AIR DENSITY AND WIND RETRIEVAL USING GOCE DATA

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ABSTRACT

In the GOCE+ Theme 3 project, ion thruster activation data from GOCE telemetry has been combined with the accelerometer and star camera data products, to derive a new set of data products on thermosphere neutral density and wind speed. These products can be seen as an extension of the successful accelerometer-derived thermosphere density data sets from CHAMP and GRACE. It is the first time that such data, spanning multiple years, is available at a fixed and very low altitude and at a near constant orientation of the orbit plane with respect to the Sun. The data processing is based on an analysis of the aerodynamic accelerations acting on the satellite, and makes use of data from all instruments onboard the satellite. The following steps are involved: 1) estimation of the bias in the gradiometer common-mode accelerations using GPS tracking data, 2) conversion of ion thruster activation data to accelerations, 3) modelling of radiation pressure accelerations based on orbit and attitude information, 4) removal of radiation pressure and ion thruster accelerations from the common-mode acceleration data, to arrive at the observed aerodynamic accelerations, 5) iterative adjustment of wind direction and density inputs of an aerodynamic model of the satellite, until the modelled aerodynamic accelerations match the observations. The resulting density and wind observations are made available in the form of time series and grids. These data can be applied in investigations of solar-terrestrial physics, as well as for the improvement and validation of models used in space operations.

Key words: GOCE; thermosphere; air density; wind.

1. INTRODUCTION

The GOCE mission was designed for recovering information on the Earth's static gravity field at high spatial resolution and accuracy [Drinkwater et al., 2007]. The mission's suite of instruments is however also ideally suited for investigations of the density and crosswind in the Earth's thermosphere. This spin-off science application was earlier developed and demonstrated using data from the CHAMP and GRACE missions [Bruinsma et al., 2004, 2006].

The GOCE density and crosswind data set was first released via ESA's GOCE Virtual Onlince Archive server in September 2013. This paper will cover the thermosphere density and crosswind processing data flow and algorithm, and will discuss the data availability and usage considerations. The paper describes the first release of the data, and discusses plans for future updates to the data processing.

2. DATA FLOW

The data processing makes use of various L1B and L2 GOCE products:

- The common-mode accelerations from the gradiometer, representing the non-gravitational accelerations of the satellite's centre of mass, computed by taking the average of the accelerations measured by two accelerometers at equal distance on both sides of the centre of mass;
- The attitude quaternions as measured by the star cameras;
- The Precise Science Orbits (PSOs), providing the locations of the measurements;
- The activation data for the ion thruster that is used in the satellite's drag free control system.

Figure 1 shows how the various types of data are used to calculate modelled acceleration contributions and relative velocity contributions. This leads to the availability of aerodynamic acceleration data and relative velocity data, which are fed into the algorithm used to determine air density and crosswind speed by using an aerodynamic model. This algorithm is further explained in the next Section.

Proc. 'ESA Living Planet Symposium 2013', Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

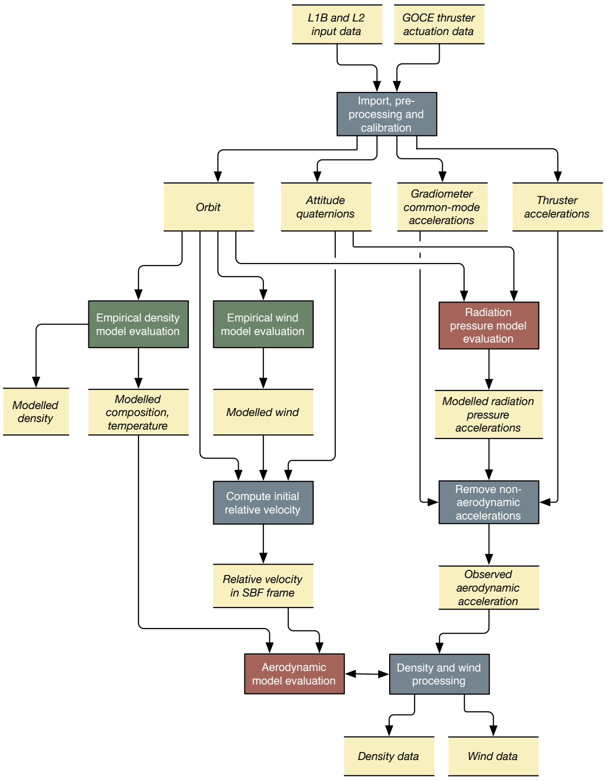

Figure 1. Flow chart of the density and wind determination algorithm.

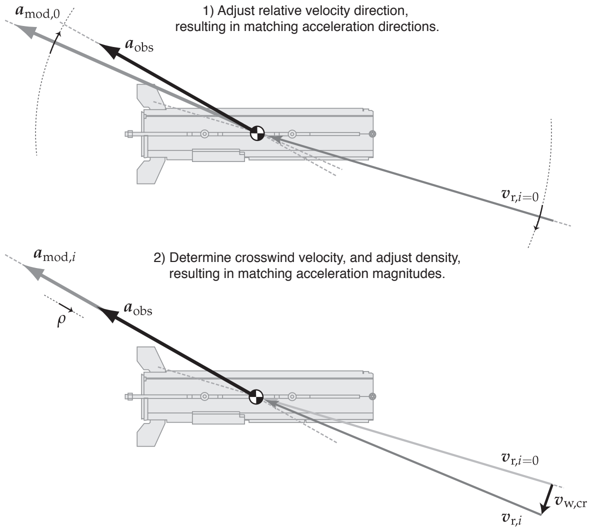

Figure 2. Schematic overview of the iterative wind and density derivation algorithm for accelerometer satellites.

3. ALGORITHM

Figure 2 illustrates schematically the principle of the density and wind determination algorithm, which is adapted from Doornbos et al. [2010]. The algorithm is comprised of two steps. The goal of the algorithm is to make the modelled aerodynamic acceleration $\boldsymbol{a}_{\mathrm{mod}}$ match the direction (top panel) and subsequently the magnitude (bottom panel) of the aerodynamic acceleration derived from the common-mode gradiometer observations $\boldsymbol{a}_{\mathrm{obs}}$.

This is achieved by first modifying the direction of the relative velocity vector $\boldsymbol{v}_{\mathrm{r}}$, without modifying its magnitude, until the modelled acceleration direction matches that of the observed acceleration. Subsequently the density ρ is modified, so that the lengths of the acceleration vectors match.

The aerodynamic model evaluation has to be called iteratively, because the relationship between relative velocity direction and aerodynamic acceleration direction is not quite linear. This is indicated by the two-sided arrow at the bottom of the flowchart in Figure 1

An initial value for the relative velocity vector is computed by taking the inertial orbit velocity and adding the contribution of winds due to an atmosphere which corotates with the Earth.

4. DATA PRODUCTS

The main data product is in the form of time series of density and wind speeds. A PDF file with gridded data is also available, which can be used for quick identification of data availability, data quality and special events, such as geomagnetic storms.

An example of the gridded data can be seen in Figure 3. The time-series data is binned as a function of epoch time on the X-axis and argument of latitude on the Y-axis. These grids are then made into monthly plots, provided in a single multi-page PDF document for the entire data set. When new data is added to the data set, this PDF document will be replaced by an updated version.

The gridded data are very useful for several purposes:

- Quick identification of data availability and data gaps. Data gaps are plotted in gray.
- Quick identification of data quality. Noisy data, outliers, jumps and biases are apparent as offsets in colour in the grids.
- Quick identification of geophysical signals in the data. Since the argument of latitude is closely related to the true geodetic latitude, patterns of changes in time at various latitudes become readily apparent in the plots.

Figure 3 shows an example of the gridded density data for the month of April 2010. From top to bottom the page shows the density data, the two crosswind components and time series of the *ap* geomagnetic activity index and $F_{10.7}$ solar EUV radiation proxies. The addition of the

Thermosphere density and crosswind speed along the GOCE orbit – gridded data

April 2010

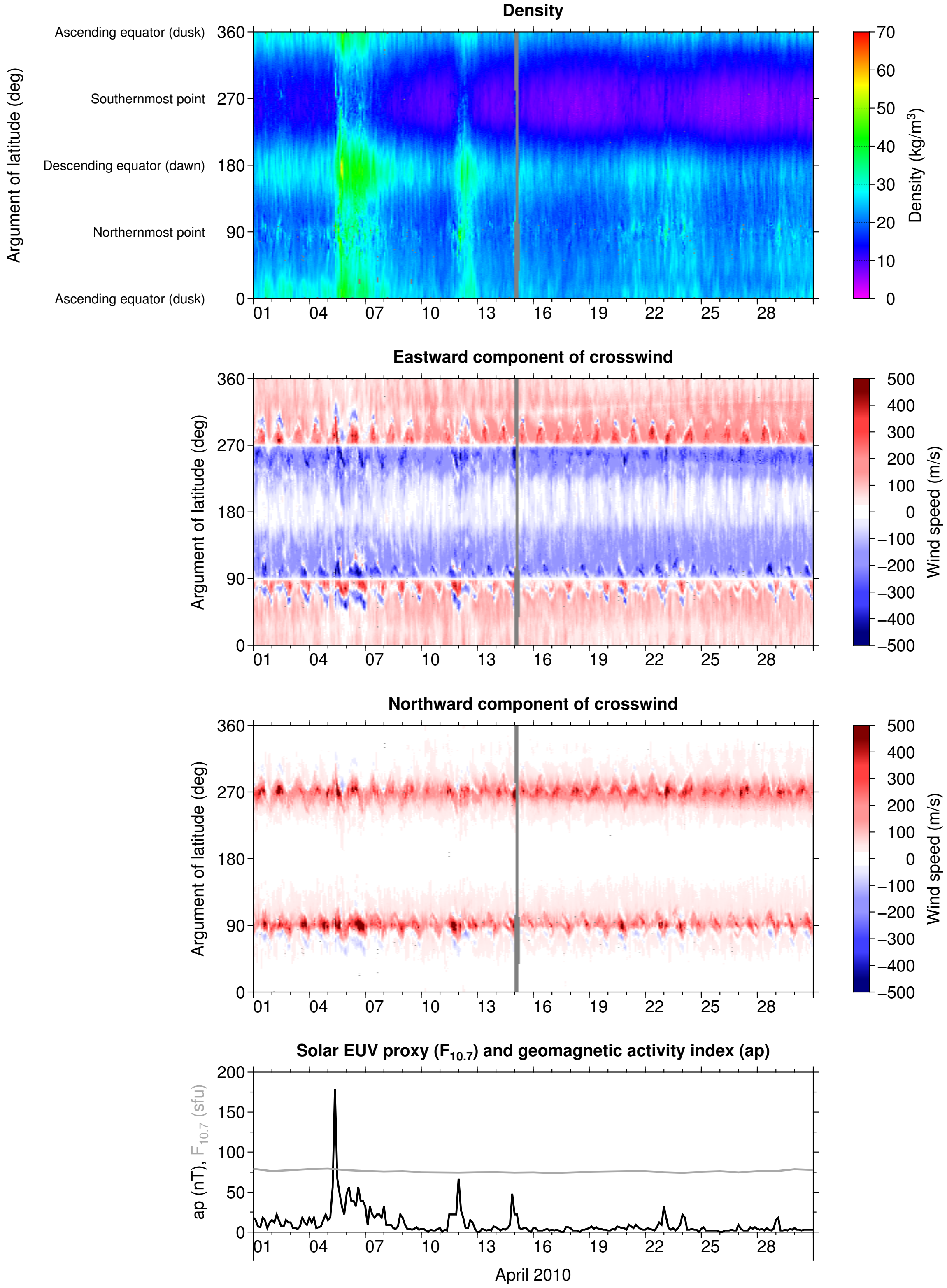

Figure 3. Example of one page of the gridded density data file, for the month of April, 2010

activity index and proxy makes it easy to identify, for example, the geomagnetic storm on April 5, as the source of the density enhancement on that day.

The highest wind speeds can be found over the poles. The daily pattern at the poles is a result of the offset between the geomagnetic pole, to which the variations in the wind field are connected, and the geographic pole, to which the orbit geometry is tied.

4.1. Data availability

Figure 4 shows the data availability for the density and crosswind products on a timeline. Currently, data is available between the beginning of November 2009 and the beginning of June 2012. Data from June 2012 until the end of GOCE gradiometer operations on November 10, 2013, will be made available during the first half of 2014. In the period between the launch of the satellite and the end of October 2009, many tests were performed on the satellite and in ground processing, as part of the commissioning, calibration and validation activities. Some data from this period will be made available as well.

There are three gaps of longer duration in the data, which coincide with anomalies on the satellite which prevented delivery of science data:

- End of February 2010
- July to September 2010
- Beginning of January 2011

Outside of these periods, the availability of thruster activation data is the major limiting factors, causing many of the smaller data gaps, often much shorter than a day. In addition, several periods have been marked for removal in the post-processing of the density and wind data, when on inspection it was clear that results were inconsistent. There is a chance that after closer investigation, corrective measures can be taken so that density and crosswind data can be made available later for some of the periods in which data is currently missing.

Currently, only data has been processed for which the drag free control thruster was active, and for which thruster activation data was made available, as is nominally the case. In principle, the data processing can also be performed for periods when the drag free control thruster is off.

5. MEASUREMENT ENVIRONMENT

The measurement environment, both in terms of the orbit geometry and solar and geomagnetic activity conditions, during the course of the GOCE mission, will be discussed in the following paragraphs.

5.1. Orbit geometry

The potential impact of the GOCE data on investigations and modelling work is largely determined by the GOCE orbit geometry and environmental conditions at the time of the measurements. Figure 5 shows the evolution of the GOCE orbital altitudes and local solar time at the nodes (equator crossings). The same information is included in the graphs for the CHAMP and GRACE satellites, for reference. The altitude is given as daily mean values (solid lines) of the altitude above the GRS-80 ellipsoid. In addition, the shaded areas indicate daily minimum and maximum altitude values. The mean altitude curves of course vary under the influence of drag and orbital control thruster activity (CHAMP and GOCE only). The variations in minimum and maximum altitude with respect to the mean are due to the flattening of the reference ellipsoid representing the oblate Earth, the eccentricity of the orbit, and the perigee rotation rate, caused by orbit perturbations.

The variation of the local solar time at the equator is due to orbital precessesion and the Earth's rotation around the Sun. The CHAMP and GRACE satellites both have a much stronger rate of the orbit plane with respect to the Sun than GOCE, which is near sun-synchronous. The Figure indicates the dates at which the orbit of GOCE was nearly coplanar with one of the other two missions.

The GOCE altitude has been kept fixed at a very low level, which is not accessable for long durations without a drag free control system. The only major exceptions to the fixed altitude are the lowering manoeuvres at the start and end of the mission life, and during and after several on-board anomalies, where the drag free control system was commanded to keep the satellite as safe as possible during recovery operations.

The satellite was launched into a sun-syncronous dawn-dusk orbit, crossing the equator at 18:00 and 06:00 local solar time. Since launch, these equator crossing times have drifted during the course of the mission, due to orbit perturbations. The fixed low altitude and near sun-synchronous orbit are unique aspects of the mission, and need to be taken into consideration by users of the data.

5.2. Solar and geomagnetic activity

Figure 5 shows an overview of how solar and geomagnetic activity evolved over the course of the mission. The mission started at the end of a period of extremely low solar activity. The intensity of solar EUV radiation has steadily increased during the current solar maximum, although the levels are still relatively low compared to earlier solar cycles. The clear 27-day variation in solar activity has become apparent during the solar maximum period.

There have been several geomagnetic storms during the GOCE mission lifetime until now. The dates of sev-

Figure 4. Timeline of availability of the initial release (Version 1.2) of the GOCE density and crosswind data product.

eral storms has been indicated in Figure 5. Because of the close proximity in time of several storms and disturbances, the dates in the Figure do not serve as an exhaustive list.

5.3. Eclipses

Figure 6 shows a graphical representation of the occurence of solar eclipses by the Earth and Moon, during the course of the GOCE mission. Due to the fact that the orbit is not quite sun-synchronous, the eclipse periods have gotten longer during the course of the mission. The eclipses affect the radiation pressure accelerations. For the density determination, these are not important, as the magnitude of the radiation pressure accelerations are much smaller than the aerodynamic accelerations. For the crosswind determination this is a different matter, as the radiation pressure acceleration acts predominantly in the cross-track direction for GOCE. During full eclipses, the radiation pressure acceleration is absent, and so are radiation pressure model errors. But the exact modelling of eclipse transitions is difficult, due to the effect of the oblate Earth and refraction and absorption of Sunlight. Radiation pressure modelling errors can be large around these eclipse transitions, and the users of GOCE crosswind data should keep this in mind.

6. CONSIDERATIONS FOR ACCURACY AND DATA USAGE

6.1. Thruster activation data

The density data from GOCE is comparable to existing data sets from the CHAMP and GRACE missions. The main difference with CHAMP and GRACE is the operation of the ion thruster, as part of the drag free control system, which is designed to keep the accelerations along the spacecraft's X-axis (it's length direction) at zero. In the algorithm, this acceleration is subtracted from the accelerometer data, just like the radiation pressure acceleration, to arrive at the aerodynamic acceleration. Since the accelerometer X-axis data is almost always near zero, the information on the density for GOCE stems from the thruster activation data.

This thruster activation data is not part of the routine GOCE scientific data stream. Instead, it is part of the housekeeping data, originally intended only for checks on the health of the satellite and performance of its subsystems. The temporal resolution is therefore lower than that of the accelerometer data: the thruster activation is sampled for downlink only every 8 seconds, approximately, while the on-board algorithm that controls the thruster activation does so at a much higher rate. Due to this downlink sampling issue, some temporal details are lost. In the density and wind processing, the 8 second data is linearly interpolated to integer 10-second time steps, before further processing is applied. Of course, this sampling rate

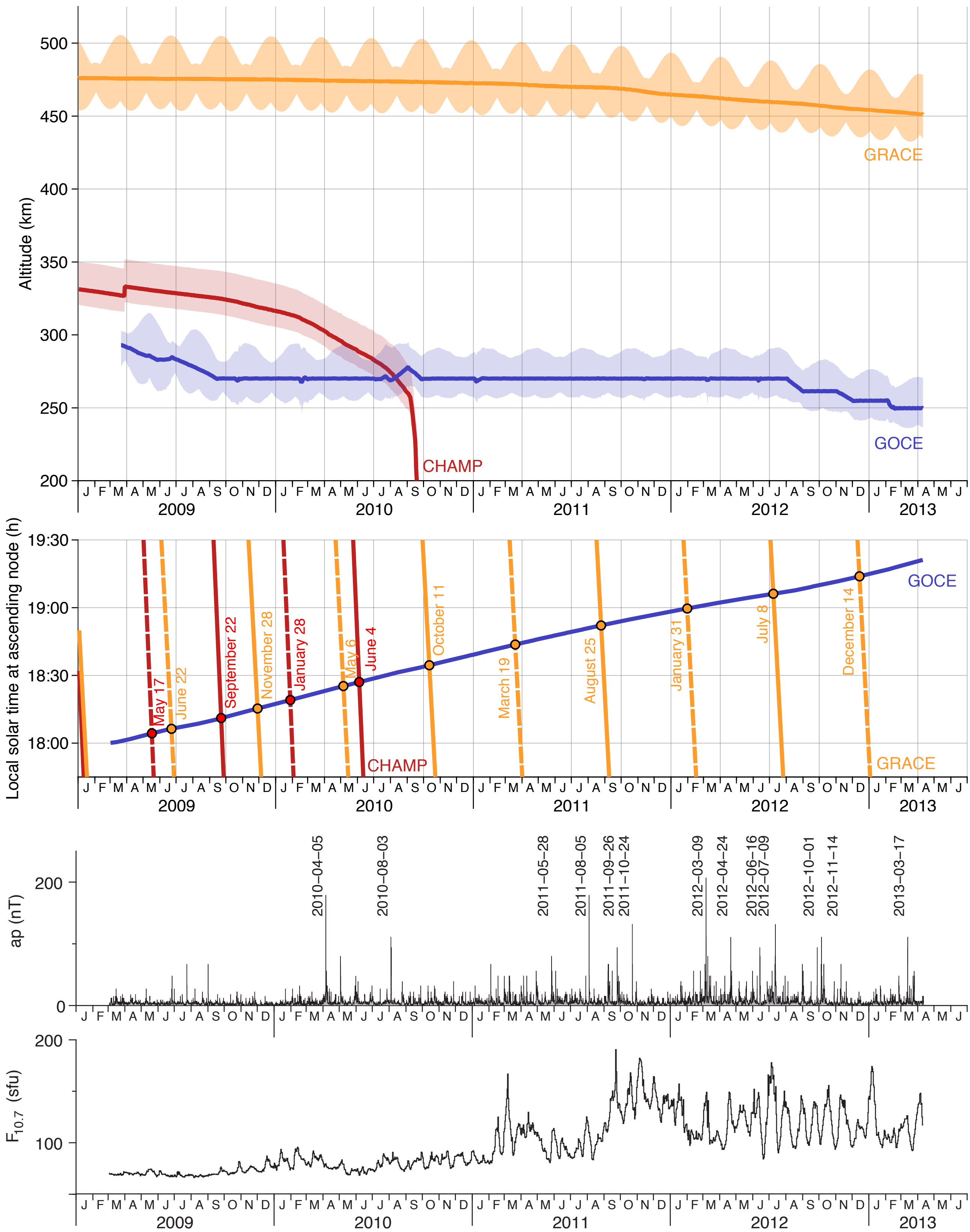

Figure 5. Orbital altitude and local solar time at equator crossings for GOCE, compared with CHAMP and GRACE. Time series of the ap geomagnetic activity index, with several geomagnetic storms highlighted, and the $F_{10.7}$ solar EUV flux proxy.

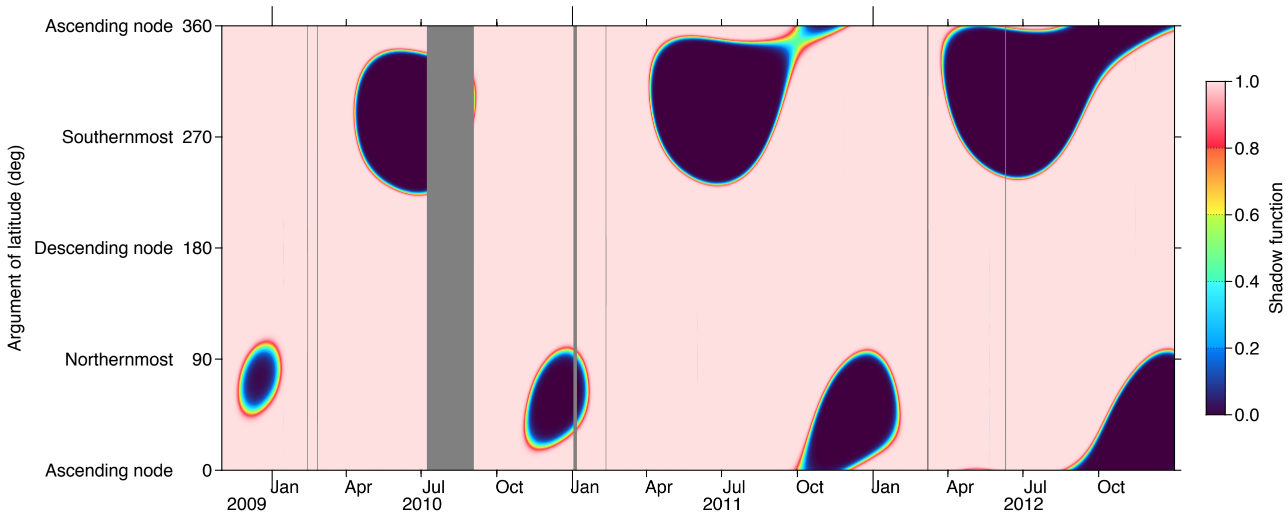

Figure 6. Time vs argument of latitude gridded plot of the so-called shadow function, which indicates whether the satellite is in full sunlight (1.0) or darkness behind the Earth (0.0). Note that due to the dusk-dawn orbit of GOCE, there are relatively long periods where the satellite is in semi-shadow. There are also a couple of occasions where the sunlight is partially or completely blocked by the Moon instead of the Earth.

also limits the temporal resolution of the density data, and thereby the spatial resolution of the along-track density time series, which is approximately 80 km.

6.2. Density accuracy and scale uncertainty

Errors in the geometry model and aerodynamic model of the satellite are the most important error sources in accelerometer-derived density data. Scale inconsistencies or errors in the density data of up to several tens of percent are common for all drag-derived densities. This is not different for GOCE.

During the course of the project, various aerodynamic models were compared for use in the density derivation, and a considerable uncertainty in density scale was encountered. Therefore, when the density data is to be compared to density model values or other density data sets, users of the data are advised to attempt to scale either the model or observed values for consistency. This is not necessary for studies of density variations with respect to a mean value, since research has shown that the effect of geometry model and aerodynamic model error on the variations is limited.

The true scale of thermospheric density is a topic of ongoing research, in which several members of the project team are involved.Therefore the possibility exists that the geometry and aerodynamic models for GOCE are updated for a later revision of the data, for improved consistency.

The reader is referred to the Validation Report for more details.

6.3. Effect of thrust level variations at low thrust on density accuracy

In an early phase of the study, it was established that the ion thruster on GOCE has a certain regime of low thrust levels, in which the thrust output is not as smooth as at lower or higher thrust levels. This phenomenon is apparently inherent in the design of the ion thruster. Due to the differences in the sampling and preprocessing of thruster activation data, it was not possible to further investigate the operation of the ion thruster in this regime with the help of accelerometer data. The thrust regime translates to density levels in the range of approximately 17.5×10^{-12} to 22.5×10^{-12} kg/m^3, at which density and wind data contain more noise-like variations, at the level of 3–4% RMS, compared to data from outside this range.

6.4. Interpretation of the crosswind vector

Note that due to limitations in the observation method, there is no possibility to retrieve the full wind vector from the accelerometer data. In the crosswind recovery, it has been assumed that the in-track wind is according to a model value, while the vertical component of the crosswind is zero. The fact that the crosswind is provided in a reference frame with components in the zonal (East), meridional (North) and vertical (Up) directions, does not mean that the measurements are to be interpreted as the full zonal or meridional winds.

Because of the near-polar orbit of GOCE, the crosswind direction is near to the zonal direction at low and mid latitudes, and reaches the meridional direction only at the instance of crossing the northernmost or southernmost latitudes.

To make a fair comparison of wind magnitudes with wind data from other sources (models or ground-based observations), it is therefore necessary to project the full wind data from these models or other measurements on the measured GOCE crosswinds. Similarly, if the crosswind data is to be used in models, they can only be used to constrain the wind component in the supplied direction.

6.5. Crosswind accuracy

The accuracy of crosswind measurements derived from satellite acceleration data was analysed by Doornbos et al. [2010]. The dominant source of errors in the crosswind data are due to acceleration errors in the spacecraft body-fixed Y-direction. These acceleration errors could be due to accelerometer bias, radiation pressure, and thruster activations in this direction. The level of these acceleration errors with respect to the aerodynamic acceleration determines the level of crosswind error. The low altitude of the GOCE satellite, at which aerodynamic accelerations are very high, is therefore a big advantage for obtaining high accuracy crosswind data. The Validation Report provides more information on this topic. A detailed error propagation study will be performed in the coming months, and the outcome of this study will likely be part of an updated version of the current data set and user manual.

7. CONCLUSIONS

A new dataset of thermosphere density and wind data has been made available via the GOCE Virtual Online Archive. The data is derived from gradiometer common-mode accelerations, in combination with ion thruster data. GOCE star camera and GPS receiver data are used in the calculations as well. The resulting density and wind observations are made available in the form of time series and grids. These data can be applied in investigations of solar-terrestrial physics, as well as for the improvement and validation of models used in space operations.

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