Computation of Scintillation Indices for the Galileo E1 Signals Using a Software Receiver

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1. Introduction

European Galileo system was designed to be inter-operable with the existing GPS and GLONASS systems with its Open Service (OS) targeted towards mass-market applications. The Galileo system provides signals in the so-called L frequency band. The frequency bands and central frequencies of E1 and E5a are common for both Galileo and GPS, i.e. E1/L1 has a center frequency at 1575.42 MHz and E5a/L5 has a central frequency at 1176.45 MHz, and thus GNSS receivers can seamlessly combine GPS and Galileo signals in their positioning and timing applications. Galileo will provide a variety of new, high accuracy services such as Commercial Service (CS), Safety of Life Service (SoL), Public Regulated Service (PRS) and Search and Rescue (SAR). In addition, a larger number of satellites will be available for the investigation of ionospheric threats and reception issues such as multi-path and interference. The use of new GNSS signals is expected to increase with the availability of the full Galileo constellation.

The ionosphere takes the upper part of the Earth's atmosphere which is ionized by solar radiation, extending from about 50 to near 1500-2000 km and completely encircling the Earth. Electron and ion densities in the ionosphere vary in complex manner with time, season, geographical location, solar and magnetic activity. The presence of small scale irregularities can disturb the radio frequency (RF) signals causing amplitude and phase fluctuations [1]. The amplitude fading or phase variations of RF signals (referred to as scintillations) can, among other effects, cause a receiver to lose lock to one or more signals broadcasted by the GNSS satellites. Very high scintillation activity levels may occur during solar maximum, in particular in the equatorial, polar and auroral regions [1].

One of the possibilities to investigate the influence of the scintillation on GNSS signals is using the so-called scintillation indices, S_4 and sigma phi (σ_ϕ). They are used to estimate the fluctuations on the signal intensity and phase. This approach, which was adopted in this study, is given in the third section of this paper. The analysis was done using real Intermediate Frequency (IF) data collected by an experimental setup placed in Vietnam during a period of high solar activity. The IF data was fed into the MATLAB based software receiver capable of tracking the Galileo E1 signals after which the scintillation indices were estimated and compared with the results obtained by a professional Septentrio PolaRxS receiver.

2. Galileo signal structure

The Galileo OS system transmits GNSS signals in three frequency bands, E1, E5a/b and E6 (planned to be 1278.75 MHz since the signals in the E6 band have not yet been fully specified). A detailed description of the signals can be found in the Galileo OS Signal In Space Interface Control Document (SIS ICD) [2]. In its full constellation, the Galileo system will consist of 30 satellites (27 regular and 3 spare; but at the present only 4 satellites are available). New complex Galileo signals are not only stronger than the signals from GPS/GLONASS, but they also provide data free channels which should bring advantages in receiver processing for signal acquisition, code tracking, carrier tracking, and data demodulation.

2.1. Galileo OS E1 signal

The Galileo E1 OS band is located in the upper L-band with the frequency centered at 1575.42 MHz and a reference bandwidth of 24.552 MHz, the same as for GPS L1. The E1 signal uses the so called Composite Binary Offset Carrier CBOC, i.e. CBOC(6,1,1/11) modulation, defined as:

$$S_{E1}=\frac{1}{\sqrt{2}}e_{E1\text{-}B}(t)\left(\alpha sc_{E1\text{-}B,a}(t)-\beta sc_{E1\text{-}B,b}(t)\right)-\frac{1}{\sqrt{2}}e_{E1\text{-}C}(t)\left(\alpha sc_{E1\text{-}C,a}(t)-\beta sc_{E1\text{-}C,b}(t)\right). \quad (1)$$

The sub-carriers $sc_{E1\text{-}B}(t)$ and $sc_{E1\text{-}C}(t)$ are defined as:

$$sc_{E1\text{-}B}(t)=sng\left(sin(2\pi F_S t)\right), \quad (2)$$

$$sc_{E1\text{-}C}(t)=sng\left(sin(2\pi F_S t)\right), \quad (3)$$

where, Fs is a sub-carrier sampling rate frequency (1.023 MHz and 6.138 MHz for CBOC(6,1,1/11)), $\alpha=\sqrt{\frac{11}{10}}$ and $\beta=\sqrt{\frac{1}{10}}$ are parameters chosen in a way to combine the Power Spectrum Density (PSD) of two sub-carriers. The E1 signal consists of two channels: the in-phase I channel and the quadrature-phase Q channel. The I channel comprises both data and pilot channels taking into account orthogonality between them, i.e. the data channel sub-carrier is orthogonal to the pilot channel sub-carrier. The Q channel is reserved for the Public

Regulated Service (PRS). Ranging codes of the Galileo E1 signal are composed of primary and secondary codes by using the tiered code construction [2]. Primary codes for both data and pilot channels represent Pseudorandom Noise (PRN) codes with chip rate of 1.023 MHz and code length of 4092 chips, i.e. code length of 4 ms. The data channel is multiplied by the navigation data (NAV), while the pilot channel is multiplied by the secondary code instead of the NAV. The duration of the pilot channel is 100 ms. The secondary code is unique for all the satellites and has a length of 25 chips.

2.2. Galileo OS E5 signal

The Galileo E5a/b band is located in the lower L-band. The E5a frequency is centered at 1176.45 MHz (the same center frequency as GPS L5) and the E5b frequency is centered at 1207.14 MHz [2]. Both signals have a bandwidth of 20.46 MHz making the Galileo E5 OS the widest signal in the GNSS spectrum. If considered the entire E5 band an Alternative Binary Offset Carrier (AltBOC) modulation has to be taken into account. The AltBOC(15,10) is characterized by a very wide bandwidth and four complex channels modulated by four different PRNs, i.e. all four channels: E5aI, E5aQ, E5bI, E5bQ. E5aI and E5bI are data channels and they carry navigation messages, while EaQ and EbQ are pilot channels and they are data free. If the E5a/b signals are considered as separate frequency bands, the signals can be treated as Binary Phase Shift Keying (BPSK) signals. Since both E5a and E5b have two components (I and Q) the chip rate is 10.23 MHz for both data/pilot channels.

The ranging codes of the Galileo E5a/b signals are composed of primary and secondary codes. Duration of the primary codes are 1 ms and they can be generated as Linear Feedback Shift Register (LFSR) pseudo-noise sequence [2] or optimized pseudo-noise sequence also called 'memory codes'. On the other hand, the secondary codes are fixed sequences defined in hexadecimal form [2]. The data channels (E5aI and E5bI) have two unique secondary codes with a code length of 20 chips and 4 chips respectively. That means that the tiered code period for both data channels are respectively 20 ms for E5aI and 4 ms for codes E5bI. Different secondary codes are used for both pilot components for the all satellites. The code length for those codes is 100 chips and thus the pilot tiered code period is 100 ms.

3. Estimation of the scintillation indices

Estimation of the signal amplitude fluctuations induced by ionospheric irregularities can be done using the amplitude scintillation index S_4 [3]. The amplitude scintillation index is based on the signal intensity (SI) computation and it is given as:

$$S_4=\sqrt{\frac{\langle SI^2\rangle - \langle SI\rangle^2}{\langle SI\rangle^2}}, \tag{4}$$

where, <.> denotes an average value computed over a 60 second time interval and SI is taken to be the difference between the Narrow Band Power (NBP) and Wide Band Power (WBP) measure over the 20 ms time interval. According to [3], the NBP and WBP are given as:

$$NPB = \left(\sum_{i=1}^{M} I_i\right)^2 + \left(\sum_{i=1}^{M} Q_i\right)^2 \tag{5}$$

$$WBP = \left(\sum_{i=1}^{M} I_i + Q_i\right)^2 \tag{6}$$

I and Q represent the accumulated samples of the prompt correlator and period M is set to be 20 for Galileo OS E5a/b (it is the same as for GPS L1 C/A) and 5 for Galileo OS E1. To remove the errors originating from ionospheric effects, tropospheric effects and inaccuracies of satellite and user clocks, a detrending method has to be used [3]. For that purpose, the SI values are filtered by the 6th order low pass Butterworth filter, i.e. the SI is obtained by dividing the raw signal intensity by the filtered output:

$$SI = \frac{NBP - WBP}{(NBP - WBP)_{lpf}} \; . \tag{7}$$

To remove the ambient noise, the S_4 index given in Eq. (4) can be estimated as:

$$S_{4corr} = \sqrt{\frac{100}{\frac{S}{N_0}}\left[1 + \frac{500}{19\frac{S}{N_0}}\right]} \tag{8}$$

where, S/N_0 is the signal to noise density within the 60 seconds estimated as:

$$\frac{S}{N_0} = 10^{\frac{C}{10N_0}} , \tag{9}$$

and, C/N_0 is the carrier-to-noise ratio estimated from I and Q samples of the prompt correlator.

The phase fluctuation, on the other hand, is realized by σ_ϕ which represents the fluctuation of the carrier phase (φ). φ is the output of the carrier tracking loop and the phase scintillation indicator is given as:

$$\sigma_\phi = std(\varphi) , \tag{10}$$

where, ***std*** represents the standard deviation. The most common version of the sigma phi index is evaluated over 1 minute and it is indicated as Phi60 and it is used in this study. Finally, to avoid any false influence of the ionosphere scintillation activity, the process of detrending has to be used to remove all the fluctuations introduced by other factors (such as multipath, receiver noise, satellite clock errors and so on). The detrending method was done processing the carrier phase measurement through the 6th order high pass Butterworth filter with a cut off frequency of 0.1 Hz [3].

4. Results and discussion

The basic analysis of S_4 and Phi60 indices was performed using the real data affected by equatorial scintillation. To collect the IF data, a GNSS front-end based Universal Software Radio Peripheral (USRP) was used with an external 10 MHz rubidium clock as reference. The reason of using the rubidium clock lies in the fact that the Temperature-Controlled Crystal Oscillator (TCXO) integrated in the USRP is not suitable for scintillation monitoring process [3]. The system of an USRP model N200 front-end, an antenna AT1675-120W SEPCHOKE_MC with Spike Radome and a Septentrio PolaRxS receiver have been used as an experimental setup installed at the NAVIS centre, Hanoi University of Science and Technology, Vietnam in collaboration with the Joint Research Center (JRC) based in Ispra and NavSaS group of Politecnico di Torino based in Turin, Italy.

Data was collected from February till September 2013 in a period of 20 minutes basis each day in the E1/L1 band using 5 mega samples per second (MS/s), which is an optimal sampling rate for both GPS and Galileo E1 signals. The IF was zero since the USRP down-converts the signals and mixes them down to baseband [4]. The Septentrio PolaRxS receiver was used together with the USRP in order to collect the additional data, such as azimuth and elevation angles, as well as C/No of the satellites in view. Finally, the data obtained by the USRP front-end was played into the Septentrio PolaRxS receiver and the scintillation indices were estimated and used as a reference case in this study. The basic analysis of the scintillation indices has been done only for a limited data set, i.e. from March 14 2013 at 14:40 LT, where among GPS signals, two Galileo signals were available.

The CBOC is usually used in the conventional Galileo receivers but this requires higher sampling rates and more complex 4-level local replica [5]. To avoid this, the Galileo E1 signals have been treated as a Binary Offset Carrier (BOC), i.e. BOC(1,1). The acquisition and post-processing algorithm used for analysing the Galileo E1 signals are based on a modified version of MATLAB Borre's software receiver given in [6] and most commonly used tracking parameters are given in Tab. 1.

PLL filter order	Third-order
PLL bandwidth	10 MHz
PLL discriminator	Early minus late (E-L)
Integration time loop	4 ms

Table 1. PLL Loop tracking details

The block diagram shown in Fig. 1 represents a typically used tracking architecture in conventional GPS receivers and it is also used for Galileo. A third-order PLL loop was chosen to cope better with the fast fluctuations which can occur under scintillations. Both DLL and PLL loop discriminator values were filtered to reduce the noise and thus produce the correct estimate of the input value. According to this, a third-order loop filter was used [7]. After selecting the proper loop filter bandwidth and the integration time interval, the filtered values were used as an update for the Numerically Controlled Oscillator (NCO) to adjust the code frequency and carrier phase error.

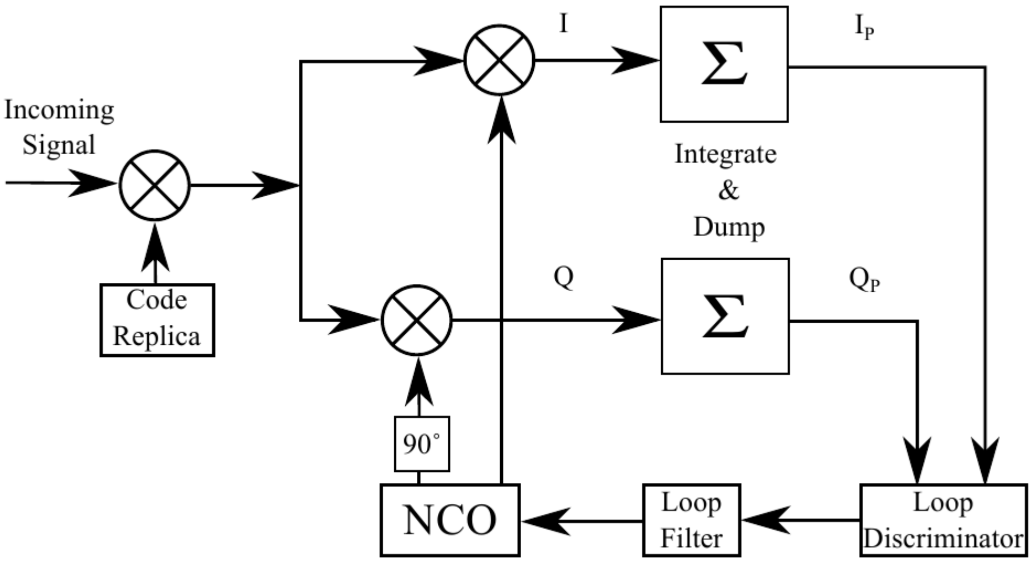

Figure 1. Carrier phase tracking loop

The same tracking parameters were used for both E1b and E1c channel. Third-order Phase Lock Loop (PLL)/ Delay Lock Loop (DLL) were chosen with bandwidths of 10 Hz and 5 Hz respectively. Integration time is 4 ms due to the duration of the primary codes. The carrier phase discriminator was set to be an atan(Q/I) [6] and the code discriminator was chosen to be a coherent early minus late power.

The data used in this study consists of both GPS L1 and Galileo E1 signals with different levels of scintillation. Fig. 2 shows S_4 values for four selected satellites, two GPS and two Galileo, estimated by the Septentrio receiver.

Accordingly, the Galileo E1 PRN 11 and PRN 12 as well as GPS PRN 19 were not affected but GPS PRN 23 shows a satellite link with a very high level of scintillations. Fig. 3 shows the Phi60 values for the same satellite links used for the S_4 estimated by the Septentrio receiver. As expected, higher values of the Phi60 are only for GPS PRN 23 due to the fact that for the equatorial scintillations the amplitude and phase scintillations are correlated [8].

In respect of the Galileo E1 satellites, the level of equatorial scintillations seems to be very low. Fig. 4 and Fig. 5 show the comparison of S_4 values obtained by the software receiver and values directly recorded by the Septentrio PolaRxS. In both figures the S_4 values for Galileo E1c PRN

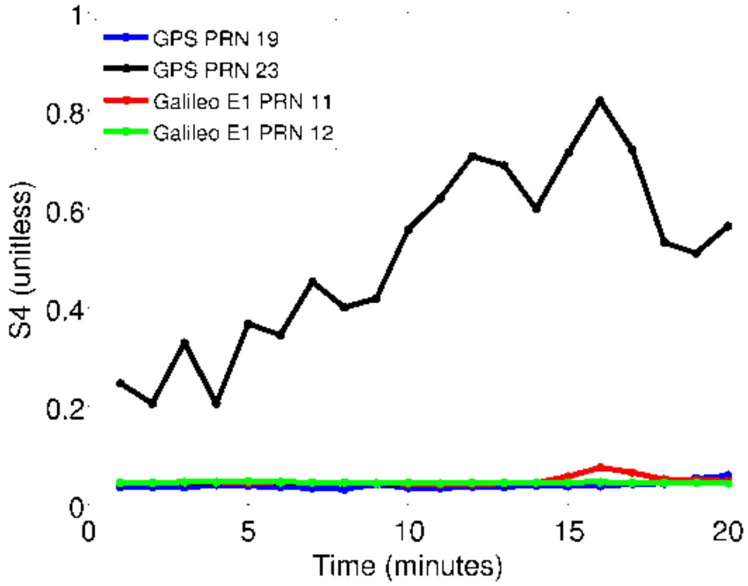

Figure 2. S_4 values obtained by the Septentrio PolaRxS receiver for GPS PRN 19 and PRN 23 and Galileo E1 PRN 11 and PRN 12 satellites. Higher S_4 values, up to 0.8, were observed only in GPS.

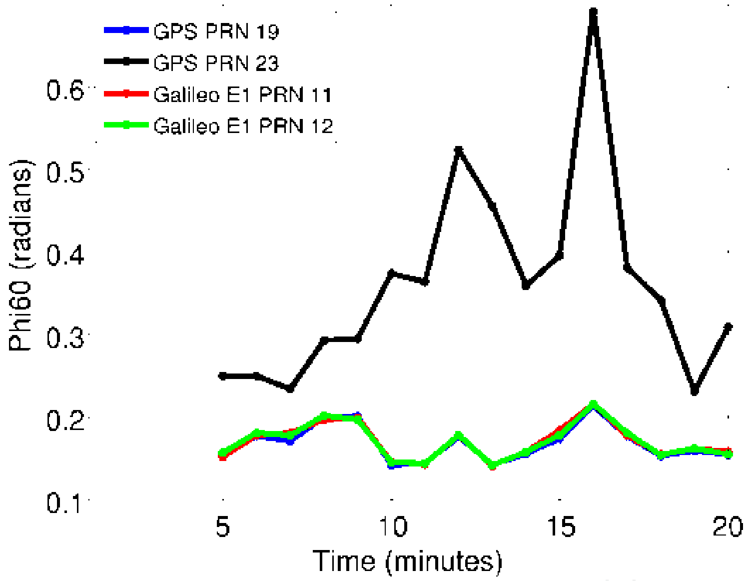

Figure 3. Phi60 index values obtained by the Septentrio PolaRxS receiver for GPS PRN 19 and 23 and Galileo E1 PRN 11 and 12 links. Higher values of Phi60, below 0.8 radians, were observed only for the GPS PRN 23. For the other satellites Phi60 was below 0.2 radians.

11 and PRN 12 signal almost overlap those obtained from the Septentrio receiver; however a significant deviation was observed for Galileo E1b.

Finally, a very good correlation was found between the estimated Phi60 values and those obtained by the Septentrio PolaRxS receiver as shown in Fig. 6 and Fig. 7.

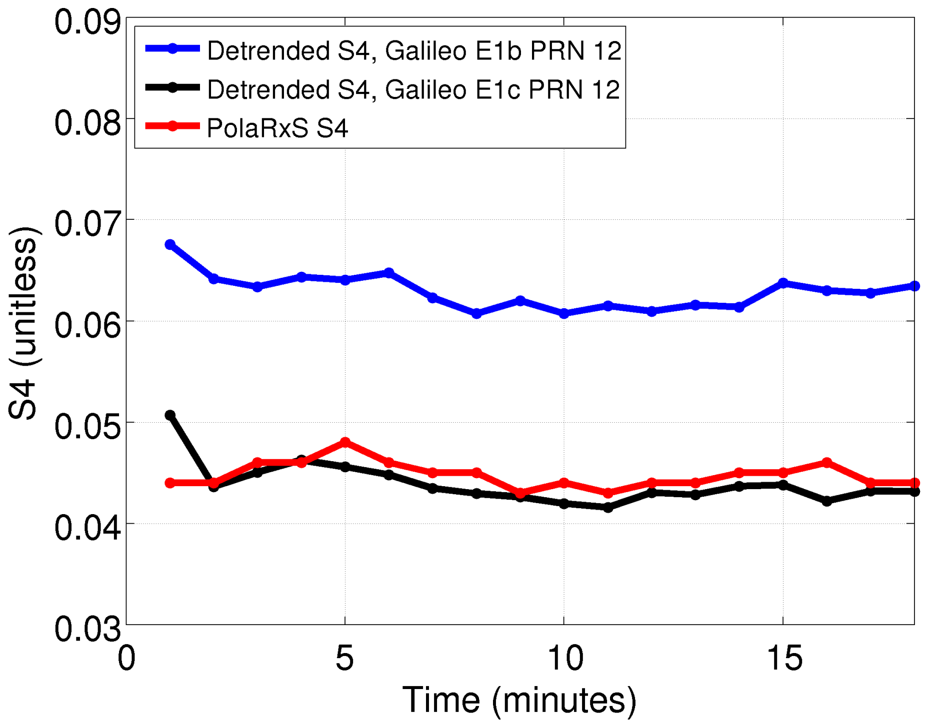

Figure 4. Comparison of S_4 values obtained by the Septentrio PolaRxS receiver and estimated values of Galileo E1b/c PRN 12 obtained by the software receiver.

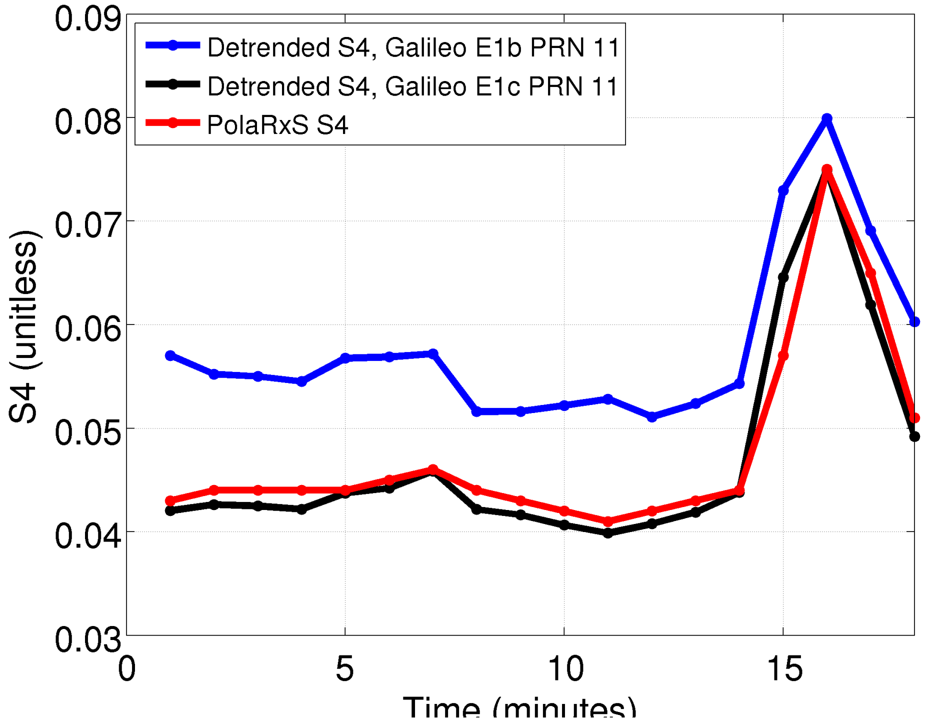

Figure 5. Comparison of S_4 values obtained by the Septentrio PolaRxS receiver and estimated values of Galileo E1b/c PRN 11 obtained by the software receiver.

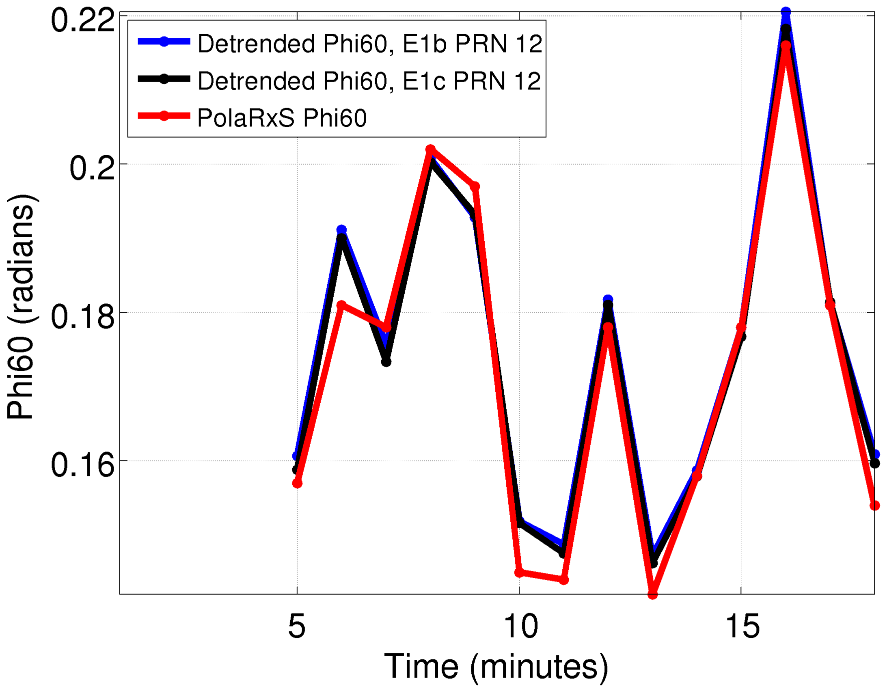

Figure 6. Comparison of Phi60 index obtained by the Septentrio PolaRxS receiver and estimated values of Galileo E1b/c PRN 12 obtained by the software receiver. Small deviations in Phi60 are due to temporal misalignment between the estimated and the Septentrio receiver values.

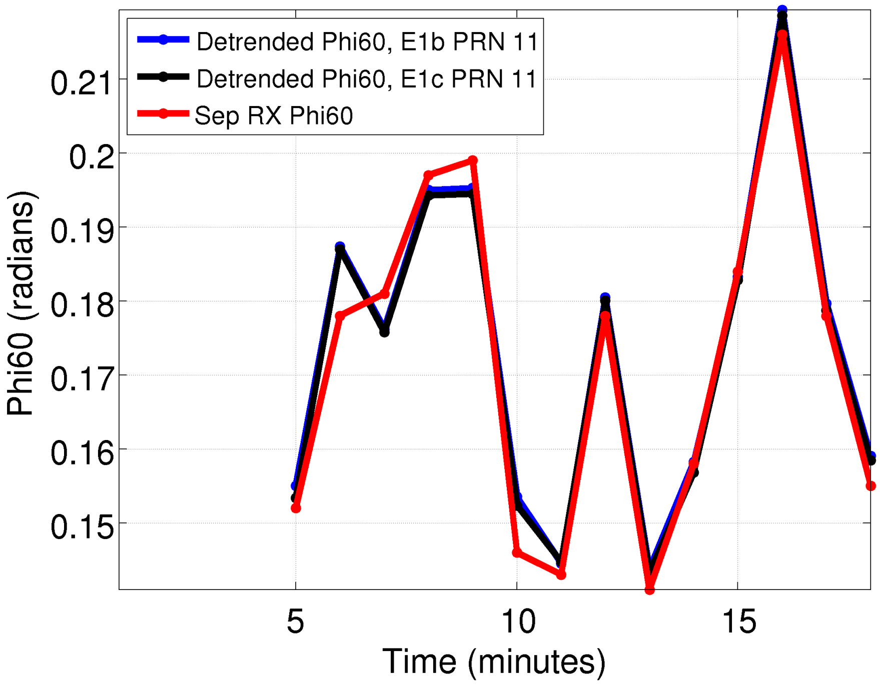

Figure 7. Comparison of Phi60 index obtained by the Septentrio PolaRxS receiver and the estimated values of Galileo E1b/c PRN 11 obtained by the software receiver. Small deviations in Phi60 are due to temporal misalignment between the estimated and the Septentrio values.

5. Conclusion

The research presented in this paper shows values of S_4 and Phi60 indices estimated for Galileo OS E1 signals for the equatorial region using a software receiver. The BOC tracking algorithm implemented into this software receiver, all together with standard third order PLL, showed good solution for this particular case study where Galileo signals seem not to be affected by equatorial scintillation. It was shown that for Galileo E1 signals the S_4 and Phi60 indices are not as high as those for GPS case estimated for this particular data set. The estimated indices by software receiver are verified by those obtained by a professional receiver and a very good correlation was found. However, the Phi60 values are almost overlapping meaning that the carrier phase was estimated properly and the detrending cut off frequency was chosen correctly.

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