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Phobos and Deimos cartography

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ABSTRACT

This paper presents an overview of developments in the cartography of the Martian moons Phobos and Deimos from the early satellite images to recent maps based on data from past and on-going Mars missions, especially *Viking* and *Mars Express*. We describe in detail the definition and use of special projections for these irregular-shaped bodies. New controlled Phobos mosaics and a topographic atlas in a scale of 1: 50,000 derived from images of the High Resolution Stereo Camera/Super Resolution Channel (HRSC/SRC) camera on *Mars Express* are presented.

1. Introduction

Developments in mapping of Phobos and Deimos correlate with the progress made in exploring Mars and its surroundings by remote sensing. Cartography began with sketch maps of differing quality, a modeled globe of Phobos, and airbrush maps. As computer technologies developed, it became possible to process satellite images into photomosaics. Increasing precision in orbital positioning and substantial progress in camera technology enabled the development and improvement of increasingly detailed control point networks and Digital Terrain Models (DTMs) (Oberst et al., 2013; Willner et al., 2013). These photogrammetric products permit accurate orthorectification of individual images and provide the basis for a global map. Two key parameters in mapping are the selection of the map projection and the resolution of the end product, since all photos ever taken of Phobos and Deimos are flyby images shot from a wide range of distances and angles of observation. Orthoimages and mosaics permit representing the irregular shape of the body in projections specifically developed for the purpose (see Section 2.0). Simple projections, like Simple Cylindrical, which use a sphere as a reference body, make it easier to import data into analysis programs for geological mapping and surveying.

This article presents an overview of developments in the cartography of Phobos and Deimos from the early spacecraft data to recent maps based on images from on-going missions. Section 2.0. consists of a historical overview beginning with the images of *Mariner 9* and ending with the *Viking* era. Section 3.0. describes map products developed from data generated by the Super Resolution Channel (SRC) (sections 3.1, 3.2) and the High Resolution Stereo Camera (HRSC) (sections 3.3, 3.4) on board *Mars Express*. Section 4.0. presents a combination of the best images of Phobos and Deimos in a global map of each moon. Section 5.0 presents a summary and outlook.

2. Phobos and Deimos cartography from *mariner 9* and *viking*

Phobos and Deimos were the first small irregularly shaped bodies in the solar system to be observed in detail, and since then they have been important test cases for the development of new mapping techniques for non-spherical worlds. Their surface features (craters and a ridge on Phobos) were first observed by *Mariner 9* in 1971 (Pollack et al., 1972). Image coverage was incomplete, especially for Deimos, but sufficient to measure their sizes and shapes and to map their surfaces. The first map of Phobos (a line drawing map) was compiled by Duxbury (1974).

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Duxbury had defined control points (small craters), locating them in three dimensions using multiple images. He then fitted a tri-axial ellipsoid to the points to define a coordinate system for Phobos and drew a map of visible features. The first Deimos map (also a line drawing map) was derived by Noland and Veverka (1977). Photomosaics using *Mariner 9* images were produced by Stooke (Fig. 1). The center of the images is at 0° latitude and 0° longitude. The 0° meridian is defined by the sub-Mars direction according to the rules of the International Astronomical Union (IAU) (Archinal et al., 2011).

These first maps were plotted on conventional (sphere-derived) map projections which did not take into account the irregular shapes of the moons. Duxbury used Mercator projections for the equatorial and mid-latitude sections and separate polar Stereographic projections for each pole, following the style adopted by NASA for global mapping of the Moon and Mars (Batson, 1990). Because of the irregular shapes of the satellites, it became clear that new mapping methods would be needed. The first steps were taken by the scientific illustrator and modeler Ralph Turner who constructed a globe of Phobos in a scale of 1: 60,000 using *Mariner 9* images and produced maps for the two polar hemispheres using azimuthal projections (Turner, 1978a, 1978b). However, as the equatorial cross-section of the satellite is elongated, Turner made the projection boundary (equator) elliptical to approximate the shape of Phobos, adjusting the graticule accordingly.

The *Viking Orbiters* obtained several hundreds of images of Phobos and Deimos (Snyder et al., 1977). Thomas (1979) made detailed line drawing maps of both satellites showing features revealed in the *Viking* data, reverting to Duxbury's use of conventional map projections based on a sphere, again Mercator and polar Stereographic. The mapped surface features on Phobos are craters, ejecta, blocks, and grooves, on Deimos craters and blocks (Thomas, 1979). Stooke (1982) then prepared a map of Phobos by combining the surface features mapped by Thomas with Turner's map projection, but in an equatorial aspect. When this approach was extended to Deimos, Stooke modified the elliptical outline further to illustrate the somewhat faceted shape of the satellite and its deep South polar depression. This spurred further development of map projections which could be modified to suit arbitrary irregular shapes, with the intention that the map should portray the shape of the body as well as the locations of surface features. An intermediate step resulted in shaded relief maps of both satellites drawn on conceptual projections derived from preliminary shape models, a project which won the National Geographic Society Award in Cartography in 1984 (Stooke, 1989) (Fig. 2).

A full mathematical treatment of the 1984 projections was the next step. Stooke (1986) modified conventional azimuthal projections by allowing the radius factor in the projection equations (normally a constant) to vary from point to point across the map, reading the local radius from a shape model at each location. This method could be applied to different versions of a shape model including a tri-axial ellipsoid approximation, the actual topography from a digital shape model, or the convex hull of the shape. The latter was generally found to be preferable for minimizing distortions (Stooke, 1998). Because the projection is designed to illustrate shapes it is termed Morphographic. Shapes were derived by manipulating radii in a matrix, beginning with an initial ellipsoidal model, until the shape model duplicated the appearance of limbs and terminators in all available images. Later on for ease of use in a Geographic Information System, a method of transformation from Morphographic to modified Bugaevsky projection (see below this section) was developed (Bugaevsky et al., 2004).

Meanwhile other approaches to the map projection problem were sought. Snyder (1985) invented a precise conformal cylindrical projection for an ellipsoid approximating the shape of Phobos, though it would not be precise when applied to the less regular shape of Phobos itself. Snyder did not use conventional planetocentric coordinates in his equations, making the projections harder to use with common datasets. Stooke (2003) attempted to overcome this problem with a simplified cylindrical projection called Prismographic, which was easy to construct but not precisely conformal.

Accurate shape, area and distance measurements were not possible using any of these methods when applied to topographic real shape models, because the projections were based on idealized shapes such as triaxial ellipsoids, but better approaches have since been developed to give good results with topographic shape models. Cheng and Lorre (2000), Nyrtsov (2000), Nyrtsov and Stooke (2002) and Berthoud (2005) all created complex analytical solutions for detailed shape models to achieve more accurate representations than Stooke obtained. Although accuracy is improved, these methods all produce maps with irregular outlines and graticules which may deter some potential users. Clark et al. (2008) also devised maps with irregular outlines but with topological characteristics designed to reveal relationships between regions. The shape is divided along ridge lines or other geologically significant boundaries and unfolded to form a flat map, or can be printed flat and folded to form a 'globe' representing the body.

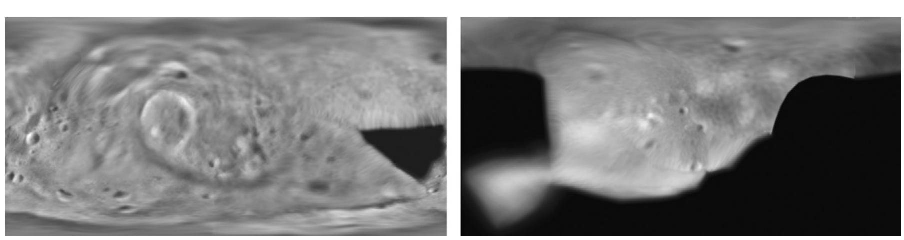

Fig. 1. Mosaics of Phobos and Deimos derived from *Mariner 9* data, left and right, respectively.

Fig. 2. Photomosaics of Phobos' and Deimos' leading and trailing hemispheres (left and right) derived from *Viking* data by Stooke (1989). The two left images show Phobos and the two right Deimos, respectively.

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