EPSC Abstracts
Vol. 5, EPSC2010-519, 2010
European Planetary Science Congress 2010

Mercury's gravity field and orbit determination from the radio science experiment of the mission BepiColombo

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Abstract

The Mercury Orbiter Radio Science Experiment (MORE) of the ESA mission BepiColombo will provide an accurate estimation of Mercury's gravity field by means of highly stable, multi-frequency radio links in X and Ka band. Thanks to a plasma noise cancellation system, two-way range rate accuracies of about 3 micron/s are expected at nearly all solar elongation angles. This paper reports on numerical simulations of the MORE experiment, providing an estimate of the attainable accuracies in the determination of the spacecraft orbit and the harmonic coefficients of the gravity field.

1. Introduction

BepiColombo is an interdisciplinary mission for the exploration of the planet Mercury, jointly undertaken by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). After launch in 2014 and a six years interplanetary cruise to Mercury, using solar-electric propulsion and exploiting gravity assists from Moon, Earth and Venus, two spacecraft will be inserted in orbit around Mercury. After arrival at Mercury (August 2020), the spacecraft will start the 1-year nominal mission, carrying out a variety of scientific investigations. The Mercury Planetary Orbiter (MPO), under the responsibility of ESA, is devoted to remote sensing observations of the planet, whereas the Mercury Magnetospheric Orbiter (MMO), provided by JAXA, will investigate Mercury's magnetosphere [1].

One of the main scientific goals of the MPO, addressed by MORE experiment (Mercury Orbiter Radio Science Experiment), is the recovery of Mercury's gravity field and rotational state by means of an extremely accurate orbit determination and landmark tracking. The estimation of Mercury's gravity field (in particular the quadrupole harmonic coefficients), together with the determination of the obliquity and physical librations in longitude, provides crucial constraints on the interior structure of the planet. In addition, by determining the motion of Mercury in the solar system, the mission will also carry out improved tests of general relativity, such as the precession of Mercury's perihelion.

The MPO will be equipped with dedicated on-board instrumentation in support of radio science experiments. A two-way, multi-frequency radio link in X/X (7.2 GHz uplink/8.4 GHz downlink), X/Ka (7.2/32.5 GHz) and Ka/Ka band (34/32.5 GHz) will provide range rate accuracies of 3 micron/s (at 1000 s integration time), independent from solar elongation angle. Range observables accurate to 20 cm (two-way) will be achieved by means of a novel, wideband (24 Mcps) ranging system, based upon a pseudo-noise modulation scheme. These measurement accuracies are possible thanks to the implementation of a plasma noise cancellation system, already used for the Cassini mission [2,3]. Radio tracking from suitably equipped ground stations will therefore provide high quality Doppler and range observables for precise orbit determination and estimation of the gravity field. Dynamical noise from non-gravitational accelerations (mainly solar radiation pressure, planetary albedo and infrared emission) will be removed to a large extent by means of an on-board accelerometer.

A full numerical simulation of the Radio Science Experiment was carried out in the early phases of the BepiColombo project in order to test if the attainable accuracies in the gravity field estimation were compatible with the scientific goals of the mission [4]. We report on a new set of numerical simulations, which take into account the development in the spacecraft design, the mission profile and the tracking system.

2. Numerical simulations

The estimation of the harmonic coefficients of Mercury's gravity field has been carried out by means of a multi-arc approach. The multi-arc analysis takes advantage of its inherent over-parameterization to absorb unmodeled perturbations and numerical errors, which would otherwise accumulate with time and cause divergence or instability of the estimation. The orbital solutions achieved from individual tracking arcs (typically 8 hours long) are combined in a single global process, which ends up in the estimate of parameters that are common to all arcs. Each local estimation exploits the a priori information on the state vector, necessary to constrain the process and ensure convergence because of the ill-conditioning of the normal matrices.

An high sensitivity accelerometer (ISA, or Italian Spring Accelerometer) is hosted onboard the MPO, with the goal of measuring the non-gravitational accelerations acting on the spacecraft. As the ISA accelerometer will provide a direct measurement of the non-gravitational accelerations, no effort has been made to model solar radiation pressure and planetary thermal effects, as well as other perturbing accelerations.

Doppler data from a single ground station, spanning one Mercury year (88 Earth days), have been simulated, assuming a constant, white and Gaussian range rate noise of 30 micron/s at 10 s sampling time.

The current spacecraft design, driven by the need of reducing mass, entails momentum dumping maneuvers approximately every 12 hours. The unbalanced thrusters produce a large, nearly 6 cm/s, delta-V, therefore degrading the a priori knowledge of the spacecraft state and affecting the accuracy in the estimation of the gravity field. Although the knowledge of the delta-V associated to desaturation maneuvers is possible to a level of 2-5% (1.2-3 mm/s), the residual unmodelled delta-V is still sufficiently large to cause substantial errors in the state propagation. In general desaturation maneuvers will be controlled by onboard control software and they will take place in the absence of Doppler tracking from ground. An available mitigation relies on the use of the onboard accelerometer to measure the velocity change due to the maneuver, although this requirement would force an extension of the dynamic range of the instrument and therefore a design change. Numerical simulations have been carried out to assess the impact of wheels desaturation maneuvers in the estimation of the gravity field.

Besides a covariance analysis assumed as benchmark, in which simulated data are fitted using the same dynamical model, more realistic operational configurations have been considered, where the dynamical model and the estimation process have been perturbed in several ways. In a particularly relevant case, the estimation of the local and global parameters has been obtained in two different steps, first focusing on the uncertainty associated to the state vector and then improving the knowledge of the gravity field coefficients.

3. Summary and Conclusions

The MORE experiment focuses on the estimation of Mercury's gravity field and the MPO trajectory. The recovery of harmonic coefficients is necessary to constrain the internal structure of the planet and to compute Mercury's geoid. This geoid heights will provide the appropriate reference for the laser altimetric measurements. We discuss the prospects of determining the geoid consistently with the mission requirement of 2-3 cm over spatial scales of ≅ 300 km. We also provide values for the accuracy in the reconstruction of the spacecraft orbit (especially the radial component of the position vector), a crucial information for the correct referencing of the laser altimeter data. A precise orbital reconstruction (to at least 1 m in the radial direction) is required by the onboard laser altimeter to determine the Mercury's topography and solid tides.

The goal of our work is an assessment and a confirmation of the expected accuracy in the determination of Mercury's gravity field with the BepiColombo MORE experiment. We conclude that the orbital reconstruction meets the scientific goals of the gravity experiment, including the determination of tidal deformations of the planet at the 88 days orbital period.

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