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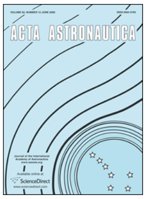

Novel orbits of Mercury, Venus and Mars enabled using low-thrust propulsion

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ABSTRACT

Exploration of the inner planets of the Solar System is vital to significantly enhance the understanding of the formulation of the Earth and other planets. This paper therefore considers the development of novel orbits of Mars, Mercury and Venus to enhance the opportunities for remote sensing of these planets. Continuous acceleration is used to extend the critical inclination of highly elliptical orbits at each planet and is shown to require modest thrust magnitudes. This paper also presents the extension of existing sun-synchronous orbits around Mars. However, unlike Earth and Mars, natural sun-synchronous orbits do not exist at Mercury or Venus. This research therefore also uses continuous acceleration to enable circular and elliptical sun-synchronous orbits, by ensuring that the orbit's nodal precession rate matches the planets mean orbital rate around the Sun, such that the lighting along the ground-track remains approximately constant over the mission duration. This property is useful both in terms of spacecraft design, due to the constant thermal conditions, and for comparison of images. Considerably high thrust levels are however required to enable these orbits, which are prohibitively high for orbits with inclinations around 90°. These orbits therefore require some development in electric propulsion systems before becoming feasible.

1. Introduction

Planetary observation is vital to gain an insight into the history of the Solar System and in turn the formulation of Earth, and can be used to determine whether extra-terrestrial habitable environments exist in the Solar System.

The Martian environment is of particular interest with recent missions including Mars Odyssey [1], Mars Express [2], Mars Reconnaissance Orbiter (MRO) [3], and the Mars Science Laboratory (MSL)[3]. Such missions have allowed a comprehensive view of Mars to be obtained through data of the Martian surface geology, mineral composition, subsurface structure, radiation environment and weather. However, additional significance has recently been placed on exploration of Mars with the reformulation of the Mars Exploration Program [4]. This program aims to assess both near-term mission concepts and longer-term foundations of program level architectures for future robotic exploration. As a result missions must be developed which are responsive to the scientific goals of both the National

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[3] http://www.nasa.gov/mission_pages/msl/index.html (accessed 14. 03.13).

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Research Council Planetary Decadal Survey [5] and the ESA Aurora Program[4].

Similarly, the NASA Vision and Voyages Decadal Survey for 2013–2022 has identified three themes for the future development of planetary science, within which the importance of investigating the evolution of the inner planets and their atmospheres is highlighted [5]. The importance of examining the chemistry, climates and geology of the inner planets is also outlined to lead to a better understanding of climate change on Earth [5]. The importance of further exploration of Mercury and Venus is therefore clear.

This paper develops novel orbits of Mars, Mercury and Venus to enable new and unique investigations and allow enhanced investigation into the surface, subsurface and atmospheres of these bodies.

Natural orbits typically used for remote sensing applications at Earth also exist at Mars. For example, sun-synchronous orbits, which have in the past been employed by spacecraft such as Mars Odyssey [1], MRO [6], and Mars Global Surveyor [7] and Molniya-like orbits with fixed values of the critical inclination [8], which can also offer benefits for remote sensing of Mars by allowing the spacecraft to spend a large amount of time over a region of interest as a result of apoareion dwell.

Similar to Mars, orbits inclined at the critical inclination also exist at Mercury and Venus; however the reciprocal of flattening of these planets is so low that natural perturbations are insufficient to generate sun-synchronous orbits. Investigation has therefore previously been conducted into the use of a solar sail to deliver a sun-synchronous orbit around Mercury [9].

This paper extends methods previously introduced by the authors for the extension of Earth orbits [10,11]; to extend existing highly-elliptical orbits at Mars, Mercury and Venus; extend sun-synchronous orbits around Mars; and enable sun-synchronous orbits at Mercury and Venus where they are otherwise not possible, as such significantly enhancing the opportunities for remote sensing of these bodies.

2. Mars

The work presented herein extends these natural orbits using continuous low-thrust propulsion to create a new set of Martian orbits for improved remote sensing, while maintaining the zero change in argument of periapsis condition essential to Molniya-like orbits. This is achieved firstly by developing a general perturbations solution, which is validated using a special perturbations solution.

These solutions can also be extended by the addition of a further element of continuous low-thrust directed out of the orbit plane to ensure that the rate of change of ascending node of the orbit matches the mean rotation of the Sun, and achieve sun-synchronous orbits with fixed critical inclinations and thus no rotation of the apsidal line. The development of such novel orbits therefore creates additional observation opportunities of the surface and atmosphere of Mars, allowing more accurate observations for possible future human exploration. One such example would be to enable a sun-synchronous HEO inclined at 90° to allow improved studies of the Martian Polar Regions.

Furthermore, these new orbits may be of use for communication relay for human missions or Unmanned Aerial Vehicles (UAVs) or detailed mapping of the Martian surface. The transition from single spacecraft exploration of Mars to fleet of vehicles both around Mars and on the Martian surface further highlights possible benefits of these novel orbits.

The importance of analyzing atmospheric and meteorological phenomena at Mars has also seen recent research into the development of multi-sun-synchronous orbits of Mars, which allow cycles of observation of the same area under illumination conditions which repeat after a periodicity multiple of the repetition of observation [12,13].

2.1. Spacecraft motion about an oblate body

At Earth the most dominant perturbation is the oblateness term, J_2, with a value of 1.082627×10^{-3}. The harmonic coefficients J_3 and J_4 are around three orders of magnitude smaller than the J_2 term, with $J_3 = -2.53266 \times 10^{-6}$, and $J_4 = -1.61962 \times 10^{-6}$, and thus have a negligible effect on the determination of the critical inclination. At Mars, the J_2 perturbation is also dominant, with a value of 1.95545×10^{-3}. However, zonal harmonics through to J_5 are only around two orders of magnitude lower than the J_2 perturbation, with values of $J_3 = 3.14498 \times 10^{-5}$, $J_4 = -1.53774 \times 10^{-5}$, and $J_5 = 9.0793 \times 10^{-6}$, and so will have an impact on the determination of the critical inclination at Mars. As a result higher order terms must be taken into consideration in this instance.

Considering the gravitational potential of a body [14]

$$U(r,\beta,\lambda) = \frac{\mu}{r}\sum_{n=0}^{\infty}\sum_{m=0}^{\infty}\left(\frac{R_B}{r}\right)^n (C_{n,m}\ \cos(m\lambda) + S_{n,m}\ \sin(m\lambda))P_{n,m}\ \sin\ \beta \tag{1}$$

Where, U is the gravitational potential, r is the orbit radius, β is the declination of the spacecraft, λ is the geographical longitude, μ is the gravitational parameter of the body under consideration, R_B, is the radius of the body under consideration, $C_{n,m}$, and $S_{n,m}$ are the harmonic coefficients of body potential, and $P_{n,m}$ is the associated Legendre polynomials. For a body possessing axial symmetry the influence of periodic effects (tesseral and sectorial harmonics) can be neglected for most orbits. The gravitational potential may be written as

$$U(r,\beta) = \frac{\mu}{r}\left[1 - \sum_{n=0}^{\infty} J_n \left(\frac{R_B}{r}\right)^n P_n\ \sin\ \beta\right] \tag{2}$$

Where, J_n, is the gravitational perturbations. Expanding Eq. (2), the gravitational potential becomes

$$U(r,\beta) = \frac{\mu}{r}[1 - J_2\frac{1}{2}\left(\frac{R_B}{r}\right)^2 (3\sin^2(\beta) - 1)$$
$$-J_3\frac{1}{2}\left(\frac{R_B}{r}\right)^3 (5\sin^2(\beta) - 3)\sin\ \beta$$

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[4] http://www.esa.int/Our_Activities/Human_Spaceflight/Exploration/Aurora_s_roadmap_to_Mars (accessed 14.03.13).