"Physics of Auroral Phenomena", Proc. XXX Annual Seminar, Apatity, pp. 158 - 162, 2007
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RESPONSE OF LEO SATELLITE DRAG PARAMETERS TO ANOMALIES IN THE UPPER ATMOSPHERE DURING EXTREME SOLAR EVENTS

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Abstract. Low Earth orbiters (LEO) are essential instruments for the investigation of the current status of the Earth and its change. Numerous satellite missions were launched aiming to extend the knowledge of the detailed structure of the Earth's gravity field. In order to separate the signal from noise the modeling of the non-gravitational forces acting on the spacecraft is of major importance. Apart of the atmospheric drag these comprise the solar radiation pressure, Earth albedo and infrared radiation, i.e. the Earth-emitted thermal radiation. For LEOs the atmospheric drag is in particular difficult to model since it depends on the atmospheric density which highly varies with both time and space. In order to measure these perturbations, CHAMP carries a high-precision accelerometer instrument.

In the present study the accelerometer data are used to investigate the atmospheric density and its temporal and spatial variation at a height level of about 400 km. We analyze CHAMP uncalibrated accelerometer and orbit ephemeris data and correlate the atmospheric drag forces with orbit height, geographic latitude and local time. We further compare the absolute density values from the in-situ measurements with the Mass Spectrometer Incoherent Scatter 1990 (MSIS90) model.

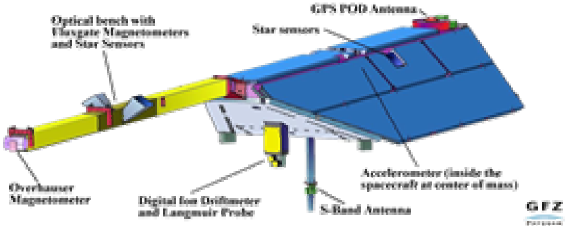
In particular we focus on the variation of the neutral atmospheric density during the extreme solar events occurred at the end of the year 2003. These Halloween events caused periods with magnetic activities up to Kp values of 9 resulting in density variations increased to about 400% compared to densities at quiet conditions.

The CHAMP Mission

The CHAMP (CHAllanging Minisatellite Payload) spacecraft is a German satellite mission managed by GFZ (GeoForschungsZentrum Potsdam) which is dedicated to the global investigation of the gravity, magnetic and electric field and to atmospheric profiling. The primary science objectives of this mission are:

- highly precise global long-wavelength features of the static Earth gravity field and the temporal variation of this field
- global estimates of the main and crustal magnetic field of the Earth and the space/time variability of these field components
- atmospheric and ionospheric GPS signal refraction data which can be converted into temperatures, water vapor and electron content.

The CHAMP spacecraft was launched in July 2000 from the Russian Plesetsk cosmodrome. The detailed mission parameters can be seen in Fig. 1.



CHAMP Mission Parameters	
Eccentricity	0.00368 deg
Inclination	87.3 deg
Local time precession	5.44 min/day
Revolution period	93.5 min
Mass	522 kg
Cross sectional area	0.72 m^2

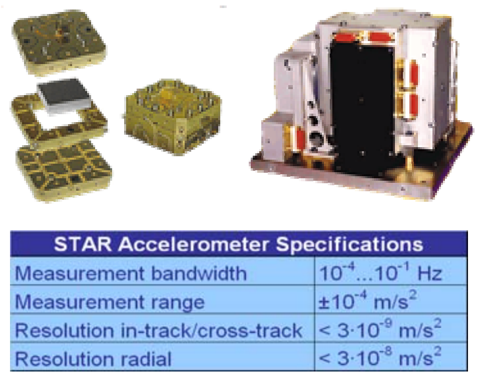
Fig. 1: CHAMP spacecraft and mission parameters.

The STAR Accelerometer

Among the numerous on-board instruments CHAMP carries a STAR accelerometer sensor, which serves for measuring the non-gravitational accelerations such as air drag, Earth albedo and solar radiation pressure acting on the CHAMP satellite. The accelerometer is rigidly mounted at the centre of the satellites mass and consists of a charged proof mass sitting in a cage that maintains an electrostatic field. The voltages measured by a feedback loop to keep the proof mass at rest are converted to accelerations. Two star sensors rigidly coupled with the instrument continuously control the satellite's attitude with respect to the inertial reference frame with an accuracy $3x10^{-9}$ m/s^2 in along-track and cross-track and one order of magnitude less in radial direction. Fig. 2 shows the main accelerometer specifications.

CHAMP was initially injected into a 454 km orbit with a decay lifetime of about 5 years (see Fig. 3) enclosing the solar maximum in 2001. This initial height and the aerobraking mission design was chosen in order to

- guarantee a multi-layer mission duration even under severe solar activity conditions
- account for the requirement imposed by the atmosphere/ionosphere application to look through the different atmospheric layers
- adequately observe the Earth's magnetic main field.



STAR Accelerometer Specifications	
Measurement bandwidth	$10^{-4}...10^{-1}$ Hz
Measurement range	$\pm10^{-4}$ m/s^2
Resolution in-track/cross-track	$< 3\cdot10^{-9}$ m/s^2
Resolution radial	$< 3\cdot10^{-8}$ m/s^2

Fig. 2: CHAMP accelerometer specifications.

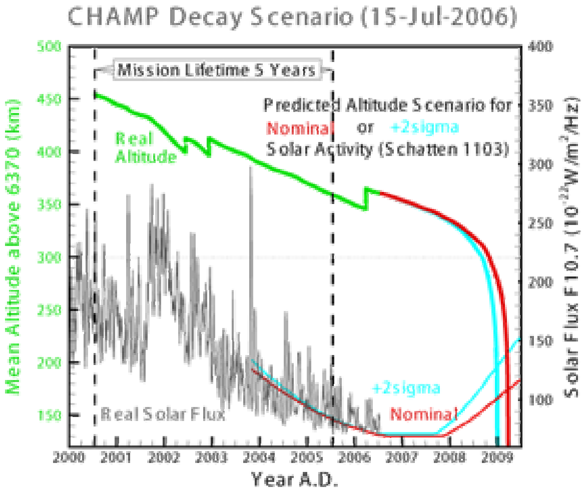


Fig. 3: CHAMP decay scenario (from GFZ CHAMP web-site).

Accelerometer Data Analysis

The accelerometer measurements are largely influenced by instrumental biases. GFZ provides calibration values for the instrumental bias and scale for the raw linear acceleration data. The analysis presented here deals with raw acceleration data (Level-2 CH-OG-2-ACC product) provided by GFZ ISDC (Information Systems and Data Center) which contain the linear and angular accelerations (0.1 Hz) as well as spacecraft attitude quaternion vectors, S/C mass data, Lorentz force correction vectors, calibration parameters and thruster information (Förste, 2005). Fig. 4 shows the sensor readings in the three directions components.

In order to investigate the atmospheric drag we take into account the linear along-track component only and apply the calibration values and the Lorentz force correction, which compensates the magnetic field perturbation on the instrument.

$$a_{cal} = (a_{uncal} + a_{Lorentz} - k_{bias}) \cdot k_{scale}$$

with $k_{bias} = 3.555\cdot10^{-6}$ m/s^2, $k_{scale} = 0.83$.

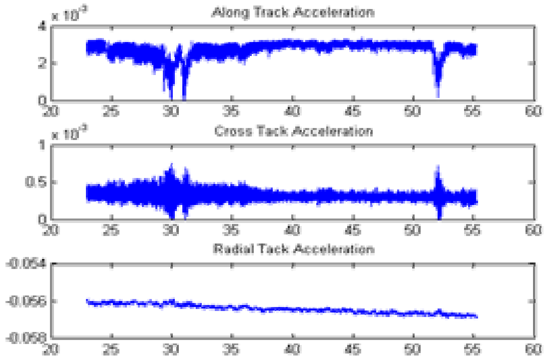


Fig. 4: Uncalibrated accelerometer readings in along-track, cross-track and radial direction.

Since atmospheric drag is by far the most dominating component in along-track direction we neglect in this study other forces like the solar radiation pressure, albedo and infrared radiation from Earth which in total induce an error of less than 1%. The atmospheric density depends among others from the orbital height and the solar activity and thus varies with local time, geographic latitude etc. The following figures demonstrate the close correlation of these parameters (Baum, 2006). Fig. 5 shows the close correlation between the calibrated absolute acceleration values (red curve) and the orbit height (blue curve) during a period of three revolutions with a duration of 92 minutes each. The orbital height variation is due to the eccentricity ($e=0.004901$) of the satellite orbit.

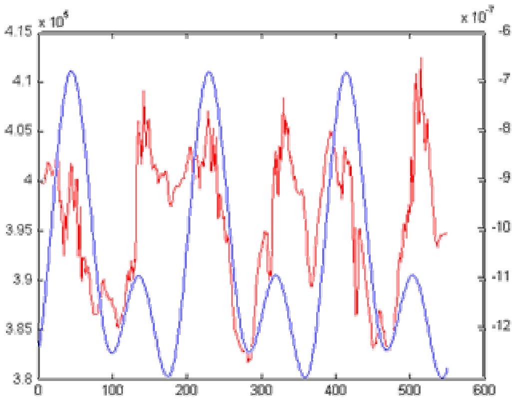


Fig. 5: Correlation between along-track acceleration and orbit height.

Fig. 6 points up the influence of the local time (blue curve) of the satellite’s ground track position on the corresponding accelerometer reading. Due to the near polar orbit of the CHAMP spacecraft the local time keeps nearly constant during each orbit arc from pole to pole and is rapidly changing by 12 hours at the pole transitions. The yellow and blue stripes indicate day- and night-time arcs, respectively, where the absolute maximum values of the acceleration become apparent at the day-side passes due to the atmospheric heating effects.

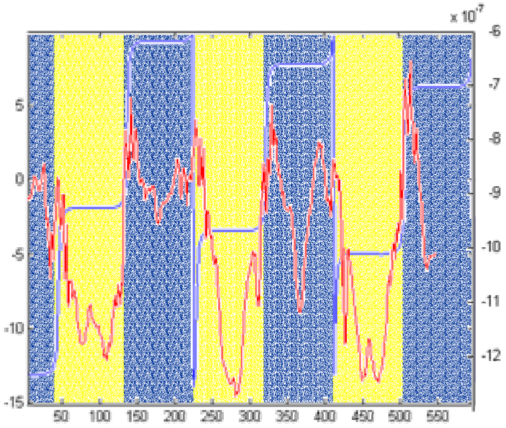


Fig. 6: Correlation of along-track acceleration with the local time of satellite ground track position.

Fig. 7 compares again the accelerometer data (red curve) and the absolute values of the geographic latitude (blue curve) of the satellites position during three revolutions, i.e. the lower peaks of blue curve always indicate an equator transition while the upper peaks alternately represent a south- and a north-pole transition. First of all, it becomes very evident that the accelerations are increasing with decreasing latitude. Secondly, between 10:00 and 20:00 local time the accelerations are found to maximize in the vicinity of 20°N (blue bar) and 25°S (red bar) latitude, with a trough at the equator.

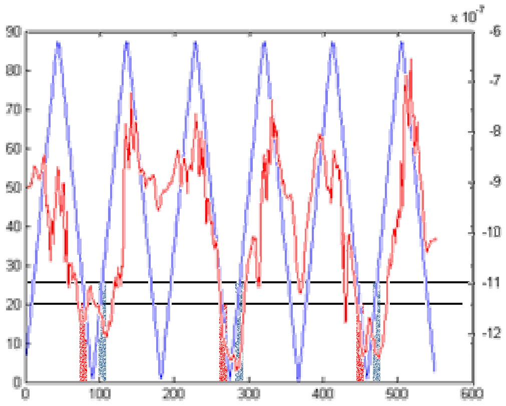


Fig. 7: Correlation between along-track acceleration and absolute geographic latitude.

This anomaly is due to the neutral plasma coupling, i.e. the neutral density shows a structure similar to that of the thermospheric temperature and of the electron density (Sutton, 2005).

Absolute Atmospheric Densities from Accelero-meter Data

From the calibrated along-track acceleration data we compute the absolute values of the atmospheric density ρ using the general formula for aerodynamic acceleration a_x acting in the opposite direction of the satellites velocity vector,

$$\rho(r,t) = \frac{\ddot{\vec{r}}}{-0.5 C_D \frac{A}{m} v^2 \vec{e}_v}$$

where C_D is the drag coefficient ($C_D = 2.2$), A the satellite’s effective cross-sectional area, m its mass, and v its velocity relative to the atmosphere, which is assumed to be co-rotating with the Earth.

A comparison between these derived densities and the Mass Spectrometer Incoherent Scatter 1990 (MSIS90) shows that the model reproduces the general structure of the observed data reasonable good. However, there is a slight underestimation of about 20% at low latitudes and up to 30% at the polar regions. Fig. 8 shows the density values derived from one full revolution of CHAMP (red) and the corresponding computed MSIS values sampled along the orbital arc (green). The variation of the density values is due to the orbital height, latitude and local time variation.

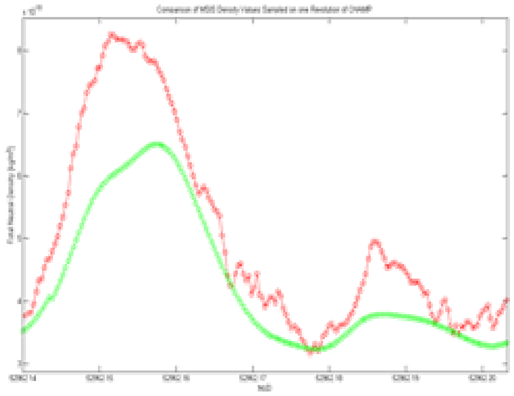


Fig. 8: Comparison of modeled MSIS density values with densities derived from CHAMP accelerations.

The MSIS90 Density Model

The Mass-Spectrometer-Incoherent-Scatter (MSIS) model describes the neutral temperature and densities in the upper atmosphere (above about 100 km). The MSIS model is based on the extensive data compilation and analysis work of A.E. Hedin (Hedin, 1987). Data sources include measurements from several rockets, satellites, and incoherent scatter radars. The model expects as input year, day of year, universal time, altitude, geodetic latitude and longitude, local apparent solar time, solar F10.7 flux (for previous day and three-month average), and magnetic Ap index (daily or Ap history for the last 59 hours). For these conditions the following output parameters are calculated: number density of He, O, N2, O2, Ar, H, and N, total mass density; neutral temperature and exospheric temperature (see Fig. 9).

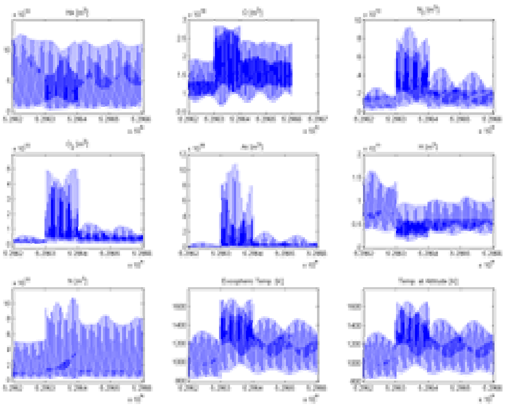


Fig. 9: Number densities of elements from the Mass Spectrometer Incoherent Scatter 1990 model (MSIS90).

Extreme Solar Events

Reaction of the thermosphere to changing solar and geomagnetic conditions occur through a lot of complex processes. We investigated the variation of the atmospheric density at CHAMP's height level of about 400 km during a geomagnetic storm occurred through Nov. 20-22 and verified a density increase of about 400% (see Fig. 10).

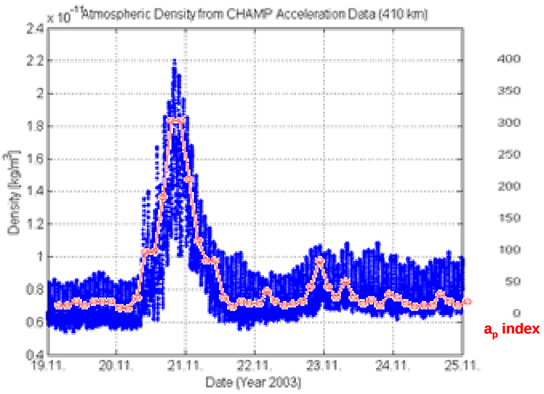


Fig. 10: Increase of neutral atmospheric density at 410 km height from CHAMP accelerometer data.

Fig. 11 show the MSIS values computed along CHAMP's orbit at about 11:00 local time during quiet conditions (upper plot) and during the mentioned solar event (lower plot), where the A_p index curve is added to the lower plot.

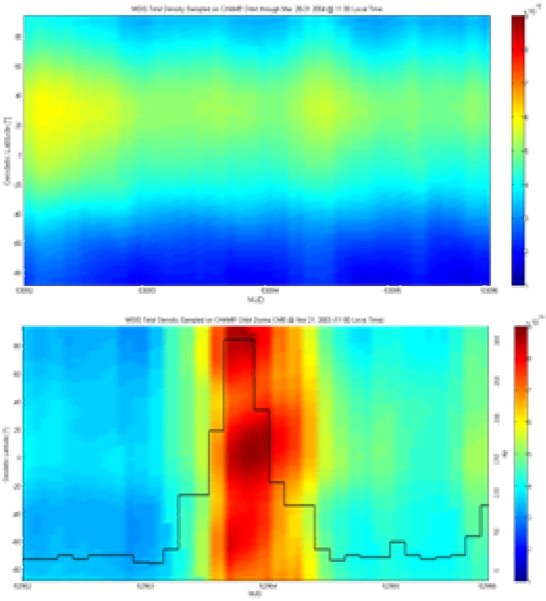


Fig. 11: MSIS total densities sampled on CHAMP orbit on day side during quiet conditions (top) and solar event (bottom).

The heating and related expansion of the thermosphere correlates with the impact of the enhanced X-ray and EUV flux of the flare and the colliding CME. The topmost plot of Fig. 12 shows the enhanced solar wind and particle density before and after the collision of the CME with the Earth's atmosphere, where the shock was observed on Nov 20, 2003 at 07:30. This event was generated by an X-ray flare occurred on Nov 18 at 07:50 (47.5 hours before).

Coincidentally another M9.6 X-ray flare was registered which affected the Earth's atmosphere only some 20 minutes later (see plot indicated blue).

These quasi-simultaneous atmospheric incidents with fairly quiet periods before and after these events were particularly interesting to be analysed. The upper of the two plots indicated green shows the density response (Nov. 19-23, 2003) from CHAMP measurements during the solar event on the day side at nearly constant 11:00 local time. The figure at the bottom shows the total neutral density along the actual CHAMP orbit during the same period (red) compared with the corresponding MSIS model values (green). It can clearly be seen that the density perturbation at about 400 km reaches up to 400% compared to quiet conditions. Furthermore, a significant underestimate of the model values, especially during the extreme solar event is evident.

Fig. 13 shows the soft X-ray and EUV flux of sun-like stars of different ages normalized to the present solar values at 1 AU. The observed peak of the flux from the M9.6 X-ray flare in the spectrum of 1-8 Å shows an increase of two orders of magnitudes (green circle in Fig. 12) which roughly correlates with the average flux of a sun-like star at the age of about 0.6 Gyr (green circle Fig. 13).

One should also note, that the exospheric temperature of the MSIS model yields values of about 1600 K during the period of maximum density. This brings us to assume that the true exospheric temperature during such extreme solar events may be much higher as well.

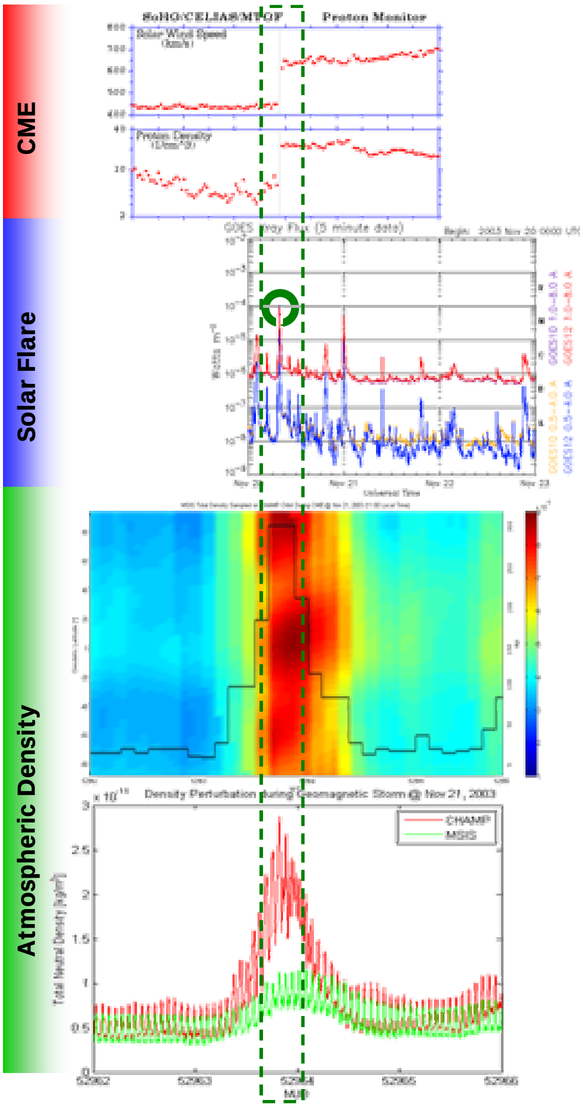


Fig. 12: Total neutral density values derived from acceleration measurements and corresponding MSIS model values during the simultaneous impact on the Earths atmosphere from a coronal mass ejection and a solar flare.

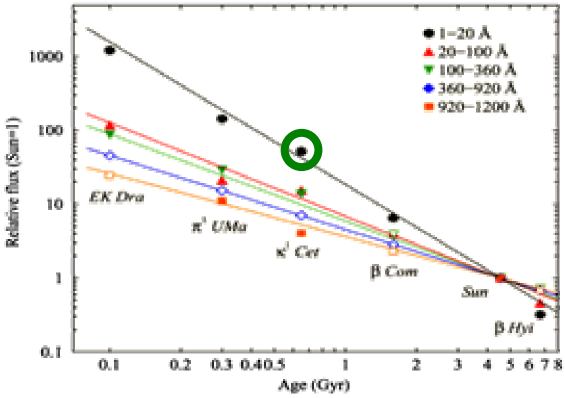


Fig. 13: Radiation flux as a function of various wavelengths for Sun-like stars of different ages (Ribas, 2005).

Conclusion and Outlook

Accelerometry using high precision along-track accelerometer data from low Earth orbiting satellites is a suitable method to investigate the density response on extreme solar events. The density perturbations near 400 km due to geomagnetic disturbances can raise up to 400% and is underestimated by the MSIS empirical model. These preliminary results indicate that a more detailed investigation of the connection between extreme solar events and the activity of solar proxies can give us further prospects, especially for studies which are related to the evolution of the early Earth atmosphere and for Earth-type atmospheres of exoplanets orbiting around active stars.

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