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STABILITY AND SPIN-ORBIT RESONANCE ANALYSIS OF LOW ALTITUDE MARTIAN ORBITS

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Orbit stability has been thoughtfully studied in various celestial bodies. In particular the focus has been placed on the Moon, due to the unstable natural perturbations of its gravity field. The increasing interest in Mars orbiters brings the question of the likelihood of natural decay in low altitude regimes. This paper studies the change in shape of low altitude Mars orbits by carrying out large sets of numerical high fidelity simulations. Results showed that various configurations of the orbital elements gave perturbations that resulted in unstable orbits. The paper also studies the potential causes of the observed unstable regions. First by taking a close look at zonal and tesseral harmonics to find the implications of Mars mass concentrations of the used gravity fields, and second by computing theoretical spin-orbit resonances to study their implications in the stability at low altitudes.

INTRODUCTION

Orbit stability typically represents a major concern for spacecraft mission design. The lunar PFS-2 orbiter was one of the first man-made objects that noticed the effects of an unstable gravity field. During the early stages of this mission, the lumpiness of the lunar gravity field severely reshaped the initial orbit of the satellite and made it crash as short as 35 days after its insertion. Since then, many studies, simulations, and theories about lunar orbit stability have been carried out. Previous work performed by Folta and Quinn (2006) propagated several orbit to study the evolution of the argument of periapsis and eccentricity in polar plots over time. Additionally, publications such as Abad (2009) or Lara (2011) focused more in the analytical implications of those irregularities of the lunar gravity field. Some of these publications successfully identified stable regions where the shape of the orbit was not altered sensibly over long periods of time. For other objects in the Solar System, previous work has been performed to address the needs of past spacecraft mission designs. In the case of Mars, the most recent gravity models, developed with data acquired from the Mars Reconnaissance Orbiter (MRO) have improved significantly the accuracy of the propagation.

Most studies suggest that the main cause of such unstable regions encountered by low altitude orbiters are the uneven distributions or mass concentrations or mascons underneath the surface of the celestial body of study. In addition to that, for fast spin bodies such as Mars, orbit stability may also have something to do with spin-orbit resonance effects and therefore we study their implication in this paper. Some publications have studied the effects of spin-orbit resonances, espe-

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cially on repeating ground tracks for geodetic applications. Repeating ground tracks imply that the satellite passes occur at particular longitudes, and therefore the effects of the mascons may be enhanced or diminished, depending on the situation. In particular, previous work from Zhi-Zhou and Chengli (2015) brought light to the existing low ‘number' resonance in the Mars case. This, together with the mascon influence in low Mars orbits (LMO) may cause severe instabilities for certain orbital element configurations.

Since Mars is becoming a target for upcoming future missions, it is fundamental to address the challenges the orbiting satellites will face. This publication present a detailed and comprehensive study of the orbital stability of the red planet, including an analysis of the influence of the spin-orbit resonance and zonal and tesseral spherical harmonics. The first section focusses on the assumptions used for this analysis, including the gravity field applied in the simulation, the orbital elements range, and the tools and software utilized. In Section II, an initial assessment of the overall low altitude Mars orbit environment stability is presented by propagating a large set of initial orbital element configurations. The third section places the focus on Mars spin-orbit resonances with orbiting spacecraft, here, theoretical calculations are computed and compared with the results from numerical orbit propagation. In section IV, orbits are computed at various configurations of gravity field order and degree spherical harmonics to find the major contributions to perturbations. Finally, in section V, some conclusions are drawn based on the numerical data obtained.

ASSUMPTIONS AND METHODOLOGY

The lower portion of the Low Mars Orbit (LMO) environment was chosen as the region of interest for this paper. A spectrum of altitudes below 400 km was studied to assess the homogeneity of the Mars gravity field and to find potential regions in the orbital elements spectrum where the large orbit instabilities exist. For that reason, the simulations in this paper do not include any atmospheric model nor any solar radiation pressure model, in order to analyze only the effects of the gravity field. We utilized a high precision orbit propagator that used the MRO110C gravity model, developed at the NASA Jet Propulsion Laboratory (JPL) (Konopliv et al., 2016), and third body gravity effects from the Sun and the Phobos and Deimos satellites. The orbits of interest were defined as circular as an initial assumption to simplify the identification of the unstable regions, and in order to easily study the re-shaping effects that the spherical harmonics cause.

The first part of the analysis consisted in the propagation of several initial orbit element configurations. The goal was to provide an overall assessment of the stability around several regions depending on initial inclinations, Right Ascension of the Ascending Node (RAAN), and circular altitude. After this initial survey, some regions that presented higher instabilities were highlighted for a further study hat consisted in addressing the relationship of the perturbations with potential spin-orbit resonances with the red planet. This analysis was followed by an assessment of the Mars spherical zonal and tesseral harmonics that contribute to the largest perturbation effects in the region of interest. Finally, observations are made that may link both phenomena, spin-orbit resonance and harmonic effects to orbit propagation. At the end of this publication, future work on this topic is suggested as well.

LOW MARS ORBIT STABILITY ASSESMENT

In this section, an initial survey of the orbit stability presented in the LMO environment was conducted. Circular orbit altitudes were propagated at various different inclinations and RAANs to observe whether the orbit was reshaped or modified by a large fraction of the initial configuration. Figure I shows three charts that represented the propagation of six initial circular orbits at 50, 75, 100, 125, 150, and 200 km altitude, at three different inclinations (0,45 and 90 degrees corresponding to plots a,b,c). These orbits are represented by plotting the minimum altitude, at a RAAN step of 30 degrees, achieved in 100 days propagation.

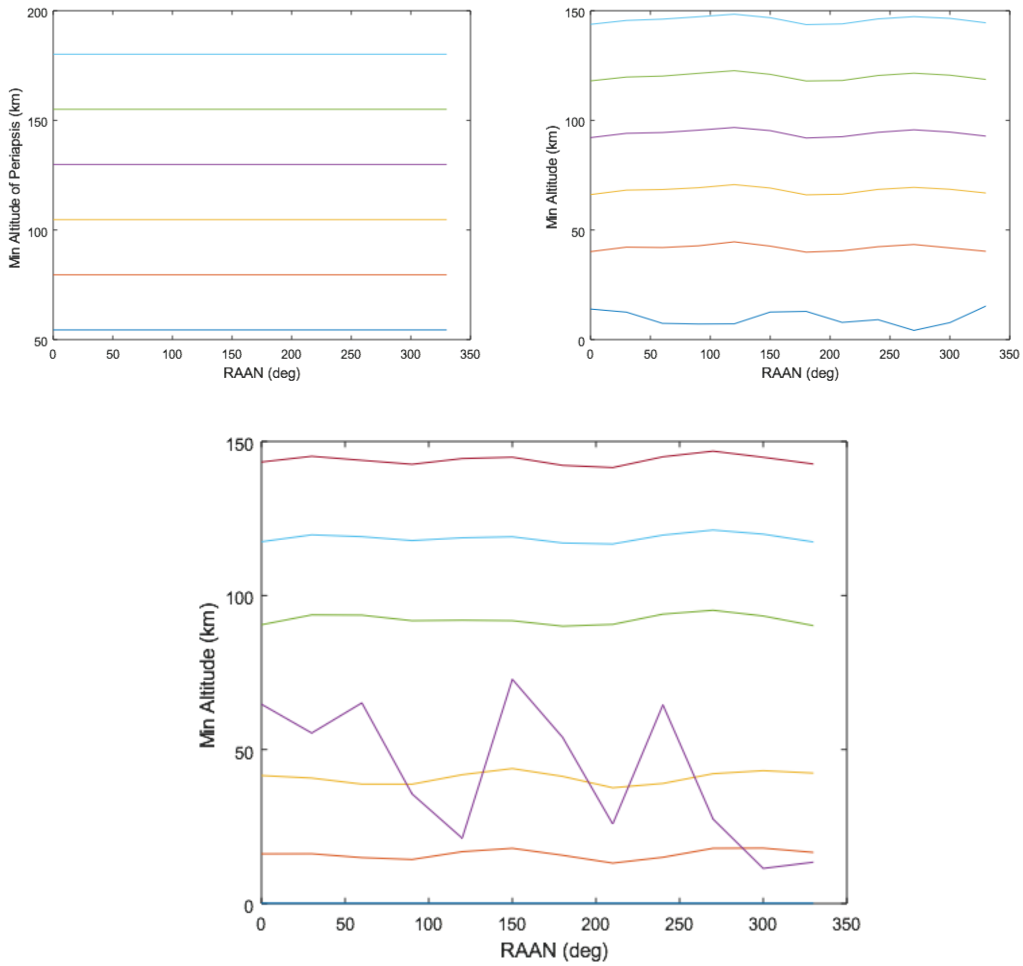

Figure 1. Evolution of the minimum altitude achieved in a propagation of 100 days. a) Initial inclination - 0 deg. b) Initial inclination = 45 deg. c) Initial inclination = 90 deg.

The first conclusion from this preliminary analysis is that both RAAN and especially inclination play an important role for some configurations such as case c). For equatorial orbits, the perturbations effects can be seen in terms of a decay in the minimum altitude from the initial configuration, but the RAAN implications are practically negligible. A similar exist for the 45 degrees case where the RAAN effects are still really small, although the overall perturbations are higher, presenting a larger decay in minimum altitude achieved. However, for polar orbits the perturbations are not just larger in magnitude but also are highly dependent on RAAN for one of the initial altitudes studied. The main observations that is drawn from the 90 degrees plot in Figure I, is that for some initial circular altitudes such as 200 km or even 100 km, these RAAN effects are not so significant, compared to the larger perturbations seen in the 125 km altitude orbit propagation, where some RAANs almost cause the spacecraft to be placed in a collision trajectory to the Mars surface., such as in the 300 deg case. This could suggest the existence of certain regions with higher mass concentrations underneath Mars surface that are causing the spacecraft to be severely perturbed when they are initially placed in certain orbit planes that pass over them. Figure II shows a representation of the altitude of periapsis and apoapsis plots over time during a 100 day propagation for the case when RAAN is 150 degrees (maximum in Figure I) and the case when RAAN is 300 degrees (local minimum in Figure I), all for an initially circular 125 km orbit.

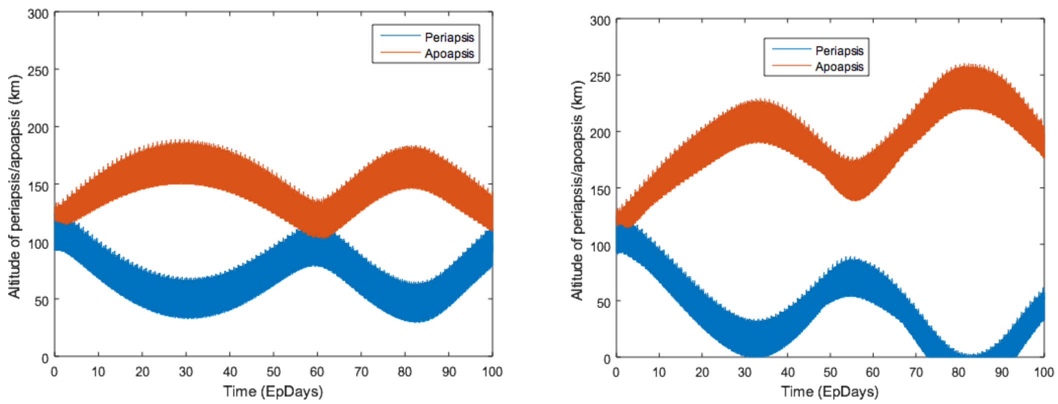

Figure 2. Altitude of periapsis and apoapsis evolution plots for an initially circular orbit with an altitude of 125 km a) 150 deg RAAN and b)300 deg RAAN.

The second initial observation is that the biggest effects in orbit re-shaping occur within a small initial altitude window, between 100 km and 150 km. Since the initial altitude step for this group of simulations was set to 25 km, these effects could only be notifiable at 125 km. Therefore, we carried out a subsequent analysis with an initial altitude step of 1 km. This analysis showed that these effects take place in several altitudes between 119 and 128 km. Figure III shows a chart with some evidence of these findings.

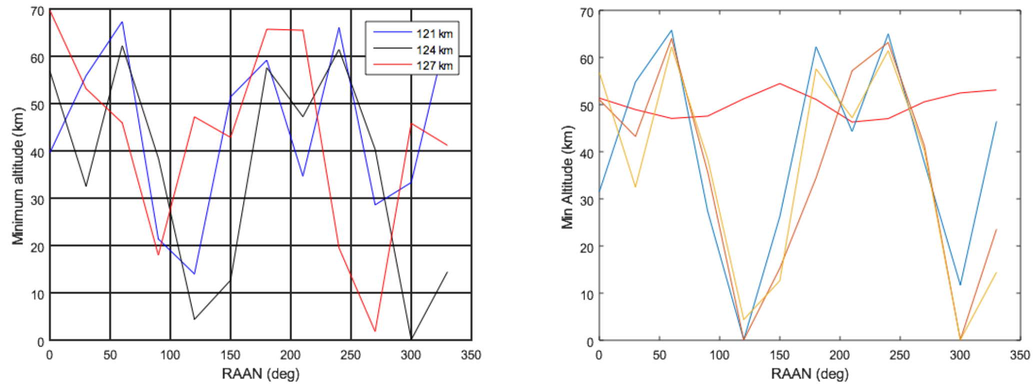

Figure 3. Geodetic altitude vs RAAN plots for initially circular orbits with a) 121, 124, and 127 km b) 122-124 km and 110 km (red stable line).

In the two plots shown in Figure III we can see how the dynamics in this region are very unstable. The second picture represents the minimum altitudes per RAAN for initial altitudes between 122-124 km, and with a step of 1 km. While there are a few discrepancy points where for a case there is a local minimum and for the rest a local maximum at 200 degrees, we can still observe a regular pattern. Note also the red line which represents a more stable case of 110 km of initial circular altitude where the results are not so heavily dependent on RAAN and are within a constrained magnitude, although the orbit re-shaping is quite significant, achieving minimum altitudes of about 50 km. In contrast, when we propagate slightly higher altitudes like in the picture on the left, this pattern does not apply anymore and the results from the perturbations are highly chaotic. This can be identified when looking at the differences between the 124 km case and the 127 km case. Just 3 km of initial altitude produced a completely different behavior as noted at 300 RAAN where for altitudes starting at 124 km there is an absolute minimum, and for altitudes starting at 127 km there is a local maximum. The characteristics of this chaotic behavior pointed to a potential resonance effect that would be affecting the orbits at particular combinations of the initial orbital elements, especially at particular altitudes.

MARS SPIN-ORBIT RESONANCE

Spin-orbit resonance has been studied in Earth orbits for a long period of time. The application of this theory has advanced the generation of highly accurate gravity fields. In the case of Mars, similar analysis can be performed. As the Earth, Mars is a fast rotation body therefore, resonance with low number beta/alpha parameters can be found. By calculating theoretical orbit resonances (Zhi-Zhou et al., 2015), it is possible to infer these parameters for various combinations of altitudes and inclination. Figure IV shows the theoretical resonances with their alpha (number of celestial body rotations) in the x-axis, their altitude in the y-axis, and their beta value (number of orbits performed) right next to each data point.

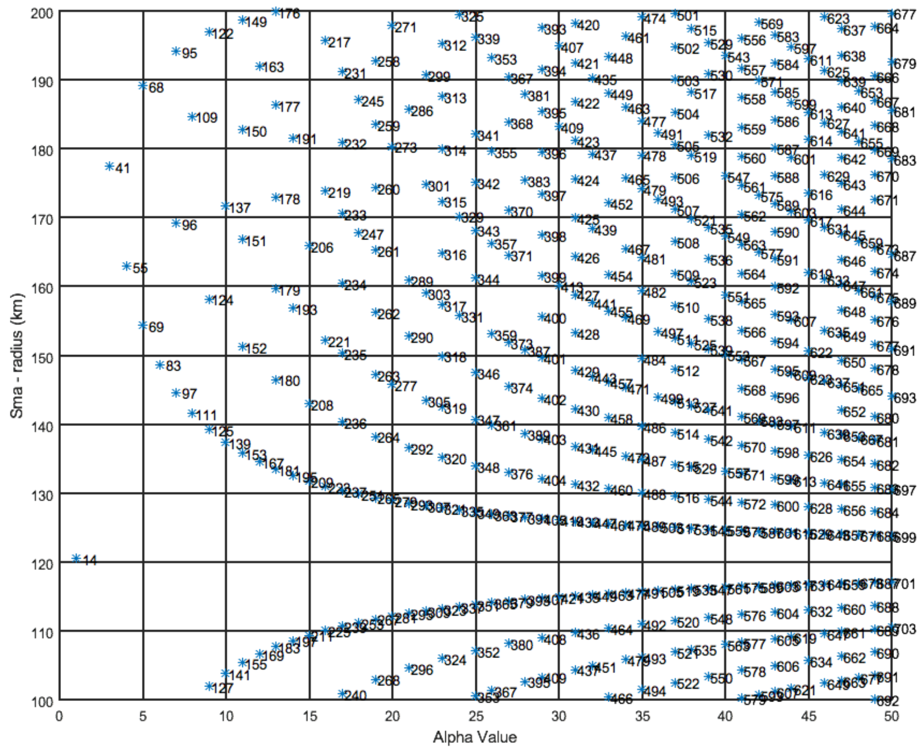

Figure 4. Theoretical spin-orbit resonances of Mars circular orbits between 100-200 km altitudes.

Figure 4 shows the computed spin-orbit resonances of Mars circular orbits between 100-200 km altitudes. The unstable region of instability found around 125 km matches the region where only a low number resonance at 14/1 can be found, which suggest a correlation of the two effects.

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