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Mercury's rotational parameters from MESSENGER image and laser altimeter data: A feasibility study

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ABSTRACT

A novel method has been developed to determine the rotational parameters of Mercury from data acquired by the MESSENGER spacecraft. We exploit the complementarity of laser altimeter tracks taken at different rotational phases and rigid stereo terrain models to determine a Mercury rotational model. In particular, we solve for the orientation of the spin axis, the rotation rate, and the amplitude of the forced libration. In this paper, we verify the proposed method and carry out an extensive simulation of MESSENGER data acquisition with assumed rotational parameters. To assess the uncertainty in the rotational parameters we use mission-typical assumptions for spacecraft attitude and position knowledge as well as for small-scale terrain morphology. We find that the orientation of the spin axis and the libration amplitude can be recovered with an accuracy of a few arc seconds from three years of MESSENGER orbital observations. The rotation rate can be determined to within 5 arc seconds per year. The method developed here serves as a framework for the ongoing analysis of data from the MESSENGER spacecraft. The rotational parameters of Mercury hold important constraints on the internal structure and evolution of the planet.

1. Introduction

Mercury, located deep in the gravity well of the Sun, displays distinctive dynamics. The rotation and orbital motion of the planet are tidally coupled, and Mercury rotates precisely three times for every two revolutions about the Sun. In addition to its mean rotation, the planet displays small forced librations in longitude, i.e., oscillations about the average rotation rate. Measurements of rotational parameters are of considerable interest, as the amplitude of the forced libration and the planet's obliquity provide (when combined with gravity field parameters) important constraints on the planet's interior structure (Peale, 1976, 1988; Margot et al., 2012; Smith et al., 2012; Hauck et al., 2013). This situation thus offers an opportunity to derive information about a planet's interior, particularly the size and state of the planetary core, not easily accessible for other planets of the Solar System family.

Measurements of Mercury's librations and obliquity with Earth-based radar revealed a large libration amplitude (approximately 450 m at the equator), suggesting that Mercury's core is at least partially molten (Margot et al., 2007, 2012). With this method, instantaneous spin rate values are obtained from radar time-lag measurements, which have provided the most accurate measurements of the spin rate variations to date. However, the precision remains somewhat limited and prevents the detection of small variations, such as those expected from long-period librations (Peale et al., 2007; Yseboodt et al., 2010).

Several other techniques have been proposed to measure the rotational parameters of Mercury. An obvious approach is to use images from different rotation phases and apply image correlation

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techniques to constrain the unknown rotation parameters (Wu et al., 1997; Jehn et al., 2004; Pfyffer et al., 2011). However, precise camera attitude and spacecraft position information must be available for this approach to be feasible. Alternative methods make use of laser altimetric cross-over points (Rosat et al., 2008) or employ a separation of the dynamic and static topography by spherical harmonic expansion of the latter (Koch et al., 2008, 2010). Observations of Mercury's gravitational field can also be used to determine the rotational parameters (Cicalò and Milani, 2012; Mazarico et al., 2014). This technique requires precise radio tracking and modeling of non-conservative forces acting on the spacecraft. However, as the dynamics of the gravity field can be influenced by differential rotation of the core, the combination of shape and core rotation could provide more information about the interior structure than either quantity alone.

Here we investigate the quality of measurements obtained by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft. Precise measurements of a planet's rotation rate from an orbiting platform are far from straightforward, as, for example, a fixed reference against which the rotation can be observed is not readily available. Knowledge of a spacecraft's orbit and instrument pointing data suffer from errors that make the accurate measurement of small libration effects challenging. The application of these methods to MESSENGER data is complicated by the spacecraft's highly eccentric orbit and observational constraints for the instruments set by that orbit as well as by limitations on spacecraft attitude relative to the planet–Sun line. Our new approach combines the benefits of both laser altimetry and stereo imaging to overcome their individual drawbacks. In particular, we discuss the combination of time-dependent, high-accuracy range measurements by the laser altimeter with the static terrain data obtained from stereo images.

In order to assess the potential as well as the limitations of our approach we carry out an extensive simulation of MESSENGER data. We adopt a given topographic model, derived from MESSENGER stereo images, and we perform a simulation of laser altimeter observations given an assumed rotational model for Mercury (see Fig. 1). Then, an attempt is made to recover the rotational parameters by analysis of the simulated data. This simulation serves as a basis for future analysis of actual data acquired by MESSENGER's instruments and the estimation of the rotational parameters of Mercury from those data.

The paper is structured as follows. First we describe the available data from MESSENGER, concentrating specifically on laser altimeter profiles and topographic models generated from stereo images. In the subsequent section we report on forward modeling to generate synthetic laser altimeter profiles. Finally, we describe our method for the measurement of rotational parameters and the results obtained with the simulation.

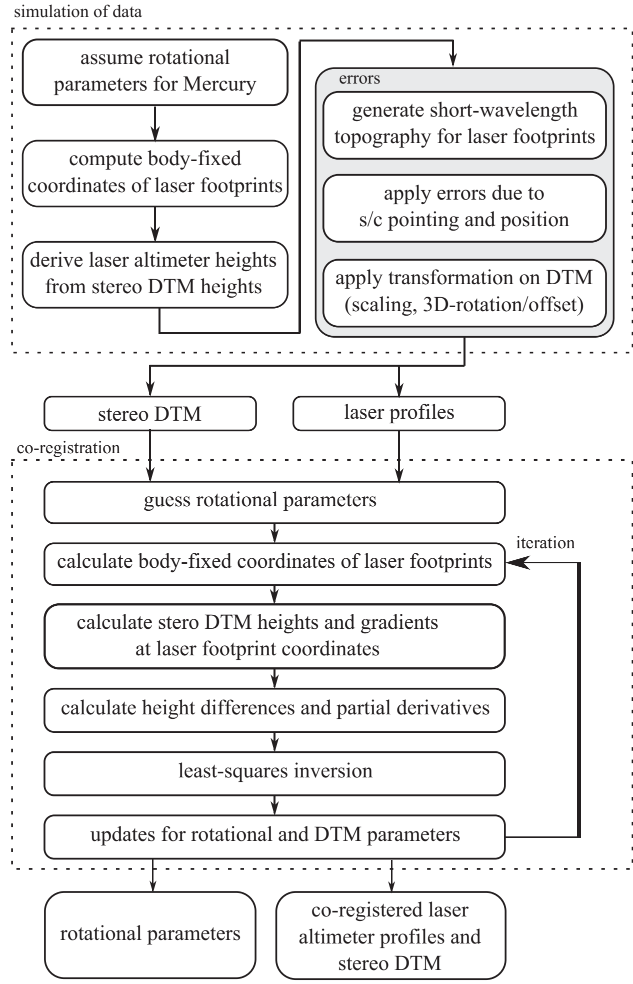

Fig. 1. Scheme of the simulation of observational data and determination of rotational parameters (s/c denotes spacecraft, and 3D denotes three-dimensional).

2. MESSENGER data

MESSENGER was inserted into orbit about Mercury in March 2011. Its initial orbit was highly eccentric and near-polar, with a 12 h period. In April 2012, the orbit period was shortened in two propulsive maneuvers to 8 h. For our study, we use data from the Mercury Laser Altimeter (MLA) (Cavanaugh et al., 2007) and the Mercury Dual Imaging System (MDIS) (Hawkins et al., 2007). We next describe the data obtained by these instruments.

2.1. Laser altimeter

MLA carries out its measurements along approximately great-circle profiles, as the spacecraft moves along its orbit track. With a pulse energy of 20 mJ, the instrument can range from altitudes as great as 1500 km in the nadir orientation and to distances as great as 1000 km at an off-nadir angle of 40° (Zuber et al., 2008, 2012). The along-track resolution of the measurements is determined by the size and spacing of the laser footprints on the surface. The distance between footprints at the 8 Hz pulse repetition rate varies with the velocity of the spacecraft between 170 m and 440 m. Depending on the ranging distance, the laser footprint diameters vary from 16 m to 134 m. As of August 2013, after an observation time of 850 days, MLA had acquired 1768 laser profiles that span the latitude range from 90°N to 20°S.

In our simulation, we used laser profiles over a small area of Mercury's surface, for which a digital terrain model (DTM) derived from stereo images is available. The area extends in latitude from 25 to 65°N and in longitude from 190 to 270°E. Clearly, the final accuracy of the rotational parameters will depend on the size of the DTM area considered and the number of laser altimeter observations within that area.

2.2. Stereo photogrammetry

We define the topography represented by the stereo DTM as the length of the local planetary radius from the center of mass of Mercury to the surface, relative to the radius of a reference sphere, here taken as 2440 km.

The production of a DTM from stereo images follows established procedures (Gwinner et al., 2010; Preusker et al., 2011). With the benefit of image correlation and least-squares block adjustment techniques, we concatenated large numbers of images,