Impact of solar and geomagnetic activity on thermospheric density during ESA's mission GOCE

Francesco Berrilli, Alberto Bigazzi, Carlo Cauli, Dario Del Moro, Luca Giovannelli, and Mija Lovric

Department of Physics, University of Rome Tor Vergata, ITALY (https://www.fisica.uniroma2.it/~solare/en/)

TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

SOLAR PHYSICS UTOV

Photography encouraged

Abstract

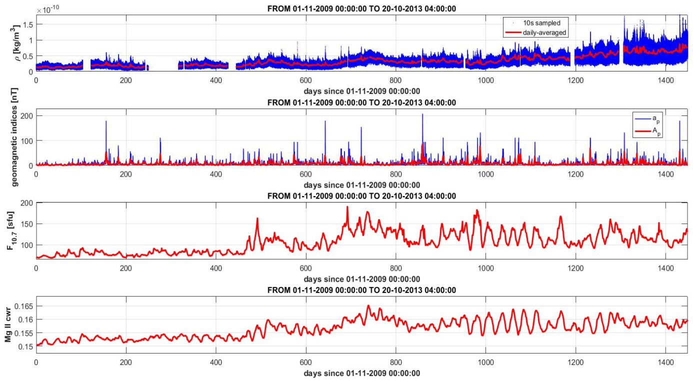
The impact of solar activity on thermospheric density during ESA's gravity mission GOCE has been investigated using different solar and geomagnetic indices. The analysed period (17 March, 2009 - 11 November, 2013) corresponds to the rising phase of solar cycle 24. Thermospheric density at a mean altitude of 254 km, derived from the high-precision accelerometers on board the GOCE satellite, represents a unique low-altitude dataset. The temporal behavior of Ap geomagnetic index and solar activity indices, i.e. the F10.7 flux and the Mg II core-to-wing ratio, have been examined and their correlations with GOCE thermospheric density studied. Then, solar indices have been decomposed into a set of modes, i.e. the intrinsic mode functions (IMFs), through the Empirical Mode Decomposition (EMD), a technique best suited in analysing non-stationary and non-periodic time signals. After the decomposition, certain subsets of of IMFs from the solar and geomagnetic indices and thermospheric density have been reconstructed and compared with the original GOCE dataset. The results suggest the relevance of using the Mg II index and EMD IMFs in describing the solar-thermospheric connection and reconstruct thermosperic density.

GOCE (*Gravity field & steady-state Ocean Circulation Explorer*)

- Drag-Free Attitude and Orbit Control System to maintain altitude constant
- on-board ultra-sensitive accelerometers used to create dataset of **10s** sampled thermospheric density at 260 km altitude (*Eelco Doornbos et al.* of TU Delft [1]) available at ESA GOCE Archive (**01/11/2009 - 20/10/2013**)
- the satellite was operated until few hours before destruction into the atmosphere.
- very high uncertainty (half an orbit) in the location of re-entry up to few hours before due to the highly variable level of solar and geomagnetic activity

The Solar Input

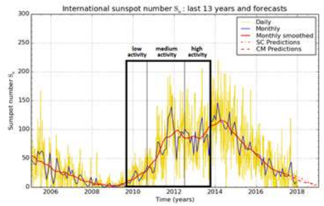
X and EUV radiation from the sun represents the most important contribution to thermospheric heating. This emission has the highest relative variability (up to 100%). The MgII index correlates to the UV flux and it is used to describe solar UV input.
Energy is also transferred from charged particles originating in the solar corona and being captured by the Earth magnetosphere at high-latitudes. Auroral phenomena result from these interactions.
This effect, which remains confined to a lunette-shaped high-latitude region during quiet solar activity, maybecome the most significant contribution to the thermosphere energy budget in case of intense geomagnetic activity.
Solar input has two major sources of modulation, that is solar rotation (about 27 days) and the 11-year solar cycle. EUV flux clearly shows these modulations.
Geomagnetic disturbances are, instead impulsive, with time scales ranging from hours to days. The Ap index correlates directly to geomagnetic activity and is used to describe

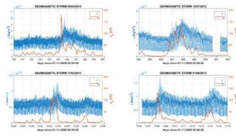


a) Atmospheric density vs time (both 10 s sampled and daily averaged) during GOCE mission; **b)** Geomagnetic index a_p and daily-averaged geomagnetic index A_p vs time during GOCE mission; **c)** and **d)** F10.7 and Mg II cwr vs time during GOCE mission (signal spikes are removed by interpolation)

1. Thermospheric density is badly-correlated with geomagnetic index and well-correlated with solar flux indices (especially with Mg II cwr)
2. The thermospheric response to a_p impulsive changes is within 6 to 9 hours
3. Impulsive variations of a_p, as well as long-term evolution of F10.7 and Mg II cwr are well reflected in the thermospheric density

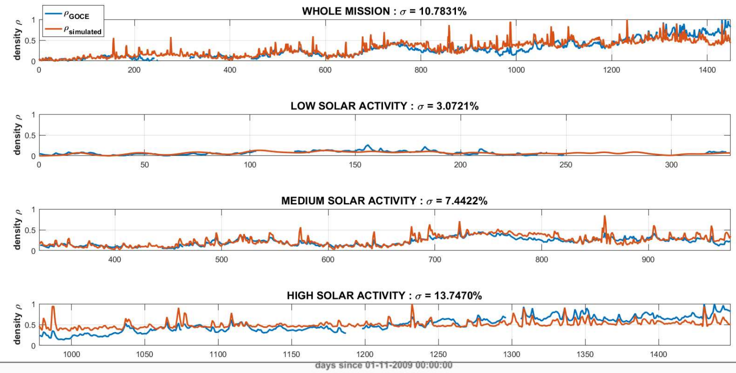
index/proxy	symbol	description	unit	sampling	source
geomagnetic index	a_p	proxy for the global level of geomagnetic activity	nT	3 hr	*NASA Goddard Space Flight Center OMNIWeb*
solar radio flux at 10.7 cm	$F_{10.7}$	good proxy for daily average level of overall solar radiation	sfu	1 day	*NASA Goddard Space Flight Center OMNIWeb*
Mg II core to wing ratio	*Mg II cwr*	excellent proxy for the solar MUV chromospheric line emission near 280 nm	-	1 day	UVSAT of *Bremen University Institut für Umweltphysik*





Plots of thermospheric density (blue line) and Ap index (red line) during four geomagnetic storms occurred in the course of GOCE mission. Lag of thermospheric response to the geomagnetic forcing is apparent. Relaxation time to the quiet state is also apparent.

	σ_{RMS} [%]	index	1	2	3	4	5	6	7	8	9	10	res	A
whole mission	10.78	A_p	✓	✓	✓	✓	✓	✓		✓	✓		✓	0.3005
		Mg II	✓			✓		✓	✓				✓	2.0232
low solar activity	3.07	A_p									✓	✓	✓	2.3317
		Mg II			✓		✓	✓	✓				✓	4.0793
medium solar activity	7.44	A_p	✓	✓	✓	✓	✓	✓						0.5406
		Mg II				✓		✓	✓				✓	3.5154
high solar activity	13.75	A_p	✓	✓	✓	✓	✓	✓	✓		✓			0.3113
		Mg II							✓				✓	2.1352

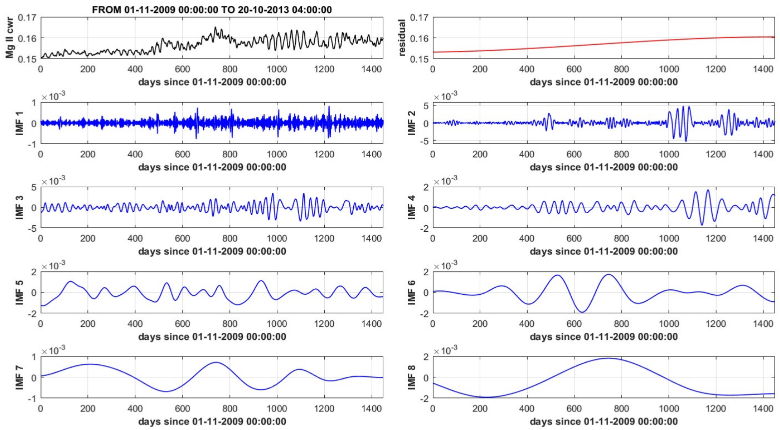


EMD (*Empirical Mode Decomposition*)

EMD is a purely empirical technique to break down a signal $X(t)$ in a number of oscillation modes in the time domain, referred as the *Intrinsic Mode Functions* (IMFs) $c_i(t)$ and the *residual trend* $r_n(t)$

$$X(t) = r_n(t) + \sum_{i=1}^{n} c_i(t)$$

Each IMF has a time-variable frequency and amplitude, useful to analyze non-linear non-stationary signals. The algorithm is based on the recursive application of a *sifting* process, that consists in removing the mean envelope obtained from a cubic spline interpolation of local minima and maxima. Aa stopping criterion is used to arrest the sifting process



Recreate thermospheric density time profile from Intrinsic Mode Functions and the residual trends of solar indices EMD

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

- $\bar{\rho}^{sim}_{norm}$: 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

normalized daily-averaged density from GOCE mission

$$IMF^{A_p}_{norm} = norm_{(0,1)}\left[\sum_{i}^{10} I^{A_p}_i \cdot IMF^{A_p}_i + I^{A_p}_{res}\cdot res^{A_p}\right]$$

$$IMF^{F_{10.7}}_{norm} = norm_{(0,1)}\left[\sum_{i}^{8} I^{F_{10.7}}_i \cdot IMF^{F_{10.7}}_i + I^{F_{10.7}}_{res}\cdot res^{F_{10.7}}\right]$$

$$IMF^{MgII}_{norm} = norm_{(0,1)}\left[\sum_{i}^{9} I^{MgII}_i \cdot IMF^{MgII}_i + I^{MgII}_{res}\cdot res^{MgII}\right]$$

IMF_i = i-th IMF res = residual trend I_i = logical operator to select the i-th IMF

ASSUMPTIONS

The Ap index is preliminary shifted by 9 h before the application of the EMD

Different cases of solar indices are analyzed:
1. Ap and F10.7
2. **Ap and Mg II**
3. Ap, F10.7 and Mg II

4 cases are investigated
whole mission, low solar activity (SA), medium SA, high SA

A Montecarlo-like approach (random extraction) is used to select for each solar index the combination of IMFs and the weighting factors to be included in the density simulation.
First and last five points of IMFs are cut to avoid boundary effects (wing removal process)

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

figure-of-merit function

Conclusions

Analysis shows how that during low solar activity, the low-frequency components from the solar flux proxies contribute most to the signal, while during both the rising phase and the high solar activity period, the geomagnetic proxy is needed to capture the impulsive geomagnetic events connected to the evolution of the interplanetary medium. During low and medium solar activity signal can be reconstructed with an RMS errors of about 2.6% and 7.4%, respectively. Semi-empirical atmospheric models (NRLMSISE-00 and Jacchia-family models above all) are usually credited to fall in the 10% error range. During high solar activity, error increses to over 10%. Mg II proves to be a better proxy than F10.7 in capturing the long-term trends of the solar input dur ing the solar cycle.