Institution: University of Strathclyde

Unit of Assessment: 12

Title of case study: Novel orbits for solar sail spacecraft: adoption by international space agencies and influence on their policies and investment

1. Summary of the impact (indicative maximum 100 words)

An ambitious programme of research has discovered entirely new families of orbits for solar sails, spacecraft propelled by the pressure of sunlight. The unique applications of these new orbits for space weather, Earth observation and communications are directly influencing top-level space agency thinking and have unlocked industry investments to bring the technology to flight readiness. The new families of orbits are now embedded in agency roadmaps (NASA, European Space Agency (ESA), German Space Agency (DLR)) and help underpin a $20M NASA solar sail demonstration mission. The supporting research has substantial reach due to its impact across a broad range of sectors and has international significance through industry-led technology demonstration missions.

2. Underpinning research (indicative maximum 500 words)

Context:

Over the past 20 years, this long-standing programme of research has been motivated by a fundamental academic interest in exploiting the continuous thrust available from solar sail spacecraft to discover rich new families of so-called highly non-Keplerian orbits. Conventional space missions exploit families of classical Keplerian orbits, but the applications of these new orbits have proved to be many and varied. As a result, this research has provided an important practical application pull for solar sailing technology development. The programme of fundamental work on the discovery and characterisation of rich new families of non-Keplerian orbits has led to entirely new ways of thinking on how space can be utilised for practical purposes.

Key Findings:

Since 2004, work at the University of Strathclyde has investigated the properties of new families of non-Keplerian orbits using modern dynamical systems theory, generating families of periodic orbits about artificial equilibrium points in the Sun-Earth system [1]. Recent work has included the investigation of families of artificially precessing orbits for space science applications [2] and a formal proof that displaced non-Keplerian geostationary orbits are possible using solar radiation pressure, thus ending a 25 year dispute in the literature [3].

Currently, a major investigation of entirely new families of non-Keplerian orbits and applications is being pursued through a highly competitive European Research Council Advanced Investigator Grant [4]. So-called heliotropic orbits have been discovered which enable enhanced Earth observation services, along with a detailed definition of so-called pole-sitter orbits. Importantly, this programme of research is investigating, for the first time, orbital dynamics at extremes of spacecraft length-scale. The families of orbits are parameterised by the spacecraft mass per unit area, so that exploitation is possible for large gossamer solar sail spacecraft and swarms of micro-scale spacecraft-on-a-chip devices.

The programme of basic research has led to the development of families of highly non-Keplerian orbits to support future human space exploration missions through European Space Agency funded contract research [5]. Similarly, families of highly non-Keplerian orbits have been devised for application to commercial communication services through EADS Astrium funded contract research. Finally, an invited review in an internationally leading Aerospace Engineering journal captures all work to-date on non-Keplerian orbits and their many applications [6].

Key Researchers:

The programme of research was undertaken by the following at the University of Strathclyde.

1. Professor Colin McInnes: Director of the Advanced Space Concepts Laboratory within the Department of Mechanical and Aerospace Engineering and originator of the programme of research on highly non-Keplerian orbits. Appointed to the Department of Mechanical and

Aerospace Engineering in 2004.
2. Dr Malcolm Macdonald: Research Fellow on solar sail mission applications, appointed to the Department of Mechanical and Aerospace Engineering in 2008; now Senior Lecturer.
3. Dr James Biggs: Research Fellow on solar sail periodic orbits, appointed to the Department of Mechanical and Aerospace Engineering in 2009; now Senior Lecturer.
4. Professor Max Vasile: Collaborator on applications of non-Keplerian obits to human spaceflight, appointed to the Department of Mechanical and Aerospace Engineering in 2010.

3. References to the research (indicative maximum of six references)

References 1, 3 and 5 exemplify the quality of research, with reference 3 included in the REF2 submission for UoA12

[1] Biggs, J.D. and McInnes, C.R.: 'Solar sail formation-flying for deep space remote sensing', Journal of Spacecraft and Rockets, Vol. 46, No. 3, pp. 670-678, 2009.
[2] Macdonald, M., Hughes, G., McInnes, C.R., Lyngvi, A., Falkner, P. and Atzei, A.: 'GeoSail: An elegant solar sail demonstration mission', Journal of Spacecraft and Rockets, Vol. 44, No. 4, pp. 784-796, 2007.
[3] Baig, S. and McInnes, C.R.: 'Light-levitated geostationary orbits are feasible', Journal of Guidance, Control and Dynamics, Vol. 33, No. 3, pp. 782-793, 2010.
[4] Heiligers, J., Ceriotti, M. and McInnes, C. R.: 'Displaced geostationary orbit design using hybrid sail propulsion', Journal of Guidance, Control and Dynamics, Vol. 34, No. 6, pp. 1852-1866, 2011.
[5] Macdonald, M., McKay, R., Vasile., M., Bosquillon de Frescheville, F., Biggs, J. and McInnes, C.R.: 'Low-thrust enabled highly non-Keplerian orbits in support of future Mars exploration', Journal of Guidance, Control and Dynamics, Vol. 34, No. 5, pp. 1396-1411, 2011.
[6] McKay, R., Macdonald, M., Biggs, J. and McInnes, C.R.: 'Survey of highly non-Keplerian orbits with low thrust propulsion', Journal of Guidance, Control and Dynamics, Vol. 34, No. 3, pp. 645-666, 2011.

Other evidence for quality of research

6 grants valued at £2.7M from 2006-present, including:

- McInnes (PI), Dynamics, stability and control of highly non-Keplerian orbits, EPSRC EP/D003822/1, 2006-2009, £166k.
- McInnes (PI), VISIONSPACE: Orbital dynamics at extremes of length-scale, European Research Council, Advanced Investigator Grant 227571, 2009-2014, 2.1M Euro.
- Macdonald (PI), McInnes, (co-I), Vasile (co-I), Biggs (co-I), Gravity gradient compensation using low thrust, high Isp motors, European Space Agency, Contract AO/1-6010/09/F/MOS, 2009-2010, 100k Euro.

Work on non-Keplerian orbits was cited in 2011 Sir Arthur C Clarke Research Award to the Advanced Space Concepts Laboratory.
Work on non-Keplerian orbits was cited in 2012 Royal Society of Edinburgh Kelvin Prize awarded to Professor McInnes.

4. Details of the impact (indicative maximum 750 words)

Process/events from research to impact:

The programme of underpinning research initiated by McInnes was initially used by the NASA Jet Propulsion Laboratory (1995/96) as the basis for studies of the Geostorm space weather mission, now being developed as the NASA solar sail Sunjammer mission scheduled for launch in 2014 (discussed later). The work also influenced US National Oceanic and Atmospheric Administration (NOAA) planning for future polar Earth observation missions by demonstrating the key advantages of non-Keplerian orbits enabled by solar sail spacecraft (1996/97). These new orbits enable unique vantage points for synoptic polar weather, ice coverage measurements and satellite communications. NOAA executive Patricia Mulligan noted that "*it appears likely that [the orbits] could inexpensively relay data much faster from both low Earth orbiting weather satellites and Sun orbiting monitors*" (Source A).

Later, families of precessing solar sail orbits developed by McInnes and Macdonald (2007-2008) formed the basis for the GeoSail mission concept and its adoption by the European Space Agency as a potential solar sail technology demonstration mission. This led directly to a major European industry study led by Kayser-Threde GmbH (2007-2008) with EADS Astrium Ltd and SciSys Ltd as sub-contractors.

Types of impact

Influence on European Space Agency Planning: The GeoSail mission concept was identified by the ESA Science Directorate as a major step in solar sail technology development and formed a key element in planning for the European Space Agency Cosmic Visions roadmap for future science missions (2003/04) (Source B). Inclusion in such ESA planning is a major indication of research impact and the infusion of entirely new thinking on orbit and mission design. The work led directly to a major European space industry Technology Reference Study led by Kayser-Threde GmbH (2007) with EADS Astrium Ltd and SciSys Ltd as sub-contractors. The study represents one of the first industry-led assessments of solar sail technology in Europe (Source C) and the incorporation into these earlier plans laid the foundations for operations from 2008.

For example the programme of research on non-Keplerian orbits has been exploited by the European Space Agency through contract work to develop new concepts to ensure, for the first time, continuous communications with crewed deep space missions (2009-2010) (Source D). Study lead Francois Bosquillon de Frescheville, European Space Operations Centre, noted that the "*research will help pave the way for future robotic missions to places we've never been, or for a human mission to Mars*" (Source E).

Most recently, families of non-Keplerian orbits are underpinning a DLR/ESA concept for the Gossamer-3 solar sail technology demonstration mission. McInnes, Macdonald and Vasile are key participants in DLR/ESA solar sail working groups which are coordinating the development of the technology (2010-present), and indeed Macdonald and McInnes chair two of three working groups. The novel families of non-Keplerian orbits driving the design of the Gossamer-3 mission and its technology development by DLR again represents a major impact on agency thinking, investments and industrial development to bring the technology to flight readiness.

The mission will provide early warning of so-called space weather events which can have potentially catastrophic impacts on terrestrial communication services, navigation systems and energy grids. The availability of such warning is key to security and resilience in a highly networked global society. It is these compelling applications of the research which has influenced agency roadmaps and industry investments to ensure their realisation.

Commercial Adoption: Applications of families of non-Keplerian orbits to deliver new commercial communication services have been developed for space prime contractor EADS Astrium Ltd through commercial contract work (2010-2011). Astrium is a global company employing 18,000 staff and is an established leader in space transportation, satellite systems and services (Source F). It was demonstrated that non-Keplerian orbits offer entirely new vantage points for commercial communications services and the programme of research has influenced company thinking on the development of orbits future commercial communication platforms (Source G).

As a further example, design tools for families of non-Keplerian orbits are now embedded in commercial MATLAB software toolboxes by the leading US space engineering software house Princeton Satellite Systems Inc. (2012-13). The tools allow users to design custom non-Keplerian orbits to meet their own mission requirements. Their adoption in this widely-used professional software suite is an indication of the influence of the programme of basic research conducted by the Strathclyde team (Source H).

Investment into NASA solar sail demonstration: Families of artificial equilibria devised by McInnes and co-workers underpin a major NASA investment ($20M programme) in a solar sail technology demonstration, currently in manufacture and scheduled for launch in 2014. The mission will exploit one of a family of artificial equilibrium points to provide enhanced warning of space weather events. McInnes and his group are working with the industry team at L'Garde Inc. to provide inputs to the mission trajectory design under a US State Department (ITAR) agreement. Contributions include devising and implementing end-of-mission experiments to validate additional families of non-Keplerian orbits, again demonstrating significant influence on the mission design.

The NASA mission will be a historic world-first operational solar sail mission and the culmination of a long-term programme of research to discover, characterise and promote novel families of non-Keplerian orbits for solar sail spacecraft. Arthur L. Palisoc, Vice President Engineering at L'Garde Inc. notes that "*work on non-Keplerian orbits for solar sails at the University of Strathclyde has greatly augmented our own active research in the field*" (Source I).

Reach and significance

The impact of the long-standing programme of basic research on families of highly non–Keplerian orbits has been three-fold; influencing high-level thinking by space agencies on future mission concepts, infusing these new ideas into agency technology roadmaps and industry investments, and the adoption of the new thinking into technology demonstration missions. The research impacts have reached national and international space agencies (ESA, DLR, NASA), overseas government agencies (NOAA) and UK and overseas companies (EADS Astrium, Princeton Satellite Systems, L'Garde).

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. Statement from Future Systems Executive, US National Oceanic and Atmospheric Administration will corroborate application of non-Keplerian orbits to Earth observation.

B. Head, Planetary and Solar System Exploration ESA/ESTEC can be contacted to corroborate application of non-Keplerian orbits to space science (ESA demonstration mission).

C. http://sci.esa.int/trs/38980-geosail/ European Space Agency web page on GeoSail industry studies.

D. http://www.esa.int/Our_Activities/Operations/New_concept_may_enhance_Earth-Mars_communication European Space Agency web page on impact of non-Keplerian orbits on space communications.

E. Future Projects Manager, European Space Agency can be contacted to corroborate application of non-Keplerian orbits to human space exploration.

F. http://www.astrium.eads.net/en/who-is-astrium/ information on Astrium

G. Head, Mission Analysis, EADS Astrium Ltd can be contacted to corroborate application of non-Keplerian orbits to communications platforms.

H. http://www.psatellite.com///ToolboxAPI/SailFunctions.php#OrbitDynamics information on toolboxes

I. Statement from Vice President, L'Garde Inc. corroborates application of non-Keplerian orbits to space weather (NASA solar sail demonstration mission).