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Mercury radio science experiment of the mission BepiColombo

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Abstract. Mercury has always excited a great interest in the scientific establishment because of its proximity to the Sun that represents, however, the principal obstacle for its observations from Earth and spacecraft exploration. BepiColombo is, therefore, one of the most challenging long-term planetary projects that foresees two spacecraft dedicated to the exploration of Mercury's environment. The mission allows better understanding of the planet itself as well as the formation of our Solar System. The density of Mercury does not conform to that of the other terrestrial planet and for this reason the evaluation of Mercury's interior structure is one of the fundamental objectives of the mission. The Mercury Orbiter Radio Science Experiment (MORE) is one of BepiColombo's investigations, designed to provide an accurate estimation of Mercury's gravity field and Love number k_2 by means of highly stable, multi-frequency radio links in X and Ka band. Gravity not only provides crucial information on the interior structure of the planet, but also, allows a good orbit determination of the spacecraft. After an introduction to the mission and the MORE experiment, we report on numerical simulations aiming at a realistic assessment of the attainable accuracy in the determination of Mercury's gravity field. The best results are obtained with a batch-sequential filter, which proves to cope well the complexity of the noise and dynamical models.

Key words. Orbit determination – radio science – gravity field – BepiColombo

1. Introduction

BepiColombo is a mission to the planet Mercury, jointly undertaken by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). It will consist in two separate orbiters: the Mercury Planetary Orbiter (MPO), under the responsibility of ESA, devoted to remote sensing observations of the planet, and the Mercury Magnetospheric Orbiter (MMO), provided by JAXA, for investigations of Mercury's magnetosphere. After launch in 2014, the spacecraft will exploit a solar-electric propulsion system and gravity assist from the Moon, Earth, Venus and Mercury itself to reach its destination. During the trip to Mercury, the two orbiters and the transfer module, consisting of electric and chemical propulsion units, will form one single composite spacecraft. After arrival at Mercury (August 2020), the spacecraft will start the 1-year nominal mission, carrying out a variety of scientific investigations (Schulz, & Benkhoff 2006).

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The MPO will be equipped with dedicated on-board instrumentation in support of radio science experiment. 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 (Bertotti et al. 1993; Tortora et al. 2004). 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 drastically reduced by means of an on-board accelerometer (ISA, Italian Spring Accelerometer).

1.1. Numerical simulations

This sophisticated on-board instrumentation will allow the Mercury Orbiter Radioscience Experiment (MORE) to accomplish the recovery of Mercury's gravity field. The accurate orbital reconstruction, together with tracking of optical landmarks on the surface provided by the onboard high resolution camera (HRIC), will allow also an accurate determination of the Mercury's rotational state. The knowledge of Mercury's gravity field (in particular the quadrupole harmonic coefficients), obliquity and physical librations in longitude provide 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 provide improved tests of general relativity, such as the precession of Mercury's perihelion. In the preliminary phase of the mission, a full numerical simulation of the radioscience experiment was carried out in order to test if the current spacecraft design was compatible with the original mission goals for gravity science (Milani et al. 2001). The current numerical simulations have taken into account a realistic scenario which includes all largest perturbations experienced by the spacecraft during the mission (unbalanced thrusters, accelerometer noise, etc).

The effects of non-gravitational accelerations on the spacecraft dynamics (quite large in the harsh hermean environment) will be removed to a large extent thanks to the ISA accelerometer. The instrument readouts will be sent to ground in the telemetry stream and referenced to the phase center of the high gain antenna. The orbit determination code will then use a smoothed version of the accelerometer measurements to integrate the equation of motion, effectively realizing a software version of a drag-free system.

Such a complex experimental setup, implemented for the first time in a planetary mission, will be used not only for the reconstruction of the Mercury's gravity field, but also for a precise reconstruction of the spacecraft orbit. Accuracies of 0.1-1 m in the radial position seem attainable. The position of the MPO in the hermean frame (whose origin is defined by zeroing the dipole terms in the harmonic expansion of the gravitational potential) will be used for the appropriate referencing of the laser altimetric measurements and the images from the high-resolution camera. The combination of altimetric and gravity measurements will provide the topographic heights, a crucial information to determine the structure of Mercury's crust and outer mantle.

The along- and across-track position of the spacecraft is crucial for the rotation experiment, aiming to determine the rotational state of the planet by means of optical tracking of surface landmark. The pole position and physical librations in longitude will be obtained from a precise georeferencing of high-resolution images (5m pixel size at pericenter). The final accuracy of this experiment rests not only upon an accurate knowledge of the spacecraft position, but also on the quality of the attitude reconstruction. The onboard star trackers and gyroscopes should allow an accuracy of 1-

2 arcsec. In addition, the spacecraft design ensures a high stability of the optical alignment between the star trackers and the camera.

Although MORE will make use of laser altimetric and optical images to stabilize the global orbital solution, the crucial observable quantities are range and range rate. These quantities are generated at the ground station after establishing a two-way coherent link. The core element of the tracking system is the reference oscillator, a H-maser with a frequency stability of one part in 10^{15} over time scales of 1000 s. The orbital solution is obtained from the observable quantities by means of a least squares fit, where the state vector of the spacecraft and the parameters of the dynamical model are jointly derived.

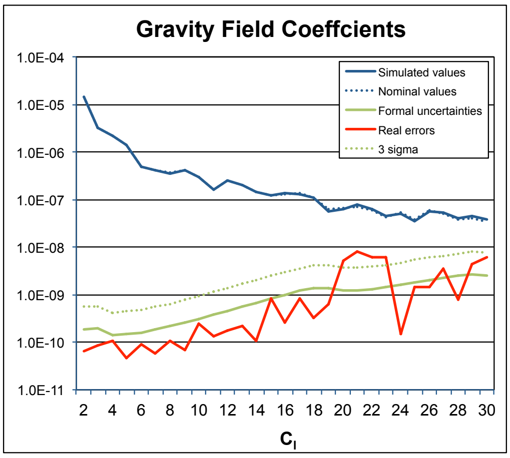

Fig. 1. Estimation of Mercury's gravity field up to degree 30

1.2. Results

A batch-sequential filter has been developed in the context of the numerical simulations of the Mercury Orbiter Radio Science Experiment (MORE) of the ESA mission BepiColombo. The filter was devised in order to cope with the uncertainties in the dynamical models (associated to wheel off-loading manoeuvres, accelerometer bias and drift, etc.). The accumulation of the errors due to unmodelled effects leads to a divergence in the trajectory reconstruction. Updating sequentially the dynamical models, the estimation of the state vector improves considerably in terms of errors and formal uncertainties. Therefore, a final multi-arc analysis provides an optimal reconstruction of the global parameters (i.e. gravity field coefficients and the Love number k_2).

The purpose of our numerical simulations was to test if the attainable accuracies in the gravity field estimation are compatible with the scientific goal of the mission. The simulation covers a full hermean year considering that the MPO orbit around Mercury is polar with pericenter and apocenter altitudes respectively at 400 km and 1500 km. . Support from ground has been limited to only one station, with Ka-band uplink and multi-link capabilities. A daily tracking period of approximately 8 hours has been assumed.

In the simulation setup the hermean gravity field is expanded in spherical harmonics up to degree 30 and the coefficients are calculated by means of the Kaula's rule $C_l^2 = \frac{A_k 10^{-10}}{l^4}$, where the constant A_k is assumed equal to 9 for Mercury (Milani et al. 2001). Tidal effects have been considered, with a dynamic Love number k_2 set to 0.3. Non-gravitational accelerations, such as direct solar radiation and thermal emission from the planet, have not been modeled, thanks to the accelerometer compensation. In the orbit determination process the accelerometer transforms de facto the real spacecraft in a virtual, drag-free test particle (Iafolla et al. 2001) . However, residual accelerometer biases and drifts, mostly due to changes in the thermal environment, have been simulated through an acceleration noise correlated over time scales of the orbital period (Milani et al. 2001).

The estimated gravity field coefficients, after the multi-arc analysis, is reported on the Fig. 1. The mission goals for the relative accuracy of the harmonic coefficients are fully met and the estimation is statistically coherent. Since the degree 20, the estimation error increases, but still remains in a range between one and three σ and can therefore be considered as statistically acceptable.

In conclusion the improved dynamical model (gravity field coefficients, Love number

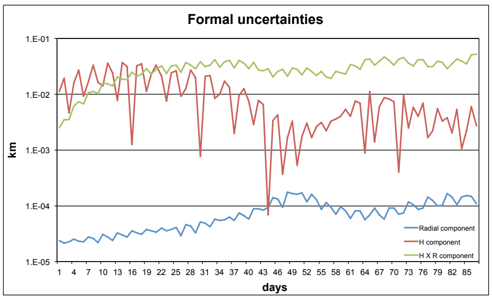

Fig. 2. Position vector reconstruction in the 88 days

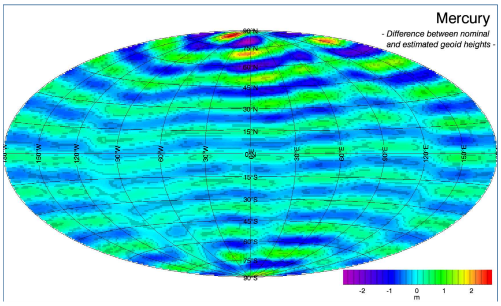

Fig. 3. Estimation errors of the geoid heights

k_2, manoeuvres and periodic accelerations) is exploited for a final single arc estimation that leads to the optimal orbit reconstruction (Fig. 2). The state vector is well determined in all three directions. Nevertheless, the along track component is characterized by a particularly high uncertainty that must be improved for the rotation experiment. This result can be certainly achieved by means of range rate observables in X-band from a second station that will be used not only for telemetry. On the other hand, the radial component of the position vector is estimated with particularly good accuracy satisfying completely the requirement of the laser altimeter on board the MPO.

This instrument will generate a series of laser-altimetric observables that will be reported on a reference surface, the geoid. The knowledge of the gravity field coefficients allows determining the geoid heights of the planet. Therefore, the errors of these global parameters affect the precision of this reference surface. In the Fig. 3 are plotted the errors of the geoid heights that satisfy the requirements of the laser altimeter considering especially the middle latitudes.

2. Conclusions

The orbital reconstruction is therefore fully adequate to support the laser altimetric observations (accurate to 1 m in the nadir direction). In the along- and across-track components the orbit determination accuracies are significantly larger, but better results are expected if additional observations becomes available. An improvement in the orbit determination is necessary for a measurement of physical librations below the arcsecond level.

In the current planning, BepiColombo's MPO will be tracked by two stations, namely ESA's 34 m antenna in Cebreros, supporting mission operations, and NASAs Deep Space Network antenna DSS 25 in Goldstone (California) for the radio science experiment. X-band Doppler data acquired at the Cebreros antenna may prove valuable for the estimation of the delta-Vs associated to desaturation manoeuvres, a major source of uncertainty in the orbital reconstruction.

Further investigations and refinements of the filter are certainly necessary. The simulation shows that the selection of the batch length depends on a trade-off between the estimation accuracy local and global parameters. A tuning of the batch duration according to some optimum criterion is desirable. A more realistic scenario where the spacecraft is tracked by two ground stations is expected to mitigate the effects of the wheel off-loading manoeuvres on the orbit determination. Finally, the evolution of the spacecraft state vector uncertainties still needs to be analyzed. The propagation of the covariance matrix along the orbit is indeed required for an exhaustive assessment of the BepiColombo radio science experiment.

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