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Analysis of Mercury Laser Altimeter crossovers with improved Mercury and MESSENGER ephemerides

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Abstract

Based on previous applications of laser altimetry to planetary geodesy at GSFC [Mazarico et al. (2014), (2016)] and taking advantage of new accurate Mercury and MESSENGER orbits by [Genova et al. (2019)], we analyze altimetric crossovers from the MESSENGER Laser Altimeter (MLA) to solve for orbital and geodetic parameters (*e.g.*, rotation and orientation). We present our results based on a new Python software package recently developed at GSFC that can simulate and process altimetry data in a closed-loop. Realistic simulations of MLA data, including an appropriate range noise from the instrument and realistic terrain roughness, are performed in order to fully characterize the robustness of the solution. The simulation results are then applied to our analysis of the full dataset acquired by the MLA instrument.

1. Introduction and data description

From March 2011 to April 2015, the MESSENGER spacecraft was orbiting Mercury in a highly elliptical, near-polar orbit with a periapsis of $\sim 200 - 400$ km, an apoapsis between $\sim 15000 - 20000$ km, and an orbital period of 12 hrs after orbit insertion (reduced to 8 hrs after one year). The spacecraft was within ranging distance for the onboard MLA for 15 to 45 mins near periapsis, typically at latitudes $30°N$. MLA collected over 22 million measurements of surface height, primarily in the northern hemisphere, with a vertical precision of ~ 1 m and accuracy of ~ 10 m. The total MLA dataset contains $\sim 3,200$ tracks and ~ 3 million crossovers, $i.e.$, instances where two ground-tracks intersect. Because of the elliptical orbit, the laser spot size on the surface varied between $\sim 10 - 100$ m and the distance between each crossover and its bracketing points was usually 400 m.

These crossovers represent repeated measurements of the same surface locations and, thus, provide an opportunity to measure Mercury's orientation and rotation from close range [Stark et al. (2015)]. Independent confirmation and refinement of the IAU libration model, developed from ground-based radar measurements [Margot(2009)], is important as it has implications for the moment of inertia of the outer solid shell and thus the mass distribution, internal structure and thermal evolution of Mercury [Genova et al. (2019), Phillips et al. (2018)].

2. Processing and solution strategy

Each crossover is the intersection of two separate ground-tracks. It can be thought of as a differential measurement between two distinct observations of the same surface location at two different times. Any difference in the height measurements at a crossover intersection is mainly due to the following effects: (1) Errors in the spacecraft orbit and attitude, or MLA boresight orientation, (2) interpolation errors of the surface topography between MLA footprints, and (3) geophysical signal due, $e.g.$, to mismodeled time-varying planetary rotation or to tidal vertical motions.

We base our analysis on the most recent orbit reconstruction of MESSENGER orbits, consistent with the latest HgM008 gravity field [Genova et al. (2019)]. In the latter, the orbits of the spacecraft and Mercury are co-estimated and co-integrated. This improves both the quality of the MESSENGER orbit reconstruction and the geodetic results, providing an improved a priori with respect to past analyses. We assess the impact of this new a priori information on crossover discrepancies. We analyze the impact of an extended parametrization, including non-constant terms, of the orbital corrections, in order to account for errors within each orbital arc.

We finally determine the best-fit of the chosen set of geodetic parameters through a weighted least-squares solution of their partial derivatives and those of the along-track, cross-track, and radial offsets to spacecraft position, and potentially of MLA roll and pitch offsets. Crossovers are weighted depending on their geographical location, off-nadir angle of the spacecraft and inter-point distances. Crossovers with abnormally large discrepancies are strongly down-weighted in our analysis.

By minimizing the total RMS crossover discrepancy, we solve for four rotational parameters (right ascension and declination of the spin pole at $J2000$; rotation rate; amplitude of the libration) and analyze our sensitivity to the tidal radial response h_2. The resulting corrections are then applied and serve as basis for the subsequent iteration, until convergence is reached.

3. Simulation environment

To fully characterize the behavior of the solutions, and in order to properly choose an appropriate parametrization and weighting scheme, we conduct extensive simulations with time-of-flight ranges consistently generated from realistic topography. In particular, we focus on exploring appropriate ways to cope with the interpolation error, one of the main residual sources of uncertainty in the analysis of past and future mission data [Steinbrügge et al. (2018)]. We introduce simulated MLA data based on different terrain roughness values in our processing algorithm. A comparative analysis of crossover discrepancies within simulated datasets and real data, provide us with a measure of the interpolation error dependency on the topography (see Fig. 1), hence allowing us to define appropriate weights for crossovers.

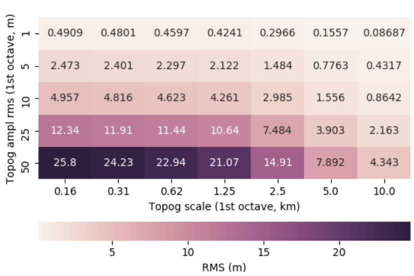

Figure 1: Crossover discrepancy RMS for multiple datasets simulated at MLA measurement epochs over January 2013, each based on different terrain roughness and no range noise. Real data over the same month show an RMS of ~ 20 m.

In addition, we analyze the impact on crossover discrepancies of a wide range of perturbations to orbital and geophysical parameters. This allows us to properly understand residual signatures in our solutions based on MLA data and to choose an appropriate parametrization to reduce them without degrading the solution of global parameters.

4. Summary and Conclusions

We present an updated analysis of MLA crossovers for the recovery of Mercury geodetic parameters, based on the full dataset of altimetric measurements and on the most recent solutions for orbit and geodetic parameters by [Genova et al. (2019)]. A new Python-based altimetry data simulation and crossover processing package, has been developed at GSFC for this study.

In addition to provide an improved background modeling, tools and findings from this study could also be applied to the ongoing preparation for the ESA BepiColombo mission, currently in cruise towards Mercury.

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