Planetary and Space Science ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

The Phobos geodetic control point network and rotation model

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ARTICLE INFO

Article history:
Received 16 August 2013
Received in revised form
4 March 2014
Accepted 7 March 2014

Keywords:
Phobos
Control points
Rotation
Libration

ABSTRACT

A new global control point network was derived for Phobos, based on SRC (Mars Express), Phobos-2, and Viking Orbiter image data. We derive 3-D Cartesian coordinates for 813 control points as well as improved pointing data for 202 SRC and Viking images in the Phobos-fixed coordinate system. The point accuracies vary from 4.5 m on the Phobos nearside, to up to 67.0 m on the farside, where we rely on Viking images (average point accuracy: 13.7 m). From tracking of the control points we detect a librational motion synchronous to the Phobos orbital period and measure libration amplitude of 1.09°, in agreement with predictions from shape information assuming a uniform interior. This suggests that the interior of Phobos is homogeneous – but small local mass anomalies, e.g., associated with crater Stickney, cannot be ruled out. Our new control point network has a higher number of data points and higher point accuracy than previous data products and will be an important basis for accurate shape models and maps.

1. Introduction

A planetary control point network is represented by a catalog of prominent surface points, for which body-fixed coordinates, i.e., latitudes, longitudes, and radii, are precisely known. Hence, control point networks are useful first-order realizations of a body-fixed coordinate system. For small planetary bodies like Phobos, the prominent points (in terrestrial geodesy called "landmarks" or "control points") are typically centers of small craters.

The coordinates of the surface points are determined from the measurements of their line/sample coordinates in large numbers of overlapping images ("image blocks") by iterative inversion techniques, which, in photogrammetry, are called "bundle block adjustments". An important byproduct of the bundle block adjustments is the corrected spacecraft position and pointing data for all images that are involved. Hence, the establishment of control point networks is essential for the production of image maps, accurately positioned in the body-fixed reference frame. Such accurate maps, in turn, are essential for spacecraft navigation, precision landing, or operation of onboard instruments, e.g., if a camera is to be pointed at a specific target of interest.

The utility of control networks is not limited to the production of image maps, however. Dense clouds of 3-D control point networks are an essential framework for shape models. From tracking of the apparent motion of control points over time, unknown rotational parameters of the planetary body (e.g., rotational axis orientation or librational motion) may be determined. Control points can also be used as reference markers for positional measurements of the target body against a star background (e.g., Pasewaldt et al., 2012).

2. Previous Phobos control point networks

Phobos control point networks have been established from the beginning of spacecraft exploration (see summary, Duxbury et al., this issue). The first control point network was based on the images from the Mariner 9 spacecraft and included 38 surface points (Duxbury, 1974). Later, Duxbury and Callahan (1989) established a new control point network based on Viking Orbiter images, consisting of 98 points. Finally, Duxbury (1991) extended the network to include a total of 315 points. Duxbury also reported on shape and libration parameters (see further details in the text).

More recently, a large control point network was derived using Mars Express SRC images (Willner et al., 2008). The network included a total of 665 points using 3898 measurements in 69 images, with mean point accuracies of 40 m. The network was the

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http://dx.doi.org/10.1016/j.pss.2014.03.006
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Please cite this article as: Oberst, J., et al., The Phobos geodetic control point network and rotation model. Planetary and Space Science (2014), http://dx.doi.org/10.1016/j.pss.2014.03.006

basis for new Phobos maps (Wählisch et al., 2010), as well as for new shape and rotation models (Willner et al., 2010).

In this paper, we present a new control point network for Phobos involving a larger image data set, larger numbers of points, and consequently, more accurately determined coordinates. We also present a new technique for the tracking of rotational motion as well as new measurements of Phobos librations. Our data set includes new image data obtained by Mars Express after 2008, not previously used for control point analysis.

3. Phobos rotation model

Phobos is in synchronous spin-orbit resonance around Mars, with identical rotational and orbital periods of 7.65 h. The analysis in our paper is based on the current Phobos rotation parameters (Table 1) recommended by the IAU (International Astronomical Union), (Seidelmann et al., 2002; Archinal et al., 2011), which include a drift of the rotational axis (~0.1°/century), a precession with a period of 826 days (amplitude of ~1–2°), as well as tidal accelerations in the rotational rate (~1°/35 years, or 0.0008864 deg/years^2). The parameters are adopted from secular theory rather than from rigorous measurements. We adopt these parameters in this paper, which define our Phobos-fixed reference frame.

Mars exerts a torque upon Phobos due to Phobos' ellipsoidal shape, slight orbit eccentricity, and slight inclination to the Mars equator. In response to this torque, librational motion, i.e., oscillations in the mean rotational motion in longitude and latitude are expected, coupled to the anomalistic (pericenter-to-pericenter) and Draconic (node-to-node) months, respectively (Gusev et al., 2008). Using updates in orbital ephemerides and the dynamical shape of Phobos, Rambaux et al. (2012) have recently revisited and updated the satellite's forced libration spectrum. Phobos is predicted to show librations in longitude at the period of its anomalistic month. With an amplitude around 1° (leading to a surface displacement around 200 m at the sub-Mars point), these dominate the libration spectrum of higher-degree harmonics by a factor of 100. Several measurement attempts of longitude librations have been reported (Duxbury and Callahan, 1989; Duxbury, 1991; Willner et al., 2010). Benefitting from the large new available data set, an attempt is made in this paper to refine the libration measurements.

The magnitudes of the short period physical librations are of interest to observers as they are related to the satellite's unknown interior structure. The measurements of librations will bring possible constraints on presence of mass anomalies, e.g., as predicted by certain geophysical models of Stickney formation (as discussed in Rambaux et al. 2012). Neglecting higher-order terms, the moment of inertia coefficients of Phobos and the amplitude of the longitudinal libration θ_A are tied by (Duxbury and Callahan, 1989; Duxbury, 1991)

$$\theta_A = \frac{2e}{1-(1/3\gamma)} \quad \gamma = \frac{B-A}{C} \tag{1}$$

where e is the orbital eccentricity of Phobos and $A<B<C$ are the moments of inertia along the principal coordinate axes. As data on internal density distribution are not available, A, B, and C, can be computed from shape assuming constant density. Comparisons of predicted with observed librations may then hint at the presence of density anomalies.

Table 1
Phobos rotation parameters (Archinal et al., 2011).

$$\alpha0 = \underbrace{317.68}_{\text{Pole Pos.}} \; \underbrace{-0.108T \quad +1.79\,\sin M1}_{\text{Precessions}},$$

$$\delta0 = \underbrace{52.90}_{\text{Pole Pos.}} \; \underbrace{-0.061T \quad -1.08\,\cos M1}_{\text{Precessions}},$$

$$W = \underbrace{35.06}_{\text{Prime Mer.}} \; \underbrace{+1128.8445850d}_{\text{Avg. Rotation Rate}} \; \underbrace{+8.864T^2}_{\text{Tidal Acc.}} \; \underbrace{-1.42\,\sin M1}_{\text{Precession}} \; \underbrace{-0.78\,\sin M2}_{\text{Long. Libration}}$$

$M1 = 169^\circ.51 - 0^\circ.4357640d$.
$M2 = 192^\circ.93 + 1128^\circ.4096700d + 8^\circ.864T^2$.
T=interval in Julian centuries (of 36,525 days) from the standard epoch.
d=interval in days from the standard epoch.
The standard epoch is JD 2451545.0, i.e. 2000 January 1, 12 h TDB.

4. SRC camera and images

The Mars Express spacecraft is equipped with the High Resolution Stereo Camera (HRSC) (Jaumann et al., 2007), which includes the Super Resolution Channel (SRC). While formally part of the HRSC experiment, the SRC is a 1024 × 1024 framing camera (effective pixel number: 1008 × 1018) with separate optics (Oberst et al., 2008), which makes the camera suitable for geodetic work. The SRC produces somewhat blurred images as the optics were replaced, but not sharply focused, at the launch site. Deconvolution with a stable 17 × 17 pixel^2 point spread function, determined from the visual pixel patterns of stars, can significantly restore image clarity.

Duxbury (2012) recently analyzed SRC star images obtained from 2004 to 2011 for a new geometric calibration of the instrument. In 389 images (containing from 1 to 13 stars) 881 stars brighter than 10th magnitude were used to estimate camera alignment and geometric parameters. The SRC mounting alignment on the MEX spacecraft was found within 0.1° of the design values and the camera pointing was within 0.01° of the commanded pointing, most of the time. The focal length was determined at f=984.5 mm, in good agreement with earlier in-flight analysis (f=983.57 ± 0.7 mm, Oberst et al., 2008). The SRC images are almost distortion free except at the very corners of the images where the distortion is at the one-pixel level. Consequently, we avoided point measurements in the extreme image corners.

Unlike other current Mars-orbiting spacecraft, Mars Express (MEX) moves in a highly elliptical orbit, which has the advantage of bringing it close to Phobos. At the time of writing (September 2012), the spacecraft has performed more than 175 Phobos flybys, during which the SRC has obtained 635 images of Phobos with resolutions ranging between 100 m/pixel and 0.9 m/pixel. During each individual 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. 176 SRC images were used in the analysis, which provided multiple coverages for approximately 91% of the surface of Phobos, from different viewing angles. The trajectory of the spacecraft, reconstructed from radio tracking data, is available from the Mars Express project.

The Viking Orbiters (VO) were launched in 1975. The two spacecraft performed about 10 Phobos's fly-bys (<200 km), and 385 images of high-resolution, 6–85 m/pixel, were obtained. Unfortunately, the Viking Orbiter images suffer from complex distortion that require sophisticated correction schemes. Also, the navigation of the VO images (i.e., knowledge of spacecraft position and camera pointing) is known to be limited (Zeitler, 1999). Nevertheless, 16 VO images were used to fill gaps (9%) in coverage within the area between 220° and 310° West, from −50° to +35° North.

We also included 10 images from the Phobos-2 mission, which provided observations from additional viewing angles of covered

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