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Thermospheric Density and Wind Determination from Satellite Dynamics

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Thermospheric Density and Wind Determination from Satellite Dynamics

Doctoral Thesis accepted by
the Delft University of Technology, The Netherlands

Springer

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Supervisor's Foreword

The thermosphere, regarded as the top level of the Earths atmosphere (100–1000 km altitude), is characterised by a high degree of variability. Despite of being investigated for several decades, our understanding of thermospheric dynamics is still incomplete. This is largely due to the lack of appropriate measurements which are sufficiently well distributed in time and space. At a few 100 km altitude the air density is twelve orders of magnitude lower than at the surface (less than any vacuum achievable in a laboratory). Even though, the remaining air exerts a significant force on satellites orbiting the Earth. This is mainly due to the high orbital velocity (7.5 km/s) and to the fact that the air drag is proportional to the square of the speed. For satellites in low-Earth orbit, air drag is the prime contributor to orbital perturbations. A proper characterisation of the atmospheric properties is therefore indispensable for precise orbit determination. This is in particular vital for monitoring the innumerable objects of space debris orbiting the Earth.

In this work it is outlined how thermospheric properties can be derived from the non-gravitational forces acting on satellites. First, the classical approach is described, which is based on interpreting orbital perturbations in terms of disturbance forces like air drag and radiation pressure. The advantage of this approach is that no active instruments on board are needed. Even passive objects in orbit can contribute to the results. The disadvantage is the coarse spatial resolution of that method. Much refined results are obtained when sensitive accelerometers are used on satellites for measuring the non-gravitational forces acting on the spacecraft. The great achievement of this work is the proper characterisation of the processes influencing the gas-surface interaction. Only after considering these processes in an adequate way, reliable values for air density and wind velocity can be retrieved. The developed algorithm has been applied successfully to the satellites CHAMP and GRACE.

These new and accurate datasets have been used for testing the reliability of commonly used atmospheric models. The comparison with measurements revealed the advantages and limitations of the different kinds of empirical models. This knowledge is of relevance for their operational application, for example, in orbit prediction software. The data obtained in this work show particularly clear the inability of present atmospheric models to properly reflect the deep depletion of the thermospheric density during the extended solar activity minimum (2008–2009). Besides these more practical aspects the novel data set has also inspired a whole range of scientific studies. Quite prominent among them are investigations of tidal signatures in the upper atmosphere. Some of the observed tides are related to weather and climate phenomena. I am convinced that many more scientific investigations will follow using this unique set of thermospheric density and wind data.

Potsdam, June 2011 Prof. Dr. Hermann Lühr

Preface

Traditionally, the value of a Ph.D. thesis will be determined by its readers in terms of its scientific content. It is a collection of pages filled with words, equations, figures and tables, that hopefully conveys some useful knowledge for certain experts in some field of research. However, for the author it usually represents much more than that. It represents the end of a journey, the journey of the start of a career in science. If the author is fortunate, this has been an exciting journey. But perhaps like in most truly exciting endeavours, there may have been periods of difficulty as well. Much more than the words, equations, figures and tables contained in a thesis, it is the people encountered along this journey, with whom the excitement and difficulties could be shared, that represent the true value of the thesis to its author.

The journey that led to the publication of this work started back in 1999. I was an aerospace engineering student who had always been fascinated by space missions and by computer technology, but at the time I had no clear idea of a possible career path or even of a suitable thesis subject. Fortunately, professor Boudewijn Ambrosius knew just the right subject for me. He introduced me to Remko Scharroo, who was working on precise orbit determination of the ERS-1 and ERS-2 radar altimeter satellites. A follow-on mission, named Envisat, was under construction at the time. Envisat was going to be a massive satellite, with ten scientific instruments, covering many aspects of geophysical and environmental research.

Remko, being an expert on the radar altimeter instruments on these satellites, and having worked on the modelling of gravitational forces which perturb their orbits, gave me the assignment to work on an improved model of the so-called non-gravitational forces: atmospheric drag and radiation pressure. The prediction of these forces requires the 3D modelling of the satellite's external surfaces on the computer. The combination of computer graphics and satellites already made it an interesting enough project from my point of view at the time. Little did I know that I had not only found a great master's thesis topic, but that I had also set my first steps on the path to a career as a research scientist. The computer graphics were nice, but the research that was required before and after that turned out to be the really interesting parts of the work.

Another very fortunate encounter occurred not much later, when I was given the opportunity to attend the International Astronautical Congress in Amsterdam. Among the wide variety of talks was one by Dr. Heiner Klinkrad, of the European Space Operations Centre ESOC in Darmstadt, Germany. His talk was on a new sophisticated software package for non-gravitational force modelling, called ANGARA, which would be perfect for use in my thesis work. Our meeting in Amsterdam led to a traineeship, partly at HTG, the developers of ANGARA, in Katlenburg-Lindau near Göttingen, and partly at ESOC, where I could implement and test the models in the orbit determination of ERS-2 and Envisat using the new orbit determination software, that was under development there at the time. The enthusiasm of my supervisors during that project (Remko Scharroo at TU Delft, Bent Fritsche and Georg Koppenwallner at HTG and Heiner Klinkrad and Rene Zandbergen at ESOC), as well as that of their colleagues (Dirk Kuijper at ESOC deserves special mention) provided the fuel to kindle my own enthusiasm for continuing this type of work after graduation.

After obtaining my master's degree, I gratefully accepted the invitation to continue working at Boudewijn Ambrosius' astrodynamics group in Delft, on several projects related to satellite radar altimetry and precise orbit determination. I substituted for Remko Scharroo on several of his running European projects, since he had moved on to live and work in the US. This fast introduction into the world of international cooperation on space projects turned out to be the ideal learning ground. I could immediately start to visit many international altimetry-related conferences and project meetings, where I quickly felt part of the vibrant satellite oceanography community. The approaches to multi-mission satellite data storage, processing and visualisation that were emerging in this field at that time, to which I could add my own small contributions, became inspirations for the way I set up the software system for my thermosphere density and wind research in later years. I have fond memories of the many encounters, conversations and collaborations with colleagues during this period, including Pascal Willis, Michiel Otten, Nikita Zelensky, Jean-Paul Berthias, John Ries, Patrick Vincent, Jérôme Benveniste, Richard Francis, David Cotton, Peter Challenor, Yves Menard, Phil Moore, John Lillibridge and many others.

While my work on the altimetry-related projects continued until well into 2008, my curiosity about possible improvements to the modelling of drag on satellites never went away, and I tried to combine these interests whenever possible. A next stage of the journey began with the invitation by Heiner Klinkrad, in 2002 and again in 2004, to work on projects concerning thermosphere density model calibration, in near real-time, for the space debris office at ESA/ESOC. The first project involved a feasibility study, and the second the delivery of a software implementation to ESOC, which was completed in early 2007. Since most of the research and programming work was done by myself, the feedback received from Heiner Klinkrad and Pieter Visser during the course of these projects was very welcome. The invitation, arranged by Heiner Klinkrad, to visit my US colleagues in Colorado in 2005, funded through the European Office of Aerospace Research & Development with the help of Barrett Flake, proved extremely valuable to my future work as well. At this meeting I met Bruce Bowman, whose HASDM calibrated model was the inspiration for the ESOC assignment, and who was always willing to help me out by providing data and advice. I also met John Wise, who later invited me to come to the Air Force Research Lab in Massachusetts in 2007. There I presented my work and enjoyed the opportunity to have discussions with him and his colleagues, Frank Marcos,William Burke and Chin Lin.

My intention at that time was to turn the results of the two ESOC projects into a Ph.D. thesis, and the drafts of the first chapters of the current book were written during that summer. However, at about the same time, ESA released an invitation to tender for a study investigating the processing of density and wind information from accelerometer data, in preparation for their forthcoming Swarm mission. I had already worked with Dries Caluwaerts on this topic for his M.Sc. thesis, using data from the similar, but already operational CHAMP and GRACE satellites. He did a great job, and I had been looking forward to further expanding his work in the future. These satellites made direct measurements of the accelerations that we had been trying to model for years, using software such as ANGARA. Not only was it now possible to make detailed comparisons of these models with real data, these data could now also be used to gain detailed knowledge on the weakest parts in our models, in this case the thermospheric density and wind. I could not let the opportunity pass to write a proposal in response to the ESA invitation to tender, even though it meant putting the thesis-writing on hold for the time being.

The project that followed from this proposal allowed me to work closely with many colleagues for nearly 2 years. It was an intense period of collaboration for me. Pieter Visser, Jose van den IJssel and Tom van Helleputte at TU Delft, Georg Koppenwallner, Bent Fritsche and Nelli Eswein at HTG, Matthias Förster and Hermann Lühr at GFZ Helmholtz Centre Potsdam, David Rees at Hovemere and Michael Kern and Roger Haagmans at ESA/ESTEC deserve much credit for their contributions to this project, of which large parts can be found in this thesis. I learned a great deal by working together with these colleagues during this period. Additional encounters mainly happened at the bi-annual COSPAR conferences and at the ESA meetings that I attended during these years. Among the people with whom I could share my enthusiasm for my research, and who were always willing to answer my questions or share their results, were John Emmert, Douglas Drob, Marcin Pilinski, Ken and Mildred Moe, Kent Tobiska, Srinivas Bettadpur, Sean Bruinsma, Kathrin Häusler, Patricia Ritter and Huixin Liu.

By mid-2009, the ESA project was finalised, but it had kept me so busy that there was still no Ph.D. thesis, except for a couple of draft chapters dating back to 2007. On the one hand, I was very eager to make use of the momentum I had gained and continue with my research, to initiate new, thermosphere-related projects. Other projects were on the horizon as well, such as the orbit determination of the CryoSat-2 radar altimeter satellite. It was not easy to reach the decision that I had to either cancel or postpone such work, in order to be able to fully concentrate on the writing of this thesis. Once that decision was reached, the writing itself was often not quite easy either, but in the end it is the result that counts, and that result is now in your hands.

With the thesis now completed, I would like to take this opportunity to first of all thank Boudewijn Ambrosius and Pieter Visser for offering me the freedom to grow professionally while working on such interesting projects, and also for providing me the time required to turn this thesis into something I can be proud of.

Sean Bruinsma, Matthias Förster, Hermann Lühr and Heiner Klinkrad deserve my gratitude for their suggestions for corrections in the final stages of preparation of this thesis. Both Pieter Visser and Erwin Mooij provided excellent feedback at earlier stages.

Many of my other colleagues in Delft deserve special mention as well, for providing such a pleasant environment to work in. First of all, Jose van den IJssel and Nacho Andres, with whom I shared my office (as well as coffee, tea and chocolate) for many years, but also Marc Naeije, Ejo Schrama, Bert Vermeersen, Ron Noomen, Karel Wakker, Relly van Wingaarden, Taco Broerse, Kartik Kumar, Jeroen Melman, Luuk van Barneveld, Hermes Jara Orue, Wouter van der Wal, Paolo Stocchi, Tom van Helleputte, Bert Wouters, Hugo Schotman and Remco Kroes.

Fortunately, there is also a life beyond work. Tom, Aynav, Kristina and Marieke, thank you for being such great friends throughout the years, and to Rachel, in addition, thanks for your encouragement and advice during the toughest part of this journey. To Bauke, Erik, Joost, Dennis, Coen, Robert and many other friends at DDS, thank you for the great times we had on and off the water.

Of course, special thanks go to my parents, sister and brother, and my extended family. It is always nice to come home to you.

And most of all, to Mieke, thank you for your gentle encouragement, your love and good humour, and for celebrating the near-finalisation of this thesis with me so many times in recent months.

Delft/Leiden, December 2010 Dr. Eelco Doornbos

Contents

Chapter 1
Introduction

Neutral density in the thermosphere is one of the most important variables to model for applications in solar-terrestrial physics and drag computations for satellite orbit determination. Thermospheric density varies over a wide range of spatial and temporal scales under the influence of the complex interactions between the Earth system and solar processes. Unfortunately, observation data on the thermosphere have always been quite sparse and measurement modelling uncertainties have often introduced a relatively high level of ambiguity. These characteristics have made the improvement of thermosphere density models quite a challenge in the past.

The availability of more powerful computers and new algorithms has made it possible to gather and process density information from the trajectory analyses of many space objects simultaneously. In addition, the accelerometer instruments on the CHAMP and GRACE satellite missions have provided density data at an unprecedented accuracy and resolution. Under favourable conditions, the data from these instruments have even enabled derivation of crosswind speeds.

Despite the fact that several basic data processing issues remain difficult to solve even with today's knowledge, data and computing power, such developments can be put to use to improve traditional empirical thermosphere models. The processing of spacecraft tracking, trajectory and acceleration data, as well as a basic strategy for adjusting density models using such observations, are the main topics of this thesis.

This introductory Chapter starts by providing an overview of the applications of thermosphere models in Sect. 1.1. The remaining sections of this introduction provide short overviews of topics which will be expanded upon in later Chapters. The various ways in which density and wind variations can be observed by satellites is introduced in Sect. 1.2. Section 1.3 provides a short discussion on the way this knowledge has been applied to build models of the thermosphere. This leads to the description of the research objective of this thesis in Sect. 1.4.

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1.1 Why Study the Thermosphere?

Thermosphere density models are applied in scientific investigations as well as in many types of satellite orbit calculations, including re-entry prediction, manoeuvre planning for ground-track maintenance and precise orbit determination for Earth observation missions. The accuracy of density models therefore does not only influence scientific results, but for many satellite missions it also affects requirements for mission operations, tracking systems and propellant consumption. This section will provide descriptions of these fields of application.

Applications in Solar-Terrestrial Physics

Models and observations of the thermosphere are applied in scientific investigations of the solar-terrestrial environment, a region which is sometimes named geospace. This environment, as defined by Hargreaves [29], includes the upper part of the Earth's atmosphere, the outer part of the geomagnetic field and the solar emissions that affect them.

The state of the neutral thermosphere, described by density, composition, temperature and wind velocity, depends in a complex way on both solar activity and geomagnetic activity. There are important interactions of the thermosphere with the Earth's ionosphere and magnetosphere [58, 63]. This has led to the development of coupled numerical models of this system. Our understanding of solar-terrestrial physics can be improved by comparing the output of such models with observational data, including data on thermosphere density and wind speed obtained from observations of satellite dynamics.

Applications in the Earth Sciences

For several Earth-observation missions, the accurate determination of the trajectory of the satellite is a requirement for fulfilling the mission's scientific objectives. Thermosphere density models are used to model the drag acceleration acting on the satellite.

For example, satellite laser ranging SLR satellites, such as Stella, Starlette and Ajisai [71] allow the very accurate determination of station positions, which provide information on Earth-orientation and plate tectonics [54]. Another example is radar and laser altimetry [27], where the altitude of the satellite is required to relate the range measurements over changing water and ice levels to the terrestrial reference frame. Altimetry missions include ERS-1, ERS-2, Envisat, TOPEX-Poseidon, Jason, CryoSat and IceSat. After the spectacular improvement of gravity field modelling and the accompanying reduction of gravity-induced orbit error in the 1990s and early 2000s, the relative importance of thermospheric density and drag on the orbit accuracy of these satellites has greatly increased [18, 21, 64].

In another application, known as synthetic aperture radar interferometry, or InSAR, the difference in position between two radar image acquisitions should be precisely known in order to study surface deformations [28, 50]. Data from the SAR instruments on ERS and Envisat have been widely used for this purpose.

The motion of satellites has also been analysed to recover information about the Earth's gravity field, by missions such as CHAMP [59] and GRACE [67]. These missions carry precise accelerometers. Any acceleration that is not due to gravity, such as atmospheric drag, will otherwise contaminate the gravity recovery.

Although these Earth observation missions and instruments were not specifically designed for the purpose, data from their precise tracking systems and accelerometers can be very useful for studying variations in the thermosphere. This will be extensively discussed in Chap. 4.

Applications in Space Mission Analysis and Operations

The atmospheric drag force causes all low Earth orbit objects to spiral downward, and eventually re-enter in the most dense layers of the atmosphere. This has profound consequences for many aspects of space mission analysis and operations.

To illustrate this, Fig. 1.1 shows photos of a specific class of space objects, known as Payload Assist Modules for Delta rocket launches (PAM- D). PAM-Ds have been used in a great number of satellite launches, including those of Global Positioning System (GPS) satellites. For these launches, the PAM- D initially remains in a highly elliptical orbit after separation from its satellite payload.

Because of the exponential decrease of atmospheric density with altitude, the drag force on a satellite in an elliptical orbit is strongest at its lowest point, the *perigee*. The drag force causes kinetic energy to be transformed into heat, causing a decrease of the size and ellipticity of the orbit, as measured by its *semi-major axis* and *eccentricity*. Figure 1.2 shows how the changing shape of the orbit of a PAM- D, that was catalogued as object 22659, has been observed during its lifetime. Chapter 3 will provide equations that describe these changes.

Close to the end of its lifetime, when the orbit became nearly circular, the decay of the orbit's semi-major axis quickly accelerated, to up to more than 30 km/day, as the density and drag forces along the trajectory rapidly increased. Occasionally, remnants of a PAM- D have been found on the ground after re-entry. The right-hand side photo in Fig. 1.1 shows such a fragment, belonging to object 22659, which landed in the Saudi Arabian desert.

As we will see in Chap. 4, the rate of change of the size of the orbit, as plotted in Fig. 1.2, is closely related to the density of the atmosphere, encountered by the satellite along its trajectory.

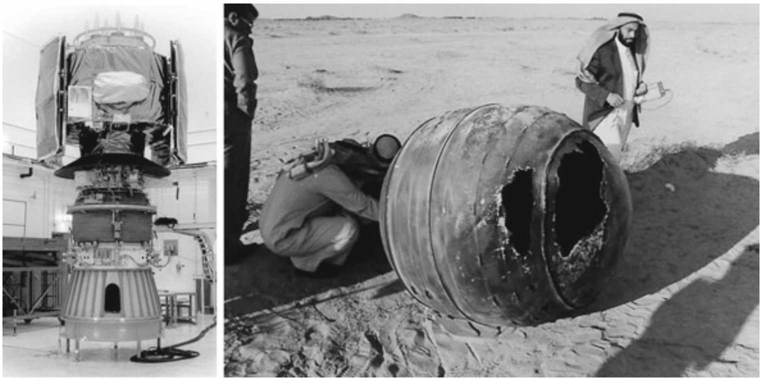

Fig. 1.1 *Left*: A GPS satellite mounted on a delta 2 payload assist module (PAM-D) before launch. Photo: air force space museum [16]. *Right*: Part of the motor casing of a PAM-D (object 22659), which re-entered the atmosphere and landed in the Saudi Arabian desert on January 12, 2001. Photo: KACST

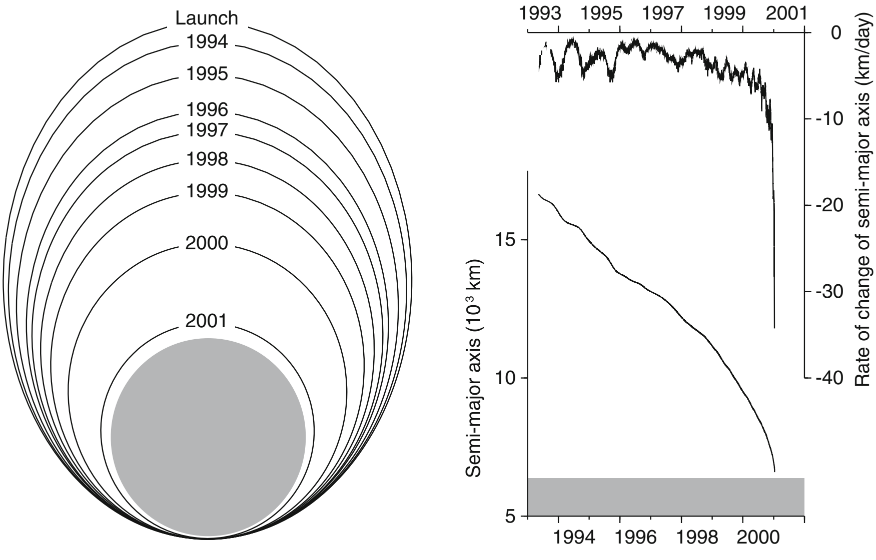

Fig. 1.2 *Left*: The changing shape of the orbit of object 22659, depicted right after its launch on May 13, 1993 and on Jan 1 of each year until its re-entry. *Right:* Time series of the semi-major axis and its rate of change for the object. Orbit data are derived from two-line elements

Orbiting Object Catalogue Maintenance

The United States Space Command has maintained a database of satellite orbit states, known as the Space Object Catalog, since the early days of the space age. In early 2010, the catalog contained over 36,000 distinct objects, of which over 15,000 were still in orbit. The oldest still orbiting object in the catalogue is Vanguard 1, launched in March 1958. Most objects, such as object 22659 mentioned above, have re-entered.

The catalog is regularly updated using observations from the Space Surveillance Network (SSN), a globally distributed network of interferometer, radar and optical tracking systems. In order to be able to identify and keep track of objects as their orbits change over time, a model of their motion, as influenced by atmospheric drag, is required.

Russia operates its own operational space surveillance system, while France has an experimental system [38]. In recent years, plans for setting up a European operational space surveillance system have materialised as well [39].

Lifetime Analysis

Figure 1.2 shows that the rate of decay of the semi-major axis of object 22659 varied between approximately 2–8 km/day for most of its lifetime. This variation was mainly caused by changes in atmospheric density due to both changes in the orbit geometry with respect to atmospheric features and changes in density due to external causes. An accurate modelling of these effects is important for predicting the orbital lifetime of satellite missions [52, 72]. Of course, such predictions are required during the stage of mission design. Often, the predictions need to be revised after launch, in order to facilitate the planning of a mission extension or the decommissioning of the spacecraft.

Re-Entry Operations

Decommssioned low-Earth orbit objects ultimately re-enter into the denser layers of the Earth atmosphere, where they mostly burn up. Occasionally, objects are involved that are large and massive enough so that one or more remaining parts can reach the ground. Figure 1.1 already showed an example: the PAM- D with catalogue number 22659. Figure 1.3 shows what happened during the final week and hours of the orbital lifetime of this object, until it finally re-entered during the afternoon of January 12, 2001.

Because such re-entry events are relatively rare, and mostly happen over the oceans or uninhabited areas, there is not a particularly large risk for damage or injury [38]. However, sometimes re-entries involve spacecraft with very large masses. Extreme examples are 40,000 kg for Salyut-7 in 1991, 74,000 kg for Skylab-1 in 1979, and 135,000 kg for Mir in 2001. Some re-entry objects also carry hazardous payloads, parts of which can reach the ground, such as the nuclear reactors on Cosmos-954 and Cosmos-1402 in 1978 and 1983, respectively. For such objects, it is desired that re-entry trajectories are predicted, and if possible, controlled. Density fluctuations have a very large influence on the accuracy of trajectory predictions that are made during re-entry campaigns. Chapter 9 of Klinkrad [38] contains extensive information on this subject.