Enhanced orbit modelling of eclipsing Galileo satellites

7-th International Colloquium on Scientific and Fundamental Aspects of GNSS
4-6 Sep. 2019, Zurich, Switzerland

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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**),
- β-dependent variations in scattering of SLR residuals seen at various analysis centers to a different extent - the longer the employed orbital arc, the bigger the effect (**Fig. 3**).

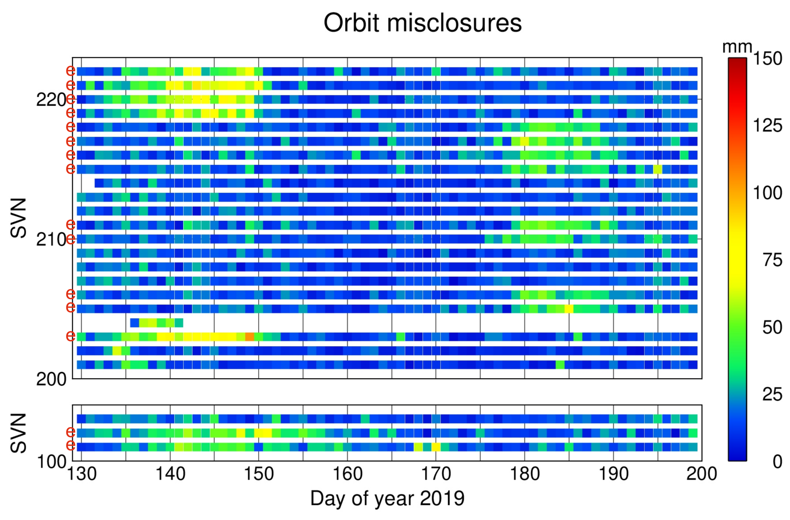

***Fig. 1**: 3d orbit misclosures of Galileo IOV (SVNs: 101-103) and FOC (SVNs: 201-222) satellites when ECOM2 is applied. Insufficient SRP and TR modelling of eclipsing Galileo satellites (marked with "e") results in elevated orbit misclosures. Overall, 15 Galileo satellites are affected during days 130-200 of 2019.*

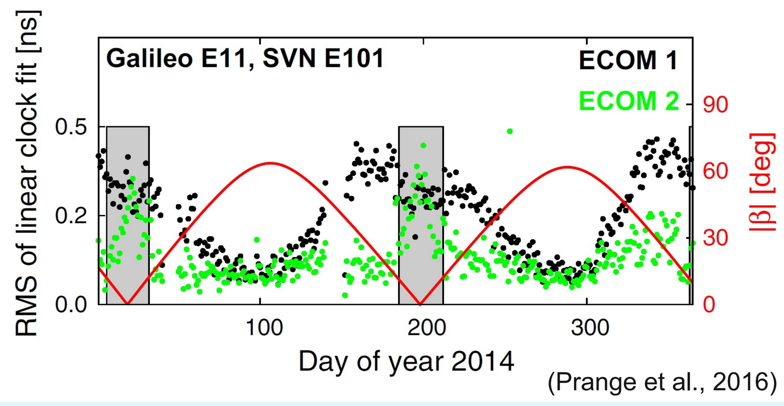

***Fig. 2**: RMS of linear clock fit computed using ECOM and ECOM2. No stochastic pulses estimated. Orbit modelling problems are apparent during eclipse seasons. β-dependency is reduced using ECOM2.*

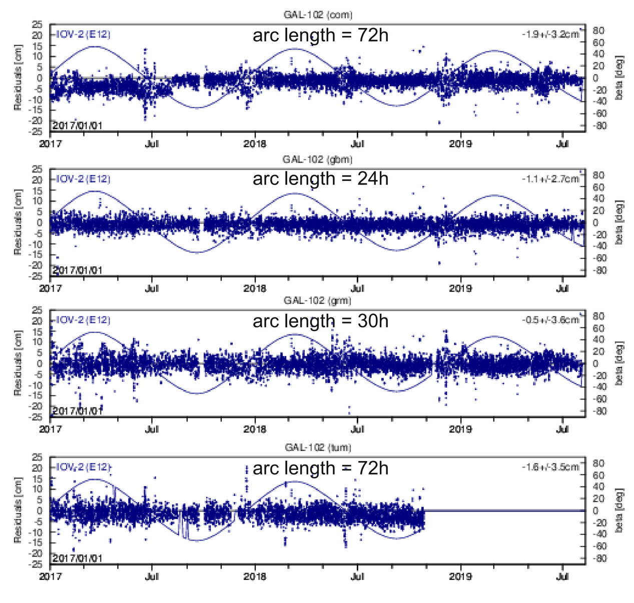

***Fig. 3**: SLR assessment of E12 orbits computed by four analysis centers (URL: http://mgex.igs.org). The scatter of SLR residuals is elevated during eclipse seasons and depends on the employed arc length.*

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 (manufacturer-specific SC-frame, i.e., not IGS-defined SC-frame) of IOV and FOC satellites, respectively (**Fig. 4**). 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. 5**). 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. 6**). The magnitude of the force was empirically estimated.

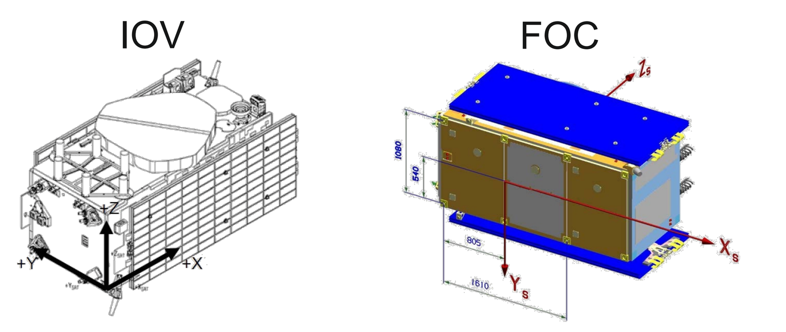

***Fig. 4**: Galileo satellites (Galileo Satellite Metadata, URL: https://www.gsc-europa.eu). Radiators are installed on +X, +Y, -Y faces and +X, +Y, -Y and -Z faces of IOV and FOC satellites, respectively.*

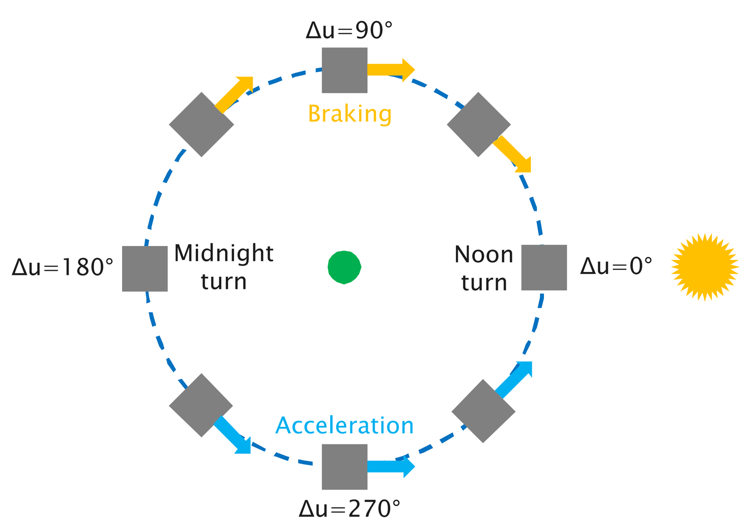

***Fig. 5**: Visualization of a TR force impact from a +X radiator when β=0°.*

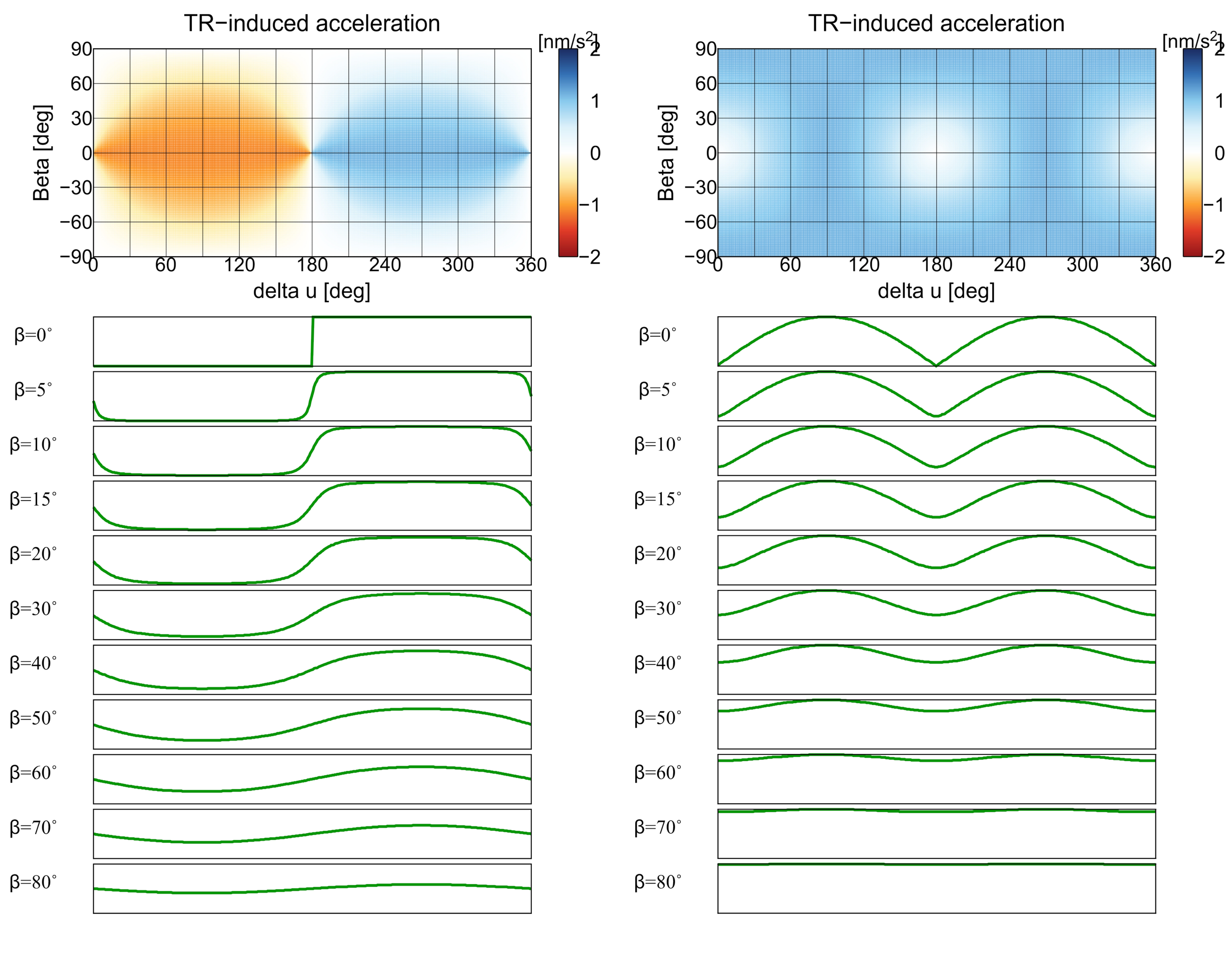

***Fig. 6**: TR-induced accelerations due to a +X radiator in the satellite along-track (left) and the satellite-Sun (right) directions. Profiles of the TR-induced accelerations at different β-angles are shown in green.*

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

- Introduce a constant acceleration equivalent to 300W (approximate power of 2 PHM and 2 RAFS 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

As a basis for the experiment, the CODE MGEX processing sequence was selected. Days 130-200 of year 2019 are of particular interest, as this period covers two eclipse seasons for Galileo, during which 15 satellites in total are affected. Two sets of MGEX solutions (orbits and clocks) were computed and analyzed for this period: using ECOM2 and adjusted ECOM2 for Galileo satellites.
The computed orbit misclosures for Galileo satellites during the aforementioned period showed a remarkable improvement w.r.t. the ECOM2-computed solutions. **Fig. 7** shows an outlook of orbit misclosures for Galileo satellites during the two eclipse seasons.
The stochastic orbital parameters, being instantaneous velocity changes in radial, along-track and out-of-plane directions were also estimated for Galileo satellites in both POD runs with a sampling of 12 hours. These so called pulses are aimed to absorb accelerations that remain unaccounted by the selected orbit model. **Fig. 8** shows stochastic pulses for 15 Galileo satellites during their eclipse seasons. The use of adjusted ECOM2 leads to a notable reduction of the magnitude of the pulses in both the radial and along-track directions.
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. The histograms of the computed residuals, **Fig. 9**, suggest that the updated force model outperforms ECOM2 during eclipses. In particular, scattering of the residuals particularly at low β-angles is reduced by approx. 13.5%.
High stability of the Galileo PHM clocks allows for an indirect assessment of the satellite orbit quality. For this reason we have also performed satellite and receiver clock estimation using the computed orbits. Then the stability of the estimated clocks of the eclipsing Galileo satellites was assessed based on the analysis of the RMS of linear clock fits during the aforementioned period. In agreement with the SLR residuals, the adjusted force modelling has also resulted in improvements of the Galileo satellite clock corrections. **Fig. 10** shows RMS of linear clock fits for E01 over one eclipse season, indicating systematic improvements of the estimated satellite clock corrections due to the adjusted force modelling. The overview of the estimated RMS of linear clock fits for other eclipsed Galileo satellites is shown in **Fig. 11**. Overall, the estimated satellite clock stability was improved across all eclipsing Galileo satellites by approx. 11.6% on average, **Tab. 1**.
Since GPS week 2054 day 3 (22 May 2019) the CODE MGEX products are computed using the adjusted ECOM2.

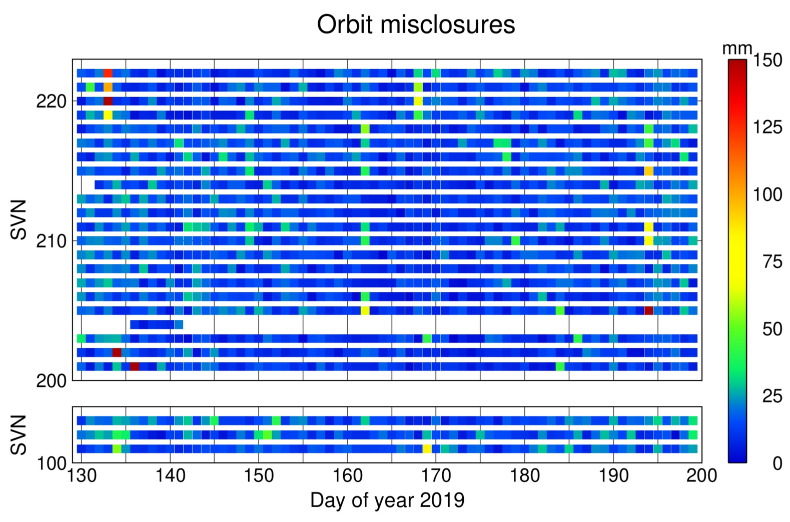

***Fig. 7**: 3d orbit misclosures of Galileo IOV (SVNs: 101-103) and FOC (SVNs: 201-222) satellites when **adjusted ECOM2** is applied (compare to Fig. 1). The misclosures of the eclipsing satellites are comparable to those of the non-eclipsing ones.*

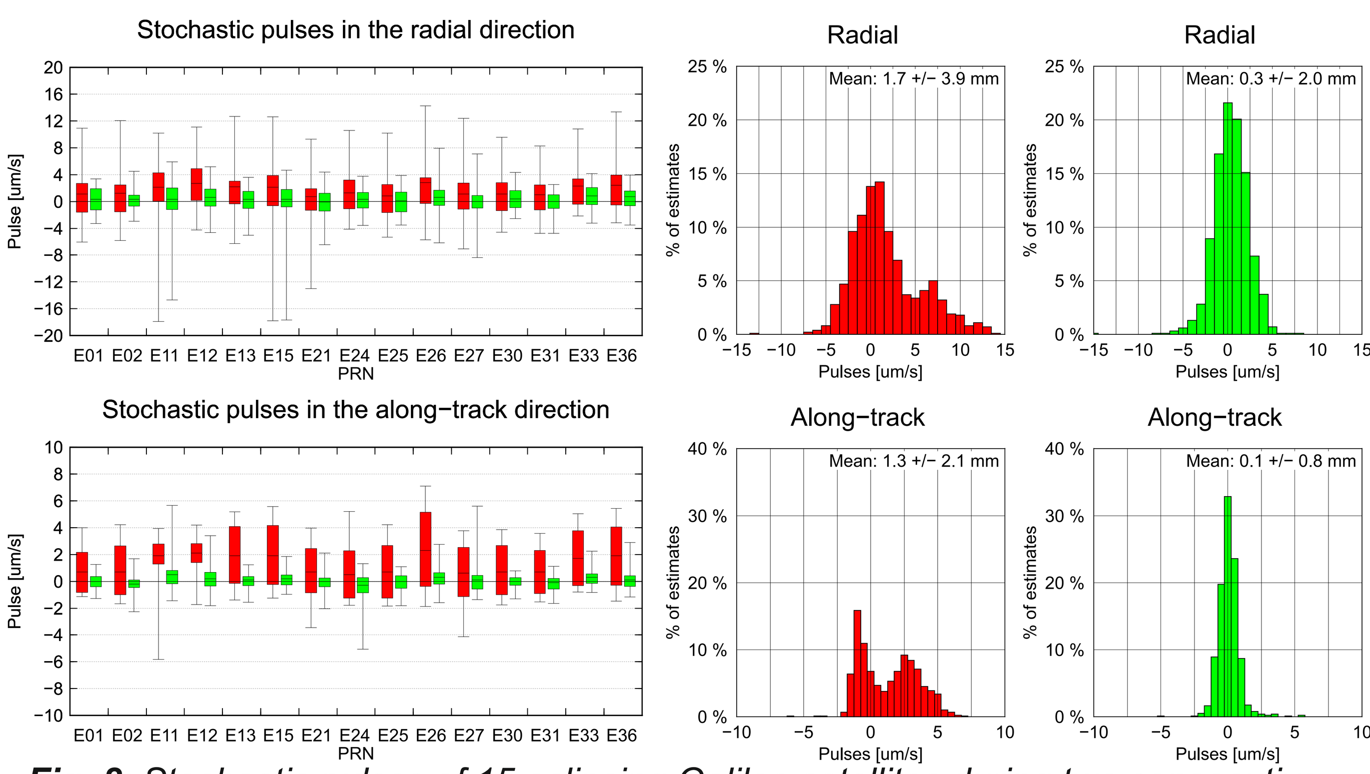

***Fig. 8**: Stochastic pulses of 15 eclipsing Galileo satellites during two consecutive eclipse seasons using ECOM2 (red) and **adjusted ECOM2** (green) over days 130-200 of 2019.*

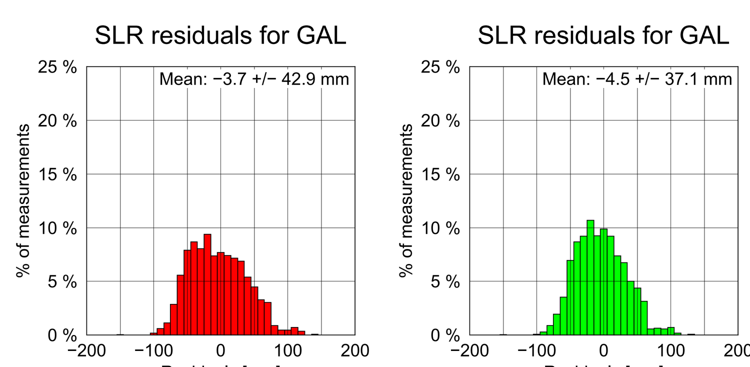

***Fig. 9**: Histograms of SLR residuals of Galileo orbits computed using ECOM2 (red) and **adjusted ECOM2** (green) over days 130-200 of 2019. Only eclipsing satellites have been considered. The use of the **adjusted ECOM2** is marked by 13.5% improvement in standard deviation of the SLR residuals.*

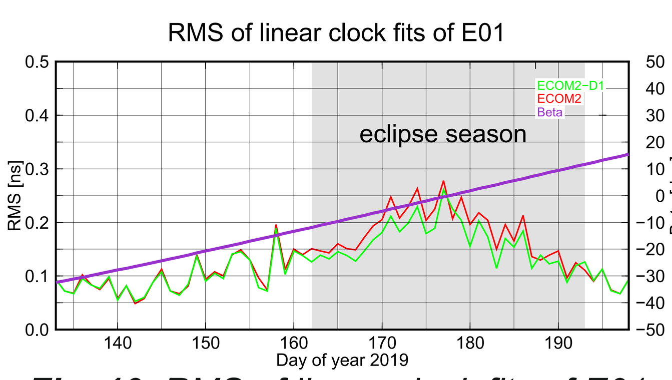

***Fig. 10**: RMS of linear clock fits of E01 computed using ECOM2 (red) and **adjusted ECOM2** (green).*

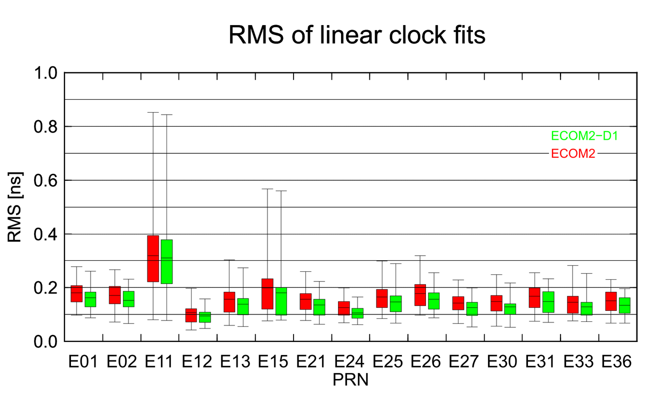

***Fig. 11**: RMS of linear clock fits of 15 eclipsing Galileo satellites during days 130-200 of 2019 using ECOM2 (red) and **adjusted ECOM2** (green), only eclipse periods have been considered.*

***Tab. 1**: Mean RMS of linear clock fits of 14 eclipsing Galileo satellites (E12 excluded) during two subsequent eclipse seasons over days 130-200 of 2019.*

PRN	RMS of the linear clock fit using		improvement
	ECOM2	adjusted ECOM2	
E12	0.107	0.095	11.2%
E13	0.156	0.138	11.5%
E15	0.199	0.180	9.5%
E26	0.178	0.157	11.8%
E33	0.146	0.129	11.6%
E36	0.151	0.134	11.3%

PRN	RMS of the linear clock fit using		improvement
	ECOM2	adjusted ECOM2	
E01	0.181	0.162	10.5%
E02	0.171	0.152	11.1%
E21	0.156	0.135	13.5%
E24	0.125	0.106	15.2%
E25	0.165	0.147	10.9%
E27	0.142	0.126	11.3%
E30	0.148	0.129	12.8%
E31	0.168	0.148	11.9%
All	0.157	0.138	11.6%

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.

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