Empirical Correction Model for Galileo Clock Estimates

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Introduction

Several authors like Montenbruck et al. (2012), Prange et al. (2014), Hackel et al. (2014), and Montenbruck et al. (2014) already demonstrated systematic errors in clock estimates of the passive hydrogen masers (PHMs) onboard GIOVE-B and the Galileo In-Orbit Validation (IOV) satellites. These errors are, e.g., visible as a clear dependence of Satellite Laser Ranging (SLR) residuals on the elevation of the Sun above the orbital plane indicating deficiencies in the orbit modeling. They also show up as a prounounced bump in the Allan deviation (ADEV), see Figure 1.

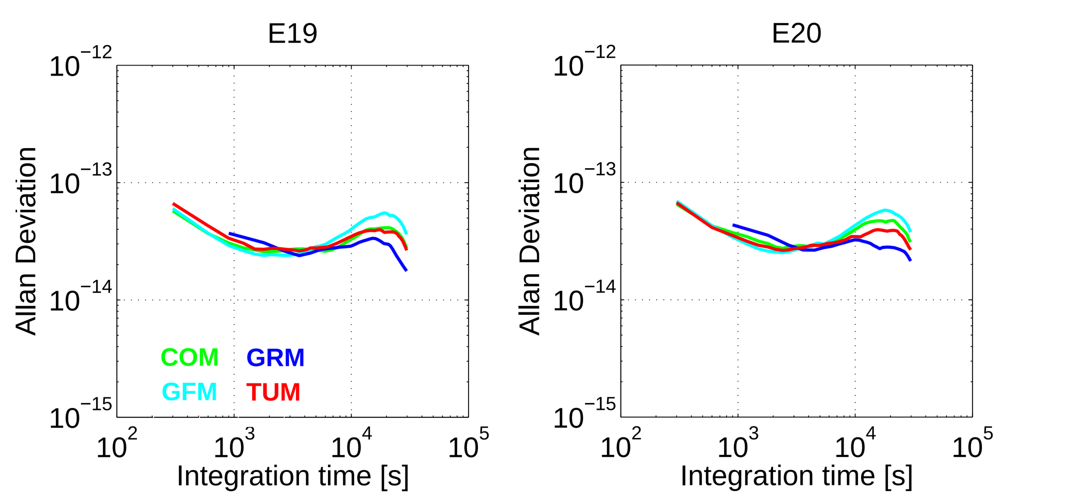

FIGURE 1: Allan deviation of the Galileo clocks estimates of the MGEX analysis centers Centre National d'Etudes Spatiales/Collecte Localisation Satellites (CNES/CLS, MGEX abbreviation GRM), Center for Orbit Determination in Europe (CODE, MGEX abbreviation COM), Deutsches GeoForschungsZentrum (GFZ, MGEX abbreviation GFM), Technische Universität München (TUM, MGEX abbreviation TUM).

We use Galileo orbits computed within the Multi-GNSS EXperiment (MGEX) of the International GNSS Service (IGS) and SLR observations provided by the International Laser Ranging Service (ILRS) for the estimation of a simple clock correction model. As an example, the results of the Galileo orbits of the Center for Orbit Determination in Europe (CODE, MGEX abbreviation COM, Prange et al., 2014) are used here.

Galileo SLR Residuals

All Galileo satellites are equipped with retro reflector arrays and they are observed by the tracking stations of the ILRS on a regular basis. Systematic errors in the SLR residuals depend on the geometry of Earth, Sun, and the satellite as shown in Figure 2.

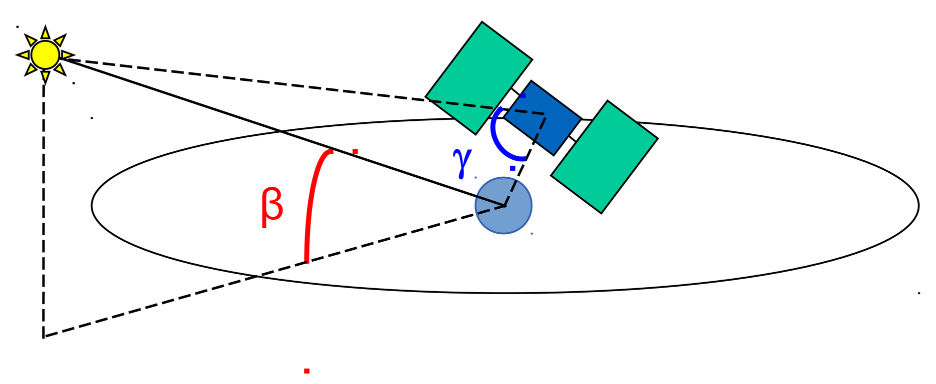

FIGURE 2: Elevation of the Sun above the orbital plane β and Earth-satellite-Sun elongation angle γ.

The dependence of the SLR residuals on the elevation of the Sun above the orbital plane β is plotted in Figure 3. The scatter of the residuals clearly depends on the β-angle with the smallest scatter during periods with a large absolute value of β.

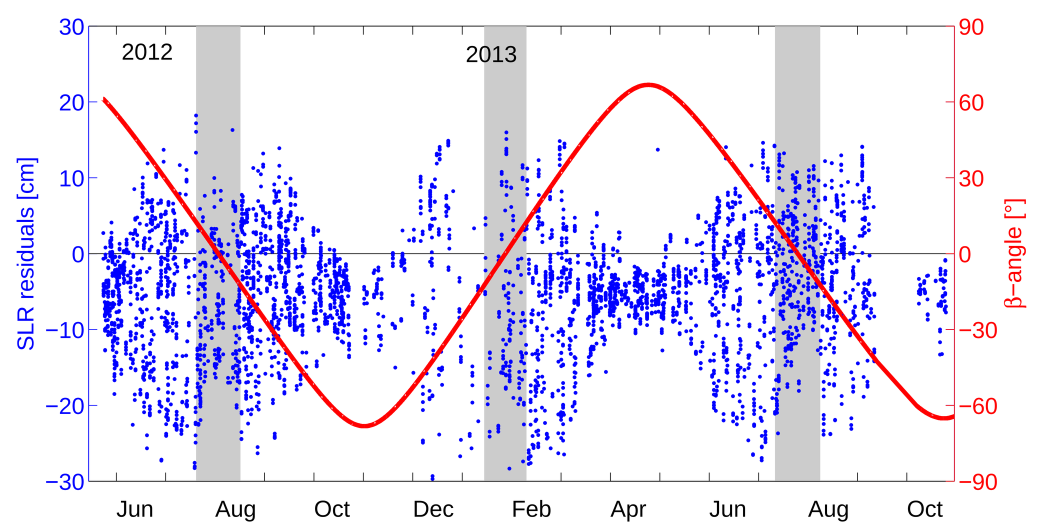

FIGURE 3: SLR residuals of the E11 COM orbits. In addition the elevation of the Sun above the orbital plane β is plotted. The grey-shaded areas indicate the eclipse periods.

The SLR residuals also show a dependence w.r.t. the Earth-satellite-Sun angle γ as illustrated in Figure 4:

- The orbit determined from GNSS microwave observations is shifted away from the Sun compared to the orbit as seen by SLR.
- The SLR residuals are in general positive when the satellite is on the bright side and negative when the satellite is on the dark side of the Earth.
- A mean bias of about -5 cm shifts the residuals in addition.
- The reason for this systematics is most probably related to SRP mismodeling issues due to its clear dependency on the geometry of Sun, Earth, and satellite.

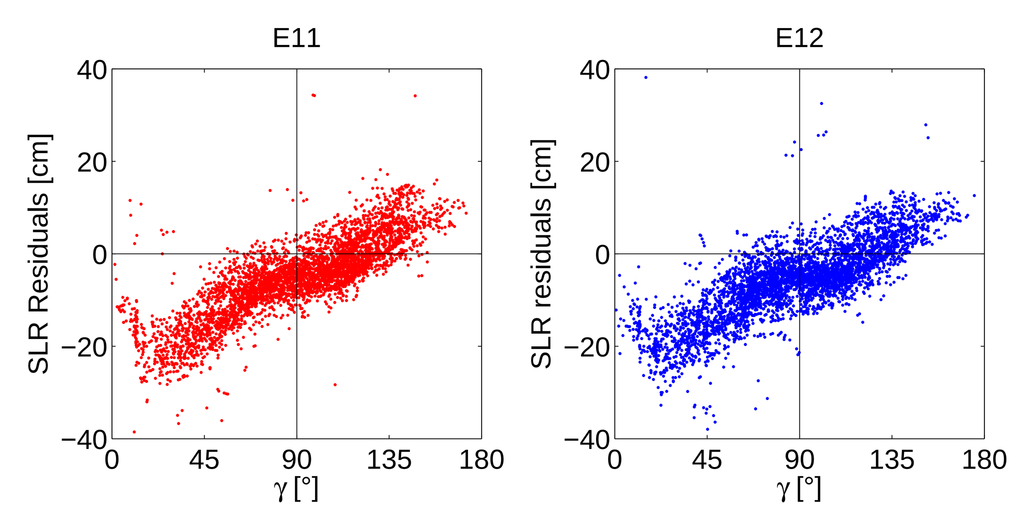

FIGURE 4: SLR residuals of Galileo E11 and E12 plotted versus the Earth-satellite-Sun angle γ.

Galileo Clock Performance

Systematic effects are also visible in the satellite clock estimates. Figure 5 shows a 3-dimensional Allan deviation plot with time on the third axis. The ADEVs at long integration times show a clear time dependence and vary between $2\cdot10^{-15}$ and $4\cdot10^{-14}$. The minimum values around day 115/2013 coincide with the maximum β-angle, see Figure 3.

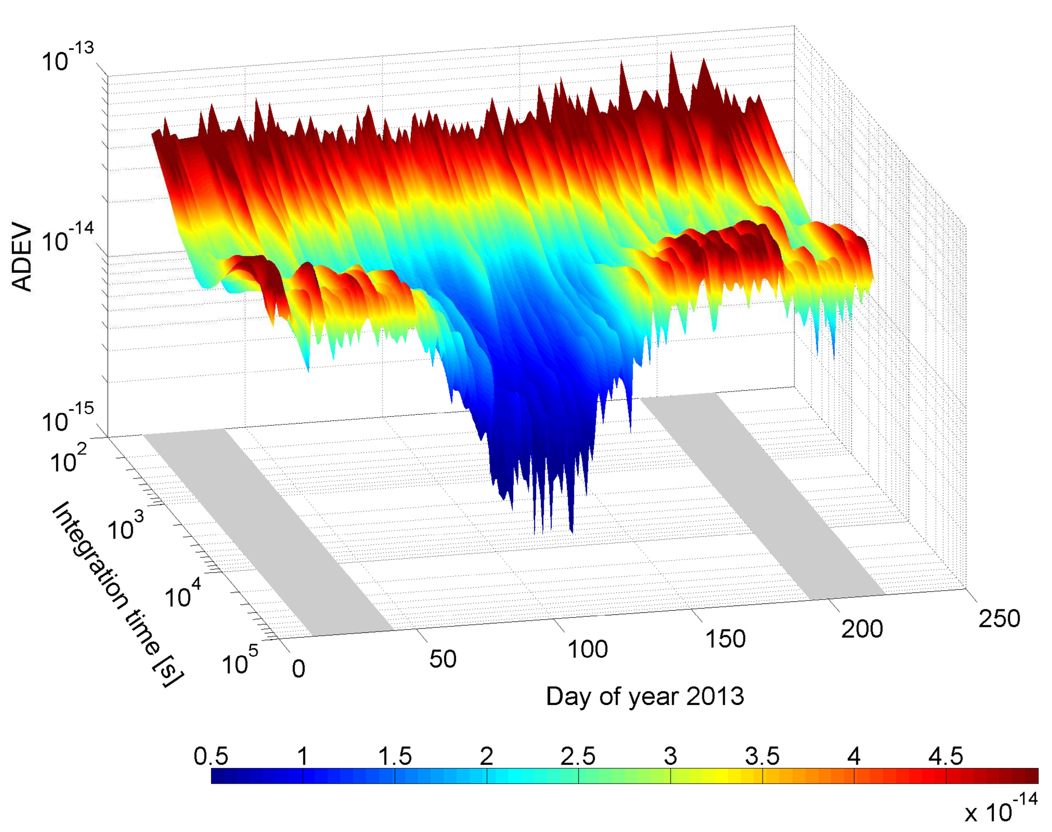

FIGURE 5: Allan deviation of Galileo E11 clock estimates as a function of time. The gray shaded areas indicate the eclipse seasons.

Empirical Clock Correction Model

Based on the γ-dependence of the SLR residuals shown in Figure 4 a simple empirical clock correction model has been estimated:

- A cubic function depending on γ was fitted to the SLR residuals.
- SLR residuals with $\gamma < 25°$ and an absolute value larger than 25 cm were excluded from the estimation.

The ADEVs computed from the Galileo E11 clock estimates corrected with the empirical model are shown in Figure 6. Compared to Figure 5 the time-dependence of the ADEV is significantly reduced by empirically correcting orbital errors.

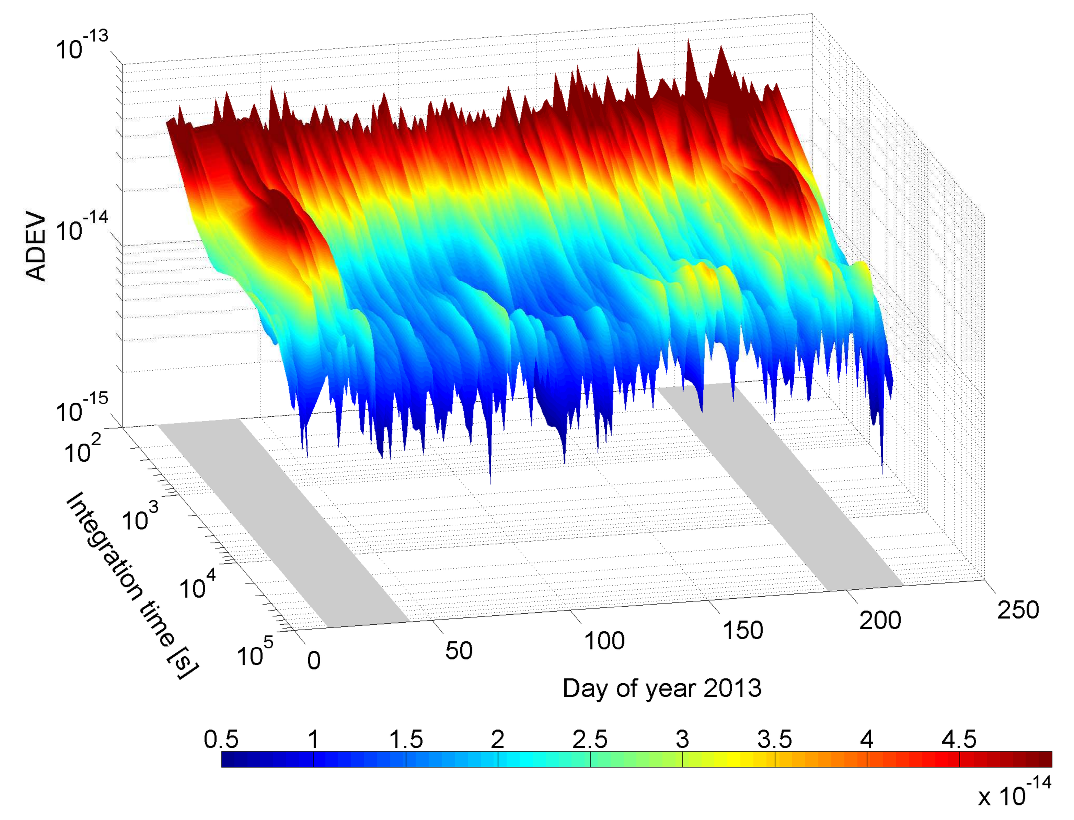

FIGURE 6: Allan deviation of Galileo E11 clock estimates as a function of time after applying the empirical correction. The gray shaded areas indicate the eclipse seasons.

However, during the eclipse periods indicated by gray rectangles additional bumps at 3,000 s are introduced and the ADEV during periods with high β-angles around day 115/2013 is also degraded.

Figure 7 shows daily E11 Allan deviations of the raw COM clock solution as well as corrected with the empirical model. The eclipse seasons have been excluded due to the deficiencies of the model shown above. For integration times up to 4,000 s the observed ADEV follows a $10^{-12}/\sqrt{\tau}$ relation indicating white frequency noise of the PHM.

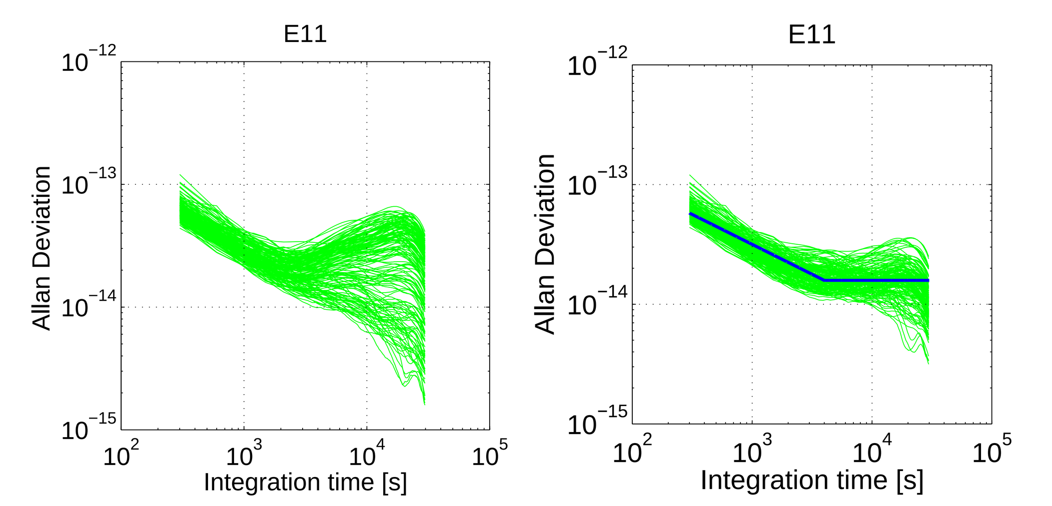

FIGURE 7: Daily Allan deviations of the COM Galileo E11 clock solution outside the eclipse season without (left) and with (right) empirical clock correction model applied. The blue line represents an Allan deviation of $10^{-12}/\sqrt{\tau}$ for $\tau < 4,000$ s and $1.6\cdot10^{-14}$ for $\tau > 4,000$ s.

For integration times larger than 4,000 s the observed ADEV tends to be constant on average at a value of $1.6\cdot10^{-14}$. This value may comprise residual orbit determination errors as well as possible thermal bias variations in the signal generation and should be considered as an upper threshold for the true PHM clock performance outside the eclipse region.

Conclusions

- An empirical correction model for Galileo clock estimates has been derived from SLR residuals.
- The model significantly reduces the bump in the Allan deviation for time periods with small β-angle.
- During periods with a large absolute value of the β-angle an even better performance of the apparent clock can be achieved as the orbit errors are minimal, see Figure 5.
- Further refinement of the Galileo IOV orbit modeling will be required to further reduce the amplitude of 1-CPR and 2-CPR harmonics and to better isolate the actual clock behavior from other effects at the respective correlation times.

Further Reading

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