AIR DENSITY MODELS DERIVED FROM MULTI-SATELLITE DRAG OBSERVATIONS
EXECUTIVE SUMMARY

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ABSTRACT

Satellite accelerometers, such as those carried on the CHAMP and GRACE satellites, can provide valuable data for improving our knowledge of thermosphere density and winds. These data are now available over a wide range of the defining conditions, including more than half a solar cycle. Continuity and enhancement of this multi-satellite accelerometer data set will be provided by ESA's Swarm mission. This paper presents an overview of a 1.5-year ESA-funded study, covering the processing steps required for accurately converting accelerometer data into density and wind data, and the subsequent use of this data for improving our understanding of the thermosphere. The study concludes with recommendations for the design of future thermosphere missions and for continued research using data from the current and planned missions.

Key words: CHAMP; GRACE; Swarm; accelerometer; drag; thermosphere; density; wind;.

1. INTRODUCTION

This paper presents a summary of an ESA-funded study in which the use of accelerometer data for thermosphere density and crosswind recovery was investigated. Full details of the study approach, processing algorithms, results, conclusions and recommendations can be found in the study's final report (Doornbos et al., 2009). In addition, the authors have published several papers (Koppenwallner, 2008; Van Helleputte et al., 2009) and intend to submit several more, to peer-reviewed scientific and engineering journals, based on the results of this study.

The density of the neutral thermosphere is one of the most important variables to model for applications in satellite orbit determination. In addition, the state of the neutral thermosphere, which can be expressed in terms of the densities of its constituents, its temperature and wind speeds, plays an important role in studies of solar-terrestrial physics. The parameters that define the thermospheric state vary over a wide range of spatial and temporal scales. This complexity, combined with an undersupply of available observation data, has made the development and improvement of models quite a challenge.

Accelerometers carried by satellites provide valuable data for improving our understanding of the thermosphere density and winds, especially when these data are available over a wide range of the most important influencing parameters: Altitude, latitude, local solar time and solar and geomagnetic activity. The CHAMP and GRACE missions provide such data. These missions carry accelerometers in order to allow the removal of non-gravitational signals from accelerations due to the Earth's gravity field, which is their subject of interest. So even though the determination of thermospheric density and winds is not part of their primary mission objectives, it is a very important spin-off application, which is generating an impressive stream of scientific results (for recent publications see e.g., Liu and Lühr (2005); Liu et al. (2005, 2006, 2007a,b, 2009a,b); Müller et al. (2009); Förster et al. (2008); Burke et al. (2007); Sutton et al. (2005, 2009); Guo et al. (2007); Thayer et al. (2008); Lei et al. (2008)). The fact that the CHAMP and GRACE missions are largely overlapping in time (see Figure 1) allows for an opportunity to study the synergy of their data. The twin GRACE satellites and the single CHAMP satellite form a constellation of which the geometrical configuration constantly changes over time. Since both missions are in polar orbits, they offer unprecedented opportunities to study the complex dynamics of the thermosphere at high latitudes.

The trajectories of both missions are spiralling downwards due to the effect of drag, so they will sample density and wind speeds at a wide range of altitudes. This also implies that the satellites will likely perish in re-entry during the next solar cycle peak, CHAMP somewhat earlier than GRACE. That raises the question of continuity of this data set. This continuity will be provided by
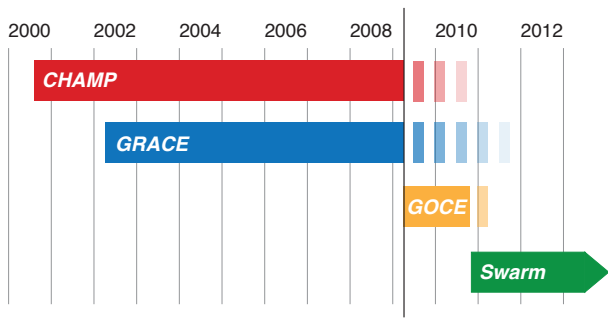
Figure 1. Timeline of accelerometer carrying satellite missions in low Earth orbit.

ESA's Swarm mission, a constellation of three satellites for studying the Earth's magnetic field. The Swarm constellation offers unique possibilities, not only for observing and separating different sources that contribute to the Earth's magnetic field, but also for improving the observation of atmospheric density and wind variations and their relation with geomagnetic activity.

Figure 2 shows the approximate altitudes of these missions, in relation to density curves for day and night and low and high solar activity conditions. The variations in density of up to several orders of magnitude that occur over the altitude range of these satellites and as a function of the local time and solar activity cycle is apparent. Note the fact that satellites at higher altitudes will measure a lower density, but also with a larger variability.

Also shown in Figures 1 and 2 is the GOCE mission, which flies under drag-free control in a near-circular polar orbit at an exceptionally low altitude. This drag-free control mode, required for its primary mission in gravity recovery, is a complicating factor for density determination. Therefore, this mission was left outside the scope of this study. Nevertheless GOCE's data could be very valuable for thermospheric density and wind investigations as well, and the combined processing of data from its accelerometer and ion thruster certainly deserves further investigation.

2. DATA PROCESSING

The investigation of the data processing is based on data from the CHAMP and GRACE accelerometers, star cameras and GPS receivers and equivalent simulated data for Swarm. The investigation encompasses the calibration of the accelerometer instrument, accurate aerodynamic and radiation pressure force modelling and the enhancement of processing algorithms. This has resulted in improved accuracy and increased insight in the possible sources of error.
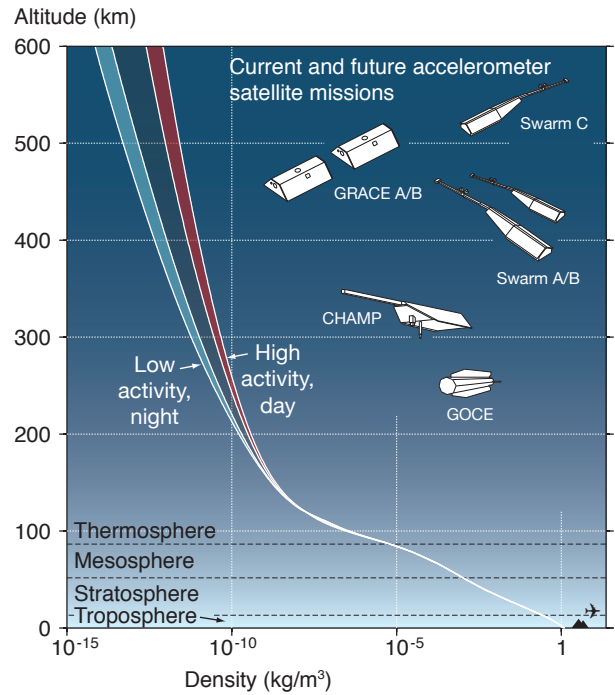

Figure 2. Density profiles of Earth's atmosphere, from the NRLMSISE-00 model, shown together with the approximate orbital altitudes of current and future accelerometer-carrying satellite missions.

2.1. Accelerometer calibration

The project's investigation into the calibration of the CHAMP and GRACE accelerometer instruments with the use of GPS tracking data has been published by Van Helleputte et al. (2009). Improved results were achieved by keeping the calibration scale factors fixed over the entire mission, and estimating only the time-varying calibration biases. In addition, investigations were made into the benefit of estimating the calibration parameters of multiple satellites in the constellation simultaneously, either separately or relative to one another, thereby eliminating common error sources.

For CHAMP, GRACE and Swarm, the principal body-fixed axes remain closely aligned with the orbit-fixed axes in the along-track, cross-track and radial directions. The calibration using GPS tracking of the accelerometer axes which point predominantly in the radial and cross-track directions proved to be much more challenging than for the axis which points predominantly in the along-track direction. Not only is the along-track acceleration signal the largest of the three directions, its direct effect on the orbital period is the easiest to observe using tracking data. For accurate wind retrieval results, a cross-track axis calibration making use of force models instead of the GPS tracking data was necessary. For future missions, a mission design in which each of the accelerometer axes samples a sufficient portion of the along-track acceleration in turn would be more beneficial for the instrument calibration and crosswind determination.
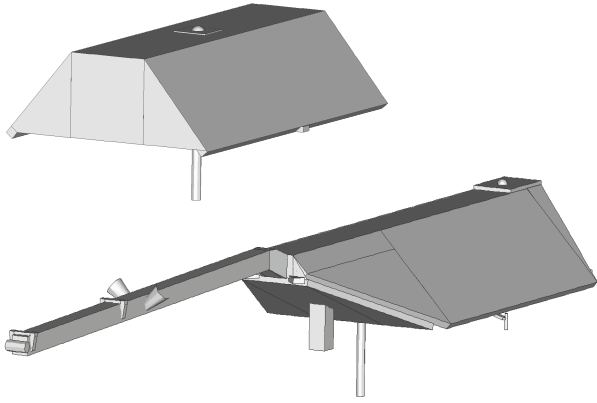
Figure 3. The CHAMP and GRACE geometry models built in the ANGARA software.

2.2. Non-gravitational acceleration modelling

The modelling of the aerodynamic interaction and radiation pressure forces was investigated using two methods for representing the satellite geometry. Design-drawings obtained from the satellite manufacturers were used to create accurate 3D representations of CHAMP and GRACE in the ANGARA non-gravitational force modelling software (see Figure 3). This software and some of its earlier results are described by Fritsche et al. (1998), Doornbos et al. (2002) and Fritsche and Klinkrad (2004). In addition, the more traditional multi-panel models (Lühr et al., 2002; Bruinsma and Biancale, 2003; Bettadpur, 2007) were implemented. These panel models do not include information on the relative position of the panels, and can therefore not be used to compute shielding or shading of one part of the satellite by another.

A comparison of frontal areas between each of the geometry models and manufacturer-supplied frontal area data uncovered unexpectedly large errors in the previously published CHAMP panel models: Up to 37% for the model provided by Lühr et al. (2002) and 14% for that provided by Bruinsma and Biancale (2003). Even the new, carefully created ANGARA CHAMP model showed a maximum frontal area difference of 7% with respect to the manufacturer data. It is likely that the irregularly shaped protruding elements on CHAMP, such as antennas and star camera baffles play a big role in this uncertainty, which is therefore difficult to reduce further. The GRACE satellites have a more simple geometry, with just a single protruding antenna. The maximum differences in frontal area between the various GRACE geometry models are within about 5%.

Another source of uncertainty in the data processing concerns the gas-surface interaction modelling as part of the aerodynamic calculations. Again, various models were compared. The Maxwell gas-surface interaction model implemented in ANGARA, and the equations by Sentman (1961) applied to the flat panels caused equally good results. The satellite aerodynamic equations for flat pan-
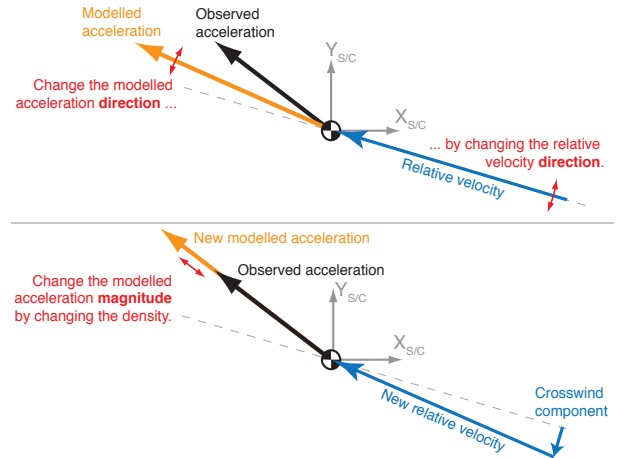

Figure 4. Schematic representation of the two steps in the iterative density and wind retrieval algorithm for multi-axis accelerometers.

els by Cook (1965), which were previously widely used in CHAMP and GRACE data processing (e.g. Bruinsma and Biancale (2003); Sutton et al. (2007)) was found to be unsuitable for these slender satellite shapes (Koppenwallner, 2008; Sutton, 2009). In fact, the results when using the Cook (1965) equations evaluated even worse in comparisons of density data with models than when a simple spherical satellite model with a fixed drag coefficient was used.

2.3. Density and wind determination

A new iterative density and wind determination algorithm was developed for this study, which can be independent of the orientation of the instrument's principal axes with respect to the flight direction. The validity of this algorithm was tested by making use of the CHAMP slew manoeuvres and sideways-flying periods. Previously published algorithms for wind determination from CHAMP data, which assumed the wind to be in the spacecraft body-fixed Y-direction (Sutton et al., 2007), or considered only the drag force, but not lift and sideways forces (Liu et al., 2006), would lead to unrealistic results under such conditions.

The new algorithm is schematically explained in Figure 4. The simple goal of the algorithm is to find the density and relative velocity direction which make the modelled acceleration vector equal to the observed one. A future journal publication on the algorithm is currently under preparation.

3. RESULTS

The data processing steps outlined above, and the resulting time series of density and wind, were analyzed in
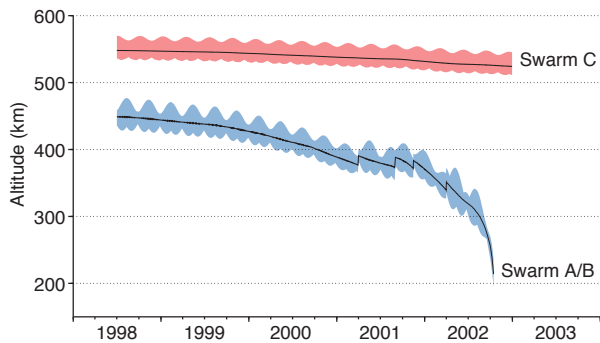
Figure 5. Altitude variation of the simulated Swarm orbits. The shaded areas indicate the minimum and maximum altitude, the black line indicates the daily mean.

many different ways during the course of the study. This Section will briefly present some of the highlights.

3.1. Error analysis

An error analysis was performed using simulated Swarm data. For this purpose, the Swarm A/B and Swarm C orbits were propagated from their initial altitudes of 450 and 550 km, over the time period between July 1998 and December 2002 (see Figure 5). This historic period was selected in order to have realistic solar and geomagnetic activity parameters available for the simulation of the future ascending phase of the solar cycle in the 2010–2015 timeframe. All the non-gravitational force models were evaluated along these orbits, after which the iterative density and wind retrieval algorithm was applied. Without any error sources, the baseline input model density and wind were recovered as expected.

The effect on the density and crosswind of 16 different error sources was evaluated. These error sources, divided into three categories, included a) instrument errors, such as noise, calibration bias and scale factors in the X- and Y-directions, b) relative velocity errors, both in terms of biases and as a fraction of the wind model velocity, and c) force model errors, such as errors in the area/mass ratio, atmospheric temperature, Helium concentration, energy accommodation coefficient of the gas-surface interaction, radiation pressure reflectivity and eclipse transition timing. The magnitudes of these input errors are based on the instrument specifications, experience using the CHAMP and GRACE data, and in several cases, conservative educated guesses. Because of the similarity of the missions, the qualitative discussion of the error analysis results below is largely valid for CHAMP (in a lower orbit, similar to Swarm A/B) and GRACE (in a higher orbit, similar to Swarm C) as well.

The statistics over the entire simulated mission of the Root-Sum-Squared (RSS) of all the error sources combined are listed in Table 1. The minimum density errors, at 11.2% of the density signal, are largely determined by the uncertainties in the satellite area and energy accom-

Table 1. Statistics over the entire simulated mission of the density and wind error magnitudes for Swarm A/B and C.

Swarm	Category	min	max	mean	std.
A/B (low)	Density (%)	11.2	63.0	15.5	0.9
C (high)	Density (%)	11.2	90.4	16.2	2.9
A/B (low)	Crosswind (m/s)	1	6023	95	103
C (high)	Crosswind (m/s)	7	11863	300	380

modation coefficient, which are nearly the same for the lower and higher-flying Swarm satellites. The nature of these error sources is largely systematic, and could therefore also partly cancel to result in lower errors than those listed here or, when acting in the same direction, result in larger errors than the RSS listed here, if the components have the same sign.

Under the right circumstances, the crosswind derivation is largely insensitive to such systematic force model errors. Therefore, the minimum wind errors are very small. The maximum errors for both density and wind are determined by eclipse transition timing errors, during which the full magnitude of the radiation pressure acceleration could either be incorrectly removed or not removed when it should. This acceleration then interferes with the aerodynamic acceleration signal. The higher-flying Swarm C is much more sensitive to such errors than its lower-flying counterparts because of the much lower density and drag signal, while the radiation pressure is largely independent of the altitude. It is clear that care must be taken in the wind determination, and interpretation of its results, because the magnitude of these maximum errors far exceeds the magnitude of the expected crosswind speeds, which is of the order of a few hundred m/s.

The mean density error for all Swarm satellites is at a level of 15–16%, based on our estimates of the input errors, and the variation around these values is limited. This number is the sum of various large error contributors from all three categories (instrument, wind and force model). The in-track wind error is the most variable of these contributors. Its contribution to the density error is expected to be small at low latitudes, and large over the auroral zones.

The errors in the derived crosswind speed are much more variable in general. An accurate wind determination can only be made at low enough altitudes (for a strong drag signal), and under favourable solar illumination geometry conditions (for a weak cross-track radiation pressure signal). All satellites are expected to deliver a much improved capability for crosswind determination when their orbits have decayed to low enough altitudes, so that the aerodynamic force far exceeds the radiation pressure and calibration error sources.
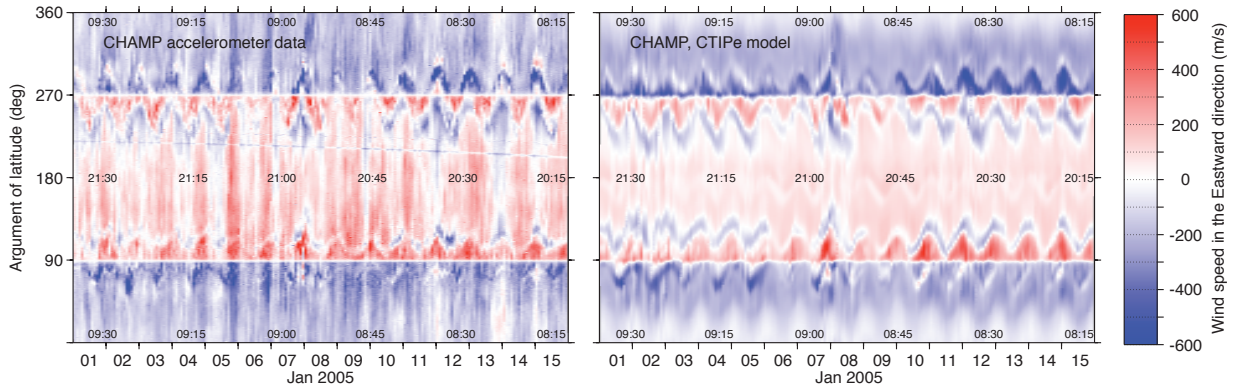
Figure 6. Comparison of zonal wind velocities from CHAMP data (left) and from the CTIPe model, evaluated at the same locations (right).

3.2. Validation and comparisons with models

The density and crosswind data was subjected to elaborate validity checks. For example, the density data was reduced to a single reference height, filtered for latitude and geomagnetic activity, and analyzed in terms of its largest influencing factors: Solar activity, local solar time and day of year. The crosswind data was evaluated and compared separately at high latitudes and mid/low latitudes.

The results are in line with the conclusions from the Swarm error analysis. Significant systematic offsets were found between the accelerometer-derived density data and density models. These offset are the result of both the uncertainties in the accelerometer processing, discussed above, and biases in the models. The density variations after the offsets were removed were consistent with expectations.

The crosswind derivation results were also consistent with the error analysis for Swarm. Due to its high altitude, the GRACE results suffered from large wind speed errors due residual calibration and solar radiation pressure modelling errors. The CHAMP wind data showed much more consistency with existing empirical models, such as HWM-93 (Hedin et al., 1996) and HWM07 (Drob et al., 2008; Emmert et al., 2008), and the physical model CTIPe (Codrescu et al., 2008). This is demonstrated in Figure 6. Note the near-horizontal line in the data, in between the descending node (180°) and the South polar crossing (270°). This is an example of the eclipse transition timing error. Both HWM models (not shown in this Figure) resulted the same general pattern, but with slightly lower peak wind speeds than the CTIPe model and CHAMP data.

3.3. Empirical model calibration

The density model calibration software, which was previously developed under ESA contract for the processing of Two-Line Element data (Doornbos, 2006, 2007; Doornbos et al., 2008), was modified to use accelerometer-derived density data. This software can adjust an existing empirical density model, such as NRLMSISE-00 Picone et al. (2002), by estimating scale factors, expanded in spherical harmonic coefficients, over preset time intervals. The rationale behind this approach is that density data obtained from one or more satellites can be used to improve the density model accuracy for satellites in different orbits. In Figure 7, this is demonstrated making use of GRACE data for the calibration, and CHAMP data for the evaluation. Each panel shows the density along the CHAMP trajectory. The top-left panel shows the observed densities, which we would expect from a perfect model. The top-right panel shows the output of the NRLMSISE-00 model, which predicts somewhat larger densities, and with considerably less detail. In the bottom-left panel, a scale factor, determined from GRACE density data, has been applied to the model, improving the consistency. A further improvement is made by estimating up to third order zonal spherical harmonics from the GRACE data, the result of which is shown in the bottom-right panel of Figure 7. Evaluated over the entire year 2003, this adjustment results in a reduction of the log-normal standard deviation of the CHAMP data/model density ratios from 1.250 to 1.155. This encouraging result warrants further investigation in the future, for example of density model calibration using all simultaneously available accelerometer satellites, combined with Two-Line Element data of space debris objects.

4. CONCLUSIONS AND RECOMMENDATIONS

The main conclusion from this study is that the accelerometer instruments on CHAMP, GRACE and the future Swarm satellites provide valuable data on the thermosphere, in the form of densities and crosswind speeds.

The largest remaining error sources in the density derivation are the gas-surface interaction modelling, modelling of the satellite geometry, the calibration scale factor for the in-track accelerometer component, and the knowledge of the atmospheric in-track wind speed, composition and temperature. These sources lead to density errors
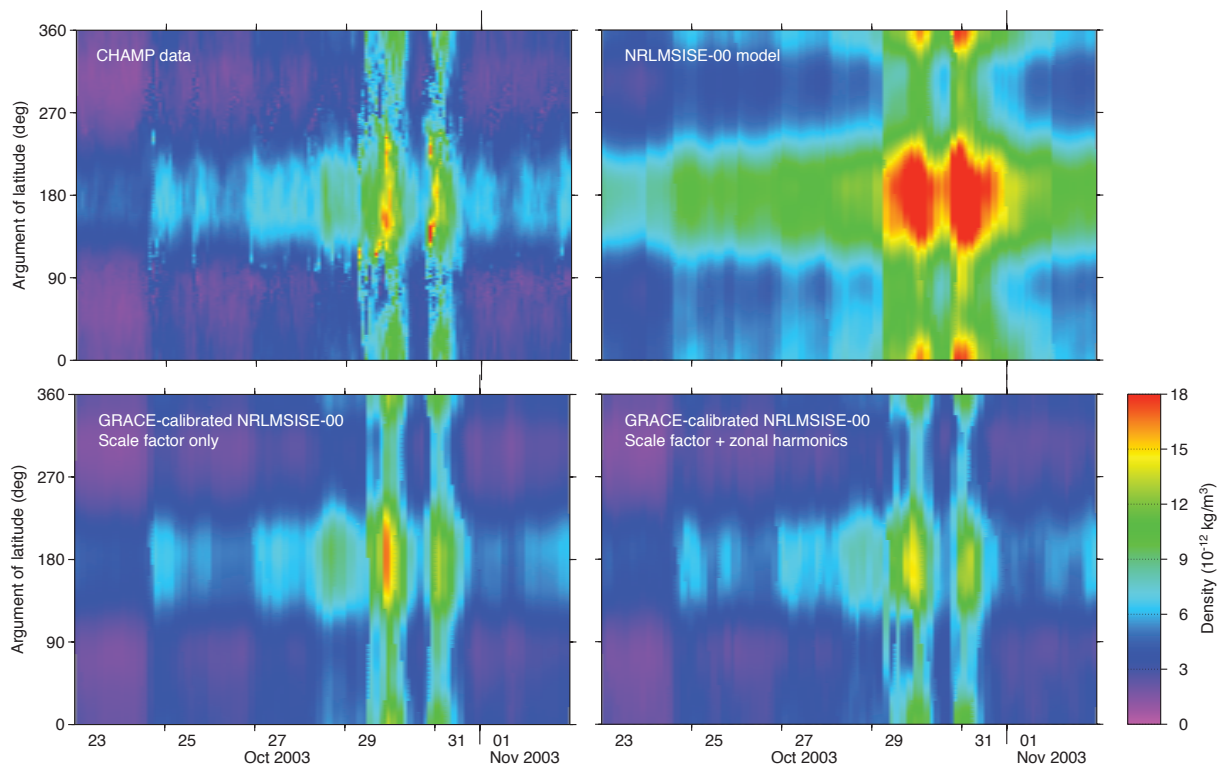
Figure 7. Comparisons of density data along the CHAMP trajectory. The panels show CHAMP accelerometer-derived data (top-left), NRLMSISE-00 model data (top-right) and NRLMSISE-00 model data, calibrated with the help of GRACE-derived density data (bottom left and right).

which are largely systematic in nature and are estimated at about 15% of the density signal for CHAMP, GRACE and Swarm.

The crosswind determination accuracy is very much dependent on the strength of the aerodynamic drag signal, compared to solar radiation pressure modelling errors and accelerometer cross-track calibration errors. Therefore, reliable results can only be obtained for a combination of a sufficiently low altitude, high enough solar activity and a favourable orbit geometry in terms of radiation pressure accelerations. For CHAMP, a multi-year time series of crosswind speeds has been obtained that is within the statistical uncertainty of current empirical thermosphere wind models. However, for the higher altitude GRACE satellites, radiation pressure modelling errors dominate.

The CHAMP- and GRACE-derived density and wind data has subsequently been used in extensive evaluations using empirical and physical models of the thermosphere, and geophysical studies of large scale structures and patterns in the data. Experiments with an accelerometer-calibrated empirical density model indicate that improvements in the standard deviation of data/model ratios of at least 30% are possible.

The study concludes with recommendations. These include a recommendation for further investigation into the systematic errors in the current density datasets and biases between datasets and models. The gas-surface inter-action modelling used for the satellite aerodynamic calculations warrants special additional attention. Further recommendations are concerned with the fact that investigations of the thermosphere are not part of the primary objectives of the missions studied. Several issues in the design of the satellites and their data processing procedures were encountered, which could be improved by future changes or in the design of future missions. These issues range from the presence of smoothed, and therefore difficult to remove thruster accelerations in the GRACE data, to the complicated elongated satellite shapes, which complicate force model calculations. For future thermosphere missions, a final important recommendation is to include additional instrumentation for simultaneous measurements of the total neutral density with the atmospheric temperature, constituent densities and wind velocities.

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