University of Strathclyde
Advanced Space Concepts Laboratory
Frontier research on visionary space systems

Study on Gravity Gradient Compensation Using Low Thrust High Isp Motors

Contract Number: 22349/09/F/MOS

Executive Summary

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Abstract

This document presents the University of Strathclyde consortium response to the ESA ITT Study on Gravity Gradient Compensation Using Low Thrust High Isp Motors (ITT AO/1-6010/09/F/MOS).

The objective of the document is to provide an executive summary of the entire Study.

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Executive Summary

This document has been produced by the Advanced Space Concepts Laboratory of the University of Strathclyde in the frame of ESA Contract Number 22349/09/F/MOS; Study on Gravity Gradient Compensation Using Low Thrust High Isp Motors.

The main objectives of the activity were: to produce a catalogue of B orbit opportunities throughout the solar system, assuming near-term low-thrust propulsion technologies, to further study a sub-selection from this catalogue of opportunities, to identify and study mission examples which use the B orbits identified, providing mission Δv budgets and timelines, and to develop and deliver a software solution which allows the modelling and visualisation of B orbits.

The model used to study displaced non-Keplerian orbits, also known as B orbits, was formulated by considering the equations of motion of a spacecraft in the circular restricted three-body problem, which provides a close approximation of the dynamics of a satellite operating in the vicinity of a planet within our solar system, or a moon about its planet, and of which the two-body problem is simply a limiting case. Consideration of the two-body problem results in the displacement of "traditional" orbits – for example, the displacement of the geostationary ring above the "traditional" ring which is within the equatorial plane. Consideration of the three-body problem results in the displacement of Lagrange points. However an extra degree of freedom arises in the two-body case as the addition of the thrust-induced acceleration generates 3 types, or families, of circular non-Keplerian orbits parameterised by the spacecraft orbit period - the orbital period is not a parameter of the three-body case due to the necessity of the spacecraft to orbit the primary mass at the same orbital velocity as that of the secondary body.

Modelling and visualisation of the B orbits is made possible by a delivered piece of MATLAB software capable of studying both the two-body and the three-body case. In using the software B orbits are identified by specifying the desired thrust range of a specific system, the type of propulsion system (either solar electric propulsion or solar sail), the system mass, and the system of interest, i.e. the Mars – Sun 3-body system, a displaced Earth orbit, et cetera. Additionally, it is possible to specify the appropriate mass ratio μ of a custom system, allowing the modelling of systems not considered in the initial study, and enabling a quick and efficient analysis of potential B-orbits for future missions and applications. Visualisation of the B orbit regions is

achieved by projecting the surfaces onto appropriate planes and surfaces including projections onto a plane perpendicular to the ecliptic plane, projections onto a plane parallel to the ecliptic plane, and projections onto surfaces that reflect the region of interest: thus providing an interface to analyse quickly and effectively the shape of the equithrust and the direction of thrust.

With this software, a catalogue of B orbit opportunities throughout the solar system has been assembled, considering the following celestial bodies: the Sun, Mercury, Venus, Earth, the Moon, Mars, Phobos and Deimos, Ceres, and Saturn. Two types of propulsion system were considered: for the case of solar electric propulsion, a thruster with a maximum thrust of 300mN and a specific impulse of 4500 seconds was considered (in order to consider mission opportunities with currently available or near-term technology such as the QinetiQ T6 thruster) for a one-tonne spacecraft, although these parameters were treated with more flexibility when it came to designing insertion trajectories. The other propulsion system considered was a 100kg solar sail capable of a maximum thrust of 30mN, with these parameters chosen purely to consider the differences between the propulsion systems for an equal thrust-to-mass ratio whilst maintaining a realistic solar sail mass. It was seen that the orientation-constrained nature of the solar sail thrust meant that there were regions of possible B orbits that were accessible with solar electric propulsion but not with a solar sail. Further, this catalogue, whilst not limited in its consideration of solar electric propulsion, only considers the solar sail in the specific cases of the two-body system around the Sun and three-body systems where the sail is about a body that is itself orbiting the Sun, due to the displacement of Lagrange points in a Planet-Moon system with a solar sail being significantly more complex than that for non-orientation constrained propulsion systems.

From the solar system bodies as listed previously, numerous possible applications and missions using B orbits may be possible, with a diverse range of potential applications, and thus a detailed discussion on possible candidate missions was made. In conjunction with the European Space Agency, a first stage-selection process outlined candidate opportunities to study in more detail. This resulted in six opportunities being taken forward to the next stage (a GeoStorm SEP mission, an Earth LEO SAR, an Earth solar sail PoleSitter, a Ceres-stationary orbit mission, an Earth-Mars communication relay and a Sun-synchronous orbit extension, the latter being beyond the scope of this study but is included as a separate deliverable regardless), where the science case for each, the possible B orbits utilised, and analysis of a mission to insert a spacecraft to the relevant point were all discussed. The mission analysis consisted of determining delta-v budgets and timescales, insertion trajectories (where both chemical and continuous low thrust options were examined), propellant consumptions and thrust profiles, and in certain cases motor failure recovery/contingency analyses. Particular attention was paid to the Earth-Mars communication relay.