Chapter 7
Conclusions and Recommendations

In this final Chapter, the conclusions of the previous Chapters will be summarised, and recommendations will be given for improvements to the processing of data from current missions, as well as for the design of possible future missions.

7.1 Conclusions

The algorithms and investigations presented in this thesis have demonstrated that the accelerometer instruments on CHAMP and GRACE, as well as the TLE-data from many space debris objects, provide valuable observations of the thermosphere in various forms. These processing techniques and the resulting data have been used to improve our understanding of upper atmospheric processes and phenomena, and will continue to do so in the years to come.

The newly developed iterative algorithm, presented in Sect. 4.2.2, has been applied to derive information on the thermospheric wind speed, with a reduced error budget. The assessment of density and wind errors due to various errors in the input models and data, has shed light on the nature and extent of these errors. In the long-term, this is perhaps the most important contribution of this work, because it is valuable both for users of the data interested in geophysical interpretation of variations in density and wind, and for investigators wishing to further improve the data processing results.

Due to the largely global nature of observed density variations, combined with large systematic errors in existing empirical density models, assimilation of contemporaneous density data to calibrate such models will result in an immediate improvement of their accuracy. This can lead to improvements in applications such as precise orbit determination of Earth observation satellites.

7.1.1 Accelerometer-Derived Density and Wind Data

In contrast to previously published direct algorithms for deriving density and wind from accelerometer data, the iterative algorithm described in this thesis can be applied

E. Doornbos, *Thermospheric Density and Wind Determination from Satellite Dynamics*,
Springer Theses, DOI: 10.1007/978-3-642-25129-0_7,

in situations without a close alignment of the accelerometer axes with the orbit's along-track and cross-track directions. In fact, it can be used for arbitrary orientations of the accelerometer axes in space. The analysis using simulated CHAMP data in Sect. 4.2.4 shows that errors due to assumptions on the orientation are significantly reduced when the new algorithm is applied. However, this analysis also shows that errors in the instrument calibration and input models that are common in the use of both algorithm types lead to more significant density and wind errors than the errors in the algorithms.

The density data suffer mainly from systematic offsets (scaled densities, with respect to the truth), due to inaccurate information of the spacecraft geometry and gas-surface interaction. These issues are not so important for the wind data. Instead the accelerometer-derived winds are extremely sensitive to small errors in the calibration and radiation pressure modelling, especially when the density and aerodynamic acceleration are relatively small as well. Such errors distort the true patterns in the crosswind output in a complex manner, making the validation and interpretation of these data difficult.

Users of the current CHAMP and GRACE data (and possibly GOCE and Swarm data in the future as well), should be aware of the level and nature of such errors in density and wind. The investigation of these algorithms and their related error sources has led to recommendations for improvements of possible future dedicated accelerometer-carrying space missions for studies of the thermosphere, presented in Sect. 7.2.

Despite these systematic errors and uncertainties, the density and wind observations resulting from this study have proven useful for thermospheric modelling, and will likely continue to be useful for a long time.

7.1.2 Two-Line Element-Derived Density Data

Density data obtained from Two-Line Elements, according to the algorithm by Picone et al. [6] have proven to be a reliable and valuable source, that compares well with accelerometer-derived data. The disadvantage that the temporal resolution of the TLE-derived density data is very low, at three days or more, is offset by the advantage of the availability for a very large number of space objects. An important condition for this is the application of a robust data editing and ballistic coefficient determination scheme, such as the one implemented by Emmert [1].

The comparison between TLE-derived and accelerometer-derived density data for CHAMP and GRACE, presented in Fig. 5.9, has shown that the accuracy of the data degrades rapidly under low drag conditions, such as at higher altitudes and lower levels of solar activity. This non-uniform accuracy has not been sufficiently addressed in earlier publications on the topic, but it is important to keep in mind for users of the data.

7.1.3 Density Biases and Trends

When both types of air density measurements are compared with models based on similar measurements from the 1960s and 1970s, a large decrease in density, of the order of 20%, can be observed. The difference between these recent measurements and historical models is larger than the contribution of systematic errors in the satellite area and aerodynamic modelling, described above. Therefore, there must have been a decrease in the true density, which is the result of a downward trend in the thermospheric temperature. This thermospheric cooling trend, which has been studied in more detail by other researchers (e.g., [2]), is consistent with the effect of raised concentrations of greenhouse gases in the lower atmosphere [4].

Comparisons of measurements and models made at solar minimum, in 2008 and the surrounding period, show evidence of additional cooling, which is related to the extremely low solar activity at the time [3]. Such a deviation from the usual 11-year cycle in density and solar activity has not been observed since the beginning of the space age.

Future measurements, processed using the algorithms presented in this thesis, will be able to tell us whether the observed thermospheric cooling trend is continuing at the same rate, and whether the unexpected deviation of the pattern in the interaction between the Sun and the thermosphere around 2008 was a one-time event, or the start of a prolonged period of low solar activity. The latter possibility would have profound consequences on satellite lifetimes and the evolution of the population of space debris objects in low Earth orbits.

7.2 Recommendations for Future Missions

The instruments, tracking techniques and satellite missions employed in this thesis were, in most cases, not designed with the objective of studying the thermosphere in mind. Nevertheless, it is indisputable that the accelerometer instruments on the CHAMP and GRACE missions, and the various types of tracking data available for many other missions and space debris objects, have proven to be very valuable sources of information for the thermosphere modelling community.

The experience gained in the study of the CHAMP data in particular, and the development and analysis of the iterative algorithm presented in this thesis, have led to several recommendations for the development of possible future thermosphere missions, with the aim to reduce density and wind errors.

First of all, a compact and simple design of the satellite external shape, without protruding antennae, camera baffles, booms, etc., will reduce the uncertainty in geometrical and aerodynamic satellite modelling, which will result in a more reliable estimate of absolute density values. The availability of additional instruments on accelerometer missions, which could make contemporaneous in-situ measurements of the atmospheric temperature, molecular mass, in-track wind, and other parameters important for gas-surface interaction, would increase the accuracy of the aerodynamic calculations required for the accelerometer processing, as discussed in Sect. 3.4.3. At the same time, such instruments would provide valuable data for atmospheric and aerodynamic modelling in general, which could in turn aid in a more accurate reprocessing of historical accelerometer datasets.

A large area-to-mass ratio of the satellite will increase the acceleration signal, which is especially beneficial for wind derivation. Flying at high solar activity and low altitude will help in that respect as well, but that will put limits on a mission's sampling characteristics. A high eccentricity orbit might aid in calibration and the separate fine-tuning of radiation pressure and aerodynamic satellite models, but again at the cost of the beneficial atmospheric sampling characteristics of circular orbits.

Finally, the example of CHAMP'S sideways-flying periods, presented in Sect. 5.2.1, shows that a more versatile or more loosely defined attitude control of an irregularly shaped satellite will provide data that can be used to identify and possibly reduce density and crosswind errors. If the attitude control can be designed such that each of the three accelerometer axes can spend a sufficient amount of time, in turn, in the satellite flight direction, this could be beneficial for the instrument calibration using orbit tracking data, and reduce the crosswind error. The data processing of such a mission is possible using the iterative algorithm presented in this thesis.

7.3 Outlook for Further Research

Even though the CHAMP satellite has ended its 10 years in orbit with a fiery re-entry, the quality of its density and wind data, as well as the utilisation of these data, can still be improved. This is even more true for GRACE, which, at its higher altitude, requires an even more precise modelling and calibration, in order to reduce density and wind errors. Meanwhile, new data from the GRACE and GOCE missions, as well as fresh TLEs, keep arriving at a steady pace. The planned Swarm and GRACE follow-on missions bring with them the promise that satellite accelerometer data will remain available in abundance, and hopefully without significant interruptions, throughout the next decade. This Section lists several possible follow-on investigations, that might aid in getting the most out of these data.

We have seen that the largest errors in the density data originate in the modelling of the spacecraft geometry and gas-surface interaction. Since the creation of the current geometry models already required a significant investment in man-hours, making use of detailed satellite drawings, a further improvement of their fidelity likely requires an even larger investment. For example, for future missions it could be feasible to convert detailed CAD models of the satellites directly into force models, or to use 3D laser scanning techniques on the finished satellite in the clean-room.

As discussed in the previous Section, in order to really solve the problem of inaccuracies in modelling of the gas-surface interaction, even bigger investments are required, in the form of a newly designed satellite mission for investigations of the thermosphere and satellite aerodynamics, carrying additional instrumentation beyond an accelerometer. But smaller improvements can already be made right now, for example by adjusting the temperature and composition output of the NRLMSISE-00 model, to compensate for the fact that this model overestimates the energy input into the thermosphere, especially at low solar activity. The resulting density bias that was examined in Chap. 5 is most likely paired with similar temperature and composition biases, skewing the current aerodynamic calculations. The $F_{10.7}$ input to the NRLMSISE- 00 model can be adjusted, so that the density bias is removed, resulting in a temperature and composition output that is consistent with this level of density. Such adjusted temperature and composition values can then be applied in the density and wind algorithm, to see if a reduction in the standard deviations of density ratios occur.

Another option would be to utilise density data from satellites which are less sensitive to the settings of the gas-surface interaction parameters, such as the ANDE spheres [5]. If there are periods where such satellites sample the density at a similar altitude and local solar time as CHAMP or GRACE, the gas-surface interaction parameters can be adjusted so that the consistency between their density outputs is optimised.

In the derivation of crosswind speeds from accelerometer data, errors in the cross-track accelerometer calibration and solar radiation pressure modelling were identified as the largest error sources. Some improvements to both these problems are possible for the current missions as well. These improvements can be tested by looking at the consistency of the derived winds with empirical and physical wind model output, and by looking at the consistency between winds before, during and after special attitude manoeuvres, such as the one in November 2002, described for CHAMP.

The current calibration strategy is based on the estimation of daily biases, while keeping the scale factor fixed at an advertised value. In reality, the advertised value of the scale factor might not be the correct or optimal one. An optimised scale factor, or a time series of such scale factors, can possibly be determined by minimising the standard deviation of measured minus modeled accelerations.

A further proposed improvement concerns the accelerometer data preprocessing. The accelerometer data products used in this thesis have already been preprocessed before release for scientific use. The preprocessing step generally includes a reduction of the data rate. In the CHAMP data processing, acceleration spikes, due to thruster activations and other sources, have been removed from the high-rate data, before conversion to the low-rate data. This is a good situation for density and wind processing, since such spikes are not part of the aerodynamic acceleration signal. It is not a good situation for the calibration of the X-axis data using GPS tracking data, since these acceleration spikes likely have a real effect on the orbit, that is also present in the GPS data. The removal of the spikes should therefore result in an error in the calibration. For GRACE the situation is more or less reversed. The spikes are not removed before the data rate conversion in the preprocessing. However, the preprocessing also includes the application of a digital low-pass filter, which causes the thruster spikes to get spread out over a longer time duration, making them much more difficult to remove. In the ideal case, which should apply for future missions as well as the currently available ones, the lower-level high-rate data should be made available to scientists, so that the appropriate digital filtering can be applied for calibration, while the spikes can be removed for further processing into density and wind information.

Finally, the modelling of solar radiation pressure can be improved in several ways as well. There are currently no efficient eclipse models available that include the effects of the Earth's flattening as well as atmospheric absorption and refraction. Such a model, employing ray-tracing techniques, would directly reduce wind errors near equator crossings. Its indirect effect on the accuracy of wind estimates, through the improvement of the acceleration calibration using models, might be even more important. A further option for improving the radiation pressure modelling would be to adjust the optical properties of the satellite surfaces, so that the resulting modelled acceleration better fits with observed accelerations. This will only lead to accurate results if data periods and acceleration components are used, for which the aerodynamic and Earth radiation pressure accelerations are very small compared to the solar radiation pressure acceleration.

References

1. Emmert JT (2009) A long-term data set of globally averaged thermospheric total mass density. J Geophys Res 114(A06315). doi:10.1029/2009JA014102
2. Emmert JT, Picone JM, Meier RR (2008) Thermospheric global average density trends, 1967–2007, derived from orbits of 5000 near-earth objects. Geophys Res Lett 35(L05101). doi:10.1029/2007GL032809
3. Emmert JT, Lean JL, Picone JM (2010) Record-low thermospheric density during the 2008 solar minimum. Geophys Res Lett 37(L12102). doi:10.1029/2010GL043671
4. Keating GM, Tolson RH, Bradford MS (2000) Evidence of long term global decline in the earth's thermospheric densities apparently related to anthropogenic effects. Geophys Res Lett 27(10):1523–1526
5. Nicholas A, Finne T, Galysh I, Davis M, Healy L (2010) The atmospheric neutral density experiment (ANDE), in 2009 NRL Review, Naval Research Laboratory, pp 138–142
6. Picone JM, Emmert JT, Lean J (2005) Thermospheric densities derived from spacecraft orbits - I. Accurate processing of two-line element sets. J Geophys Res 110(A03301). doi:10.1029/2004JA010585