

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.

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