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Simulation Study for Precise Orbit Determination of a Callisto Orbiter and Geodetic Parameter Recovery

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Introduction

Callisto, the outermost of the four Galilean satellites, is a key body to answer present questions about the origin and the formation of the Jovian system. It appears to be the least differentiated and the least geologically evolved of the Galilean satellites, and therefore the one best reflecting the early ages of the Jovian system. The Tianwen-4 mission (CNSA) is in his early preparation stage to explore this system, and to go in orbit around Callisto.

We perform a closed-loop simulation of spacecraft tracking (2-way Doppler), altimetry, and accelerometer data of a high inclination, low altitude orbiter. We first use Doppler data only to recover its precise orbit and Callisto's geodetic parameters, e.g., gravity field, rotation, and orientation parameters and the k_2 tidal Love number. We consider several ways to mitigate the mismodeling of non-gravitational accelerations, such as using empirical accelerations and pseudo stochastic pulses, and we evaluate the benefits of an on-board accelerometer.

We also investigate the added value of laser altimeter measurements to enable the use of altimetry crossovers to improve orbit determination and geodetic parameters, but also to estimate the recovery of surface tidal variations (via the h_2 Love number). For our closed-loop analyses, we use both a development version of the Bernese GNSS Software (BSW) and the open source pyXover software.

Simulation pipeline

The orbits are propagated in the 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 reference synthetic gravity field CALGLMo was derived from Anderson et al. (2001) (d/o 2), by rescaling the Moon's gravity field, up to d/o 100. We simulate 2-way Doppler obervables (X-band and Ka-band) for the three antennas of the Chinese Deep Space Network (Jiamusi, Kahshi and Neuquén) using a realistic noise model (σ_{dop} < 0.063 mm/s at 60s integration time). We finally use the PyXover software package (Bertone et al., 2021) to simulate altimetry measurements at 10Hz sampling based on the propagated orbits.

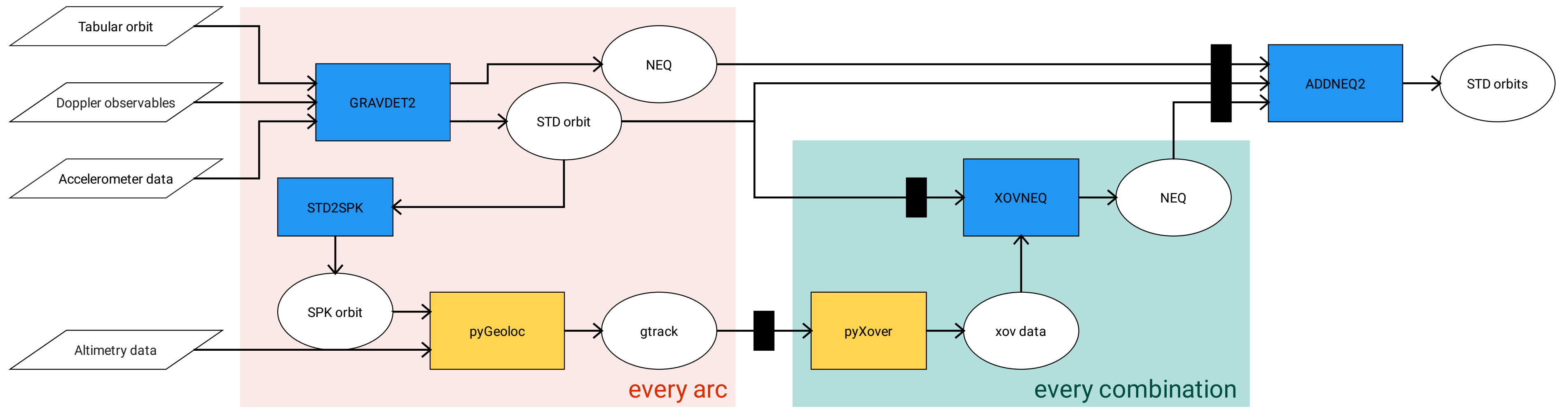

Figure 1: Simulation flowchart. Blue boxes refers to BSW software, yellow boxes to PyXover software.

The orbital elements are estimated for arcs of about 24h length. After a first orbit fit using only Doppler observations, the reconstructed (but still imperfect) orbit is used to geolocate the altimetry observations on the surface of Callisto (Bertone et al., 2021). Then for each 7-days combination, we search for all possible crossovers and compute their partial derivatives w.r.t. the estimated parameters in pyXover. These partial derivatives are then used to build normal equation systems (NEQs) in the BSW. Finally, following the Celestial Mechanics Approach (Beutler et al., 2010), the NEQs established for the individual arcs and combinations are stacked for a total of 3 months to estimate all orbit and geodetic parameters.

Non-gravitational acceleration mitigation

Non-gravitational accelerations (NGA) are difficult to model. Considering solar and planetary radiation pressure, for a JUICE-like orbiter, the accelerations reach up to a 15nm/s^2. We evaluate several ways to mitigate the mismodeling of these non-gravitational accelerations for a 200 km altitude polar orbit with β_{Earth} close to -45° during 3 months, using Ka-band Doppler tracking data only with:

- realistic accelerometer data affected by white noise and biases in 3 directions
- pseudo-stochastic pulses (every 80min = ½ orbital period)
- 1 Cycle-Per-Revolution accelerations in 3 directions and one bias in cross-track direction

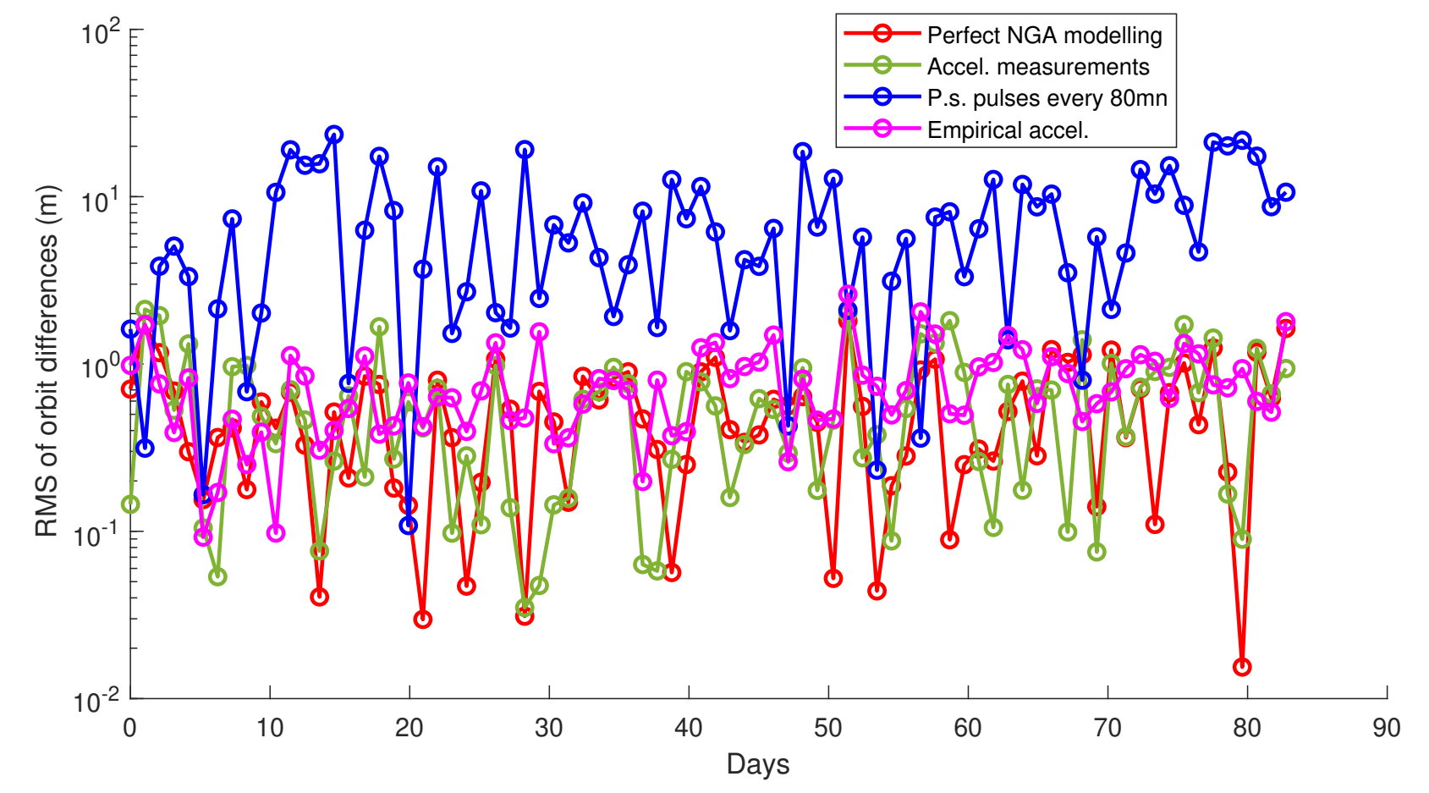

Figure 2: RMS of orbit differences for every arc, considering several mitigation strategies.

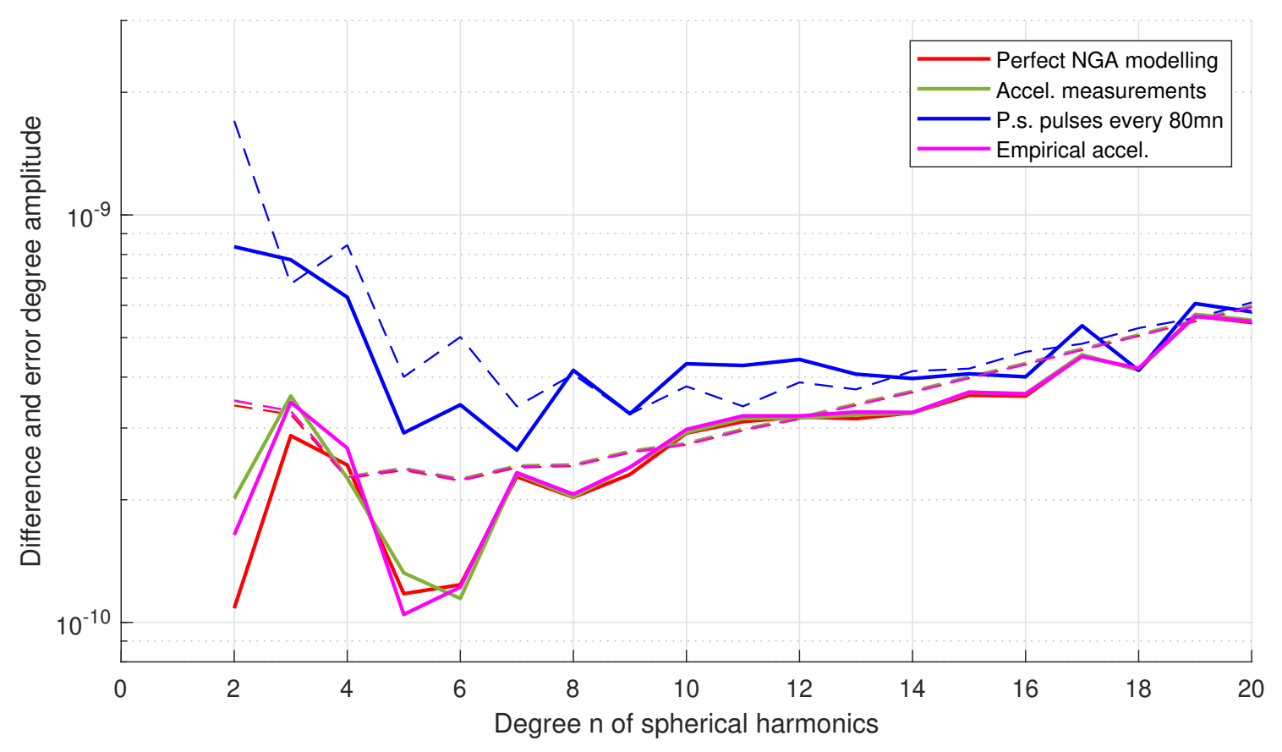

Figure 3: Low degree gravity field coefficients estimated using different mitigation strategies. Difference (solid) and error (dashed) degree amplitudes.

Pseudo-stochastic pulses are very efficient reducing the Doppler residuals, but they can have a negative impact on the orbit (Fig. 2) and on the low degree of the gravity field (Fig. 3). Empirical accelerations are a good compromise in case no accelerometer data are available. The estimation of biases, also necessary if accelerometer data are incorporated, turned out to be challenging. This could partly be explained by the low magnitude of the considered NGA, which forced us to consider biases which are constant over one Callisto day (16,7 Earth days).

Geodetic parameter recovery

In this section we focus on the estimation of geodetic parameters, i.e., gravity field, rotation, and orientation parameters and the k_2 tidal Love number, based on radio tracking only. The procedure of arc-wise NEQ accumulation (for 3 months) to solve for global parameters is described in Desprats et al. (2023). Table 1 summarizes the accuracy to which we could recover these parameters from polar and circular orbits ($\beta_{Earth} \approx 80°$), using 2-way Doppler data from two stations of the Chinese Deep Space Network (one station operating in X-band and the two other operating in Ka-band) in two cases:

- h=100km, Ka-band (Kahshi, China and Neuquén, Argentina)
- h=200km, Ka-band (Kahshi, China) and X-band (Jiamusi, China)

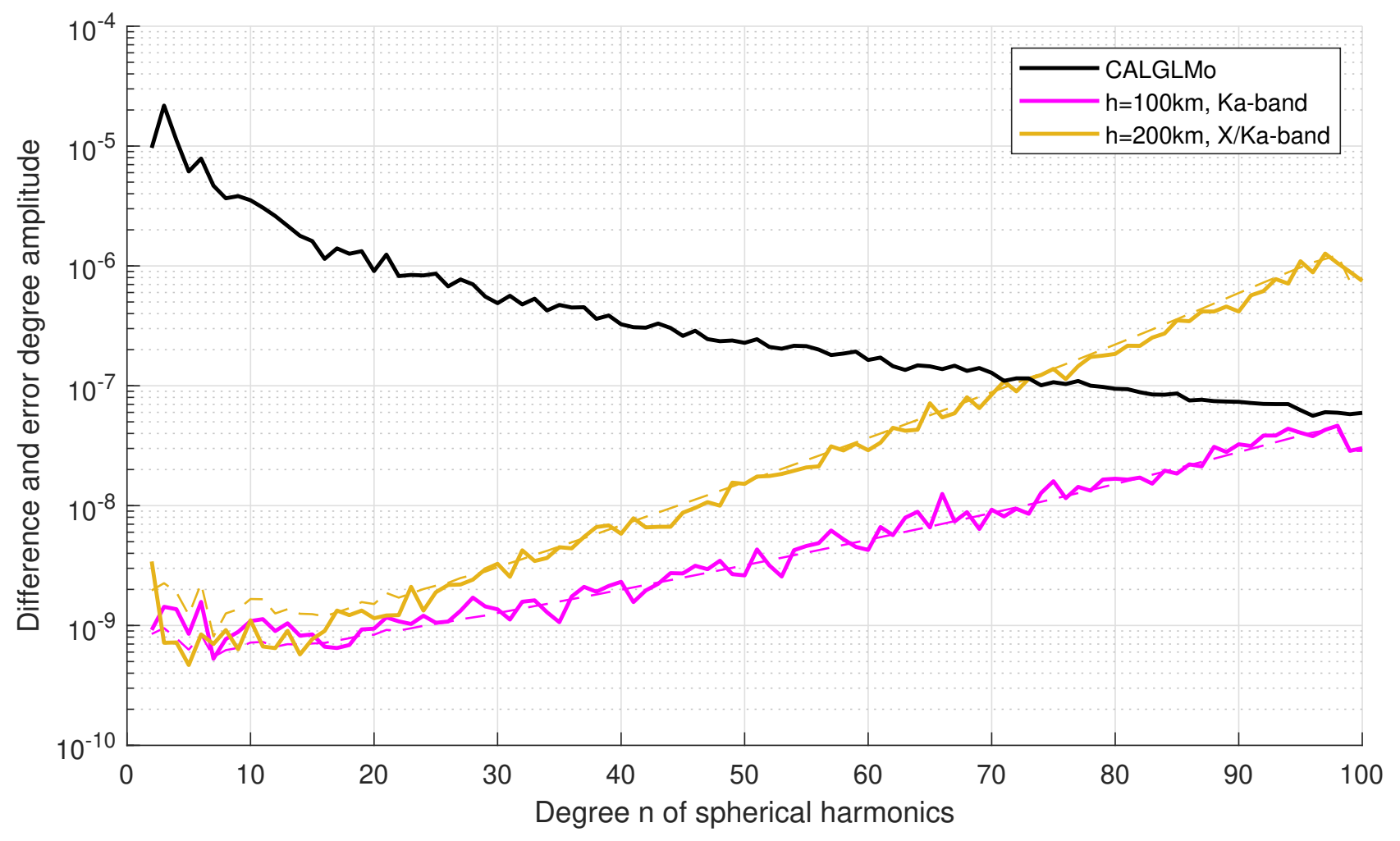

Figure 4: Gravity field solutions for both cases. Difference (solid) and error (dashed) degree amplitudes.

	Nominal value	h=100km Ka-band	h=200km X/Ka-band
k2 Love number	0.3	$5.3.10^{-5}$	$2.2.10^{-4}$
R.A. of the pole	268.7 deg	0.095 mdeg	0.26 mdeg
Dec. of the pole	64.83 deg	0.004 mdeg	0.023 mdeg
Angular velocity	21.57 deg/day	0.089 μdeg/day	0.30 μdeg/day
Libration amp.	0 deg	3.5 μdeg	14 μdeg
$\overline{C}_{20}$	$-1.462.10^{-5}$	$1.62.10^{-9}$	$2.34.10^{-9}$
$\overline{C}_{22}$	$-1.580.10^{-5}$	$7.70.10^{-10}$	$3.19.10^{-9}$

Table 1: Unconstrained estimation errors of a subset of Callisto geodetic parameters.

Difference degree amplitude:

$$M_n = \sqrt{\frac{\sum_{m=2}^{n}(\Delta\overline{C}_{nm}^2+\Delta\overline{S}_{nm}^2)}{2n+1}}.$$

First analyses of crossovers contribution

As mentioned above, NGA mismodelling might harm the orbit solution. We studied the contribution of altimetric crossovers to orbit determination. We consider a 200 km altitude polar orbit, tracked only by Jiamusi station (X-band only) for 2.5 months, with $\beta_{Earth} \approx 80°$. Without any parameter to absorb the NGA deficiency, the RMS error of the estimated error can reach 16 m. Since the orbital plane is close to perpendicular to the Earth direction, the along-track component of the orbit is the worst determined in case of a Doppler-only orbit fit (see, e.g., Desprats et al., 2023).

We first examine the contribution of crossovers alone on an orbit previously fitted using Doppler observations. Using PyXover, we were able to find $442,416$ crossovers from the 66 combinations of 7-days batches of noise-free altimetry data (Fig. 5). Because the orbit is polar, most of the crossovers are found at high latitude (95% of them located at latitudes >70°). We then estimate orbit corrections in PyXover, parameterized as biases per track in the local orbital frame. The largest corrections are in the along-track direction (Fig. 6), so that we expect a beneficial contribution when combining altimetry and radio tracking data.

Combining altimetric crossover discrepancies with the $27,280$ Doppler observables in the BSW requires an adaptation of the orbit correction parameterization, as we estimate corrections on the initial orbital elements of each arc, and not a single shifts of orbit tracks in Radial, Along-track and Cross-track directions (Fig. 1). Once the NEQs related to the crossover discrepancy observable are set for each combination, we combine them to the arc-wise Doppler NEQs by weighting down the crossovers discrepancies by a variance co-factor of 10^{-7}. Solving only for the 6 orbital elements per arc with the contribution of altimetry allowed us to improve the orbit (mainly in the along-track direction) up to a factor of 4 (Fig. 7).

We present only first tests here, and the situation is expected to change when estimating other geodetic parameters, e.g., gravity field and h_2 Love Number, and with other mismodellings. We also expect to improve the altimetry contribution with a more careful weighing scheme.

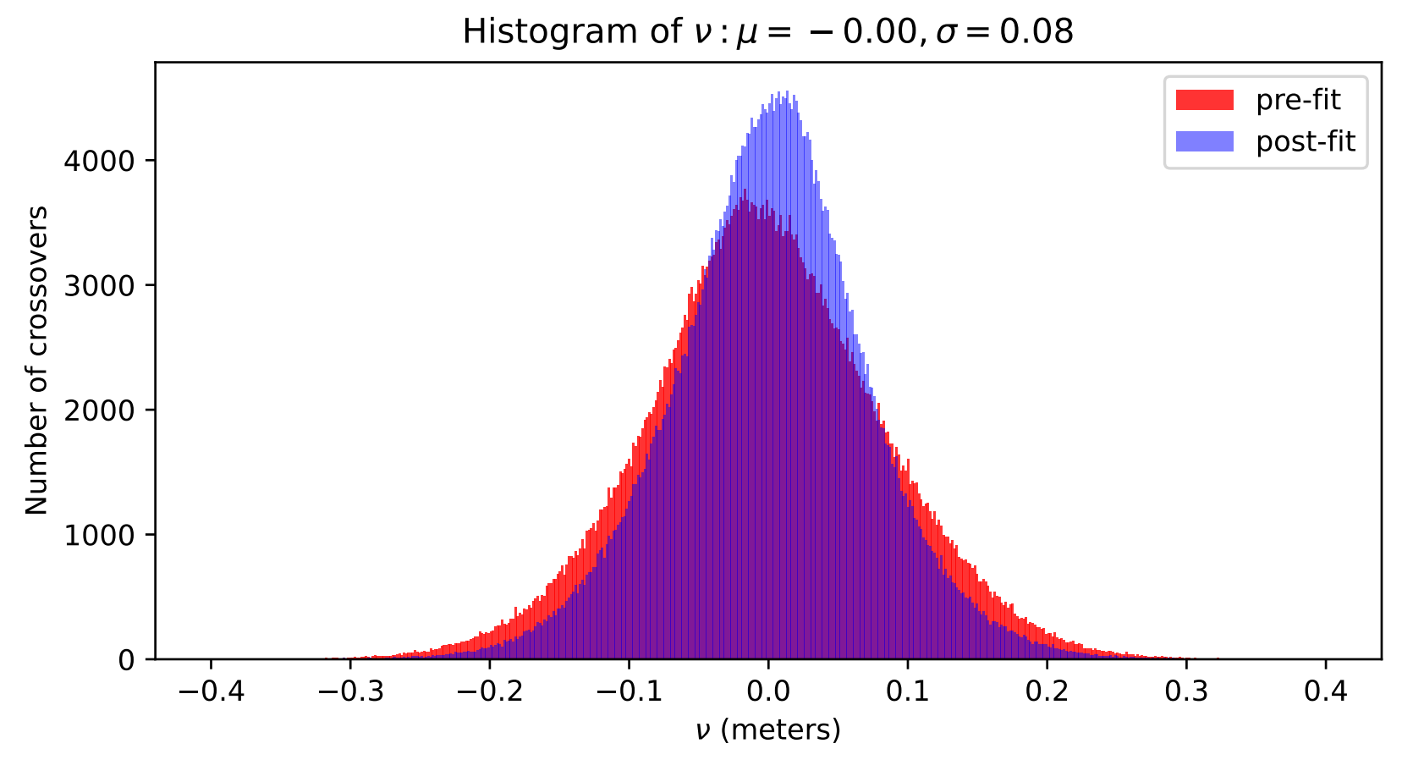

Figure 5: Residuals (pre- and post- pyXover fit) of crossover discrepancies ν.

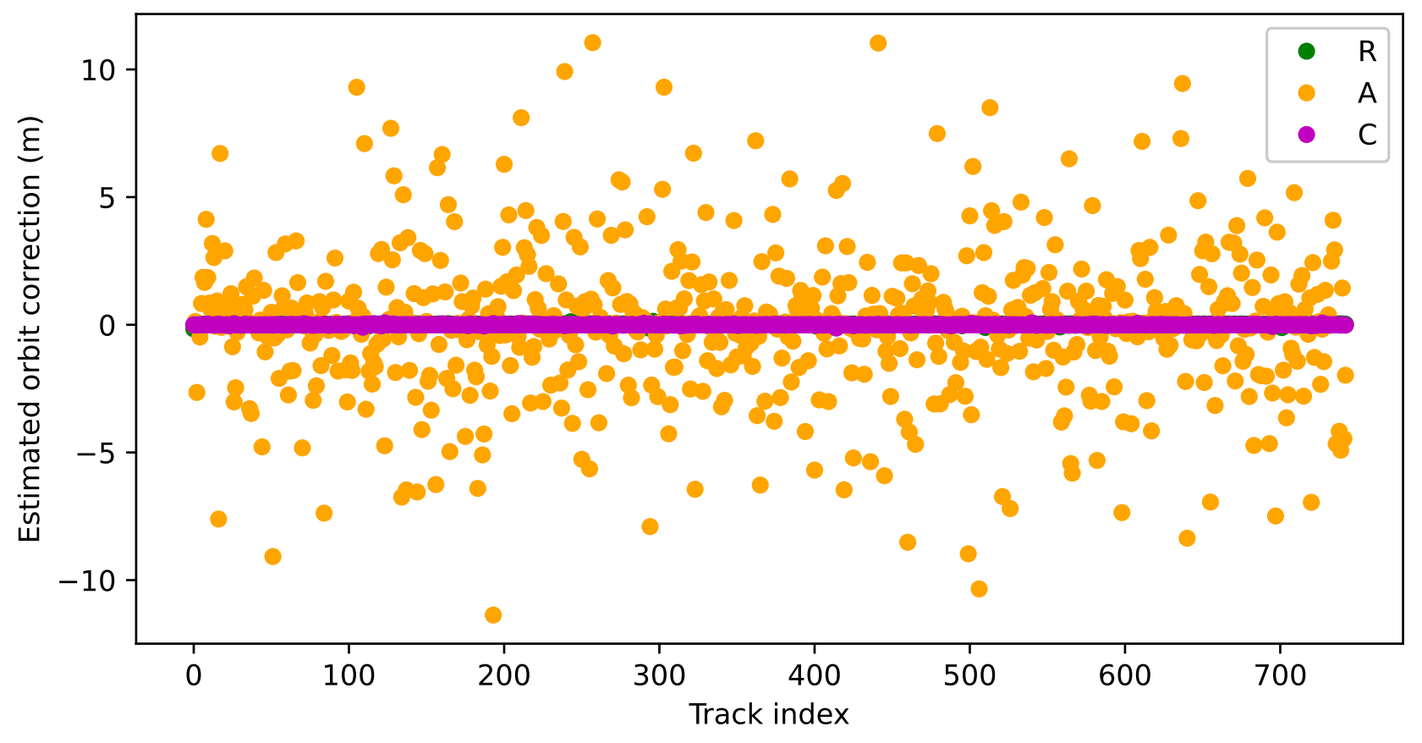

Figure 6: Orbit corrections estimated in pyXover, estimated for each track (i.e. once per orbit revolution).

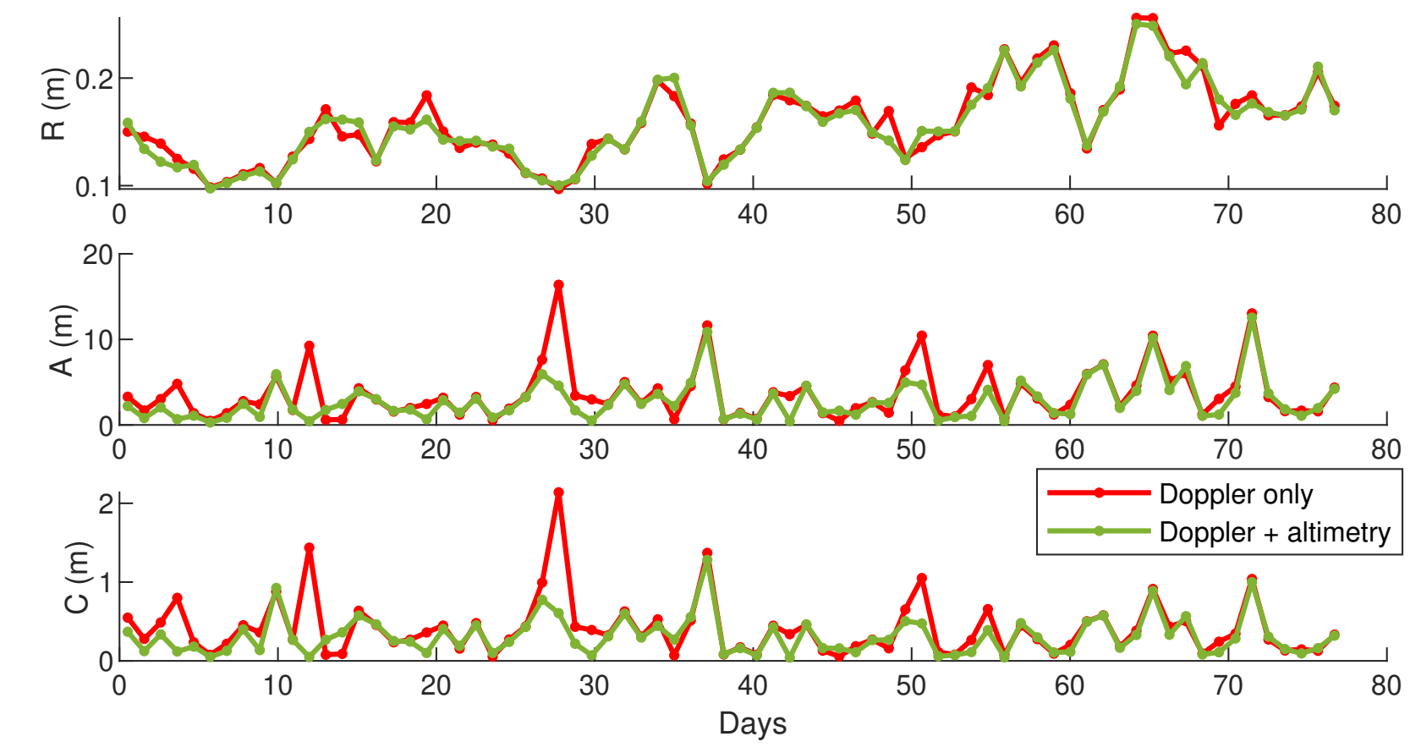

Figure 7: RMS of orbit differences for each arc using Doppler only, and using Doppler + altimetry

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