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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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DEPARTMENT OF EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

1 - Grant Title: Mars Orbiter Laser Altimeter

2 - Type of Report: Summary of Research

3 - Principal Investigator: Maria T. Zuber

4 - Period of Performance: 11/1/95 - 9/30/97

5 - Recipient's Institution: Massachusetts Institute of Technology
Department of Earth, Atmospheric and Planetary Sciences
Building 54, Room 918
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Cambridge, MA 02139

6 - Grant Number: NAG5-2222

Summary of Research

Grant Title: Mars Observer Laser Altimeter (NAG5-2222)
Principal Investigator: Maria T. Zuber

Introduction

The objective of this study was to support the rebuild and implementation of the Mars Orbiter Laser Altimeter (MOLA) investigation and to perform scientific analysis of current Mars data relevant to the investigation. The instrument is part of the payload of the NASA Mars Global Surveyor (MGS) mission. The instrument is a rebuild of the Mars Observer Laser Altimeter that was originally flown on the ill-fated Mars Observer mission. The instrument is currently in orbit around Mars and has so far returned remarkable data.

Work Completed

The following tasks were accomplished as part of the investigation:

- Participated in initial planning of the Mars Global Surveyor mission after the loss of Mars Observer, including instrument re-design and rebuild.

- Attended meetings and reviews in support of the MOLA investigation.

- Assisted in preparation of budgets, schedules and documentation.

- Participated in the development of a new gravitational field for Mars from re-analysis of Mariner 9 and Viking Orbiter Doppler tracking data.

- Performed re-analysis of Mariner 9 and Viking Orbiter occultations to develop an new shape of Mars.

- Participated in simultaneous estimation of the masses of Mars and its natural satellites Phobos and Deimos.

- Determined a formalism to remove the attraction of the Tharsis bulge from the Mars gravity field. Published results.

- Performed simulation of the mass variation of the polar caps over the Martian seasonal cycle. Submitted results for publication.

- Supported MGS orbit insertion activities and mission planning in spacecraft aerobraking and elliptical orbit.

- Programmed instrument to collect data in initial calibration pass and during aerobraking hiatus period.

- Analyzed data.

- Participated in preparation of initial report of data results, submitted to *Science,* January, 1998.

- Submitted 11 abstracts on results to Lunar and Planetary Science Conference.

- Prepared releases for 3 press conferences.

- Participated in numerous public outreach activities discussing investigation results.

Refereed Publications

Smith, D.E., F.J. Lerch, R.S. Nerem, M.T. Zuber, G.B. Patel, S.K. Fricke, and F.G. Lemoine, An improved gravity model for Mars: Goddard Mars Model-1 (GMM-1), *J. Geophys. Res., 98,* 20,871-20,899,1993.

Smith, D.E., and M.T. Zuber, New gravity field for Mars fuels new research, *EOS Trans. Am. Geophys. Un., 75,* 97, 1994.

Smith, D.E., F.G. Lemoine, and M.T. Zuber, Simultaneous estimation of the masses of Mars, Phobos, and Deimos from spacecraft distant encounters, *Geophys. Res. Lett., 22,* 2171-2174,1995.

Smith, D.E., and M.T. Zuber, The shape of Mars and the topographic signature of the hemispheric dichotomy, *Science, 271,* 184-188, 1996.

Zuber, M.T., and D.E. Smith, Mars without Tharsis, *J. Geophys. Res., 102,* 28,673-28,685,1997.

Smith, D.E., M.T. Zuber, R.M. Haberle, D.D. Rowlands, and J.R. Murphy, The Mars seasonal CO_2 cycle and the time variation of the gravity field: A General Circulation Model simulation, submitted to *J. Geophys. Res.,* 1997.

Smith, D.E., M.T. Zuber, H.V. Frey, J.B. Garvin, J.W. Head, G.H. Pettengill, R.J. Phillips, S.C. Solomon, H.J. Zwally, W.B. Banerdt, T.C. Duxbury, Topography of the northern hemisphere of Mars from the Mars Orbiter Laser Altimeter, submitted to *Science,* 1998.

Budget Summary

To be provided by MIT Office of Sponsored Programs.

Topography of the Northern Hemisphere of Mars from the Mars Orbiter Laser Altimeter

D.E. Smith,[1*] M.T. Zuber, H.V. Frey, J.B. Garvin, J.W. Head, D.O. Muhleman, G.H. Pettengill, R.J. Phillips, S.C. Solomon, H.J. Zwally, W.B. Banerdt ,T.C. Duxbury

Submitted to: *Science*
January 15, 1998

The first 18 tracks of laser altimeter data across the northern hemisphere of Mars show latitudes above 50° to be unusually flat, with regional slopes and surface roughness increasing toward the equator. The polar layered terrain shows evidence of being a thick ice-rich formation with a non-equilibrium planform indicating ablation near the periphery. Many impact craters show quantitative evidence for ejection of fluidized surface material. Slope relationships indicate a significant uplift contribution to regional topography in the northern Tharsis province. A profile across the Ares Vallis channel indicates a much greater discharge than previously estimated. Comparison with Viking albedos shows significant 1-µm atmospheric opacities, particularly in low-lying areas such as Valles Marineris.

Characterization and modeling of the processes that govern planetary evolution require accurate knowledge of surface topography over a broad range of spatial scales. On September 15, 1997 the Mars Orbiter Laser Altimeter (MOLA) *(1)*, an instrument on the Mars Global Surveyor (MGS) spacecraft *(2)*, acquired its first pass across the surface of Mars. The altimeter obtained measurements of topography *(3)*, surface reflectivity *(4)*, and backscattered laser pulse width *(5)*. This profile was followed by a further 17 tracks

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The Mars seasonal CO_2 cycle and the time variation of the gravity field: A General Circulation Model simulation

David E. Smith[1], Maria T. Zuber[2,1], Robert M. Haberle[3], David D. Rowlands[1], James R. Murphy[3]

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December 16, 1997

Abstract. We investigate the time variation of the long wavelength gravitational field of Mars due to mass re-distribution associated with the annual cycle of CO_2 exchange between the atmosphere and polar caps. Our analysis utilizes simulated monthly estimates of atmospheric pressure and CO_2 polar frost as calculated by the NASA/Ames General Circulation Model (GCM) for a "typical" year. We show that the deposition and sublimation of CO_2 polar frost is expected to be the dominant effect on the gravity field at all low degrees. Variations in the amplitude and phase of time variations of gravity are sensitive to multiple factors, including polar elevation and the eccentricity of the Martian orbit. Phase effects associated with additive and competing influences at the summer and winter poles dictate that odd numbered harmonic coefficients produce an annual signal in the gravity field while even-numbered coefficients show a semi-annual signal. The predicted changes in the planetary flattening and pear-shaped terms of the field are at or above the noise level of expected X-band Doppler tracking observations from Mars Global Surveyor, and so could conceivably be detected from an orbital spacecraft.

Introduction

Carbon dioxide is the primary ingredient of the atmosphere of Mars, constituting about 95% at the surface [*Owen et al.*, 1977], though the amount is seasonally variable. The atmosphere exhibits an annual cycle in the CO_2 concentration which represents primarily an exchange between the atmosphere and the seasonal polar caps. The polar caps consist mainly of CO_2 frost in which the solid/vapor equilibrium represents a balance, at the poles, of absorbed solar energy and the re-radiation of that energy [*Leighton and Murray*, 1966]. As much as 25%-30% of the atmospheric CO_2 is transported from one pole to the other during the annual cycle [*Hess et al.*, 1980; *James et al.*, 1992], and this large-scale movement results in changes in the distribution of atmospheric mass, and hence, planetary mass. As illustrated schematically in Figure 1, carbon dioxide, and to a much lesser extent water [*Haberle and Jakosky*, 1990], sublime at the summer pole and move toward the equator via the zonal mean circulation [*Leovy*, 1979; 1985], decreasing the mass at that pole while increasing

The Shape of Mars and the Topographic Signature of the Hemispheric Dichotomy

David E. Smith and Maria T. Zuber

Reanalysis of occultation data from the Mariner 9 and Viking Orbiter spacecraft to determine the shape of Mars indicated that the hemispheric dichotomy is not a fundamental feature of the shape of the planet. It is a consequence of an approximately 3-kilometer offset between Mars's center of mass and center of figure, and the boundary, along most of its length, consists of broad, gradual surface slopes over distances of thousands of kilometers. This result was supported by analysis of high spatial resolution Earth-based radar topographic profiles. Any successful model for the origin of the dichotomy must explain a planet with an ellipsoidal shape and a long wavelength gradual topographic transition between the northern and southern hemispheres.

The surface of Mars is distinctly different in the northern and southern hemispheres. The south is old and heavily cratered, whereas the north is younger and lightly cratered and was probably volcanically resurfaced early in Mars's history (*1*, *2*). This hemispheric dichotomy is characterized by a geologic boundary between the hemispheres that is expressed as knobby and fretted terrains and detached plateaus (*2*–*4*) distributed over a relatively limited width of ~700 km (*5*). Along the boundary, elevations have been interpreted to decrease from south to north by ~1 to 3 km (*1*, *6*, *7*), and the change in topography has been correlated with geologic features (*8*).

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The formation of the dichotomy has been attributed to internal processes, such as postaccretional core formation (*9*), and to crustal delamination (in the northern hemisphere) and underplating (in the southern hemisphere) by vigorous mantle convection (*10*). It has also been proposed that the low northern hemisphere was the result of a massive impact (*5*, *11*) or impacts (*12*), and this region may have been the site of an early martian ocean (*13*). The lack of gravity anomalies along the boundary (*14*) may indicate thick crust beneath the southern highlands and thinner crust beneath the northern lowlands (*1*, *15*). In addition, the boundary region has been proposed as the site of relic plate boundaries (*16*). Consequently, understanding the origin of the hemispheric difference has implications for the evolution and internal structure of Mars.

Most analyses of the origin of the dichotomy have been based on global topographic models (*8*) with poor long-wavelength accuracy (*17*). The topography has also been studied by means of higher spatial resolution measurements derived from photoclinometry, stereo imaging, and ultraviolet spectra (*7*, *18*). Although these methods yield information on relative heights within an individual image frame or mosaic, the heights cannot be placed in a global reference frame and are of limited utility in relating local structure to global structure.

Radio occultation measurements (*19*–*22*) provide estimates of the radius of the planet at the time (and location) when the radio signal from a spacecraft is lost (occulted) behind the planet or emerges from behind the planet in its orbit (*23*). Occultation data formed the basis of several early determinations of Mars's topography (*21*, *22*, *24*) and were included in more recent U.S. Geological Survey (USGS) digital elevation models (DEMs) (*8*), but the data have not been analyzed since the 1970s. Here, we reanalyzed these data by using improved spacecraft orbital information (*25*), the latest planetary ephemerides and dynamical information (*26*), and revised atmospheric refraction correc-

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Mars without Tharsis

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Abstract. The significant power in the Martian gravitational field due to the Tharsis rise may mask or modify gravitational signatures that contain important information on Martian geophysical processes. In order to isolate gravity signals in regions where the field is significantly affected by Tharsis as well to investigate characteristics of the global field, we present a numerical technique to "remove" Tharsis from the Martian gravitational field. Our analysis will show that to first order Tharsis can be represented as a sixth-degree spherical harmonic zonal gravitational feature in a reference frame in which the axis of symmetry runs through the center of the province. We produced the "Mars without Tharsis" (MWT) field by subtracting the gravitational signature of Tharsis from the full field and rotating the spherical harmonics back to the original coordinate system, in which the z-axis is coincident with the planetary rotation axis. Our study yields limits on the moment of inertia factor of $0.361<C/MR^2<0.366$ for the range of allowable non-hydrostatic contributions to the flattening. The analysis indicates that the formation of Tharsis may have resulted in re-orientation of the spin axis, though if the planet retained rotational fossil bulge due to a thick elastic lithosphere then changes in the global figure could have been inhibited. The zonal and tesseral components of the degree 2 field in the GMM-1 and rotated configurations indicates that Tharsis is ~5 times more axisymmetric about its "pole" than Mars as a whole is about the rotation axis. With the removal of Tharsis' long wavelength gravitational power, regional structures become better defined in a spatial sense while maintaining their local dynamic range. The Olympus Mons volcanic shield displays clear evidence of a gravitational flexural moat. Our method for removing Tharsis may also be applied to analyze other global-scale geophysical features that may be considered axisymmetric to first order, such as mantle plumes, major volcanic constructs, or large impact basins.

1. Introduction

The Martian gravitational field contains significantly more power at long wavelengths than does Earth's [*Phillips and Lambeck*, 1980; *Balmino et al.*, 1982]. The difference reflects the fact that topographic excursions on Mars are greater than on Earth, because Mars is a smaller planet with a smaller mass. Topographic variations are characterized by large gravity and geoid anomalies, of which the most prominent planet-scale feature is the Tharsis bulge. Tharsis, which is conspicuous in the global Martian geoid in Figure 1, is the dominant locus of volcanism and tectonism on Mars and rises up to 10 km above its surroundings [*Carr*, 1981]. The widespread and diverse distribution of tectonic features and the high topography represent evidence that Mars has undergone complex thermal and stress histories which have been influenced on both the global and regional spatial scale by Tharsis [*Banerdt et al.*, 1992]. The large amplitude, long wavelength gravity and geoid anomalies associated with the Tharsis rise must certainly influence both long and short wavelength gravitational signatures that are relevant to a range of geophysical processes. In order to isolate gravity signals in regions where the field is especially affected by Tharsis, as well as to investigate aspects of the global field that have been influenced by Tharsis, we have developed a numerical technique to "remove" Tharsis from the Martian gravity field. Our method exploits the ability to quantify an axisymmetric signal in an arbitrary coordinate system in a spherical harmonic gravity model.

Other workers have also recognized the utility of isolating the gravitational influence of Tharsis, and our approach has both similarities and some important differences compared to previous work. *Reasenberg* [1977], *Kaula* [1979] and *Kaula et al.* [1989] accounted for the contribution of Tharsis to the second degree (flattening term) of the gravity field by assuming that the non-hydrostatic contribution to the moment of inertia is axisymmetrically distributed along an axis in the direction of the province. In a study concerned with re-orientation of the planetary rotation axis, *Melosh* [1980] removed the attraction of Tharsis by deleting point masses from a then-current gravity model [*Sjogren et al.*, 1975]. In order to estimate the contribution of Tharsis to the Martian flattening, *Willemann and Turcotte* [1982] employed an approach that is conceptually similar to that invoked here: they moved the center of Tharsis to Mars' rotation pole using the spherical harmonic addition theorem [*Kaula*, 1968].

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