Galileo FOC Satellite Group Delay Estimation based on Raw Method and published IOV Metadata

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1. Introduction

In December 2016, the European GNSS Agency (GSA) published the Galileo In-Orbit Validation (IOV) satellite metadata [1]. These metadata include among others the Galileo IOV absolute satellite group delays (SGD) for the three frequency bands E1, E5 and E6, which indicate that the signals are not transmitted at exactly the same epoch.

In the **standard GNSS ionosphere-free dual-frequency processing approach** it is common practice to estimate and apply the differences of these satellite group delays, commonly known as differential code biases (DCBs, [2]). The ionosphere-free clock offset estimates include a bias, which is defined by the linear combination of the involved signal group delays. Therefore these clock offset estimates are only valid for positioning solutions, derived from the same signal combination, which prohibits them to be seen as correct clock offsets in a physical sense.

For ionosphere estimates a similar problem exists in the commonly used approach, where only dual frequency data is processed to generate global ionosphere maps, which are distributed for example in the ionosphere map exchange format (IONEX, [3]). This leads to the fact, that using different dual frequency observations results in different ionospheric delay estimates, which does not make sense, as there is only one physical ionosphere.

In this work, the **GNSS raw observation processing approach** [4] is adopted in order to make use of the published IOV metadata. Satellite group delays for the Galileo Full Operational Capability (FOC) satellites are estimated together with clock offset and ionosphere parameters, which are not only valid for and derived from a specific dual frequency signal combination, but which can serve as products in a true multi-GNSS/multi-signal processing environment.

Group delay, clock offset and ionosphere parameters are highly correlated in terms of estimation in a least squares adjustment. It is therefore a delicate task to estimate these parameters in a single adjustment. To be able to separate these fundamentally different physical contributions to the pseudorange and phase observations, additional external information from calibration campaigns have been applied.

2. Processing Approach

The Raw Method

In the raw observation processing method, developed by the Navigation Support Office at ESOC (European Space Operation Centre), neither differences nor linear combinations of GNSS observations are formed and clock offset parameters, multi-signal group delay parameters and ionosphere parameters can be jointly estimated by making use of all available code and phase observations on multiple frequencies. Absolute calibration values, like the IOV metadata SGDs can be directly applied in the undifferenced processing method to obtain more realistic (in a physical sense) clock and atmosphere estimates.

Multi-GNSS/Multi-Signal processing

The raw method not only allows to jointly process all available signals on different frequencies of a certain GNSS, but also to combine observations of different GNSS in a common adjustment. To demonstrate this functionality, Galileo and GPS observations on 5 different frequencies have been processed.

Used data and products

GNSS code and phase observations from 17 stations of ESOC's global GNSS station network and 44 GNSS satellites have been processed for a 2 week period from 01/11/2016 until 14/11/2016 for the observations (in RINEX v. 3 notation):

Galileo 1C, 5Q, 7Q, 8Q; GPS 1C, 2W, 5Q

ESOC's multi-GNSS orbit products are used together with IOV metadata SGDs and additional information from several calibration campaigns.

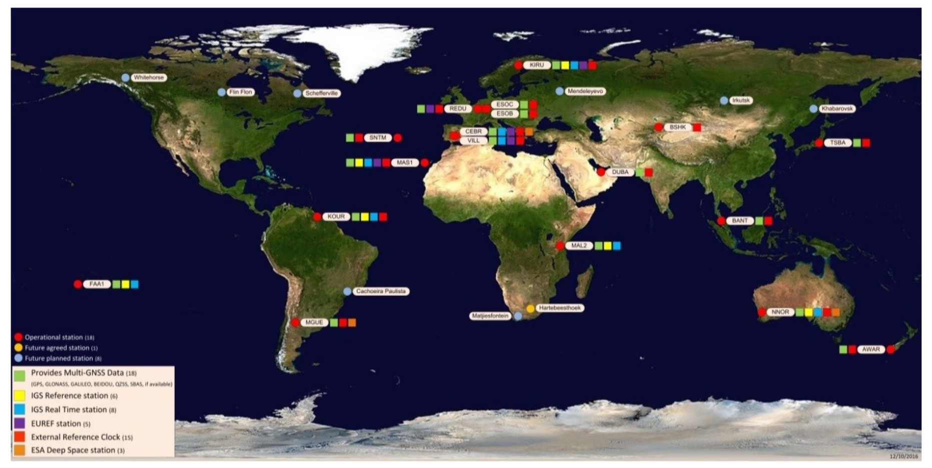

Figure 1: ESOC's global GNSS station network

3. Group Delay and Clock Offset Estimation

The GNSS station setup at ESOC is composed of several receivers and H-Masers and ESA's contribution to UTC together with all relevant calibrations performed in this context, allows to refer all estimated clock offsets to the local UTC realisation and therewith finally to UTC. In addition, receiver group delays have been determined in a calibration campaign with a GNSS signal simulator.

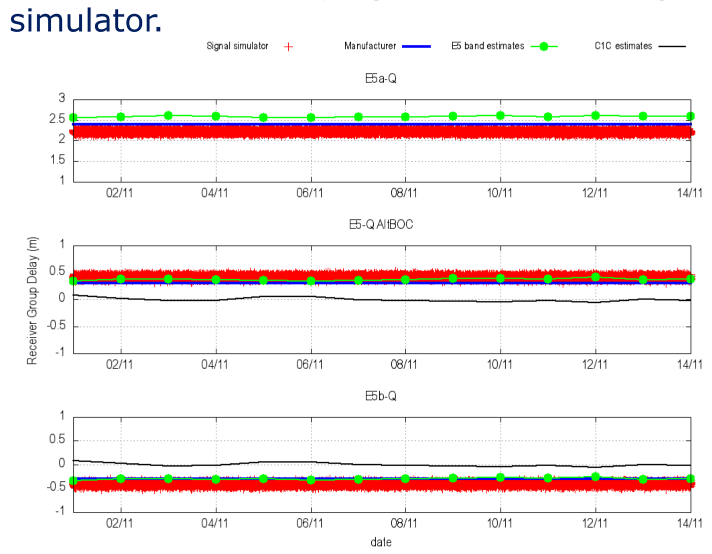

Figure 2: ESOC receiver group delays for Galileo signals on E1, E5a, E5b and E5 AltBOC. The mean value of the absolute receiver C1C group delay estimates (black) has been subtracted from all estimates

Figure 2 shows the Galileo signal group delays of the receiver at ESOC (ESOC). In order to compare the daily absolute group delay estimates to the results of the signal simulator calibration campaign and nominal values provided by the receiver manufacturer, the mean value of the absolute receiver group delay estimate for the E1 OS pilot (C1C) signal SGD_{C1C} = *222.2* ns has been subtracted from all estimates. The Galileo IOV satellite group delays have been loosely constrained

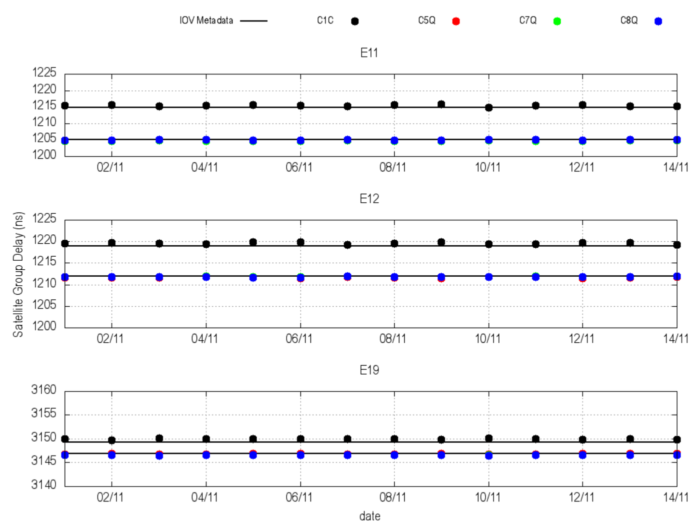

Figure 3: Galileo IOV absolute satellite group delay estimates and metadata values [1]

to the IOV metadata values to allow for variations in the absolute biases due to the 4-5 years lifetime of the Galileo IOV satellites.

Figure 3 shows that the absolute IOV satellite group delay estimates agree very well with the published IOV metadata values.

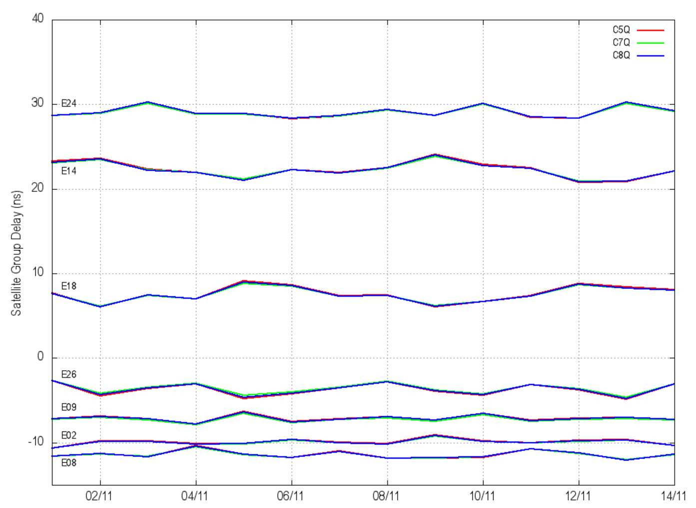

Figure 4: Galileo FOC satellite group delay estimates relative to C1C

The Galileo FOC satellite group delay estimates in Figure 4 were constrained by introducing a zero mean condition per signal among all FOC satellites and by setting the C1C satellite group delay to zero. The zero mean condition was necessary, as there are no FOC satellite metadata publicly available and the satellite clock offsets are also estimated in the least-squares adjustment.

However, setting one signal group delay to zero just results in a redefinition of the clock offset estimates, which can be handled straight forward in the Raw Method, as all signals are processed together without forming any linear combinations.

Satellite clock offsets which are derived by processing the ionosphere-free linear combination of GNSS code observations include a bias, which is defined by the linear combination of the involved satellite signal group delays. From this definition the ionosphere-free group delay ($SGD_{IonoFree}$) for the Galileo I/NAV broadcast clock offsets of the IOV satellites can be calculated from the published IOV metadata as *1228.6* ns (E11), *1228.7* ns (E12) and *3152.7* ns (E19). With the Raw Method and the known absolute signal group delays for the IOV satellites, satellite clock offsets can be estimated, which are a more realistic representation of the true satellite clock.

Equation (1) shows the relation between the estimates of the commonly used ionosphere-free clock offset $dt_{IonoFree}$, the true clock offset from the Raw Method dt_{raw} and the ionosphere-free combination of the signal group delays $SGD_{IonoFree}$.

$$dt_{IonoFree} = dt_{raw} - SGD_{IonoFree} \quad (1)$$

To verify this relation, the estimated true clock offsets for the IOV satellites have been subtracted by the ionosphere-free bias and the broadcast I/NAV clock offsets, which should be equal to zero. Figure 5 shows this clock offset difference for the three IOV satellites for the complete time interval. It can be seen, that the relation holds true for the first 8.5 days of November 2016, which demonstrates the successful estimation of the true satellite clock offsets with the Raw Method.

The jump on 09/11/16 and subsequent offset are due to a known constellation test period, which was announced in the notice advisory to the Galileo users (NAGU) number 2016049 with the description: "all available satellites may broadcast marginal signals until further notice".

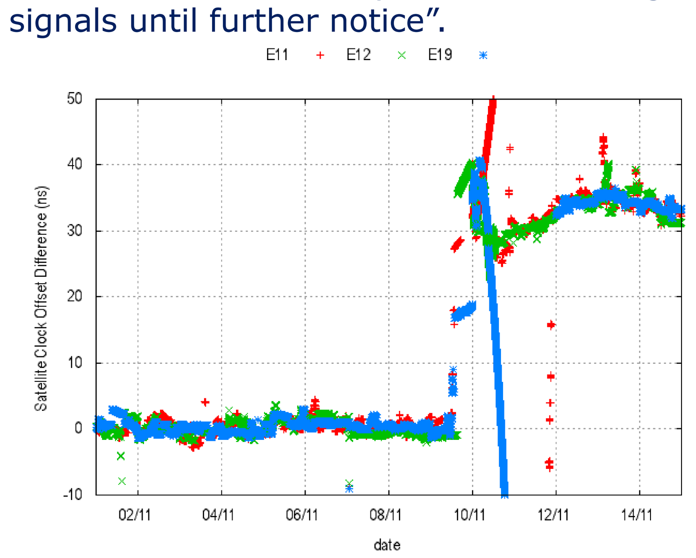

Figure 5: Difference between Galileo IOV satellite true clock offset estimates and I/NAV broadcast clock offsets, corrected by the ionosphere-free satellite group delay

A similar verification of the satellite clock offset estimates has been performed for the Galileo FOC satellites. However, due to the re-definition of the FOC satellite clocks, the I/NAV broadcast clock offsets have been corrected by the estimated broadcast group delay (BGD) values. As expected, Figure 6 shows the same jump on 09/11/16 and subsequent offset for the FOC satellites, however for the first 8.5 days it can be seen, that the clock offset difference is not centered at zero but has an offset of about 3 ns. This can be explained by the already mentioned introduction of a zero mean constrain, which is not correct in a physical sense, but is needed to remove the rank deficiency of the design matrix in the least-squares adjustment. As discussed in the next section, this also has an impact on the ionospheric signal delay estimation.

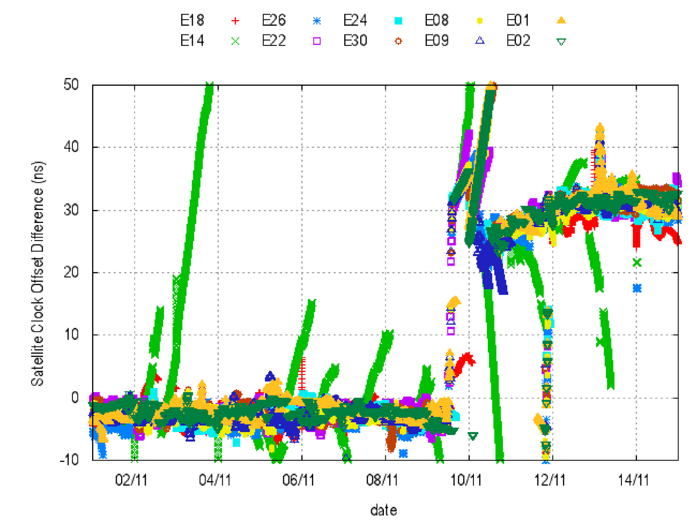

Figure 6: Difference between Galileo FOC satellite clock offset estimates and I/NAV broadcast clock offsets, corrected by the BGD estimates

4. Ionospheric Delay Estimation

In addition to clock offset and group delay parameters, the ionospheric slant path delay between all stations and GNSS satellites has to be estimated, since in the Raw Method no linear combinations are formed to cancel the first order ionospheric effects. The total electron content (TEC) along the signal path is estimated per epoch from code and phase observations on all frequencies and signals for a specific receiver satellite link. This allows to determine realistic ionosphere parameters based on multi-signal code and phase measurements rather than using only dual frequency observations as in the conventional method. Figure 7 shows the ionospheric delay estimates in TEC units (TECU = 10^{16} e^-/m^2) for the signal paths

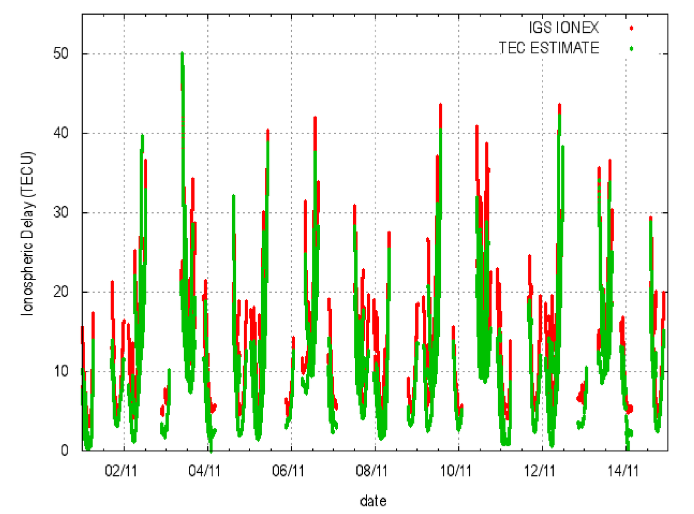

Figure 7: Ionospheric slant path delay between ESOC station and all Galileo IOV satellites

between the ESOC receiver and the three Galileo IOV satellites. For comparison, the slant path TEC values from IGS IONEX files (igsg*) are also given. It is expected, that the TEC estimates deviate from the IONEX file values, which are based on dual frequency data only and have a limited temporal and spatial resolution, however the introduction of the absolute receiver and IOV satellite group delays leads to a comparable level of the ionospheric delay.

For the FOC satellites, no absolute satellite group delays are available and the introduction of the necessary, but not physical zero mean constrain leads to a shift of the absolute TEC estimate level, as seen in Figure 8. The problem with any kind of zero mean condition is, that additional or

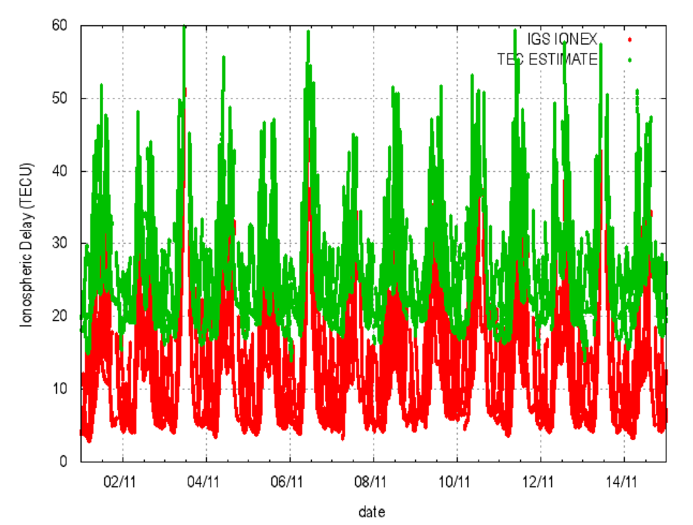

Figure 8: Ionospheric slant path delay between ESOC station and all Galileo FOC satellites

less values, in this case when new satellites join the constellation or drop out, change the mean value and therefore would have a direct impact on the estimates of other parameters, like the ionospheric delay.

This example shows on one side that the attempt to estimate satellite group delays, true clock offsets and realistic ionosphere parameters requires at least some a-priori approximation of the absolute satellite group delays. On the other side it shows the potential of the Raw Method, which in case of the Galileo IOV satellites was successfully used to jointly process code and phase measurements on 4 frequencies to determine true satellite clock offsets and realistic ionospheric delay estimates.

To show that realistic ionosphere parameters for the Galileo IOV satellites have not only been estimated for the ESOC station, but for the whole ESOC station network, Figure 9 shows the epochwise TEC (EPOTEC) estimates for the signal path between satellite E19 and four ground stations, all located in Europe. The two stations in Spain CEBR and VILL, which are separated by only 40 km show the exact same estimates, whereas the two stations at similar latitude REDU (Belgium) and ESOC (Germany) indicate a similar satellite path with only small differences in the EPOTEC estimates.

However, the absolute level of the ionospheric delay estimates is identical for all four stations, which demonstrates the capabilities of the Raw Method.

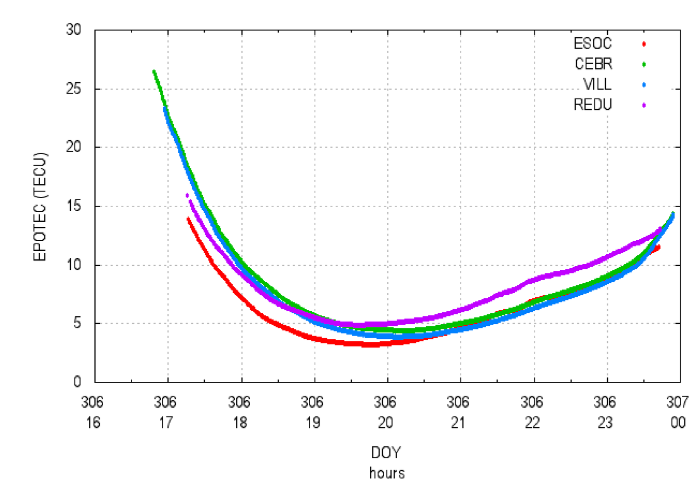

Figure 9: Ionospheric delay estimates for satellite E19 and stations at ESOC, in Cebreros, Villafranca and Redu on 01/11/16 (DOY 306)

5. Applications

The Raw Method provides a universal GNSS processing approach, which in combination with absolute calibrated signal group delays

- Increases the accuracy, robustness and reliability of **Positioning** and **Navigation** solutions by jointly processing multi-GNSS, multi-signal code and phase raw observations
- Provides realistic ionosphere parameters for **Atmosphere** science and other geodetic observing techniques, like VLBI
- Provides true satellite and receiver clocks offsets relative to UTC for precise Positioning and **Timing** applications

6. Conclusions & Outlook

- Absolute calibration values, like the published Galileo IOV satellite group delays can be directly applied in the Raw Method to provide a major step into the direction of more realistic (in a physical sense) clock and ionosphere estimates
- Galileo is the first GNSS to provide absolute satellite calibration values and therefore paves the way to exploit the full benefits of the Raw Method
- Products generated with the Raw Method for satellite orbits, clock offsets, signal biases and ionospheric delays provide a comprehensive basis for multi-GNSS/multi-signal processing in the user segment
- The attempt to estimate satellite group delays, true clock offsets and realistic ionosphere parameters requires at least some a-priori approximation of the absolute satellite group delays
- As soon as publicly available, Galileo FOC absolute satellite group delays will be possible to process a fully calibrated Galileo satellite system for the first time and to determine true clock offsets and ionosphere parameters for the whole constellation
- If available, additional external ionosphere delay measurements will be used to verify the absolute level of the TEC estimates, determined with the Raw Method

References

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