Improved orbit modelling of Galileo satellites during eclipse seasons

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Introduction

The solar radiation pressure (SRP) is the largest non-conservative force that impacts the GNSS satellites. Because of the dependency on area-to-mass ratio, Galileo satellites are notably sensitive to such forces due to their low weight. In particular, orbit modelling complications arise at low angles of the Sun direction w.r.t. the satellite orbital plane (β). During these periods not only different faces of the satellites are periodically illuminated, but also their cross-sectional area w.r.t. the Sun direction reaches its extreme values. In addition to the SRP, thermal radiation (TR) is a non-negligible effect in particular for Galileo satellites. In contrast to SRP it acts also on the satellite during its crossing of the Earth's shadow.

Related modelling deficiencies of Galileo satellites may be visible in:

- elevated orbit misclosures at day boundaries (**Fig. 1**),
- degradations in satellite clock modelling, e.g., represented as linear clock fit (**Fig. 2**),
- error propagation to other constellations (**Fig. 3**),
- β-dependent variations in scattering of SLR residuals seen at various analysis centers to a different extent (**Fig. 4**)

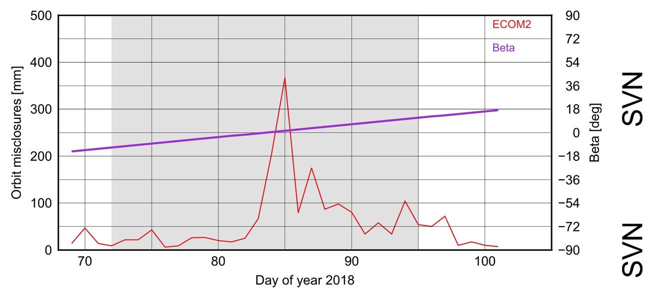

Fig. 1: 3d orbit misclosures of E07 when ECOM2 is used, the shaded area indicates an eclipse season.

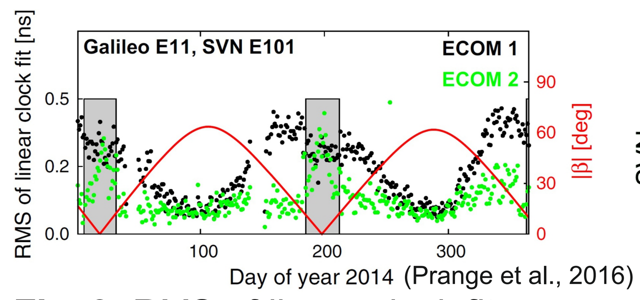

Fig. 2: RMS of linear clock fit computed using ECOM and ECOM2. Orbit modelling problems are apparent during eclipse seasons. β-dependency is reduced using ECOM2.

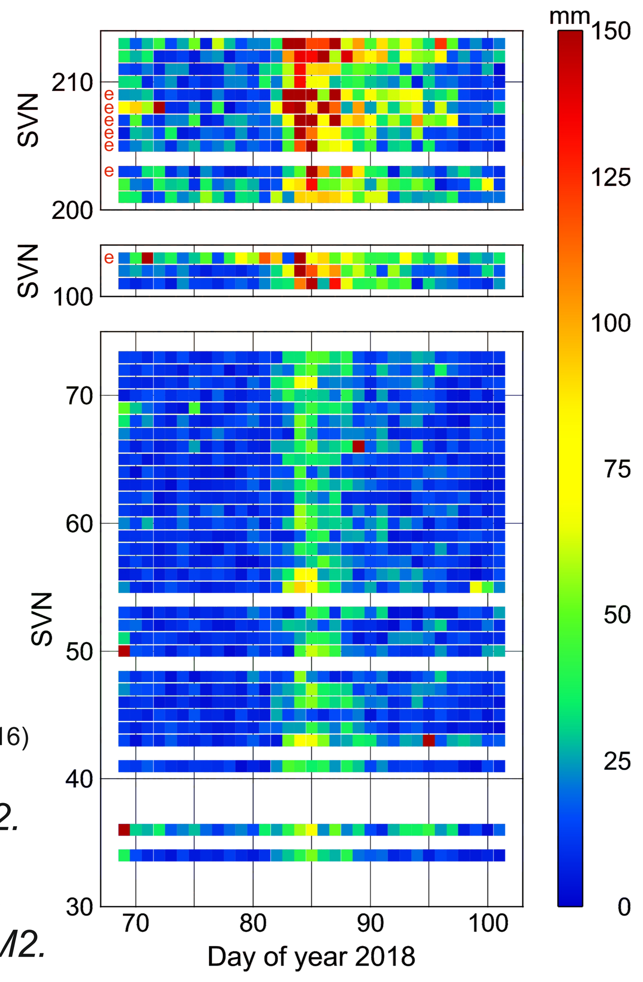

Fig. 3: 3d orbit misclosures of GPS (SVNs: 34-73), Galileo IOV (SVNs: 101-103) and FOC (SVNs: 201-213) satellites when ECOM2 is applied. Insufficient SRP and TR modelling of seven eclipsing Galileo satellites (marked with "e") affects other constellations.

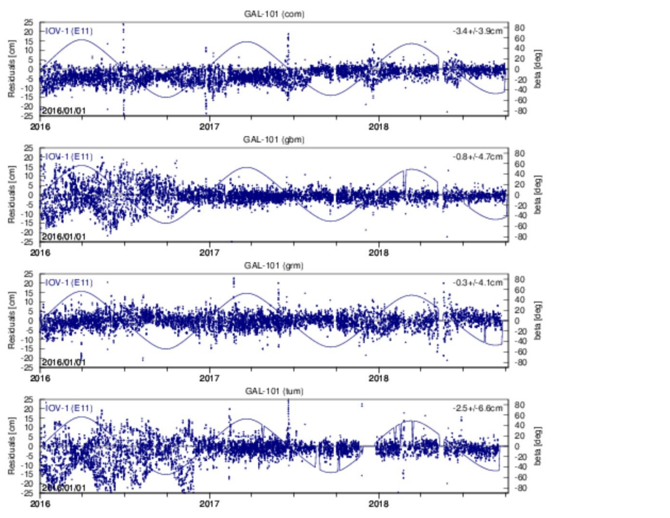

Fig. 4: SLR assessment of E11 orbits computed by four analysis centers (URL: http://mgex.igs.org). The scatter of SLR residuals is elevated during eclipse seasons.

Potential origins of the problem

The detailed metadata package published by the European GNSS Agency, made the mass, dimensions, optical properties of the surfaces of Galileo satellites, antenna phase center variations and the attitude law (particularly crucial during eclipse seasons) publicly available.

The Galileo spacecrafts carry thermal radiators that are installed on +X, +Y, -Y faces and +X, +Y, -Y and -Z faces of IOV and FOC satellites, respectively (**Fig. 5**). TR emitted from these radiators creates a non-negligible force along the satellite orbit. In particular, a radiator on +X face (where satellite clocks are installed) at β-angles close to 0° mostly creates a force that acts in the satellite along-track direction (**Fig. 6**). Such a force cannot be fully captured by empirical SRP parameters because they are switched off in eclipse. Simulations show that the force creates harmonic accelerations at low β-angles that diminish with the increase of β when projected in the along-track or in the satellite-Sun directions (**Fig. 7**). The magnitude of the force was empirically estimated.

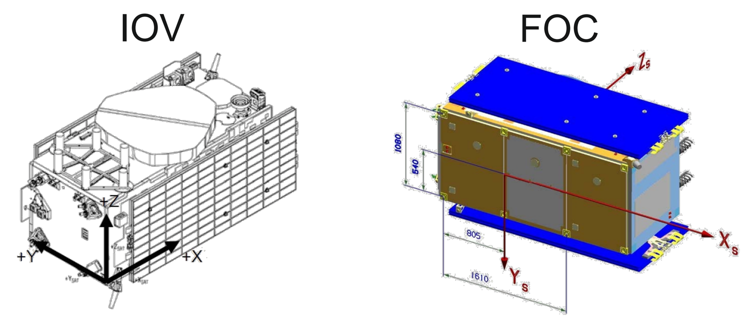

Fig. 5: Galileo satellites (Galileo Satellite Metadata, URL: https://www.gsc-europa.eu). Radiators are installed on +X, +Y, -Y faces and +X, +Y, -Y and -Z faces of IOV and FOC satellites, respectively.

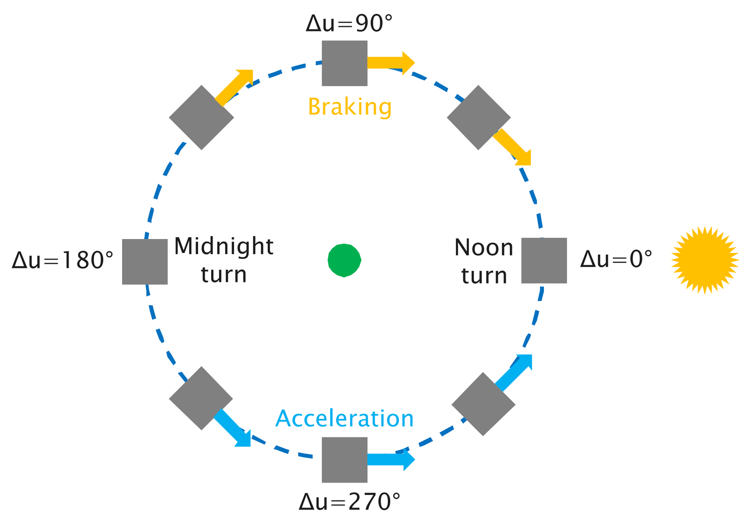

Fig. 6: Visualization of a TR force impact from a +X radiator when β=0°.

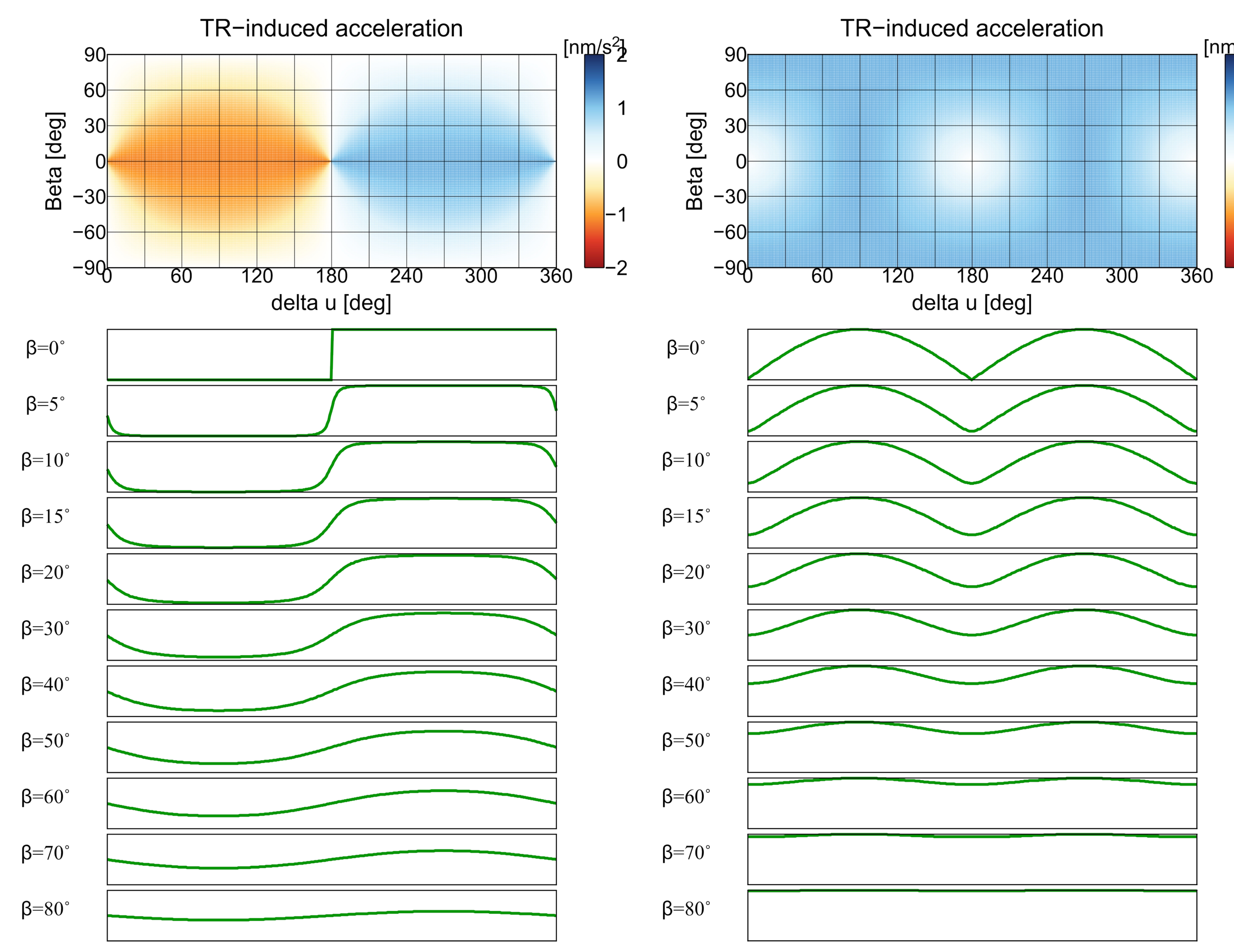

Fig. 7: TR-induced accelerations due to a +X radiator in the satellite along-track (left) and the satellite-Sun (right) directions. Profiles of the TR-induced accelerations at different β-angles are shown in green.

Proposed solution (modifications w.r.t. ECOM2)

- Introduce a constant acceleration equivalent to 300W (approximate power of 2 PHM and 2 Rb clocks) in the satellite +X direction.
- Activate Y0 for FOC satellites also in eclipses to account for different radiator sizes on +Y and -Y faces.
- Introduce D1S during eclipse seasons for Galileo satellites.

Results

The combined GPS and Galileo POD solutions were recomputed using the proposed model changes. Days 70-100 of year 2018 are of particular interest, as seven out of fifteen Galileo satellites during this period were passing the Earth shadow.

The computed orbit misclosures for Galileo satellites during the aforementioned period showed a remarkable improvement w.r.t. the ECOM2-computed solutions. **Fig. 8** compares orbit misclosures computed using both force models for one eclipsing Galileo satellite.

The adjusted force modelling has also resulted in improvements of satellite clock corrections (**Fig. 9**). However, RMS of linear clock fit during eclipse season still remains slightly elevated, indicating that some modelling issues persist.

An outlook of orbit misclosures computed for all GPS and Galileo satellites using the adjusted ECOM2 and covering days 69-102 of year 2018 is shown in **Fig. 10**. Compared to the previously discussed ECOM2 solutions (Fig. 3), the impact of eclipsing Galileo spacecrafts on other satellites is significantly reduced.

The SLR residuals of Galileo orbits computed using ECOM2 and the adjusted ECOM2 bring a closer look at mainly the radial component of the computed solutions (**Fig. 11**). Scattering of the residuals particularly at low β-angles is significantly reduced. However, shrinking at orbit noon and expansion at orbit midnight in the recomputed solutions is still pronounced. The histograms of the computed residuals also suggest that the updated force model outperforms ECOM2 during eclipses (**Fig. 12**).

The time series of the estimated coefficients of the adjusted ECOM2 clearly indicate benefits from the introduced changes. The previously highly uncertain behavior of the coefficients (**Fig. 13**) in eclipses is replaced by more regular and predictable estimates (**Fig. 14**).

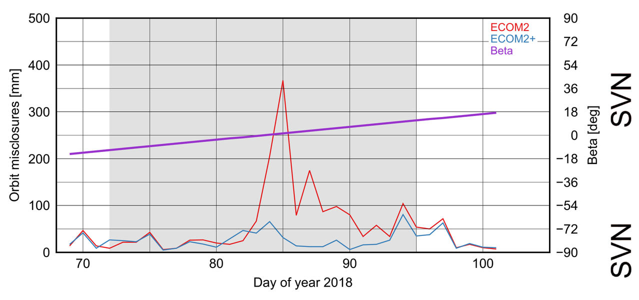

*Fig. 8: Orbit misclosures for E07 using ECOM2 and **adjusted ECOM2**.*

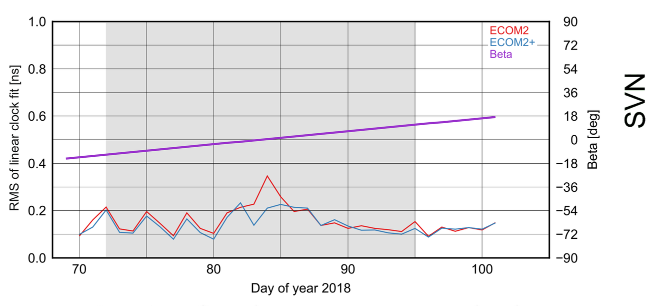

*Fig. 9: RMS of linear clock fit for E07 using ECOM2 and **adjusted ECOM2**.*

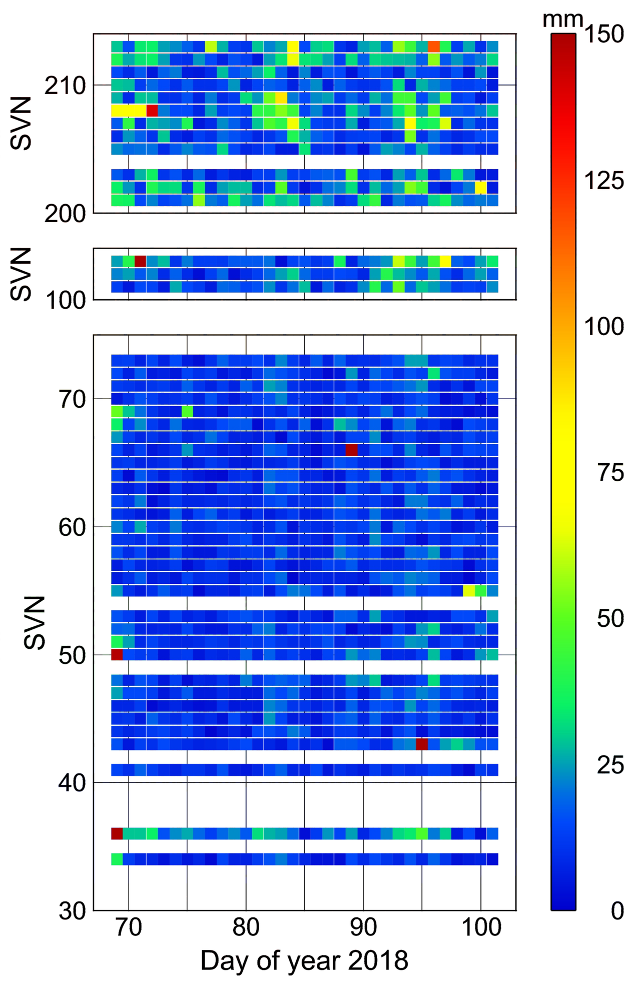

*Fig. 10: 3d orbit misclosures of GPS (SVNs: 34-73), Galileo IOV (SVNs: 101-103) and FOC (SVNs: 201-213) satellites when **adjusted ECOM2** is applied (compare to Fig. 3).*

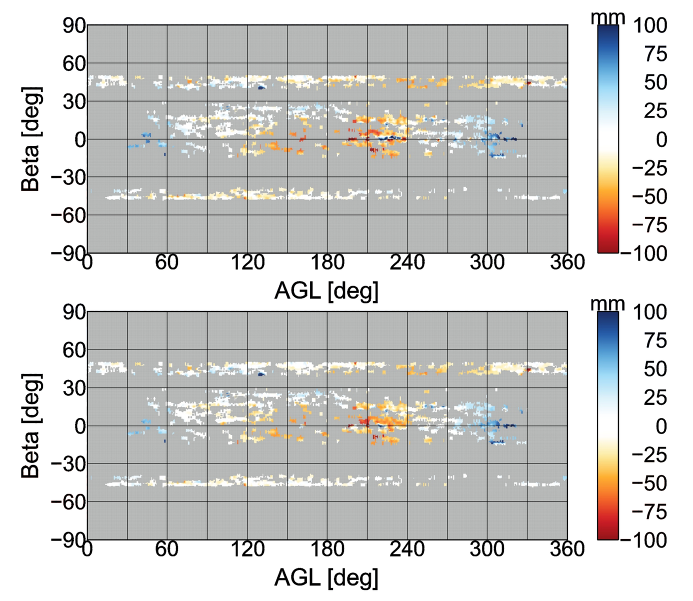

*Fig. 11: SLR residuals of Galileo orbits computed using ECOM2 (top) and **adjusted ECOM2** (bottom) over days 70-101 of 2018.*

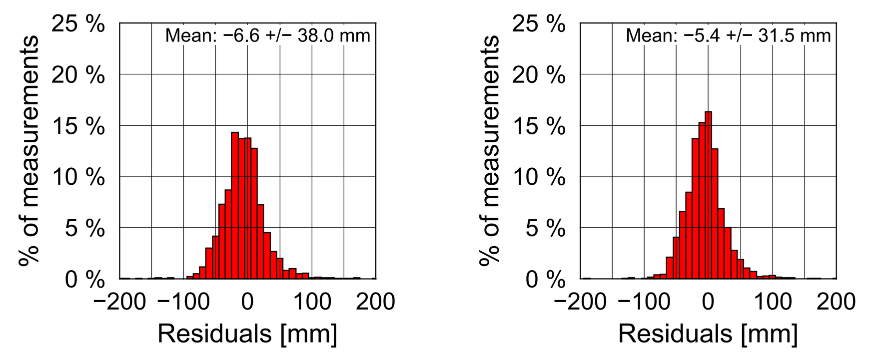

*Fig. 12: Histograms of SLR residuals of Galileo orbits computed using ECOM2 (left) and **adjusted ECOM2** (right) over days 70-101 of 2018.*

Summary

- The derived modifications to the existing ECOM2 are aimed to address thermal forces acting on Galileo satellites.
- If left unaccounted, the thermal effects may significantly deteriorate the estimated orbits.
- The proposed model changes significantly improve orbit modelling during eclipse seasons for Galileo satellites showing the high value of available spacecraft metadata.

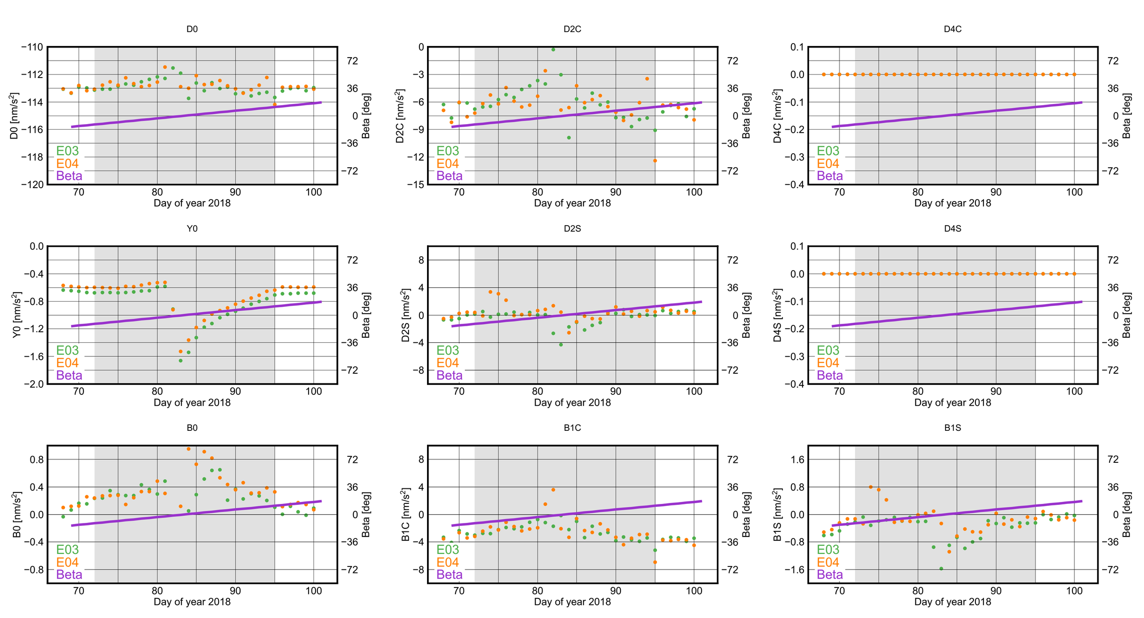

Fig. 13: SRP coefficients of ECOM2 for E03 and E04 estimated over days 68-100 of 2018. Note that D4 terms are constrained. The elevated scattering of the estimated coefficients is particularly observed when β is close to 0°. In turn, this suggests the presence of high correlations and an exchange among the coefficients in attempt to absorb the unaccounted forces.

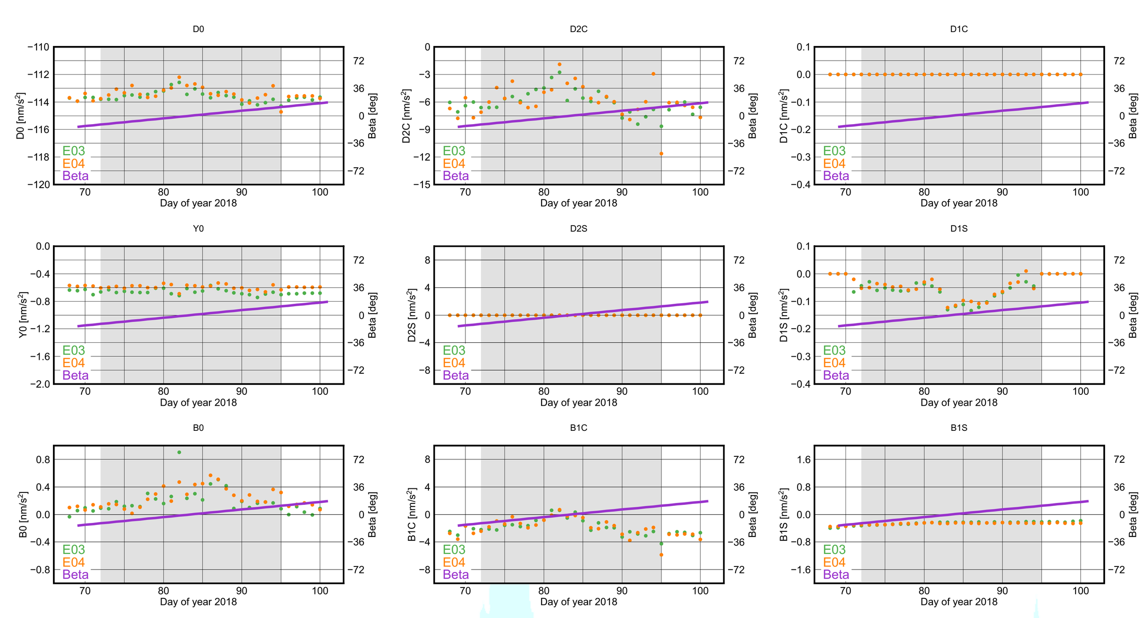

*Fig. 14: SRP coefficients of the **adjusted ECOM2** for E03 and E04 estimated over days 68-100 of 2018. The introduced modifications significantly reduce scattering of the coefficients during the entire eclipse phase. Note that the **D1S** term being relatively small has a similar shape for both satellites.*

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