A refined non-gravitational force modelling for GPS and Galileo satellites with a focus on orbit prediction

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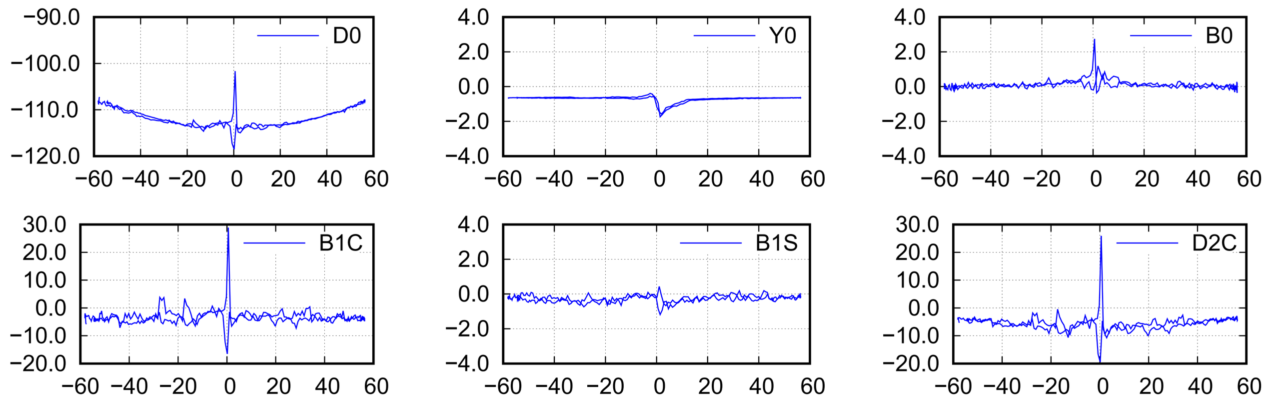


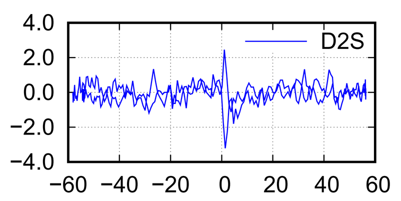


Fig. 1: ECOM2 parameters [nm/s²] for Galileo E26 estimated over one year and plotted against β-angle. β-dependency of the estimated SRP parameters can be seen. The parameters are poorly defined when β is close to 0°.

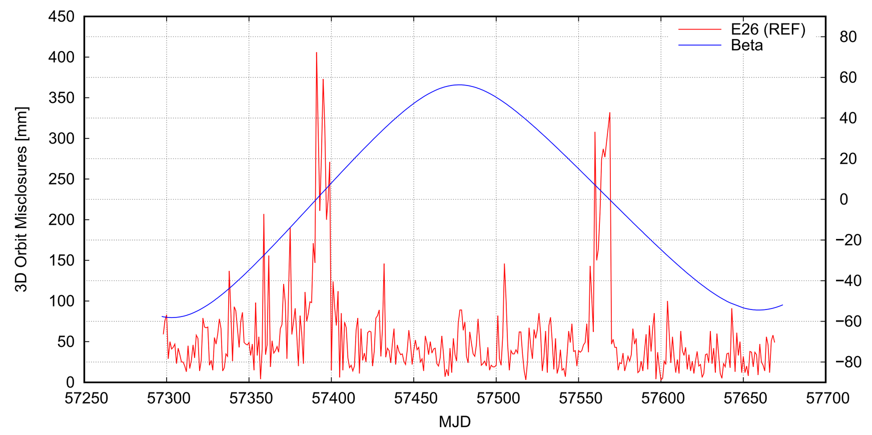


Fig. 2: 3d orbit misclosures of Galileo E26 in Oct. 2015 - Oct. 2016. ECOM2 is used, no stochastic pulses are allowed.

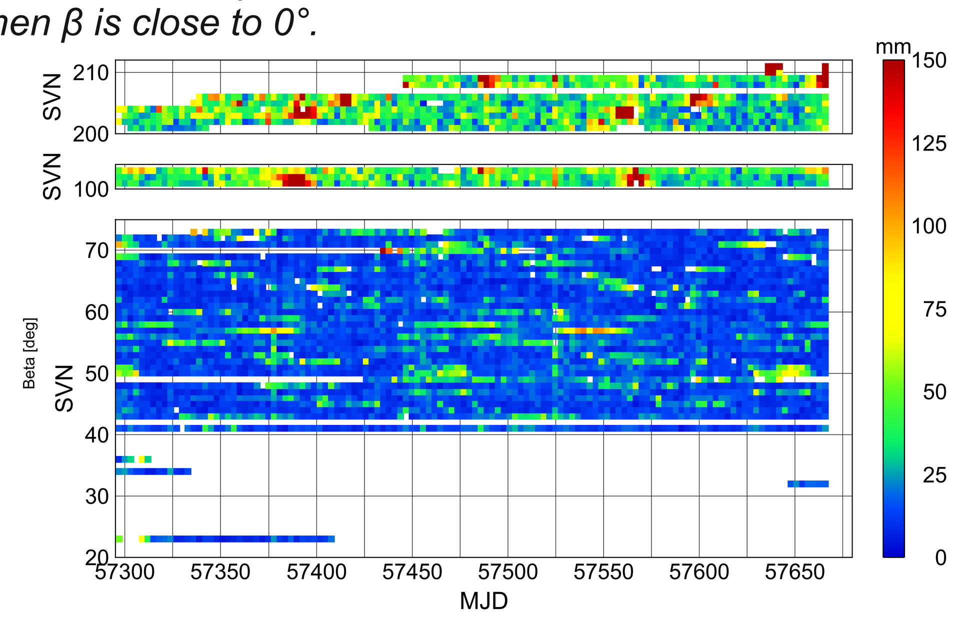


Fig. 3: 3d orbit misclosures of GPS (SVNs: 34-73), Galileo IOV (SVNs: 101-103) and FOC (SVNs: 201-213) satellites when ECOM2 is applied. Elevated orbit misclosures are observed for both GPS and Galileo satellites.

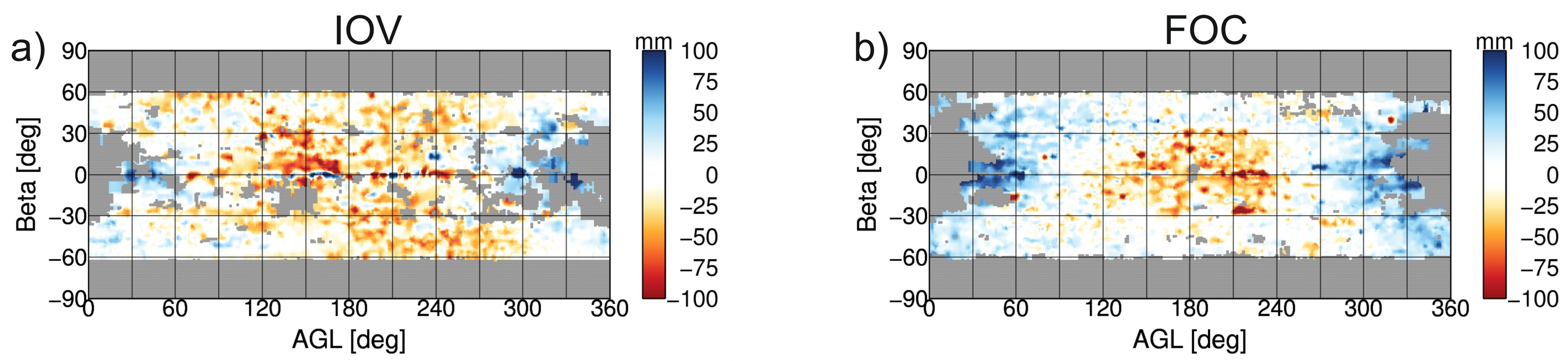


Fig. 4: SLR residuals for Galileo IOV and FOC satellites computed over Oct. 2015 - Oct. 2016 using ECOM2.

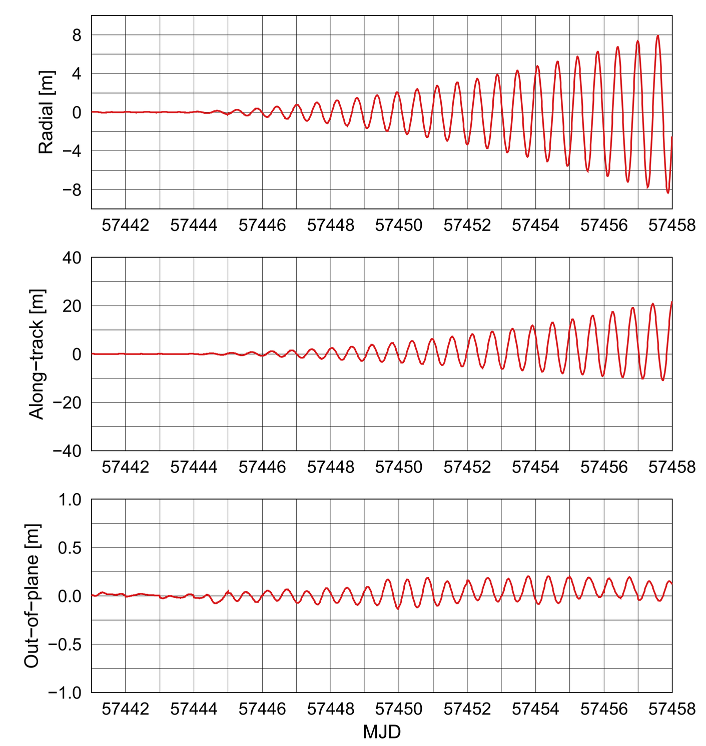


Fig. 5: Evolution of orbit prediction error for Galileo E26 in radial, along-track and out-of-plane directions over 14 days. The first three days are used to estimate initial conditions and SRP parameters. ECOM2 is used for SRP modelling.

Orbit part of SISRE is computed using

$$SISRE_{ORB} = \sqrt{w_R^2 \cdot R^2 + w_{A,C}^2 \cdot (A^2 + C^2)}$$

GNSS	w_R^2	$w_{A,C}^2$
Galileo	0.9674	0.0163
GPS	0.9593	0.0203

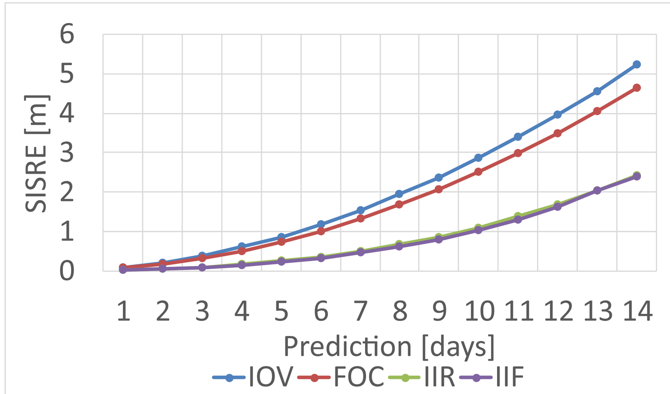


Fig. 6: SISRE evolution over 14 days computed using predicted orbits. ECOM2 is used for SRP modelling.

Introduction

Between 2011 and 2019 the European Global Navigation Satellite System (GNSS) Galileo was built up. Meanwhile the full 24 satellite constellation is available to the user segment. A specific characteristic of the Galileo satellites is their low weight compared to the other GNSS satellites. This makes them in particular sensitive to non-gravitational forces. The solar radiation pressure (SRP) is the biggest one and needs careful modelling. For the Galileo satellites also other effects (e.g., thermal radiation) that are typically neglected for other GNSS satellites, become relevant.

The present study is initiated by ESA and is targeting to develop more advanced approaches to model SRP acting on GPS and Galileo satellites for long-term orbit prediction.

Problem Description

- Modelling deficiencies persist, in particular, for Galileo satellites during eclipse seasons (*β* close to 0°). The unaccounted thermal radiation effects that remain active in the Earth shadow contribute to these deficiencies. The ECOM2 SRP coefficients for E26 estimated during 10/2015 - 10/2016 in the combined GPS and Galileo processing are shown in **Fig. 1**.
- The modelling errors are amplified in multi-day orbital arc solutions, when the use of ECOM2 alone is clearly insufficient. **Fig. 2** shows orbit misclosures of E26 from 3-day solutions (the middle day is extracted). **Fig. 3** shows an overview of orbit misclosures of GPS and Galileo satellites computed over a year.
- The SRP modelling deficiencies are also seen in SLR residuals, suggesting orbit deformations at low *β*-angles, **Fig. 4**.
- The instability of ECOM2 parameters over time results in rapidly growing orbit prediction errors, **Fig. 5**. Signal-in-space range error (SISRE) of predicted orbits suggests more pronounced modelling errors for the Galileo rather than for the GPS satellites, **Fig. 6**.

SRP Modelling Approach

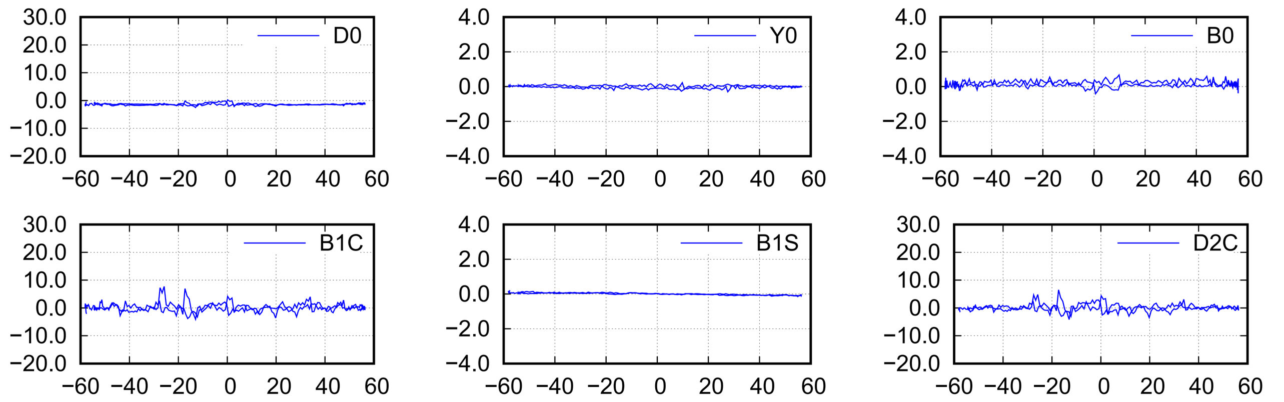
Basic idea: **a priori box-wing model + adjusted ECOM2**

Two types of a priori models have been evaluated:

- **EMP-BW** models - box-wing models (for GPS Block IIR, IIF, Galileo IOV and FOC satellites) based on the computed set of ECOM2 coefficients;
- **RT** models - a priori models based on a comprehensive ray-tracing analysis.

Results

- *β*-dependency of the estimated empirical parameters is significantly reduced, improving their stability over time, **Fig. 7**.
- The computed orbit misclosures suggest that the employed approaches for SRP modelling allow for a significant improvement in orbit modelling during eclipse seasons, **Fig. 8**. The GPS orbit misclosures are also reduced, **Fig. 9**.
- SLR residuals suggest notable reduction of orbit deformations during eclipse seasons using EMP-BW models, **Fig. 10(a,b)**. Performance comparison of EMP-BW and RT models for Galileo FOC satellites indicates that some (possibly thermal) effects are not accounted by the RT models, **Fig. 10(c)**.
- Orbit prediction errors are considerably reduced, **Fig. 11**.
- The non-conservative (e.g., thermal) forces that remain unaccounted by the RT-based models have an impact on orbit prediction results, **Fig. 12**.



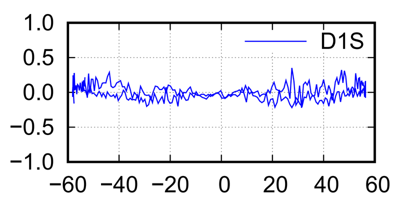


Fig. 7: ECOM2 parameters [x10⁻⁹nm/s²] for Galileo E26 estimated over one year and plotted against β-angle. A priori EMP-BW model is applied complemented by adjusted ECOM2.

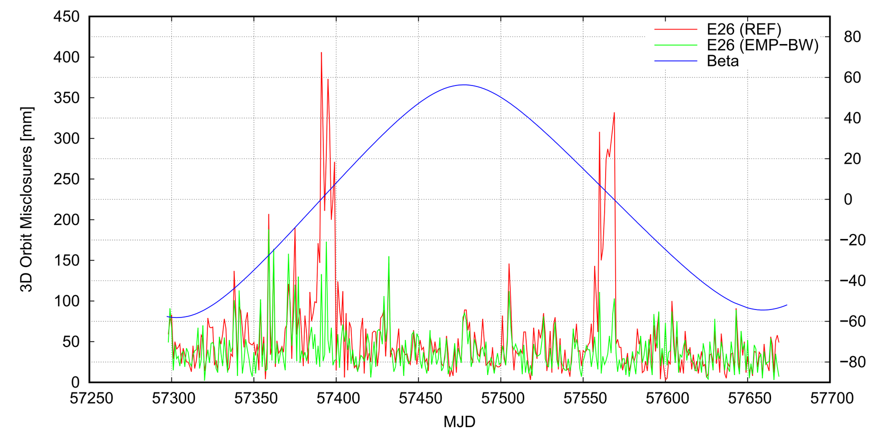


Fig. 8: 3d orbit misclosures of Galileo E26 in Oct. 2015 - Oct. 2016. ECOM2 (REF) and a priori EMP-BW complemented by adjusted ECOM2 (EMP-BW) are used, no stochastic pulses are allowed.

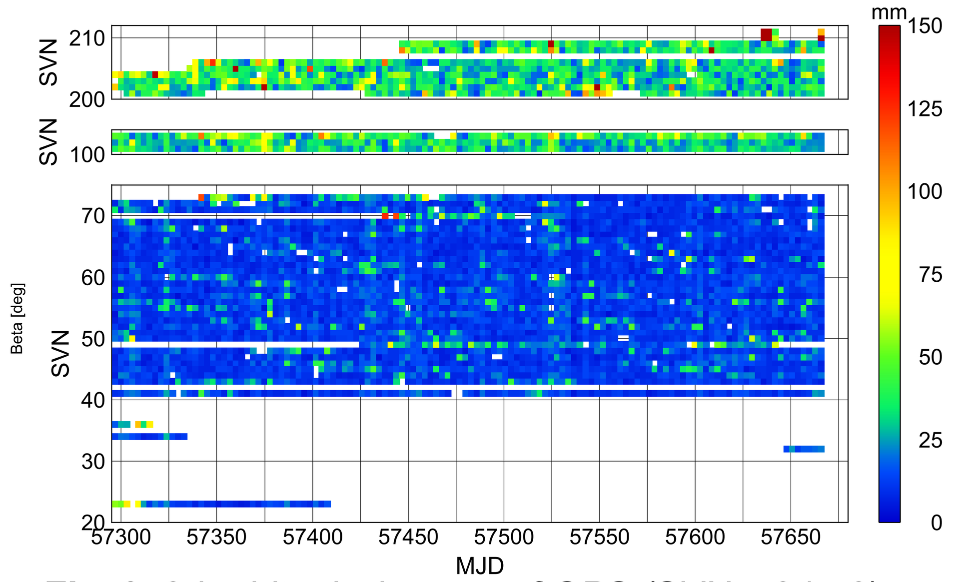
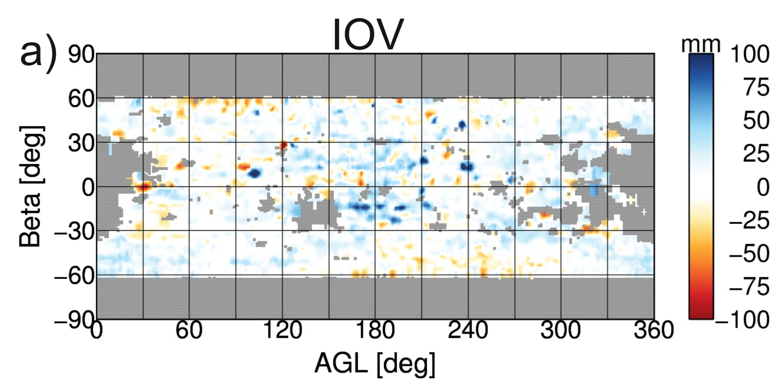


Fig. 9: 3d orbit misclosures of GPS (SVNs: 34-73), Galileo IOV (SVNs: 101-103) and FOC (SVNs: 201-213) satellites when a priori EMP-BW and adjusted ECOM2 is used. The orbit misclosures remain small also during eclipse seasons (compare to Fig. 3).



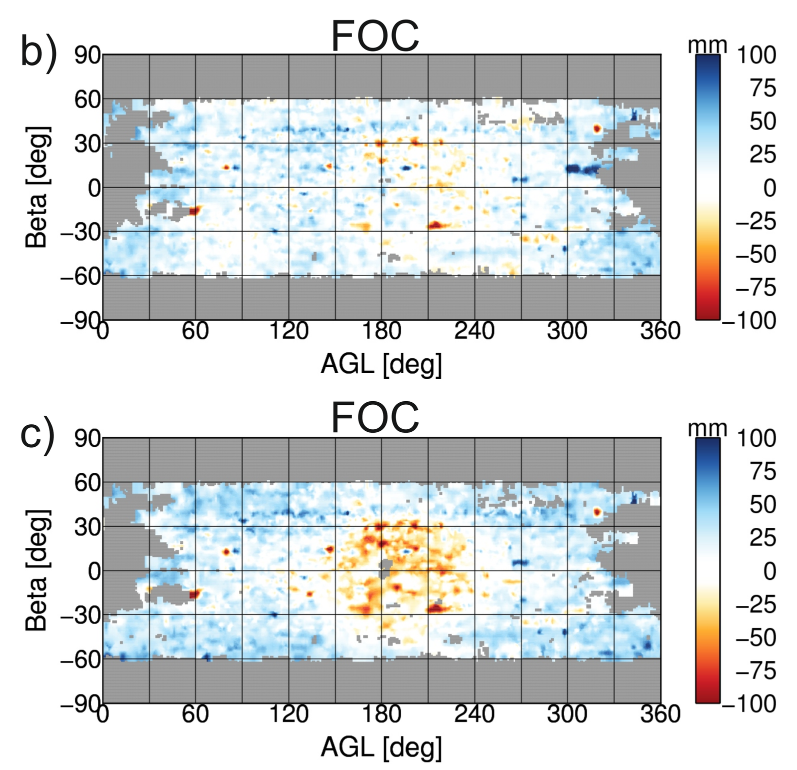


Fig. 10: SLR residuals for Galileo IOV and FOC satellites computed over Oct. 2015 - Oct. 2016 using a priori EMP-BW (a,b) and RT models (c) complemented by adjusted ECOM2.

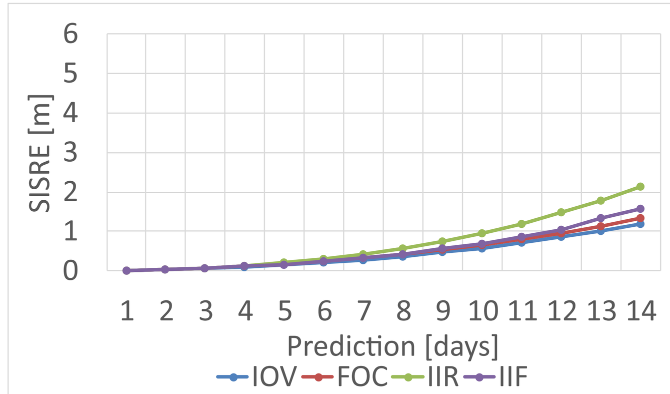


Fig. 11: SISRE evolution over 14 days computed using predicted orbits. A priori EMP-BW models complemented by adjusted ECOM2 are used for SRP modelling.

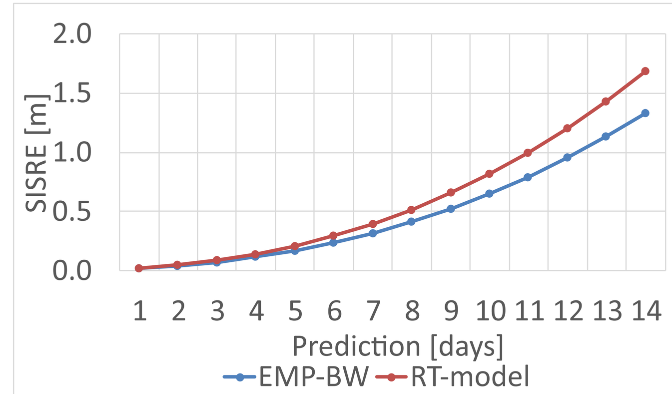


Fig. 12: SISRE evolution over 14 days computed using predicted orbits. Performance of EMP-BW and RT models as a priori is compared.

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