Satellite Clock Modelling and Multi-GNSS Solutions

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Introduction

In traditional GNSS processing, an independent set of clock parameters is estimated every processed epoch. It represents a huge number of parameters which highly correlate with station height and troposphere parameters. However, no use is made from the fact that the most stable clocks (on the ground and in space) could be modeled, and in turn, help stabilizing the overall GNSS solution.

In Section 1, based on data from the Multi-GNSS EXperiment (MGEX) from the International GNSS Service (IGS), we first analyze the performances of the GPS Block IIF and Galileo IOV satellites from the clock time series as computed by CODE (Center for Orbit Determination in Europe) over carefully selected periods where, among other criteria, IOV satellites had their H-Maser clock active.

In Section 2, still using MGEX data, we investigate the impact of clock modelling and solar radiation pressure models on the determination of orbits and clock parameters for the IOV satellites. Kinematic orbit determination with stochastic clock modelling is also investigated for all GNSS satellites carrying highly stable clocks and results are compared.

In Section 3, clock modelling is performed on the high-performance clock onboard the GPS Block IIF satellite G25 in the frame of the kinematic orbit determination.

1. Performance of GPS Block IIF and Galileo IOV satellites

In order to provide a fair comparison between the performance of the GPS Block IIF and the Galileo IOV satellites, a solution using only MGEX data was produced, so that exactly the same number of stations contribute to the determination of GPS and Galileo satellite clock corrections. The stations composing this network are shown in red in Fig. 1. The official triple-GNSS CODE solution (GPS/GLONASS/Galileo) uses several times more sites (shown in blue in Fig. 1) and provided the orbit, ERP, station coordinates, and troposphere information (double-difference solution) for the reduced-size network used for GPS/Galileo clock estimation (zero-difference network solution). The resulting Galileo orbits have been evaluated using SLR measurements. A mean value per week and Galileo satellite is shown in Fig. 2.

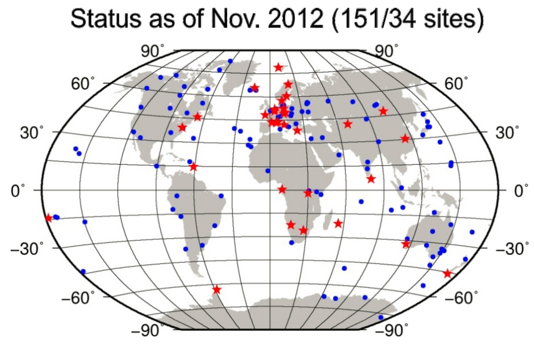

Figure 1: Network used for official CODE MGEX triple GNSS solution (GPS + GLONASS + Galileo). Blue: GPS-only sites (151 sites). Red: MGEX sites providing GPS and Galileo observations (34 sites). Status as of Nov. 2012.

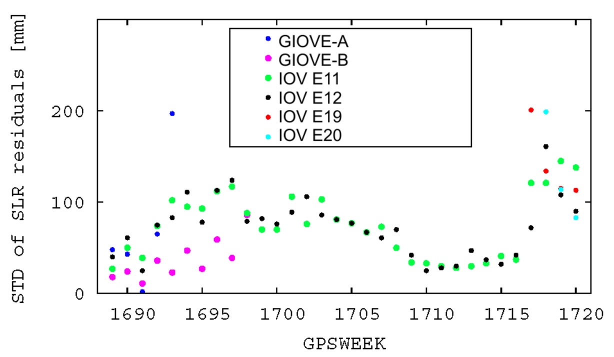

Figure 2: Weekly standard deviation of SLR residuals for the IOV satellites. The quality of the Galileo orbits varies in time (depending on the elevation of the Sun above the orbital plane). Since the estimated satellite clock corrections highly depend on the orbit quality we decided to choose the interval with the lowest SLR residuals for the Galileo satellites E11 and E12 (GPS week 1711 (DoY 295 to 301 of 2012) – instead of a later period with all four Galileo IOV satellites.

In the clock determination run, a single inter-system bias parameter per station and per day has been setup. A zero-mean condition over all those parameters per day for all stations has been applied.

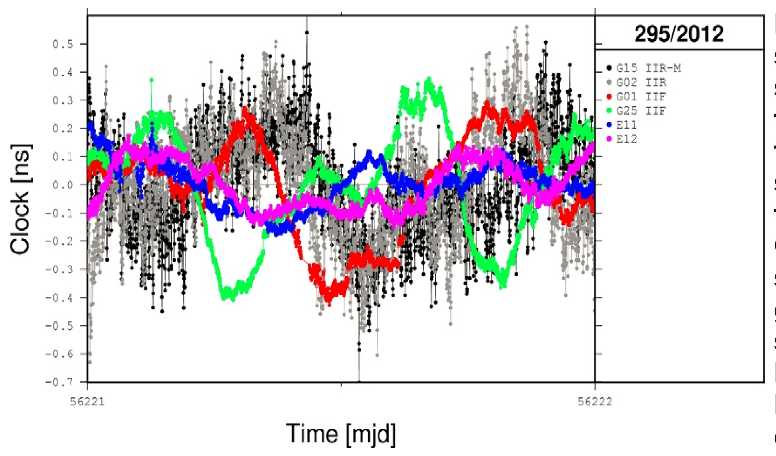

Figure 3: 30-s clock time series estimated from the solution using only Galileo tracking (MGEX) stations from Fig.1 for Galileo IOV satellites E11 and E12 and the GPS Block IIF G01 and G25 satellites. Two satellites from earlier generation of GPS satellites, namely G15 from Block IIR-M and G02 from Block IIR were added for comparison.

The different noise levels between the IOV satellites and the Block IIF (E11, E12, G01, and G25) and that of older generations of GPS satellites (G02 and G15) is already obvious from Fig. 3. The modified Allan deviation plot presented in Fig. 4 clearly confirms the much improved stability of the newest satellites clocks. At 30 s, they perform one order of magnitude better than the Rubidium clocks of previous generations of GPS satellites. Galileo IOV satellite clocks overall outperform those of GPS Block IIF satellites. In particular, they show a much less pronounced once-per-revolution variation.

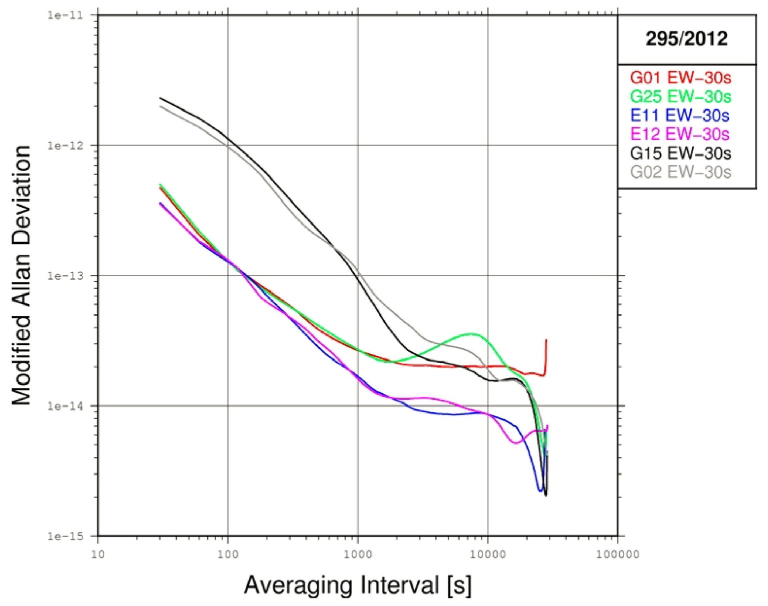

Figure 4: Modified Allan Deviation plot for Galileo IOV (E11 & E12), GPS Block IIF (G01 & G25), and selected older GPS (G15 from Block IIR & G02 from Block IIR-M) satellites, as estimated from the solution only using Galileo tracking (MGEX) stations from Fig.1 to reduce the network effect when comparing the performance of GPS and Galileo satellite clocks (DoY 295 of 2012).

2. Clock modelling for Galileo IOV satellites

Two time intervals of 30 resp. 50 days were carefully selected over which the H-masers of E11 and E12 were uninterruptedly on and 37 MGEX stations were tracking. Those intervals are DoYs 209-235 of 2012 with low Sun elevation [11.1°, -12.4°] and DoYs 250-305 of 2012 with high Sun elevation [-26.0°, -69.2°]. Fig. 5 presents the clock time series of Galileo IOV satellites E11 and E12 on DoY 214 of 2012, from the selected period with low Sun elevation. In Fig. 6, the clock time series are plotted against the elevation of the Sun, for all days selected.

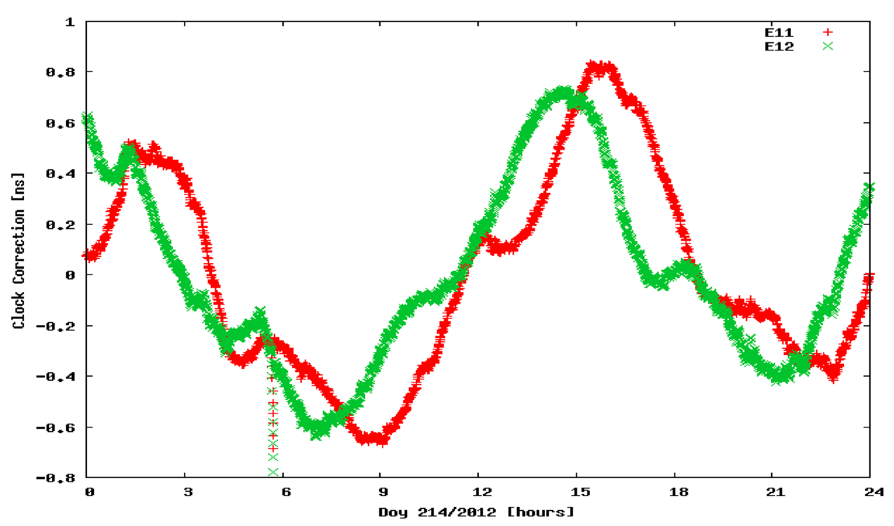

Figure 5: Clock corrections for DoY 214/2012 for both satellites (low Sun elevation). As expected we find a once-per-revolution variation. Both satellites show an amplitude of about 0.8 ns. They are shifted by a time interval which just corresponds to the lag of E11 with respect to E12 along the orbit. Both satellites show a very similar behaviour.

Fig. 6 shows that the pattern repeats for every satellite revolution nearly identically and that the pattern seems well aligned with the direction to the Sun. The amplitude is much smaller for high elevation of the Sun. The pattern however resists and shows an asymmetry.

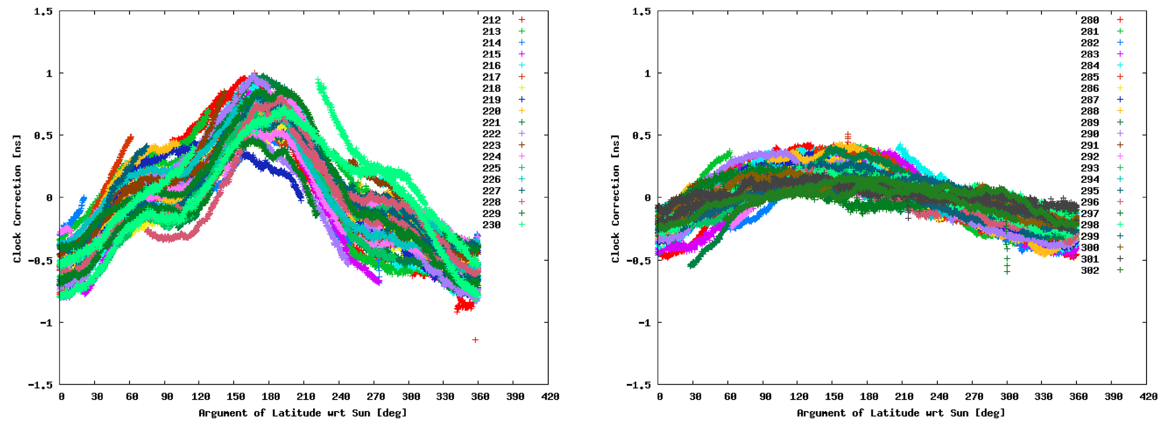

Figure 6: Clock corrections for E11 as a function of the argument of latitude with respect to the Sun. Left: low Sun elevation; right: high Sun elevation.

The reason for the observed variations may thus be the temperature sensitivity of the oscillator or elements along the signal chain, or orbit errors caused by deficiencies in the radiation pressure model. Fig. 7 shows the same clock corrections based on two radiation pressure models (CODE 5-parameter and box-wing), indicates that the second reason seems more realistic. For the box-wing model, for high beta angles the amplitude remains rather constant while for low beta angles the clock corrections are very large. This may indicate that the satellite does not use the standard satellite yaw model.

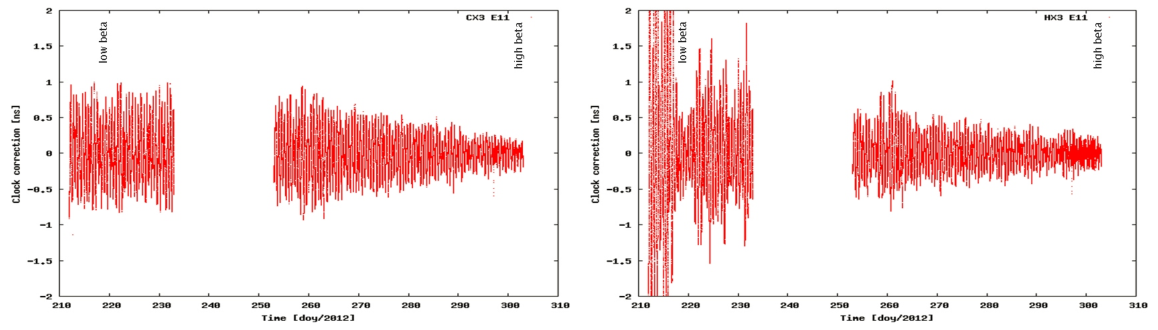

Figure 7: Clock corrections for E11 for different Sun elevations with different solar radiation pressure models. Left: CODE 5-parameter model; Right: box-wing model, 3-day arcs.

If the once-per-revolution variations observed in the clock corrections are not caused by thermal effects but by systematic radial orbit errors, modelling the clocks should have the potential to improve the orbit. In the following, clock corrections were modelled by a daily independent linear function (offset and drift) as well as an epoch-wise clock offset with a variable constraint towards the linear model. Solved-for parameters are: orbit initial conditions, radiation pressure parameters (CODE model and box-wing), clock parameters (offset, drift, and epoch-wise offsets), and ambiguity parameters. Validation of the orbits computed with different orbit models and clock parameter constraints was performed by investigating the short-term orbit prediction. Fig. 8 shows that a minimum orbit prediction error is obtained if the constraints applied to the epoch-wise clock estimates are between 3 and 10 ps, i.e., around the phase measurement noise level.

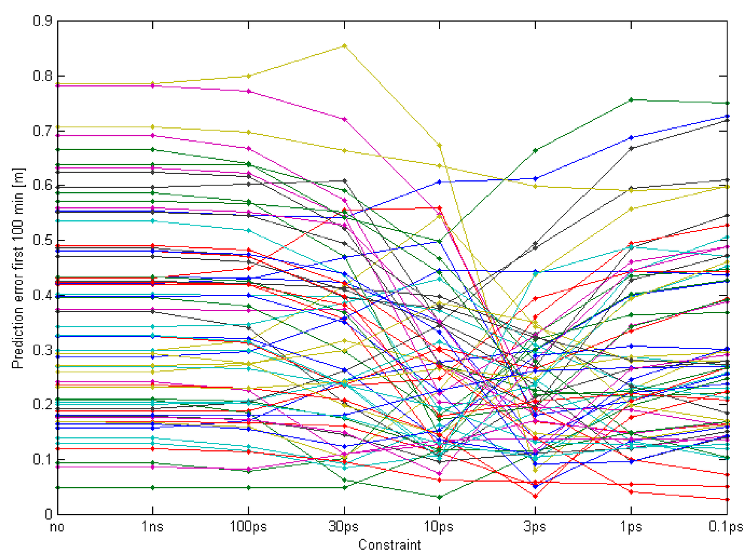

Figure 8: Maximum orbit error for satellite E11 for first 100 minutes prediction for different clock constraints to daily linear model. Different colours refer to different days. CODE 5-parameter model, 3-day arc.

In summary, the deficiency of the solar pressure models are likely the origin for the prominent once-per-revolution variation observed for the IOV satellites. Also, stable clocks may be used as a tool for verifying orbit mismodelling and assessing different orbit models.

3. Clock modelling in kinematic orbit determination

Kinematic positions on ground are correlated with the clock parameters. The same is expected for the satellites. High performance satellite clocks allow a clock modelling to reduce this correlation as it has been shown already earlier for receivers on ground. The modified Rubidium clocks mounted on the GPS Block IIF satellites or H-Masers onboard of the Galileo IOV satellites now allow to study the impact of clock modelling on kinematic orbit determination.

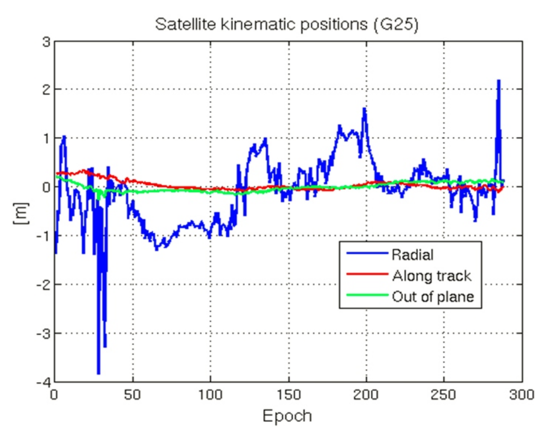

Figure 9 shows the differences between the estimated kinematic orbits and the (reference) CODE orbits for G25 on DoY 295, 2012. The satellite clocks were estimated epoch-wise without constraints. If the satellite clocks and the kinematic orbits are estimated together, the orbit solutions, especially in the radial direction, are significantly disturbed by the strong correlation between the satellite clock estimates and the radial component of the orbit.

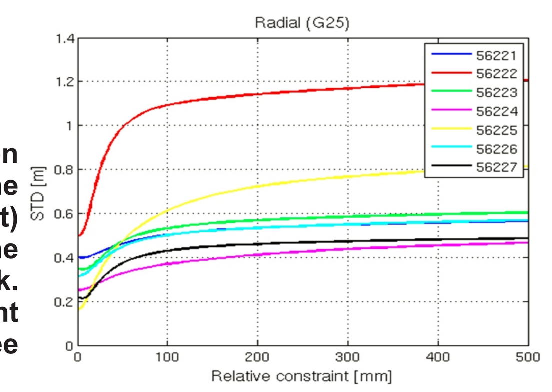

Figure 10 shows that the standard deviation of the radial orbit difference (between the estimated kinematic and the reference orbit) decreases when increasing the weight of the relative constraint imposed on the clock. Very strong weights, e.g. a relative constraint of 0.1 mm, may cause slight degradation (see e.g. the black line).

With optimal clock constraining, the standard deviation of the radial orbit difference can be reduced by a factor of up to 16 compared to the epoch-wise solution. The reduction is not that significant in the along-track and out-of-plane directions (see Fig. 11 below). A too strong relative clock constraint may easily lead to degradations in the orbit solutions.

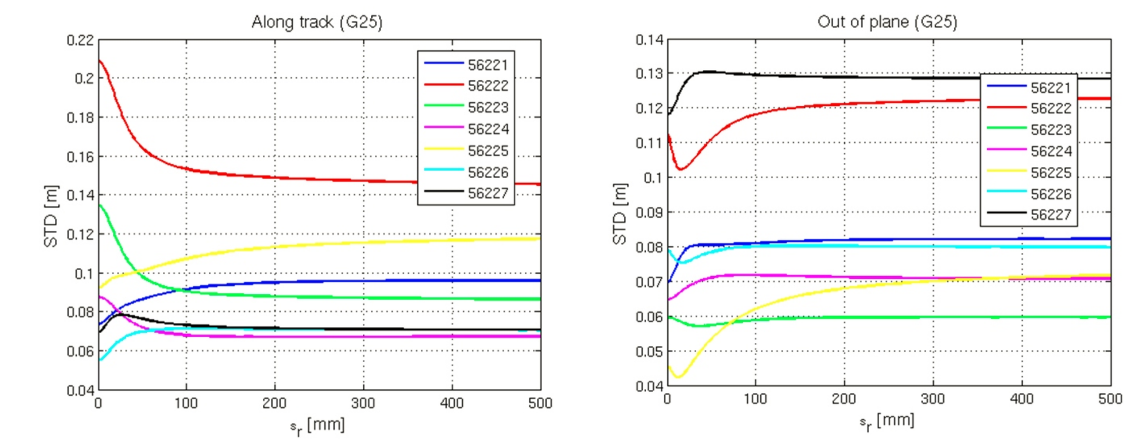

Figure 11: As per Fig. 10 for the along-track (left plot) and out-of-plane (right plot) directions.

4. Conclusions

The improved stability of the clocks onboard the Galileo IOV or GPS Block IIF satellites achieved such a quality, allowing the modelling of the clocks. This way, clocks themselves can be used as a tool to monitor the quality of the orbit modelling. Clock modelling also improves predicted orbits and their consistency with (predicted) clocks, what would directly impact all navigation applications.

Acknowledgments

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