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Phobos control point network, rotation, and shape

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ABSTRACT

A new independent control point network for Phobos was computed from image data obtained by the SRC (Super Resolution Channel) on board the European Mars Express Mission. The network solution includes 3D coordinates of 665 surface control points and was used to observe the forced libration amplitude of Phobos. Based on the network control points a spherical harmonic function model to degree and order 17 was derived, from which volume, bulk density and moments of inertia were computed. The modeled forced libration amplitude agrees to our observation within the error bands, indicating a homogeneous mass distribution for Phobos. To bring both values into exact agreement with the observations, different mass distribution models were applied. It appears that the amplitude is relatively insensitive to a simple two-layer density model.

1. Introduction

In 1877, Asaph Hall, an astronomer at the United States Naval Observatory, discovered that Mars is accompanied by two satellites, Phobos and Deimos. The origin of the two has remained uncertain to the present day. While the two satellites may represent ejecta from Mars that reaccreted in planet orbit, their origin as captured asteroid fragments from the main belt cannot be ruled out. Spectral signatures (Bell et al., 1993; Pieters et al., 1999) and the overall density (approx. 1.9 g/cm^3) suggest that Phobos (the larger of the two) is similar in composition to carbonaceous chondrites and therefore raises the possibility that Phobos contains a large fraction of volatiles. US and Russian space mission planners have identified Phobos as a target, from where the recovery of extraterrestrial samples may be comparably straightforward (Pieters et al., 1999; Marov et al., 2004).

Clues on the origin of Phobos and Deimos may be obtained from their overall shape, surface morphology, and interior structures. Phobos is orbiting Mars in a near-circular near-equatorial orbit with a mean distance to the center of the planet of 9375 km, i.e., deep in the gravity field of Mars. Inferences on its interior structure may be obtained by studies of Phobos' librational motion, caused by tidal forces interacting with the odd shape of the satellite.

While early data on size, shape, and rotation of Phobos were obtained during the Mariner-9 and Viking missions (Duxbury and Callahan, 1989), we concentrate on the analysis of more recent image data obtained by the SRC (Super Resolution Channel) of the HRSC (High Resolution Stereo Camera) on the European Mars Express spacecraft (MEX).

In this paper, we present a new control point network which includes a solution for the librational motion of Phobos. From the control point data we derive a model for the shape of Phobos and we report new values for total volume and moment of inertia factors. We finally discuss implications for the interior structure of the satellite.

2. Previous shape models

Various previous models exist to describe the shape of Phobos. Limb analyses were used to derive ellipsoidal models (Thomas, 1989). The combination of limb observations with 3D coordinates of control points led to a numerical shape model with a 2 × 2 degree grid spacing (Simonelli et al., 1993).

Other modeling efforts involved the identification of landmarks and image block adjustments to derive large numbers of control point coordinates. The Turner (1978) shape model involved 260 control point coordinates. Spherical harmonic expansion models were fitted to control point coordinates by Duxbury (1991) to degree and order 8. Approx. 315 craters with depths-to-diameter ratios between 0.1 and 0.2 were added separately to the shape model for added detail (see also Table 1).

In this paper, we compute a network of 3D coordinates for a large number of surface points fitted by spherical harmonic expansion models.

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Table 1
A variety of Phobos shape models was previously established. In most cases models are based on control point information.

Method	Necessary observations	Reference
Plaster model	Control points	Turner (1978)
Ellipsoidal models	Limb coordinates	Thomas (1989)
Spherical Harmonic Expansion model low degree and order	Ground Control Points, depth to diameter ration for large crater	Duxbury et al. (1991)
Numerical models	Limb measurements	Simonelli et al. (1993)
Spherical Harmonic Expansion model	Dense distributed Ground Control Points	This study

3. Control point network

3.1. Duxbury and Callahan control point network

From July 1976 to October 1978, the two Viking orbiters and their framing cameras obtained global image coverage of Phobos. Image resolutions were in the order of 200 m/pixel and better, showing Phobos under excellent phase angles. Duxbury and Callahan (1989) established one of the first global control point networks consisting of 98 ground control points (GCP). Duxbury (1991) extended the network for a total of 315 points. Control points were represented by craters of various sizes, covering several pixels. Uncertainties of the 3D-coordinates, which referred to the centers of local planes on the crater rims, ranged from ±74 m to ±900 m.

3.2. SRC image data

Mars Express is on an elliptical trajectory and currently the only Mars orbiting spacecraft making regular Phobos flyby maneuvers. As of December 2008, the spacecraft has engaged in 114 Phobos flybys, and the SRC obtained 345 images of Phobos with resolutions ranging between 100 m/pixel and 0.9 m/pixel. The SRC is a 1 k × 1 k framing camera with a large focal length of 988.5 mm (Oberst et al., 2008).

During a flyby, the SRC is pointed at a fixed direction in the stellar sky. Hence, multiple coverage of areas, observed under different viewing angles during different flybys, is required to determine 3D-Coordinates of control points. SRC images are covering approx. 84% of the surface of Phobos, approx. 75% in stereo (cf Fig. 1).

Viking Orbiter (VO) framing camera images were used to fill gaps (20%) in the image coverage within the area between 180° and 270° West. Control point measurements in SRC and VO images were combined in the block adjustment to establish a global coverage at high spatial resolution. Likewise, HRSC data were used to fill remaining gaps (estimated 10%) in the shape model, though HRSC control points were not included in the adjustment because of the comparably low HRSC image resolutions.

Table 2
Object point accuracies for the different bundle block adjustment models.

	SRC			Viking orbiter		
No. of points obs.	2989			871		
	x	*y*	*z*	*x*	*y*	*z*
σ_{max} [m]	91.7	56.1	63.6	156.6	156.2	192.0
σ_{min} [m]	17.8	13.2	14.6	115.0	86.5	109.0
σ_{mean} [m]	27.1	17.2	19.5	122.5	94.1	114.2

Combined adjustment of SRC and Viking

No. of points obs.	3898		
	x	*y*	*z*
σ_{max} [m]	92.26	103.28	79.93
σ_{min} [m]	8.47	7.24	7.87
σ_{mean} [m]	21.24	16.19	16.70

3.3. Object point determination

Suitable control points were selected and their line/sample coordinates were measured in 53 SRC images and 16 VO images. Pixel resolution range from 5 m/pixel to 48 m/pixel but on average 17 m/pixel for SRC images and from 6 m/pixel to 77 m/pixel (average 17 m/pixel) for VO images. Contrary to the definition of the control points of Duxbury and Callahan (1989), where crater coordinates represented the center of a local plane on the crater rims, control points were defined as the centers of the crater floors. Image resolutions permitted to observe very small surface features — even small features within larger craters. Hence, we estimated that the observed points represent the mean surface with a better approximation.

A total of 665 points were observed 3898 times with a minimum of 2 observations and a maximum of 14 observations, but on average 6 observations per point in both image data sets.

For the block adjustment camera orientation data are transformed into the Phobos body fixed coordinate space. To detect gross errors in the predicted orientation of the cameras, least-squares adjustments were computed for both data sets separately. Orientation data for the SRC was of good quality and could directly be used to determine object point coordinates in the bundle block adjustment. However, normalized residuals indicated larger errors than the preliminary assumed uncertainties for camera orientations. Significantly improved results were computed after an adopted weighing scheme was applied to the camera orientation data. Mean object point accuracies σ_x, σ_y, σ_z of 27.1 m, 17.2 m, and 19.5 m, respectively, were computed for control points measured in SRC images. An uncertainty of 1 pixel for the image coordinate observations was assumed.

The orientation data of Viking orbiter images are known to suffer from large errors (Zeitler, 1999). Hence, we applied corrections to the orientation of the Viking orbiter cameras prior to a bundle block adjustment by fitting the predicted limb position to the observed position of Phobos in the images. This relates to rotations about two axes of the camera. Very high resolved images do not necessarily depict parts of the limb. Therefore, an overlay was produced, containing the control point positions of the Duxbury (1991) control point network, which was then fitted to the surface features. The stochastic model was again adjusted according to the computed normalized residuals of the orientation data. The least-squares bundle block adjustment of the Viking orbiter data set was very sensitive to variations of the stochastic model. Due to the uncertain VO navigation data, we re-computed the positions and orientations for VO observations during a first least-square bundle block adjustment. The computed camera orientations for SRC and the VO cameras were included in a second bundle block adjustment to compute the object point coordinates of the GCPs. A Baarda gross error detection was applied (Baarda, 1968) to rule out misidentified point observations. After removal of these points, uncertainties of the 3D ground coordinates were reduced marginally for points in SRC images and by a factor of approx. 6 for points in Viking images (cf. Table 2) when computing the combined data set.

3.4. Reference frame

We note that the center of figure was not explicitly observed and introduced as a control point during this analysis. Hence, the resulting 3D-coordinates are not tied to the center of figure of Phobos. Instead the control point reduction relies on the computed position of Phobos from an orbit prediction model. In the course of this analysis we used the latest JPL release of ephemerides of the Martian satellites *MAR080* (Jacobson, 2008a,b). All results are related to this orbit prediction model and may differ if other ephemerides are used.