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Combination of altimetry crossovers and Doppler observables for precise orbit determination of a Callisto orbiter and geodetic parameter recovery

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Introduction

Callisto is a key body to answer present questions about the origin and the formation of the Jovian system. The outermost of the four Galilean satellites appears to be the least differentiated and the least geologically evolved of the Galilean moons, and therefore the one best reflecting the early ages of the Jovian system.

ESA's JUICE mission will perform 21 flybys of Callisto, but an orbiter would allow to measure geodetic parameters to much higher resolution (see e.g., the Tianwen-4 mission by CNSA and the MAGIC mission proposal). Recovering Callisto's gravity field, its tidal Love numbers, and its orientation in space would help to significantly constrain Callisto's interior structure models, including the characterization of a potential subsurface ocean.

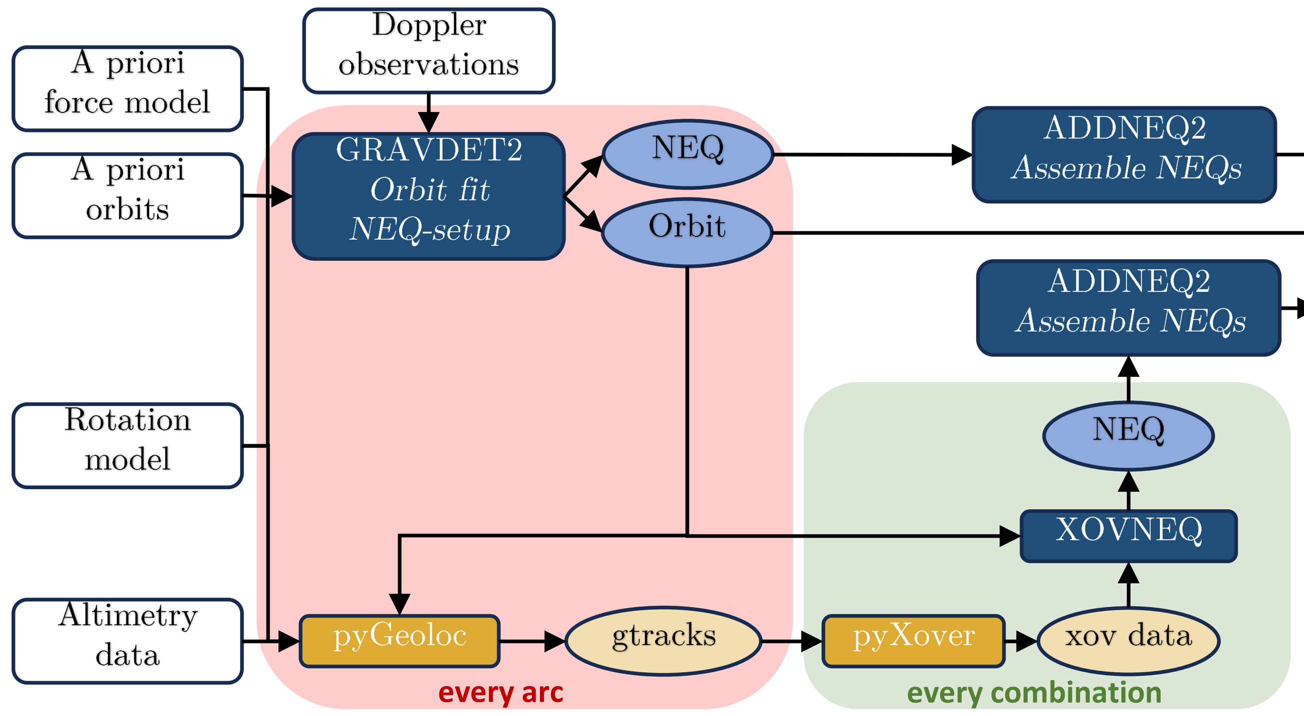
We perform a closed-loop simulation of spacecraft tracking and altimetry data of a 200 km altitude polar orbiter, which we then use for the recovery of its precise orbit and of Callisto's geodetic parameters. We compare our results for different orbital configurations. By minimizing a combination of altimetry crossover discrepancies and radio tracking (2-way Doppler) residuals, we estimate the following parameters:

Estimated Parameter	#	Type
Osculating orbital elements	6	local
Tidal Love number k_2	1	global
Tidal Love number h_2	1	global
Gravity field coefficients (d/o 100)	8278	global
Pole orientation offsets α_0, δ_0	2	global
Rotation rate w_1	1	global
Main libration amplitude W_l	1	global

Description of the observation combinations

Our orbits are propagated in the Bernese GNSS Software (**BSW**) starting from 2031-May-01, taking into account Callisto's gravity field and tidal deformations, Jupiter (point mass and zonals up to d/o 6), other 3^{rd} body attractions (Galilean moons, Sun and planets) and non-gravitational accelerations. Callisto's synthetic gravity field CALGLMo was derived from [1] (d/o 2), and by rescaling the Moon's gravity field, up to d/o 100.

We simulate 2-way X-band Doppler observables from Jiamusi ground station of the Chinese Deep Space Network using a realistic noise model (σ_{dop} < 0.036 mm/s at 60s integration time). We finally use the **PyXover** software package [2] to simulate altimetry measurements based on the propagated orbits, introducing a topography model.

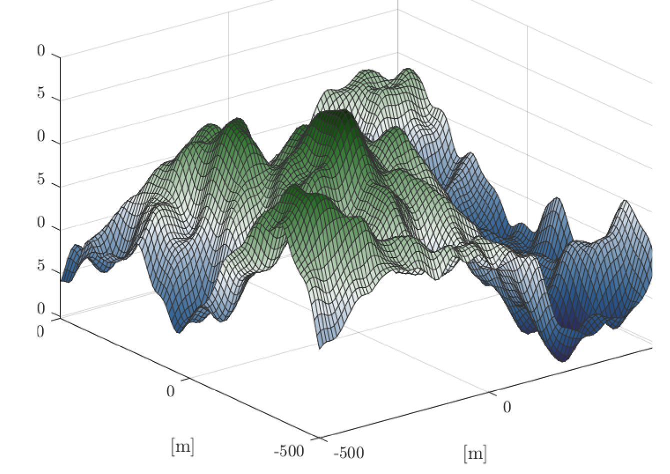


First, an orbit is fitted using only Doppler obs. (about 27,280 observations) for 80 **arcs** of about 25 h [3]. The reconstructed (but still imperfect) orbit is used to geolocate the altimetry observations on the surface of Callisto [2]. Then for each of the 66 **combinations** between the 12 altimetry batches of 7 days, we search for all possible crossovers (intersections between projected ground tracks) and compute their elevation discrepancies ν and their partial derivatives w.r.t. the estimated parameters in **PyXover**. These partial derivatives are then used to build normal equation systems (NEQs), adapting from the orbit correction parameterization of **PyXover** to the **BSW**. Combined NEQs for individual arcs and combinations are then stacked observation-wise for a total of 83 days w.r.t. all parameters. The two global NEQs are finally combined, generally by using Variance Component Estimation (VCE) to derive optimal weights for the different observation types. The solution is then compared to the true orbit and true geodetic parameters.

Crossover discrepancies & orbit improvements for different topography models

The elevation computed at crossover locations is strongly affected by errors from the interpolation between altimetry bouncing points, which depend on the altitude, surface roughness, and altimeter sampling frequency. Altimetry ranges were simulated considering an orbit with $\beta_{Earth} \approx 1°$, and a nominal 10 Hz sampling (leading to a 160 m inter-spot distance), following different assumptions:

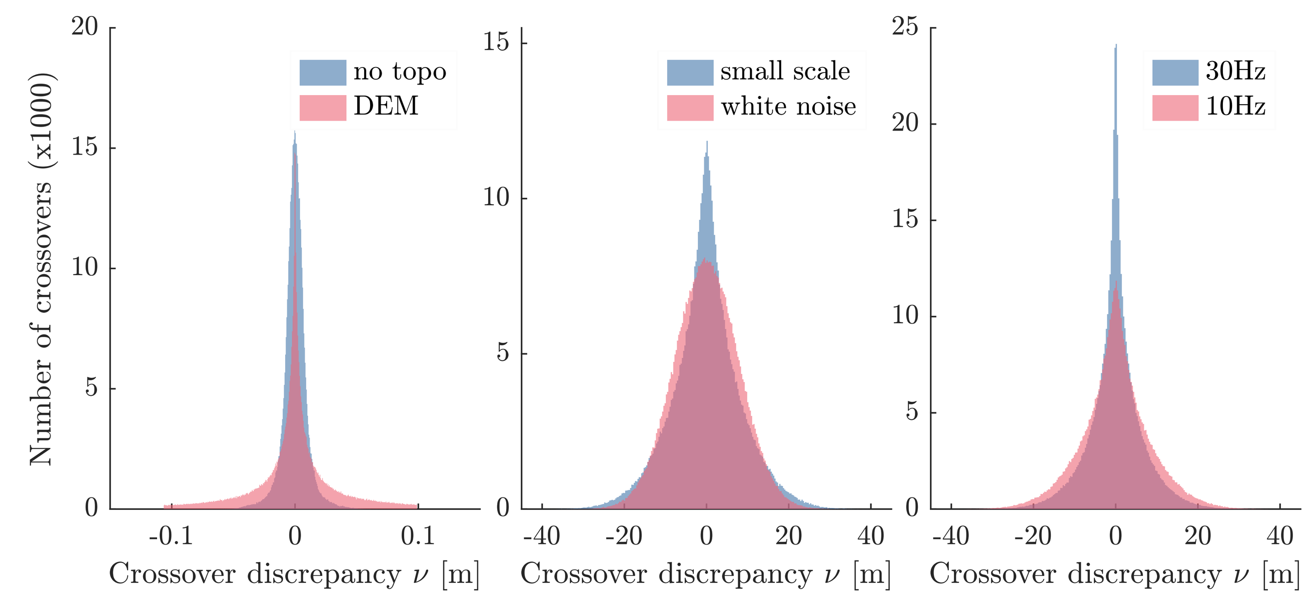
- No topography and no noise
- Only Mercury DEM large scale and no noise
- DEM and 12 m white noise on ranges
- DEM and synthetic small-scale topography [2] (10 m res., see right)
- DEM and synthetic small-scale topography at 30 Hz



Crossovers discrepancies were computed from an orbit fitted only with Doppler obs., which resulted in

Post Doppler-only fit	
RMS Dop.	0.78 mHz
RMS Orb.	1.9 m

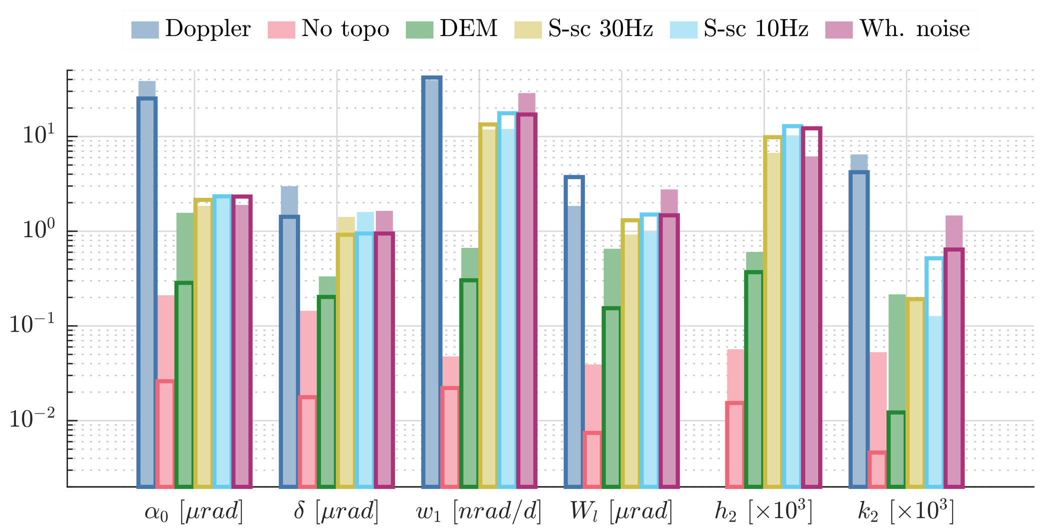
Because the orbit is polar, most of the ≈ 520,000 crossovers are found at high latitude (95% located at latitudes >70°). The orbit benefits from combining Doppler observations with altimetry crossovers, except for the equivalent white noise case.



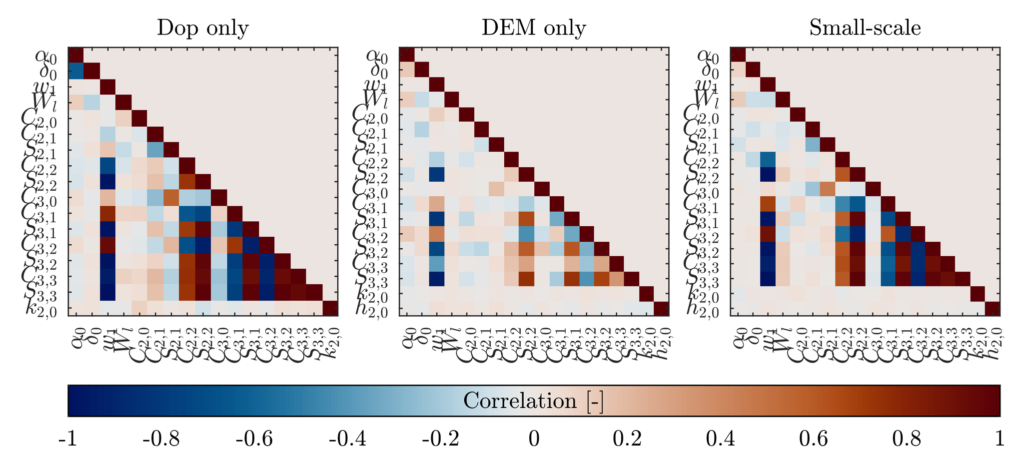
In more ideal cases, increasing the weight given by VCE to favor crossovers helps reducing post-fit orbit differences. The largest orbit improvements are observed in the cross-track direction (weakly determined using Doppler obs. only).

Topography	Weight ratio	Post-fit Stdev ν [m]	Post-fit RMS Dop. [mHz]	Post-fit RMS Orb. [m]
No topography	1×10^3	0.00026	0.79	0.35
DEM	1	0.089	0.78	0.85
Small-scale 30 Hz	1.2×10^{-3}	6.4	0.78	0.93
Small-scale 10 Hz	6.9×10^{-4}	8.3	0.78	1.4
White noise	7.7×10^{-4}	7.8	0.78	1.9

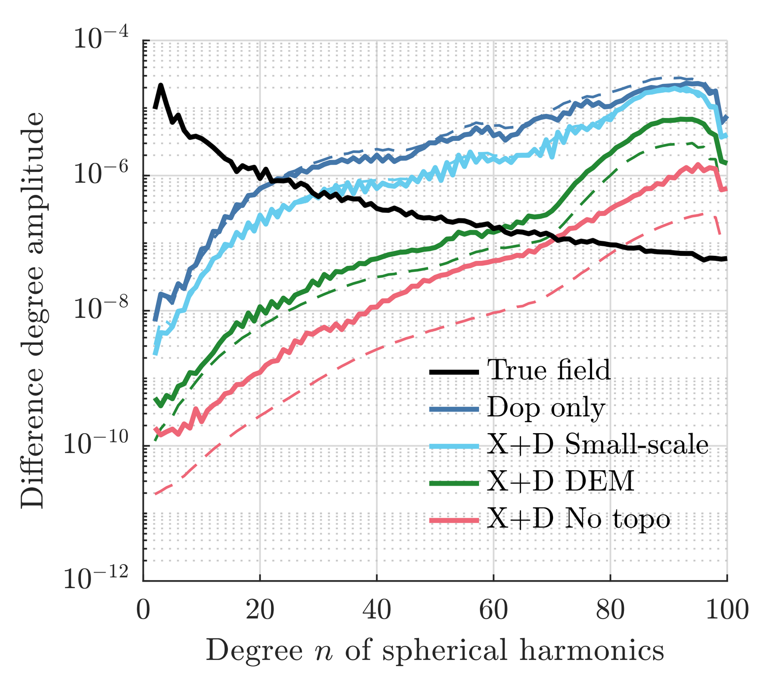
Geodetic parameter recovery for different topography models



True (filled bars) and formal (empty bars and solid line) errors.



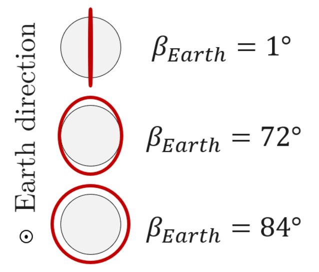
All parameters are estimated for $\beta_{Earth} \approx 1°$, and the same topography models. Altimetry reduces the errors in the rotation parameters, as well as existing correlations. Correlations between gravity parameters and rotation rate w_1 remain large in more realistic cases. w_1 may be less challenging to estimate for longer mission and/or with crossovers in lower latitudes.



Gravity formal errors (dashed) and difference (solid).

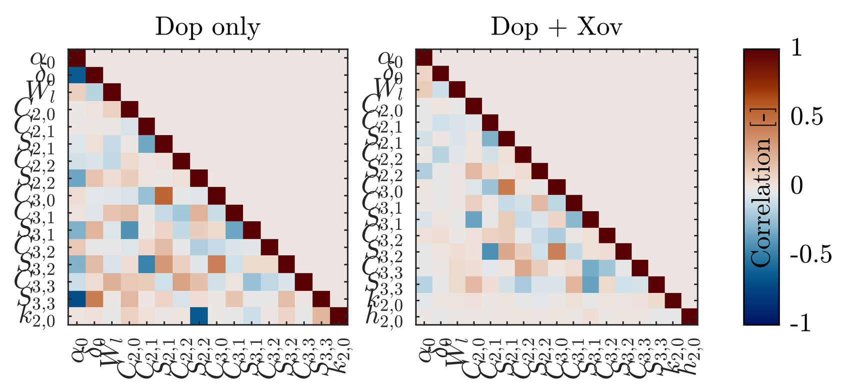
Crossovers contribution for different orbit configurations

Here, we fixed the topography model to the small-scale topography added to the DEM, and the altimeter sampling to 10 Hz. We considered three different orbit configurations from edge-on to face-on, and fixed the value of the rotation rate w_1 to the true value. A Kaula constraint was applied in case of the nearly edge-on orbit, to compensate for the limited ground coverage.



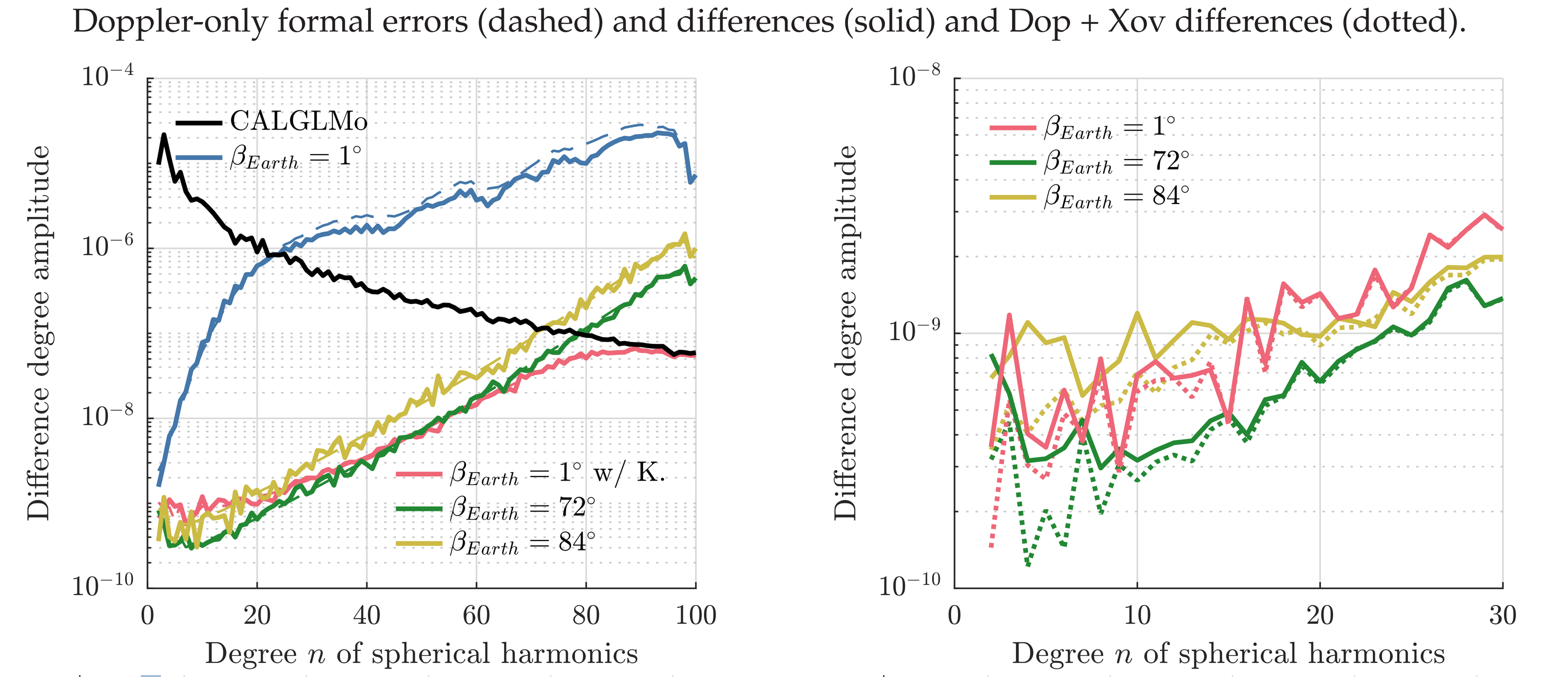
β_{Earth} avg. [°]	Weight ratio	Stdev ν [m] post-fit	RMS orb. diff. [m] pre-fit	RMS orb. diff. [m] post-fit
1	6.9×10^{-4}	8.3	1.9	1.4
72	6.5×10^{-4}	8.5	4.6	3.3
84	6.5×10^{-4}	8.6	7.0	4.5

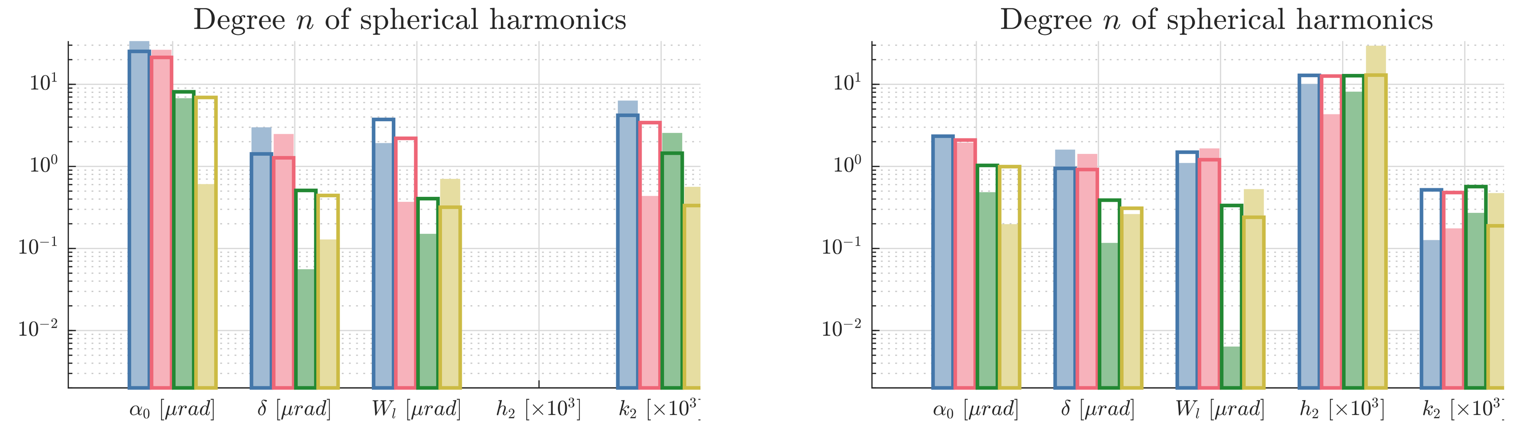
$\beta_{Earth} = 1°$, no estim. w_1



Low-degree gravity field and orientation parameters benefit from the combination, and their correlations get reduced. The improvement in terms of orbit differences is more significant when the orbit is face-on (detrimental configuration for Doppler obs. [3]). We also expect to improve the altimetry contribution with a more careful weighing scheme between crossovers.

Doppler-only formal errors (dashed) and differences (solid) and Dop + Xov differences (dotted).





True (filled bars) and formal (empty bars and solid line) errors for Doppler only (left) and Dop + Xov (right).

Acknowledgements

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Poster compiled by W. Desprats (william.desprats@unibe.ch), April 2024
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