Accuracy Limits of Orbit Predictions for GNSS Satellites

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Scope of the study

The primary objective of this study is to identify the optimal strategy for providing short- and long-term orbit predictions for navigation satellites. For this aim, we evaluate the impact of the length of the orbit fit on the quality of the GNSS orbit predictions. Subsequently, we focus on selecting the optimal strategy for modeling solar radiation pressure (SRP), including a series of tests involving the incorporation of the extended Empirical CODE orbit model (ECOM2) and a priori box-wing models. The quality of the solution is evaluated by comparing the predicted orbits generated with the appropriate SRP modeling with the reference orbit (**Fig. 1**). Finally, we analyze the impact of using predicted Earth rotation parameters (ERPs) instead of operational products on the quality of orbit predictions.

We analyze five constellations of navigation satellites with the distinction between types and groups in each constellation. The number of solutions performed for each group provides a comprehensive overview of the impact of the various factors on the quality of the orbit predictions.

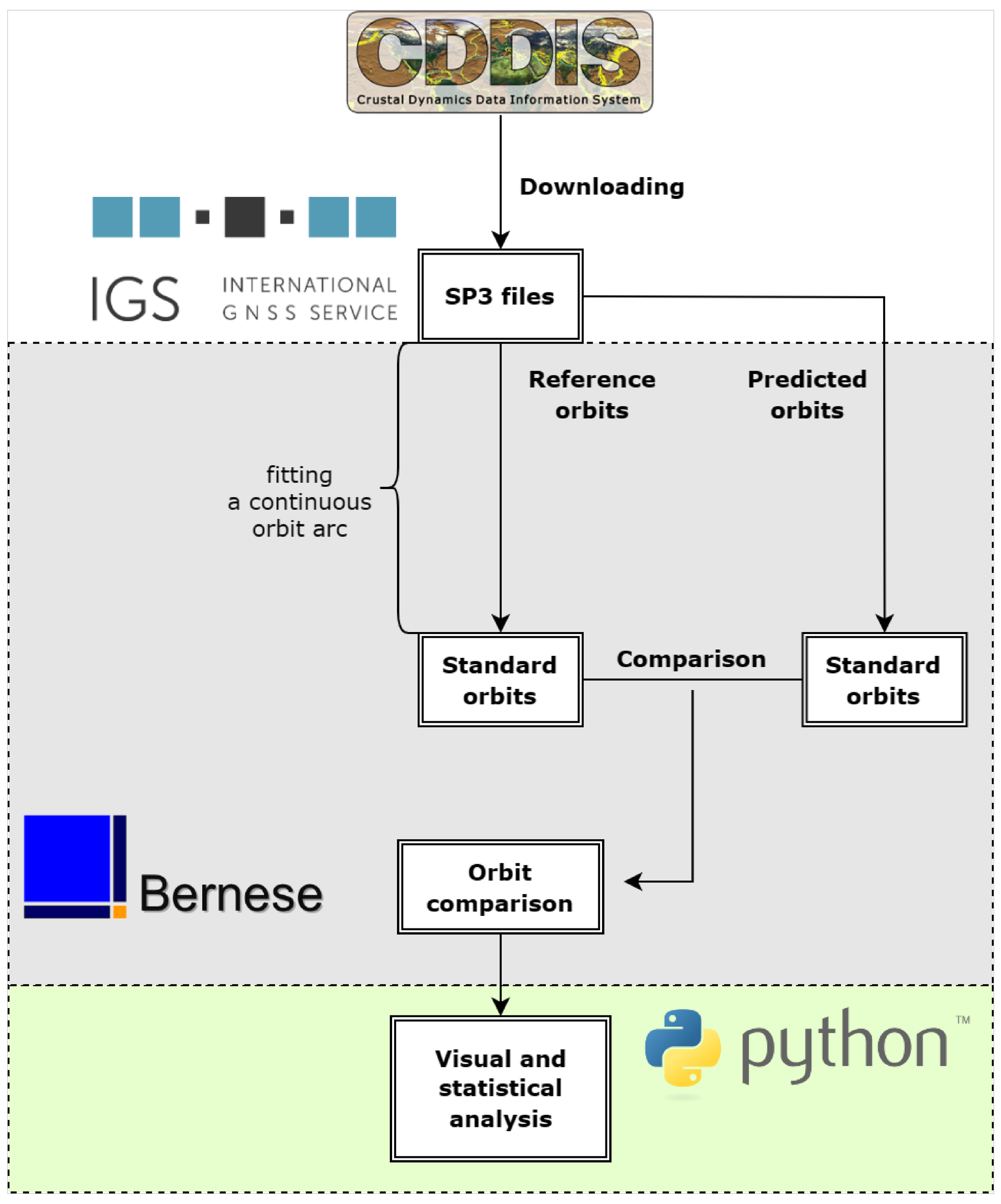

Fig. 1. Scheme of data processing.

Solution	Box-wing	Empirical orbit parameters (ECOM2)
E5	✗	D_0, Y_0, B_0 + B_S, B_C
E7	✗	E5 + D_{2C}, D_{2S}
E9	✗	E7 + D_{4C}, D_{4S}
B_E5	✓	D_0, Y_0, B_0 + B_S, B_C
B_E7	✓	E5 + D_{2C}, D_{2S}
B_E9	✓	E7 + D_{4C}, D_{4S}

Tab. 1. The characteristics of the orbit modeling in different predictions.

Optimizing the GNSS orbit prediction accuracy

1. Impact of the initial orbital arc fit

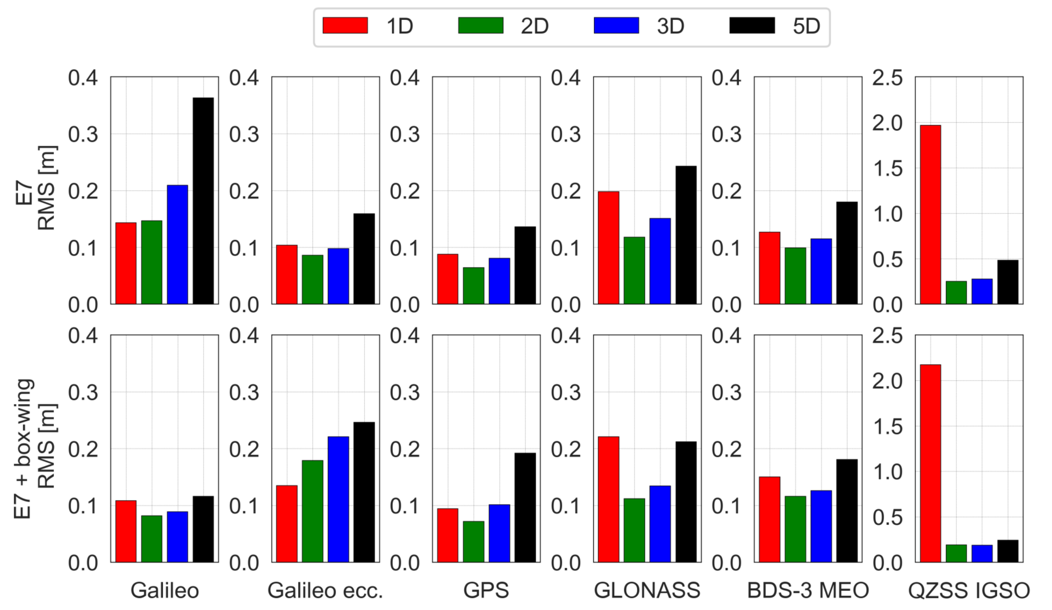

Fig. 2. Impact of the arc length of the initial orbit fit on the quality of the prediction on the 1st prediction day (the impact of ERP error is neglected).

Four solutions are evaluated based on the arc lengths of 1, 2, 3, and 5 days. **Fig. 2** shows the RMS values for the 3D spatial vector for solutions based solely on the ECOM2 with 7 parameters (E7, top) and in a hybrid configuration: 7-parameter ECOM2 with a box-wing model (bottom). The results of the analysis indicate that a 2-day arc fit is an optimal solution for all systems. Furthermore, it was found that extending the orbital arc beyond 2-days does not significantly improve the solution.

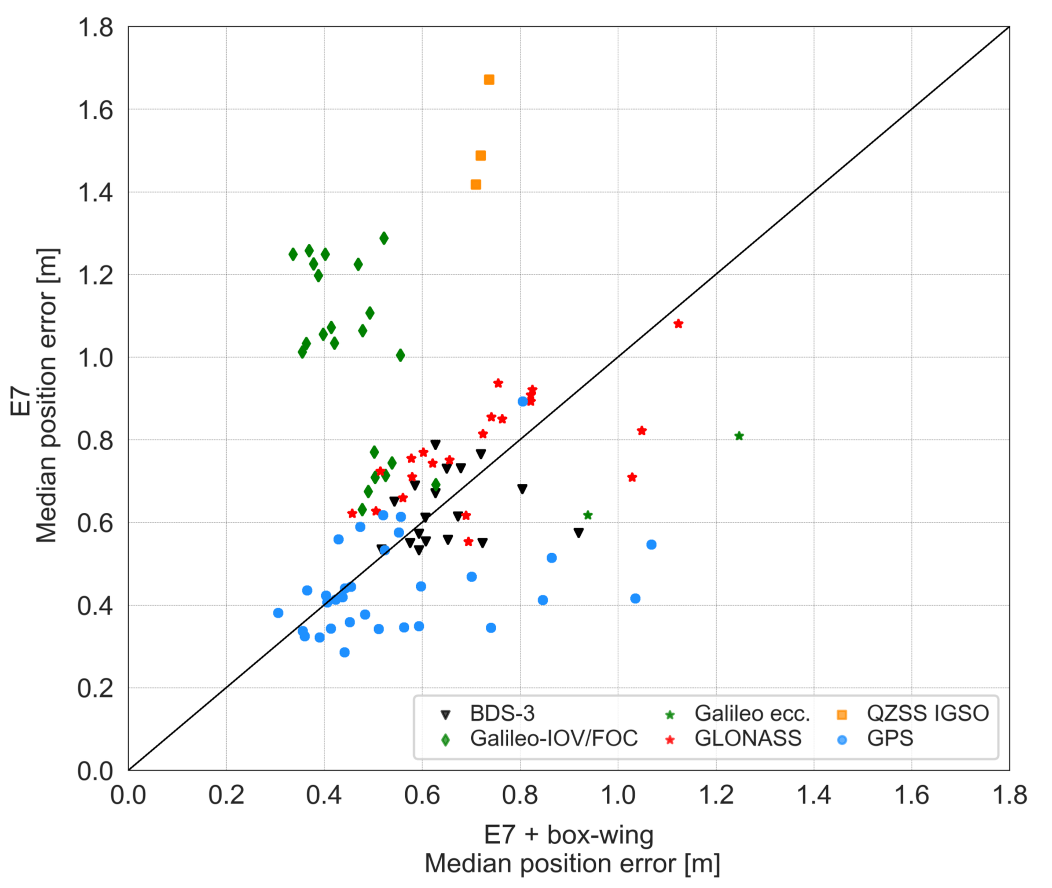

Fig. 3. Median position error for all satellites and the 4th day of the prediction (the impact of ERP error is neglected).

2. Impact of the SRP modeling

The detailed characteristics of each solution are provided in **Tab. 1**. **Fig. 3** illustrates the median position error for the solution incorporating ECOM2 with 7 parameters (y-axis) in comparison to the values obtained for the corresponding hybrid solution with the box-wing model applied (x-axis). Points above the diagonal indicate that the solution incorporating the a priori box-wing model achieves lower errors than the empirical ECOM2. The results indicate that **using a box-wing model substantially improves the accuracy of predictions for systems that provide official detailed metadata, such as Galileo and QZSS**. Conversely, the simplified satellite parameters have a minimal impact on the quality of predictions for GPS, BeiDou-3, and GLONASS. The initial 24 hours of prediction for individual satellites from the groups exhibit a degradation in quality (see **Fig. 4**).

Tab. 2. shows the optimal orbit parameterization for predicting the orbits using different modeling of the SRP for individual representative satellites from the groups for the 1st and 4th day of the prediction (median position error of the 3D spatial vector).

Type	Satellite (SVN)	Median position error [cm]		Best solution for modeling
		1st day	4th day	
GPS-IIR	G061	8	39	E5/E7/E9
GPS-IIR-M	G050	6	40	B_5/B_7/B_9/E5/E7/E9
GPS-IIF	G073	6	32	E5/E7/E9
GPS-III	G077	6	50	B_5/B_7/B_9/E5/E7/E9
Galileo-1 IOV	E103	12	51	B_5/B_7/B_9
Galileo-2 FOC (ecc. orbit)	E201	7	62	E7/E9
Galileo-2 FOC	E222	8	51	B_5/B_7/B_9
GLONASS-M	R852	10	58	B_5/B_7/B_9
GLONASS-M+	R859	8	73	B_5/B_7/B_9
GLONASS-K	R802	10	70	E5/E7
BDS-3 SECM	C208	8	52	E5/E7
BDS-3 CAST	C206	10	58	B_5/B_7/B_9/E5/E7/E9
QZSS IGSO	J002	15	71	B_5/B_7/B_9

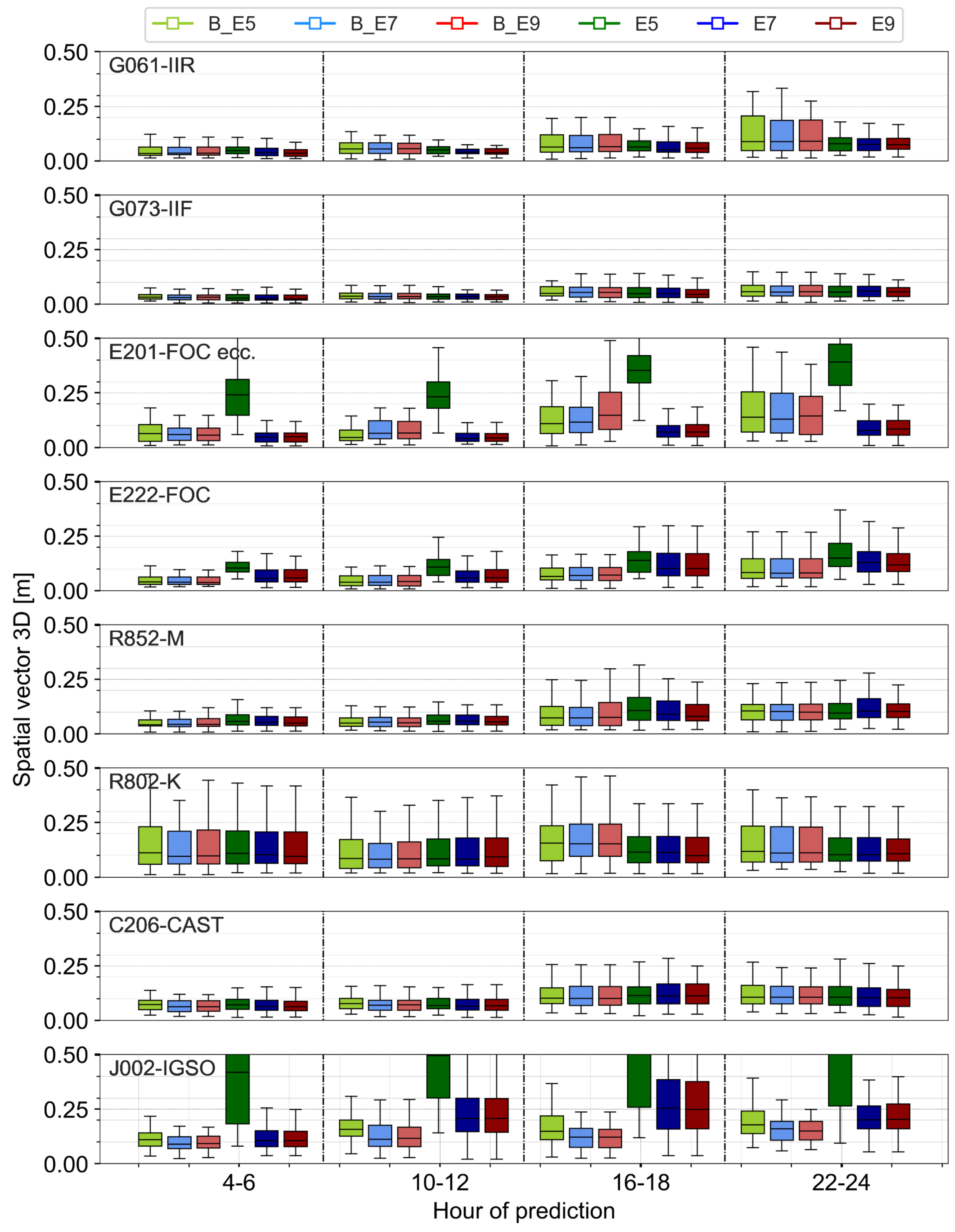

Fig. 4. Degradation in the quality for the initial 24 hours of predictions for individual satellites representing different groups.

3. Impact of the Earth Rotation Parameters

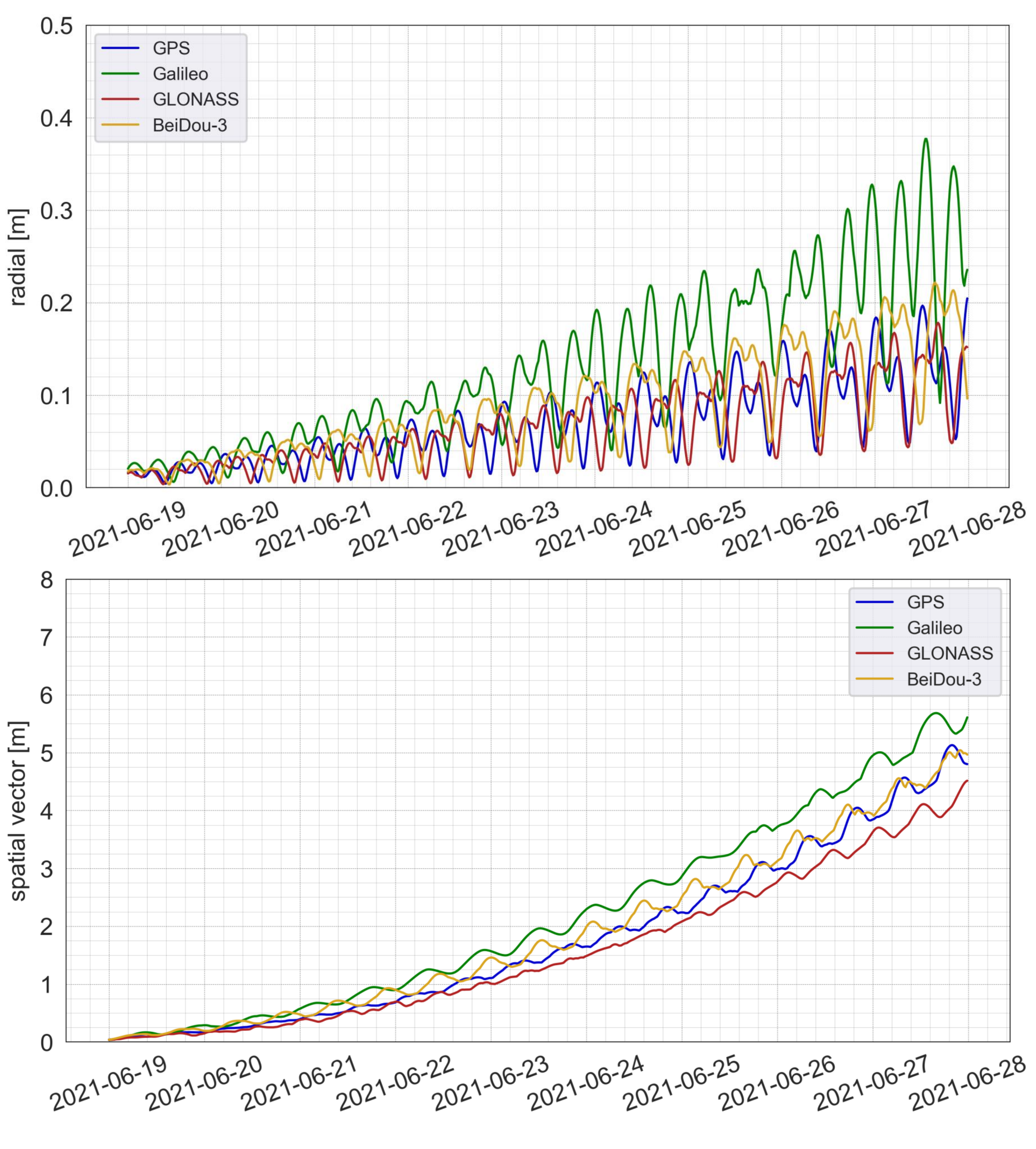

Fig. 5. The differences in the quality of orbit prediction between the series using either IERS C04 or IERS Bulletin A for radial (top) and 3D spatial vector (bottom).

Fig. 5 illustrates the impact of using ERP predictions from the International Earth Rotation and Reference Systems Service (IERS Bulletin A) instead of operational final products (IERS C04) on the orbit predictions. The analysis was conducted for all satellites considering a 9-day prediction with a 2-day fit of the initial arc and box-wing models + 7-parameter ECOM2 for SRP modeling. The results are averaged for all satellites in each constellation, namely GPS, GLONASS, Galileo, and BeiDou-3 MEO.

The impact of the ERP error depends directly on the orbital altitude. Therefore, the error is largest for Galileo (altitude of about 23 200 km) and decreases for lower altitudes as follows: BeiDou-3 (21 500 km), GPS (20 200 km), and GLONASS (19 130 km). In addition to the effect of orbital altitude, the instantaneous position of the Earth satellite also plays a role. This is reflected in the temporal variation in the magnitude of the orbit prediction error resulting from the ERP error.

Signal-in-space range error

Fig. 6 shows the quality of the 24h orbit prediction solutions evaluated in terms of the potential user positioning accuracy using the orbital component of the Signal in Space Ranging Error (SISRE). SISRE values are grouped according to each navigation satellite group analyzed and decomposed into the total orbit error, as well as the values reduced to the influence of the radial component. The rapid degradation of the orbit prediction for the along-track component contributes significantly to the total SISRE despite its low weight in orbital SISRE.

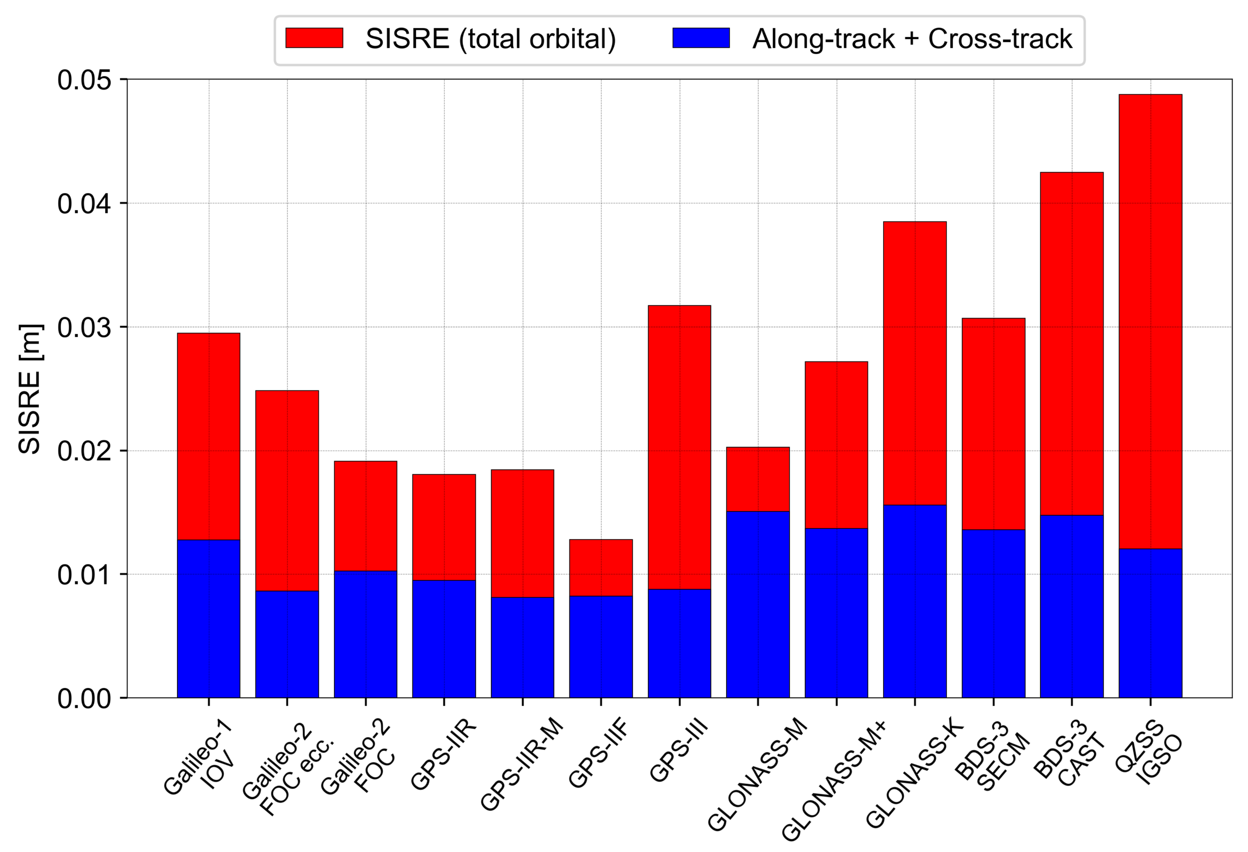

Fig. 6. The 95th percentile position errors for the orbit predictions after 24 h with a decomposition of the orbital Signal-in-Space Ranging Error (SISRE) into subcomponents.

Insights

- Orbit prediction quality for navigation satellites is of special importance to the community that requires the precise orbits for real-time applications. Current predictions offer accuracy up to 1-5 cm after 24h in terms of SISRE (**Fig. 6**).
- The optimal method for predicting the orbits is to fit a 2-day orbital arc.
- For the majority of GNSS satellite types, using ECOM2 with 7 parameters provides the best predictions. The most effective SRP modeling varies depending on the specifications of each group of satellites (see **Tab. 2**).
- For Galileo and QZSS with high-quality metadata (satellite surface properties: absorption, reflection, dispersion coefficients), using the box-wing model with ECOM2 leads to the best prediction results with the improvement even of a factor of 3 (**Fig. 3**). This is not the case for constellations without detailed metadata: GLONASS, BeiDou-3, and GPS. **Having high-quality metadata is essential.**

Reference

Nowak A, Zajdel R, Sośnica K (2023)
Optimization of orbit prediction strategies for GNSS satellites
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