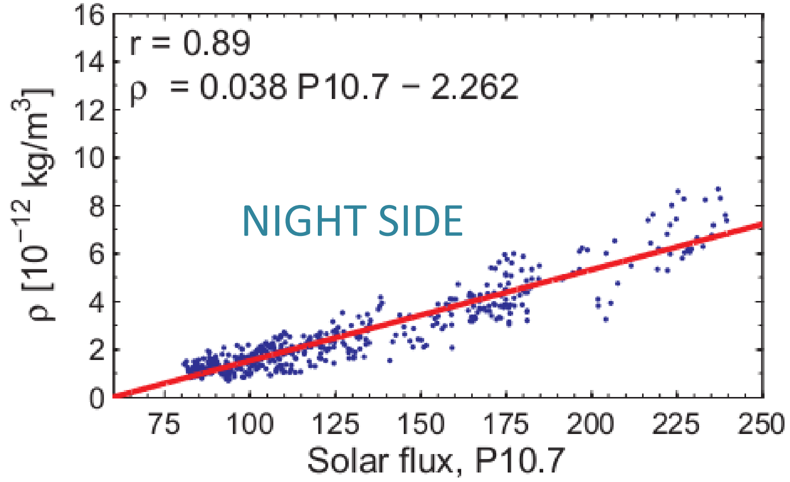


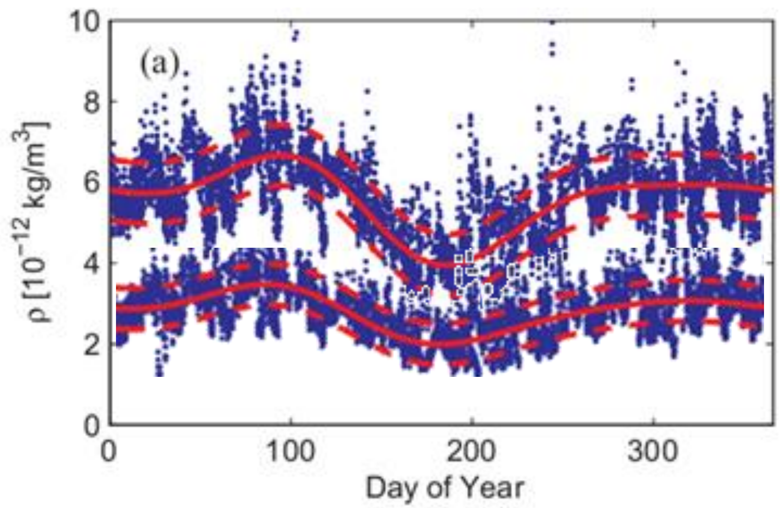
*Liu et al. (2005, 2007 and 2009)

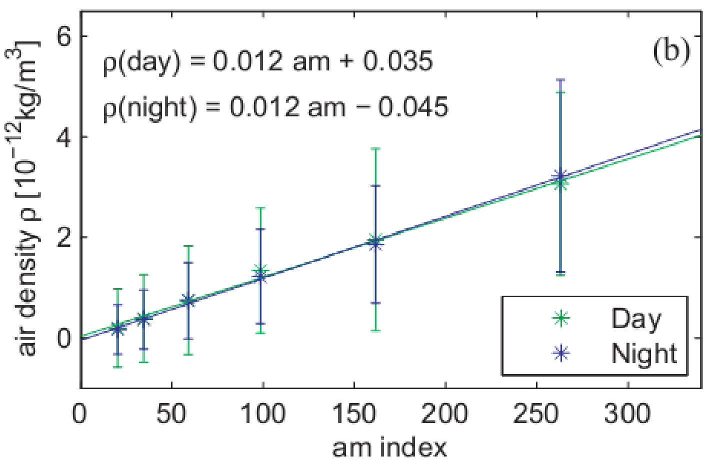
2. Progress, Problems & Motivation

Solar and magnetospheric forcing





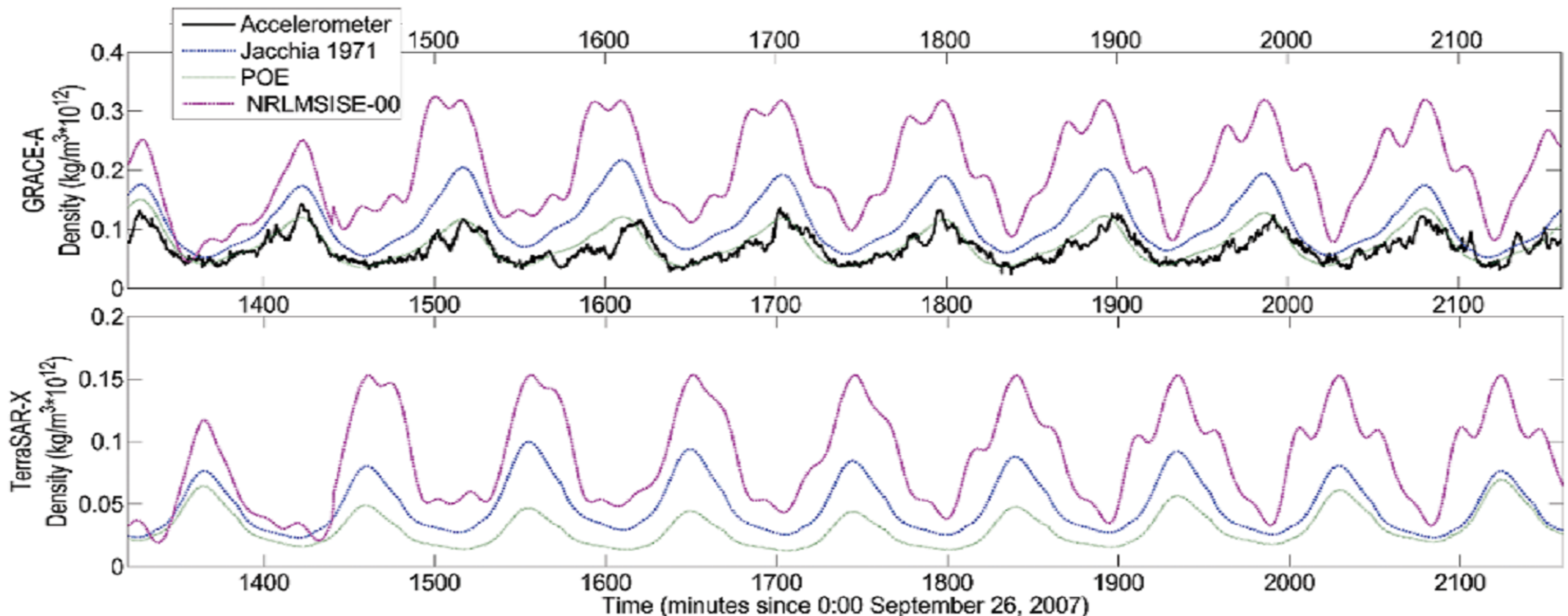




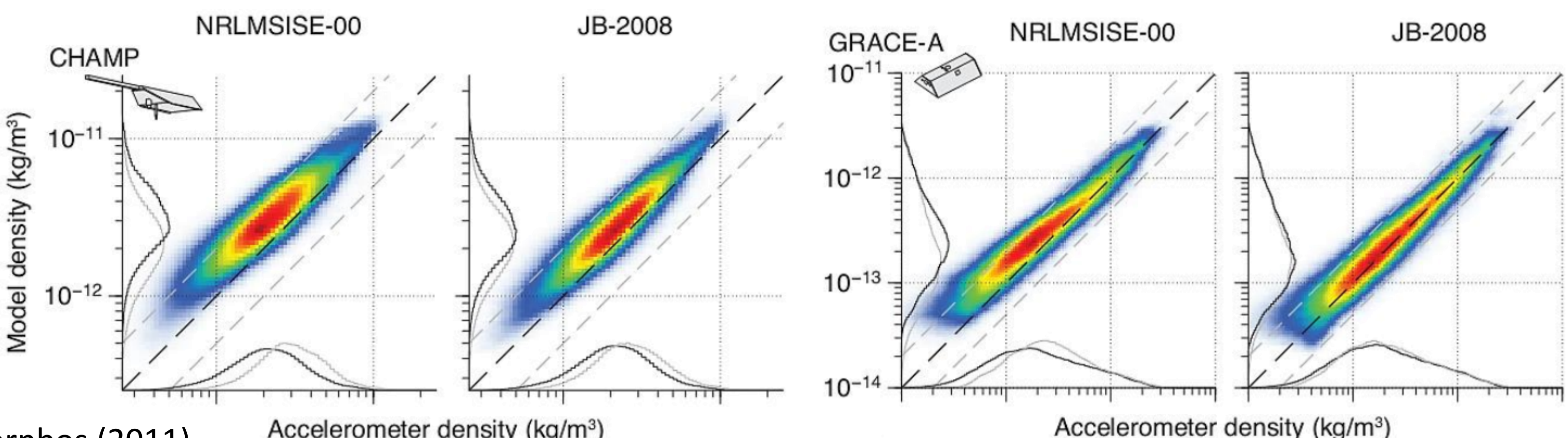
*Muller et al. (2009)

2. Progress, Problems & Motivation

Measurements & Empirical models

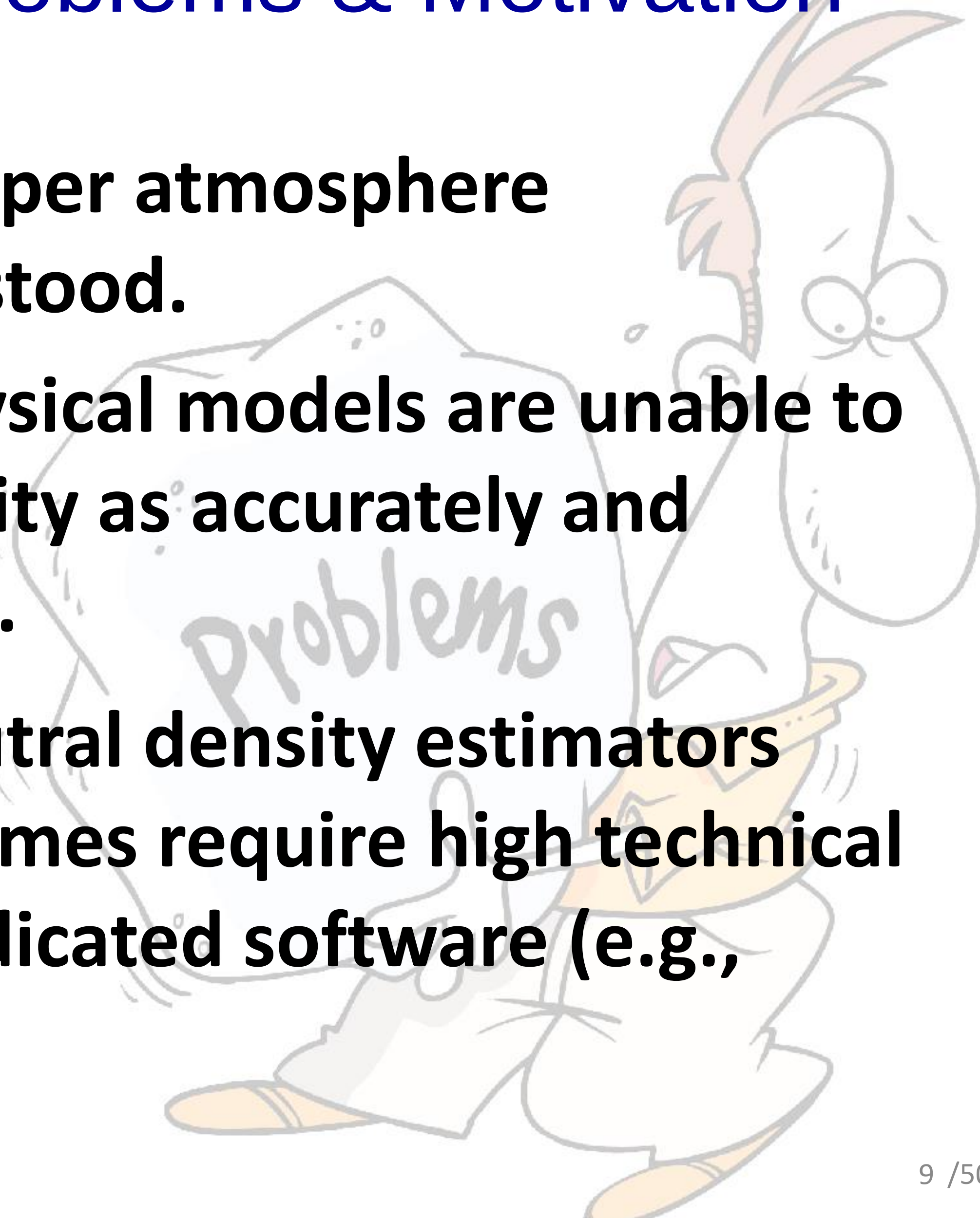


*McLaughlin et al. (2013)



*Doornbos (2011)

2. Progress, Problems & Motivation



- **Processes in the upper atmosphere are not well understood.**
- **The current geophysical models are unable to predict the variability as accurately and efficiently required.**
- **Thermospheric neutral density estimators based on POD schemes require high technical knowledge and dedicated software (e.g., GEODYN, ODTK).**

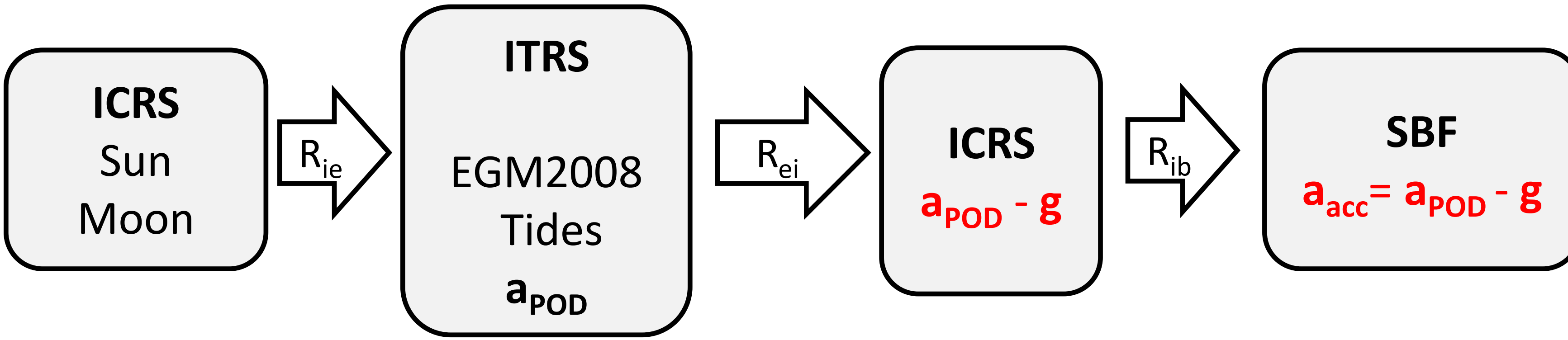
2. Progress, Problems & Motivation

- **A new technique based on numerical differentiation of POE is proposed for accelerometer calibration and density estimation.**
- **A new technique based in the PCA for the spatiotemporal analysis of satellite measurements along orbits is employed in 3 case-studies:**

  1. **Conservative-force anomalies from analytical TVG, POE, and accelerometer measurements.**
  2. **Differences between accelerometer-based densities and the NRLMSISE00 estimates (2003-2015).**
  3. **Thermospheric neutral density distribution and variations from GRACE (2003-2015).**

3. Methods & Data processing

Reference systems for accelerometer calibration



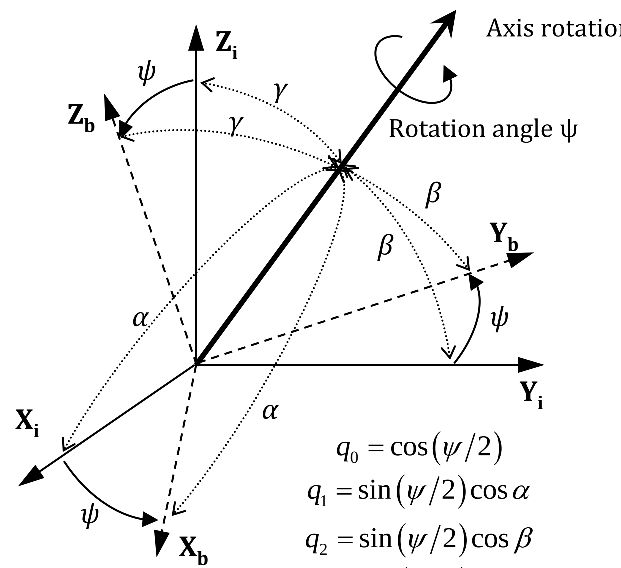
- R_{ei} rotation Earth-fixed to ICRS :

$$\boldsymbol{r}_{ICRS} = [P][N][S][PM]\dot{\boldsymbol{r}}_{ITRS}$$

$$\dot{\boldsymbol{r}}_{ICRS} = [P][N][S]\{[PM]\dot{\boldsymbol{r}}_{ITRS} + \boldsymbol{\omega}_{\oplus} \times [PM]\boldsymbol{r}_{ITRS}\}$$

- R_{ib} rotation ICRS to SBS by using star camera quaternion:

$$\mathbf{r}_{\mathbf{SBS}} = [\mathrm{R}_{\mathrm{ib}}]\mathbf{r}_{\mathbf{ICRS}} = \begin{bmatrix} q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2+q_0q_3) & 2(q_1q_3-q_0q_2) \\ 2(q_1q_2-q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3+q_0q_1) \\ 2(q_1q_3+q_0q_2) & 2(q_2q_3-q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2 \end{bmatrix}\mathbf{r}_{\mathbf{ICRS}}$$



$$q_0 = \cos(\psi/2)$$
$$q_1 = \sin(\psi/2)\cos\alpha$$
$$q_2 = \sin(\psi/2)\cos\beta$$
$$q_3 = \sin(\psi/2)\cos\gamma$$

3. Methods & Data processing

Drag force for density retrieval

- Drag-force formula:

$$F_D = ma_D = \frac{1}{2} C A \rho v_r^2$$

C Drag coefficient (Cook, 1965; Metha et. al, 2013)
A Cross-sectional area
ρ Atmospheric density
v_r Relative velocity of the atmosphere
m Satellite mass
a_D Aerodynamic acceleration

- Normalization to common altitude :

$$\rho(475km) = \rho_{obs}(h) \frac{\rho_{mod}(475km)}{\rho_{mod}(h)}$$

*Bruinsma et al. (2006)

3. Methods & Data processing

POE-based non-gravitational accelerations

$$\boldsymbol{a}_{ng} = \boldsymbol{a}_{acc} = \boldsymbol{a}_{POE} - \boldsymbol{g}$$

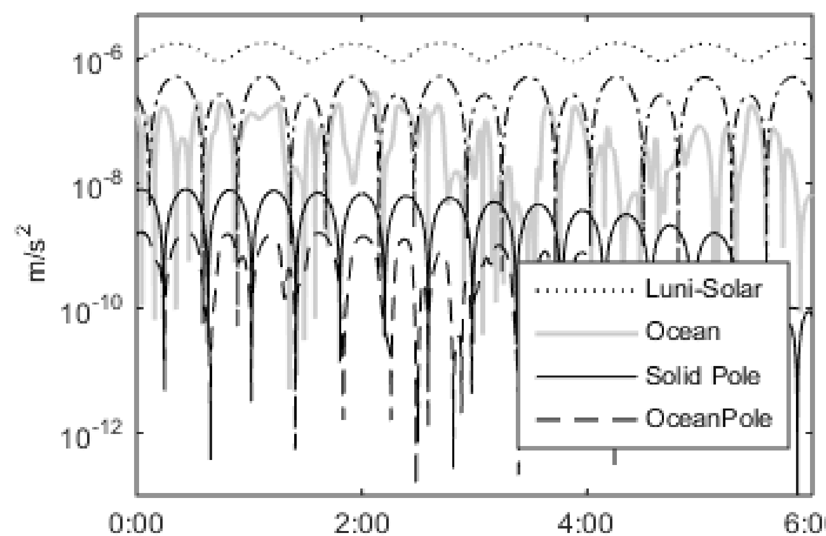
- First derivatives of precise-orbit velocities are numerically differentiated under arc-to-chord interpolation-threshold

$$\ddot{\boldsymbol{r}}_{t_0} = \lim_{\Delta t \to 0} \ddot{\boldsymbol{r}}''_{t_0} = \lim_{\Delta t \to 0} \frac{\dot{\boldsymbol{r}}'_{t_1} - \dot{\boldsymbol{r}}'_{t_{(-1)}}}{\Delta t} = \lim_{\Delta t \to 0} \frac{\boldsymbol{r}_{t_2} - 2\boldsymbol{r}_{t_0} + \boldsymbol{r}_{t_{(-2)}}}{(\Delta t)^2}$$

Interpolation threshold
And corresponding error

Δt (s)	Error (nm/s^2)
0.05	1
0.1	3
0.2	12
0.5	50
1	120
2	1500

- Varying gravity field model (**g**)
  - Conventional model EGM2008.
  - Secular low degree C_{20} (zero-tide),
  - C_{30} and C_{40} rates.
  - C_{21} and S_{21} mean pole coefficients.
  - Third body direct tides (Luni-solar).
  - Solid Earth tides.
  - Ocean tides (EOT11a).
  - Solid Earth pole tide.
  - Ocean pole tide.
  - Schwarzschild terms for relativity.



*Calabia and Jin (2015)

3. Methods & Data processing

Aerodynamic acceleration

Radiation-pressure removal:

Solar radiation

$$a_{sr} = \sum_{i=1}^{n_p} -\frac{E_{sr} A_i \hat{n}_i \hat{s}_{Sun}^{sat}}{mc}\left[2\left(\frac{c_{rd,i}}{3} + c_{rs,i} \hat{n}_i \hat{s}_{Sun}^{sat}\right)\hat{n}_i + \left(1 - c_{rs,i}\right)\hat{s}_{Sun}^{sat}\right]$$

Earth albedo

$$a_{ea} = \sum_{i=1}^{n_p}\sum_{j=1}^{grid} -\frac{E_{ea,j} A_i \hat{n}_i \hat{s}_j^{sat}}{mc}\left[2\left(\frac{c_{rd,i}}{3} + c_{rs,i} \hat{n}_i \hat{s}_j^{sat}\right)\hat{n}_i + \left(1 - c_{rs,i}\right)\hat{s}_j^{sat}\right]$$

$$E_{ea,j} = \mathrm{E}_{\mathrm{ea}}^{\mathrm{R}} + \mathrm{E}_{\mathrm{ea}}^{\mathrm{IR}}$$

$$\mathrm{E}_{\mathrm{ea,j}}^{\mathrm{R}} = f_j v_j E_{sr} \frac{A_j \left(\hat{n}_j \hat{s}_j^{Sun}\right)\left(\hat{n}_j \hat{s}_j^{sat}\right)\sigma_{\mathrm{TOMS}}}{\pi \left|\hat{s}_j^{sat}\right|^2}$$

$$\mathrm{E}_{\mathrm{ea,j}}^{\mathrm{IR}} = f_j 239 \left(\frac{1\mathrm{AU}}{s_{Sun}^{j}}\right)^2 e_{IR,j} \frac{A_j \hat{n}_j \hat{s}_j^{sat}}{\pi \left|\hat{s}_j^{sat}\right|^2}$$

$$\boldsymbol{a_D} = \boldsymbol{a_{ng}} - \boldsymbol{a_{sr}} - \boldsymbol{a_{ea}}$$

*Luthcke et *al*. (1997)

3. Methods & Data processing

Reference systems in density retrieval

ENU Winds $\xrightarrow{R_{le}}$ **ITRS** Velocity $\xrightarrow{R_{ei}}$ **ICRS** Co-rotating atmosphere $\xrightarrow{R_{ib}}$ **SBF** Relative velocity & Effective cross-section area

R_{ei} rotation Earth-fixed to ICRS :

$$\dot{\boldsymbol{r}}_{ICRS} = [\boldsymbol{PREC}][\boldsymbol{NUT}][\boldsymbol{ST}]\{[\boldsymbol{PM}]\dot{\boldsymbol{r}}_{ITRS} + \boldsymbol{\omega}_{\oplus} \times \boldsymbol{r}_{ITRS}\}$$

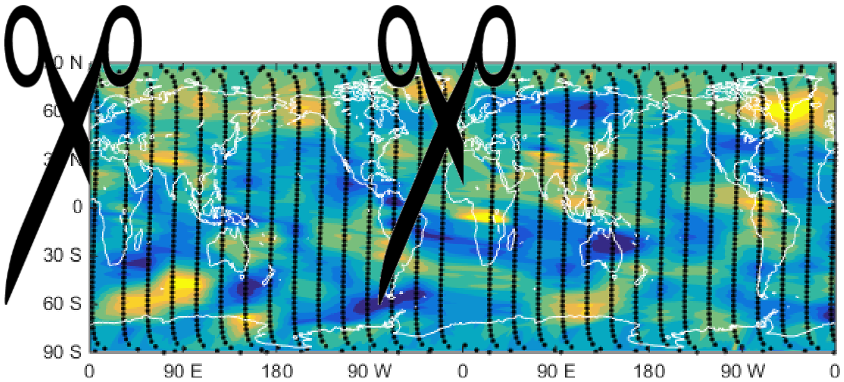
R_{ib} rotation ICRS to SBS by using star camera quaternion.
Relative velocity of the atmosphere with respect to the spacecraft

$$\mathbf{v_r} = -\dot{\mathbf{r}} + \mathbf{v_{r,c}} + \mathbf{v_{r,w}}$$

Horizontal winds from HWM07 and the co-rotating atmosphere:

$$\mathbf{v_{r,c}} = \boldsymbol{\omega}_{\oplus} \times \mathbf{r} = \mathrm{R_{ei}}[0, 0, 0.7292115 \cdot 10^{-4}\mathrm{sec}]^{\mathrm{T}} \times \mathbf{r}$$

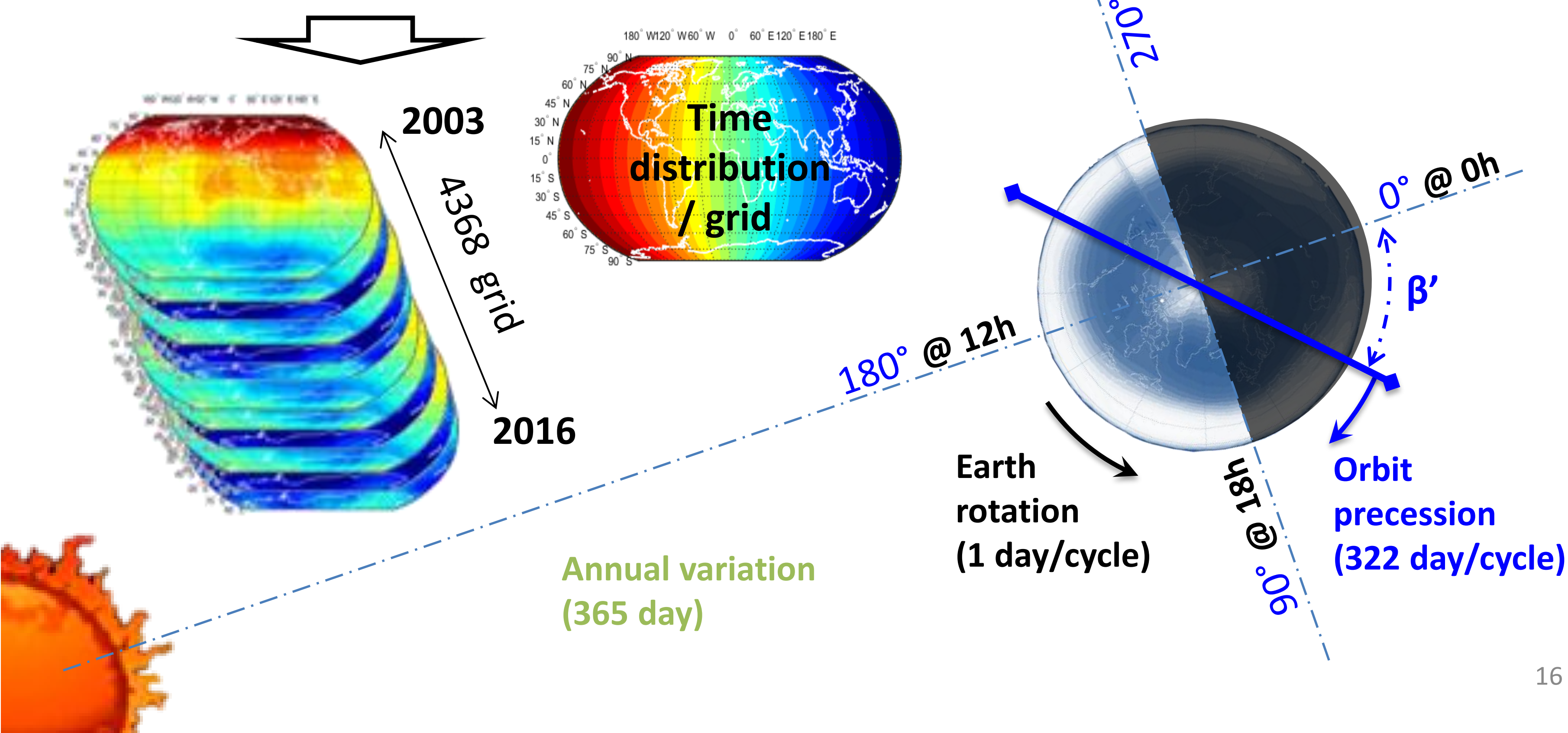
3. Methods & Data processing



1st Density along orbit

2nd Data interpolation

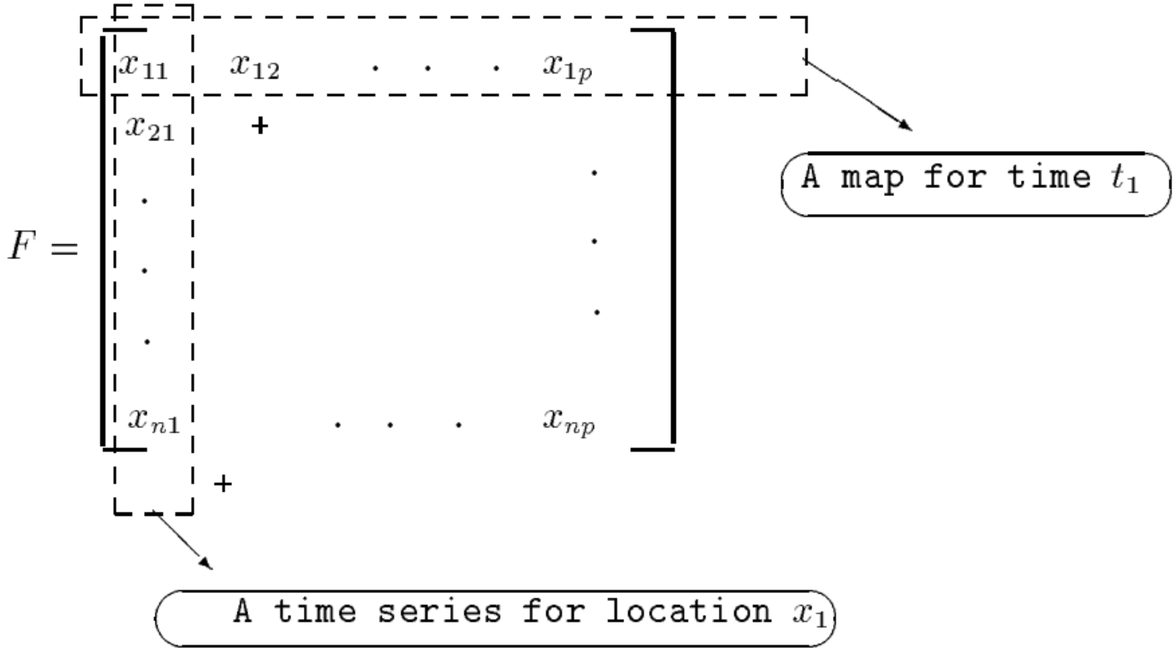
3rd Grid clipping



3. Methods & Data processing

Principal Component Analysis (PCA)

4th Arrange each grid in a column.



5th Find the covariance matrix.

6th Find eigenvalues (time-coefficients) & eigenvectors (maps).

3. Methods & Data processing

Parameterization of time-expansion coefficients

7th Normalization to common flux (Muller et al. 2009):

$$\rho(P10.7=110)=\rho\frac{Fa(P10.7=110)}{Fa(P10.7)}$$

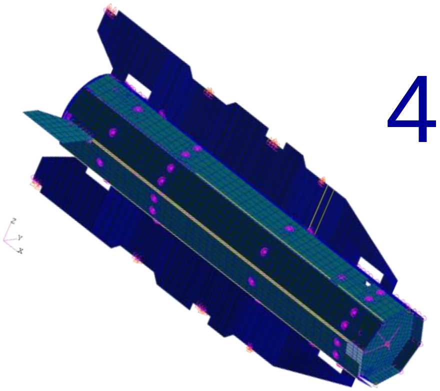
8th Fourier least-squares fitting:

$$\sum_{i=1}^{n}\left[an\cdot cos(n\cdot\chi\cdot w)+bn\cdot sin(n\cdot\chi\cdot w)\right]$$

9th Polynomial fitting modulates the amplitude of the sinusoidal function computed in previous step:

$$G(\chi,P107)=10^{-15}\cdot 10^{a}\cdot P107^{b}\cdot\left(a0+\sum_{i=1}^{n}\left[an\cdot cos(n\cdot\chi\cdot w)+bn\cdot sin(n\cdot\chi\cdot w)\right]\right)$$

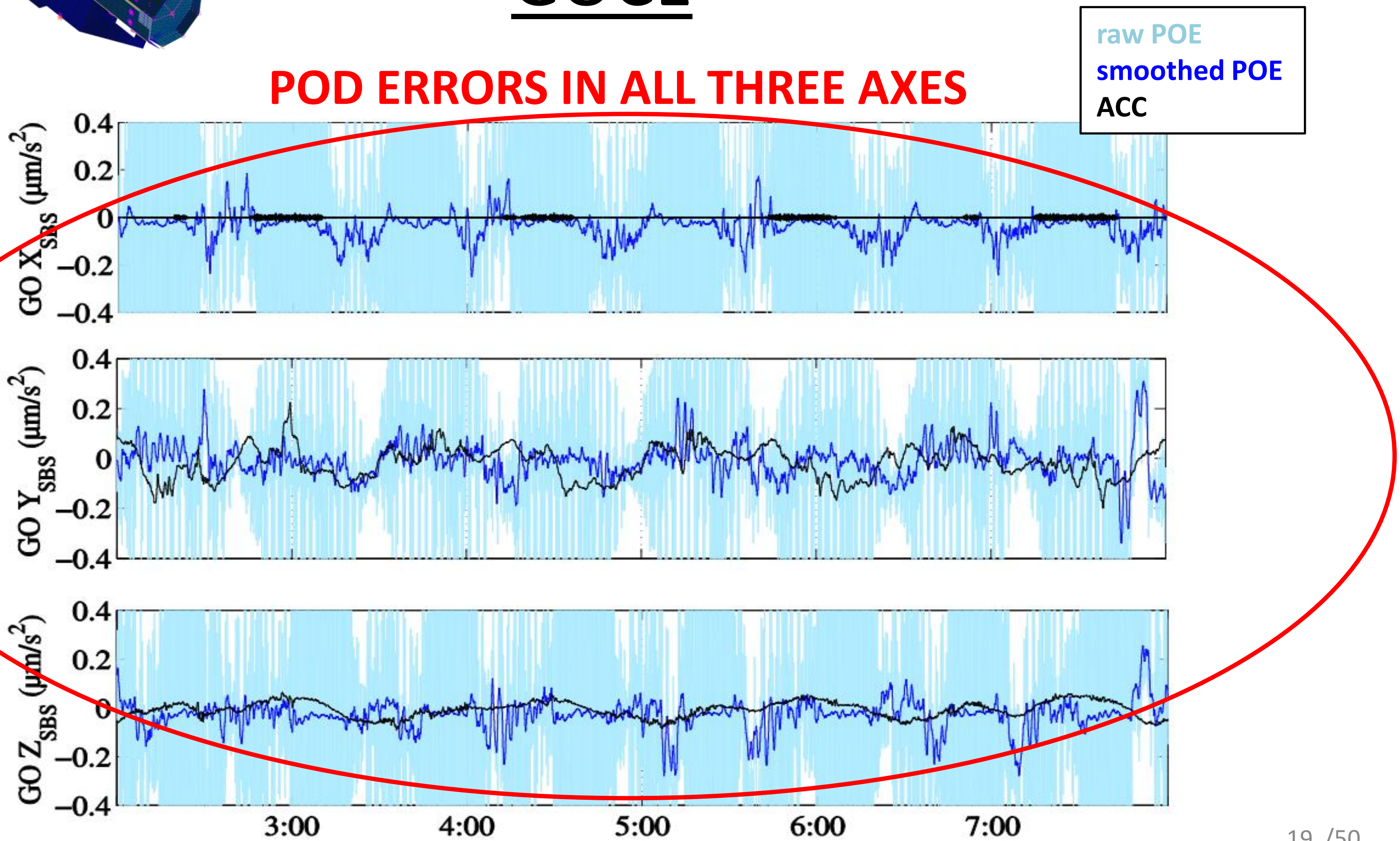
* a, b, a0, an, bn and w are the constant and amplitudes, and χ = (doy, β').



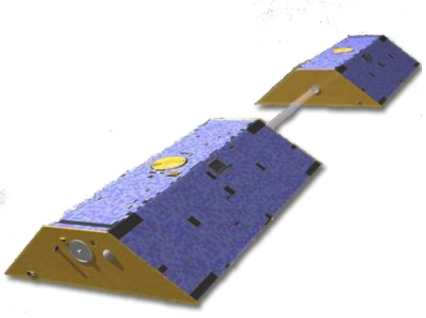
4.1. Results: POE vs ACC

Smoothing and error removal

GOCE



*Calabia and Jin, 2016a

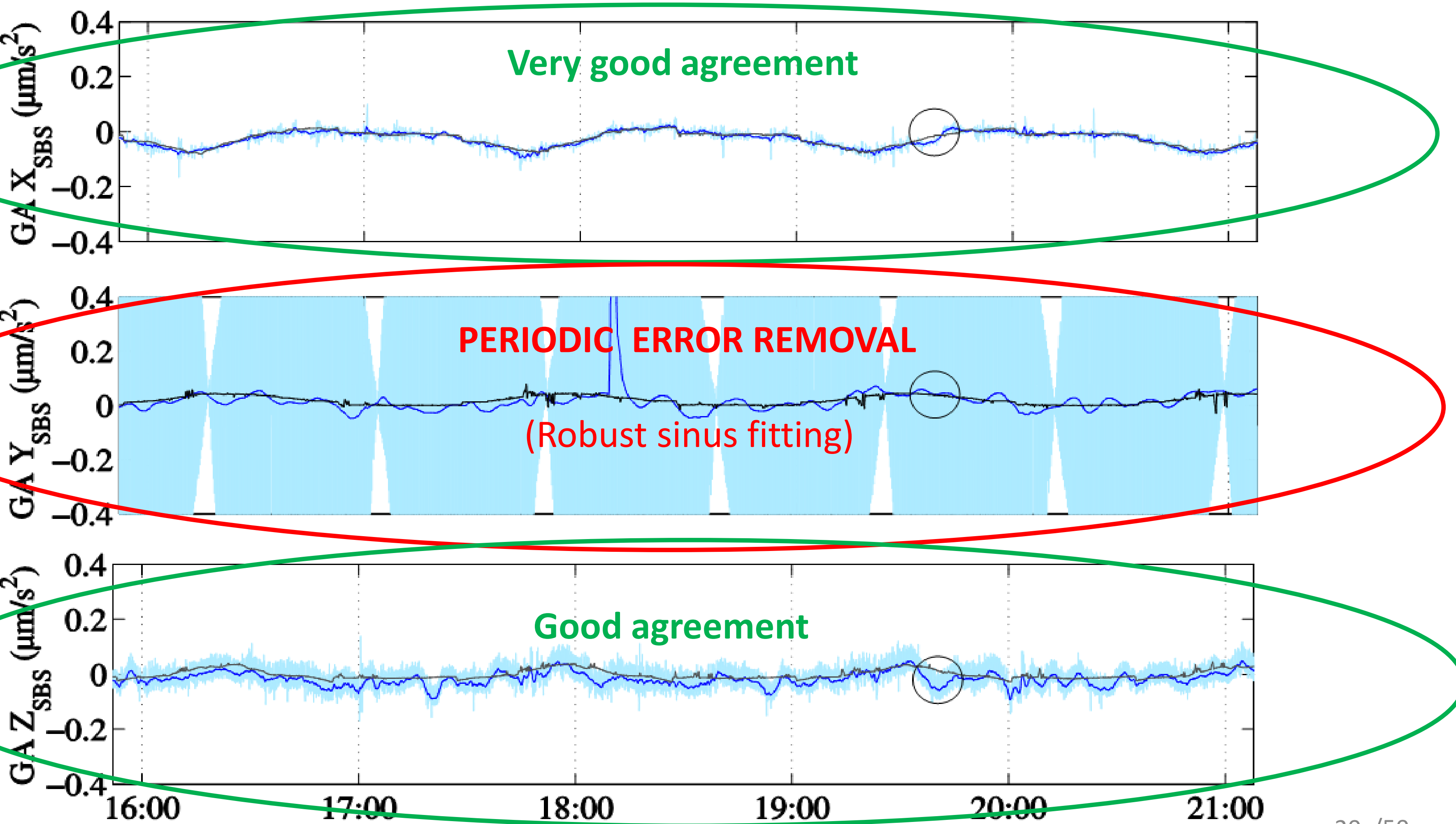


4.1. Results: POE vs ACC

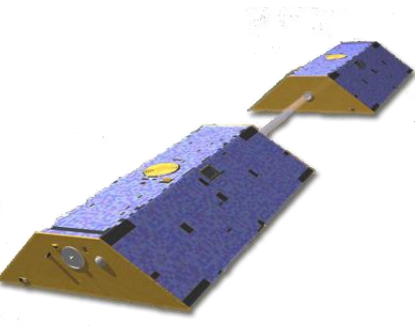
Smoothing and error removal

GRACE

raw POE
smoothed POE
ACC



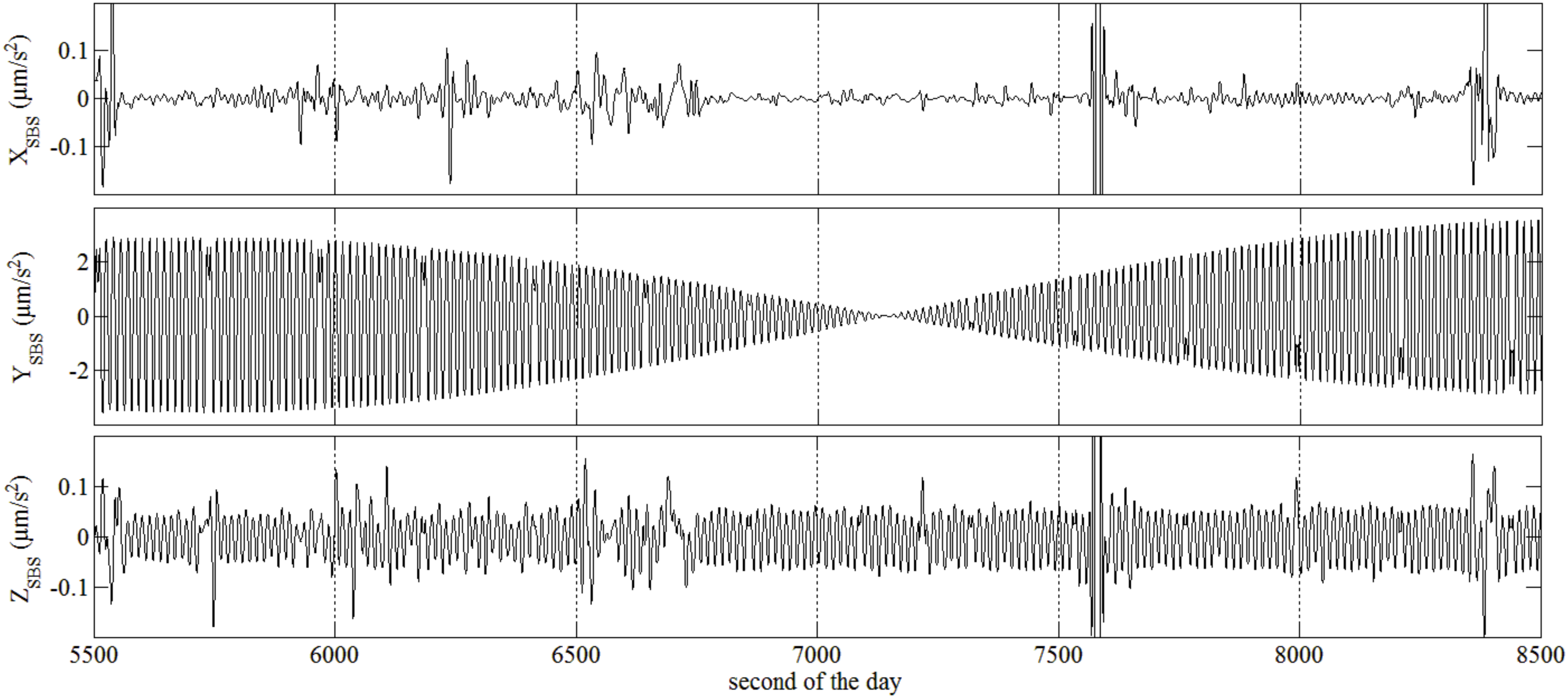
*Calabia and Jin, 2016a



4.1. Results: POE vs ACC

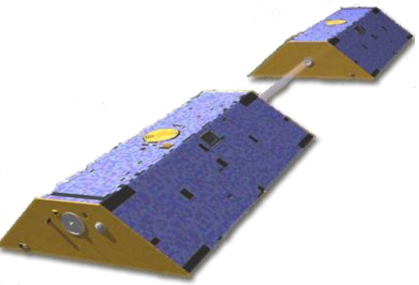
Assessment of POD and force models

GRACE



Residuals after smoothing the solution and removing the systematic error on axis Y_{SBS}

*Calabia et al, 2015



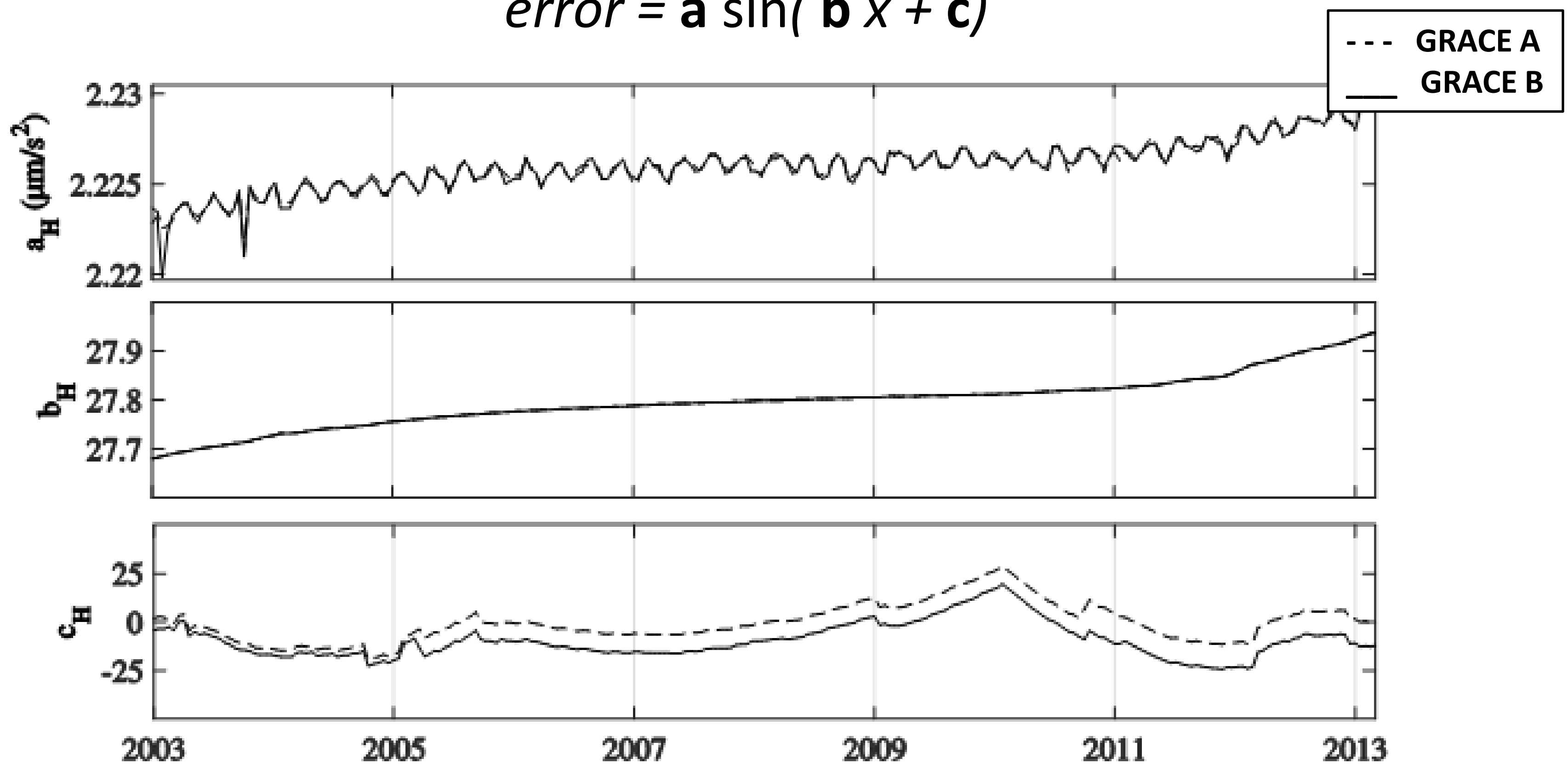
4.1. Results: POE vs ACC

Assessment of POD and force models

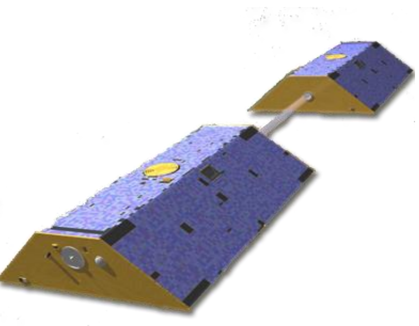
GRACE

Fitted parameters for Y_{SBS} error:

$$error = \mathbf{a}\sin(\mathbf{b}\,x + \mathbf{c})$$



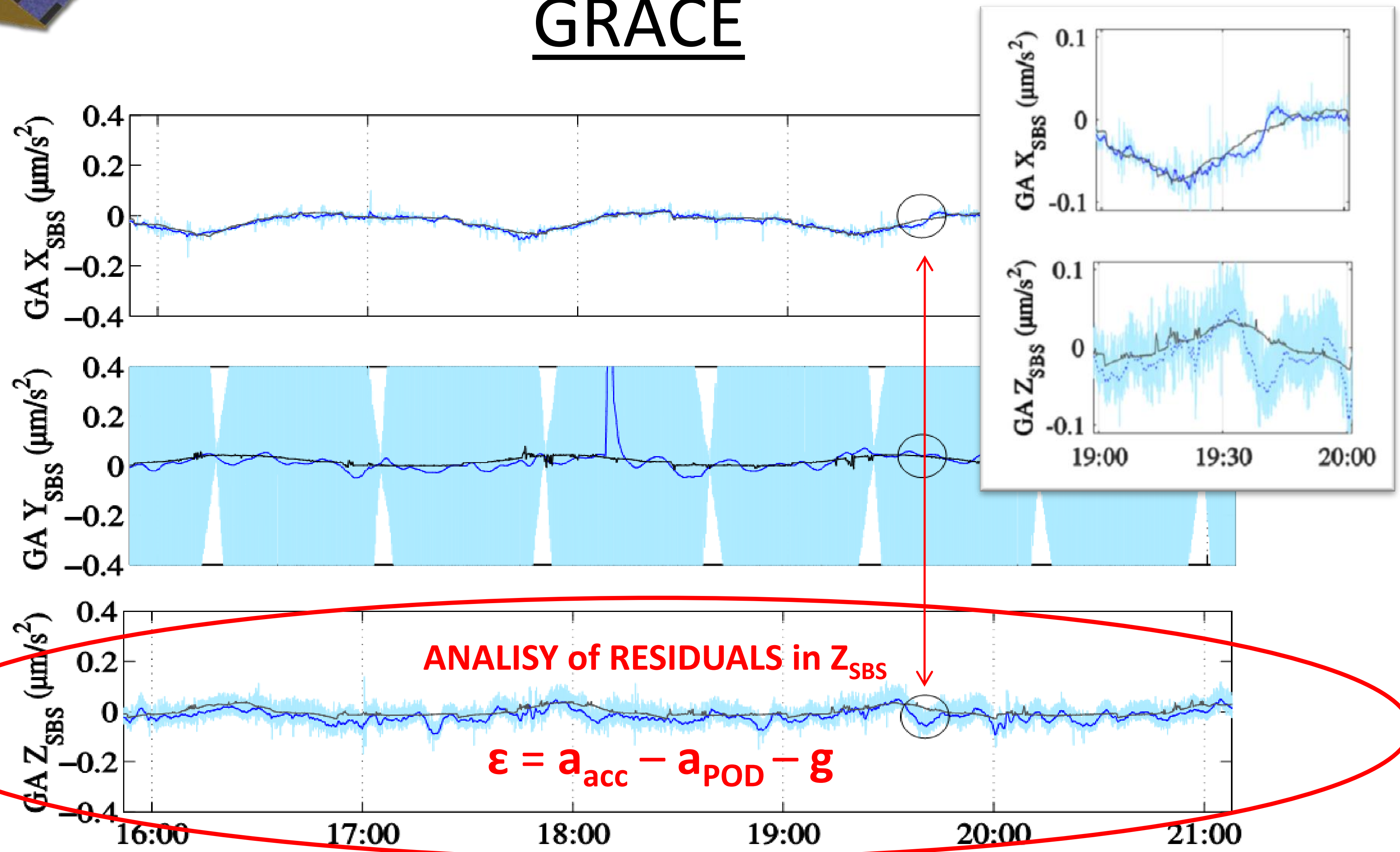
*Calabia et al, 2015



4.1. Results: POE vs ACC

Assessment of POD and force models

GRACE



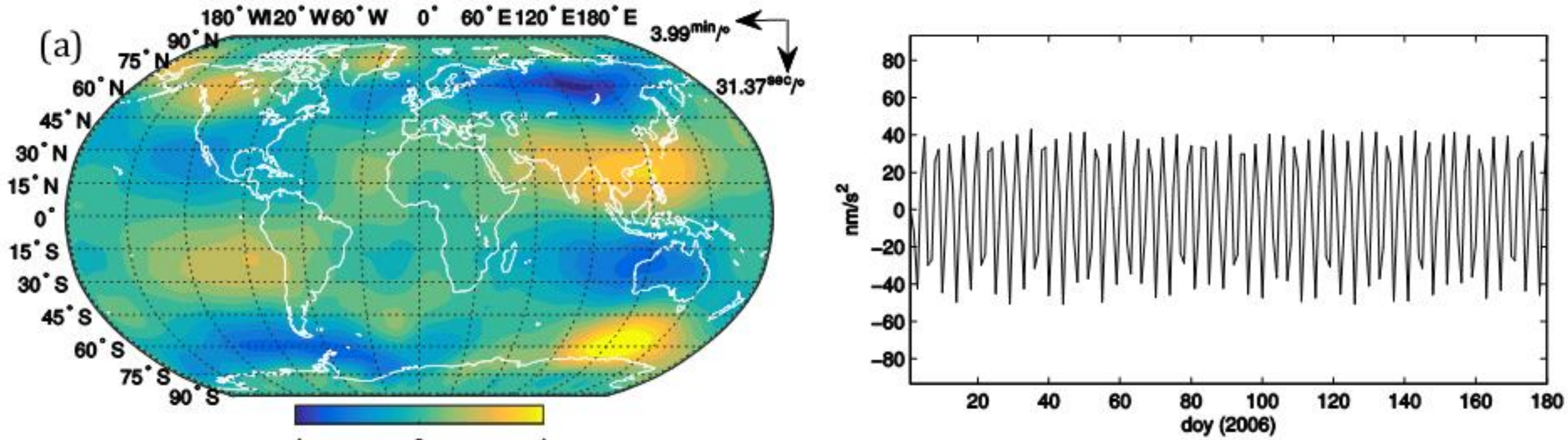
*Calabia and Jin, 2016a

4.1. Results: POE vs ACC

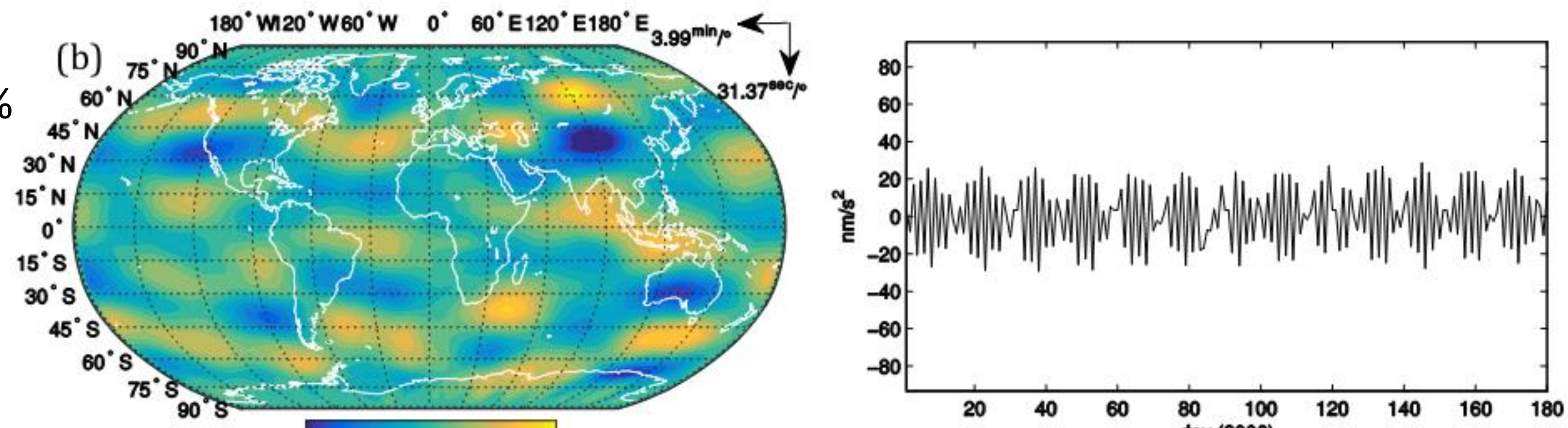
Assessment of POD and force models with PCA

Structures at the sub-daily frequency probably related to atmospheric tides.

~25%



~10%



*Calabia and Jin, 2016a

4.1. Results: POE vs ACC

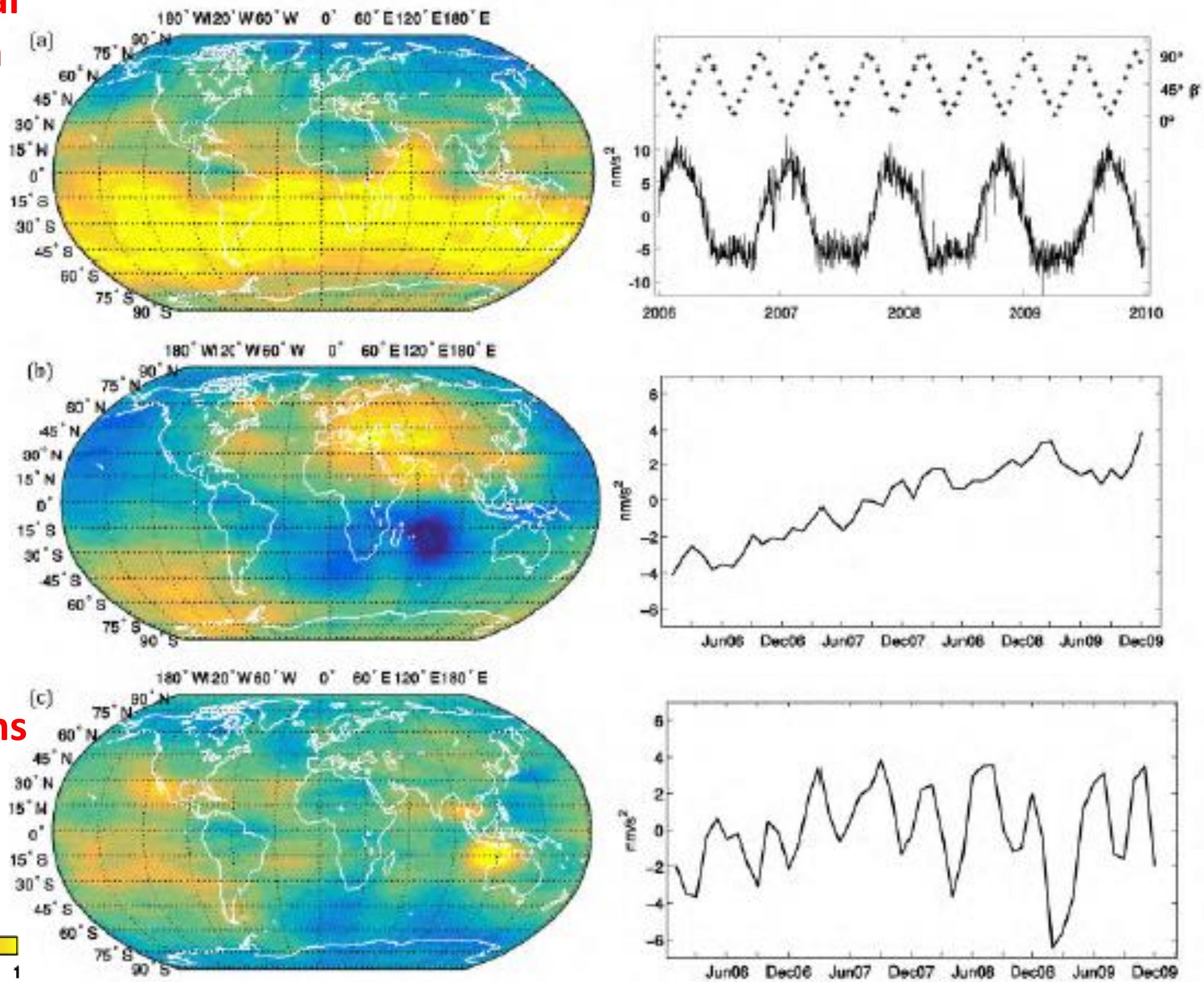
Assessment of POD and force models with PCA

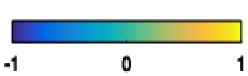
Latitudinal variation

~5%

Trend

Local variations



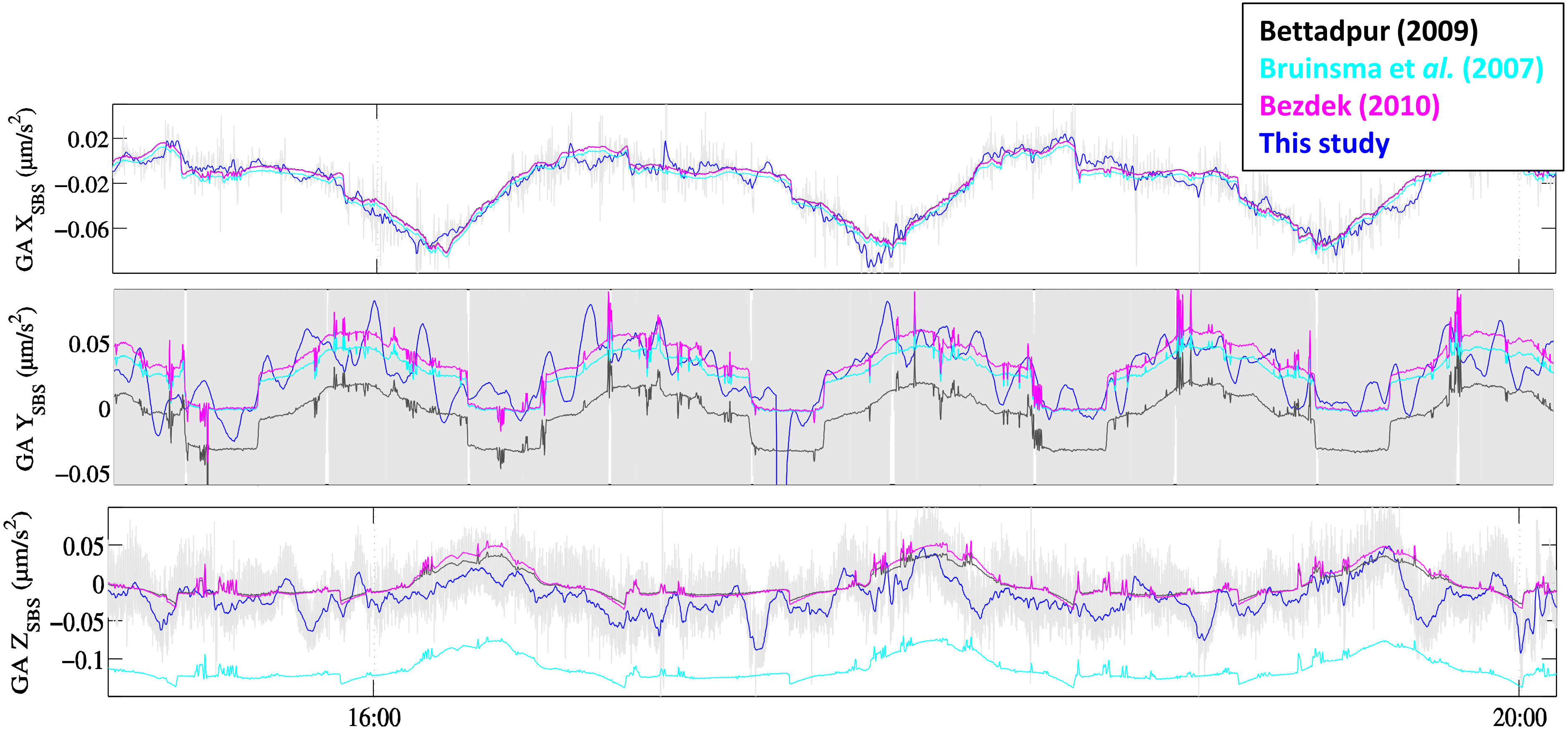


null at β'=±90°

*Calabia and Jin, 2016a

4.1. Results: POE vs ACC

Accelerometer calibration

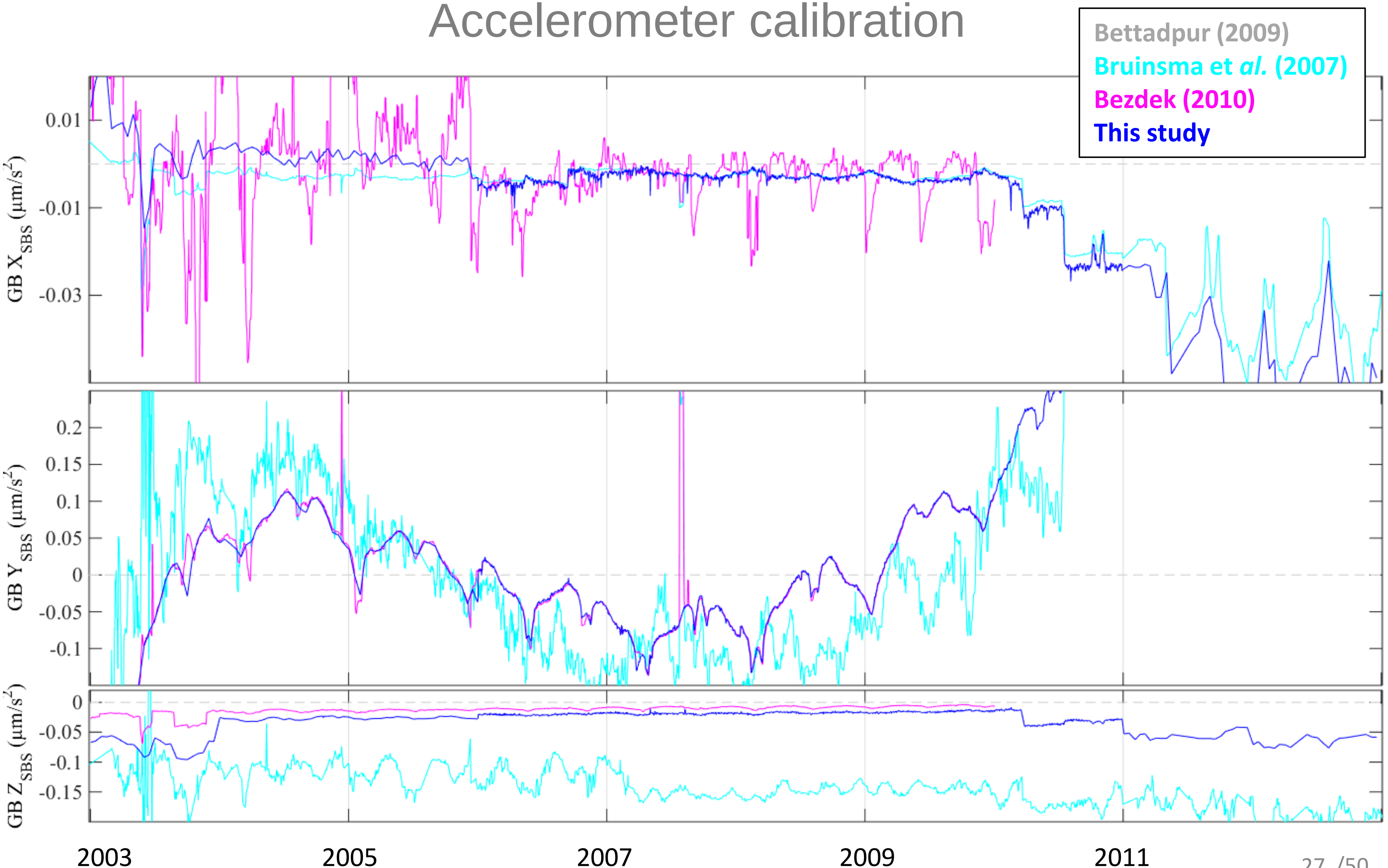


July 15th 2006

*Calabia et al, 2015

4.1. Results: POE vs ACC

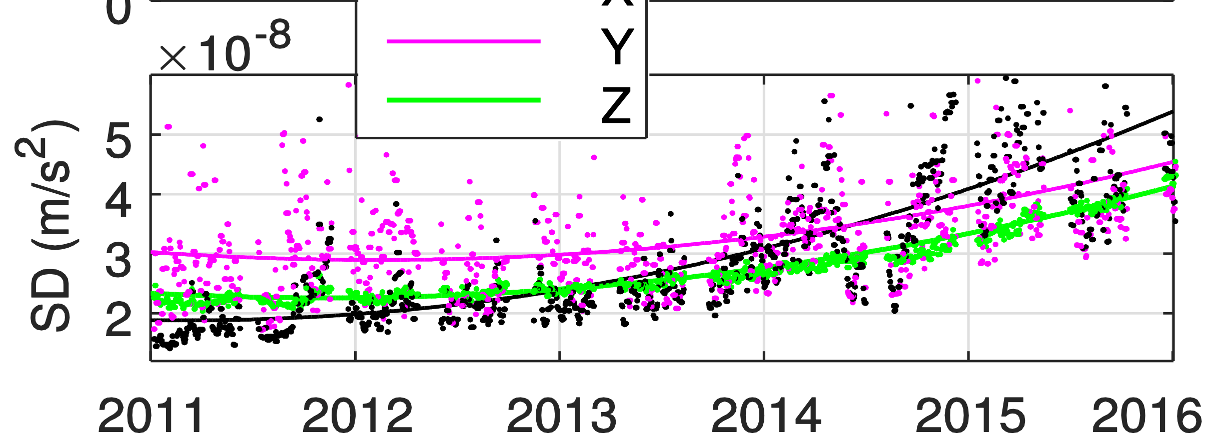
Accelerometer calibration



*Calabia et al, 2015

4.1. Results: POE vs ACC

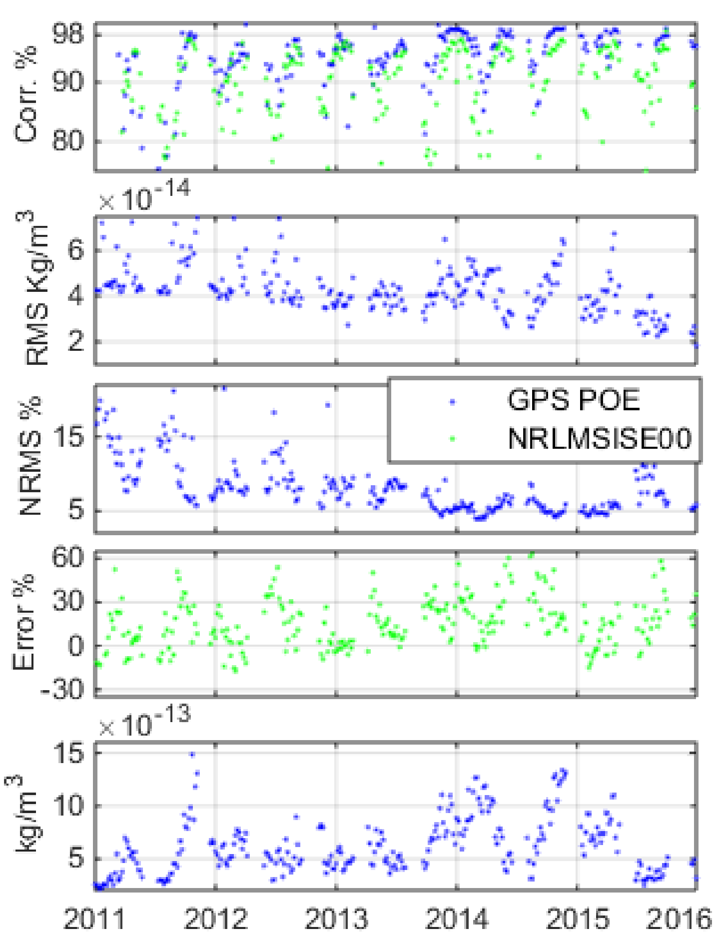
Uncertainty of POE-based non-gravitational accelerations

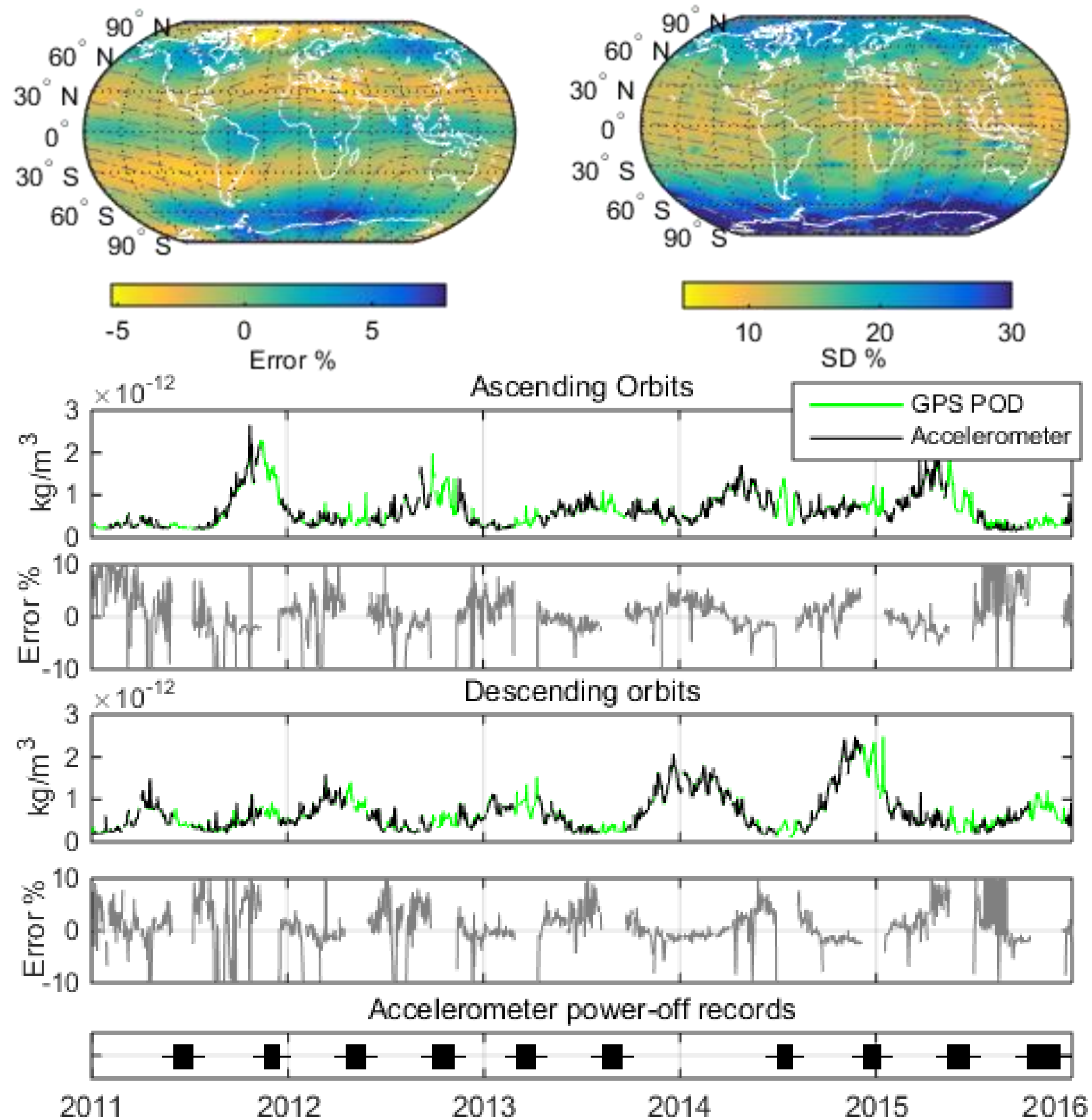


*Calabia and Jin, 2017

4.1. Results: POE vs ACC

Uncertainty of new density estimates



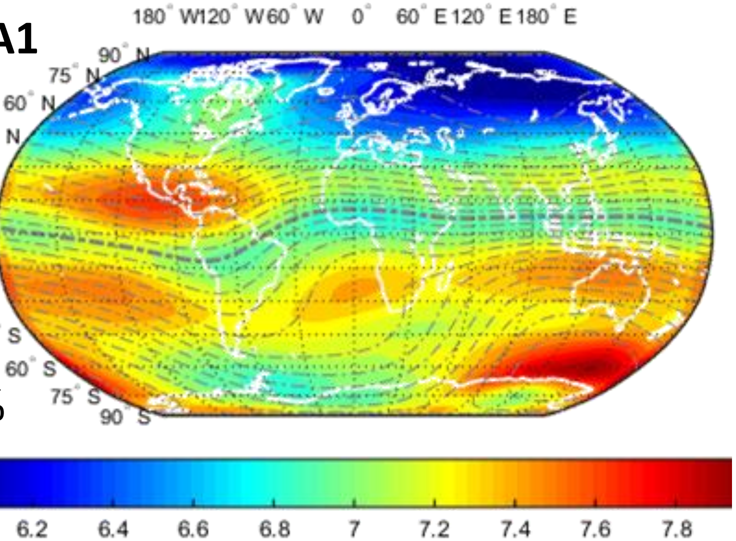


*Calabia and Jin, 2017

4.2. Results: PCA parameterization

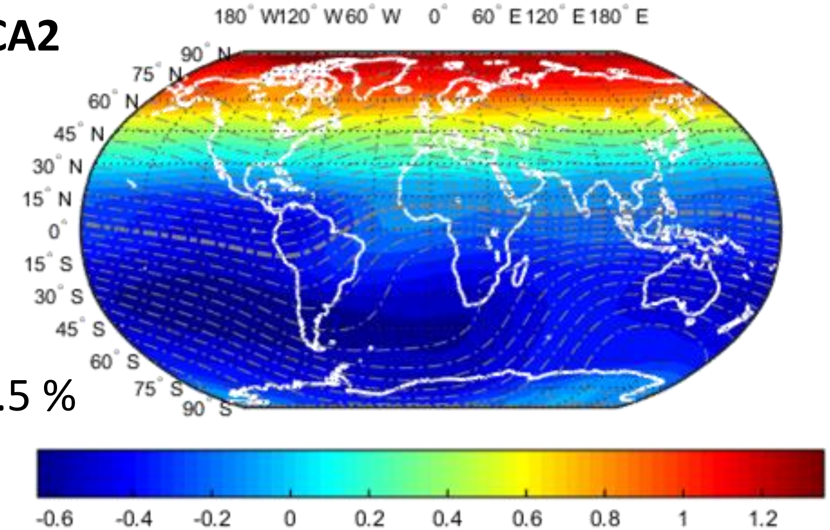
Main PCA: **98.5%** variability

PCA1



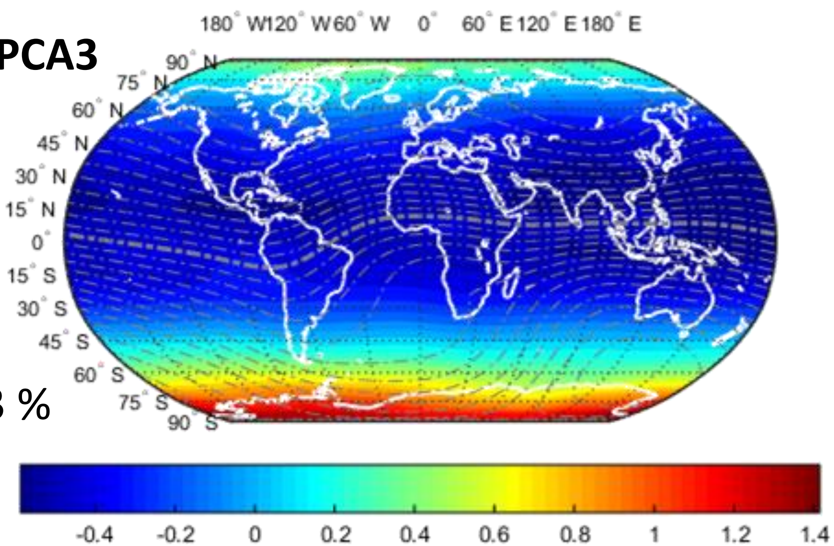
92 %

PCA2

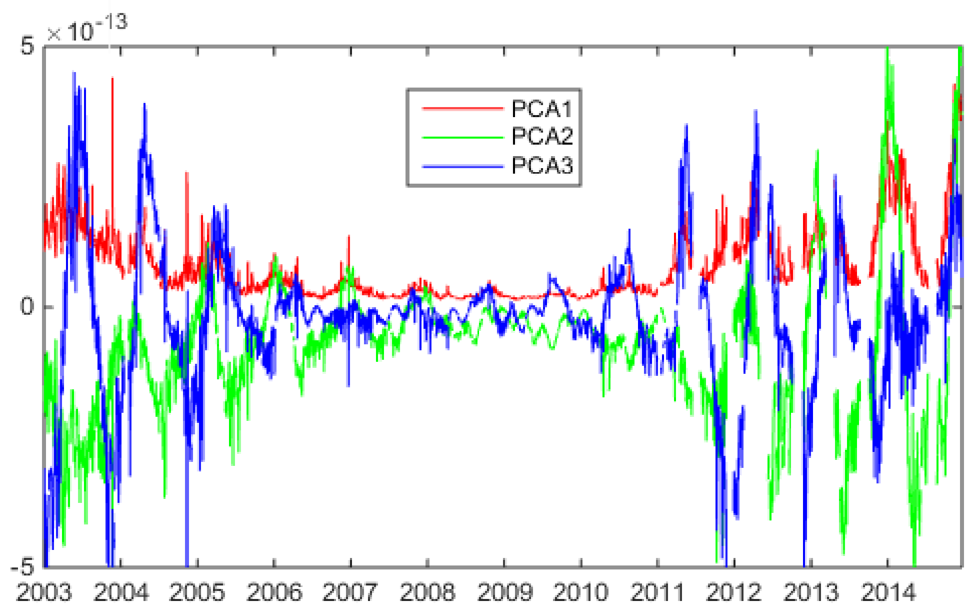


3.5 %

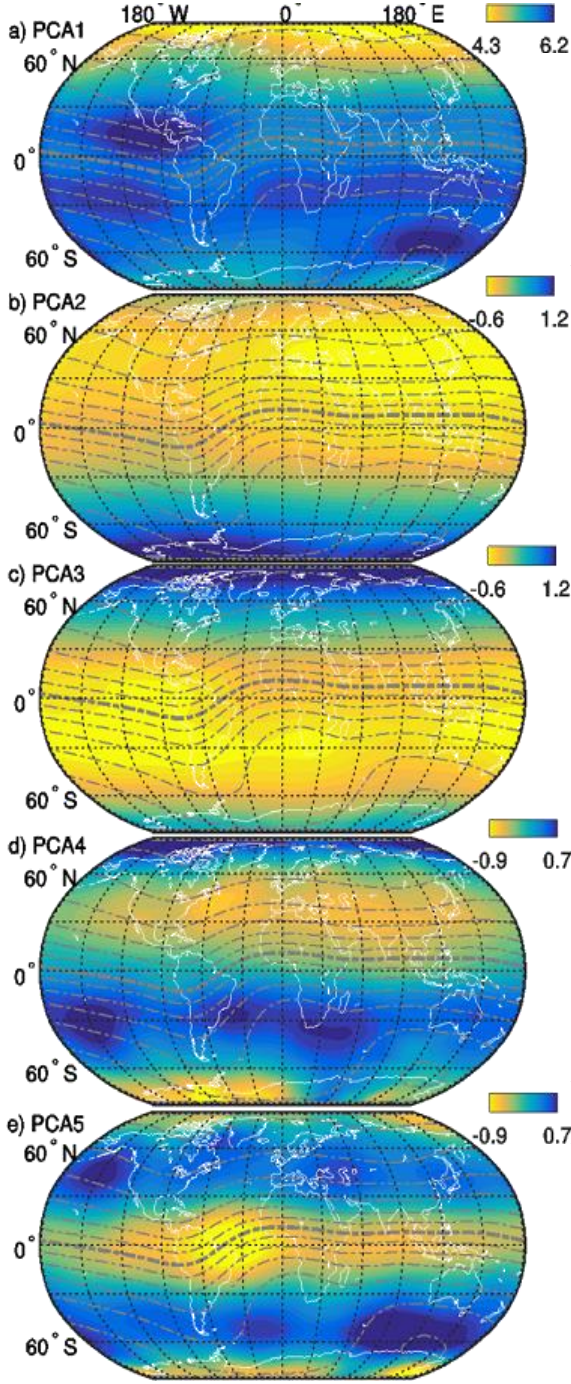
PCA3

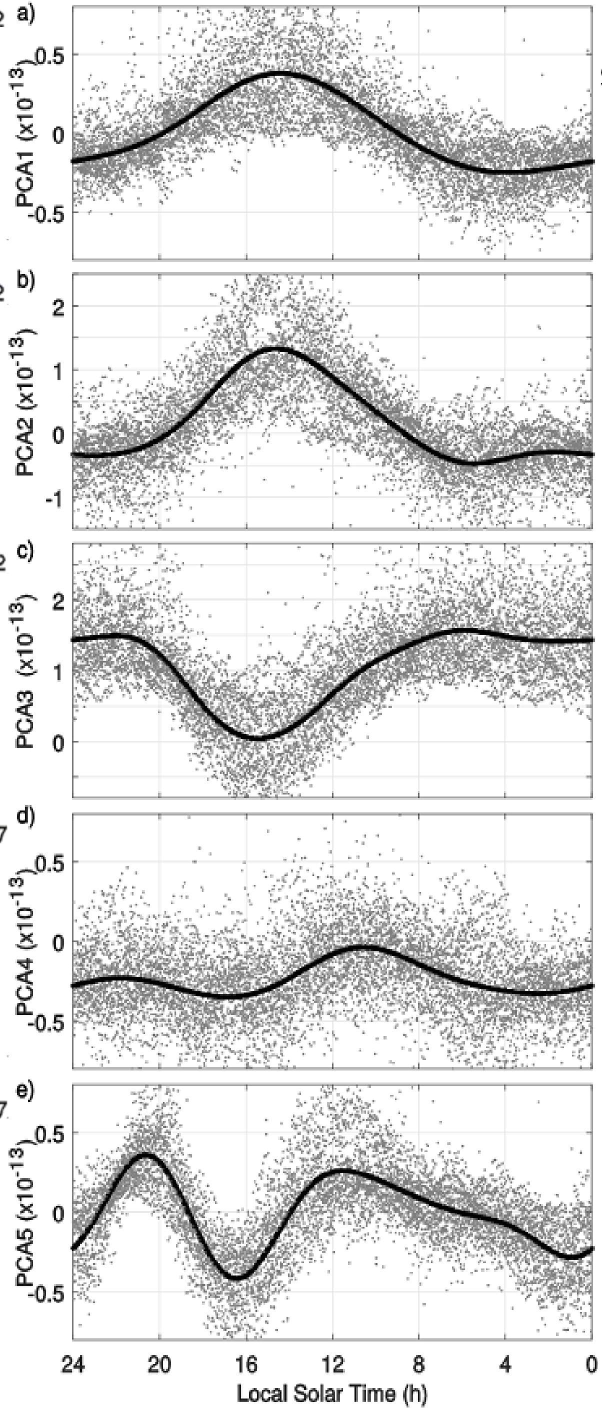


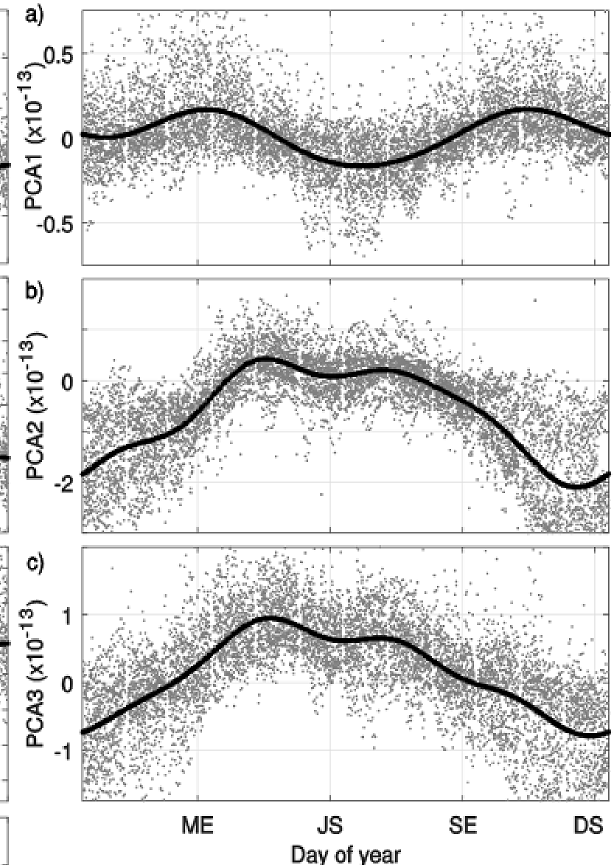
3 %



4.2. Results: PCA parameterization



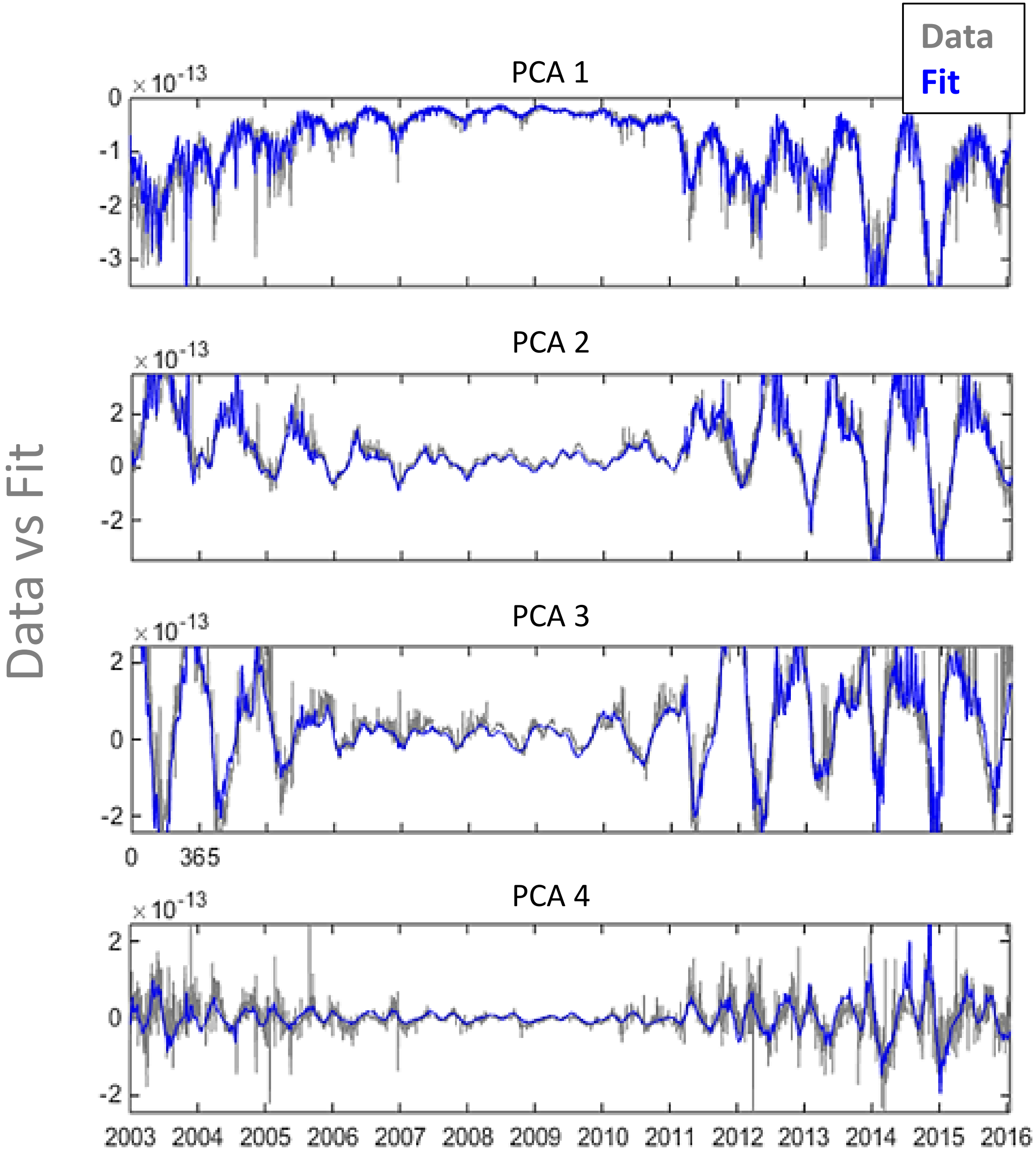




*Calabia and Jin, 2016b

*Data normalized to P10.7=110

4.2. Results: PCA parameterization

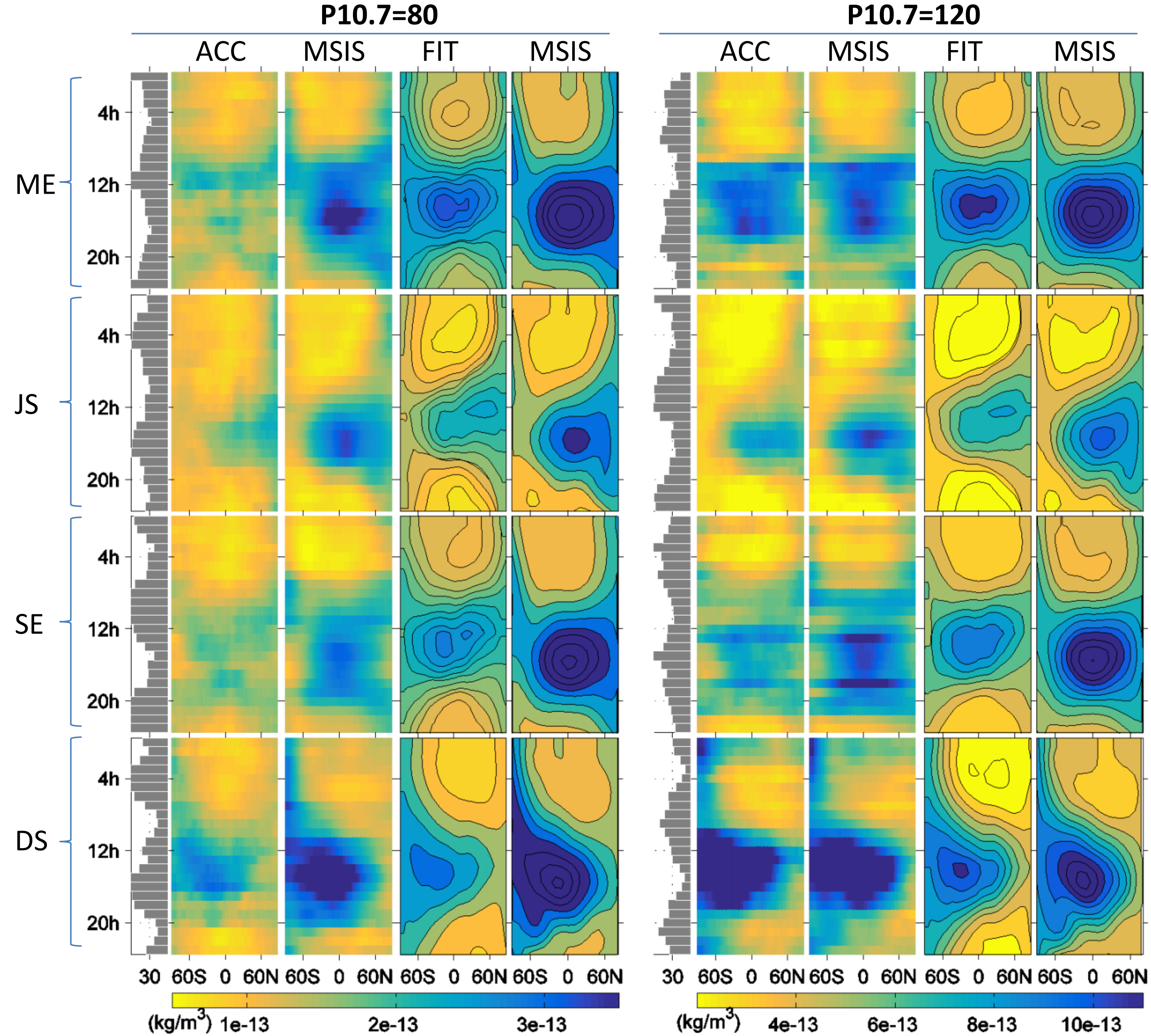


*Calabia and Jin, 2017

Variance explained	Data - Fit correlation
92 %	96 %
3.5%	93 %
3%	90 %
1.3 %	83 %

4.2. Results: PCA parameterization

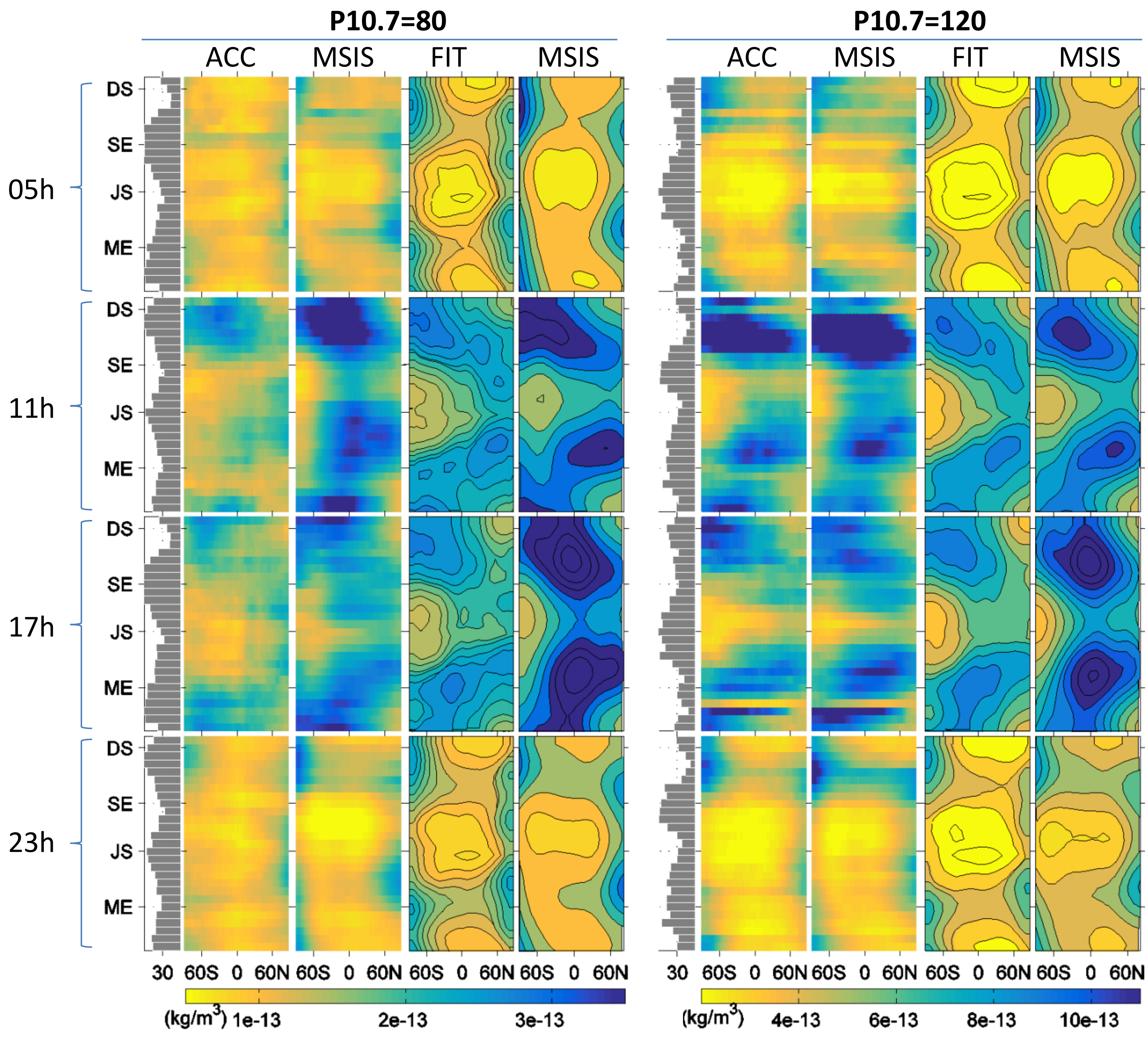
Measurements and models



*Calabia and Jin, 2016b

4.2. Results: PCA parameterization

Measurements and models

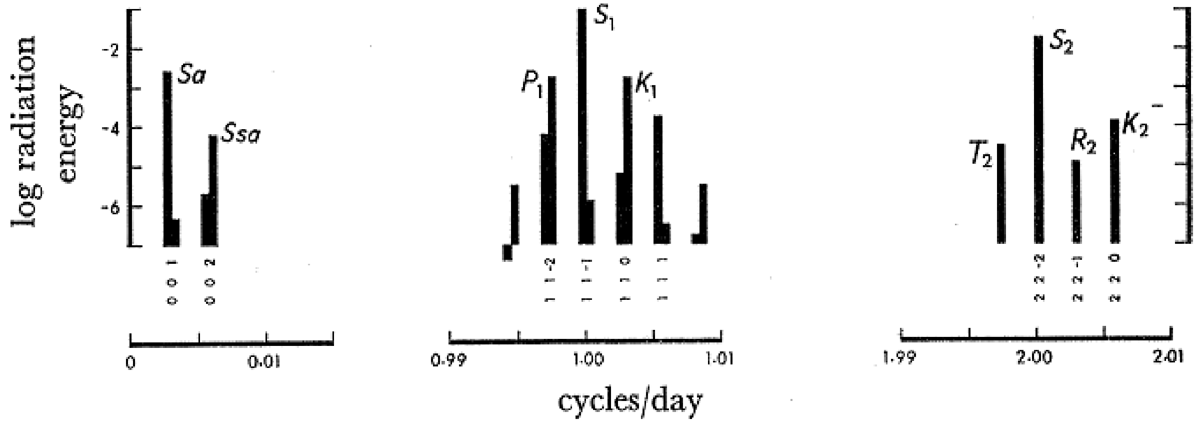


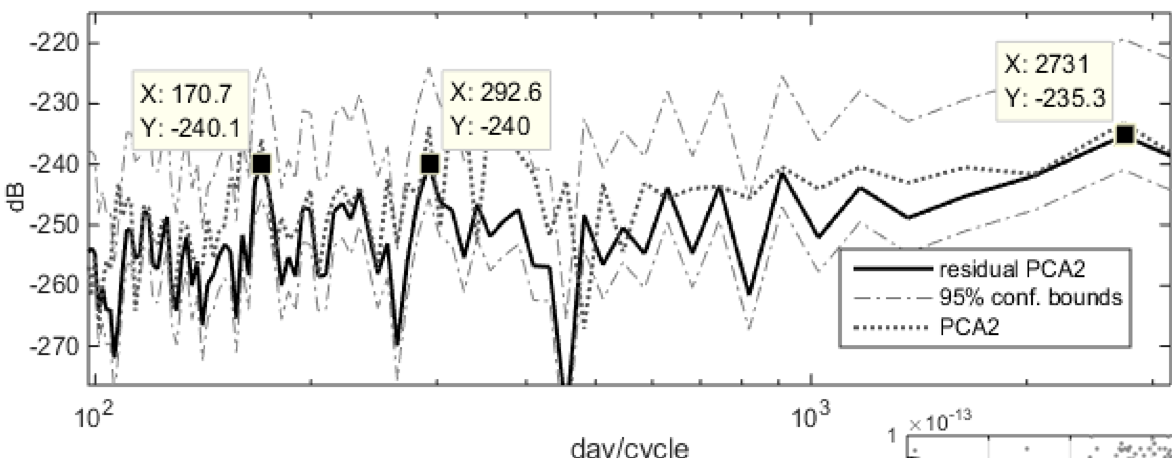
*Calabia and Jin, 2016b

4.3. Results: Residuals analysis

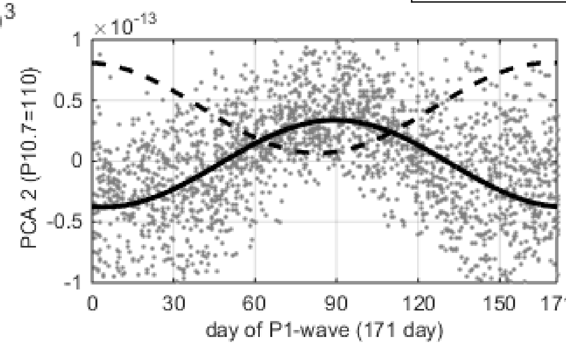
Spectrum of radiational waves

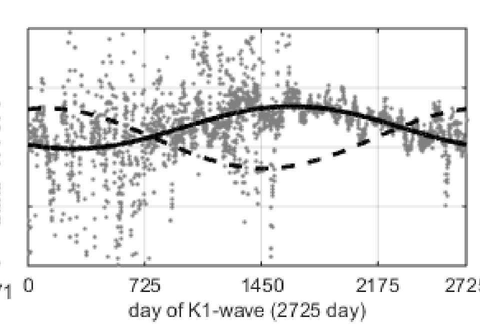
* Radiational tide spectra
(Munk and Cartwright,1966)





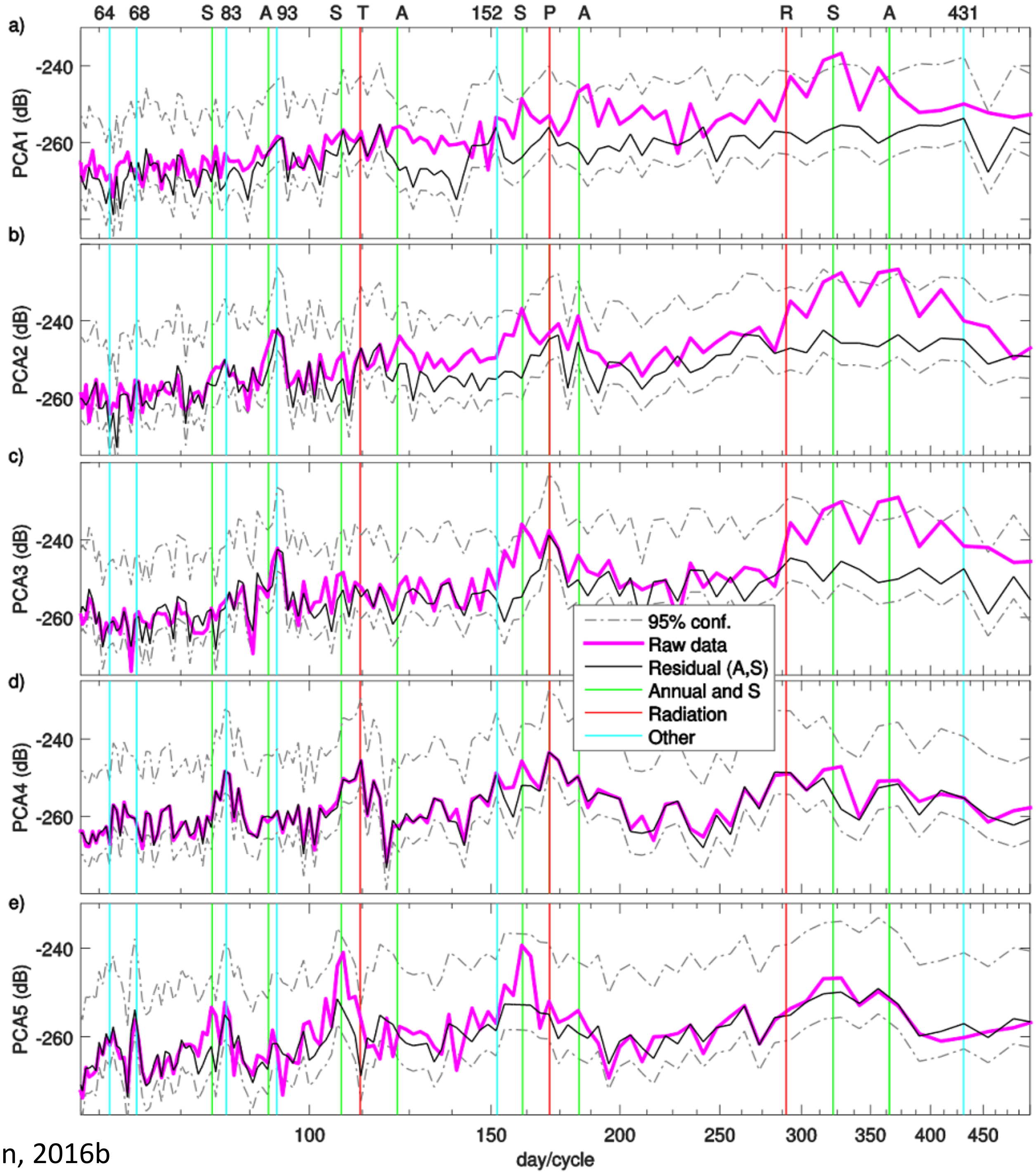
Darwin symbol	Period (day)	Alias period (day)
P1	1.0027454	171.13
S1	1	322
K1	0.9972696	2719.68
K+2	0.9971964	1700
T2	0.5006854	111.74
R2	0.4993165	287.89





4.3. Results: Residuals analysis

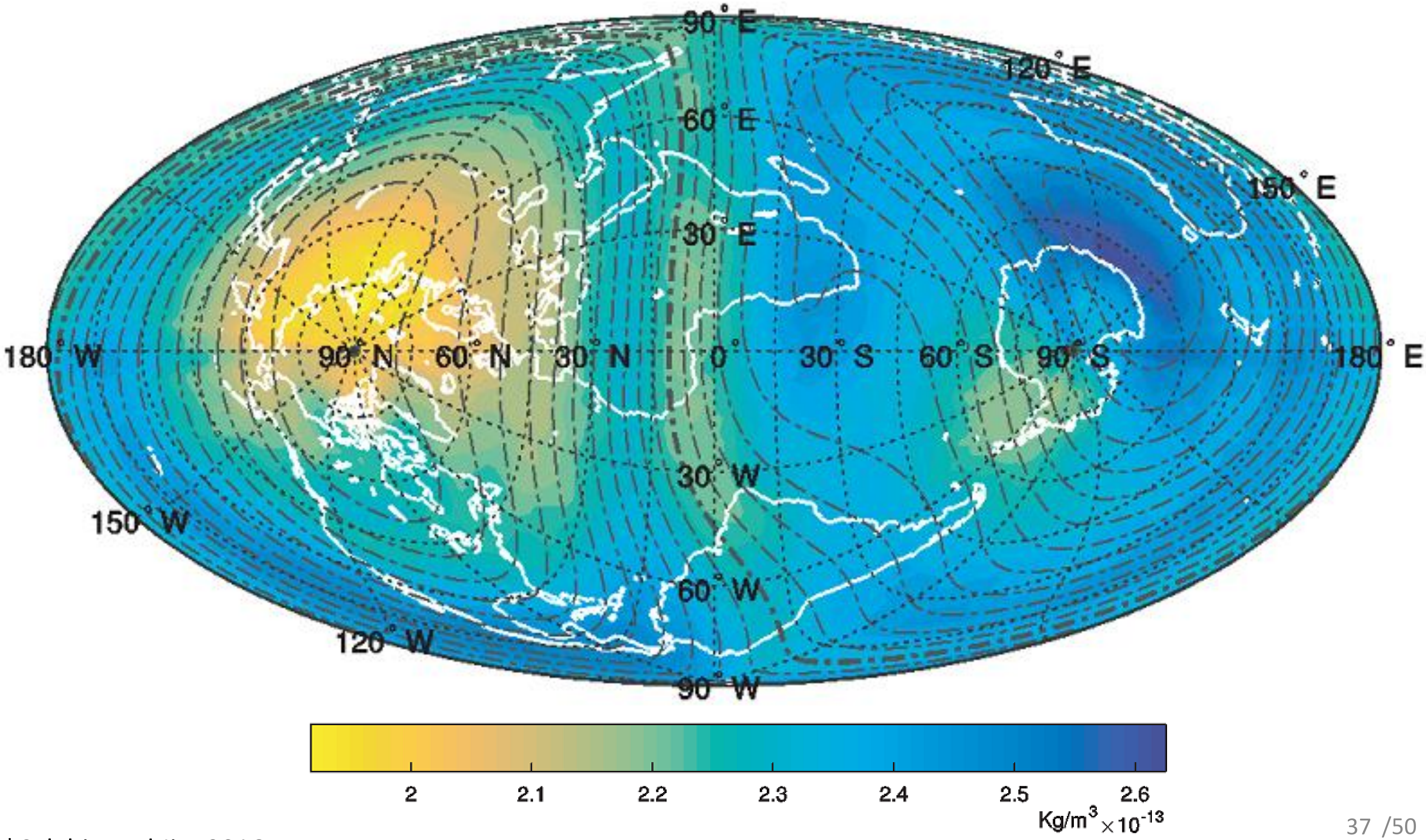
Periodogram



*Calabia and Jin, 2016b

4.4. Results: Global distribution

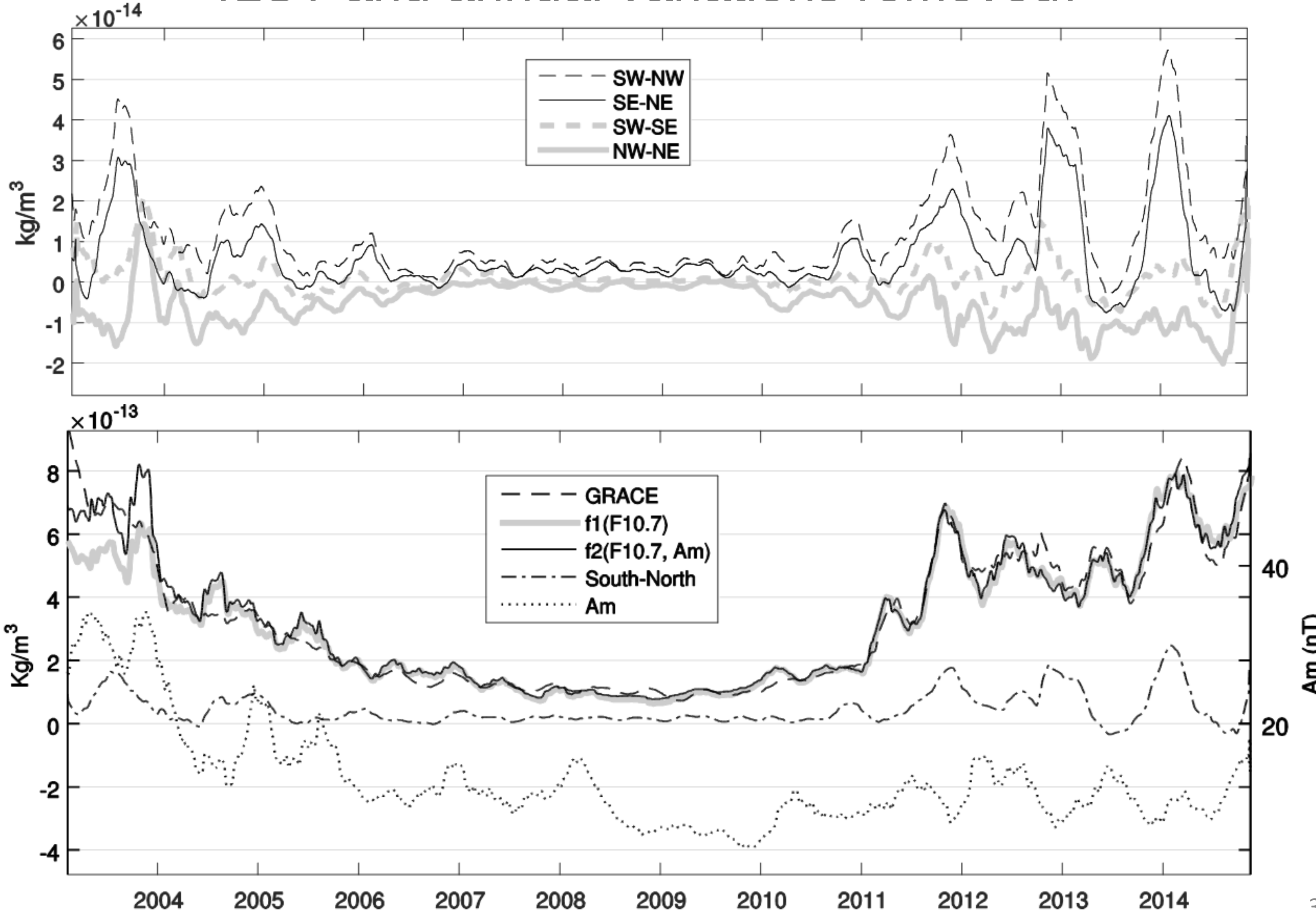
Averaged thermospheric neutral density (475 Km)
(LST and annual variations removed)



*Calabia and Jin, 2016c

4.4. Results: Long-term trend

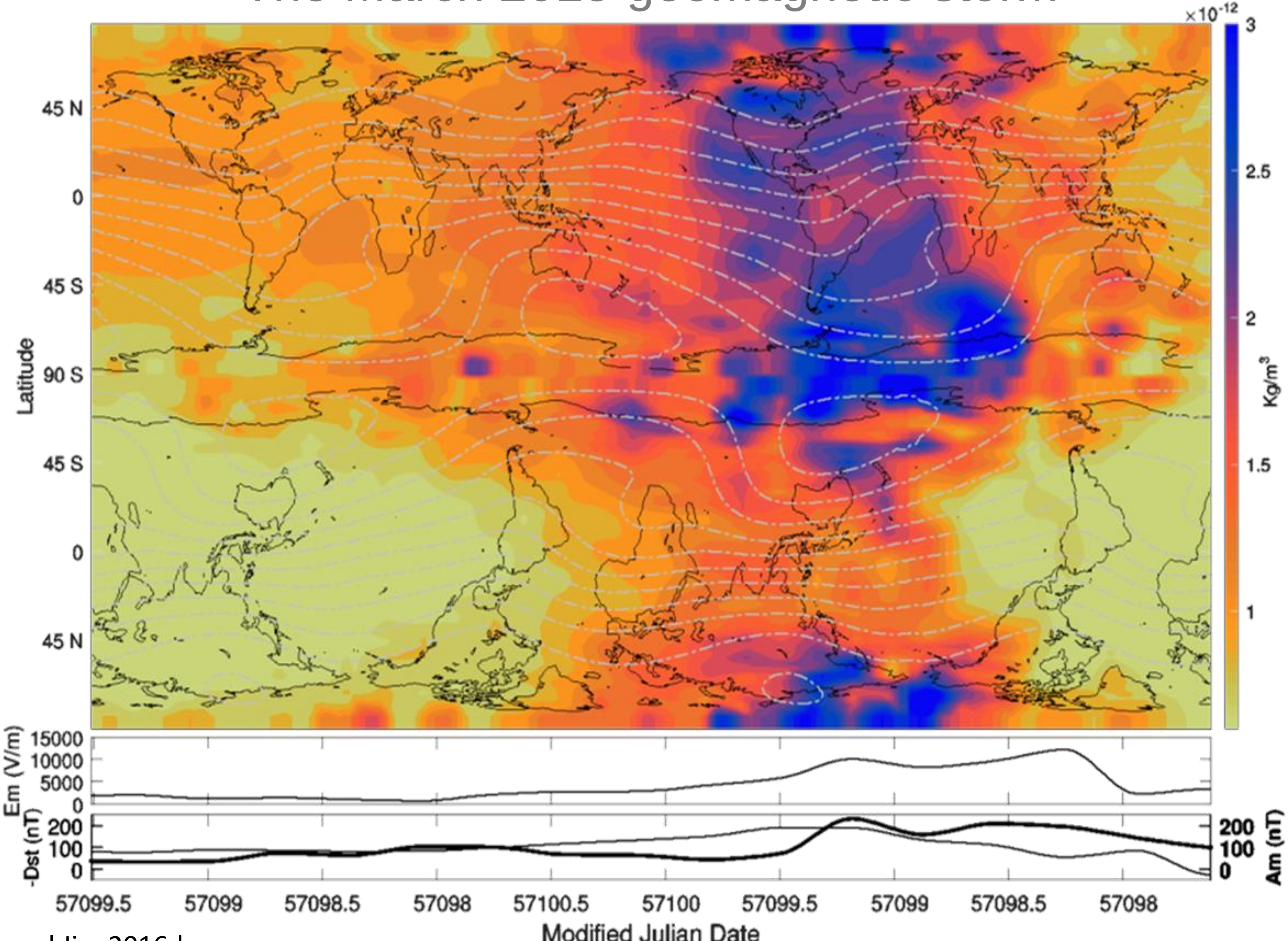
Daily mean density (475 Km) 81-day smoothed
(LST and annual variations removed)



*Calabia and Jin, 2016c

4.5. Results: Geomagnetic storm

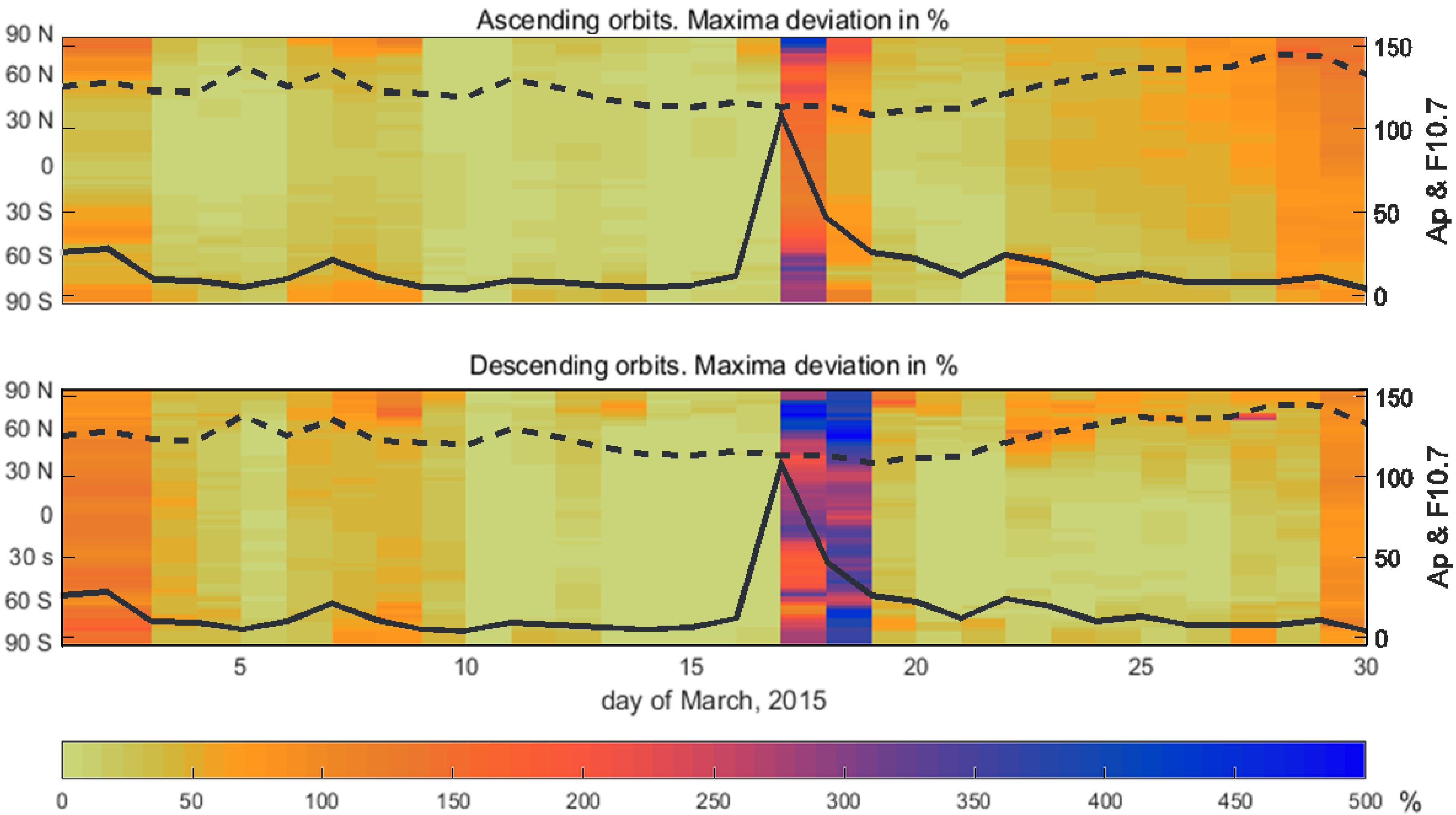
The March 2015 geomagnetic storm



*Calabia and Jin, 2016d

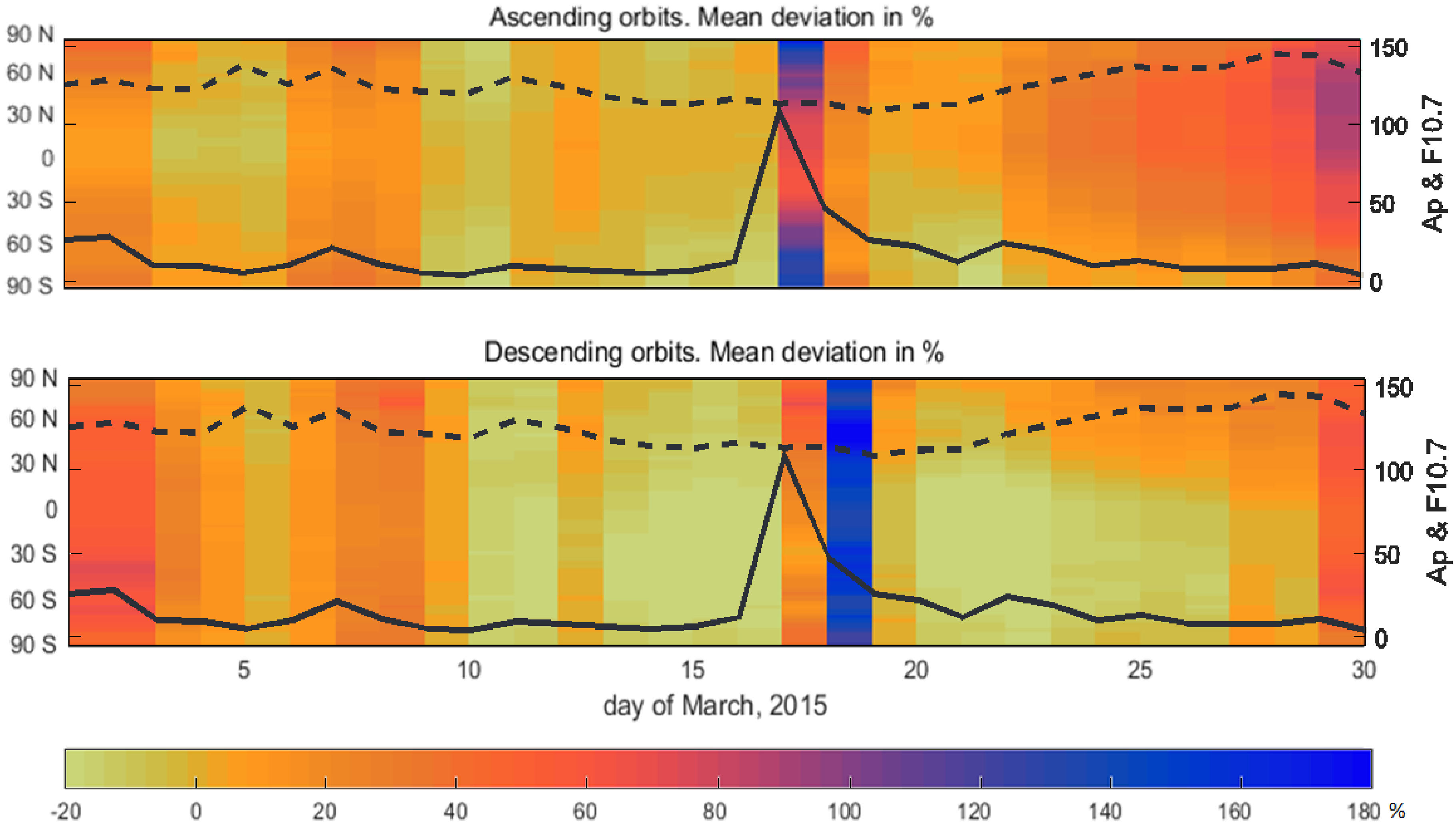
4.5. Results & Discussion

Maxima deviation



4.5. Results & Discussion

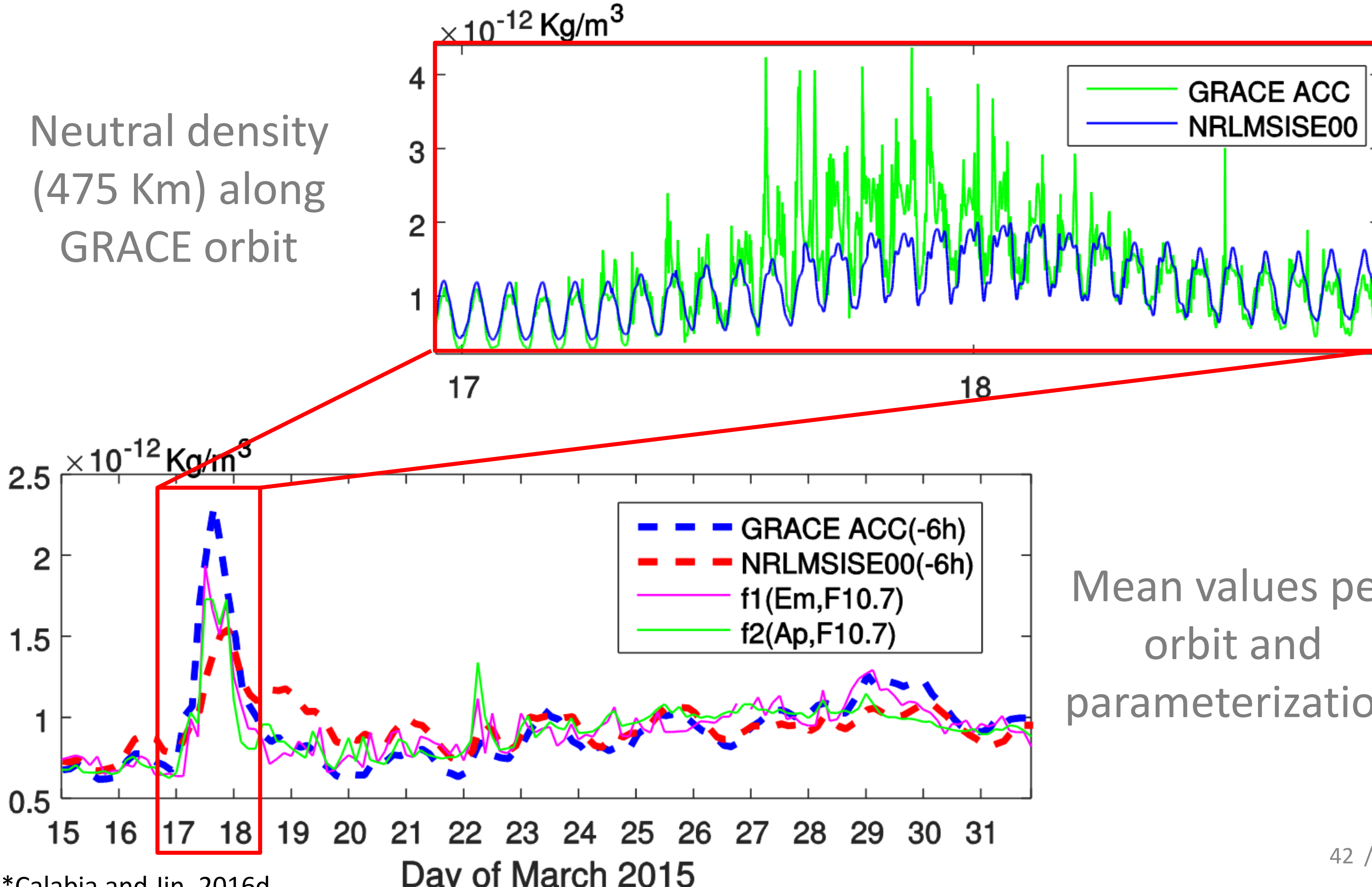
Mean deviation



4.5. Results: Geomagnetic storm

The March 2015 geomagnetic storm

Neutral density (475 Km) along GRACE orbit

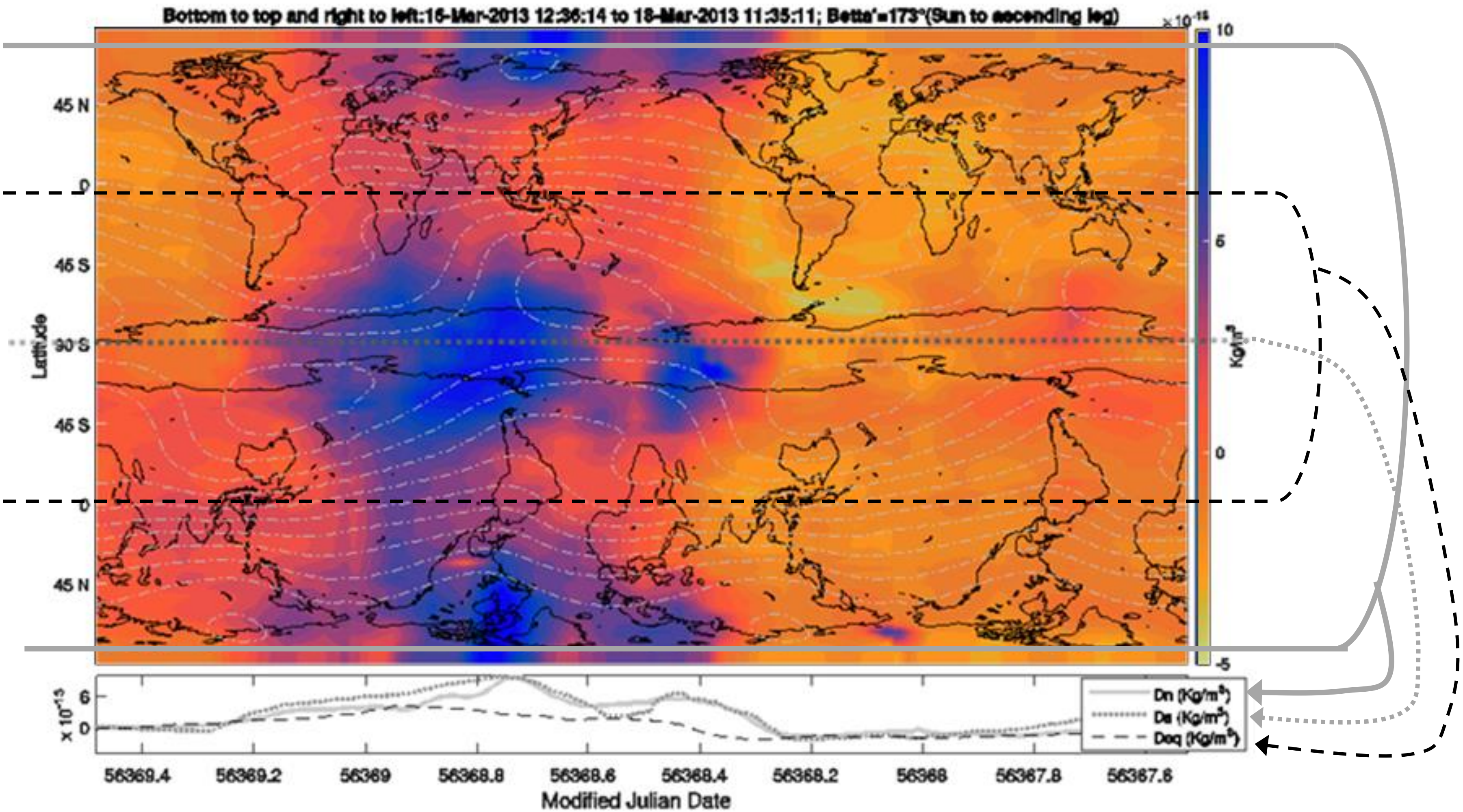


Mean values per orbit and parameterization

*Calabia and Jin, 2016d

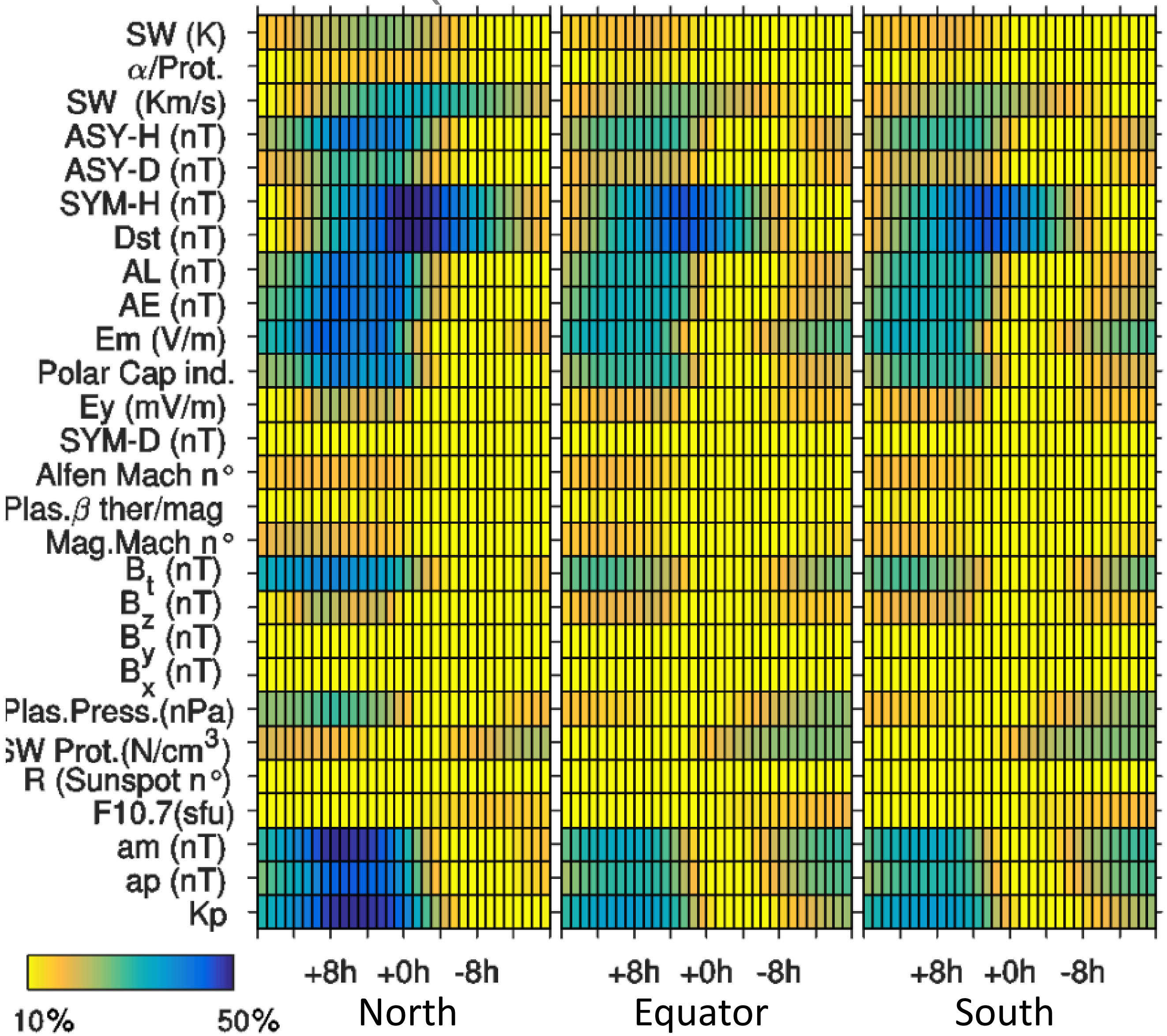
4.5. Results: Geomagnetic storm

Northern, Equatorial, and Southern profiles



4.5. Results: Geomagnetic storm

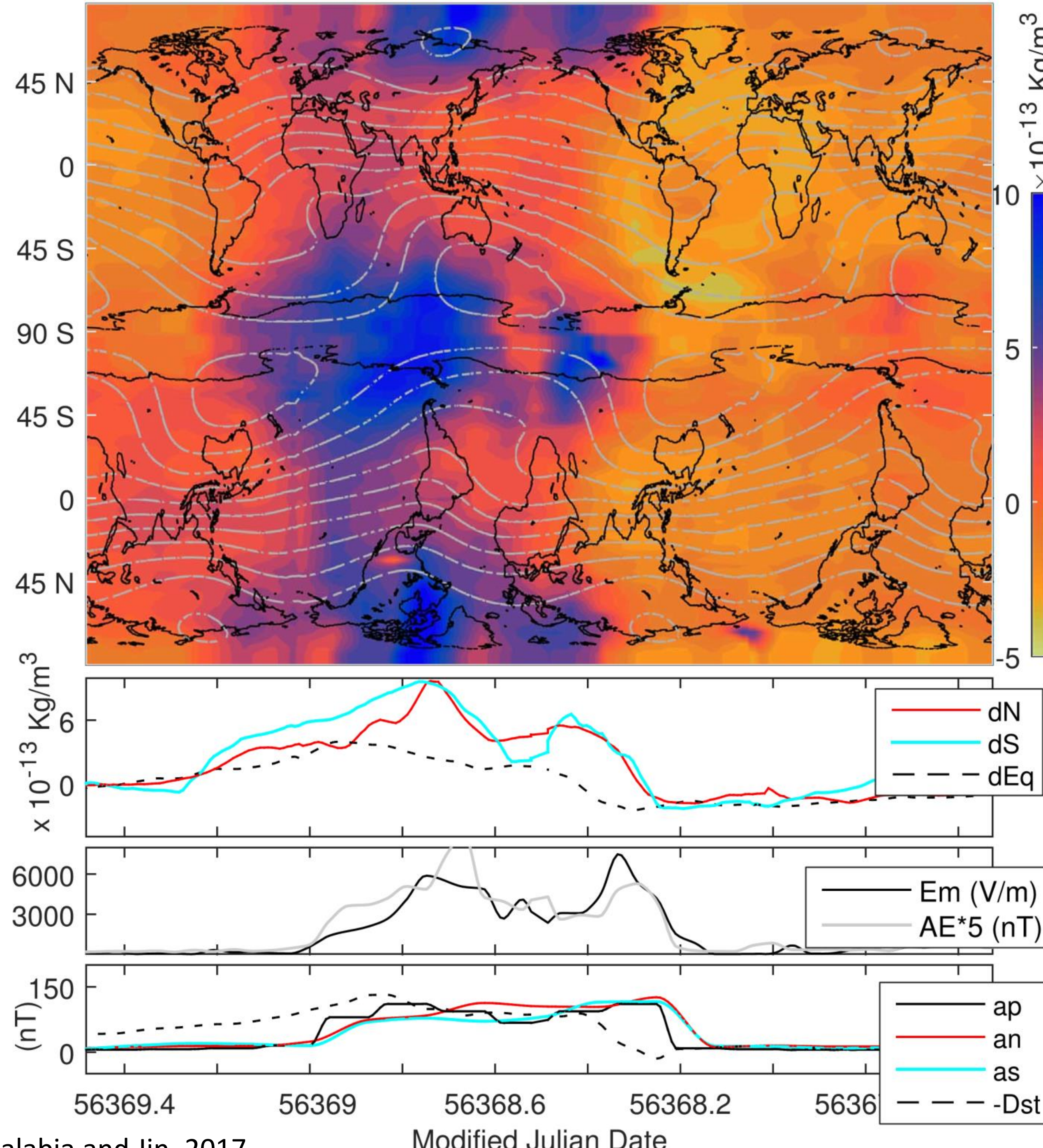
Correlation versus delay-times with respect to density variations 2011-2016 (free from annual and LST variations)



*Calabia and Jin, 2017

4.5. Results: Geomagnetic storm

The March 2013 geomagnetic storm
(LST and annual variations removed)



*Calabia and Jin, 2017

5. Conclusions

- **The new technique to derive non-gravitational accelerations from numerically differentiated POE has shown good agreement with accelerometer measurements, and good results for accelerometer calibration and neutral density estimation.**
- **A new systematic error inherent to the generalized POD scheme has been found in GRACE's and GOCE's solution.**
- **The new PCA-based technique for the spatiotemporal analysis of satellite measurements along orbits has shown great feasibility with very good results.**

5. Conclusions

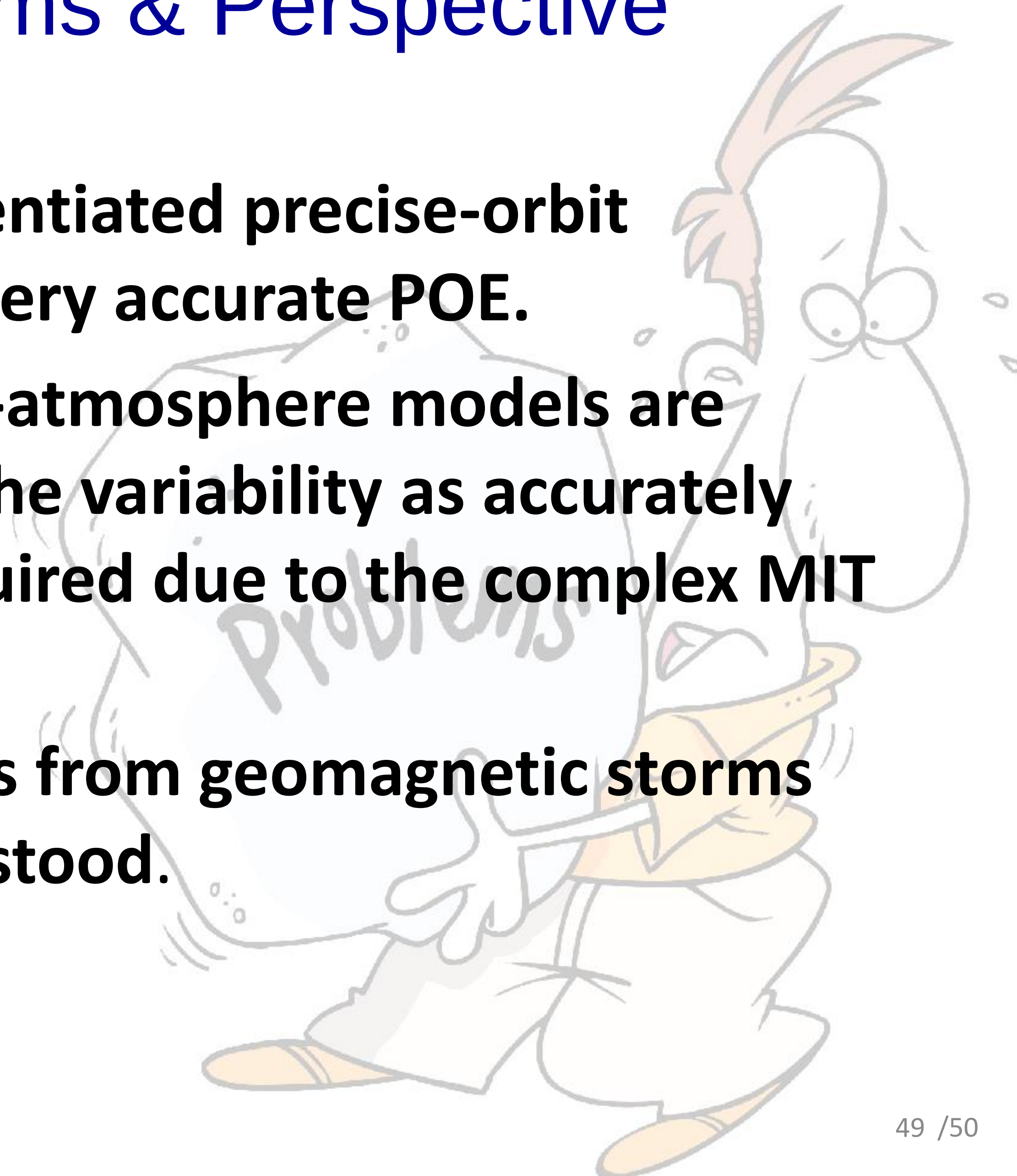
- **Conservative-force anomalies derived from analytical TVG, POE, and accelerometer measurements have shown strong structures at LST and sub-daily frequencies.**
- **A better understanding of thermospheric neutral density distribution and variations is presented.**
  - ✓ **The new model is suitable to represent small scale variations including, e.g., EMA and MDM.**
  - ➢ **The residuals have shown periodic contributions at the frequencies of the radiational tides (P1, K, T2, and R2) and at the periods of 83, 93, 152 and 431 days.**

5. Conclusions

- **The long-term distribution shows a alignments with the geomagnetic field, higher density in the southern hemisphere, and two asymmetric cells located in the polar caps.**
- **Thermospheric neutral density variations during geomagnetic storms better correlate to *Dst* index at low latitudes, and to *Em* and *k*-planetary indices at high latitudes.**

6. Problems & Perspective

- **Numerically differentiated precise-orbit velocities require very accurate POE.**
- **The present upper-atmosphere models are unable to predict the variability as accurately and efficiently required due to the complex MIT coupling.**
- **Resulting processes from geomagnetic storms are not well understood.**



6. Problems & Perspective

- **Study density variations from other missions (e.g., SWARM, GRACE FO) and models.**
- **Modeling of simultaneous measurements in a combined solution of wind and density estimates.**
- **Integrate other techniques (e.g., ultraviolet remote sensing, incoherent scatter radar, atmospheric occultation, Broglio Drag Balance instrument, pressure gauge devices).**

UNIVERSITY OF CHINESE ACADEMY OF SCIENCES

SHANGHAI ASTRONOMICAL OBSERVATORY

THAT'S ALL !

The End

Thank you very much!

See you soon!

Andy