Institution: University College London

Unit of Assessment: 14 – Civil and Construction Engineering

Title of case study: Space vehicle surface force modelling for orbit prediction (engineering applications) and orbit determination (science programmes)

1. Summary of the impact

Departmental research led to changes in how radiation forces on several classes of space vehicle (low earth orbit environmental measurement satellites and medium earth orbit navigation missions like GPS) are modelled by two NASA laboratories (Jet Propulsion Laboratory and Goddard Space Flight Centre). This includes NASA's adoption of a UCL model as an operational standard for Jason-1, which measured global sea level change from 2001 to 2013. Jason-1 measurements are a critical component of data supplied to the Intergovernmental Panel on Climate Change, thereby feeding into policy formulation seeking to mitigate the effects of climate change upon the entire population of Earth. The techniques also changed the way in which GPS satellite orbits are calculated, with products used by many millions of users.

2. Underpinning research

Space geodesy uses satellites to measure planet characteristics such as gravity field, sea level and ice cap variations, and tectonics. Modelling the forcing effects of radiation (solar, terrestrial and radiation from the satellites) is important for accurate predictions of GPS (and other) satellite orbital trajectories. GPS positioning accuracy depends directly upon our ability to determine, and predict, satellite orbits. Millions of real-time users rely upon navigation devices decoding messages that include mathematical models of instantaneous satellite locations – this relies fundamentally upon accurate satellite force models. Put another way, mis-modelling satellite motion introduces errors into user position estimates.

Novel research on modelling space vehicle surface forces was undertaken between 2001 and 2007 by Marek Ziebart (Professor of Space Geodesy, at UCL since 2000) and his team (primarily Ant Sibthorpe, now at NASA JPL, at UCL 2002-2008, and Sima Adhya, now running a space mission insurance group in the City of London, at UCL 2002-2005). Ziebart developed these ideas [1] in his PhD and through further EPSRC and NERC-funded projects whilst at UCL. The major developments – specifically design and implementation of novel tool sets, and extension of the basic concepts – all took place at UCL (2001-2007). The project demonstrated that high-accuracy radiation flux models, detailed computer simulations of space vehicle geometry and attitude, and surface material properties (both optical and thermal) could be used in a novel and original fashion to model radiation surface forces on satellites for engineering, scientific and commercial applications [3]. The approach broke new ground and was well received by the engineering and scientific community because although the effects were known to be important, existing approaches were considered overly simplistic and error-prone.

The techniques developed (efficient spacecraft surface modelling, custom ray-tracing methods, treatment of thermal response of both satellite multi-layered insulation and solar panels, earth radiation force modelling and antenna thrust modelling [3,4,5]) led to research collaboration (from 2003) with NASA Jet Propulsion Laboratory, NASA Goddard Space Flight Centre and the US Air Force Research Laboratory. The UCL team proved their approach's effectiveness to determine satellite positions in 2004 [2,3]. Improvements were shown in quality metrics both in orbit prediction (for GPS satellites) and in sea surface height models (for altimetry satellites). UCL space vehicle surface force models for satellite altimetry platforms were subsequently adopted by NASA in 2010 for operational production of orbits for scientific data processing.

Specific innovations developed during the 2001-2007 programme of research include: using geometric primitives to reduce computational runtime; using pixel arrays and enhanced ray-tracing methods to model radiation interactions with satellite surfaces; modelling thermal forces on multi-layered insulation; developing models of thermal gradients across solar panels; modelling short and long-wavelength earth radiation fluxes; and modelling antenna output thrust. These models were rigorously tested by research groups external to UCL and were found to be superior to all other approaches [6].

3. References to the research

1. Ziebart, M., Cross, P., and Adhya, S., (2002). Photon Pressure Modeling: The Key to High Precision GPS Satellite Orbits. GPS World. 13. [9 citations]. Available on request.
2. Ziebart, M., Edwards, S., Adhya, S., Sibthorpe, A., Arrowsmith, P., and Cross, P., (2004) High Precision GPS IIR Orbit Prediction using Analytical Non-conservative Force Models, Proceedings of ION GNSS 2004, Long Beach, California, USA, pp 1764-1770 [7 citations] Available on request.
3. Ziebart, M., (2004) Generalised Analytical Solar Radiation Pressure Modelling Algorithm for Spacecraft of Complex Shape, Journal of Spacecraft and Rockets, Vol.41, No.5, pp 840-848(9) [peer reviewed, 19 citations] http://doi.org/d9wm9x
4. Ziebart, M., Adhya, S., A. Sibthorpe, S. Edwards and P. Cross, (2005) Combined Radiation Pressure and Thermal Modelling of Complex Satellites: Algorithms and On-orbit tests, Advances in Space Research, Volume 36, Issue 3, 2005, Pages 424-430 [peer reviewed, 25 citations] http://doi.org/bwkhqh
5. Adhya, S., Ziebart, M., and Cross, P., (2005), Thermal Force Modelling for Precise Prediction and Determination of Spacecraft Orbits, Navigation, 52(3): 131-144 [peer reviewed, 5 citations]. Available on request.
6. N. P. Zelensky, F. G. Lemoine, M. Ziebart, A. Sibthorpe, D. S. Chinn, D. D. Rowlands, S.B. Luthcke, B. D. Beckley, D. Pavlis, S.M. Klosko, P. Willis, and V. Luceri, DORIS/SLR POD Modeling Improvements for Jason-1 and Jason-2, Advances in Space Research, Volume 46, Issue 12, 15 December 2010, Pages 1541-1558 [peer reviewed, 14 citations] http://doi.org/dj6jnq

Grants

The research was supported by grants of more than £0.6 million from the EPSRC and NERC awarded to Professor Ziebart between 2002 and 2007. Further grants from NERC totalling circa £1m followed in the period 2008-2013, as well as a number of commercial contracts.

4. Details of the impact

The long-standing relationship between UCL and NASA Jet Propulsion Laboratory and NASA Goddard Space Flight Centre founded on the research outlined above has been sustained to the present day via invited presentations at those institutions; publications in scientific journals (including joint publications with NASA scientists, e.g. [6]) and in conference presentations. Ziebart has convened conference sessions on orbit dynamics at the American Geophysical Union and the European Geosciences Union, stimulating further work in the field. As well as supporting this important relationship with NASA's research centres, the work led to the UCL's participation (2003 onwards) in the NASA Ocean Surface Topography Science working team. Ziebart became a board member of the International GNSS Service (IGS) in 2011, and provided leadership of the IGS working group on satellite orbit dynamics. These relationships have provided vital pathways for the impacts of the research described above. They have led, in particular, to the use of UCL research to correct errors in the orbit prediction and orbit determination of satellites, enabling these satellites to provide more precise data for a range of applications, including monitoring the effects of climate change, and in GPS satellite navigation systems.

Contributions to the work of the Intergovernmental Panel on Climate Change (IPCC):
Because thermal expansion and ice cover loss (glaciers, ice sheets) contribute to rising sea level, ocean monitoring provides one of the best ways of modelling long-term climate effects. Sea level monitoring is carried out using high-accuracy altimetry satellites that are able to record millimetre-level changes, enabling precise calculations of temperature changes in the ocean over time. NASA's primary mission for measuring sea level change was the Jason-1 satellite, which was

operational from 2001 to 2013. Every ten days, Jason-1 produced a model of the shape of the world's oceans, providing accurate indications of long-term changes in sea level. Jason-1 data constituted a critical element in the geophysical data records (GDRs, compiled by NASA, and used widely by oceanographers to monitor and model ocean dynamics) determining changes in the ocean's surface, thus forming one of the most powerful pieces of evidence to show that the Earth's climate is changing. Throughout Jason-1's lifetime, the GDRs were submitted to the Intergovernmental Panel on Climate Change (IPCC), the world's principal climate science assessment body whose members include representatives of 195 governments. The solar radiation pressure and thermal re-radiation modelling techniques established by Ziebart's team, which were adopted as operational standards by NASA in 2010 removed significant systematic biases in the satellite orbits, reducing aliasing and anomalies in the sea level records passed to the IPCC [6].

In December 2007, the IPCC released its Fourth Assessment Report on the scientific basis, impacts and mitigation of climate change. It included details of the recorded change in sea level to that point, based on Jason-1 outputs. Between 2008 and 2013, data from Jason-1 continued to be passed to the IPCC, feeding into its 2008 Climate Change and Water Technical Report [f] and informing the subject matter of its Working Group 1, which monitors and reports on the physical science bases of climate change. Reports from this working group are discussed by policymakers and other stakeholders at the UN's annual climate change conferences (UN COP, four of which have been held between 2008 and July 2013). The first draft of the group's contribution to the IPCC's Fifth Assessment Report, including a summary for policymakers, was made available to governments for comments in July 2013. A lead author for IPCC Working Group 1 says: "This mission [Jason-1] provides one of the fundamental inputs to the IPCC... the computation of orbits is an integral step in the chain of producing meaningful data. This data is being used by sea level scientists to improve projections of future sea level rise."

In turn, the IPCC's data "then affects directly the formulation of policy seeking to mitigate the negative impacts of climate change upon the entire population of the Earth." One direct application he points to is the use of the data to determine planning for coastal infrastructure. [d]

GPS satellites: The development of Ziebart's techniques and their subsequent testing (in particular the demonstration of the effectiveness of earth radiation pressure and antenna thrust modelling) changed the way in which the orbits of all GPS satellites are calculated – specifically considering the directions and characteristics of forces previously not considered. Those satellites have applications in monitoring the earthquake cycle, measuring plate tectonics, precision agriculture as well as for routine navigation applications in electronic devices such as smartphones, which are used by many millions of people worldwide. The main impact has been at the scientific end of the spectrum leading to an accuracy improvement by a factor of 2.5 in the computed satellite orbits [b].

These techniques were adopted as standard in 2010 by the International GNSS Service, a voluntary federation of more than 200 worldwide agencies that generates precise open-data GPS and GNSS products. The IGS produces daily orbit calculations for all satellites; its adoption of the techniques developed through UCL's work allowed it to improve its orbit accuracy from 5cm to 2cm. IGS data usage is characterised by 700,000 site visits a year, with circa 90 million downloads [e]. This data is used to determine the terrestrial reference frame (TRF), the system of coordinates used for monitoring the shape of the earth. The TRF forms the fundamental basis for monitoring plate tectonics and height variation at tide gauges, among other applications such as modelling sea level change and post-glacial rebound, as well as commercial positioning services.

5. Sources to corroborate the impact

[a] Corroboration of the performance and use of UCL's Jason-1 model can be found in Lemoine, F.G., Zelensky N.P., Chinn, D.S., Pavlis, D.E., Rowlands, D.D., Beckley, B.D., Luthcke, S.B., Willis, P., Ziebart, M., Sibthorpe, A., Boy, J.P., Luceri, V., (2010) Towards development of a consistent orbit series for TOPEX/Poseidon, Jason-1, and Jason-2, Adv. in Space Research,

http://doi.org/ft6g4p, Volume 46, Issue 12, Pages 1513-1540, 2010.

[b] The statement from the Director of the IGS Central Bureau, NASA Jet Propulsion Laboratory, corroborates the impact on GPS orbit calculations and downstream global reference frame modelling. Available on request.

[c] NASA Space Geodesist, Space Geodesy section, NASA Goddard Space Flight Centre, Washington DC, USA can confirm the use of the UCL Jason-1 force model as a NASA standard, and its influence on the modelling of global sea level rise. Contact details provided.

[d] The statement from the Lead Author for IPCC WG1 can corroborate the use of Jason-1 data – and UCL's involvement therein - in the Intergovernmental Panel on Climate Change work, and the use of this data by policymakers and other stakeholders. Available on request.

[e] Usage figures for the IGS data, January-December 2012. Available on request.

[f] Climate Change and Water: IPCC Technical Paper VI, June 2008, http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf