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Long dwell time orbits for lander-based Mars missions

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ABSTRACT

This paper deals with the possibility of retrieving orbits around Mars able to provide long dwell times over a given area of the planet, without needing expensive orbital corrective manoeuvres. After a general description of the fundamental principles associated with the obtainment of the repeating ground track orbits which satisfy the aforesaid requirement, the concepts have been applied to Mars to gain trajectories which make it possible to maximise the daily contact time between a probe orbiting around the planet and a lander on the surface. The lander has been considered as equipped with an antenna of 0.5 m of diameter, working in the bands C, X, Ku, and the cases of both fixed and mobile antennas have been taken into account.

1. Introduction

Trajectories around Mars have been investigated and employed to meet a broad range of requirements related to observational constraints (e.g. spatial coverage, resolution, synchronism with the Sun) [1–4], orbital perturbations (e.g. [5]), problems concerning the aerobraking (e.g. [6]) and linked to the release of landers and rovers (e.g. [7]). As for the coverage, the requirement has often been to gain global rather than local coverage, whereas this latter is becoming more and more interesting for Mars exploration. In fact, the feasibility of retrieving trajectories able to provide long dwell times over a given region would translate into both wide intervals of observation of the planet in quasi-steady conditions (useful for both remote sensing and communication applications) and long contact times with a lander (or a rover) positioned inside a certain region of the surface of Mars. Such a requirement may be fulfilled by considering the AreoStationary Orbit (ASO), a circular and equatorial orbit having an altitude of about 17 000 km, which (in the Keplerian case) allows the probe to remain permanently steady with respect to the planet [8,9]. However, due to the orbital perturbations, this kind of orbit needs periodic corrective manoeuvres during the entire probe operational life [10, 11]. Therefore, in order to avoid the aforesaid corrective manoeuvres and thus extend the probe operational life, it is important to find alternative orbits to the ASO, which are able to guarantee long dwell times over a given region of Mars without requiring orbital corrections associated with expensive velocity variations. In [12], elliptical orbits which make the fulfilment of this goal possible have been obtained. However, in the cited study, the requirement of long dwell time has been considered as a secondary property with respect to the principal one, concerning the design of periodic orbits for monitoring time-varying phenomena. In fact, the argument of pericentre of two particular orbits, already designed to meet requirements based on solar illumination conditions, has been set so as to obtain, in an orbit arc around the apocentre, a behaviour similar to the one offered by the ASO. For such reasons, in the present paper, the feasibility of gaining orbits able to guarantee long dwell times over a given area of Mars has been investigated. After having described the basic concepts related to obtaining trajectories which provide both cyclic observations and long dwell times (Section 2), such concepts have been applied to Mars (Section 3), gaining orbits at critical inclination which make the fulfilment of these conditions possible without requiring expensive orbital manoeuvres. Then, the most profitable solutions have been investigated to optimise the lander–probe link time, assuming the constraint of daily contact (Section 4).

2. Orbital properties

In a planetary observation mission, a fundamental requirement is the feasibility of observing a given region at regular time intervals and this condition can be fulfilled by considering repeating ground track orbits, also called periodic orbits [13]. In addition to this, another requirement is considered here: the possibility to observe a region with long dwell times. Such a property is achieved if, in a wide time interval, the sub-probe point (intersection between the position vector of the probe and the surface of the

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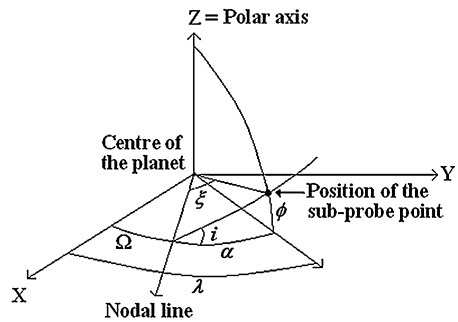

Fig. 1. Sub-probe point in the (X, Y, Z) reference frame for a prograde orbit.

planet) is characterised by small shifts with respect to the surface of the planet. These two requirements, strictly related to the probe ground track (Section 2.1), will firstly be discussed separately (Section 2.2 and Section 2.3) and then matched (Section 3) in order to obtain both repeated and long-lasting observations of Mars.

2.1. Ground track determination

The motion of a probe around a planet can be described in a reference system (X, Y, Z) centred at the centre of mass of the planet and having X axis given by the intersection between equatorial plane of the planet and plane of the orbit of the planet around the Sun, Z axis coincident with the polar axis of the planet (rotation axis of the planet) and Y axis defined so as to form a right reference frame. In this reference, the instantaneous values of the absolute longitude λ and of the latitude ϕ of the sub-probe point can be expressed as a function of the orbit elements of the probe. According to Fig. 1, the relationships representing this correspondence (coming from spherical trigonometry) can be written as:

$$\lambda(t) = \Omega + \alpha = \Omega + tg^{-1}(tg\xi \cdot \cos i) \quad (1)$$

$$\phi(t) = \sin^{-1}(\sin i \cdot \sin\xi) \quad (2)$$

where t is the time, α is the angle (measured on the equatorial plane) between the nodal line and the meridian related to the position of the sub-probe point and Ω, i, ξ are, respectively, the instantaneous values of the Right Ascension of the Ascending Node (RAAN), of the orbit inclination and of the argument of latitude of the probe ($\xi = \omega + \theta$, with $\omega =$ argument of pericentre and $\theta =$ true anomaly of the probe).

Therefore, once the values of Ω, ξ and i are known, it is possible to retrieve λ and ϕ by Eqs. (1) and (2). Of course, in the general case of "perturbed Keplerian motion", it is necessary to take the temporal variations of the orbit elements into consideration ($\dot{\Omega}, \dot{i}, \dot{\xi} = \frac{h}{r^2} - \dot{\Omega}\cos i$, with $\mathbf{h} = \mathbf{r} \times \mathbf{v}$ angular momentum per unity of mass of the probe, $\mathbf{r}$ position vector of the probe and $\mathbf{v}$ velocity of the probe), which lead to a continuous modification of the spherical triangle formed by α, ϕ and ξ in Fig. 1. To construct the ground track of a probe, it is necessary to know the temporal trends of the geographical longitude $\lambda_G(t)$ and of the latitude $\phi(t)$. While the latitude is given by Eq. (2), the geographical longitude of the sub-probe point can be retrieved by subtracting, from the absolute longitude λ (Eq. (1)), the reference longitude, which varies as $\omega_P t$, where ω_P is the angular velocity of the planet around its polar axis (in this paper the Airy-0 longitude has been assumed as a reference longitude).

2.2. Periodicity condition

As mentioned, a fundamental requirement is represented by the feasibility of observing a certain zone at regular time intervals. In the present study, the fulfilment of this goal is particularly important because it allows a probe to periodically gain contact with a lander on the surface of the planet. To satisfy this objective, it is possible to design an orbit whose ground tracks repeat themselves after a given time interval (repeating ground track orbit). This condition is satisfied if $mD_n = RT_n$, where D_n is the nodal day of the planet (time elapsing between two consecutive nodal line crossings given by a point on the equator of the planet), m is the integer number of nodal days after which the ground track is repeated (revisit time), T_n is the nodal period of the probe (time elapsing between two consecutive ascending node passes) and R is the integer number of nodal periods accomplished in m nodal days (R and m are prime one to the other). Taking into consideration the zonal harmonic J_2 of the gravitational field (planetary oblateness), it is possible to find an analytical solution for the semi-major axis of a repeating ground track orbit [12]:

$$a^{3.5} + b_1 a^2 + b_2 = 0 \quad (3)$$

where:

$$b_1 = -\frac{\sqrt{\mu_P}}{q\omega_P},$$

$$b_2 = -\frac{3J_2R_P^2\sqrt{\mu_P}}{2\omega_P(1-e^2)^2} \times \left\{\frac{1}{2q}\left[\left(5+3\sqrt{1-e^2}\right)\cos^2 i - \sqrt{1-e^2} - 1\right] - \cos i\right\},$$

R_P is the mean equatorial radius of the planet, μ_P is the gravitational constant of the planet, e is the orbit eccentricity and the parameter q represents the number of orbits per day (orbits and day are counted with respect to the nodal line: $q = D_n/T_n = R/m$). Assuming a certain value for the orbit inclination, Eq. (3) provides a curve which links semi-major axis and eccentricity, for each value of q. This curve, referred to as curve of periodicity, gives all the repeating ground track orbits corresponding to those i and q values. In particular, the choice of integer values for the parameter q leads to the possibility of revisiting every day the same region of the planet (the same ground tracks are repeated at a regular interval of one nodal day).

2.3. Synchronism condition

The other principal requirement of this study is related to the possibility of obtaining long permanence over a given region of the planet and this requirement can be fulfilled designing orbits whose sub-probe point is quasi-steady with respect to the surface for a long part of the orbital period. With reference to Fig. 2, point P can be considered both as a sub-probe point and as a point belonging to the planet. In the first case, the eastward component of the velocity of the sub-probe point (v_{EP}), which is in a plane parallel to the equatorial plane (projection of $\mathbf{v}$ on the equatorial plane and then in the eastward direction), can be written as:

$$v_{EP} = \omega_Z R_P \cos\phi \quad (4)$$

where ω_Z is the angular velocity of the probe in the motion of rotation with respect to the polar axis of the planet. In the second case, the velocity of point P, considered as in-built to the surface of the planet at a latitude ϕ, is given by:

$$v_P = \omega_P R_P \cos\phi \quad (5)$$

If, at a given instant, the following equality is satisfied (it is possible only if $i < 90$ deg, which also implies $\phi < 90$ deg, according to Eq. (2)):

$$v_{EP} = v_P \quad (6)$$