**NEW SOLUTION FOR MERCURY GEODETIC PARAMETERS WITH ALTIMETRIC CROSSOVERS FROM THE MERCURY LASER ALTIMETER (MLA).** S. Bertone[1,2], E. Mazarico [1], M. K. Barker [1], S. Goossens [1,2], G. A. Neumann [1], T. J. Sabaka [1], and D. E. Smith [3] [1] NASA Goddard Space Flight Center (GSFC), Code 698, 8800 Greenbelt Road, Greenbelt, MD 20771, USA [2] Center for Research and Exploration in Space Science and Technology, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore MD, USA [3] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Based on previous applications of laser altimetry to planetary geodesy at GSFC [1] , we analyze altimetric crossovers from the Mercury Laser Altimeter (MLA) and improve geodetic parameters via least squares minimization of crossover discrepancies. We use the recently developed PyXover software package to produce synthetic MLA data and to perform a recovery of MESSENGER orbits and Mercury geodetic parameters to evaluate the quality of the solution and the reliability of the retrieved errors in different scenarios. We then solve for Mercury pole right-ascension (RA) and declination (DEC) coordinates, prime meridian (PM) rate and librations (L) using the full MLA dataset. We calibrate the formal errors of our solution based on closed-loop simulations and on the level of independence from *a priori* values.

**Data description:** From March 2011 to April 2015, the MESSENGER spacecraft orbited 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 initially and reduced to 8 hrs after one year. The spacecraft was within ranging distance for the onboard MLA over 15-45 min periods near periapsis, typically at latitudes $> 30°N$. MLA collected over 22 million measurements of surface height with a vertical precision of $\sim$ 1 m and an accuracy of $\sim$ 10 m. The total MLA dataset contains $\sim 3,200$ tracks and $\sim$ 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 provide an opportunity to measure Mercury's orientation and rotation [2]. Independent confirmation and refinement of the IAU libration model, developed from ground-based radar measurements [3], 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 [4, 5].

**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 height at the crossover point 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.

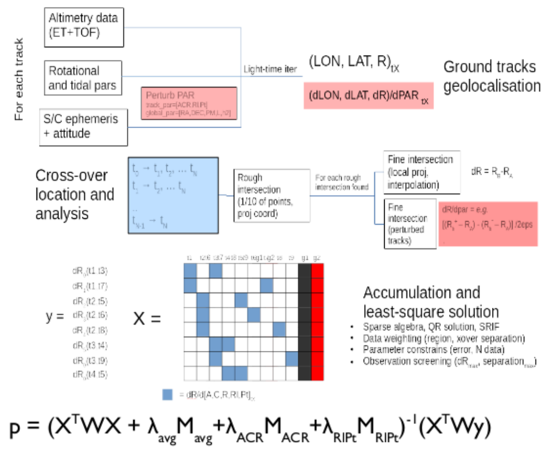


Figure 1: Workflow of the PyXover code: geolocation of altimetry data, crossovers location and setup of observation equations, QR-filter solution for a chosen set of parameters, with given weights and constraints.

We perform the analysis of MLA data within the PyXover python code, whose modular structure is sketched in Fig. 1. Laser altimetry ranges are geolocated to the planetary surface and partial derivatives of the ground-tracks are computed with respect to the chosen parameters by finite differencing. Initial geolocation is based on the MESSENGER orbit navigation reconstruction by KinetX and on the values provided by the IAU for Mercury orientation. Horizontal coordinates of crossover points are recovered in stereographic projection in a two-steps process, to balance computational time. Expected elevations at intersection points are then interpolated from neighbouring points on each track. Their discrepancies $dR$ constitute the observation residuals to be minimized in the least-square procedure. Huber weighting is then applied to the crossovers depending on their geographical location, off-nadir angle of the spacecraft and inter-point distances. Crossovers with abnormally large discrepancies are strongly downweighted in our analysis. By minimizing the total RMSE of crossover discrepancies, we solve for four rotational

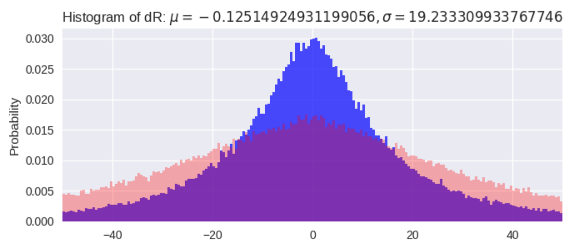


Figure 2: Distribution of pre-fit (red) and post-fit (blue, 10th iteration) crossover discrepancies $dR$ (meters).

parameters (RA and DEC of the spin pole at $J2000$, PM rate, and L) 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.

**Parametrization and error assessment:** To fully characterize the behavior of the solutions, and in order to choose an appropriate parametrization and weighting scheme, we conduct extensive simulations with time-of-flight ranges consistently generated from realistic topography. We first analyze the impact of the interpolation error on crossover discrepancies. The same modeling is used in both the data simulation and analysis, so that any error results from small scale terrain roughness only. We then perturb the orbit (radial, along-track and cross-track offsets), the pointing (roll and pitch offsets), and the geodetic parameters to test the quality of the recovery in different scenarios. These tests are performed for subsets of 500 tracks of synthetic MLA data homogeneously distributed in space and time. The results of these simulations allow us to evaluate the reliability of the formal errors provided by our analysis, by comparing them with the actual differences between "true" and recovered value. This provides a calibration for the error bars associated with our subsequent analysis of the MLA dataset. Moreover, such preliminary analysis allows us to properly identify the sources of different residual signatures in our solutions based on MLA data and to choose an appropriate parametrization and constraining to reduce them without degrading the solution of the geodetic parameters.

**Processing of MLA crossovers:** Regarding the analysis of the MLA dataset, we first process the same subset of tracks as used for the simulation runs. We iterate the solutions, until convergence is reached when parameters changes are below formal errors ($<20$ iterations).

We check both the reduction of the RMSE of post-fit discrepancies $dR$, as shown in Fig. 2, and the level of independence of the solution from the choice of *a priori* orbital and rotational parameters values. We compare multiple solutions starting from different Doppler orbit reconstructions (KinetX and [6]) and from both IAU [7]

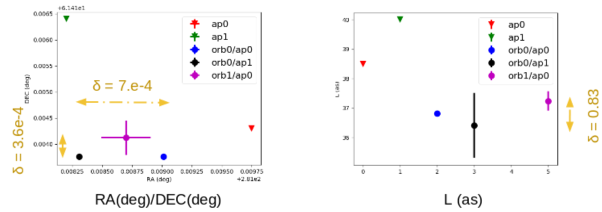


Figure 3: Comparison of our solutions for [RA, DEC, L] based on same data and parametrization, but on different combinations of MESSENGER orbit reconstructions (KinetX - orb0 - and orb1 [6]) and rotational parameters (ap0 [7] and ap1 [4]) as a-priori values.

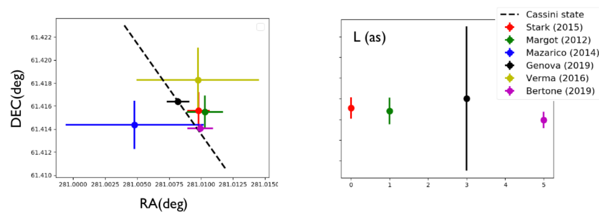


Figure 4: Our solutions for Mercury [RA, DEC, L] based on MLA crossovers analysis (purple), compared with [3, 1, 2].

and [4] values for Mercury rotational parameters. The dispersion at convergence is shown in Fig. 3 and it contributes to the systematic errors budget associated with the final solution.

Finally, we perform a weighted least square solution of orbit and rotational parameters based on the full MLA dataset and on the presented processing setup. Our results are shown in Fig. 4 and are consistent with previous solutions provided by other groups using various techniques (camera and altimetry, Doppler, Earth-based radar). Moreover, as for [4], our solution also puts Mercury in a Cassini state. The errors are calibrated based on both our closed-loop simulations and the analysis shown in Fig. 3.

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## References

[1] Mazarico et al. (2014), GRL 41, 2282. [2] Stark et al. (2015), GRL 42, 7881. [3] Margot(2009), CeMDA, 105, 329. [4] Genova et al. (2019), GRL 46, 3625. [5] Phillips et al. (2018), Mercury: The View after MESSENGER. [6] Genova et al (2018), Nature Com. 9, 289. [7] Archinal et al. (2018), CeMDA, 130, 22.