Galileo IOV Orbit Determination and Validation

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Introduction

On 21st October 2011, Europe's Global Navigation Satellite System (GNSS) Galileo has reached the in-orbit validation (IOV) phase through launch of the first two IOV satellites IOV-1 (E11) and IOV-2 (E12). This commissioning phase is aimed at qualifying the Galileo space and user segments through extensive in-orbit/on-ground tests and operations of a core spacecraft constellation as well as the associated ground segment. Since 16th January 2012, both satellites are transmitting navigation signals.

Monitoring Network

The satellites are continuously tracked by the Cooperative Network for GIOVE Observation (CONGO), a global network of 23 tracking stations established by the German Space Operations Center (GSOC/DLR) and the German Federal Agency for Cartography and Geodesy (BKG) in cooperation with several agencies including the Technische Universität München (TUM). Moreover, various stations of the IGS Multi-GNSS Experiment (M-GEX) are tracking the IOV satellites.

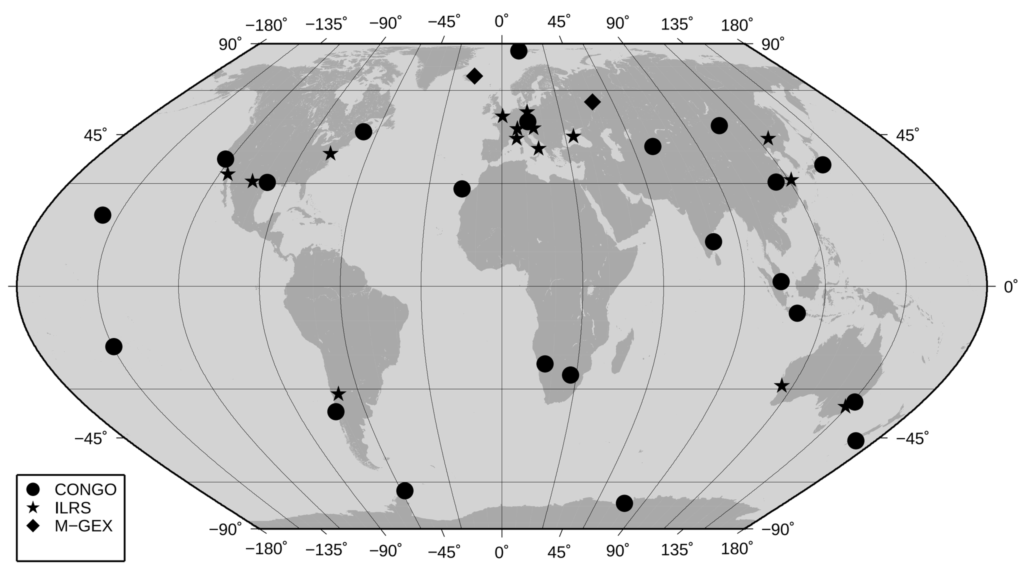

FIGURE 1: Distribution of the IOV and ILRS tracking stations.

Altogether 24 operational IOV-capable stations with 22 CONGO and two M-GEX stations are taken into consideration. The analysis covers a period of 40 days. Within the time interval from day of year (DOY) 100/12 to 140/12, 19 sites are equipped with Javad Triumph, four with Leica, and one with Trimble receivers. All stations provide dual-frequency observations of the IOV satellites in the E1 and E5a bands.

Apart from single gaps in tracking statistic, both IOV satellites have been tracked continuously since start of transmission. Within the range of DOYs 20/12 to 31/12, E11 was off-line. E12 was emitting no signals within the time range from DOYs 50/12 to 59/12.

Orbit and Clock Determination

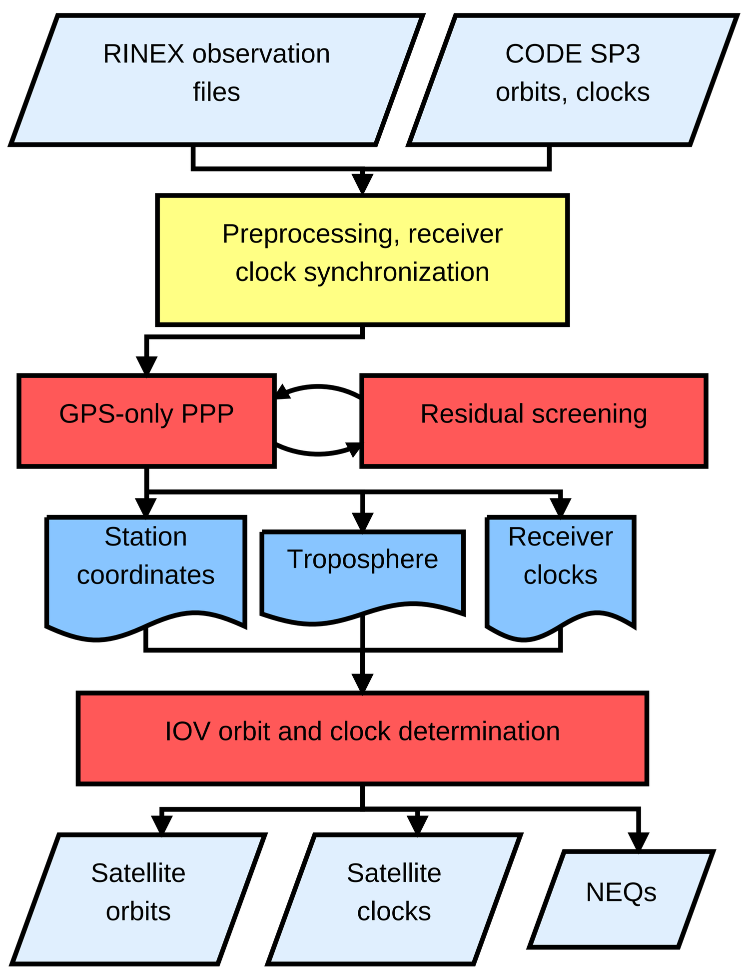

FIGURE 2: Flowchart of the IOV processing.

Orbits and clocks are basically derived from RINEX observation files that are processed with the Bernese GPS Software. In a first step, station coordinates, receiver clocks, and troposphere parameters are estimated in a GPS-only precise point positioning (PPP) solution. These parameters are kept fixed in the second step, the IOV orbit and clock estimation. Differential code biases (DCBs) are estimated additionally. Multi-day solutions are generated on the normal equation (NEQ) level, the final solution is based on the middle day of a 3-day orbit arc.

Orbit Quality

The orbit quality in terms of accuracy and repeatability can be assessed by internal and external methods. The consistency of consecutive orbits is determined by means of 3D orbit discontinuities, which are visualized in Figure 3.

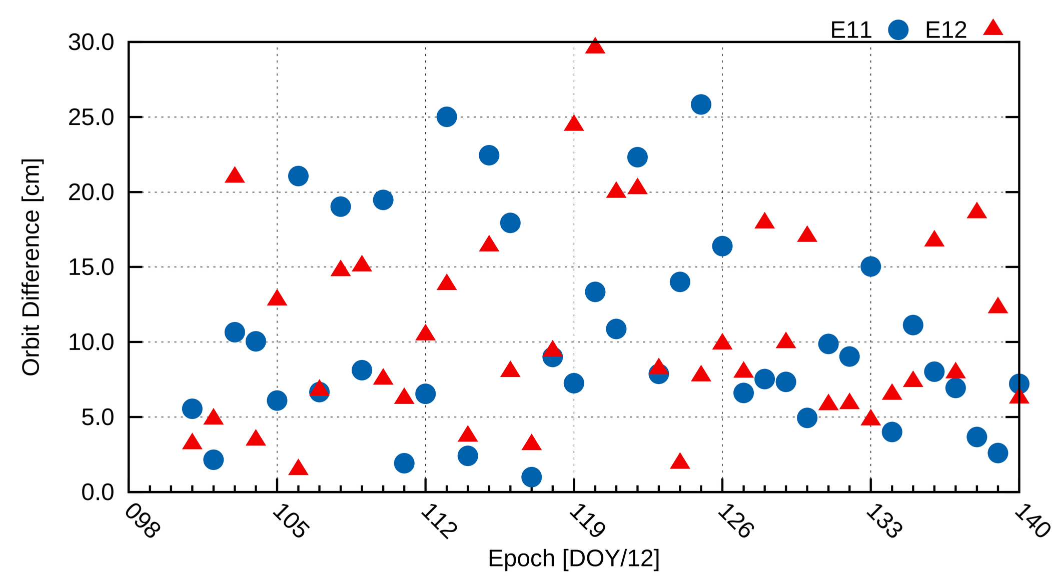

FIGURE 3: 3D orbit discontinuities at day boundaries.

The orbit repeatability was assessed by multi-day orbit fits w.r.t. the original orbits. The orbit repeatability from a 2-day fit through daily orbit solutions is shown in Figure 4. The arithmetic mean values of the orbit fits are 2.5 ± 1.5 cm for E11 and 2.8 ± 1.5 cm for E12, respectively.

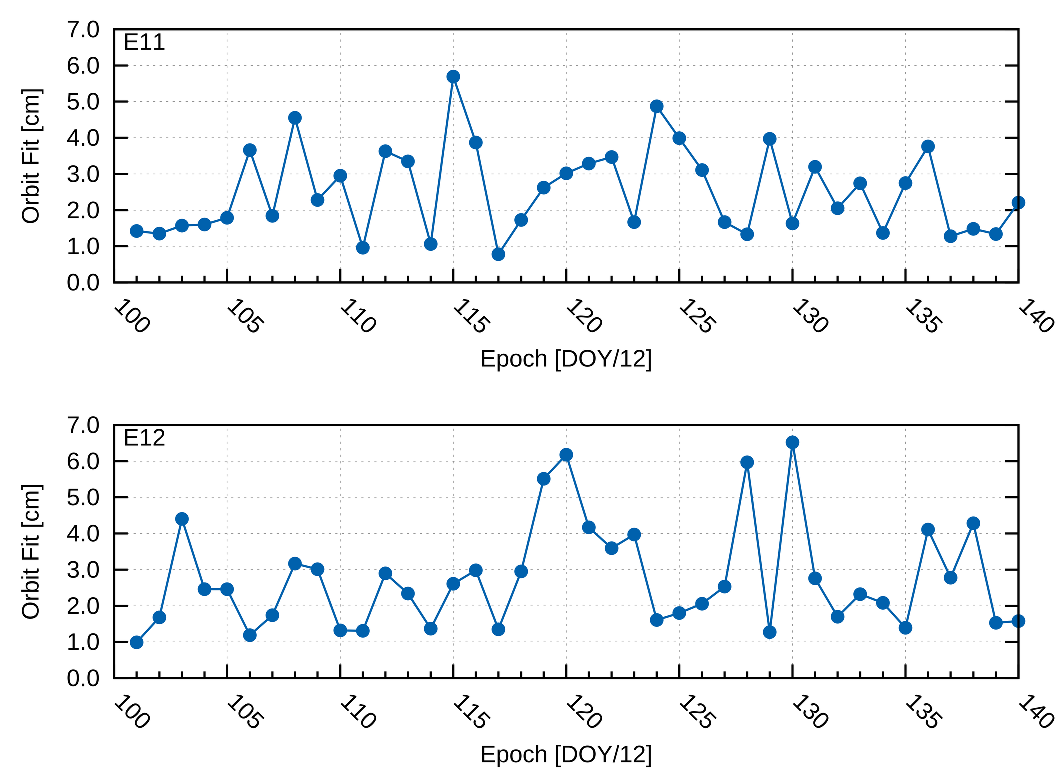

FIGURE 4: E11 and E12 2-day orbit fit time series.

Satellite Laser Ranging (SLR) observations to the IOV satellites are used as an independent validation for satellite orbits derived solely from IOV microwave observations. The IOV satellites are observed on a regular basis by the SLR tracking stations of the International Laser Ranging Service (ILRS), more precisely by 18 stations within the analysis interval.

TABLE 1: SLR residuals to IOV satellites.

PRN	Mean [cm]	RMS [cm]
E11	-5.5	3.8
E12	-5.7	3.4

The residuals are visualized in Figure 5, corresponding numerical values are available in Table 1. The comparison of these three independent validation method shows quite realistic values for the day boundaries, while the orbit fits are assessed as too optimistic due to smoothing effects. On the contrary, the SLR validation can be considered as an independent validation method, whereby the residuals are comparable to GIOVE A/B results. [c.f. Steigenberger et al. (2011)]

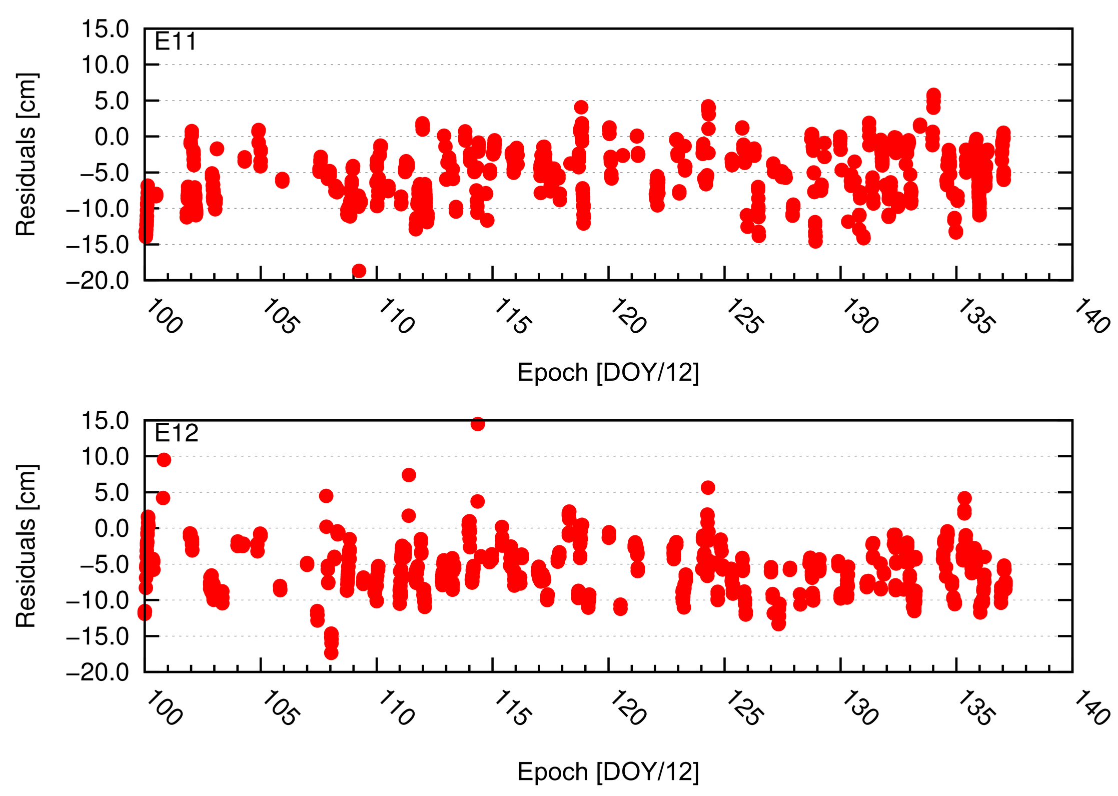

FIGURE 5: E11 and E12 SLR residual time series. For DOYs 138 to 140 no SLR observations are available.

Clock Performance

A satellite navigation system relies on satellite signals that are broadcast synchronously. In order to achieve this, each of both IOV satellites is equipped with 4 atomic clocks. One of the two passive Hydrogen (H)-maser clocks on board each satellite is the master clock with a high stability over long time scales. One of two Rubidium (Rb)-clocks is used as a second, technologically independent frequency normal. The main advantage of this clock is a quite high accuracy on short time scales. Prototype versions of these clocks have already been flown on previous missions. Concerning the investigated time interval, only the Rb normals were enabled on both satellites.

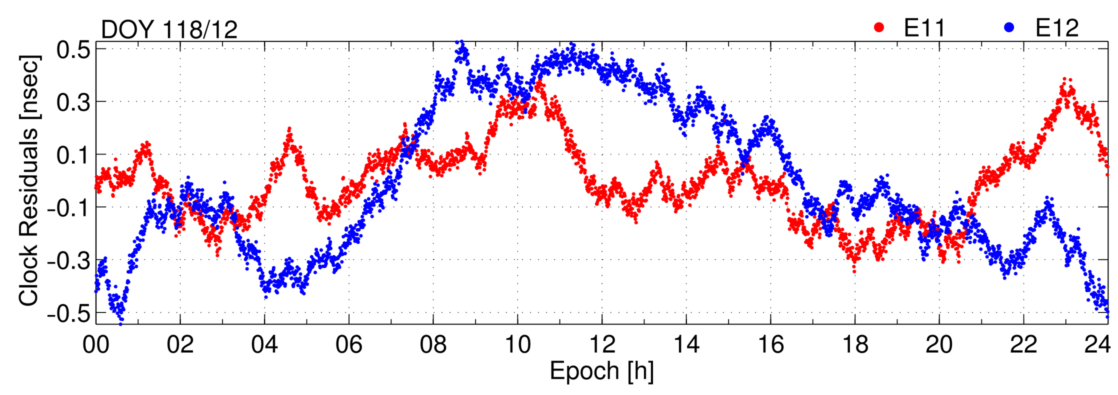

FIGURE 6: Clock residuals, quadratic terms removed.

Over a day interval, the Rb clock exhibits stochastic variations with peak amplitudes of about 1 nsec (30 cm) after removing a linear trend and offset.

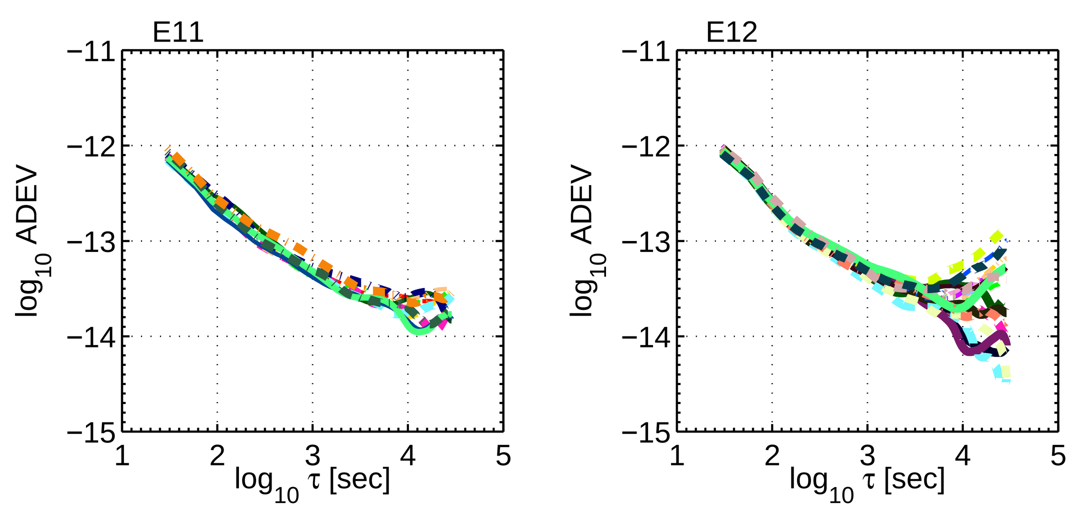

FIGURE 7: Daily Allan Deviations of E11 and E12.

The Allan deviation (ADEV) is a measure for frequency stability over varying integration times. The behavior of clocks with time, especially the flattening of the ADEV between the integration range 10^3 s and 10^4 s is typical for Rb-clocks. The range covered by the daily ADEVs indicate that the H-masers were not enabled in the analyzed time interval.

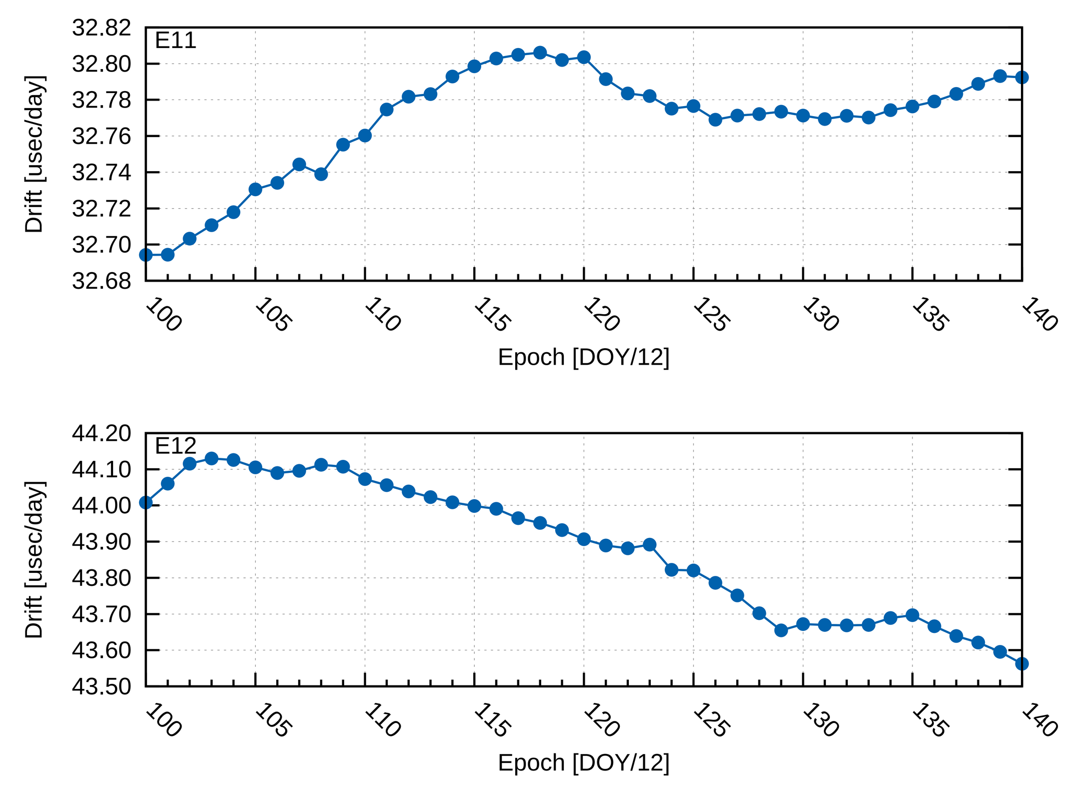

FIGURE 8: E11 and E12 clock drifts.

In the reporting period, the Rubidium clocks showed a frequency drift of about 32 μsec/d and 44 μsec/d, which indicates that the clock frequencies have not been finally steered to their nominal value. Over the 40 days time frame, clock drifts up to 0.6 μsec/d could be observed.

Further Reading

Steigenberger P, Hauschild A, Montenbruck O, Hugentobler U, Hessels U, Weber G, Noack T (2010a) GIOVE orbit and clock determination based on the CONGO network. General assembly of the European Geosciences Union, 27 May, Vienna, Austria.

Steigenberger P, Hugentobler U, Montenbruck O, Hauschild A (2011) Precise orbit determination of GIOVE-B based on the CONGO network. Journal of Geodesy (85), p 363.