Change log

July 18, 2013  First issue, coinciding with data release v1.2.
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Introduction

This manual is intended for users interested in the density and wind data derived from the GOCE mission. The manual will explain the contents of the data set, will supply some additional information which might be of interest to users, and it will provide some warnings on limitations of the data. For detailed information on the data processing and validation, readers are referred to the Final Report, Algorithm Theoretical Basis Document and Validation Report of the GOCE+ Theme 3 study, which will be made available for download, as one PDF file, together with the data set and this manual.

Acknowledgements

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- Eelco Doornbos, Pieter Visser, Jose van den IJssel and Joao Encarnacao at Delft University of Technology (TU Delft), Astrodynamics and Space Missions research group, at the Faculty of Aerospace Engineering, located in Delft, The Netherlands;
- Sean Bruinsma at Centre National d’Études Spatiales (CNES), in Toulouse, France;
- Bent Fritsche and Georg Koppenwallner at Hypersonic Technology Goettingen (HTG), Katlenburg-Lindau, Germany.

Sadly, Georg Koppenwallner passed away in October 2012.

Questions

For questions on how to access the data, users can contact the ESA Earth Observation helpdesk at eohelp@esa.int. The homepage of ESA Earthnet Online can be found at http://earth.esa.int.

Questions related to the data and the contents of this user manual can be addressed to Eelco Doornbos at TU Delft, via e.n.doornbos@tudelft.nl.
The main data product is in the form of time series of density and wind speeds. These will be shown in Section 1.1. Section 1.2 shows the gridded data, which can be used for quick identification of data availability, data quality and special events, such as geomagnetic storms. Section 1.4 will discuss data availability, while more detailed information for users of the data is provided in Chapter 2.

1.1 Density and wind data time series

1.1.1 File name and file format

The density and wind data time series are supplied as plain text files, with each file storing one month worth of data. Because the data are stored as plain text, they should be readable on any operating system, and can be easily imported for further processing using many different software packages.

On the download server, the files are compressed using gzip, to save storage space and network bandwidth. They therefore have the extension .txt.gz. The files can be decompressed using the gunzip command-line utility on UNIX like systems, or software such as WinZip on Windows.

An example of the full name of an uncompressed text files is:

```
goce_denswind_v1_5_2009-11.txt
```

This filename contains the following information: the satellite name (goce), the data product name (denswind), the data major and minor version number (v1.5) and the year and month numbers (2009-11 for November 2009).

1.1.2 Structure

The plain text data files contain a short header at the top of the file, followed by many data records, in subsequent lines. A data record is defined as a single line in the text file, which provides data for a single epoch. Each record is subdivided into various fields,
Figure 1.1 Example of the first lines of a time series data file, including the header and the first couple of data records.

which are separated by spaces. Each field contains a numerical or text value for a certain variable. A sample of the start of one data file is supplied in Figure 1.1.

Header

The header lines are marked with a hash-sign (#) as the first character in the line. The first header lines contain attribution information and contact details. Subsequent header lines give a FORTRAN format specifier and description of each of the data fields (columns) in the data records that are to follow. The last three header lines contain the complete FORTRAN format specifier used for the output of the data, abbreviated column headings, and units for the data fields.

Data records

The data records always start with a time tag, including the time system. In this case, the data will always be in the GPS time system.

In subsequent columns, the data files contain information on the satellite orbit position, in the form of altitude, longitude, and geodetic latitude. These quantities are computed from the GOCE Precise Science Orbits (PSO), making use of the GRS-80 reference ellipsoid. The local solar time is currently computed from the longitude and time of day, and therefore represents an approximation to the mean local solar time only.

The argument of latitude is the angle along the orbit starting at the ascending node. It is also computed from the Precise Science Orbits, which are first converted to a True of Date inertial reference frame, and then converted to Keplerian orbit elements. The argument of latitude is computed as the sum of the argument of perigee and the true anomaly. It is a convenient angle for making the distinction between between ascending (270° to 360° and 0° to 90°) and descending arcs (90° to 270°), or to plot data which crosses
the poles (at around 90° for the North Pole and around 270° for the South Pole). The last four columns in the data file contain the actual observations of density and crosswind.

1.2 Plots of gridded data

A secondary data product is the gridded data. 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 1.2 shows an example of gridded density and wind data for the month of April 2010. From top to bottom the left-hand column 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 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 right-hand column contains the error estimates of the density and wind data, as well as a graph of the variation of the altitude of the satellite over the month.

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.

Figure 1.3 shows all the processed data over the entire mission. Note that the commissioning phase and deorbit phase data have not yet been included in data release 1.4.

1.3 Versions

The data version is an indicator of the state of the software and models used in the data processing. The current version is v1.5. Versions, v1.0 and v1.1, were used for internal testing and validation, and were not released for distribution. Version v1.2 was the first public release.

Each new version number reflects updated processing software, implementing either more accurate algorithms and models, or bug fixes. It is important to always use a consistent data set, with a single version, and not mix older and newer data. Users are therefore recommended to check the version number of previously downloaded data, when downloading new data, and discard the older data if necessary.
Figure 1.2 Example of one page of the gridded density and wind data file, for the month of April, 2010
Figure 1.3 Gridded data for the entire mission.
1.3.1 Version history

The list below provides a short description of each of the data set versions, and the changes made with each new version.

**Version 1.0** First internal test version for initial validation, September 2012;

**Version 1.1** Second internal test version, February 2013. Extended dataset with more months; Improved accelerometer calibration; Adjusted thruster pointing; Data editing applied: removal of incorrect data after inspection of time series.

**Version 1.2** First release version, July 2013. Improved accelerometer calibration, leading only to negligible differences in density and wind with respect to Version 1.1. Improved data editing.

**Version 1.3** Second release version, September 2013. There were three changes:

1. Data editing of version 1.2 was only applied to the figures of gridded data. It was inadvertently not applied to the time series data files. This has been corrected, resulting in removal of incorrect data for several periods, ranging from hours to days.

2. A bug in the iterative density and crosswind determination algorithm was fixed, leading to slightly different density and wind values. The bug was related to the projection of the HWM wind on the spacecraft body-fixed Z-axis (SBF-Z), described in equation (6.55) in the Algorithm Theoretical Basis Document (ATBD). This projected wind was added to the a-priori value, but was not subtracted when determining the final crosswind value in equation (6.52). Since the HWM model only supplies horizontal wind velocities, and the SBF-Z axis is kept closely aligned with the vertical direction, the wind component was of the order of a few tenths of 1 m/s.

3. The unit vector \( \hat{e}_{up} \) in equation (6.42) of the ATBD is now pointing in the vertical direction, defined by a reference ellipsoidal representation of the Earth. In earlier versions, this unit vector was aligned with SBF-Z. The small angle between SBF-Z and vertical is the result of pitch and roll motion of the satellite.

The combined effect of changes 2 and 3 on the data is dependent on the satellite’s small pitch and roll angles, which continuously change over time. The mean effect is close to zero, while the standard deviations are of the order of 0.01% for the relative change in density and of the order of 2 m/s for the change in crosswind velocity.

**Version 1.4** Third release version, July 2014. This release includes data from the start to the end of GOCE’s nominal mission operations, so from November 2009 until October 19, 2013. There have been numerous additional modifications to the data processing.

1. New input data: ESA made available new thruster data. This includes data from during the commissioning phase, before November 2009, data after May 2012 up to the end of the mission, and several additional passes of data which appeared as gaps in the earlier versions of the data set. Note that not all data
has proved to be consistent with our models and data processing procedures. For this reason, data from selected periods has been processed into density and wind data, but the results were in some cases excluded from this release. Most notably, this concerns the commissioning phase data (April to October 2009) and deorbit phase data (end of October and early November 2013). There is a possibility that this data will be added in a future release, when the inconsistencies have been studied and corrected.

2. New acceleration bias calibration functions. New bias calibration piecewise polynomial functions were created to fit through the daily bias value estimates. Because of this, the acceleration bias values for pre-existing data has also shifted slightly.

3. Error estimates have been added, based on an error propagation approach. The error estimates are the root-sum-square of various error contributions, computed from artificially introduced acceleration errors due to various known sources. More details are available in the Algorithms Theoretical Basis Document.

4. Four binary flag fields have been added. One flag indicates whether the satellite was on an ascending or descending pass. The other three flags can be used for quality control, because they represent the status of the ion thruster assembly used for drag free control, as well as whether there is a possibility of an eclipse transition.

5. Information on the optical properties of the GOCE solar arrays was received and implemented in the solar radiation pressure model. In addition, low drag data from during the commissioning phase allowed the determination of a solar radiation pressure model scale factor, and Y-axis acceleration correction. This has resulted in a reduction in the discrepancy between sunlit and shadow period crosswind data in 2010. Crosswind data in shadow has been affected the most.

Version 1.5 Fourth release version, July 2016. In previous versions, the telemetry data field used to reconstruct the ion thruster acceleration was the current_thrust field from the AUX_NOM data, which represents the output thrust as reported by the thruster electronics. For version 1.5, this has been changed to the field with the title thrust_demand, which represents the input to the thrusters. While the control loop for the ion thruster used a high data rate (10 Hz) for the input, the telemetry downlink is at a low data rate (0.125 Hz). Therefore, in the presence of noisy variations, the low rate downlinked input to the thruster actually provides a more accurate representation of the actual acceleration at the low rate used for computing the density and wind data than the reported thruster output.

### 1.4 Data availability

Figure 1.4 shows the data processed for the density and crosswind products on a timeline. Detailed information on data availability can be viewed in the PDF file of monthly gridded data.
Figure 1.4 Timeline of GOCE density data processed. The data gaps seen here are the result of unavailable input data. Note that part of the density data indicated here has not been included in the data release, because of quality issues related to inconsistencies between the data and the processing algorithms and models used. This concerns mainly the commissioning phase data (up to November 2009) and deorbit phase data (starting at the end of October 2013).
This Chapter will provide practical background information and more in-depth information, which might be of interest for users of the GOCE density and crosswind data. Section 2.1 will give details on the orbit, solar activity and geomagnetic activity which together largely determine the environmental conditions in which the measurements were made.

2.1 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.

2.1.1 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 2.1 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 precession 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
Figure 2.1 Orbital altitude and local solar time at equator crossings for GOCE, compared with CHAMP and GRACE.

Figure 2.2 Time series of the ap geomagnetic activity index and the $F_{10.7}$ solar EUV flux proxy.
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 accessible
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-synchronous dawn-dusk orbit, crossing the equa-
tor 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 alti-
tude and near sun-synchronous orbit are unique aspects of the mission, and need to be
taken into consideration by users of the data.

2.1.2 Solar and geomagnetic activity

Figure 2.2 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 cy-
cles. 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.

2.1.3 Eclipses

Figure 2.3 shows a graphical representation of the occurrence 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 determi-
nation, 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 absorp-
tion 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.

2.2 Considerations for accuracy and data usage

2.2.1 Thruster activation data

The density data from GOCE is comparable to existing data sets from the CHAMP and
GRACE missions. The data processing algorithm is based on [Doornbos et al. 2010].
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 of [Doornbos et al.]
Figure 2.3 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.

[2010], 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 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.

2.2.2 Density accuracy and scale uncertainty

According to [Doornbos et al. 2010], 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 encoun-
tered. 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.

2.2.3 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. This thrust regime translates to density levels in the range of approximately \(17.5 \times 10^{-12}\) to \(22.5 \times 10^{-12}\) kg/m\(^3\), at which density and wind data in thermosphere data versions v1.4 and lower contained more noise-like variations, at the level of 3–4% RMS, compared to data from outside this range. In version 1.5 data, instead of the reported output thrust level, the input to the thruster was retrieved from the housekeeping data (the thrust\_demand field was used instead of current\_thrust). This has removed the variations with higher noise from the dataset. The current assumption is that the sample of the thrust input is a better representation of the average thrust level during the 8-second housekeeping data sampling interval than the sampled thrust output, containing this higher noise range.

2.2.4 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.
2.2.5 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.

2.2.6 Error estimates

Version 1.4 of the data adds the results of an error propagation to the data set. These results are available per measurement, both in the time series data and in the gridd representation. The following error sources have been taken into account:

- **Acceleration errors**, mainly attributable to accelerometer bias calibration uncertainty:
  - An acceleration error in the X-direction of 0.5 nm/s²;
  - An acceleration error in the Y-direction of 10 nm/s²;
  - An acceleration error in the Z-direction of 10 nm/s²;
- **Thruster error of**
  - 1% of the thrust acceleration (new in version 1.5, previously this error had a dependency on the thrust range);
- **Radiation pressure model error of**
  - 50% of the modelled radiation pressure acceleration when the data is flagged to be close to an eclipse transition;
  - 15% of the modelled radiation pressure acceleration during full sunlit conditions;
- **Wind model error of 50% of the HWM07 model values**;

The density and crosswind speed have been recomputed using all of the above error sources. The differences between the densities and wind speeds with and without the above errors have been added in a Root-Sum-Squared (RSS) sense.

Note that not all possible error source have been taken into account. For example, errors in the GOCE geometry model and aerodynamic model, described above, have not been taken into account. These are expected to have a relatively large effect on the densities, in the form of a scale factor. But this type of error will be more or less consistent throughout the mission. The error sources listed above, as well as the RSS combination of error sources, might also be too optimistic or pessimistic. Therefore, the error estimates
can not be assumed to represent accurate weighting factors when using the data in models. Nevertheless, the results of the error propagation can give valuable insight in relative density and wind data quality.

Figure 2.4 shows an overview of the RSS density and wind errors, throughout the mission. The following observations can be made about the density error estimates:

- The density error propagation results are dominated by the noise in the thruster activation data. The regions where the thrust level is in the ‘noisy’ range, where the noise is about 4% clearly stands out in the plot. The quality of the density data should be best during periods where the thruster was switched off or throttled down to lower the orbit, such as the . Inspection of the data itself confirms the lower noise level.

- Radiation pressure model errors at eclipse transitions only play a significant role in the density error estimate during the first half of the mission lifetime.

- In-track wind model errors play a role at high latitudes. Due to the use of scaled HWM07 model values in the error estimates, these error estimates might be smaller than reality.

Concerning the crosswind error propagation results, the following observations can be made:

- The wind errors, which are dominated by errors in the Y-axis acceleration and radiation pressure, get much smaller in time, as the relative magnitude of the aerodynamic acceleration increases.

- Wind errors can be exceptionally large during eclipse transitions, especially at the start of the mission. This error estimate might be too pessimistic however, as the gridded data at the start of the mission show only limited artefacts around the eclipse transitions.

- From the error propagation results, it is expected that the crosswind data during the final months of the mission is of exceptionally good quality. The data earlier on in the mission looks quite similar however, again indicating that the error estimates might perhaps be on the pessimistic side for the crosswind data, and in reality the error in the earlier data are smaller than these estimates.
Figure 2.4 Results of the error propagation, in terms of RSS relative density error and RSS wind error.
Bibliography