# Combined MLA and BELA altimetry crossover analyses for Mercury geodesy and interior studies

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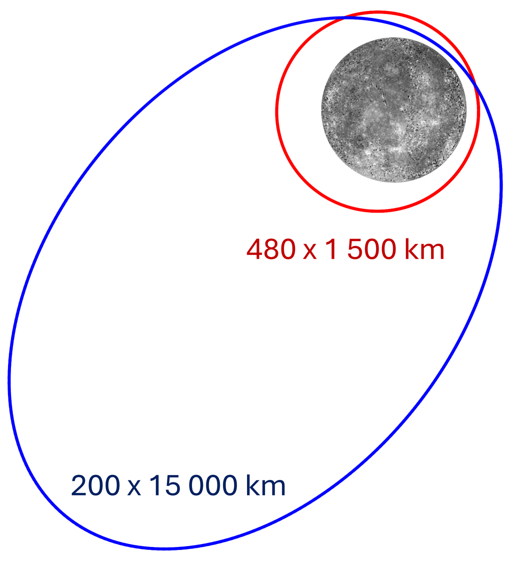
## MESSENGER and BepiColombo missions

Our work focuses on **Mercury's geodetic parameters**, which have implications for our understanding of Mercury's interior structure [1], and on the role of **on-board laser altimeters** in their determination.




MESSENGER (2011 – 2015):

- highly eccentric orbit and high latitude periapsis
- Mercury Laser Altimeter (MLA)

Mercury Planetary Orbiter (MPO) (2026 - ?) component of BepiColombo:

- Lower altitude apoapsis and lower latitude periapsis
- BepiColombo Laser Altimeter (BELA)

→ We investigate the added value of BELA in the framework of crossover-based solutions of orbit and geodetic parameters.

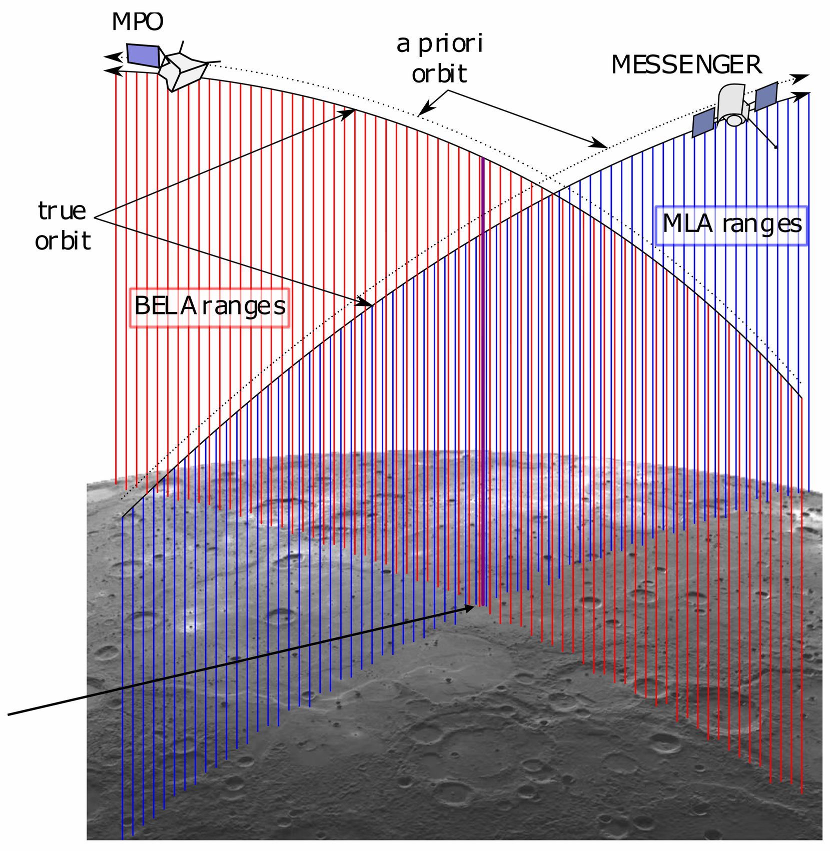
## Laser altimetry crossover analysis

Crossover analysis is performed within the pyXover software package [2].

In a least-squares improvement of simulated crossovers generated by MLA and BELA we solve for the following parameters:

- for each ground track an independent **orbit offset** in the Along-track (A), Cross-track (C) and Radial (R) directions;
- Mercury's **geodetic parameters**: right ascension RA and declination DEC of the North pole, rotation rate PM, libration amplitudes L) and the tidal Love number $h_2$.

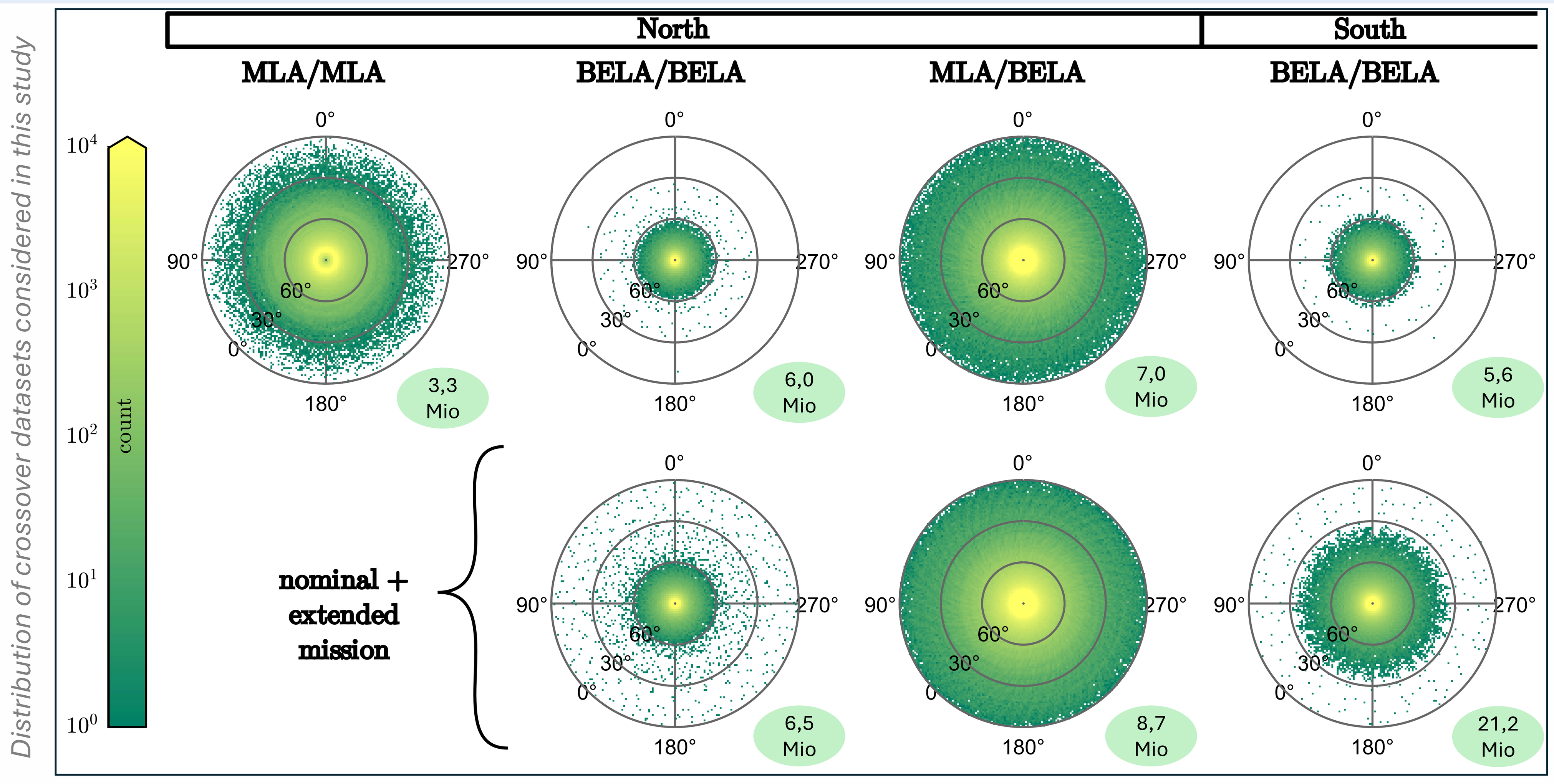
At each crossover between two altimeter tracks, the true elevation difference is 0, as the topography cancels out, so that the elevation discrepancy the quantity to minimize.




## Combined MLA/BELA crossover analysis

- MLA observations are restricted to high northern latitudes, thus limiting Mercury's ground surface coverage.
- BELA has a more uniform altimetry mapping of Mercury's surface, but the polar orbit limits the crossovers to even higher latitudes, although in both hemispheres.
- MPO extended mission would densify BELA crossover distribution, especially in the Southern hemisphere since the periapsis' drift causes the altitude over high northern latitudes to become too large.
- Setting up crossovers between the ground tracks of both altimeters results in a higher density of lower latitude crossovers in the Northern hemisphere.

A combination of BELA and MLA altimetry would ensure extended crossover coverage at lower latitudes, which is helpful for most geodetic parameters.




## Closed loop simulation results for orbit and geodetic parameter improvement

Hypotheses:

- Simulated small scale topography on top of large-scale DEM
- Altitude threshold: 1050 km
- Variance Component Estimation (VCE) provides optimal weights for each dataset and constraints (per direction, per probe)

Benefits of MLA/BELA combination for MESSENGER/MPO orbit determination:

- Lower orbit biases for MESSENGER (Cross-track and Radial)
- Smaller Along-track errors for both probes
- Smaller Cross-track errors for MESSENGER
- Better constraints on Northern hemisphere BELA tracks towards the end of the extended mission.

Improvements on geodetic parameters:

- BepiColombo extended mission visibly improves Mercury's north pole orientation (and thus its obliquity).
- MLA/BELA combination significantly improves Mercury's rotation estimates (rate and librations).
- Tidal deformation improvement is more modest.

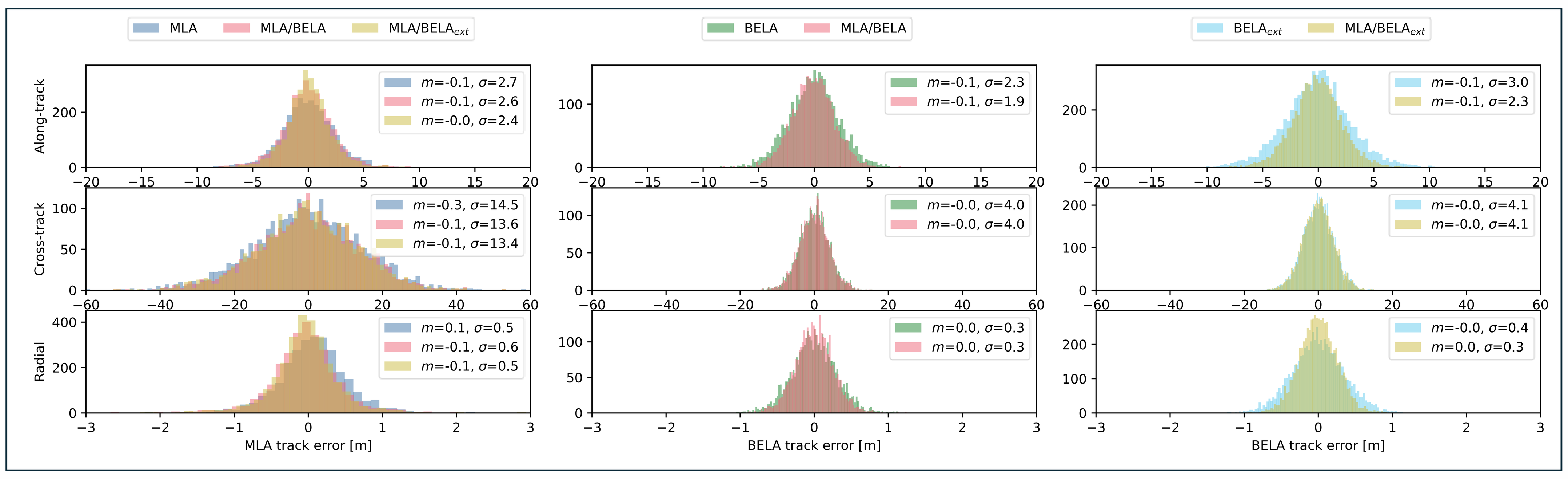
*Simulation setup & constraints*

| Altim. | | MLA | BELA |
|---|---|---|---|
| Range error | | 0,2m white noise | model $f$(alt,slope) |
| Orbit error | A | 20m | 10m |
| | C | 20m | 5m |
| | R | 5m | 0,2m |
| Constr. | A | 20m | 10m |
| | C | 20m | 5m |
| | R | 5m | 0,2m |

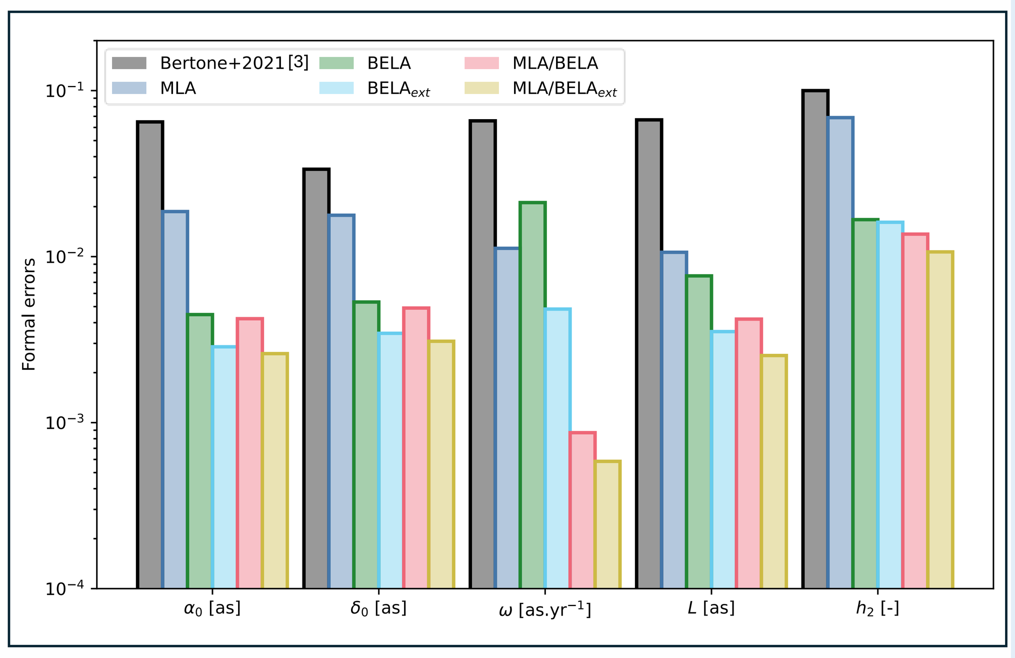
*VCE-derived weight*

| Dataset | VCE σ |
|---|---|
| MLA | 20m |
| BELA | 50m |
| MLA/BELA | 28m |

*Histograms of tracks errors (true orbit – orbit solution)*

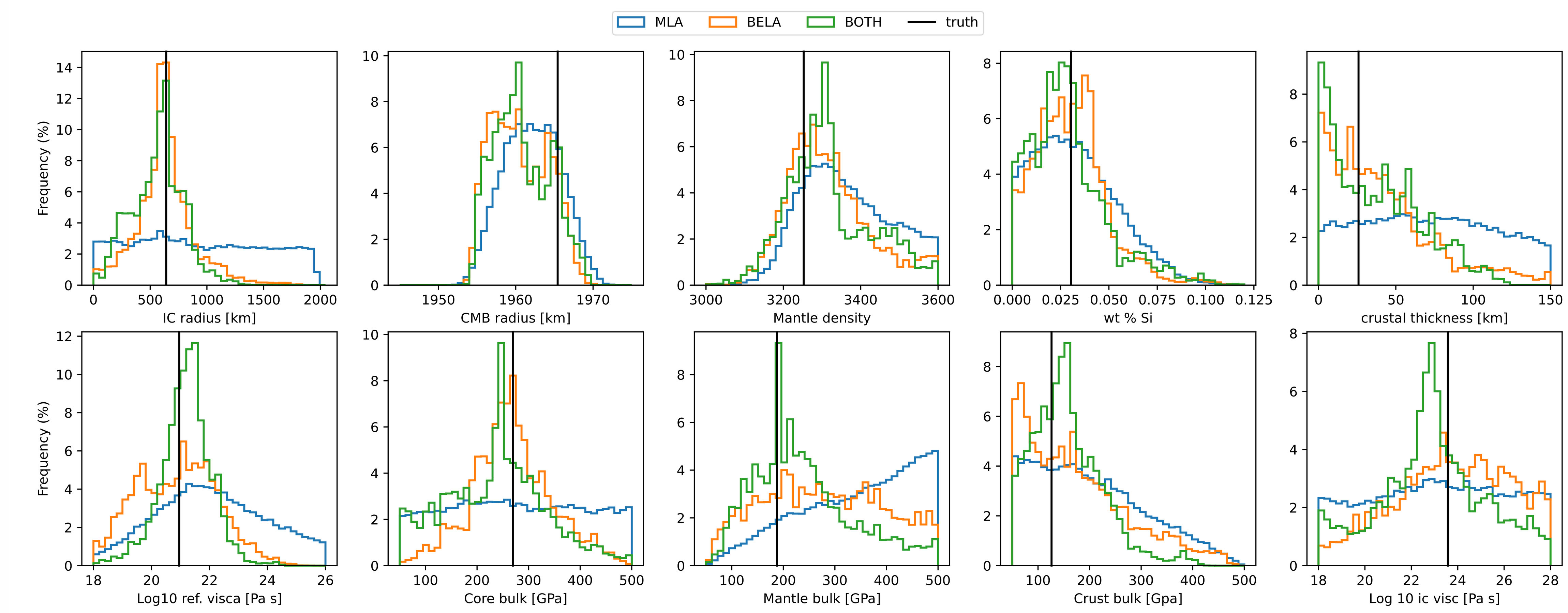



*Formal errors of geodetic parameters*




## Impact on internal structure models via MCMC analysis

We derived moments of inertia and tidal Love numbers based on a realistic interior model, and performed a Markov Chain Monte Carlo (MCMC) method [1], using 5 times the uncertainties derived from our closed-loop simulations.




*Probability distribution of a subset of internal structure parameters (considering BepiColombo extended mission)*

| | Model value | Uncertainties [$10^{-2}$] | | | | |
|---|---|---|---|---|---|---|
| | | MLA | BELA | BELA$_{ext}$ | BOTH | BOTH$_{ext}$ |
| $C/MR^2$ | 0,3345857 | 0,0240 | 0,0071 | 0,0048 | 0,0067 | 0,0043 |
| $C_m/C$ | 0,4586047 | 0,0658 | 0,0436 | 0,0204 | 0,0248 | 0,0149 |
| $k_2$ | 0,613 | 2,5[4] | 0,87[5] | 0,87[5] | 0,87[5] | 0,87[5] |
| $h_2$ | 1,129 | 30 | 8,35 | 8,05 | 6,85 | 5,35 |

Improvement on the knowledge of Mercury's interior:

- BELA data will already significantly improve our knowledge of the **inner core radius**.
- The extended mission will help constraining the **core bulk**.
- Combining MLA/BELA would allow to tightly constrain the **mantle and crust bulk**.
- With the mission extension, the **mantle density** and **wt % Si**, the **reference and inner core viscosities** will benefit from the combination.
- Although the improvement on the rotation rate is significant, its uncertainty is not included in our current interior model.y

Reduced uncertainties on geodetic parameters lead to a better determination of Mercury's internal structure, as shown by comparing MCMC results based on each individual and combined datasets.

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## References

[1] Goossens et al., PSJ, 3, 37 (2022)
[2] Bertone et al., *pyXover v0.2.0* (2024)
[3] Bertone et al, JGR, 126, e2020JE006683 (2021)
[4] Genova et al., GRL, 46, 3625 (2019)
[5] Iess et al, SSR, 217, 21 (2021)