ESA Project on Improving GNSS-Based Precise Orbit Determination by Using Highly Accurate Clocks

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0. PROJECT OVERVIEW

The European Space Agency (ESA) is running a project entitled «Improved GNSS-Based Precise Orbit Determination by Using Highly Accurate Clocks». The driving motivation is to take advantage of the high stability of the modern (GNSS and Low Earth Orbit, LEO) satellite clocks by establishing appropriate clock models. Fig. 0.1 illustrates the great improvement in clock stability reached for the latest generation GPS satellites (Block IIF, Rb clocks) and the Galileo IOV satellites (PHM activated) compared to older GPS satellites.

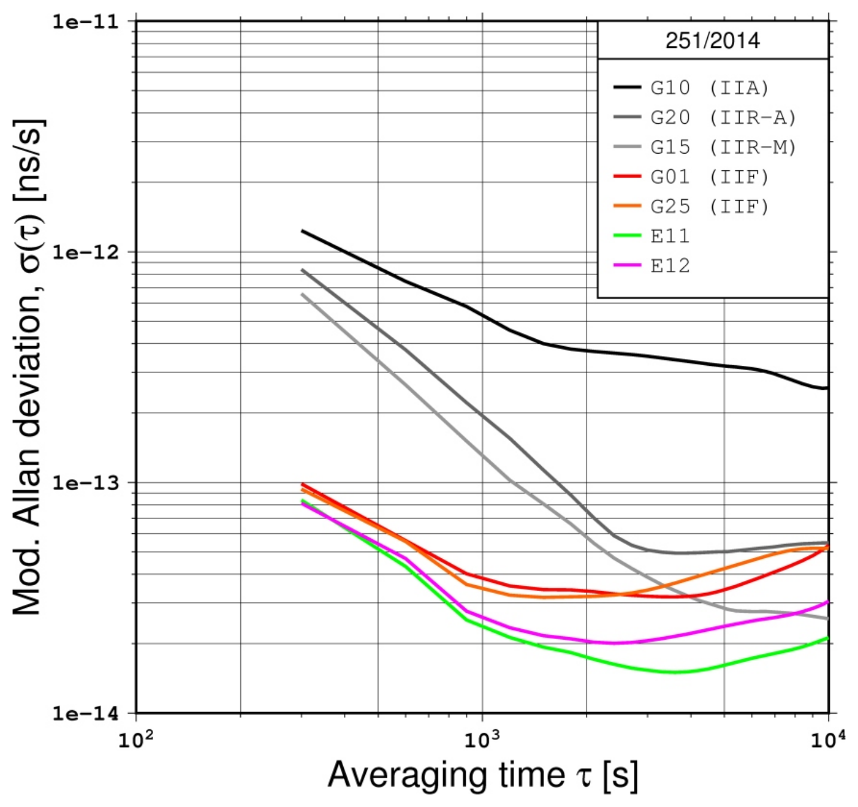

Fig. 0.1: Clock stability of GPS satellites of different generations and two Galileo IOV satellites (clock performance derived from the CODE MGEX solution with a sampling rate of 300 s).

The feasibiliy of modelling a clock depends on:

- The quality and sensitivity of the oscillator itself,
- the disturbing effects on the clock itself (temperature, etc.),
- the sensitivity of the signal paths in the reception/transmission chain,
- the stability of biases in the hardware components used for the signal generation/correlation and
- the capacity to handle any other model deficiencies that can be absorbed/compensated by estimating independent epoch-wise clock parameters.

An extensive literature survey was conducted in order to qualify and quantify all effects a clock can be subjected to. They include e.g. relativistic effects, orbit modelling deficiencies (such as solar radiation pressure (SRP), see Fig. 0.2), stability of code and phase observations biases and environmental factors such as temperature variations.

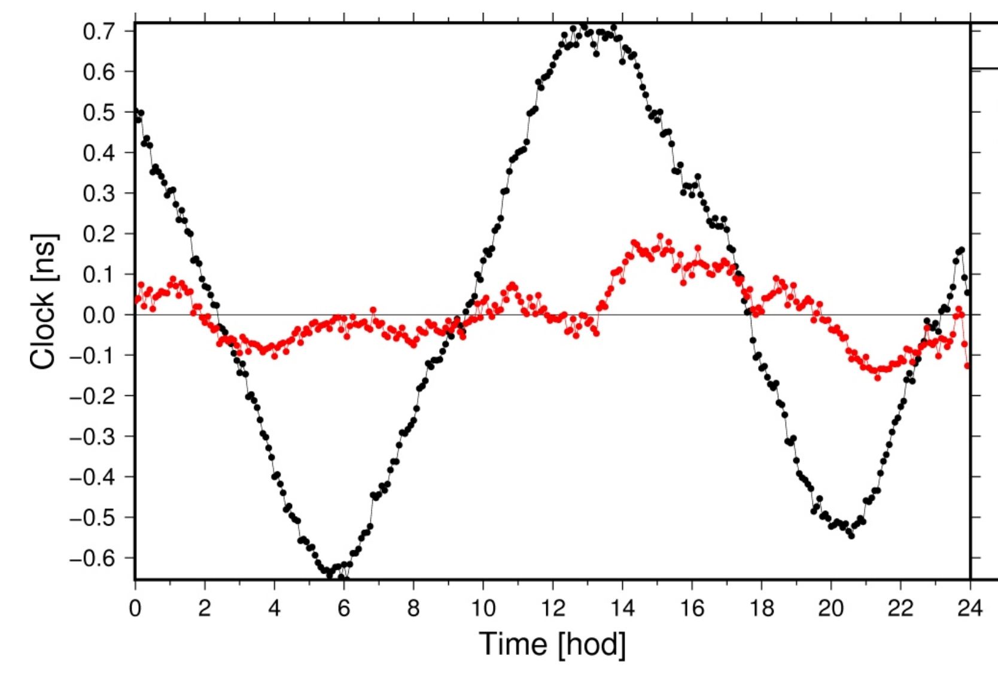

Fig 0.2: Impact of the new ECOM model (Arnold et al., 2015) on satellite clocks for E11 on day 180 of 2014.

With all potential effects listed, models and concepts shall be developped to represent the apparent clock behavior. Test scenarios were identified to evaluate the proposed models by processing real data.

The following key aspects will be studied in the frame of the project:

- Impact of (station and satellite) clock modelling on GNSS POD and estimated global parameters,
- Impact of clock modelling for absolute and relative LEO POD,
- Impact of clock modelling on the tracking network requirements.

1. GNSS SATELLITE CLOCK MODEL

The IGS final and MGEX satellite clock corrections show a deterministic behavior (in addition to a stochastic component) that can be represented with the following model:

$$\delta t(t) = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + c_1 \cos nt + s_1 \sin nt + c_2 \cos 2nt + s_2 \sin 2nt$$

The 1/rev and 2/rev variations may be caused by radial orbit errors and/or temperature sensitivity of clock frequency and hardware biases.

1.1 Behavior of Galileo satellite clocks

Fig. 1.1 shows the amplitude of 1/rev and 2/rev clock variation from MGEX for Galileo IOV satellites GSAT101 and 102. The 1/rev variations are mainly due to radial orbit errors caused by radiation pressure mismodeling.

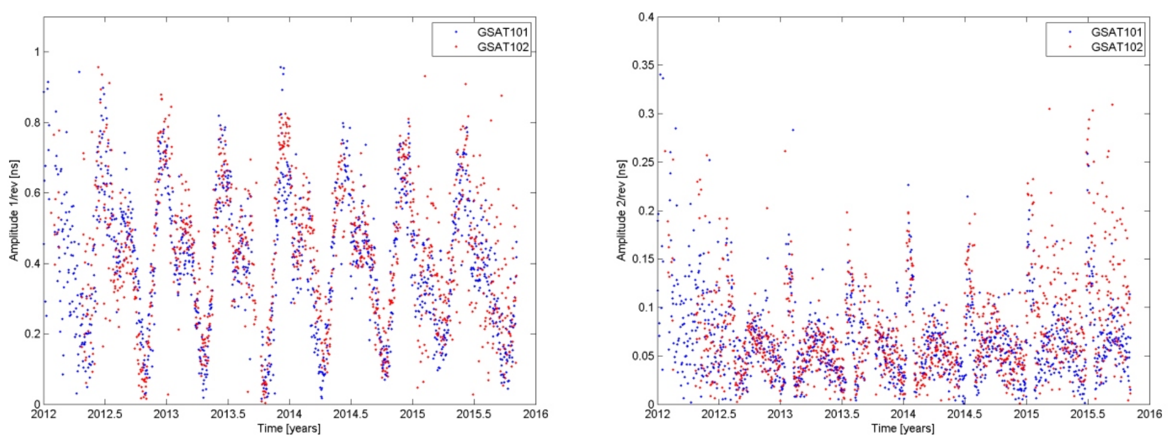

Fig. 1.1: Amplitude of 1/rev and 2/rev clock variation from MGEX for Galileo IOV satellites GSAT 101 and 102.

1.2 GNSS Clock Modelling Supporting Precise Orbit Determination

Experiment: 16 MGEX stations were used to observe the Galileo IOV satellites. In the POD procedure, the epoch-wise estimated satellite clocks were constrained to a daily linear model (offset+drift). Different clock constraints from 100 ps to 1 ps were tested. The effect on the estimated clocks is illustrated on the left plot of Fig. 1.2. The quality of the different solutions was evaluated in terms of 24 h orbit prediction accuracy.

Results: The clock constraint at 10 ps level provides best orbit predictions (Fig. 1.2 right).

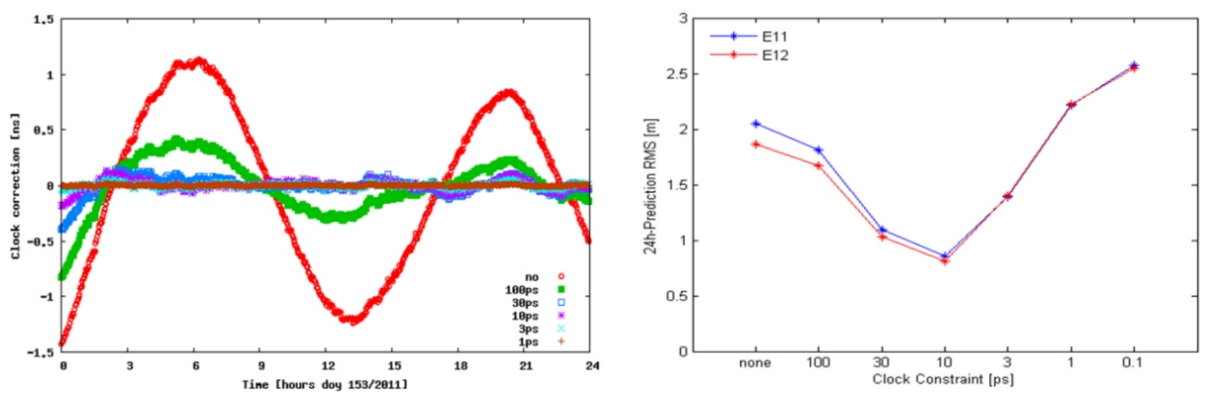

Figure 1.2: Clock constraining of Galileo IOV clock to daily linear model (left). Prediction error of Galileo orbits generated with clocks estimated with varying clock constraints applied (right).

Conclusion: The Galileo onboard Passive H-Masers are stable enough to be modelled as linear function over one day at the 10 ps level. Clock modelling eliminates the 1/rev clock variation associated with the radial orbit error. The study will assess the user benefit of an increased consistency of predicted orbits and clocks.

2. CLOCK MODELLING IN LEO KINEMATIC POD

Part of the study will concentrate on the feasibility of modelling the clocks of LEO satellites equipped with GPS receivers. Of special interest are the twin GRACE satellites, since the ultra-stable oscillator on-board used to drive the K-Band instruments is also connected to the GPS receiver.

Fig 2.1 shows the pre-launch measured stability of the GRACE B satellite together with the ionosphere-free phase observation noise projected onto the receiver clock (Weinbach & Schön, 2013). It indicates that the stability of GRACE clocks is such that clock modelling is feasible over intervals of 40 s, or slightly more.

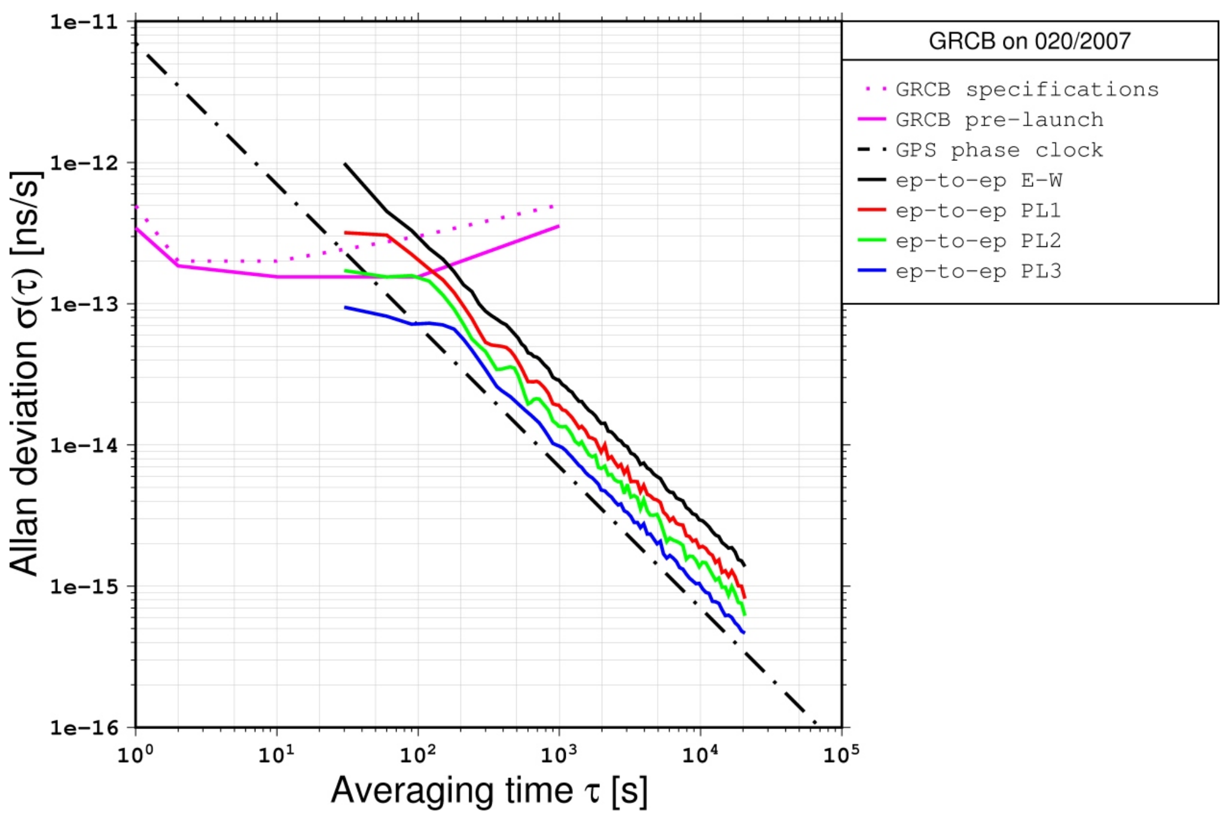

Figure 2.1: Measured (pre-launch) GRACE B receiver clock stability against ionosphere-free phase observation noise projected onto the receiver clock, together with estimated stability of the epoch-to-epoch clock differences for epoch-wise estimated clock parameters (E-W), or clock modelled as piece-wise linear functions (PL) with 3 different node spacing (1, 2 and 3 minutes, solutions PL1, PL2 and PL3 respectively).

Fig. 2.1 shows that GRACE receiver clock modelling shall be possible over intervals up to 2 minutes. Beyond that, the model becomes unrealistic, with apparent stability beyond what is possible.

Fig. 2.2 shows the impact of the different clock modelling on the estimated radial component of the kinematic positions of GRACE B over Jan. 2007. It confirms that up to a node spacing of 2 minutes, a piece-wise linear function may be used to model the GRACE receiver clocks. Above, the solution degrades.

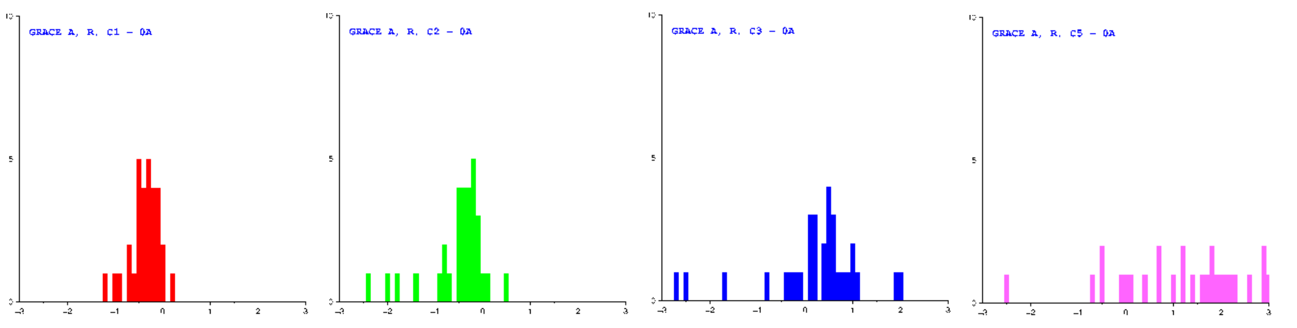

Fig. 2.2: Impact of receiver clock modelling on GRACE radial component of kinematic positions (distribution of daily RMS over Jan. 2007). Negative numbers indicate a better consistency between the solution with clock modelling with a reference reduced-dynamic solution than the standard kinematic solution (with epoch-wise estimated clock parameters).

3. CLOCK MODELLING AND RECEIVER-RELATED PARAMETERS

Due to the high correlations between the receiver clock corrections, the height estimates and the troposphere zenith path delay parameters (Rothacher and Beutler, 1998), appropriately modelling the high-performance receiver clocks may play an important role in stabilizing these parameters. As shown in Fig. 3.1, different kinds of atomic clocks are nowadays connected to IGS stations and offer us opportunities to model receiver clocks in network solutions. In this study, only H-Masers are considered for the receiver clock modelling in phase-based solutions.

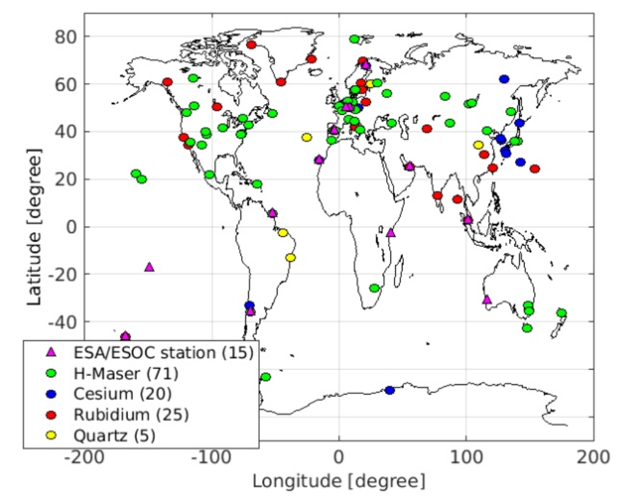

Fig. 3.1: IGS and ESA/ESOC stations connected to different types of clocks from 1 August 2014 to 31 July 2015.

The receiver clock model consists of a deterministic part, i.e., a low-order polynomial and a stochastic part, i.e., relative constraints with appropriate weights. Apart from that, the influences of temperature on the hardware delays are also considered in the clock modelling. Based on the model introduced by Weinbach (2013), it is possible to observe unignorable temperature influences on the receiver clock estimates, as shown on Fig 3.2.

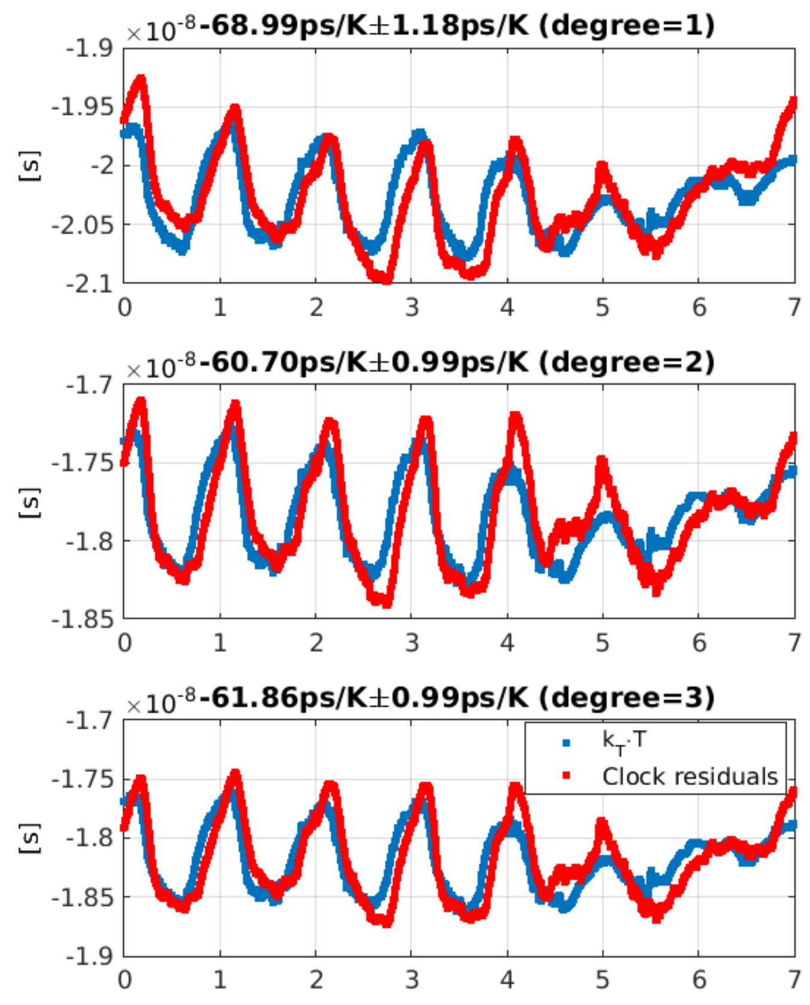

Fig. 3.2: Correlation between the clock residuals and the product of the temperature and the temperature coefficient (a constant) for the station SVTL for the 7 days of GPS week 1752.

The study will exploit the benefits of the receiver clock modelling on station-related parameters, such as the station height, the troposphere parameter and the phase ambiguity. Apart from that, the benefits of satellite clock modelling on kinematic orbit determination, especially in the radial direction, is also of great interest.

4. OUTLOOK

During the initial phase of the study, concepts and models for clock modelling have been identified. The next phase of the project will be dedicated to the implementation of these models and their evaluation and fine-tuning by processing real data from GPS and Galileo over selected periods.

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