PHOBOS MASS ESTIMATIONS FROM MEX AND VIKING 1 DATA: INFLUENCE OF DIFFERENT NOISE SOURCES AND ESTIMATION STRATEGIES

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ABSTRACT. The mass of Phobos is an important parameter which, together with second-order gravity field coefficients and libration amplitude, constrains internal structure and nature of the moon. And thus, it needs to be known with high precision. Nevertheless, Phobos mass (GM, more precisely) estimated by different authors based on diverse data-sets and methods, varies by more than their 1-sigma error. The most complete lists of GM values are presented in the works of R. Jacobson (2010) and M. Paetzold et al. (2014) and include the estimations in the interval from $(5.39 \pm 0.03) \cdot 10^5$ (Smith et al., 1995) till $(8.5 \pm 0.7) \cdot 10^5 [m^3/s^2]$ (Williams et al., 1988). Furthermore, even the comparison of the estimations coming from the same estimation procedure applied to the consecutive flybys of the same spacecraft (s/c) shows big variations in GMs. The indicated behavior is very pronounced in the GM estimations stemming from the Viking1 flybys in February 1977 (as well as from MEX flybys, though in a smaller amplitude) and in this work we made an attempt to figure out its roots. The errors of Phobos GM estimations depend on the precision of the model (e.g. accuracy of Phobos a priori ephemeris and its a priori GM value) as well as on the radio-tracking measurements quality (noise, coverage, flyby distance). In the present work we are testing the impact of mentioned above error sources by means of simulations. We also consider the effect of the uncertainties in a priori Phobos positions on the GM estimations from real observations. Apparently, the strategy (i.e. splitting real observations in data-arcs, whether they stem from the close approaches of Phobos by spacecraft or from analysis of the s/c orbit evolution around Mars) of the estimations has an impact on the Phobos GM estimation.

1. ANALYSIS OF REAL RADIOSCIENCE DATA

In February 1977 orbiter Viking1 performed several consecutive close encounters (or, flybys) of Phobos. Radio-tracking measurements acquired during those flybys are used here for Phobos GM estimations. Those measurements were originally collected by E. Christensen at JPL and split into data-arcs by G. Balmino at Centre National des Etudes Spatiales (CNES) in such a way that they do not contain any maneuvers inside. Since four out of five data-arcs of G. Balmino contained two flybys and this could affect GM_{PH} estimations, we split them further so that the new arcs have duration 24 hours and contain only one flyby.

In case of Mars Express (MEX), we use the radioscience data acquired during the flybys of Phobos performed by MEX in 2006, 2008 and 2010. The duration of data arcs is about 1.5-2 days depending on the maneuvers performed by the s/c. This means that we try to choose a data-arc which either does not contain any maneuvers or at least does not start/finish with a maneuver.

All the Viking1 and MEX flybys have been processed using the GINS (Géodésie par Intégration Numériques Simultanées) software (Rosenblatt et al., 2008).

The only test done with the real observation is the evaluation of the impact of the a priori Phobos ephemerides error on the GM_{PH}. For this purpose we took ephemerides published by Lainey et al. (2007) and by R. Jacobson (2010) and which differ by about ± 0.5 km at the time interval under consideration (see Fig. 1). Thus, the estimation of GM_{PH} with different a priori ephemerides (under the condition that all the other models/parameters are the same) is equivalent to introduction of upto $\|0.5\|$ km error

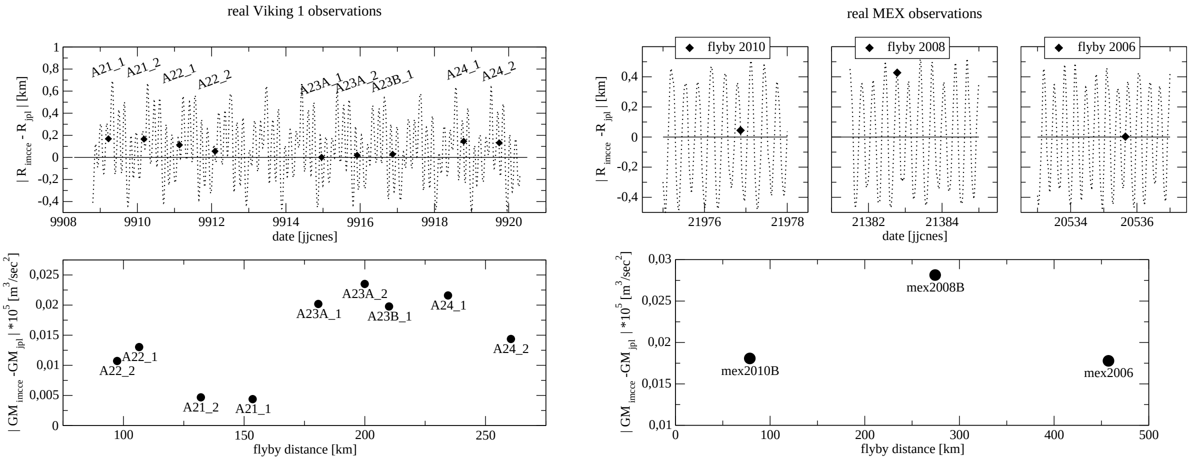

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Figure 1: Difference in GM estimations due to the errors in a priori Phobos positioning: a) Viking real radioscience observations; b) the same for MEX. The lower panel represents the absolute value of the differences in the GM estimations, obtained with different a priori ephemerides: $\Delta GM_{IMCCE}^{JPL} = |GM_{IMCCE} - GM_{JPL}|$ versus flyby distance. The upper panels depict the differences in the Mars-Phobos distances given by the above mentioned ephemerides for each flyby. The difference between two ephemerides at the moment of flyby is represented by the diamonds.

into a priori ephemeris. Estimated parameters for both s/c are: initial state vector, Phobos GM and radiation pressure coefficients. Additionally, in case of MEX, we estimated also atmospheric drag, doppler frequency offset, range bias as well as thruster parameters.

In case of Mars Express there is a clear dependence between Phobos GM estimations and a priori ephemerides used: the bigger are the difference in a priori ephemerides (which reaches 0,5 km for the flyby of the year 2008) the bigger are the difference in GM estimations (see Fig. 1). While Viking 1 data doesn't show such kind of dependency.

2. ANALYSIS OF SIMULATED DATA

We used simulations in order to clearly distinguish the impact of each factor on the radioscience observables. Furthermore, in order to avoid any additional source of errors, we simplified our dynamical

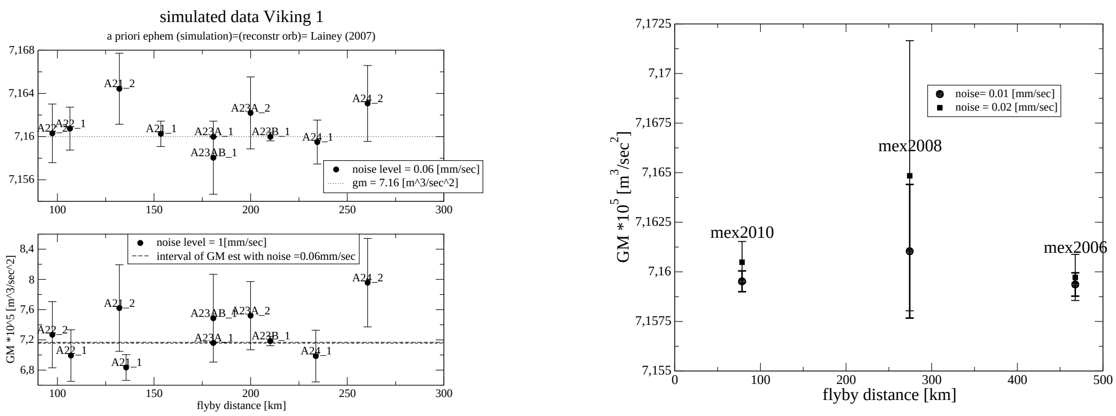

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Figure 2: Comparison of GM estimations under different observational noise level. a) Simulated Viking 1 data: upper panel shows GM_{PH} obtained with noise level 0.06 mm/s. The lower panel – the same values obtained under 1 mm/s noise level. The scale on both graphs is essentially different. Thus, the grey dashed line on the latter graph presents the area shown on the upper plot. b) MEX simulated data (noise levels are $\sigma_1^{MEX} = 2 \cdot 10^{-5}$ and $\sigma_2^{MEX} = 1 \cdot 10^{-5}$ m/s).

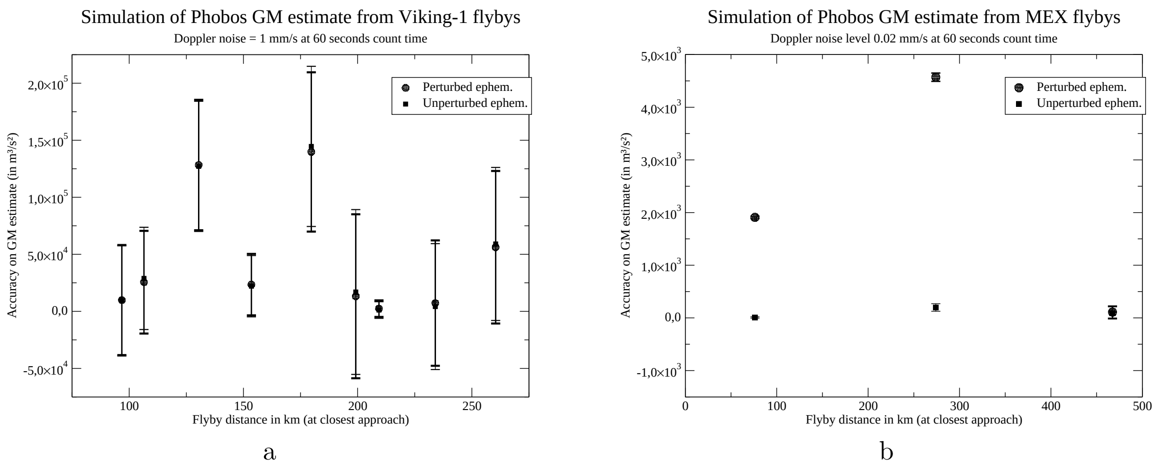

Figure 3: Sensitivity of the GM_{PH} w.r.t. a priori Phobos position (simulated data): left panel – Viking1; right panel – MEX. Squares depict deviation of GM estimations from a nominal GM value ($GM_{nominal} = 7.16 \cdot 10^5 m^3/s^2$) when the orbit have been reconstructed with perturbed Phobos ephemerides; in circles – unperturbed.

model: the radiation pressure (as well as atmospheric drag for MEX) has been fixed to its model value in all our simulations; no maneuver-like accelerations have been introduced neither for the same reason. Therefore, there is no need to estimate these parameters during the subsequent procedure of fitting the model to the simulated observations. Below we present the tests, carried out in this work.

TEST 1: sensitivity of the Phobos GM estimations to the observational/modelling noise

We used several noise levels to simulate MEX/Viking 1 observations and then to reconstruct its orbits. We restore the orbit with the *same* noise level and Phobos ephemeris (IMCCE) as simulations was done. Both, for Viking 1 and MEX simulated observations cover the same time intervals as real data-arcs. For both satellites we suppose that the noise is the only source of errors, and thus, during the subsequent orbit reconstruction process, we estimate only initial state vector and Phobos GM.

TEST 2: impact of errors in a priori Phobos ephemeris on the Phobos GM

Observations have been simulated with the IMCCE a priori Phobos ephemeris and typical X-band/S-band noise level for MEX/Viking1 correspondingly. While the reconstruction of the orbits have been done by using perturbed IMCCE ephemeris (IMCCE Phobos ephemeris to which 1 km error have been added) and the same noise level. In this test, estimated parameters are GM_{PH} and spacecraft initial state vector.

TEST 3: sensitivity of the estimated GM w.r.t. a priori GM value

The main idea of this test is to simulate Doppler observations with certain value of $GM_{PH} = 7.16 \cdot 10^5\ \mathrm{m}^3/\mathrm{s}^2$ and subsequently to reconstruct the orbit by fitting the model with a wrong value $GM = GM_{PH} \pm \Delta GM$. An erroneous value of one of the parameters of dynamical model should produce a certain signal in the post-fit residuals. Therefore, from the analysis of post-fit residuals one can estimate the response of simulated data to the introduced errors in Phobos GM. In this test the data have been simulated with $\sigma^{noise} = 0.0$. During the fitting process we estimate only initial state vector and fix Phobos GM to some deliberately wrong values: $\Delta GM_1^{PH} = 0.5 \cdot 10^5\ \mathrm{m}^3/\mathrm{s}^2$ (i.e. $GM_1^{PH} = 7.66 \cdot 10^5$) and $\Delta GM_2^{PH} = 10^5\ \mathrm{m}^3/\mathrm{s}^2$ (i.e. $GM_2^{PH} = 8.16 \cdot 10^5$).

3. CONCLUSIONS

Accuracy and precision of GM estimations increase with decreasing of the value of the noise for both spacecraft (see Fig. 2).

VIKING1: *observational noise dominates all other considered sources of errors;*

- both simulated and real data show that observational noise prevails inaccuracies in Phobos a priori positions during GM estimation process (see Fig. 1 (a) and Fig. 3 (a), correspondingly);

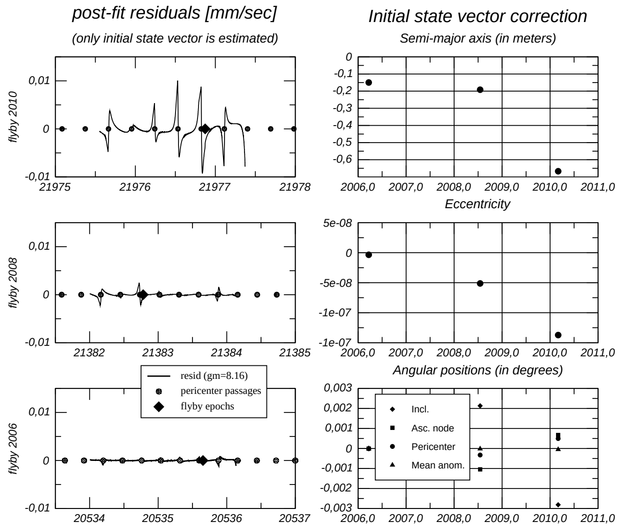

Figure 4: The post-fit doppler residuals after the s/c orbit reconstruction from simulated MEX data. Left-hand panels: Phobos GM in legend is given in $10^5 \mathrm{m}^3/\mathrm{s}^2$ units. Solid line represents post-fit residuals; circles – epochs of pericenter passages by s/c; and in diamonds – the epoch of flyby. Right-hand panels: corrections to the initial state vector.

- the post-fit Doppler residuals are not very sensitive to the errors in GM_{PH}: changes of the spacecraft velocities due to $\Delta GM_{PH} = 10^5[\mathrm{m}^3/\mathrm{s}^2]$ are at the level of 0.06 mm/s which corresponds to the most optimistic estimation of the observational noise level in case of Viking 1.

MEX: *the uncertainties in Phobos a priori position dominate other sources of errors.*

- there is a clear dependence between Phobos GM estimations and a priori ephemerides used (see Fig. 1 (b) and Fig. 3 (b), correspondingly): the bigger the difference in a priori ephemerides (which reaches 0,5 km for the flyby of the year 2008) the bigger the difference in GM estimations;
- Changes of the spacecraft velocities due to $\Delta GM_{PH} = 10^5[\mathrm{m}^3/\mathrm{s}^2]$ could be observed: they are between 0.02 mm/s (flyby in the year 2006 at the distance about 467 km) and 0.2 mm/s (flyby of the year 2010 at the distance about 78 km) while the typical noise level of MEX observations is about 0.02 mm/s (Fig. 4).

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