Validation of the Phobos Orbit and Control Point Network with HRSC and SRC on Mars Express

K. Willner, J. Oberst, M. Wählisch, K.D. Matz, T. Roatsch, J. Bendig

Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany
(Konrad.Willner@dlr.de)

Abstract:

Early astrometric measurements by the Super Resolution Channel (SRC) on Mars Express (MEX) [15], Mars Orbiter Laser Altimeter (MOLA) ranging data [1], and solar eclipse observations [2], showed large discrepancies between predictions of the Phobos position and observations of its position.

As a consequence, new orbit models were developed and released by the Jet Propulsion Laboratory (JPL) and the Royal Observatory of Belgium (ROB).

Since 2006 many more Phobos flybys were carried out by Mars Express, and more images were obtained by the SRC. We made new astrometric measurements in the new image data to validate the released orbit models. We devised new analysis methods, making use of a known control point network [5] and background star observations to control the pointing of the camera. In addition we analyzed Phobos' shadow observations on the Martian surface obtained by the High Resolution Stereo Camera (HRSC) on MEX as well as by the Mars Observer Camera (MOC) on Mars Global Surveyor (MGS). Shadow observations are thought to be independent from spacecraft position and camera pointing.

While good agreement of current orbit models with our flyby observations was achieved, the analysis of the shadow observations on the other hand showed large offsets between models and predictions.

Introduction:

Asaph Hall, an astronomer at the United States Naval Observatory discovered the two Martian moons, Phobos and Deimos 1877. Ever since, there has been great interest in the long term motion of the natural satellites in the gravity field of the planet. Properties of the Martian interior might be determined by the tidal acceleration of Phobos or ultimately even the thermal evolution of Mars. Orbital evolution of both satellites is studied by means of ground-based observations during Mars oppositions up to the present date. Uncertainties for ground based observations are in the order of several kilometers [12] [9] . Besides, a number of flyby observations obtained by NASA spacecraft missions like Mariner 9, Viking, and Mars Global Surveyor were analyzed and resulted in positional information for Phobos with accuracies between 3km -10 km [3] [4]. The Russian ill-fated Phobos mission operated for 2 month in 1989 astrometric measurements with accuracies of approx. 2km were possible [8]. A decade later the MGS satellite performed several flyby maneuvers of Phobos. Positional measurements of the Phobos shadow using Mars Orbiter Laser Altimeter (MOLA) Radiometry [13] as well as laser ranging measurement [1] were carried out further constraining the orbit of Phobos. The Mars Exploration Rovers observed Phobos transits across the solar disc which gave positional observations constraints [2]. Offsets between observations and predictions of Phobos' position of 11 km in along track direction and 0.5 km out of orbit plane were observed. These offsets were confirmed through astrometric measurements in SRC images [14] obtained during several close Phobos encounters of Mars Express since May 2004. In this paper we report on the validation of the orbit models released in 2006 with the aid of many more SRC observations and Phobos shadow observations obtained by MOC and HRSC.

Missions and Cameras:

The Mars Observer Camera (MOC) on Mars Global Surveyor (MGS) is a push broom line scanning system consisting of three components one narrow-angle- and two wide-angle cameras [11]. It is capable of imaging the surface of our neighboring planet with ground sampling resolutions between 14 m/pixel when making use of the narrowangle camera and lower than 7.5 km/pixel when obtaining a global image reaching from limb to limb. To maintain a consistent pixel resolution in global images a pixel summing in along-track and across-track direction was applied. The shadow of Phobos was captured in over 300 such images. Due to a wide range of quality we only considered the 19 images which showed the shadow in excellent quality.

The High Resolution Stereo Camera (HRSC) is also a push-broom line scanning system. The 9 different line sensors are forming a fan-like set of viewing angles to obtain sets of stereo images. HRSC is capable to capture images with a resolution as low as 10 m/pixel in the nadir channel at 258 km pericenter altitude. The SRC in contrast is a framing camera with best ground resolution of 2.3 m/pixel [7] on Mars at the pericenter of MEX. It is also used to capture the two natural satellites of Mars with high resolution. For the orientation the spacecraft is equipped with star sensors, mounted on the opposite side as the HRSC. During Phobos flyby maneuvers the star sensor are usually looking toward the Martian surface and a verification of the camera pointing is not possible. To control the camera pointing during flybys the first and last image of an 8 image SRC sequence is dedicated to long-time exposures to observe background stars.

Measurements:

Flyby observations

MEX is in a nearly polar highly elliptical orbit with an apocenter altitude of 10,117 km and a pericenter altitude of 258 km [7]. Phobos is orbiting Mars in a nearly equatorial orbit at an altitude of 9,515 km and with a similar period (7.65 h) as MEX (6.72 h). Thus close Phobos encounters occur in a periodical manner with periods of many encounters and periods of no encounters at all. Nevertheless, over 100 flybys were successful showing Phobos or parts of its surface in over 150 SRC images. Unlike previous Phobos observations, background star observations are now available for all flyby image sequences since mid 2005 to control and correct for camera pointing errors. Furthermore we now improved our method to obtain redundant information of the center of figure (COF) of Phobos from each flyby image making use of the control point network established by Duxbury and Callahan [5]. The control points determined in [5] are all craters which are easily recognized (see. fig. 1). To rule out misidentifications, the surface features point ID's were projected onto the image. An ellipse fit routine was used to determine the image coordinates, x_m,y_m, of the crater lids as the points were defined in [5]. For each observed control point we calculated the predicted image coordinates, x_p,y_p, using the Phobos orbit model and the corrected camera pointing. These predicted image coordinates, x_p,y_p, were then transformed to the measured image coordinates, x_m,y_m, using the functional model shown in Eq. 1.

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = s\, R(\alpha) \begin{bmatrix} x_p \\ y_p \end{bmatrix} + \begin{bmatrix} x_{trans} \\ y_{trans} \end{bmatrix} \qquad (1)$$

The free parameters, rotation R(α), scale s and translation, x_{trans},y_{trans}, were determined using an iterative least-squares analysis involving all identified surface features of one image at a time. Likewise, the Phobos center of mass (COM) was converted to predicted image space coordinates. The translation parameters from above were used to calculate the corrected image position of the COF of Phobos. Applying the corrected camera pointing we obtained stellar positions for Phobos. Even though over 120 images were available we only analyzed 96 images from 34 flybys where background star observations were available before and after the Phobos encounter. Likewise, Images with too little coverage of the Phobos surface were not considered.

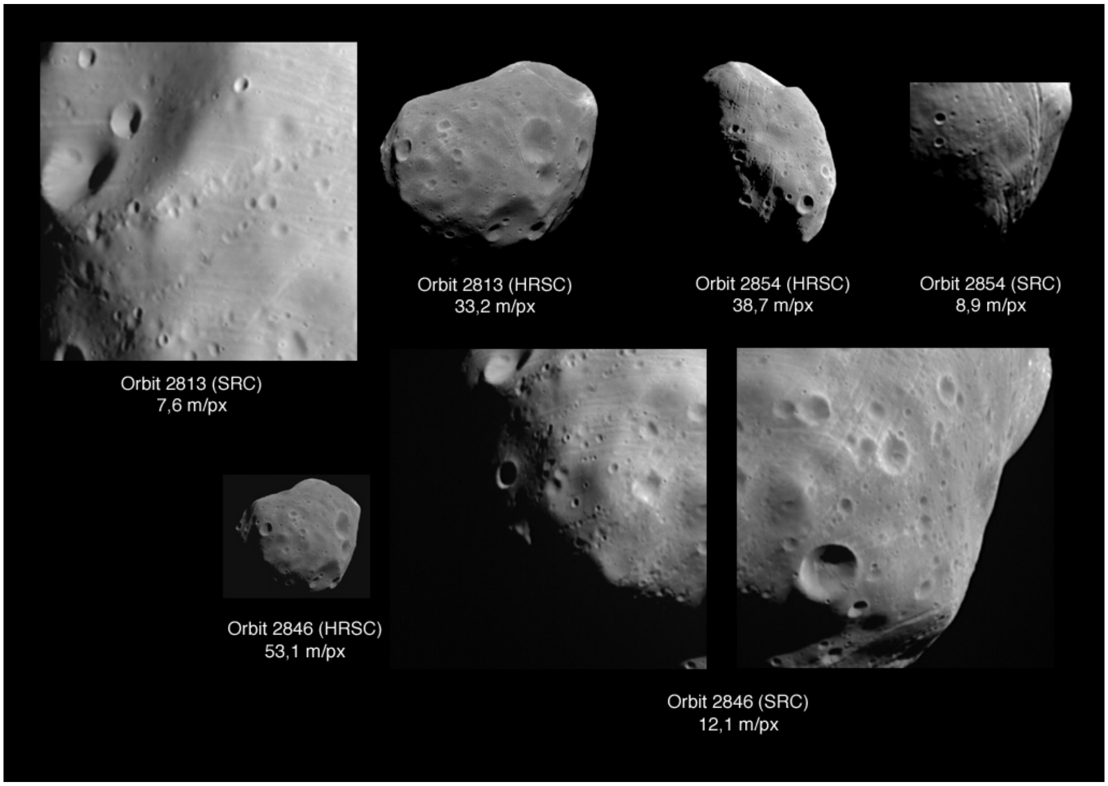

Figure 1: Examples of SRC and HRSC images from different flybys.

Shadow observations

Due to the relative motion between Phobos and orbiter (MEX or MGS) and the push-broom technique of the cameras the shadow of Phobos is in most cases captured as an elongated ellipse (see. fig. 2). To determine the position of Phobos in the stellar sky we determined the exact position of the shadow center, the height above a reference body and we extracted the exact time from the image data. We projected all images into an equidistant map projection on a Mars Orbiter Laser Altimeter (MOLA) reference sphere and registered the images to the Mars digital Image Map (MDIM) 2.1. Thus a direct measurement of the ellipse center with an ellipse-fit method was possible. The corresponding height of the surface was extracted from the Mission Experiment Gridded Data Record (MEGDR) of the MOLA-dataset. The stellar position of the sun at the time of the observation of the Phobos shadow center as seen from the center of the shadow on Mars equals the stellar position of Phobos at the time.

Figure 2: Sample of a Phobos shadow from orbit 2345 in the green channel.

Results

In flyby observations the least squares analysis to determine the transformation parameters converged rapidly after only 3 to 4 iterations. The resulting translation vector showed no significant offset in the across-track direction (out of orbit plane and towards/away the center of the orbit ellipse) of Phobos. Offsets in the direction of motion of Phobos were small but significant. Phobos was observed to be 1.5 km to 2.6 km ahead of its predicted position depending on the orbit model used for comparison (see. Table 1). We estimate uncertainties to be in the order of ±0.1 km to ±0.5 km depending on the distance to Phobos r, the error of the spacecraft position σ_{sc}, the accuracy of determination of the transformation parameters σ_t, and the camera pointing σ_p (confer [3][4] and Eq.2).

$$\sigma = \sqrt{\sigma_t^2 + \sigma_p^2 + \left(\arctan \frac{\sigma_{sc}}{r} \right)^2} \qquad (2)$$

An average accuracy of ±200 m for the spacecraft orbital position, σ_{sc}, is stated in [7] where as we still used the previously reported accuracy of ±500 m [15] for all images in the analysis. All other σ vary depending on the situation.

Shadow observations in HRSC and MOC images were compared with the recent orbit model of Lainey et al. [10] and the orbit model released by the JPL. Results from the HRSC image show that Phobos is ahead of its predicted position by an average value of 4.5 km with an accuracy of ±0.8 km. The across-track offset varied between 0.2 km and 10.8 km with an approx. accuracy of ±0.3 km. In contrast results from MOC images show discrepancies of 1 km to 18 km in along-track and 0.1 km to 6 km in across-track direction with accuracies of ±5.9 km and ±1.6 km, respectively.

Orbit model	along-track offsets	across-track offsets
Lainey [10]	+1.5km	±0.3km
Jacobson [16]	+2.6km	±0.5km

Table 1: Comparison of orbit models with flyby observations. Note that positive along-track offsets indicate that Phobos is ahead of its predicted position.

	HRSC images	
Orbit model	along-track offsets	across-track offsets
JPL[16]	2.5 km to 7.9 km	1.4 km to 10.8 km
ROB[10]	1.6 km to 7.0 km	0.2 km to 10.6 km
	MOC images	
JPL[16]	0.9 km to 17.8 km	0.1 km to 6.0 km
ROB[10]	0.4 km to 18.4 km	0.2 km to 4.9 km

Table 2: Results of shadow observations in HRSC and MOC images.

Discussion

Two teams made orbit predictions considering all observations until 2006. The Solar System Dynamics Group at JPL and the group around V. Lainey at the ROB significantly improved previous predictions were differences between observations and predictions of approx. 11km were found [15][2] [6]. The two orbit models show similar offset to our flyby observations, whereas the orbit model computed by the JPL shows larger offsets to the observed positions than the orbit model provided by the ROB (cf. table 1). Since the trajectories of Phobos and MEX are nearly perpendicular to each other the observed offsets of 1.5 km to 2.6 km truly correspond to the along-track motion of Phobos. Figure 3 shows the differences between the orbit model of the ROB and results from flyby observations in along-track direction in kilometers over time.

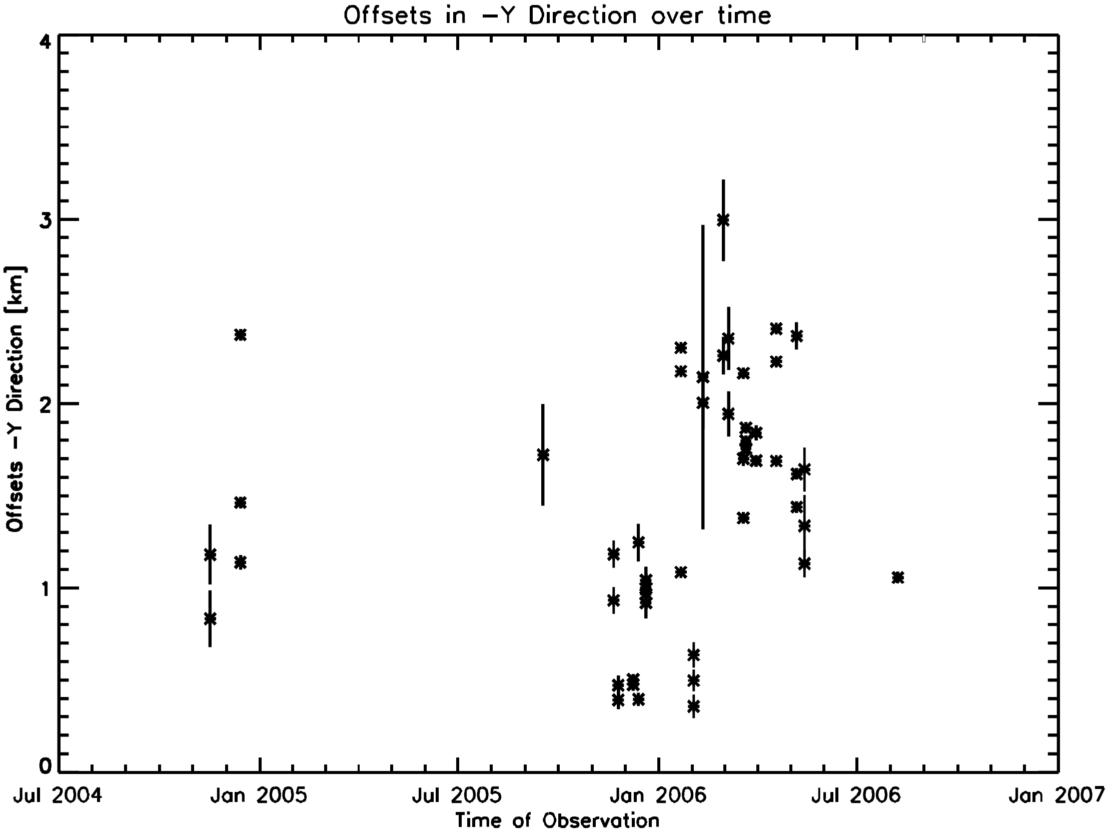

Figure 3: Differences between orbit predictions by the ROB orbit model and observations in flyby images in along-track direction. Positive numbers show that Phobos is ahead of its predicted position.

In contrast, results from the analysis of the Phobos shadow show large scattering in the offsets. For the timespan over which both kinds of observations are available, the results of the shadow observations show much larger discrepancies to the orbit models than the observed positions in the flyby images (cf. figure 4). A very likely reason is a systematic error in the reduction of the data from a complex process, during which the shadow in the images forms. Studies of a different attempt to solve for the position of Phobos in the stellar sky are now under way.

There is much interest in the question whether Phobos is faster accelerating than estimated in previous and current orbit models or not. This can not be clearly answered. Even though one could argue that the observed discrepancies are slightly increasing toward the end of 2006 (figure 3) the time span covered with these observations is rather short and a definite statement cannot be made.

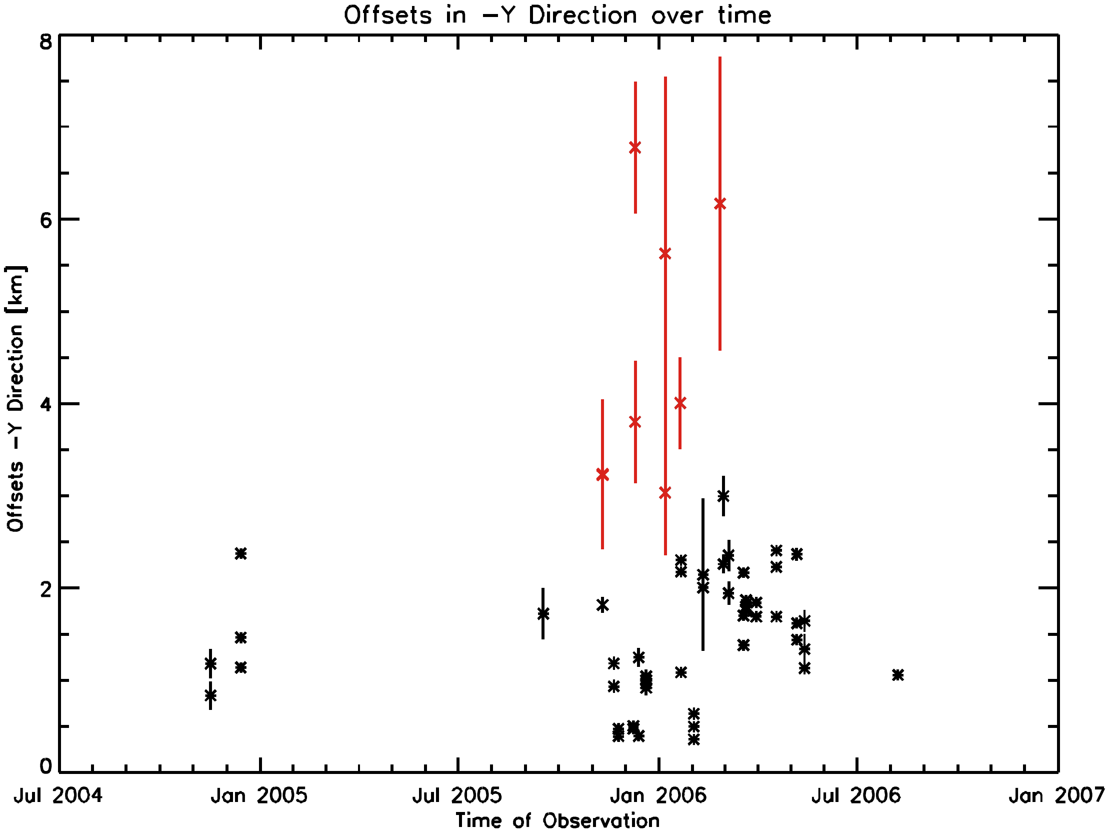

Figure 4: Offsets of shadow observations (red) in comparison with flyby observations (black) in along track direction.

References

[1] W. B. Banerdt and G. A. Neumann. The Topography (and Ephemeris) of PHOBOS from MOLA Ranging. In Lunar and Planetary Institute Conference Abstracts, pages 2021–+, March 1999.

[2] J. F. Bell, M. T. Lemmon, T. C. Duxbury, M. Y. H. Hubbard, M. J. Wolff, S. W. Squyres, L. Craig, and J. M. Ludwinski. Solar eclipses of Phobos and Deimos observed from the surface of Mars. Nature, 436:55–57, July 2005.

[3] T. C. Duxbury and J. D. Callahan. PHOBOS and Deimos astrometric observations from Viking. Astronomy and Astrophysics, 201:169–176, July 1988.

[4] T. C. Duxbury and J. D. Callahan. PHOBOS and Deimos astrometric observations from Mariner 9. Astronomy and Astrophysics, 216:284–293, June 1989.

[5] T. C. Duxbury and J. D. Callahan. PHOBOS and Deimos control networks. Icarus, 77:275–286, February 1989.

[6] B. Giese, J. Oberst, F. Scholten, H. Hoffmann, M. Spiegel, and G. Neukum. Ein hoch auflösendes Oberflächenmodell des Marsmondes Phobos. Photogrammetrie Fernerkundung Geoinformation, (5):439 – 444, 2005.

[7] R. Jaumann, G. Neukum, T. Behnke, T. C. Duxbury, K. Eichentopf, J. Flohrer, S. v. Gasselt, B. Giese, K. Gwinner, E. Hauber, H. Hoffmann, A. Hoffmeister, U. Köhler, K.-D. Matz, T. B. McCord, V. Mertens, J. Oberst, R. Pischel, D. Reiss, E. Ress, T. Roatsch, P. Saiger, F. Scholten, G. Schwarz, K. Stephan, and M. Wählisch. The high-resolution stereo camera (HRSC) experiment on Mars Express: Instrument aspects and experiment conduct from interplanetary cruise through the nominal mission. Planetary and Space Science, 55:928–952, May 2007.

[8] Y. Kolyuka, V. Tikhonov, N. Ivanov, V. Polyakov, G. Avanesov, V. Heifetz, B. Zhukov, E. Akim, V. Stepanyants, O. Papkov, and T. Duxbury. PHOBOS and Deimos astrometric observations from the PHOBOS mission. Astronomy and Astrophysics, 244:236–241, April 1991.

[9] V. Lainey, V. Dehant, J. Oberst, and M. Pätzold. New ephemerides of the martian moons. Poster. EGU05-A-07117, 2005.

[10] V. Lainey, V. Dehant, and M. Pätzold. First numerical ephemerides of the Martian moons. Astronomy and Astrophysics, 465:1075–1084, April 2007.

[11] M. C. Malin, G. E. Danielson, A. P. Ingersoll, H. Masursky, J. Veverka, M. A. Ravine, and T. A. Soulanille. Mars Observer Camera. Journal of Geophysical Research, 97:7699–7718, May 1992.

[12] T. A.Morley. A catalogue of ground-based astrometric observations of the Martian satellites, 1877-1982. Astronomy and Astrophysics Supplement Series, 77:209–226, February 1989.

[13] G. A. Neumann, B. G. Bills, D. E. Smith, and M. T. Zuber. Refinement of Phobos Ephemeris Using Mars Orbiter Laser Altimeter Radiometry. In S. Mackwell and E. Stansbery, editors, Lunar and Planetary Institute Conference Abstracts, pages 1820–+, March 2004.

[14] J. Oberst, H. Hoffmann, K. D. Matz, T. Roatsch, M. Wählisch, B. Giese, and G. Neukum. New Observations of Phobos and Its Shadow with the HRSC/SRC on Mars Express. In S. Mackwell and E. Stansbery, editors, 37th Annual Lunar and Planetary Science Conference, pages 1312–+, March 2006.

[15] J. Oberst, K. D. Matz, T. Roatsch, B. Giese, H. Hoffmann, T. Duxbury, and G. Neukum. Astrometric observations of Phobos and Deimos with the SRC on Mars Express. Astronomy and Astrophysics, 447:1145–1151, March 2006.

[16] R.A.Jacobson. pers. communication.