Variations of thermospheric air mass density derived from GRACE accelerations and GPS POD

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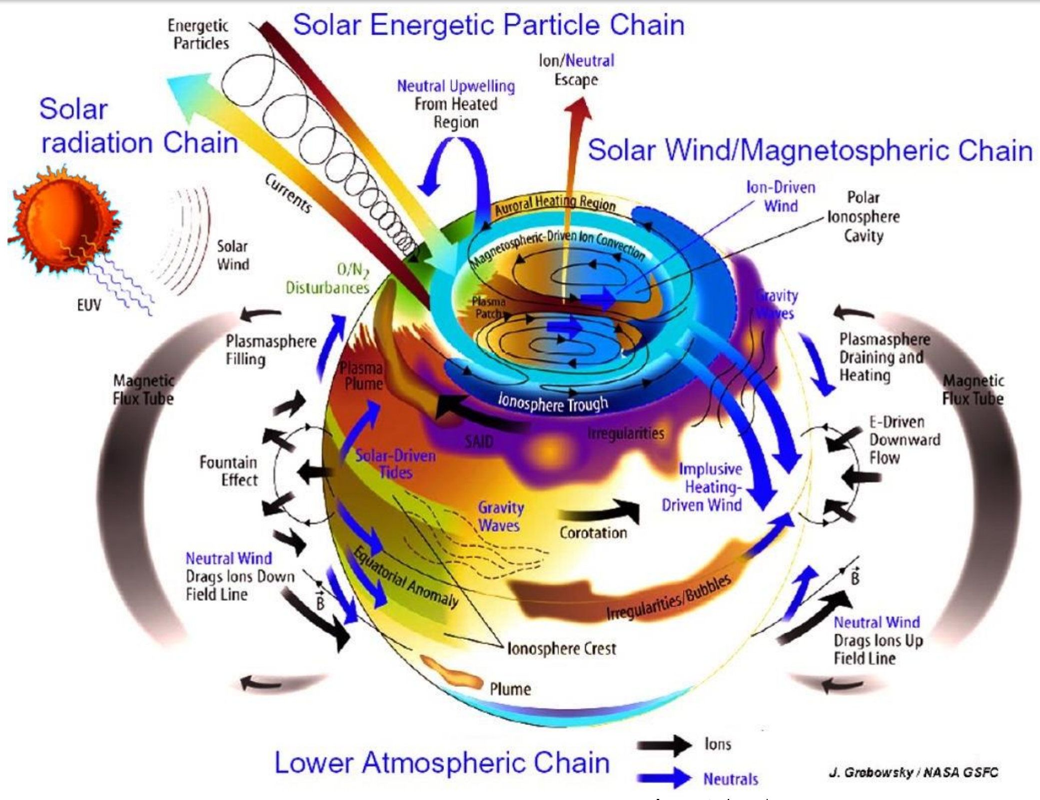
SUMMARY: Monitoring and understanding the upper atmosphere processes is important for orbital decay and space physics. In this study, thermospheric mass densities are estimated from both accelerometer (ACC) measurements and precise orbit ephemeris (POE) of GRACE, for the period 2003-2015. We employ POE-based densities to fill ACC data-gaps, and investigate long-term and short-term variations for accurate modeling. The time-series have been parameterized in function of solar flux, Local Solar Time (LST), and annual variations, with the use of the principal component analysis (PCA). Furthermore, the residuals are investigated in the frequency domain, and in relation to space weather and geomagnetic indices. We have found periodic contributions at the frequencies of the diurnal P and K radiational-waves, and good correlation with the *Dst* and k-derived geomagnetic indices, as well as the auroral electroject activity index *AE* and the merging electric field *Em*. A better understanding of global thermospheric mass density variations is presented, which validates the suitability of our technique and modelling.

INTRODUCTION:

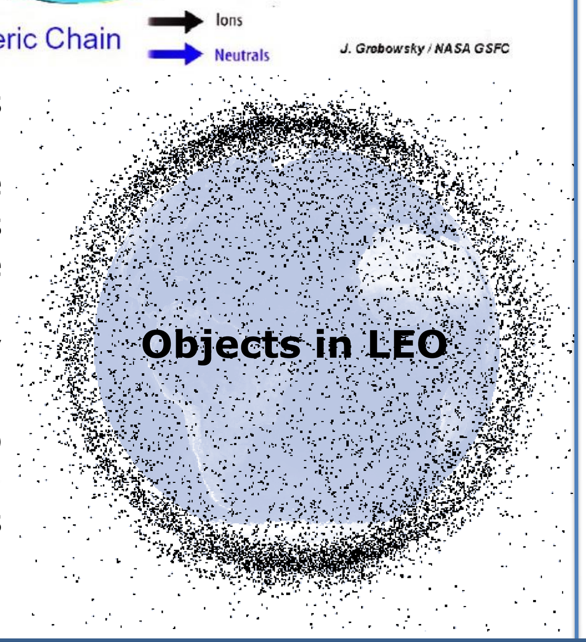
The thermosphere is highly variable in time and space, and its geophysical processes are still not well understood. Currently, half of the world's active satellites and about 20,000 inactive debris operate in low Earth orbit (LEO), where atmospheric drag produce orbital decay and perturbations.

Therefore, mass density measurements and models are indispensable to study the coupling between the thermosphere and ionosphere, and its physical processes. In addition, accurate air-density models are essential for ephemeris prediction, orbital tracking and satellite guidance.



NRLMSISE00 is an empirical, global model of the Earth's atmosphere from ground to space. Its primary use is to aid predictions of satellite orbital decay due to atmospheric drag. The earlier models MSIS86 and MSISE90 are based on Mass Spectrometer and Incoherent Scatter Radar measurements, and the current model has been updated with satellite drag data. However, NRLMSISE00 is still incapable to predict the variability as accurately and efficiently required.

Currently, ACC on-board LEO satellites are being used to measure non-gravitational accelerations, and equaling the drag-force formula to synthetically-derived aerodynamic accelerations is recently providing an unprecedented accuracy.



Besides ACC measurements, GPS POD observations can also derive accurate density measurements, and both ACC and GPS POD based densities be investigated in relation with space weather and geomagnetic indices, so more accurate modeling can be achieved.

METHODOLOGY:

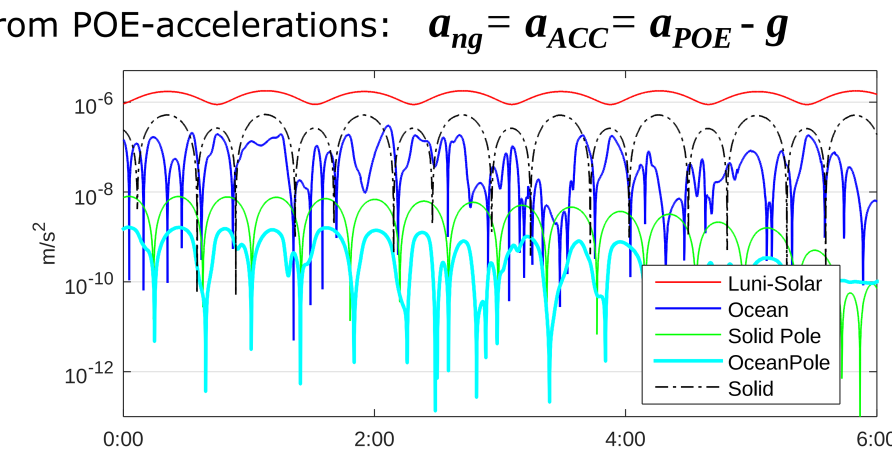
1. First derivatives of precise-orbit velocities are numerically differentiated under arc-to-chord interpolation-threshold.

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

Interpolation threshold

Δt (s)	Error (nm/s²)
0.05	1
0.1	3
0.5	50
1	120

2. Varying gravity field model (g) is removed from POE-accelerations: $a_{ng} = a_{ACC} = a_{POE} - g$
   - Conventional model EGM2008.
   - Secular low degree C20 (zero-tide), C30 and C40 rates.
   - C21 and S21 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.



3. Accelerometer calibration using daily mean values.

4. Compute aerodynamic acceleration (a_D) by removing solar radiation and Earth albedo from ACC:

$$a_D = a_{ACC} - a_{sr} - a_e$$

5. Compute ACC-based and POE-based density along orbital path:
   Drag-force formula:

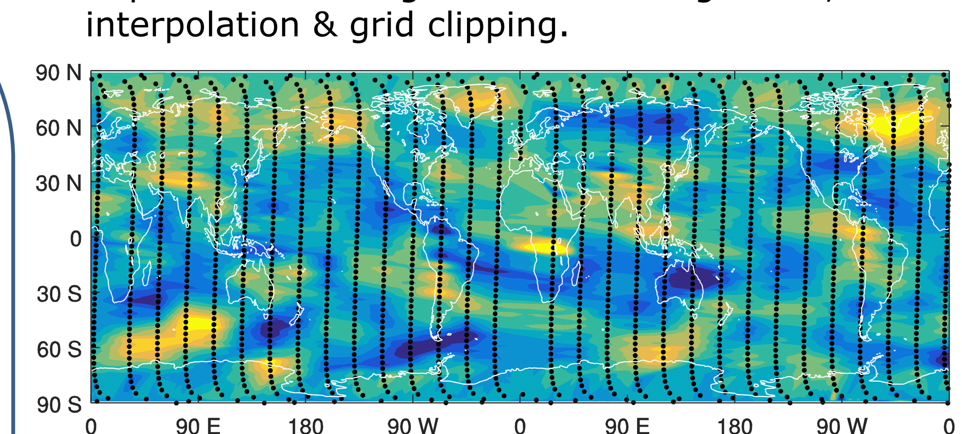
$$F_D = m\,a_D = \frac{1}{2} C A \rho v_r^2$$

C Ballistic coefficient vector
A Cross-sectional area
ρ Atmospheric density (model, observed)
v_r Relative velocity of the atmosphere
m Satellite mass

Altitude normalization:

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

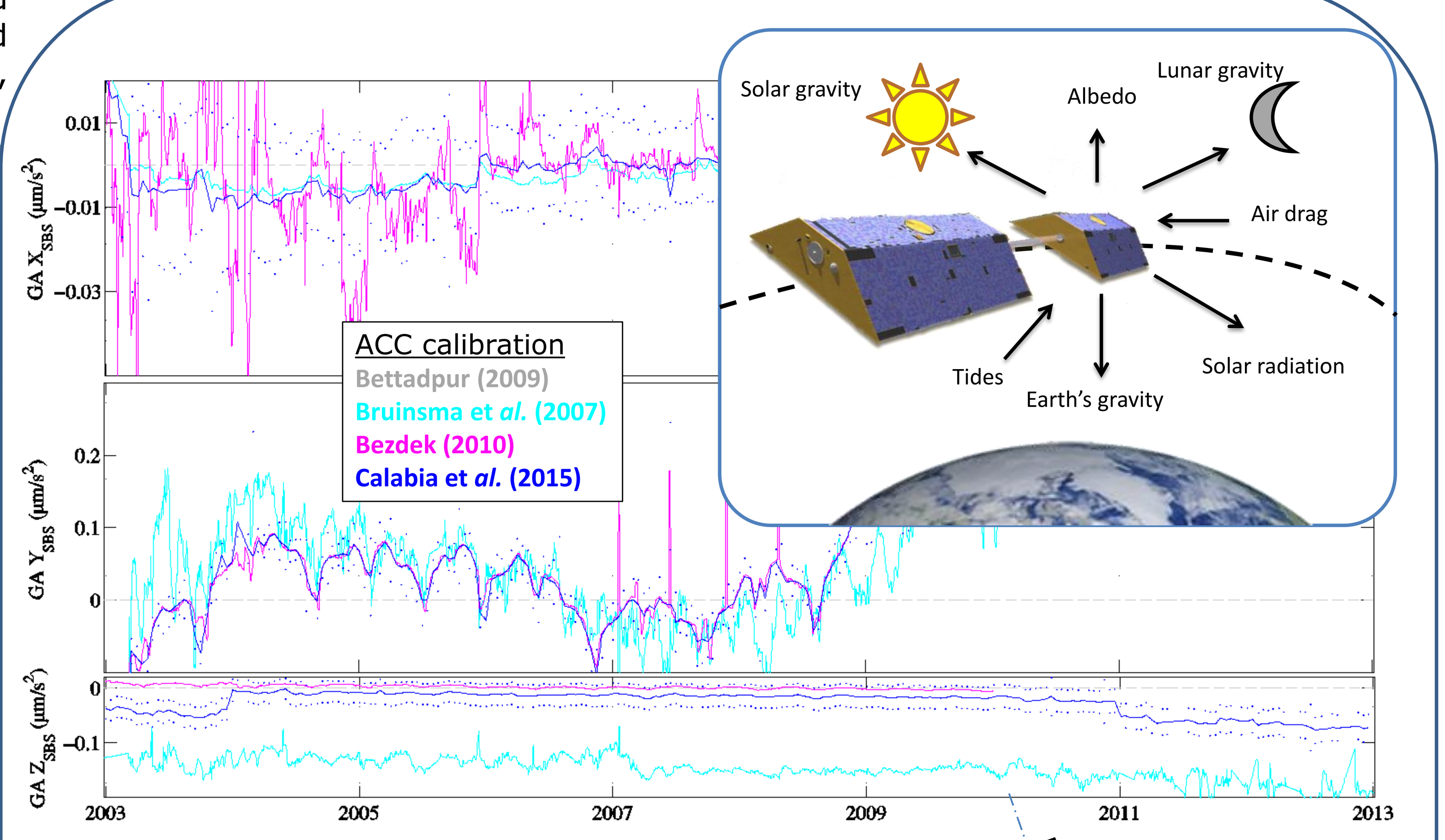
6. Separate ascending from descending orbits, data interpolation & grid clipping.



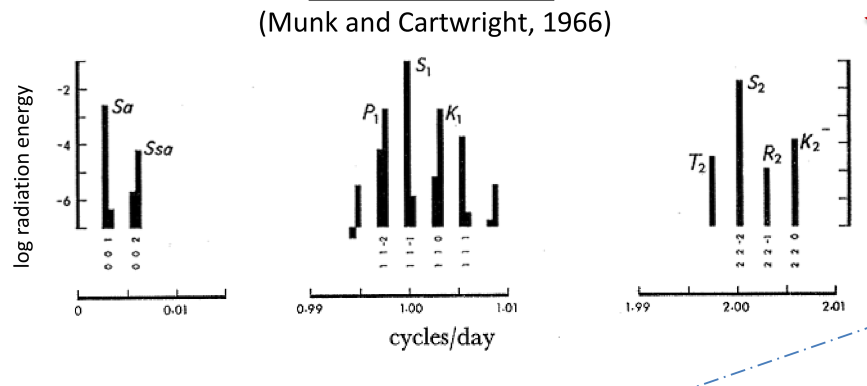
7. Temporal PCA
   a) Arrange each grid in a column.
   b) Find the covariance matrix.
   c) Find eigenvalues & eigenvectors.

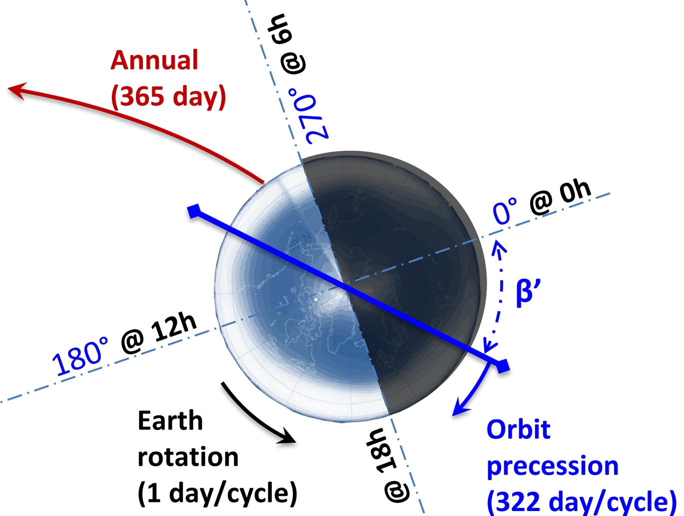
8. Periodic variations in time-expansion coefficients are modeled with sinusoidal functions modulated in amplitude:
   a) Data normalization to common flux.
   b) Sinusoidal fitting.
   c) Polynomial fitting modulates the amplitude of the sinusoidal function computed in previous step .

9. Reconstruct fitted model and remove it from the original time-series.



RADIATIONAL TIDES
(Munk and Cartwright, 1966)

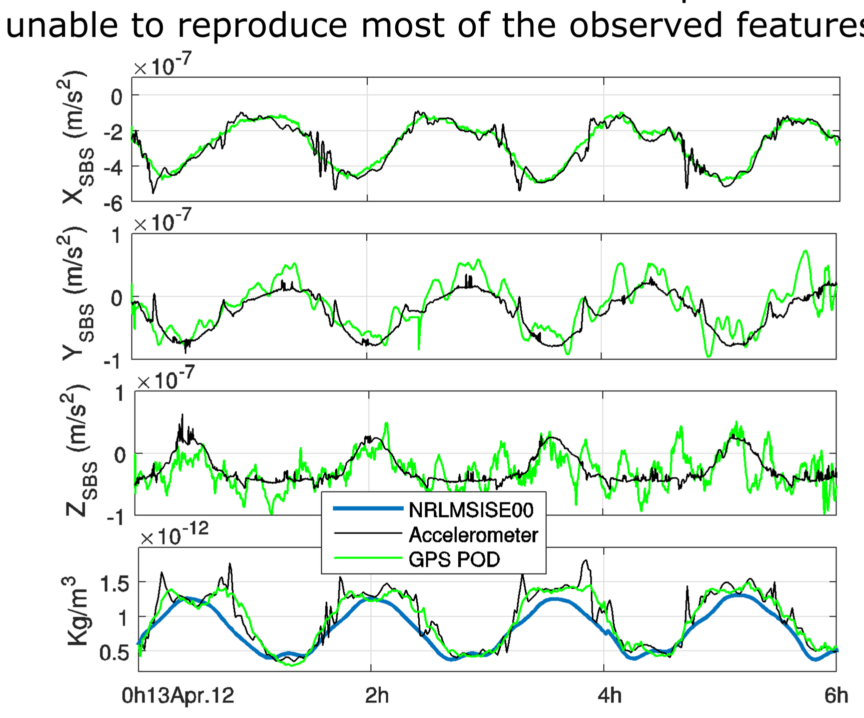




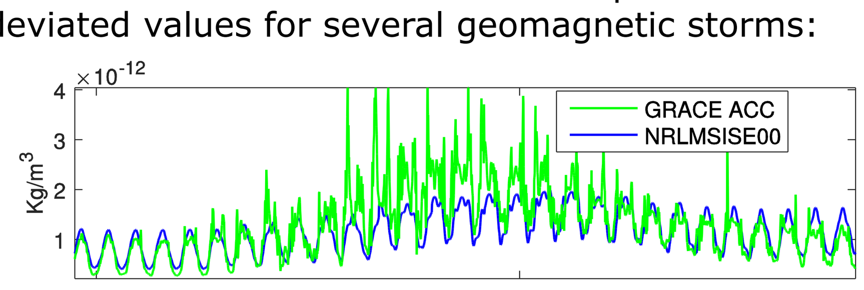
Darwin symbol	Period (day)	Alias period (day)
P1	1.0027454	171.13
S1	1	322
K1	0.9972696	2719.68
R2	0.4993165	287.89

RESULTS:

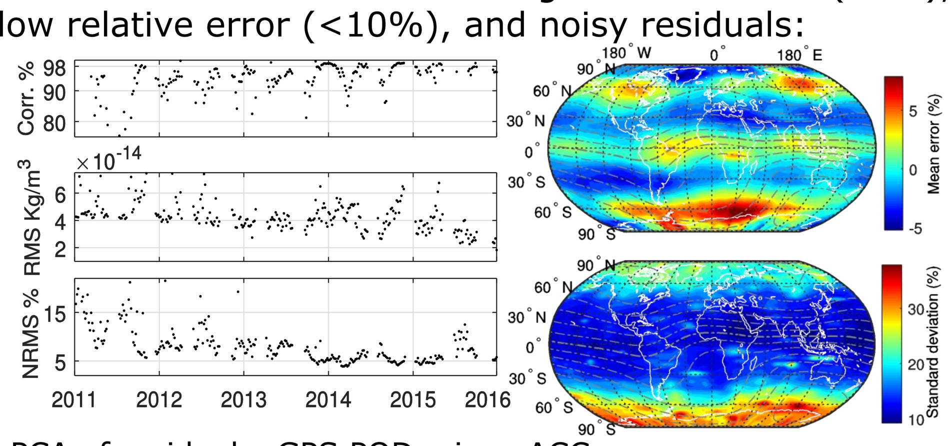
Non-gravitational accelerations and inferred densities from GPS POD show excellent agreement with ACC measurements. The NRLMSISE00 empirical model is unable to reproduce most of the observed features:



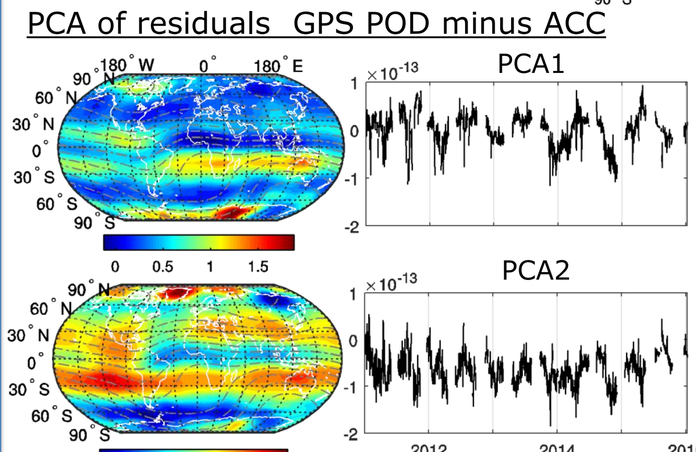
NRLMSISE00 shows smaller amplitudes and mean deviated values for several geomagnetic storms:



The uncertainty analysis of GPS POD with respect to the ACC measurements has good correlation (98%), low relative error (<10%), and noisy residuals:



PCA of residuals GPS POD minus ACC

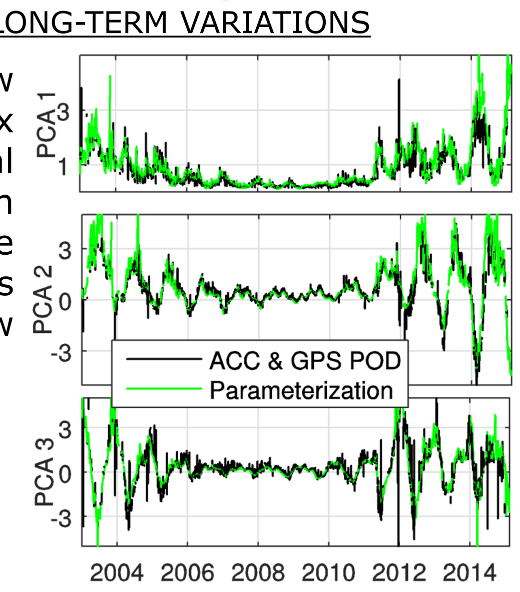


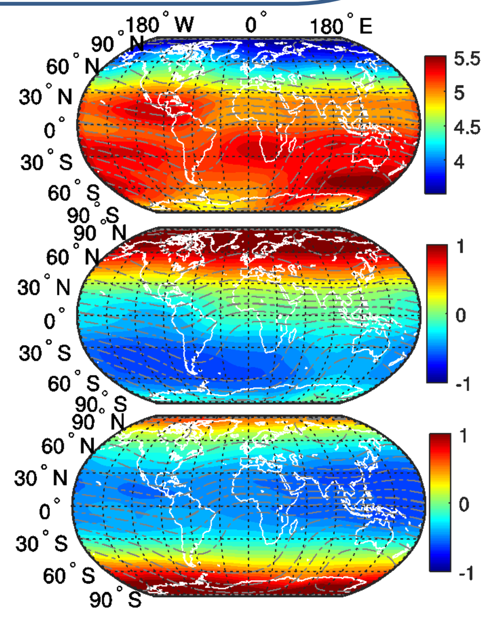
	Variance
PCA1	11%
PCA2	8%
PCA3	5%
PCA4	4%

PARAMETERIZED LONG-TERM VARIATIONS

Long-term variations show dependence on solar flux (F10.7), LST, and annual fluctuations. The high percentage for the sum of the four leading PCA components indicates low noise with few marked patterns of variability.

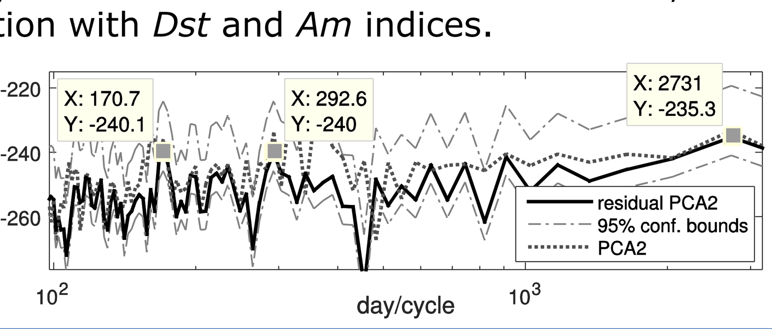
	Variance	Correlation
PCA1	92%	96%
PCA2	3.5%	93%
PCA3	3.0%	90%
PCA4	1.3%	83%

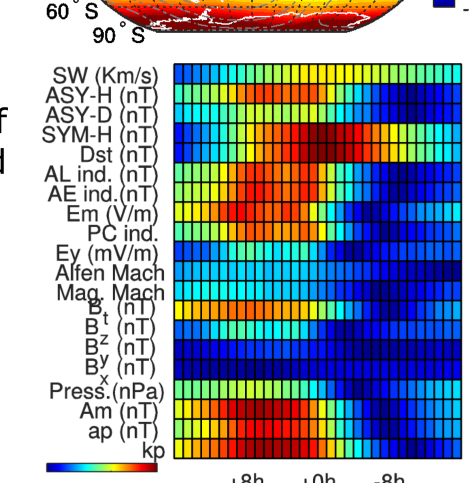




RESIDUAL VARIATIONS

Periodic contributions are found at the frequencies of the P1, R2 and K1 radiational constituents, and good correlation with *Dst* and *Am* indices.





CONCLUSIONS:

Numerically differentiated precise-orbit velocities can be used to calibrate accelerometers and estimate thermospheric mass densities when accelerometers are not available.

The NRLMSISE-00 empirical model is unable to reproduce most of the observed features, with smaller amplitudes and mean deviated values.

The modeling of long-term variations is optimally performed by modulating in amplitude a series of sinusoidal functions, which are previously fitted into a common-flux normalized data. Explaining the 99% of the total variance, the parameterization of the three first PCA components achieve 96% of correlation.

The residuals have been analyzed in the spectral domain, and additional periodic contributions have been found at the frequencies of the P1 and K1 radiational constituents (theory of tides). The possible hypothesis on thermospheric air mass density variations driven by the complete spectrum of diurnal radiational-waves is suggested.

The correlation study has shown that short-term density variations better correlate with the *Dst* and k-derived (*kp, ap, Am*) geomagnetic indices. The corresponding time-delays are 0 h for *Dst* and about 5 h for the k-derived indices.

These results are intended to promote the improvement of the current force-models used in POD with the analysis of accurate GPS POD and accelerometer measurements.

Andrés Calabia is a Ph.D candidate at the Shanghai Astronomical Observatory, CAS, China. He is a recognized academic and accomplished professional engineer and scientist with over 5 years' experience in academic research, and about 7 years' experience in civil industry. He has several publications and his research interests include satellite geodesy, navigation and remote sensing.

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