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Analysis of orbit determination from Earth-based tracking for relay satellites in a perturbed areostationary orbit

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ABSTRACT

Areostationary satellites are considered a high interest group of satellites to satisfy the telecommunications needs of the foreseen missions to Mars. An areostationary satellite, in an areoequatorial circular orbit with a period of 1 Martian sidereal day, would orbit Mars remaining at a fixed location over the Martian surface, analogous to a geostationary satellite around the Earth. This work addresses an analysis of the perturbed orbital motion of an areostationary satellite as well as a preliminary analysis of the aerostationary orbit estimation accuracy based on Earth tracking observations. First, the models for the perturbations due to the Mars gravitational field, the gravitational attraction of the Sun and the Martian moons, Phobos and Deimos, and solar radiation pressure are described. Then, the observability from Earth including possible occultations by Mars of an areostationary satellite in a perturbed areosynchronous motion is analyzed. The results show that continuous Earth-based tracking is achievable using observations from the three NASA Deep Space Network Complexes in Madrid, Goldstone and Canberra in an occultation-free scenario. Finally, an analysis of the orbit determination accuracy is addressed considering several scenarios including discontinuous tracking schedules for different epochs and different areoestationary satellites. Simulations also allow to quantify the aerostationary orbit estimation accuracy for various tracking series durations and observed orbit arc-lengths.

1. Introduction

Telecommunications play a key role in the planned robotic missions to Mars. Satellites in areostationary orbit are efficient candidates to combine both the return of engineering and scientific instrument data and the necessity of continuous telecommunication for crew to teleoperate surface assets (a Mars-forward technology). A design for a Mars Areostationary Relay Satellite, to provide a continuous coverage of a specific region of Mars, has been proposed, for instance, in [1–7]. The use of satellites orbiting in areostationary orbit to remotely supervise the robotic explorers on the Martian surface can be seen, for example, in [8–11].

An areostationary satellite would orbit Mars in a circular areoequatorial orbit with a semi-major axis of a_s=20,428 km to be at rest with respect to the rotating Mars with a period of 1 Martian sidereal day (sol) P=88775.244 s. However, natural perturbations tend to shift an areostationary satellite from its nominal station point. The dominant disturbing forces on the aerostationary orbit are perturbations due to the non-spherical mass distribution of the Mars gravitational field, the gravitational attraction of the Sun and the Phobos and Deimos moons and the solar radiation pressure. The satellite longitude evolution, due to the drift caused by the perturbing terms of the Mars potential has been described, for instance, in [12–14], the oscillations in latitude due to Solar and Phobos and Deimos gravitational perturbations on the inclination of the satellite's orbit in [15], and the non-zero eccentricity because of the solar radiation pressure effects in [14]. These perturbations result, as for geostationary satellites [16], in oscillations in longitude and latitude as seen from Mars surface.

The geostationary orbit parameters estimation is a challenge because of the very slight geometrical variation of the observables. It is therefore of interest to characterize the short-term tracking requirements necessary to obtain a specified areosynchronous orbit accuracy using Earth-based measurements. To this aim, we have performed an analysis of the effects of the observation geometry from Earth on the accuracy of the areostationary estimated orbit.

The paper is divided into five sections. In Section 2 we provide an overview of the perturbed areostationary orbit evolution. In Section 3 we discuss the observation geometry relative to an Earth observer and the possible Earth-based tracking coverage. In Section 4 we present results of some simulations of Earth observability for different scenar-

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ios of observations availability and we estimate the achievable orbit accuracy. Finally, in Section 5 we briefly summarize the results.

2. Areostationary orbit evolution

The perturbing forces due to the Mars gravitational field, the gravitational attraction of the Sun and the Martian moons, and the solar radiation pressure change the values of the areostationary orbit parameters.

The classical Keplerian elements, $\{a, e, i, \Omega, \omega, M\}$ [17], are not suitable for the description of areostationary orbits, as the eccentricity, e, and the orbital inclination with respect to the Mars equatorial plane, i, are near zero. Thus, to avoid singular configurations in the analysis of the orbit evolution, it is convenient to use the synchronous elements, $\{a, l, \vec{e}, \vec{i}\}$ [16]; being a the semi-major axis; l the mean longitude from Airy-0; $\vec{e} = (e_x, e_y)$ the two-dimensional eccentricity vector pointing to the periapsis, and $\vec{i} = (i_x, i_y)$ the inclination vector pointing to the ascending node:

$$l = \Omega + \omega + M - V_M,$$
$$\vec{e} = (e\cos(\Omega + \omega), \quad e\sin(\Omega + \omega)), \tag{1}$$
$$\vec{i} = (i\cos\Omega, i\sin\Omega),$$

where Ω is the right ascension of the satellite orbital ascending node measured on Mars Equator from Mars Equinox; ω is the periapsis argument; M is the mean anomaly; and V_M is the Airy-0 Martian sidereal time.

2.1. Effects on the semi-major axis and the mean longitude

The main Martian gravitational perturbative effects at the areosynchronous altitude, h_s=17031.8 km, have been described in [12–14]. These perturbations, which are functions of the satellite longitude, cause a change of the semi-major axis that, in turn, induces a longitude drift, $\dot{l}$. Fig. 1, shows the longitude drift rate, $\ddot{l}$, in deg/day^2 for the areostationary orbit due to the perturbative tangential acceleration caused by the tesseral harmonics of the Mars potential. The zero tangential acceleration localizations correspond to the two stable longitudes at 17.92 °W and 167.83 °E; and to the two unstable longitudes at 75.34 °E and 105.55 °W, respectively. This longitude drift rate implies a parabolic evolution with time of the mean longitude that, according to its specific location, tends to shift areostationary satellites east or westward.

2.2. Effects on the inclination vector

The evolution of the inclination is due to the attraction of the Sun and the Martian moons, which generates several perturbations. The magnitude of the long-term perturbations and the two main periodic

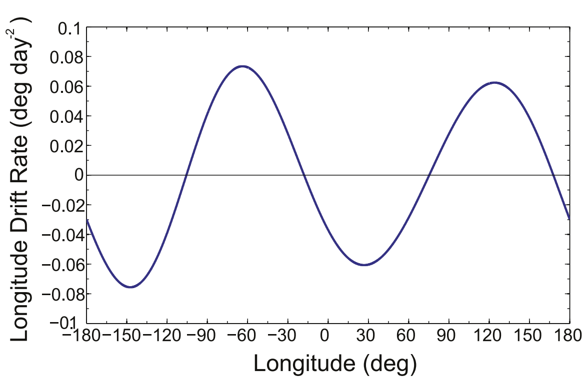

Fig. 1. Longitude drift rate, $\ddot{l}$, in deg/day^2 due to the Mars gravitational field for the areostationary orbit.

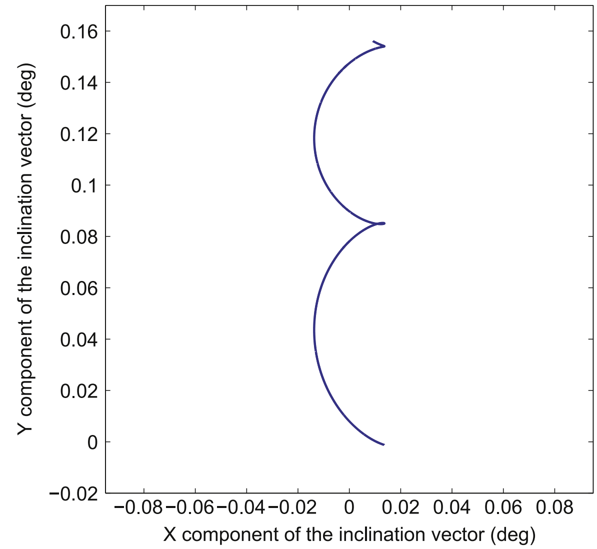

Fig. 2. Inclination vector evolution due to the Sun attraction in a Martian year.

solar perturbations (as well as the Phobos and Deimos negligible variations, lower than 0.0003 °/year and 0.0002 °/year) has been modeled in [15] by the equations:

$$i_x = 0.0137°\cos 2(\omega_M + \nu_M - \theta_M), \tag{2}$$

$$i_y = 0.0826°\, t -$$
$$-0.0124°\sin 2(\omega_M + \nu_M - \theta_M).$$

Fig. 2 shows the evolution of the inclination vector for 1 Martian year (687 days) with the secular drift, at a constant rate of 0.0826 °/year, in the i_y direction and the half Martian year periodic components (of argument $2(\omega_M + \nu_M - \theta_M)$) superimposed, with amplitudes of 0.0137° for the i_x component and 0.0124° for the i_y component.

The inclination of the satellite orbit causes oscillations in latitude.

2.3. Effects on the eccentricity vector

The evolution of the mean eccentricity vector, caused by the Solar Radiation Pressure (SRP), has been analyzed and evaluated in [14] and the temporal patterns of solar eclipses on areostationary satellites to model SRP properly in [18]. The equations governing the change in the eccentricity vector are [14]:

$$\vec{e}(t) = \vec{e_0} + R_e\begin{pmatrix}\cos s_{\odot}(t)\\ \sin s_{\odot}(t)\end{pmatrix}, \tag{3}$$

where $s_{\odot}(t)$ is the Sun areoequatorial right ascension at time t. Equation (3) represents that $\vec{e}$ moves in a circle pointing to the Sun with center $\vec{e_0}$ and a radius, R_e, that depends on reflectivity and orientation to the Sun of each surface elements.

Fig. 3 shows the annual circular evolution of the eccentricity vector for $R_e = 8.07\cdot 10^{-4}$, with

$$R_e = \frac{3}{2}(1 + \rho)\frac{A}{m_s}\frac{P}{na\Omega_{\odot}}, \tag{4}$$

evaluated for a ratio of $A/m_s = 0.0429$ m^2/kg, between a cross-sectional area facing to the Sun of A=30 m^2 and a mass of the satellite of $m_s = 700$ kg; and values for the solar pressure and reflectivity of $P = 1.9\cdot 10^{-6}$ N/m^2 and $\rho = 0.02$, respectively; and $\Omega_{\odot} = ds_{\odot}/dt = 1.09\cdot 10^{-7}$ rad/s.

The nonzero eccentricity will induce daily oscillations in longitude.