Solar activity and Space Weather effects on Earth's upper atmosphere

Analysis of thermosphere density from ESA GOCE mission

Scienza
Tecnologia
Spaziale

Francesco Berrilli, Carlo Cauli, Mija Lovric, Alberto Bigazzi, Marco Colace

Department of Physics, University of Rome Tor Vergata, Italy

francesco.berrilli@roma2.infn.it

https://www.fisica.uniroma2.it/~solare/en/

S. Scardigli, F. Berrilli, S. Jefferies, N. Murhy, B. Fleck

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Summary

- What is Space Weather?
- Space Weather scientific background
- Solar activity and thermosphere: an example of operational space weather service
- Analysis of thermosphere density from ESA GOCE mission
- Outcomes

What is Space Weather?

Although “space weather” is a fairly recent term, there is a rich history of similar terms being used beginning in the middle to late 1800s. “Solar meteorology,” “magnetic weather,” and “cosmic meteorology” all appeared during that time frame.
(Cade & Chan-Park, The Origin of “Space Weather,” Space Weather, **13**, 99, 2015)

Table 1. Summary of the First Uses of Various Terms Related to Space Weather

Year	Term	Usage	Originator
1847	Solar meteorology	Sunspots and the conditions of the Sun’s atmosphere	John Herschel, *Herschel* [1847]
1850	Magnetic weather	Disturbances in the Earth’s magnetic field	John Phillips, *Phillips* [1851]
1872	Cosmic meteorology	Solar-terrestrial interaction	Giovanni Donati, *Donati* [1872]
1953	Outer space weather	Fictional aliens, studying the Earth, might ask “would the climate be suitable for us since we are used to outer space weather?”	Fred Hague, *Hague* [1953]
1955	Electrical weather	Dynamics of the ionosphere and resulting magnetic disturbances	Ann Ewing, *Ewing* [1955]
1956	Interstellar meteorology	Motions and transformations of interstellar clouds	Lyman Spitzer, *Spitzer* [1956]
1957	Space “weather”	“The weather of interstellar space, the motions and composition of the vast clouds of matter in the void between stars”	Science News Letter, *Society for Science and the Public* [1957]
1959	Space weather	Refers to measurements of the radiation belts by Explorer VI	Science News Letter, *Society for Science and the Public* [1959]
1964	Space weather	Scientists are “trying to set up a space weather bureau which could give astronauts advance notice of solar storms.”	Walter Wingo (editor, Science News Letter), *Wingo* [1964]
1968	Space weather (first appearance in peer-reviewed literature)	Space weather forecasting as a part of the new Environmental Science Services Administration	Walter Hahn, *Hahn* [1968]

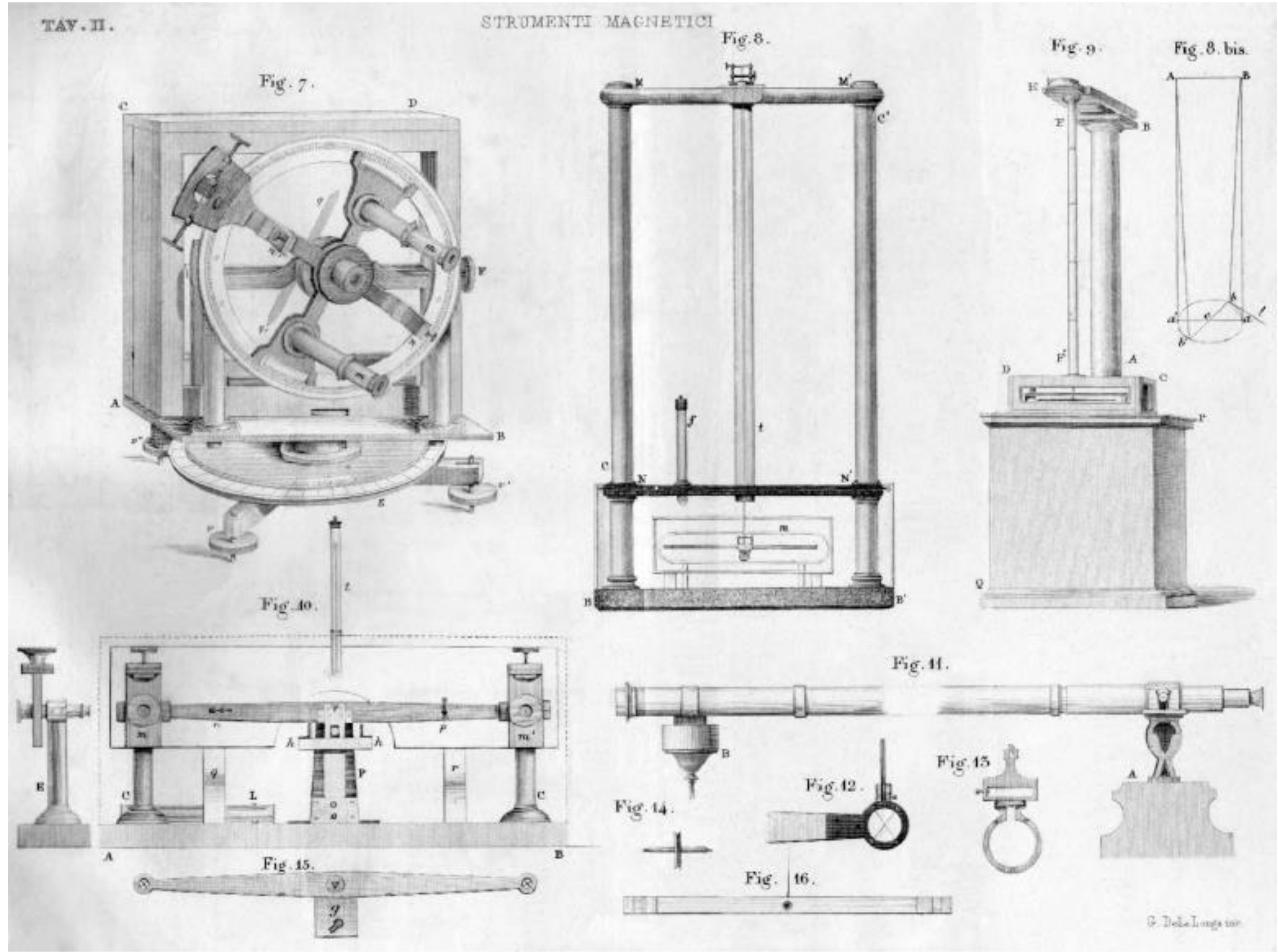

Plate II (“Tav. II”) showing the instruments installed in the Collegio Romano Magnetic Observatory (Secchi, 1861)

Father Angelo Secchi (**International Conference - THE LEGACY OF ANGELO SECCHI 200 YEARS AFTER HIS BIRTH, Rome, September 3-5, 2018, Biblioteca Casanatense**) realized a permanent magnetic observatory in 1858 in Rome in connection with magnetic observatories in Stonyhurst (UK), Manila, Ebro (SP) and Zi-ka-wei (China).

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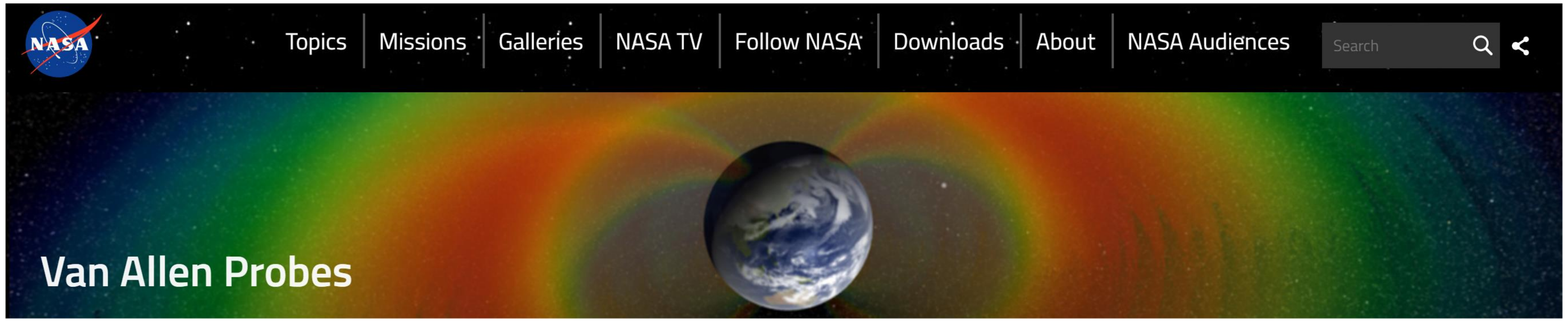
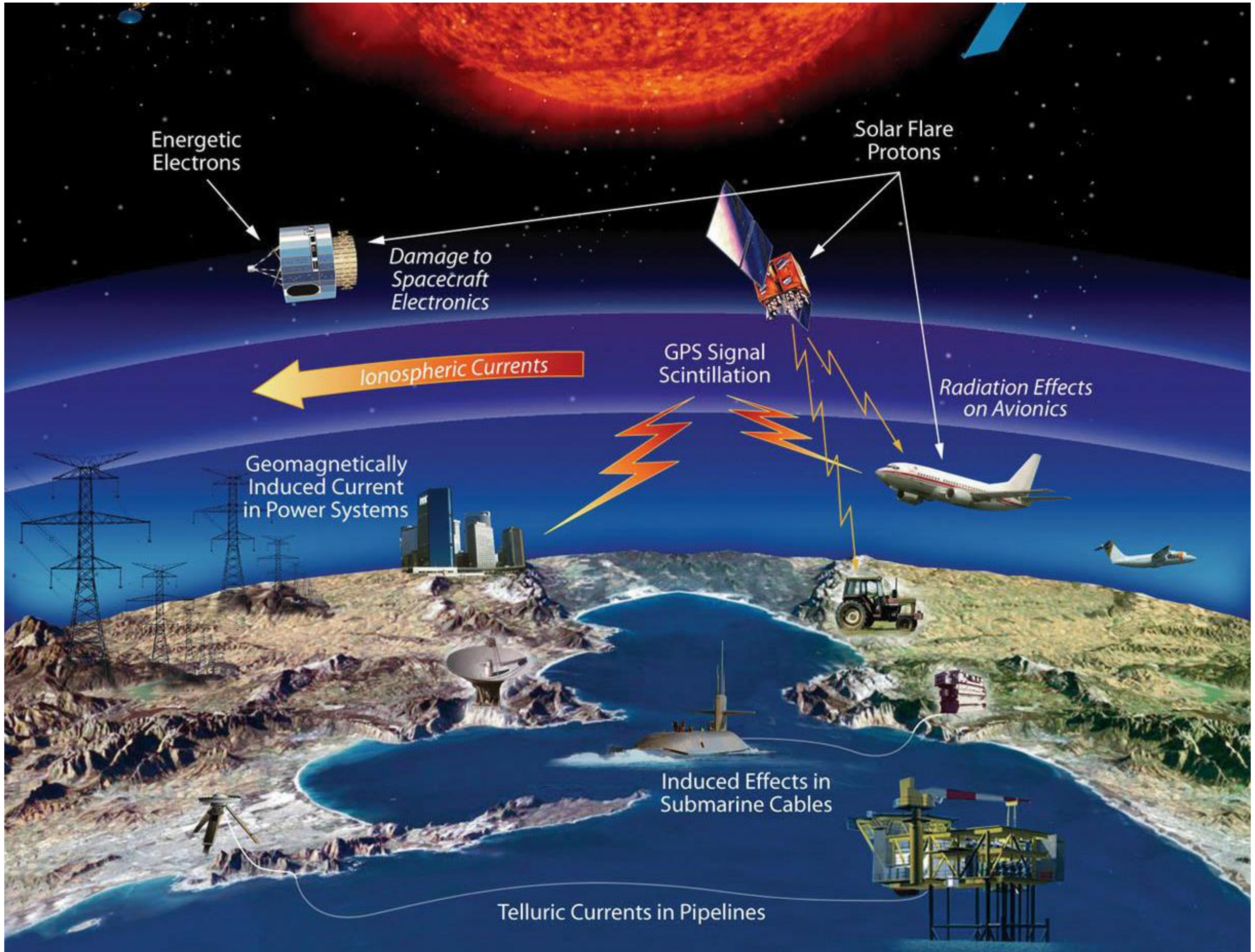
What is Space Weather?

The term space weather generally refers to **conditions on the sun**, in the **solar wind**, and **within Earth's magnetosphere, ionosphere and thermosphere** that can influence the **performance** and **reliability** of **space-borne** and **ground-based** technological systems and can endanger **human** life or **health**.





https://www.nasa.gov/mission_pages/rbsp/science/rbsp-spaceweather.html

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Space Weather Scientific Background

6. Impact of Solar Activity on the Ionosphere/Thermosphere

2. Modification of the coronal magnetic field in response to the emergence of new magnetic field and photospheric advection

4. Transport in the interplanetary medium of CME and Solar Wind

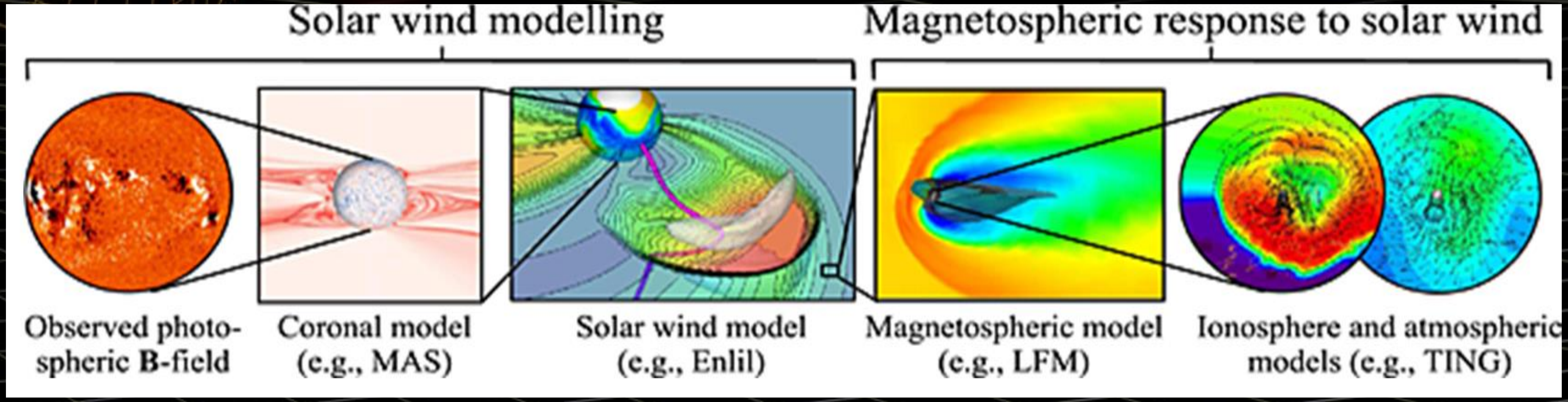
7. GCRs and solar particles in the near-Earth environment

5. Magnetic interaction of CME with the Earth's magnetosphere

1. Emergence of magnetic flux from the solar interior in active regions

3. Eruptive events in the Sun
MHD instabilities (flares, CME, SPE, ..)

Convective Global Dynamo



from "Sol-Terra: A Roadmap to Operational Sun-to-Earth Space Weather Forecasting", Marsh et al., in www.stce.be/esww12

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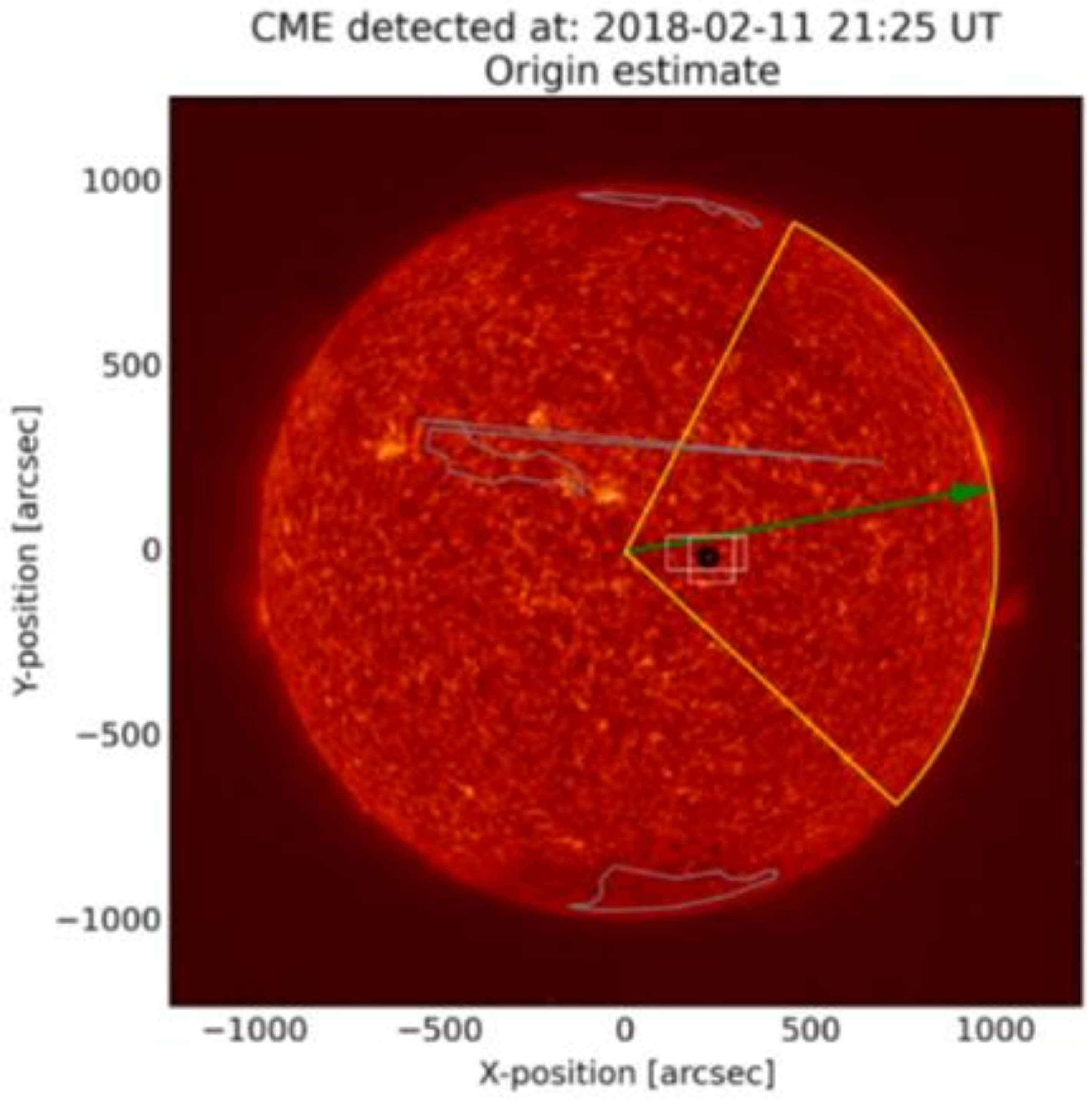

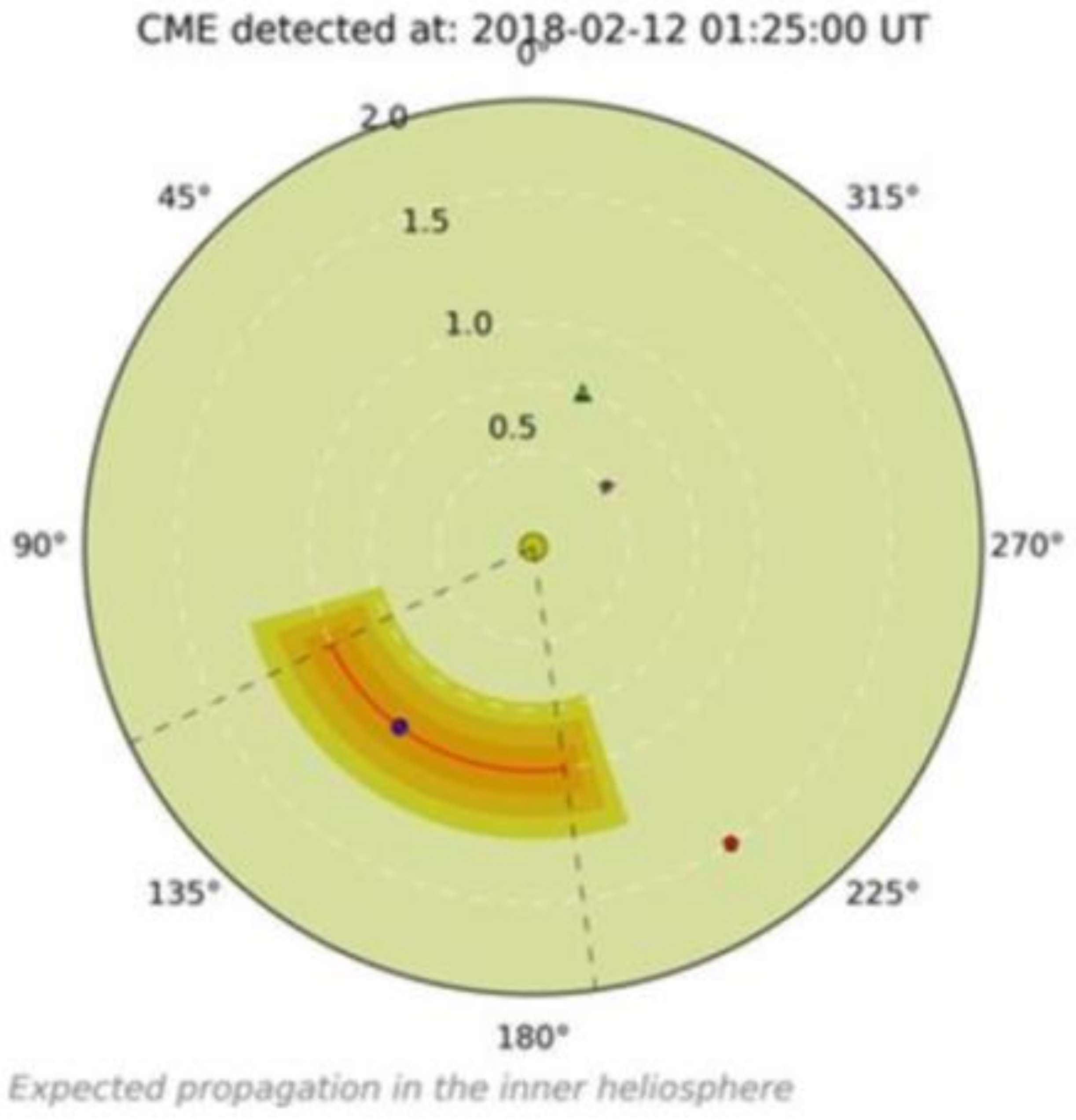

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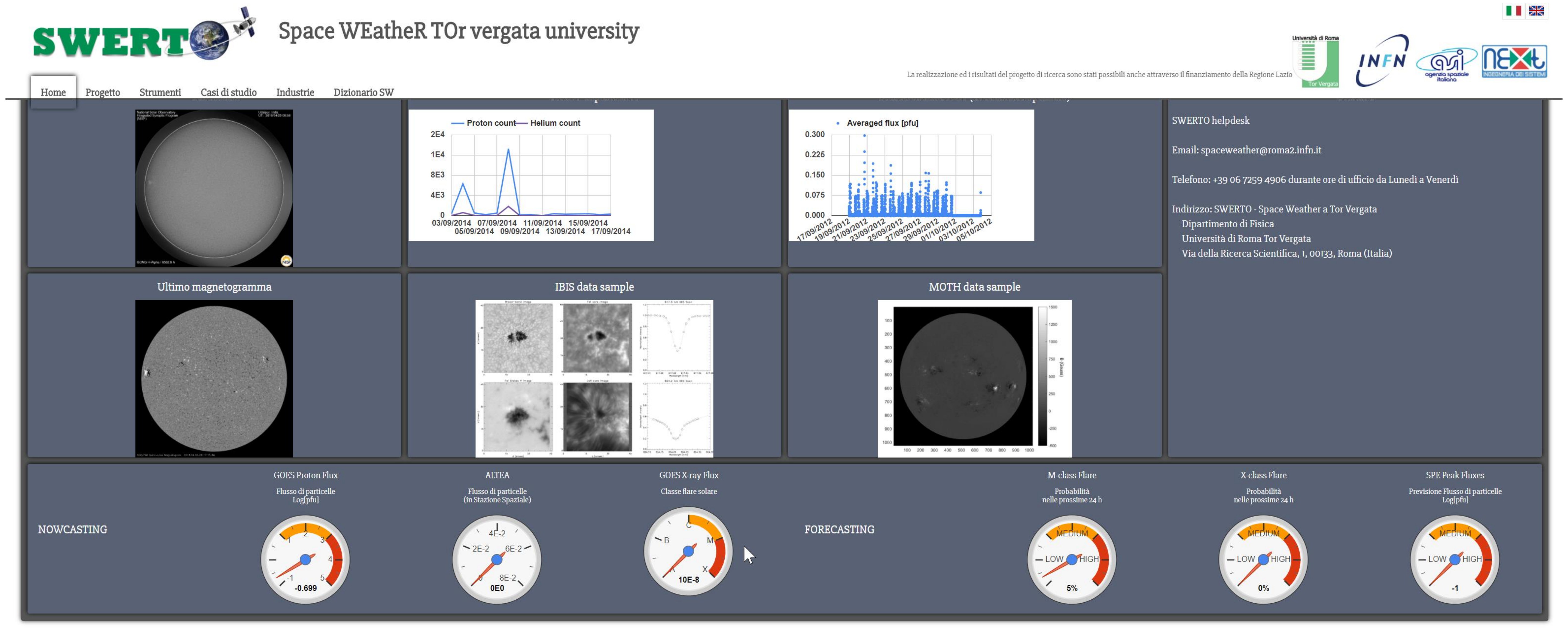
spaceweather.roma2.infn.it



Berrilli *et al*., *SWERTO: a Regional Space Weather Service*, in Proceedings IAUS No. 335, 2018 in press

Del Moro *et al*., Forecasting the CME propagation with the P-DBM model, Proceedings IAGA Italia Symposium, 2018 in press

Napoletano *et al*., A probabilistic approach to the dragbased model, Journal of Space Weather and Space Climate, 8, 25 A11, 2018

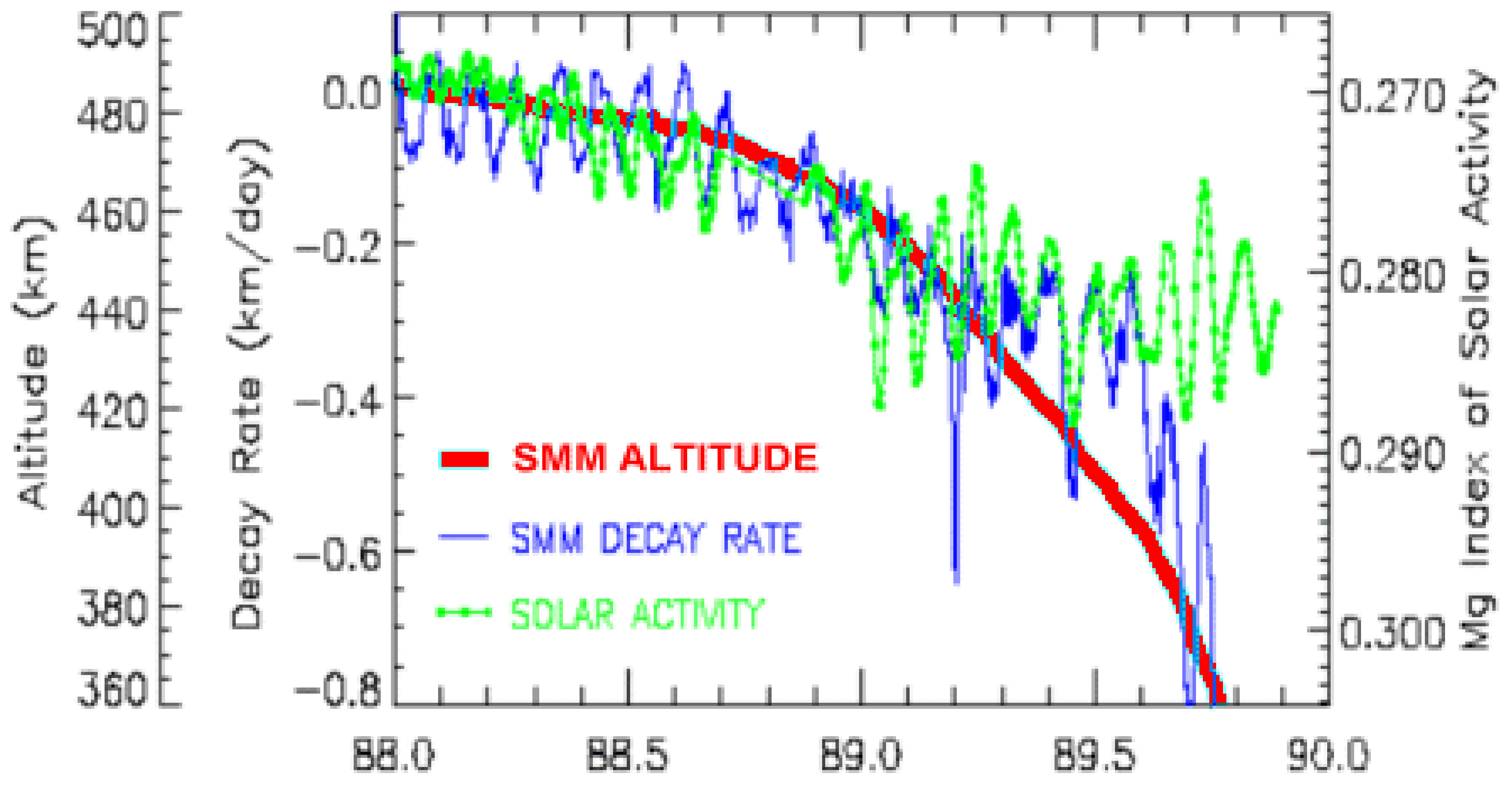
Density modeling of the thermosphere for the de-orbiting timeline of satellites and debris (ESA/SSA) is key issue of Space Weather.

Two main topics in the description of the thermosphere density are:

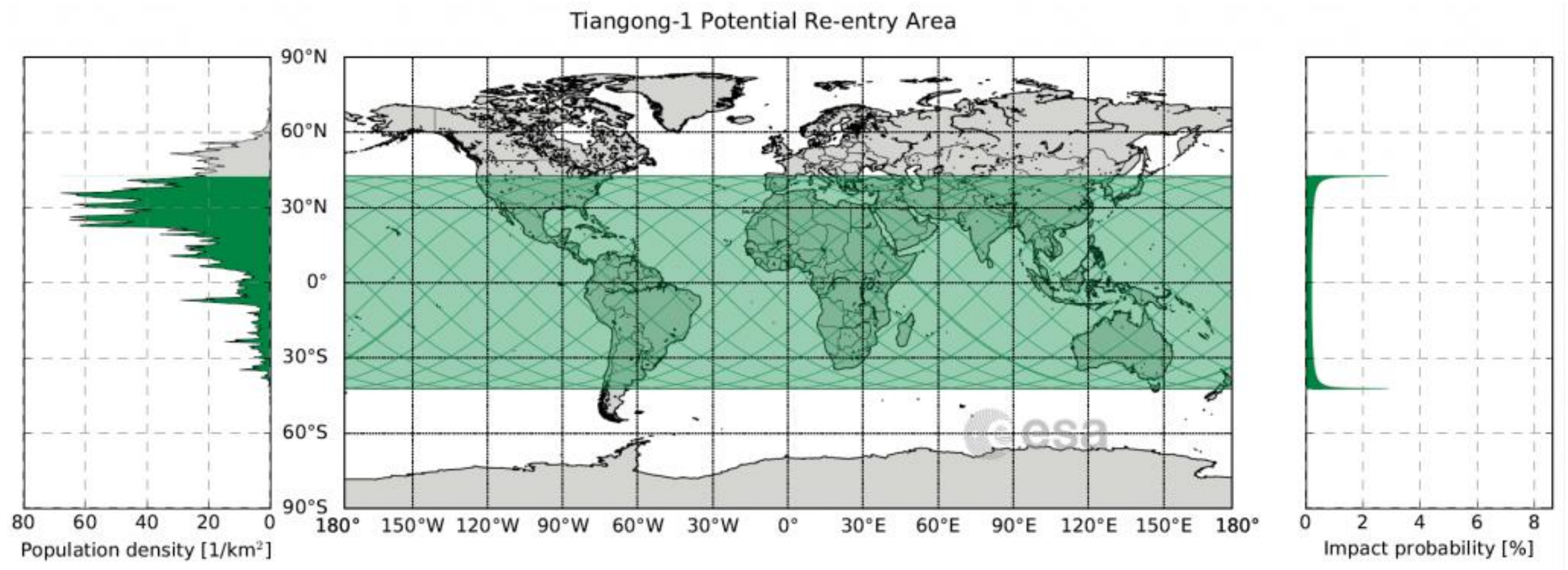
1. the use of appropriate solar inputs (especially solar EUV)
2. the empirical modeling of thermosphere response to solar and to geomagnetic forcings.

This specification is crucial for the tracking of low Earth orbiting satellites.

(e.g., Dudok de Wit and Bruinsma, Geophys. Res. Lett., **38**, L19102, 2011)



The decay rate of the Solar Maximum Mission, which deorbited in December 1989, varied with the Sun's 27-day rotation and the solar cycle. This image, which originally appeared in The Sun's Variable Radiation and its Relevance for Earth (Annual Reviews of Astronomy & Astrophysics, 1997) is courtesy of Dr. Judith Lean.



http://blogs.esa.int/rocketscience/2018/03/26/tiangong-1-reentry-updates/

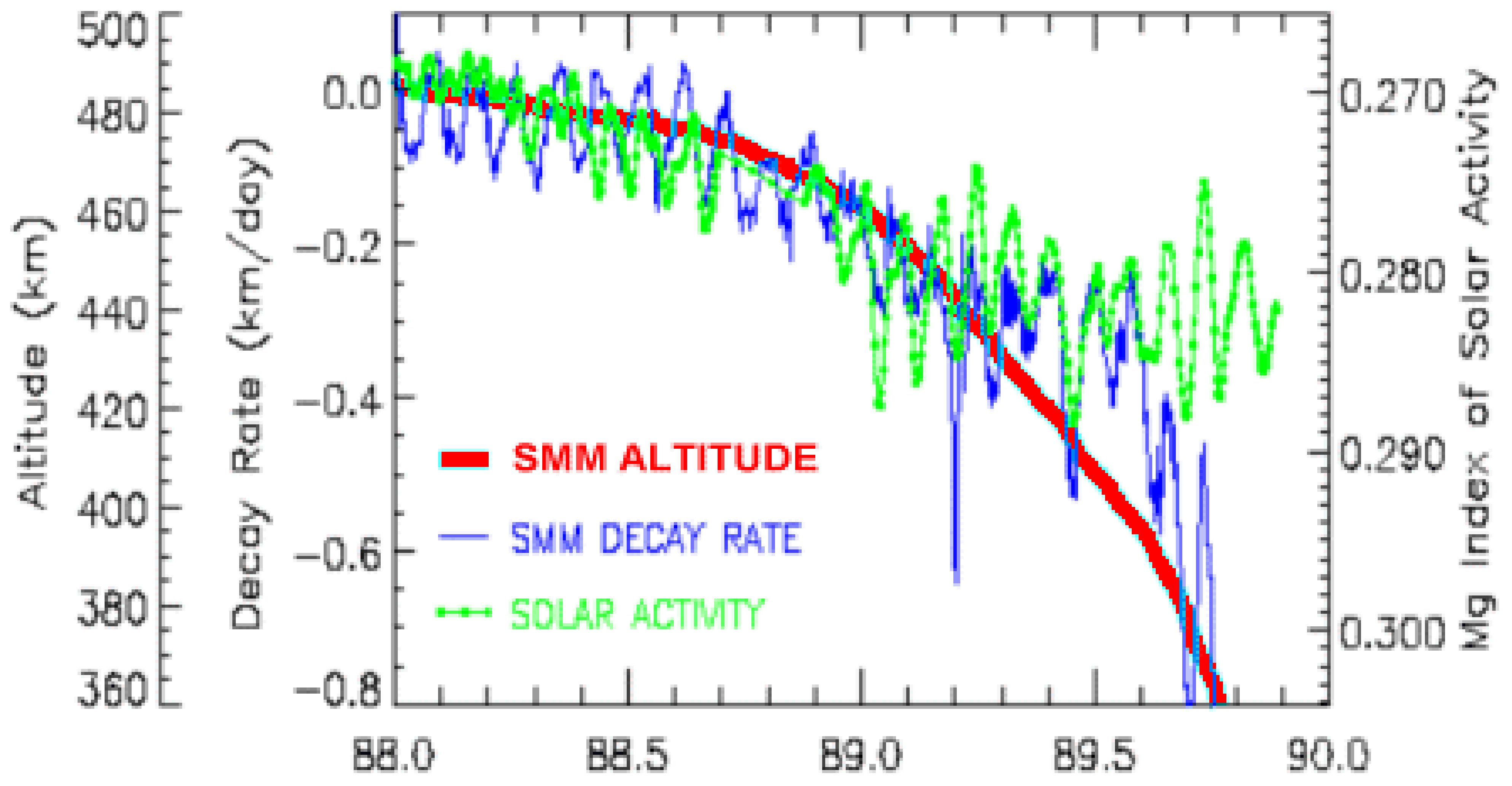
Berrilli+, 2018, Isradynamics

Various EUV solar flux proxies can be considered:

1) the F10.7 index from Penticton Observatory, Canada;
2) the MgII index (LASP composite/Bremen Mg II composite);
3) the integrated flux between 26–34 nm from the SEM radiometer onboard SoHO;
4) the s10.7 index, which has been built for orbitography purposes;
5) Lya, the intensity of the bright Lyman-a line (LASP composite);
6) XUV, the baseline of the daily soft X-ray flux in the 0.1–0.8 nm band (GOES).

Geomagnetic activity is represented by the planetary geomagnetic index *Ap* (the Ap-index is thus a geomagnetic activity index where days with high levels of geomagnetic activity have a higher daily Ap-value..

From Dudok de Wit and Bruinsma, Geophys. Res. Lett., **38**, L19102, 2011)



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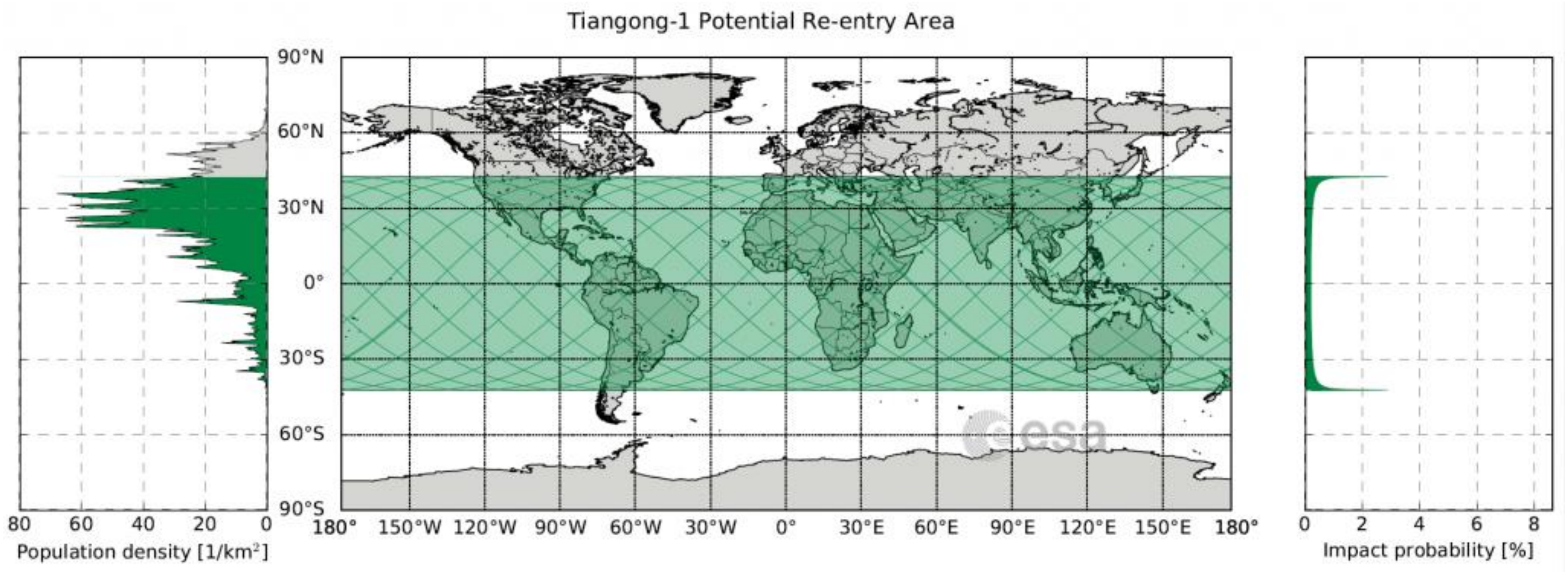

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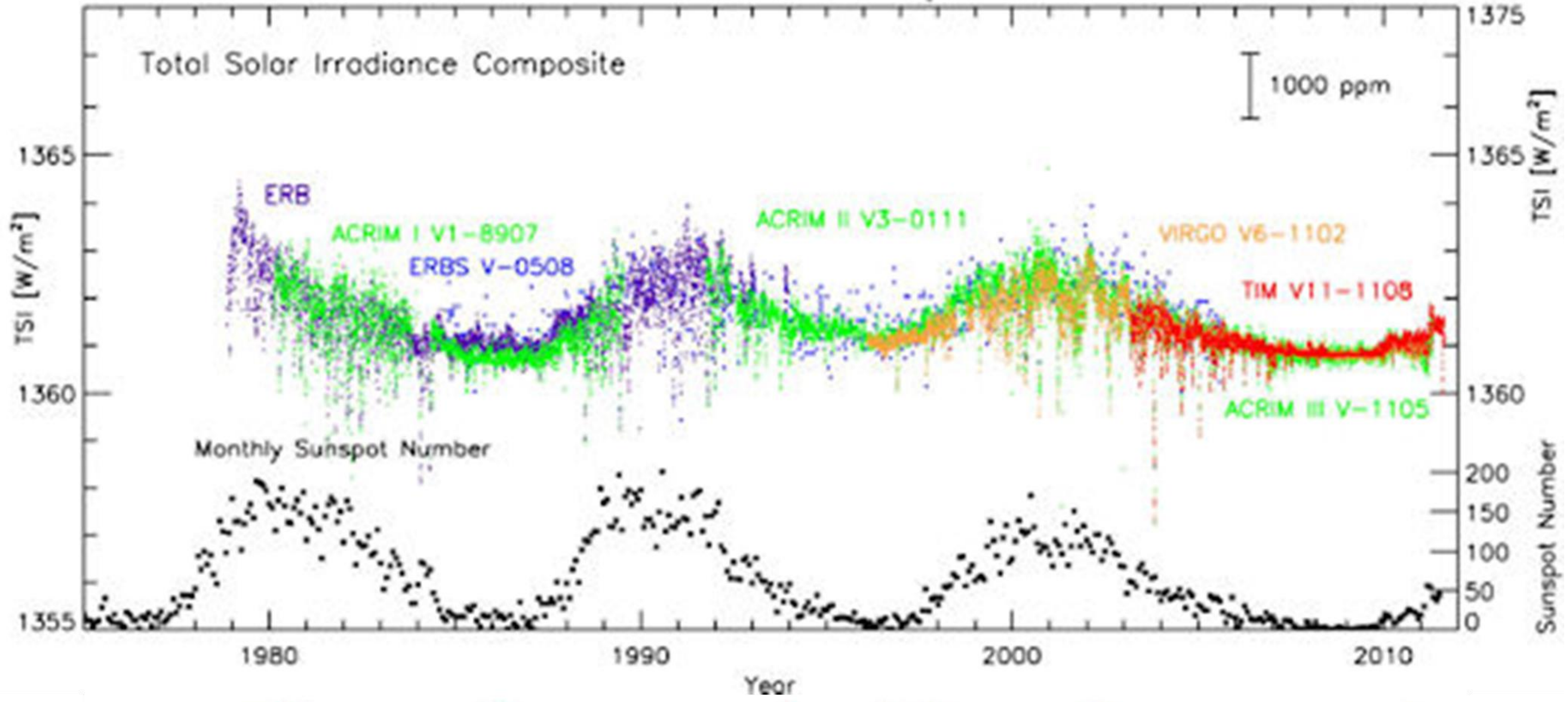
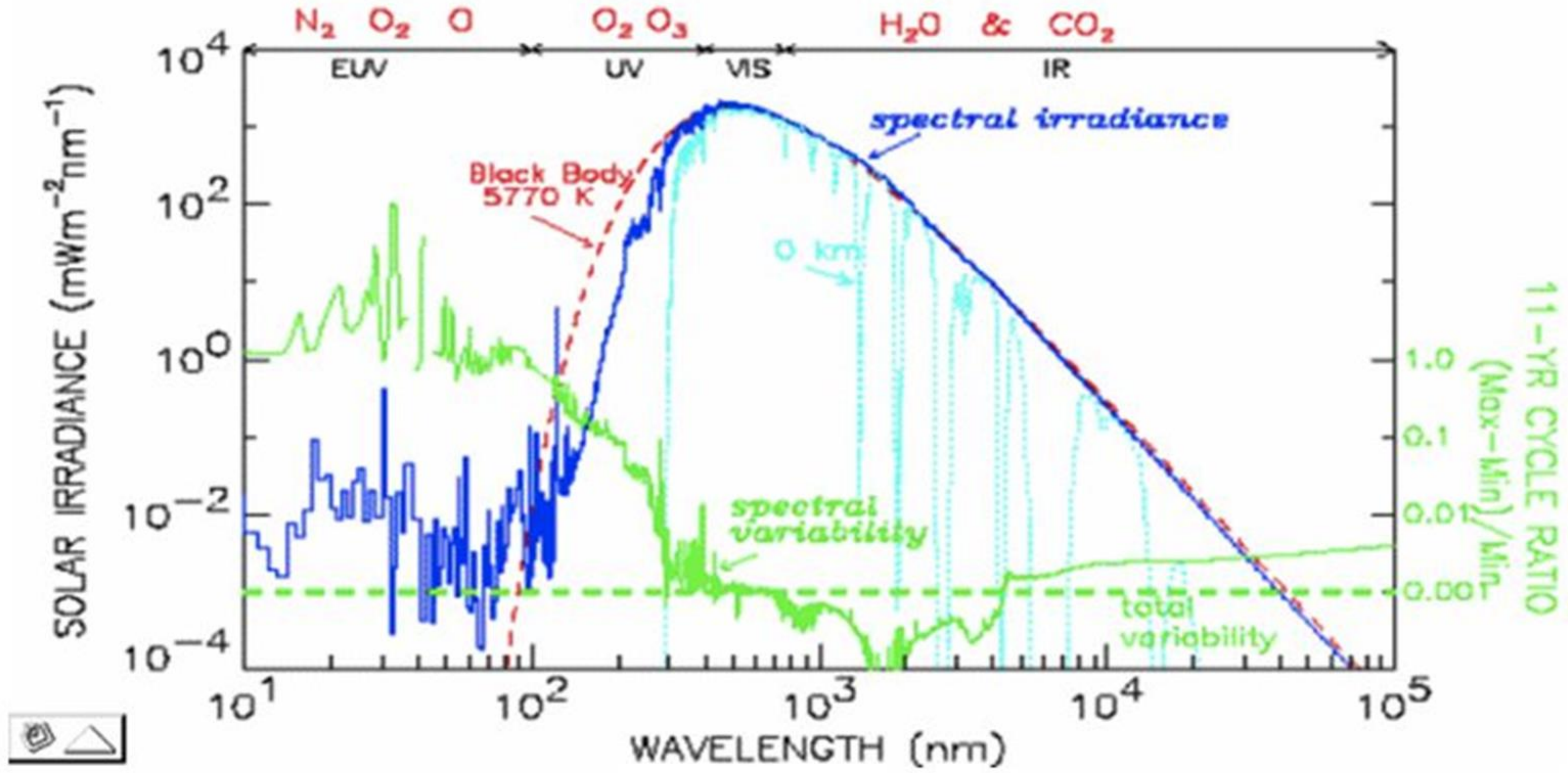
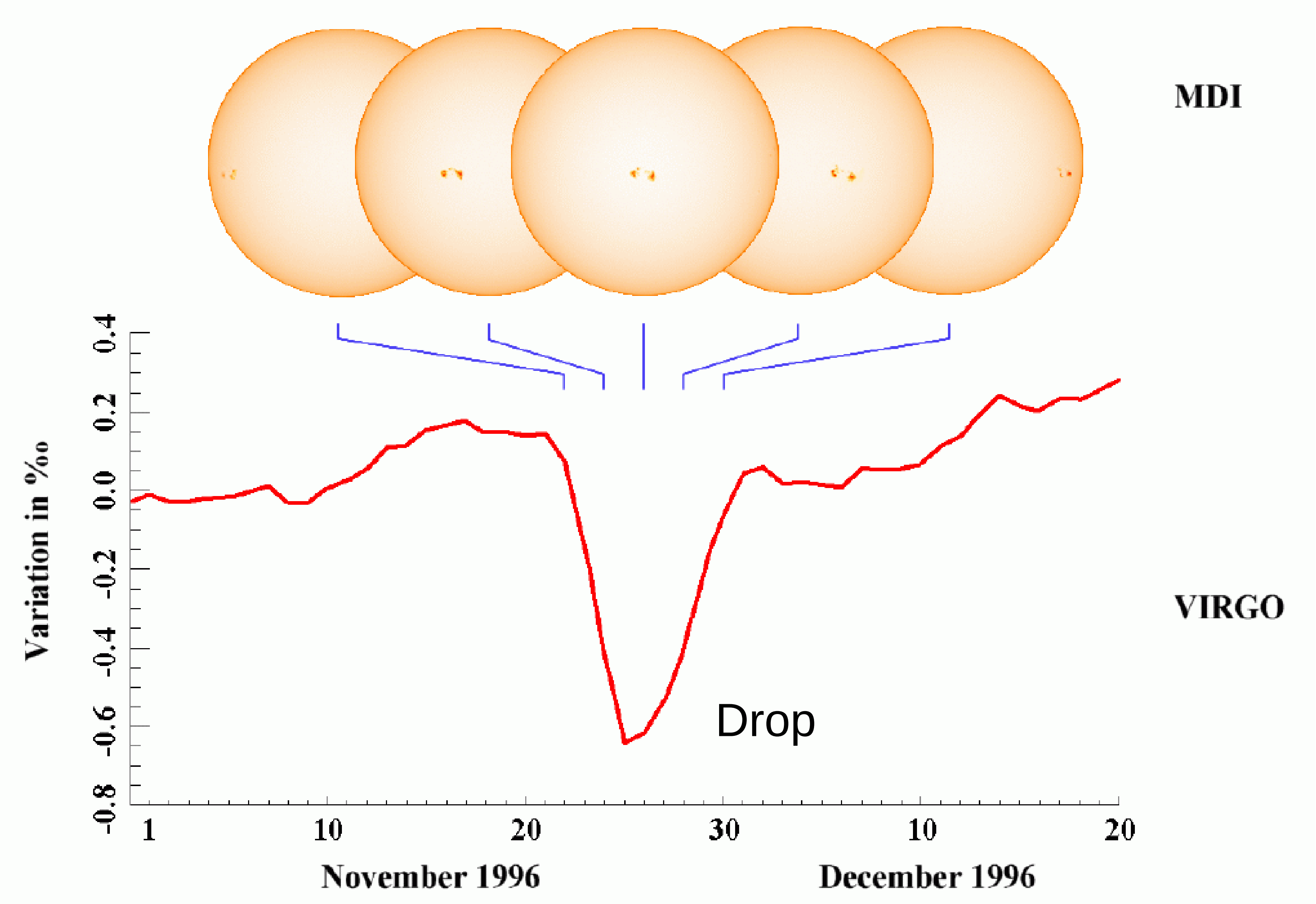


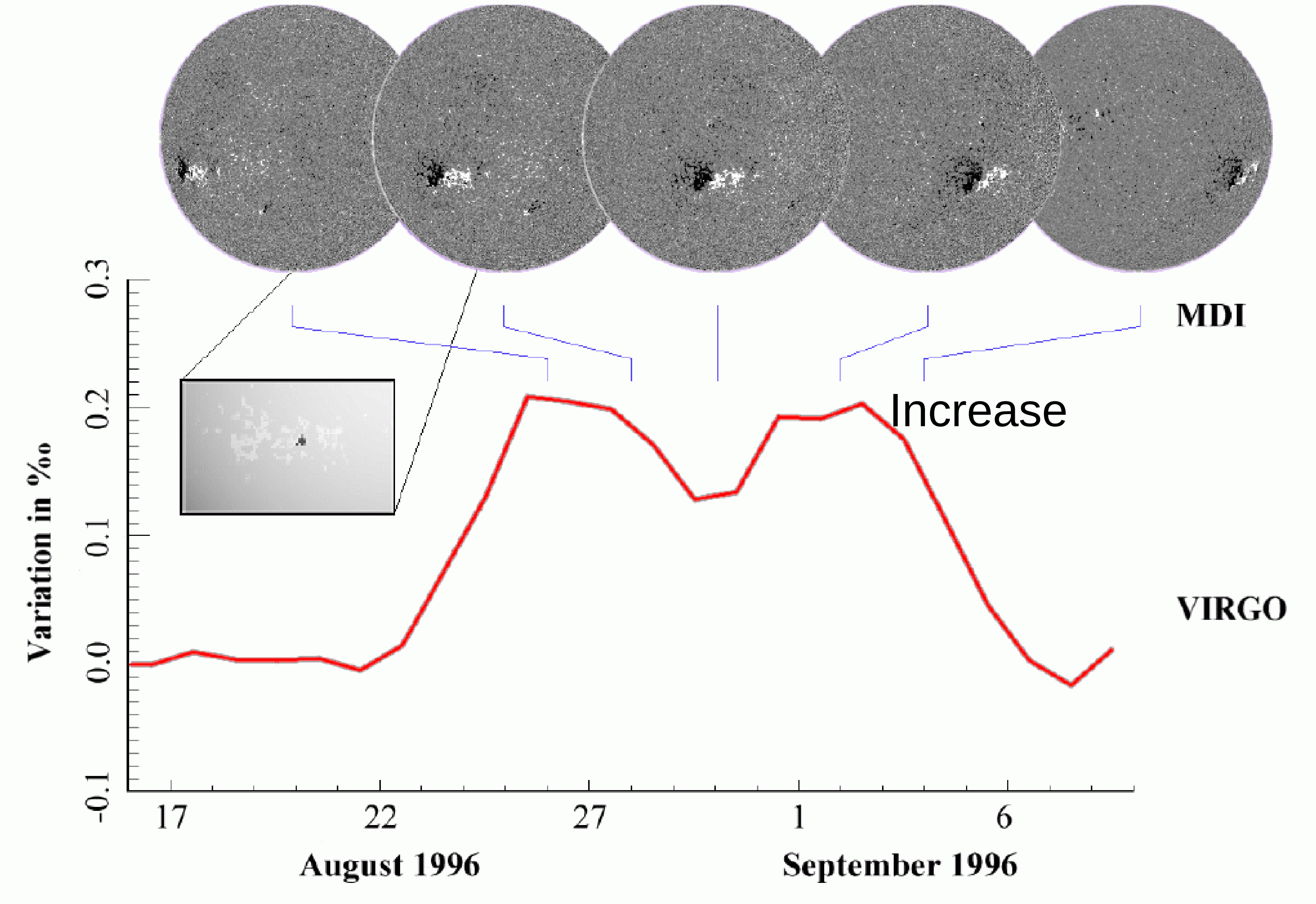
The solar spectral irradiance



Plot by J. Lean, NRL, courtesy NASA

From UV to X-Rays, variability increases a lot with decreasing wavelength;
However, the bulk of electromagnetic energy at these wavelengths
is absorbed very high in the Earth's atmosphere (stratosphere and higher).
The UV (120-400nm) accounts for 1% of the TSI, but 14% of its variability.





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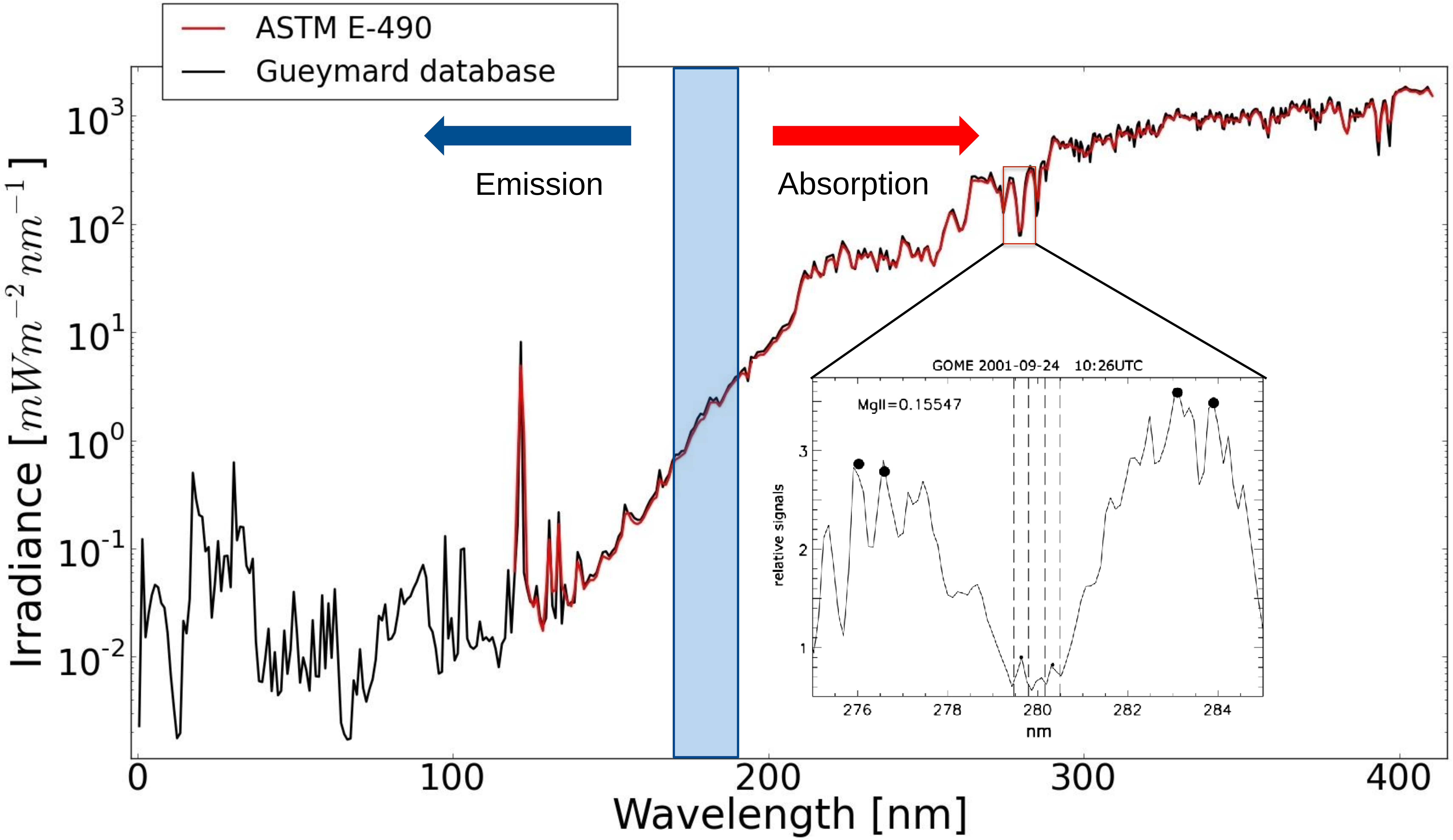

Solar UV irradiance at 1 AU (astronomical unit). The red line shows the data from ASTM E-490 while the black line shows the spectral data of Gueymard. These data are representative for average solar activity conditions. L'indice Mg II index is a good describer of solar facular TSI and UV components (Dudok de Wit *et al*., 2009).

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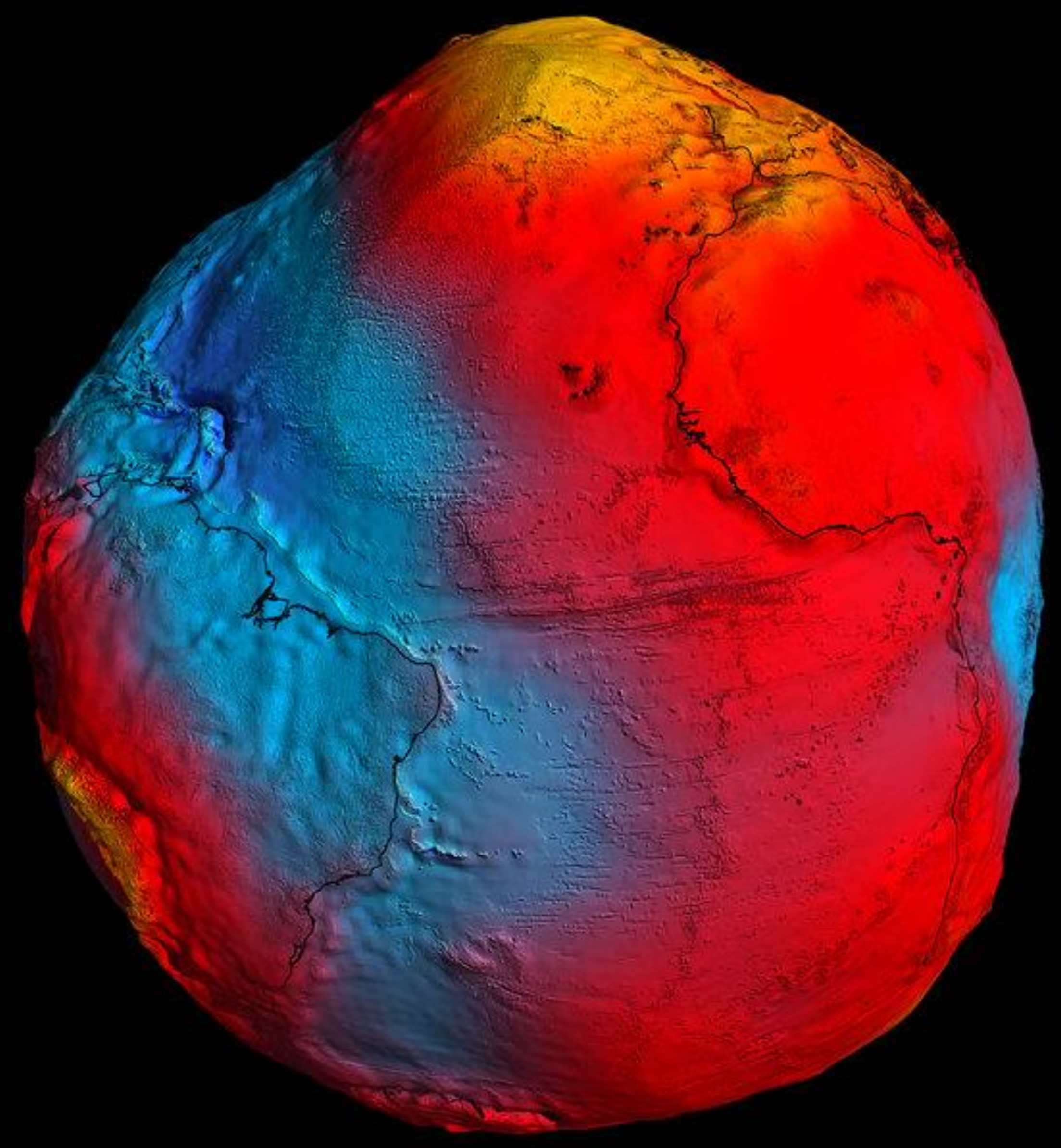
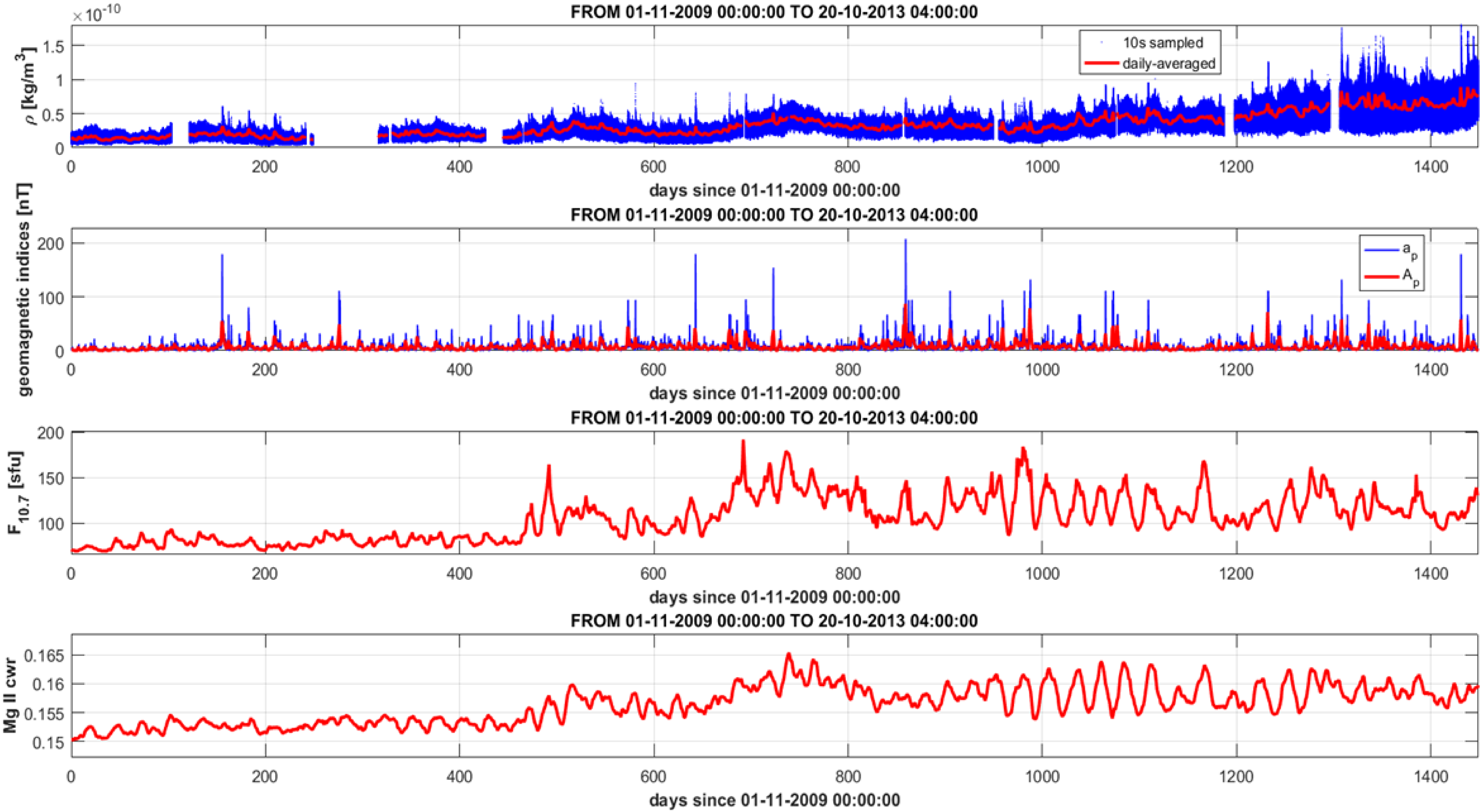
- Launched on 17 March 2009, ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission was the first Earth Explorer mission in orbit.
- GOCE mission delivered a wealth of data to bring about a whole new level of understanding of one of Earth's most fundamental forces of nature – the gravity field.
- This high-tech gravity satellite embodied many firsts in its design and use of new technology in space to map Earth's gravity field in unprecedented detail.
- On-board ultra-sensitive accelerometers used to create dataset of 10s sampled thermospheric density at 260 km altitude available at ESA GOCE Archive (01/11/2009 - 20/10/2013)



The colours in the image represent deviations in height (–100 m to +100 m) from an ideal geoid. The blue shades represent low values and the reds/yellows represent high values.
http://www.esa.int/spaceinimages/Images/2011/03/New_GOCE_geoid

https://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Introducing_GOCE

Berrilli+, 2018, Isradynamics



a) Atmospheric density vs time (both 10 s sampled and daily averaged) during GOCE mission; b) Geomagnetic index ap and daily-averaged geomagnetic index Ap vs time during GOCE mission; c) and d) F10.7 and Mg II cwr vs time during GOCE mission (signal spikes are removed by interpolation). Mg II index seems "cleaner" and less noisy than F10.7.

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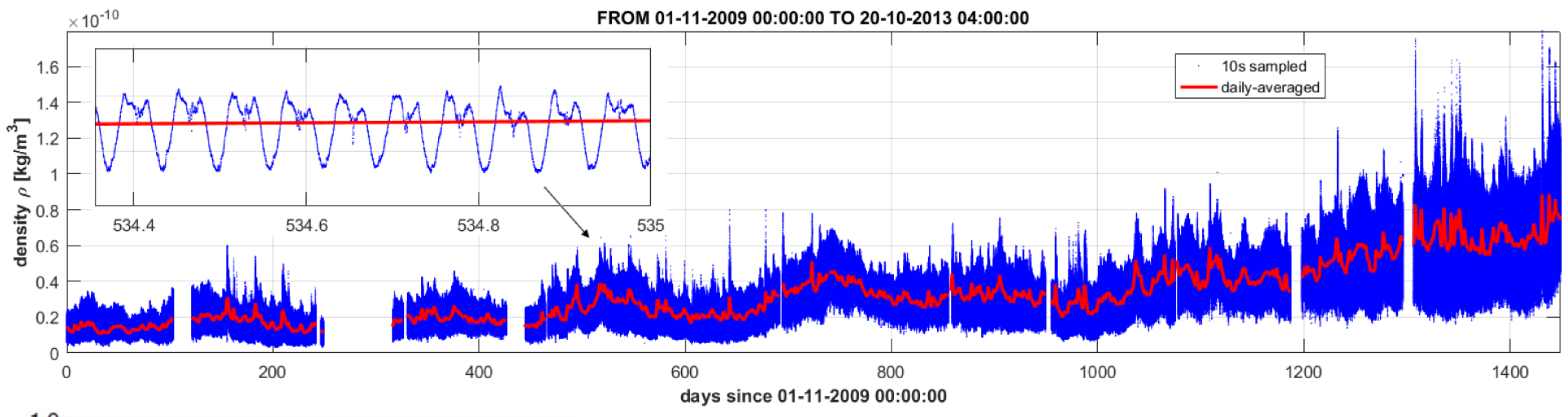
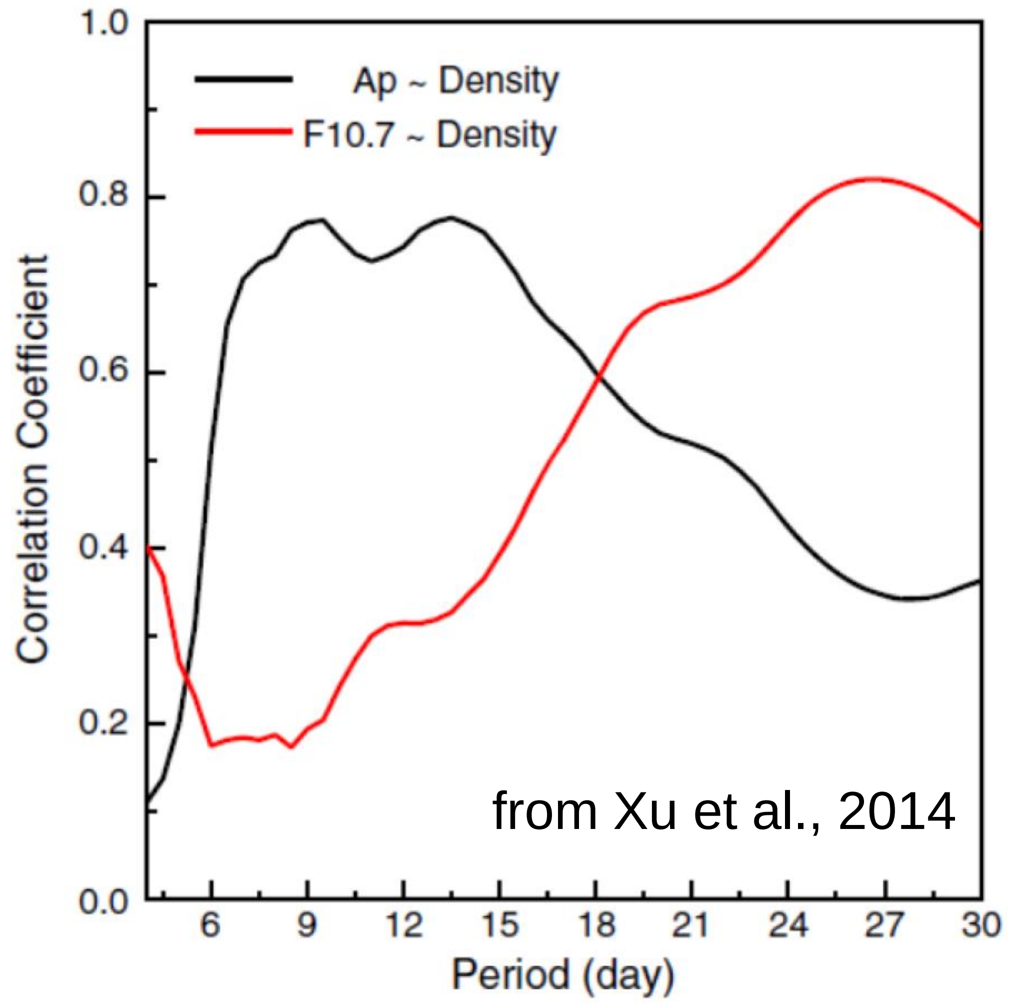
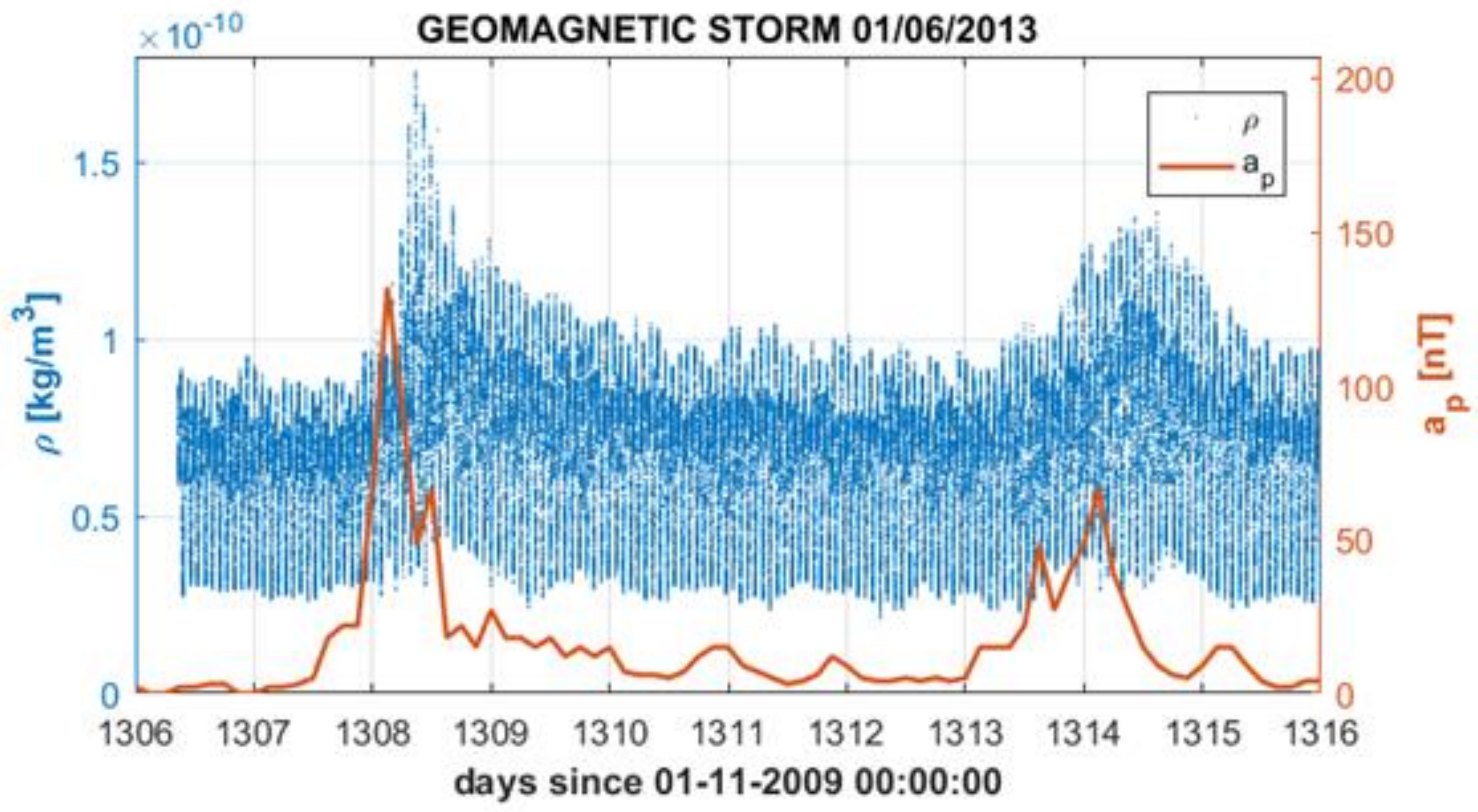
1. Impulsive variations of *ap* and long-term evolution of F10.7 and Mg II indices are well correlated with thermosphere density variability.

2. The long-term thermosphere density variations are poorly-correlated with geomagnetic index and well-correlated with solar flux indices (especially with Mg II index).

3. The thermosphere response to impulsive changes of *ap* index is within 6-9 hours.







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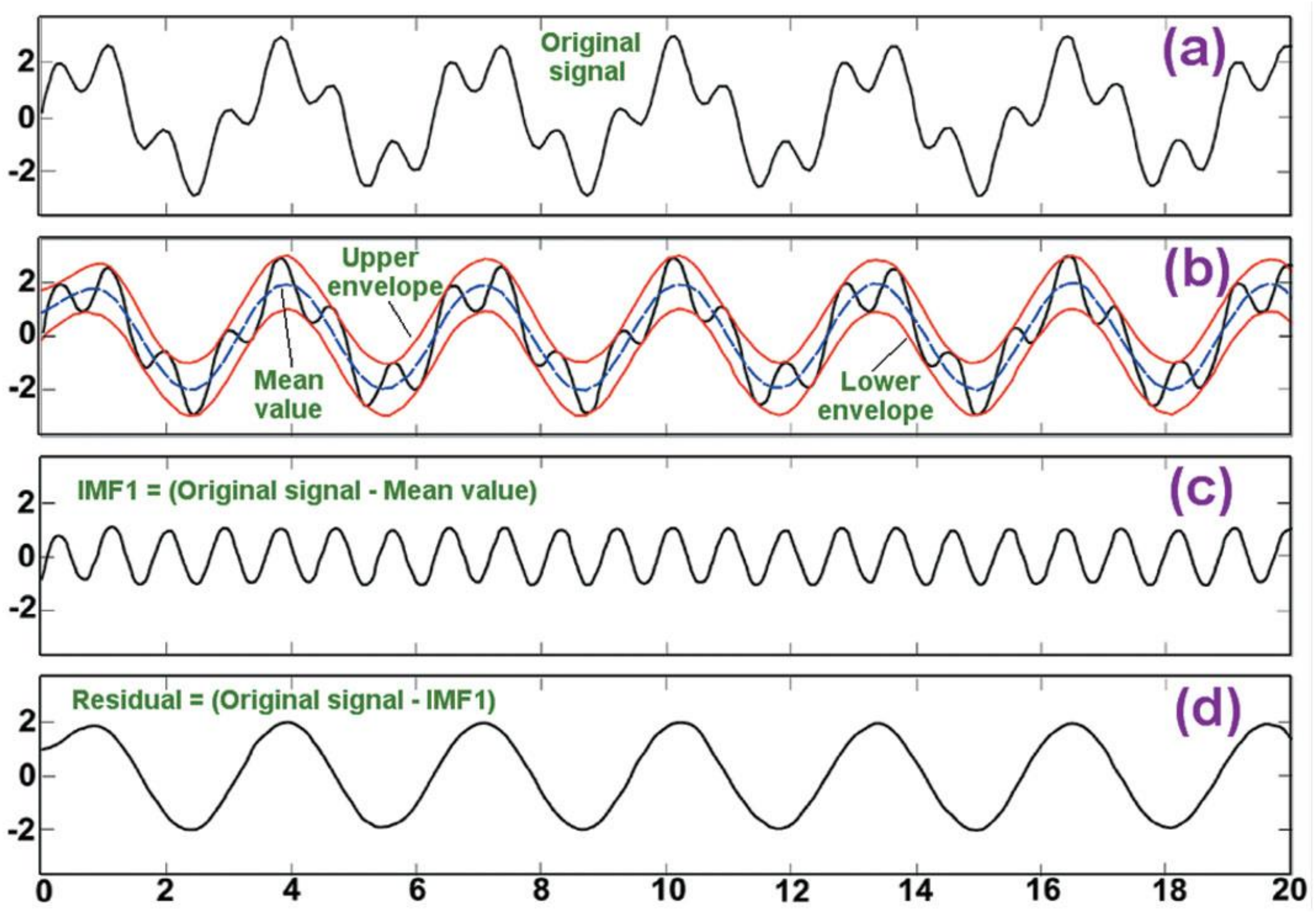
In order to investigate the different contributions to variations in **ρ**, the empirical mode decomposition (**EMD**) of thermosphere density and **solar** and **geomagnetic indices** (quasi-periodic and non-stationary) during **GOCE** mission has been performed.

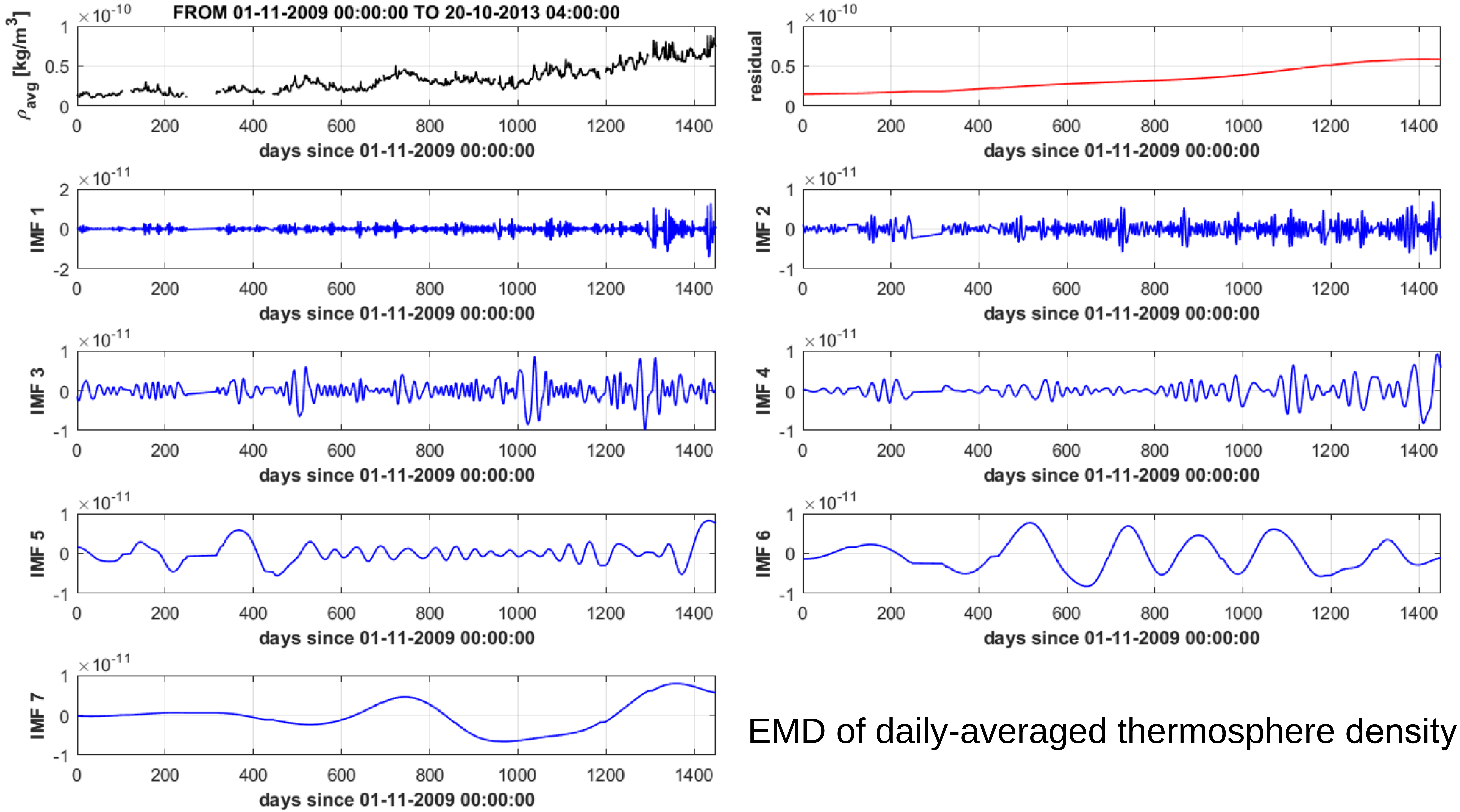


EMD decomposition of two waves signal, (a) sum of two waves, (b) lower and upper envelopes (red) and their mean (blue), (c) the first IMF and (d) the first residual (after Oonincx and Hermand, 2004).

Generally speaking, the sifting process (to separating out components of a signal one at a time) produces a **set of IMFs that represent the original data vector broken down into frequency components from highest to lowest frequency.**

If all of the IMFs for a given signal are added together, the resulting “summation” signal is a near perfect match for the original signal (i.e., with little or no leftover), yielding a high level of confidence in the EMD results.

(from Hassan & Peirce, 2008)



EMD of daily-averaged thermosphere density ρ

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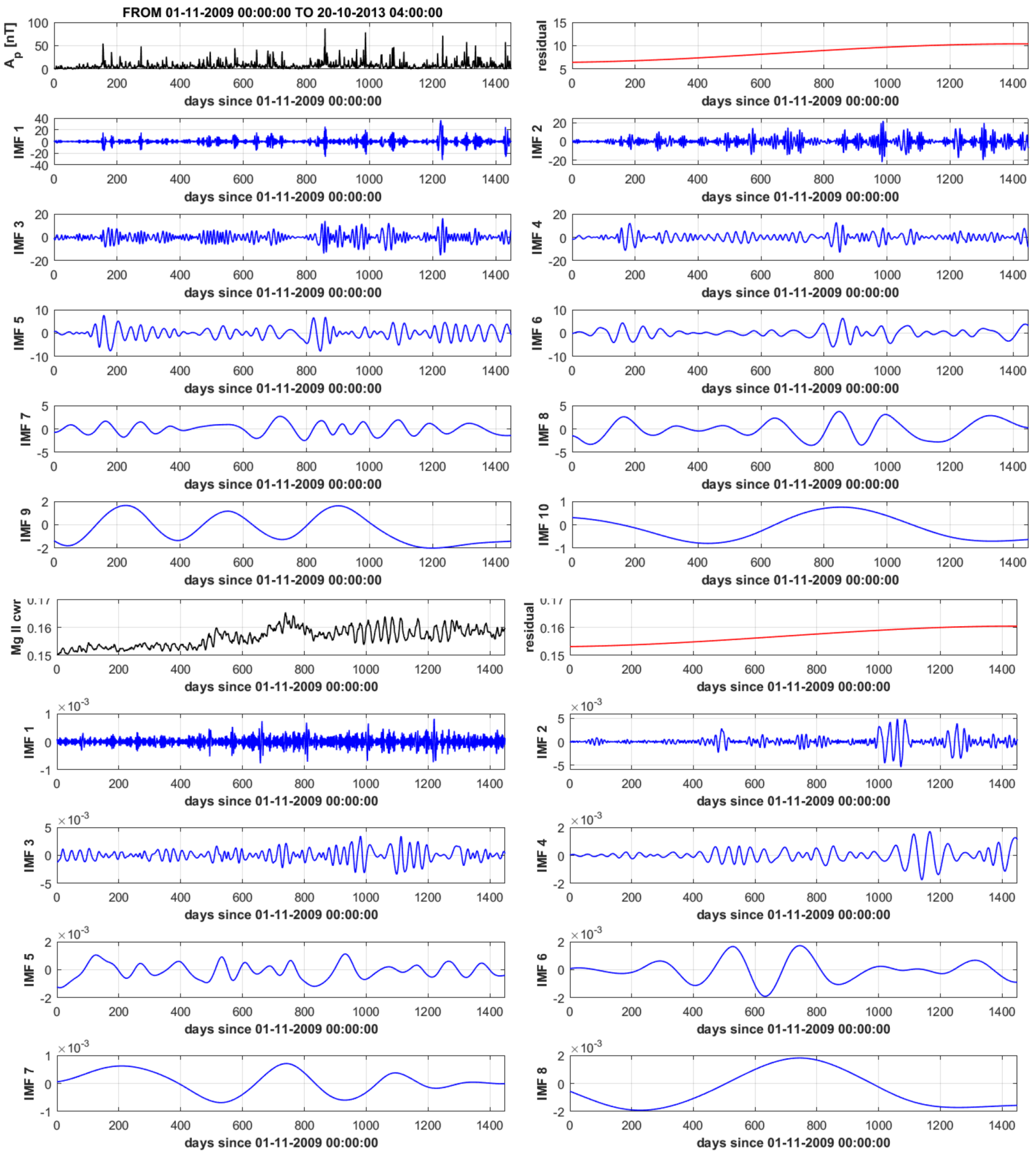
10 IMFs for **Ap** have been identified (+ residual trend)

- the first IMFs are relevant for the impulsive Ap index;
- the residual shows a monotonic profile (geomagnetic activity ↑ when solar cycle ↑);
- the amplitude of the oscillations ↑ during magnetic storms.

8 IMFs for **MgII** have been identified (+ residual trend)

- IMF3 (and 2) are associated to 27-day solar rotation;
- the residual trend shows that MgII index ↑ when solar cycle ↑ because chromosphere/photosphere ratio ↑;
- IMF2 and IMF4 are particularly important during the of high solar activity period.



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The approach used to reconstruct the GOCE mission thermosphere density signal is schematized in the following steps:

1. **Input data loading**: the daily-averaged thermosphere density $\bar{\rho}$, the daily-averaged geomagnetic index Ap and the solar flux indices $F10.7$ and $Mg\ II$ are considered.

2. **Solar and geomagnetic indices time shifting**: A 9h time delay is assumed for Ap, no time delay for solar indices. A cubic spline interpolation is used for Ap (1d sampling).

3. **EMD sifting process**: applied to GOCE density and activity indices to extract the corresponding IMFs (IMF_i^{Ap}, $IMF_i^{F10.7}$, IMF_i^{MgII}) and trends (res^{Ap}, $res^{F10.7}$, res^{MgII}).

4. **Thermosphere Density Model(s)**: Iterative data analysis for Ap and solar indices a *weighting factor* and a sub-set of IMFs (including the residual trends) are selected (Monte Carlo approach and exhaustive analysis).

Density signals are reconstruction for the whole period and for different solar activity levels.

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$$\bar{\rho}^{sim}_{norm} = norm_{(0,1)}\left[A^{A_p}\cdot IMF^{A_p}_{norm} + A^{F_{10.7}}\cdot IMF^{F_{10.7}}_{norm} + A^{MgII}\cdot IMF^{MgII}_{norm}\right]$$

- $\bar{\rho}^{sim}_{norm}$ → simulated normalized daily-averaged density
- $norm_{(0,1)}$ → normalization in the range [0,1]
- A^{A_p} → weighting factor for Ap
- $IMF^{A_p}_{norm}$ → normalized sum of pre-selected IMFs for Ap
- $A^{F_{10.7}}$ → weighting factor for F10.7
- $IMF^{F_{10.7}}_{norm}$ → normalized sum of pre-selected IMFs for F10.7
- A^{MgII} → weighting factor for Mg II cwr
- IMF^{MgII}_{norm} → normalized sum of pre-selected IMFs for Mg II cwr

$$IMF^{A_p}_{norm} = norm_{(0,1)}\left[\sum_i^{10} I_i^{A_p}\cdot IMF_i^{A_p} + I_{res}^{A_p}\cdot res^{A_p}\right]$$

$$IMF^{F_{10.7}}_{norm} = norm_{(0,1)}\left[\sum_i^{8} I_i^{F_{10.7}}\cdot IMF_i^{F_{10.7}} + I_{res}^{F_{10.7}}\cdot res^{F_{10.7}}\right]$$

$$IMF^{MgII}_{norm} = norm_{(0,1)}\left[\sum_i^{9} I_i^{MgII}\cdot IMF_i^{MgII} + I_{res}^{MgII}\cdot res^{MgII}\right]$$

IMF_i = i-th IMF

res = residual trend

I_i = logical operator to select the i-th IMF

$$\sigma_{RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left|\bar{\rho}_{norm}(n) - \bar{\rho}^{sim}_{norm}(n)\right|^2}$$

$\bar{\rho}_{norm}(n)$ → normalized daily-averaged density from GOCE mission

Merit function

	σ_{RMS} [%]	index	1	2	3	4	5	6	7	8	9	10	res
whole mission	10.78	A_p	✓	✓	✓	✓	✓	✓		✓	✓		✓
		Mg II	✓			✓		✓	✓				✓
low solar activity	2.62	A_p	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		$F_{10.7}$		✓				✓					✓
		Mg II					✓	✓		✓			✓
medium solar activity	7.37	A_p	✓	✓	✓	✓	✓	✓	✓				✓
		$F_{10.7}$	✓	✓									✓
		Mg II	✓			✓		✓	✓				✓
high solar activity	13.75	A_p	✓	✓	✓	✓	✓	✓	✓		✓		
		Mg II							✓				✓

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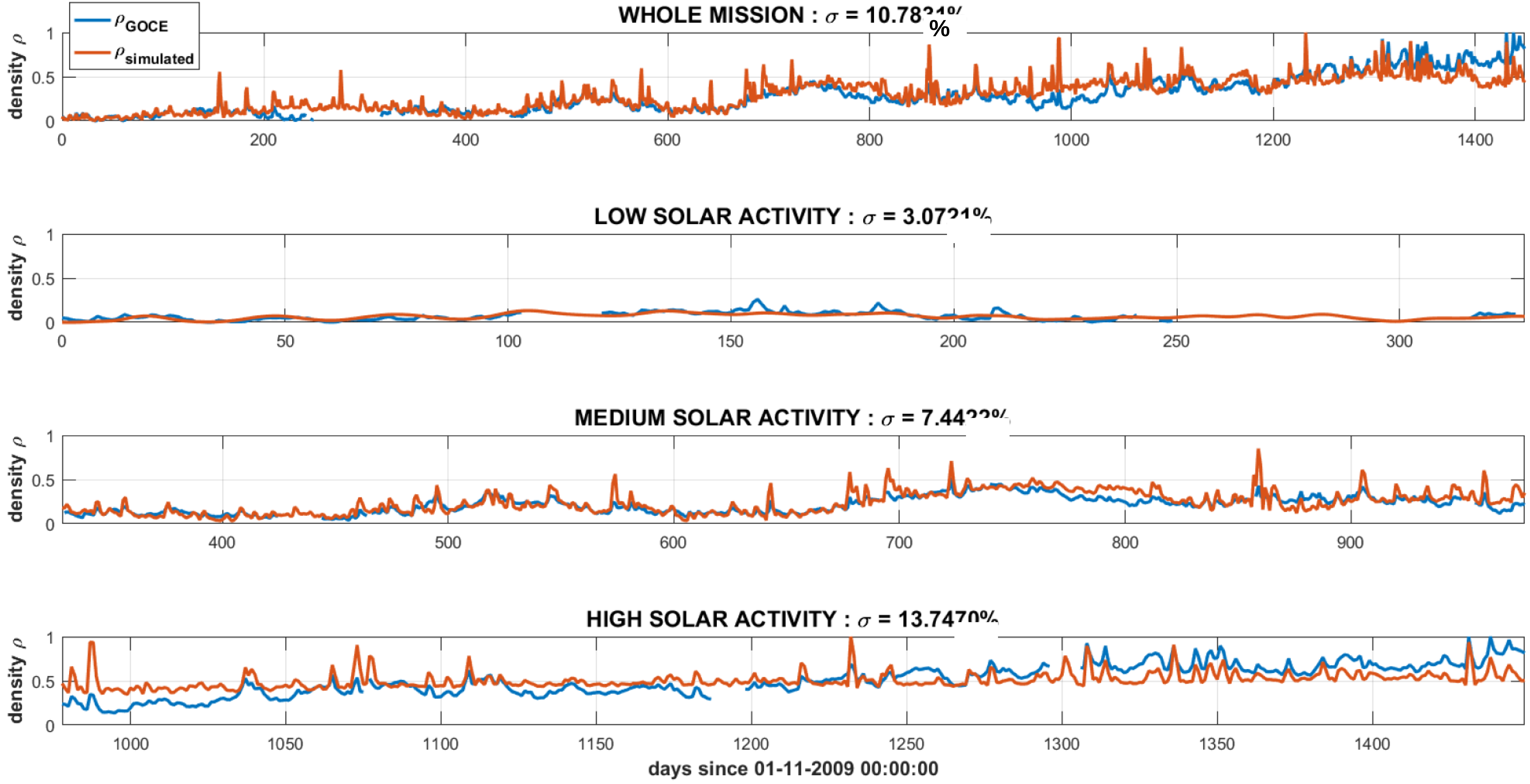
Best-solutions for the analyzed periods.

✓ indicates that the corresponding IMF, labeled from 1 to 10, or the residual trend *res* is used



Normalized daily-averaged real and simulated density signal *vs* time

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Conclusions

- **Low and medium solar activity:** the best reconstruction combine IMFs from Ap, $F10.7$ and $Mg\ II$ solar flux indices. For medium activity the use of only $Mg\ II$ does not lead to significant worsening and can be preferred for simplicity. Density can be reproduced with a RMS error of 2.6% and 7.4% for low and medium activity, respectively.

- **High solar activity:** the best reconstruction combines IMFs from Ap and $Mg\ II$ indices. The RMS error is below 14%. Peaks are well-reproduced.

- **Whole mission:** the best reconstruction combines IMFs from Ap and $Mg\ II$ indices. The reconstruction presents period of over/under-estimation. The RMS error is about 11%.

- Secular trends in the thermosphere density can be derived using historical records of MgII, F10.7 and Ap.

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