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ACCURATE MARS EXPRESS ORBIT DETERMINATION TO IMPROVE THE MARTIAN MOON MASSES AND EPHEMERIDES.

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Abstract. The determination of the ephemerides of the Martian moon Phobos and Deimos benefits from images taken by the cameras onboard spacecrafts orbiting Mars. Ones of the latest images have been obtained by the Super Resolution Camera (SRC) onboard Mars Express (MEX). From these images the position of the moons in the plane-of-sky are determined and then used to derive the ephemeris of each body on the basis of the fit of a complete dynamical model of their orbiting motion around Mars. However, the plane-of-sky positions are derived from the relative position of the spacecraft when images are taken, thus one needs to know the spacecraft position as accurately as possible. In this paper, we present accurate MEX orbit determination obtained by fitting two years of tracking data of MEX performed by the Mars Express Radio Science (MaRS) experiment onboard MEX. We show the gain in precision which is obtained for Phobos and Deimos' ephemerides at epoch of SRC camera observations. In addition, the accurate MEX orbit that we have performed allows re-estimating the mass of Phobos and Deimos. The new solutions have comparable or better formal uncertainties than previous estimates performed with the Mars Global surveyor (MGS) and Mars Odyssey (ODY) spacecrafts. With the MEX extended mission (up to 2009), it would be possible to refine these estimates by fitting also the second order coefficients of the gravity field of Phobos. Such a fit could greatly benefit from close-encounters (at a distance less than 300 km) between MEX and Phobos, given tracking data are performed at such events. This study also demonstrates the advantage of combining observations from spacecrafts and from the Earth to improve the precision of natural satellites ephemerides and thus to better understand their origin and evolution through the fine analysis of their orbital motion.

1 Introduction

Numerous efforts have been undertaken to obtain ephemerides of the Martian moons, Phobos and Deimos as accurately as possible, in order to understand their origin and evolution as well as to get some insight into the interior of the planet Mars (through the secular acceleration of the orbital motion of the moons induced by the tides of Mars). For more than one century, several dynamical models of the orbital motion of these two moons have been established and fitted to Earth-based observations and more recently to spacecraft observations (see Lainey et al., 2007 and references therein). One of the latest observations used images taken by camera onboard spacecrafts orbiting Mars like the Super Resolution Camera (SRC), part of the High-Resolution Stereo Camera (HRSC) onboard Mars Express (MEX) (Oberst et al., 2006). Recently, Lainey et al. (2007) have used these observations together with those from previous missions and historical Earth-based observations to derive new ephemerides of the two moons. The post-fit residuals of these new ephemerides are ranging a kilometer and reflect not only errors on the dynamical model of the moon orbital motion, on the pointing of the camera, on the Phobos and Deimos positioning in the images but also errors on the spacecraft positioning when taking

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these images. Indeed, similarly of observations from the Earth, the spacecraft observations need to be corrected from the relative position between the spacecraft and the moon in order to remove parallax effects in the determination of the angular position between the moons and the stars in the field of the images. For the SRC camera, Lainey et al. (2007) have used the position of MEX provided by the flight dynamics team of the European Space Operation Center (ESOC). However, these MEX orbits have been designed for navigation purpose and may lack sufficient precision for the purpose of precise moon ephemerides determination.

In this paper, we have re-determined the MEX orbits in order to improve the precision on MEX's positioning and in turn the precision on the derived Phobos and Deimos ephemerides. We use the radio-tracking data (Doppler and range) of MEX, which have been acquired at Earth's stations over the last two years in order to fit a model of MEX orbiting motion. We describe in section 2 this MEX dynamical model, in section 3 the result of the fit to tracking data and in section 4 the improvement on Phobos ephemerides when using the new accurate MEX orbits at epoch of SRC observations. In this section, we also show new estimates of the masses of the Martian moons obtained by stacking all MEX orbits over the 2004-2006 period and compare them with recent studies based on radio-tracking data of the MGS and ODY spacecrafts (Konopliv et al., 2006). The last section contains conclusions and perspectives.

2 MEX dynamical model and tracking data

The period of the orbit of MEX is about 7 hours with an altitude range from 250 km (pericenter pass) to 11500 km (apocenter pass). Such an orbit is quite different from usual circular near-polar orbits such as those of the MGS and ODY spacecrafts. However, it provides a unique opportunity to get additional information about geophysical parameters of Mars such time variations of gravity field due to seasonal mass transport in its atmosphere or tidal deformation induced by the Sun. In addition, the MEX orbit is expected to be more sensitive to the gravitational attraction of the Martian moons because of its higher eccentricity. In order to access to these effects through the monitoring of the MEX motion, we determine an accurate orbit of MEX by using the Géodésie par Intégration Numérique Simultanée (GINS) software developed by the Centre National d'Etudes Spatiales (CNES) and further adapted at the Royal Observatory of Belgium (ROB) for planetary geodesy applications. This software numerically integrates the equation of motion of the spacecraft based on a model of the forces acting on it. It also allows for an iterative least squares fit of several parameters of this model to tracking observables by calculating the partial derivatives of observables with respect to these parameters. The force budget takes into account the gravitational and non-gravitational forces. The latest spherical harmonics model of Mars' gravity field, JGM95J developed up to degree and order 95 and the associated Mars' rotation model (Konopliv et al., 2006) are considered as well as a point mass representation of the Sun and other planets given by the JPL DE414 ephemeris. The gravitational attraction of the two Martian moons is also modeled with a point mass representation, considering the latest estimates of their masses (Konopliv et al. 2006) and of their ephemerides (Lainey et al. 2007). The non-gravitational forces act on each face of the spacecraft, which are represented by flat plates (6 for the bus and 4 for the two solar arrays) with known areas and optical properties. The orientation of the bus with respect to an inertial frame is provided by sets of quaternions. We did not get sets of quaternions for the orientation of each solar array with respect to the bus, and thus we assume that the solar arrays are oriented toward the Sun given the orientation of the bus (T. Morley, pers. comm. 2005). This representation of the spacecraft (called *macro-model*) permits to calculate the acceleration imparted to the spacecraft, and due to the atmospheric drag (especially at altitude lower than 700 km), to the solar radiation pressure and to the albedo and thermal infra-red radiation pressure from Mars. For the drag, we use a model of the Mars' atmosphere density (DTM model, Bruinsma & Lemoine, 2002). The Mars radiation pressure is modeled using spatially and temporally dependent models of the albedo and of the thermal emission (Lemoine, 1992). In addition to drag and radiation pressure accelerations, we must take into account acceleration due to the inertial wheels desaturation or Wheel off-Loading (WoL) event. Indeed, such events produce a delta-velocity imparted to the spacecraft at each event, which occurs once a day in average and when the spacecraft is at high altitude. The three components of this acceleration are calculated from the delta-velocity and duration of each event as provided by ESOC. As the atmospheric density and the WoL delta-velocity are not very well known, the associated forces are the most inaccurate ones of the force model. This inaccuracy is the main limit of the precise orbit determination of any spacecraft orbiting around Mars (Rosenblatt et al., 2004; Konopliv et al., 2006), and thus of the determination of geophysical parameters from tracking data.

The tracking data consists in measuring round-trip time delay and Doppler shift of the carrier frequency

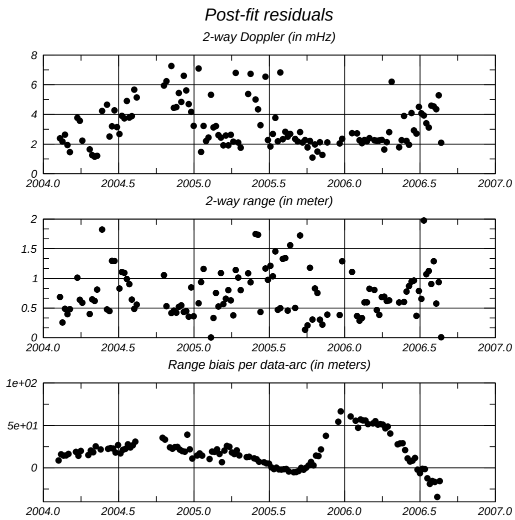

Fig. 1. Post-fit residuals and range bias estimate.

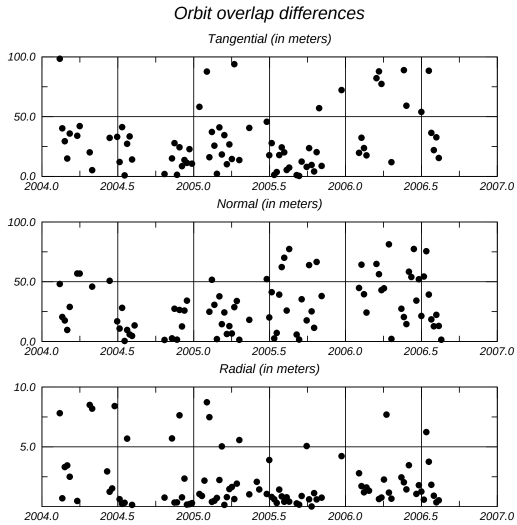

Fig. 2. RMS value of overlap difference.

(X-band at 8.5 Ghz) of the radio link between the spacecraft and stations at Earth's surface. The precision of these measurements are 2.5 mHz (or 0.02 mm/s) and 3 meters for the Doppler and range, respectively. The tracking stations belong to the NASA's Deep Space Network (DSN) located at Madrid (Spain) and Goldstone (California, USA) and to the ESA's network (NNO station located at New Norcia, Australia). At a same time, only one station can track the spacecraft and the duration of each tracking pass varies from about 40 minutes to several hours. In one tracking pass Doppler are most often acquired every 60 seconds while ranging data are most sparse (every 200 seconds in average). However, the tracking passes are not performed successively, so that gaps in the tracking coverage often occur with a duration ranging from several hours to a few days. This results in a non-continuous tracking, which cannot permit to fully compensate the inaccuracy of the force model, especially at pericenter pass when the drag is maximal and at WoL events.

3 Fit of MEX dynamical motion to tracking data

The least squares fit to tracking data is performed on successive 7 days data-arcs over the period from February 2004 to August 2006. We chose such duration of data-arc in order to enhance the signal expected from the masses of the Martian moons. To initiate this iterative process we take the MEX position and velocity from the ESOC's orbits for the initial state vector of MEX at the beginning of each data-arc. Then, we fit this initial state vector as well as one scale factor for each drag and solar pressure radiation force and the three components of the WoL acceleration at each event. In addition, we fit Doppler and range biases at each tracking pass in order to take into account systematic errors generated by the devices at each tracking station and an overall range bias for each data-arc to absorb systematic errors on the Mars-Earth position from the DE414 ephemeris.

The rms values of the post-fit residuals for each data-arc are shown in Fig. 1. These are about 2 mHz and less than 1 meter for the Doppler and range, respectively. These values are similar to the ones obtained from fitting MGS and ODY tracking data, thus meaning that the applied MEX dynamical model does not include large errors. To estimate the associated error on MEX positioning, we perform orbit overlap differences between successive data-arcs (Fig. 2). Each data-arc has an overlap period of 21 hours (or 3 revolutions of MEX around Mars) with both previous and next ones. The larger differences are in the cross-track and along-track directions and vary from less than one meter to 100 meters, with an average value of about 20-25 meters. These differences vary significantly from one pair of data-arc to the next. This is due to the non-uniform tracking coverage from one data-arc to the other. Indeed the distribution of tracking gaps make a tracking coverage which can vary from about 30 percent to 80 percent (about 40 percent in average) of the total data-arc duration. These tracking gaps have a particular effect when the pericenter passes within a data-arc are systematically not tracked (Fig. 3). Indeed, the drag scale factor becomes negative which would mean that the atmospheric density is negative. In this case, due to correlations between the drag scale factor and the adjusted WoL accelerations and the initial

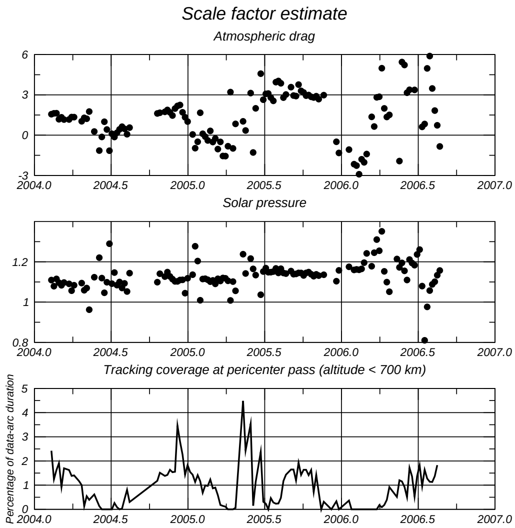

Fig. 3. Fit of atmospheric drag and solar pressure scale factors, and tracking coverage at pericenter pass.

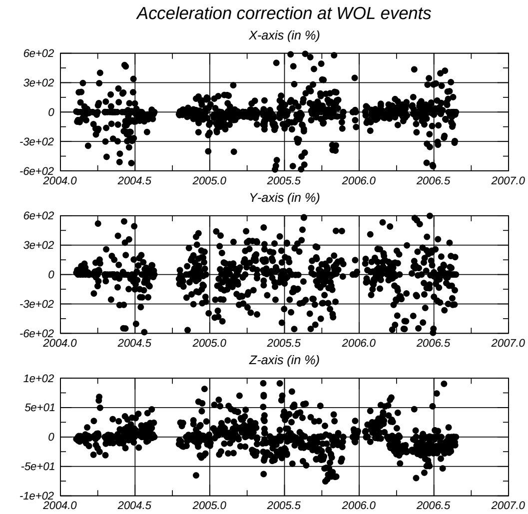

Fig. 4. Fit of the three components of the perturbing acceleration at WoL each event.

state vector, the drag scale factor absorbs information from other phenomena than the drag effect alone. This especially occurs during about three successive months in the second half of 2006 (Fig. 3). The gaps in the tracking also occur systematically around the WoL event. As a consequence the WoL acceleration cannot be perfectly adjusted and the corrections to the initial value are in average tens of percents and sometimes up to 600 percents (Fig. 4). This difficulty to properly adjust drag effect and WoL acceleration effect makes difficult to get orbit overlap systematically lower than 10 meters. The range bias per data-arc is displayed in Fig. 1. A quasi-constant value of about 20 meters is found for a first period (up to mid-2005). After this date, it increases up to 60 meters and then decreases. This behavior is due to error in the DE414 ephemeris since after 2005 no range data of Mars orbiting spacecrafts have been introduced into the determination of these ephemerides (Folkner et al., 2007). Before mid-2005, the range bias from Konopliv et al. (2006) is, however, about 1-2 meters. The value of 20 meters probably reflects the residual error in the MEX orbit related to the imperfect fit of drag and WoL accelerations. An alternative explanation is that unmodeled additional time-delay are generated by the transponder onboard MEX due to either temperature variations or electronic perturbations from other devices. However, it seems difficult to take account for about 60 nano-seconds of delay from such perturbations (T. Morley, pers. comm., 2007).

4 Improvement of Martian moon masses and ephemerides

We use the accurate MEX orbit determined with GINS instead of the orbit determined by ESOC to re-derive both Phobos and Deimos' ephemerides at epochs of SRC observations. We treat orbits relative to 34 observations of this MEX camera acquired between 2004 and 2006. Figure 5 displays a comparison of the post-fit residuals in right ascension and declination between ephemerides using MEX orbits determined in this paper and those using orbits determined by ESOC. A gain of about 30 meters on the mean value and of about 20 meters on the standard deviation of the post-fit residuals over the 34 observations is obtained when using the MEX orbit that we have determined. This shows the impact of an accurate spacecraft orbit on the derivation of Martian moon ephemerides using images from camera onboard those spacecrafts. On the other hand, these results are comparable to the overlap differences and serve as an external validation of the MEX precise orbit performed with the GINS software and the MaRS tracking data.

The Martian moon masses exert a gravitational attraction on all Mars' orbiting spacecrafts. This causes secular variations of the orbital elements of the spacecraft (ascending node of the orbit plane, argument of the pericenter and mean anomaly). These secular drifts are roughly proportional to the cube of the semi-major axis times the mean motion of the spacecraft orbit. Since the MEX orbit has a semi-major axis about 3 times larger

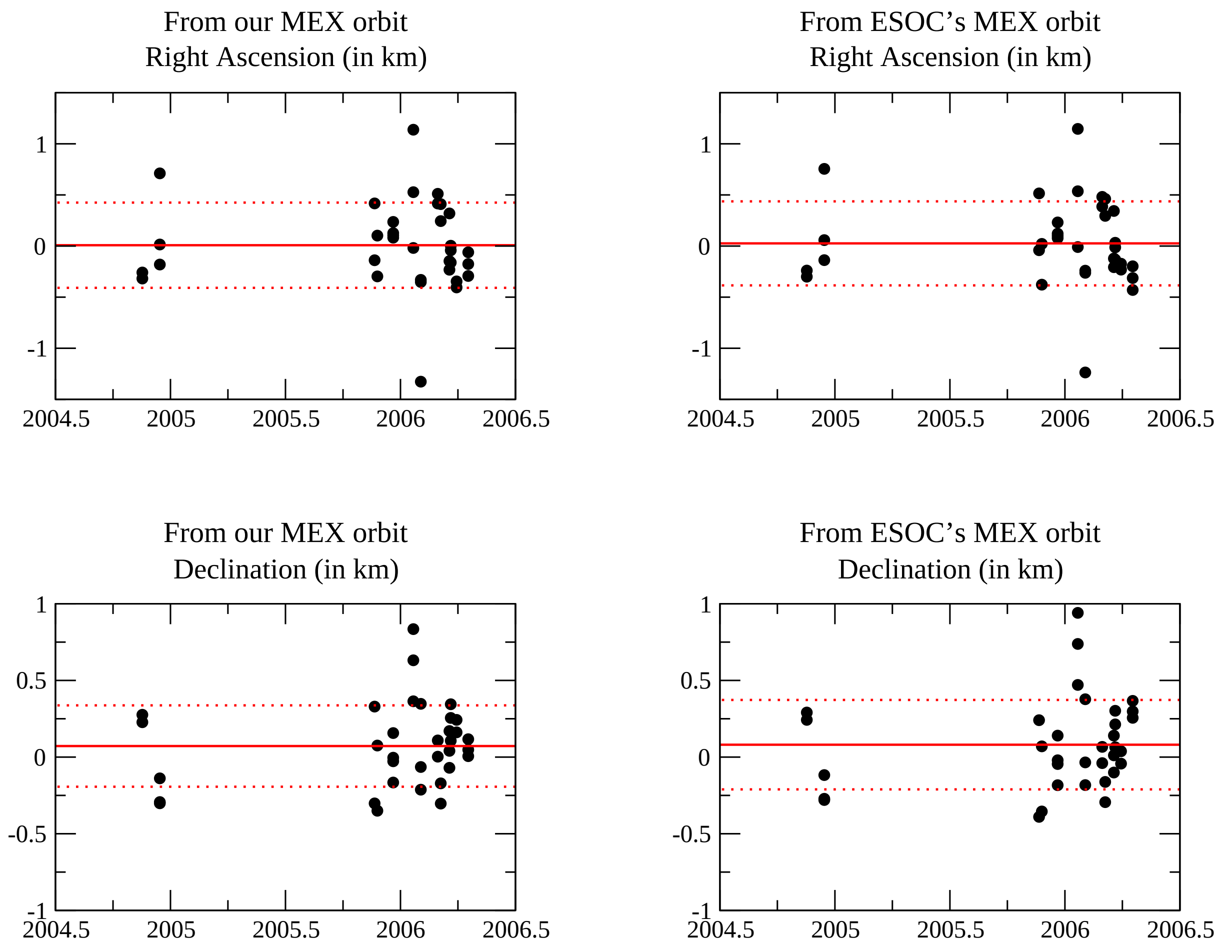

Fig. 5. Post-fit residuals of Phobos' ephemeris: Present-paper MEX orbit vs ESOC MEX orbit.

than the semi-major axis of MGS or ODY, it results in a secular drift of its orbit that is about 5 times larger than the secular drift of MGS/ODY orbits. This secular drift makes more sensitive the MEX orbit to the mass of Phobos and Deimos. Thus, we have stacked together the normal matrices resulting from the least squares fit of each data-arc in order to estimate the GM value (the universal gravitational constant times the mass) of each Martian moon. The solutions, called distant-encounter solutions, are displayed on Fig. 6 & 7. This method has been employed only recently by Konopliv et al. (2006) with tracking data of MGS and ODY spacecrafts. As expected, we obtained comparable solutions with a better uncertainty for Phobos than the solution from MGS and ODY. In contrary of Konopliv et al. (2006) we do not adjust the ephemerides of the Martian moons, which give us more confidence on the solution that we obtained. Nevertheless, the formal uncertainty on the GM of Deimos is larger than previous solutions. This is certainly due to the residual error on the MEX orbit that we have performed (around 20 meters). In addition, to these distant-encounter solutions, figure 6 & 7, show the Viking close-encounter solutions recently re-calculated by Konopliv et al. (2006). These solutions are the most accurate since Viking spacecrafts flew over each Martian moon at distance of a few hundreds kilometers. Up to date, tracking data of MEX have been acquired at the closest MEX-Phobos distance of 465 km. The signal-to-noise ratio is only 1 and thus it was not possible to improve the Phobos' mass determination with as much precision as with Viking close-encounter data. We expect future close-encounters between MEX and Phobos since the MEX mission has been extended up to 2009.

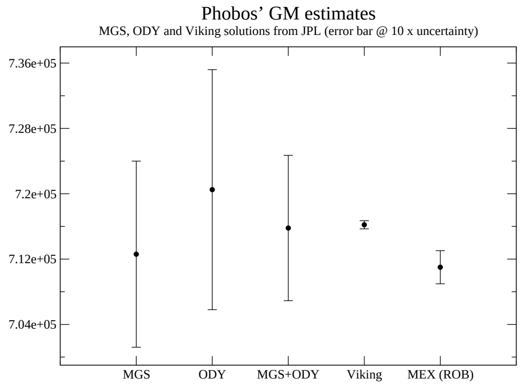

Fig. 6. Fit of Phobos' GM (in m^3/s^2).

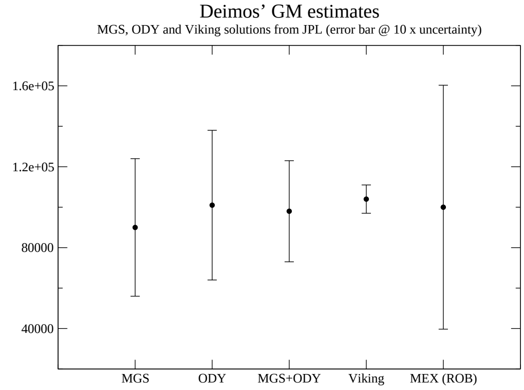

Fig. 7. Fit of Deimos' GM (in m^3/s^2).

5 Conclusions and perspectives

We have improved the MEX orbit determination by a factor of up to 2 with respect to the navigation orbits provided by ESOC. The precision of the MEX orbit obtained in this paper is limited by the non-continuous coverage of the available tracking data. A possibility to overcome this problem would be to perform MEX orbit determination on data-arcs with variable duration in order to avoid periods when gaps in the tracking coverage are too numerous and/or too long. Nevertheless, that will probably result in less data-arc and thus will not improve significantly solutions on the determination of the masses of the Martian moons (distant-encounter solutions). Tracking data at a close-encounter (at a distance less than 300 km) between MEX and Phobos would provide the opportunity to determine the second-order coefficients of the gravity field of Phobos. Lainey et al. (2007) tried to estimate the c_{20} and c_{22} coefficients from the fit of their ephemerides but the c_{22} coefficient was found to be negative, which means negative density within Phobos. Thus, better estimates of these coefficients are needed to better constrain the repartition of mass within this Martian moon.

The ephemerides of the Martian moons have benefited from MEX orbits presented in this paper, showing the interest to merge both approaches: space geodesy and orbital dynamics in order to enhance the information contained in the astronomical and spacecraft observations of the natural satellites of the solar system. Such strategy could be applied to the Galileo and Voyager data for the Galilean satellites, and to the Cassini and Voyager data for the moons of Saturn and to increase the scientific return of the future missions like the Europa orbiter of the Laplace mission proposed for the ESA cosmic vision.

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