Analysis of Bitgrabber Data Affected by Equatorial Ionospheric Scintillation Events During 2013 Solar Maximum

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***Abstract*— The following article present the analysis of the post-processing of raw GNSS signal recorded in Cape Verde during 2013 solar maximum and affected by ionospheric scintillation. The post-processing is done using a fast GPU software receiver developed by Thales Alenia Space France, allowing an observation of the scintillation effect at the signal processing level.**

Keywords—Ionosphere, scintillation, MONITOR, equatorial, equinox

I. INTRODUCTION

Since a couple of years, GNSS is taking a more and more important place in the society, both for Safety of Life and mass market applications. For the critical applications that require positioning integrity, the error contributors have to be well known and modeled.

One of the main error contributors is the ionosphere. The classical effect of the ionosphere on the GNSS signal is the introduction of a positive delay on the code measurement and of a negative one on the phase measurement. The mean effect of the ionosphere can be coped using bi-frequency receivers. On the contrary, a mitigation technique aiming to remove the scintillation effect on the GNSS signal is much more difficult to implement.

The scintillation phenomenon is related to the ionosphere variability. It is more likely to be encountered at low and high latitude locations (near the equator (-20° to +20°) and the poles (> 65°)) lasting a few hours after sunset (periods where the variation of the ionosphere activity is the highest). It is related to the solar activity. There is a climatology for this effect with higher activity periods during equinoxes. The amplitude scintillation mainly impacts the GNSS signal power while the phase scintillation produces quick variations of the GNSS signal phase.

In order to study and characterize the scintillation phenomenon (and more generally the ionosphere activity), the European Space Agency (ESA) launched in 2010 the MONITOR project with a consortium of 11 European partners, led by IEEA. In the frame of this project, 16 monitoring stations have been deployed, well distributed over the world (mainly at low and high latitude locations). These stations upload their measurements, including ionosphere an scintillation measurements every hour onto a central server that implements post-processing and analysis tools.

One of these stations, located in Cape Verde (14°55′N 23°31′W), has been equipped with a bitgrabber module, developed by Thales Alenia Space, which is able to record a baseband GNSS signal at L1 and L2 frequencies. The goal of the equipment is to record GNSS signal during scintillation events, when standard receivers may fail tracking in order to allow performing a detailed analysis at the signal processing level.

This paper shows the results of the analysis of the GNSS signal recorded in Cape Verde during 20 evenings (between 20h and 22h UTC) from the 15th of March 2013 to the 21st of April 2013. For this analysis, a software GNSS receiver using GPU processing and developed by Thales Alenia Space has been used. This GNSS software receiver allows fast replay (thanks to GPU power) of the recorded signal and permits to test the behavior of different receiver configuration against scintillation while giving access to the lowest levels of the signal processing of a GNSS receiver (e.g. correlator outputs).

The paper will be organized as follows:

- In a first section, the scintillation phenomena and its impact on GNSS is introduced
- In a second section, the collection and processing tools will be presented

- In a third section the results of the analysis of all the signal collected will be presented to draw general observations. An analysis on receiver robustness during scintillation will also take place in this section.

II. The Scintillation Phenomenon

As a result of propagation through ionosphere electron density irregularities, transionospheric radio signals may experience amplitude and phase fluctuations. In equatorial regions, these signal fluctuations specially occur during equinoxes, after sunset, and last for a few hours. They are more intense in periods of high solar activity. There is also a longitudinal dependency. Scintillations are more common in South America near the December solstice than at the equinoxes. These fluctuations result in signal degradation from VHF up to C band. They are a major issue for many systems including Global Navigation Satellite Systems (GNSS), telecommunications, remote sensing and earth observation systems.

The signal fluctuations, referred as scintillations, are created by random fluctuations of the medium's refractive index, which are caused by inhomogeneities inside the ionosphere. These inhomogeneities are sub structures of bubbles, which may reach dimensions of several hundreds of kilometers as can be seen from radar observations. These bubbles present a patchy structure. They appear after sunset, when the sun ionization drops to zero. Instability processes develop inside these bubbles with creation of turbulences inside the medium. As a result, depletions of electron density appear. In the L band and for the distances usually considered, the diffracting pattern of inhomogeneities in the range of one kilometer size, is inside the first Fresnel zone and contribute to scintillation.

Two indices are defined to characterize the scintillations: the standard deviation of the normalized intensity, named S4, and the phase standard deviation. The scintillation event strength is defined with respect to the S4 value which is between 0 and $\sqrt{2}$. A value of 1 will correspond to about 35 dB peak to peak of intensity fluctuations. The scintillation strength is weak ($S4 < 0.3$), medium ($0.3 < S4 < 0.6$) or strong ($S4 > 0.6$) depending on the case. This usual classification refers to the fade levels and the resulting constraints on a navigation system, from -2 dB to + 2 dB in the weak regime to more than 20 dB peak to peak for the strong regime.

The results of scintillations on GNSS are manifold. The amplitude scintillation has the effect to decrease the C/N0 budget link and thus the tracking accuracy. The phase scintillation degrades the correlation by destroying the phase coherence required for this operation. In the worst case the tracking is lost, increasing the DOP and by consequence the positioning error.

III. Presentation of the Tests

A. Record site

The results presented hereafter were obtained in the frame of the ESA Monitor project [1]. The site location considered is Praia, Cape Verde (see Fig. 1), close to the magnetic equator. The same tendencies have been observed at the other Monitor receiver locations.

Fig. 1. Site location

Fig. 2 and Fig. 3 shows the scintillation activity in cape Verde during year 2013.

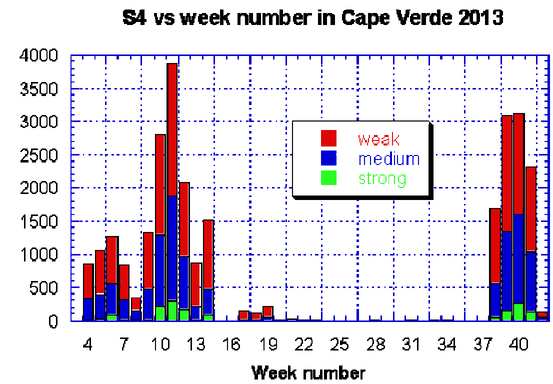

Fig. 2. Number of S4 event vs the week number

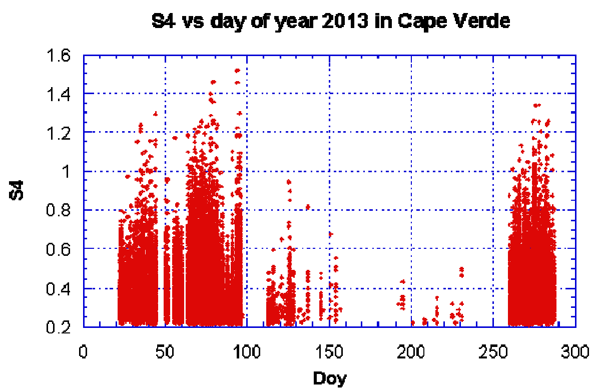

Fig. 3. : Intensity scintillation depending on the day number in Cape Verde

The peak of the scintillation activity occurs at the equinoxes and the number and the strength of the scintillation events increase with the solar activity (peak in 2013).

The phase scintillation shown on Fig. 4 exhibits the same behavior than the intensity scintillation.

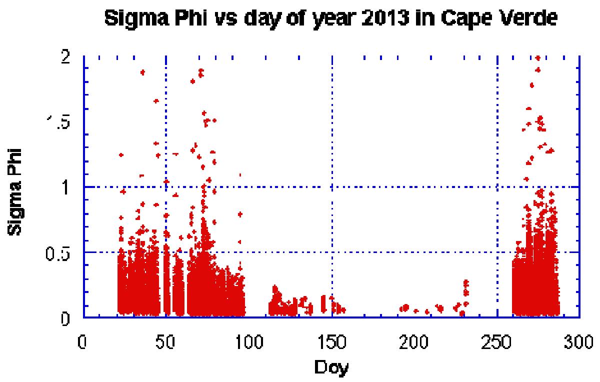

Fig. 4. : Phase scintillation depending on the day number in Cape Verde

To capture signal affected by this scintillation phenomenon, 2 hours of raw GNSS signal have been recorded every day during 20 days between the 15 of march, 2013 and the 21 of April, 2013. The records was between 8 PM UTC (7 PM local) and 10 PM UTC (9PM local), which are the typical hours of scintillation apparition in equatorial region.

Two bands were recorded, L1 and L2, with a 5 MHz bandwidth and 8-bit quantization. That's represents 3 TB of data to be processed.

B. Bitgrabber

The bitgrabber is the equipment that allows to record the GNSS signal and store it to hard drive of a PC. An on-the-shelf, low-cost and open source equipment has be selected for that purpose : the USRP2 from Ettus research/National Instrument. This product allows to digitize a large variety of frequency bands and especially GNSS bands.

Two of this device have been used to digitize 5MHz signal bandwidth around L1 and L2 frequencies. They are connected through a MIMO cable allowing their mutual synchronization (see Fig. 5)

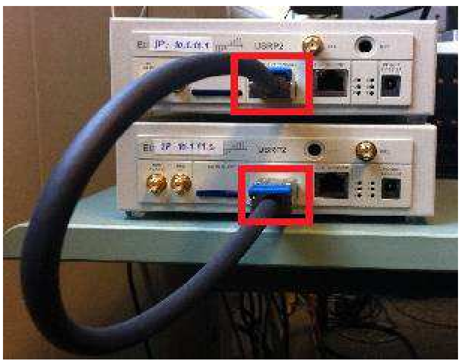

Fig. 5. MONITOR Bigrabber equipment

The bitgrabber is controlled by a software developed by TAS-F that allows to trigger signal recording on a periodic base (date and time are configurable) or when a scintillation flag is raised by an external receiver. The signal used in this article have been obtained using the periodic recording.

C. Processing sofware

The post-processing chain diagram is shown on the Fig. 6.

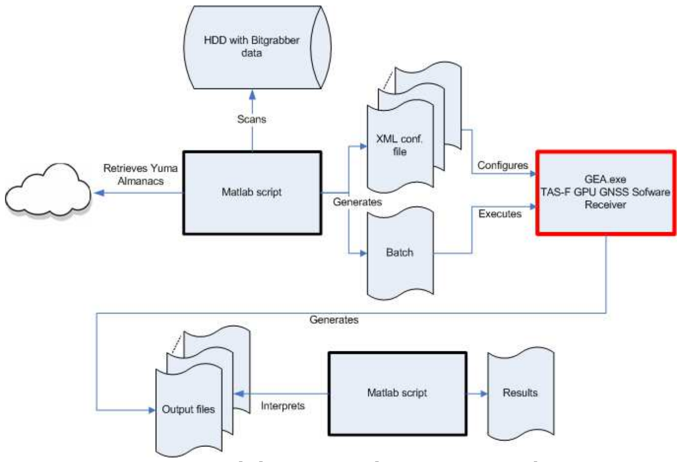

Fig. 6. Recorded GNSS signal post-precessing chain

The core module of the post-processing chain is a GPU GNSS software receiver developed by TAS-F and called GEA (GNSS Environment Analyzer). It allows fast replay of the recorded signal (about 5 to 10 times faster than real-time for the present study), it is highly configurable (chip spacing, number of correlator, loop bandwidth, discriminators…) and is able to output observable at each level of the receiver processing, from the spectrum to the pseudo-range, along with correlators outputs and discriminator outputs.

Fig. 7 shows a screenshot of GEA MMI, with a layout showing the 3D view of the correlation function over time for each tracked signal.

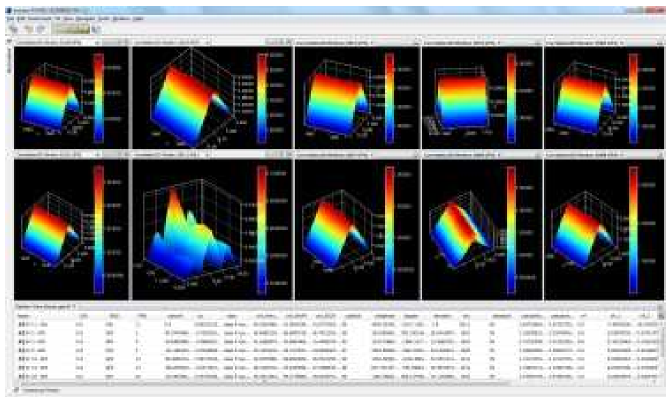

Fig. 7. Example of layout of the GEA MMI

IV. Record Analysys

A. Impact of scintillation on receiver observables

In this section the impact of phase and amplitude scintillation on different GNSS receiver observables is analyzed.

For this analyze, one particular day has been selected (15 of March) for its strong scintillation activity and one GPS satellite: PRN31 having periods with no scintillation (first hour), period with amplitude scintillation only and periods with both phase and amplitude scintillation. As shown on Fig. 8 representing the instantaneous (1 second average) values of C/N0, S4 and sigma phi (in that case the phase discriminator variance), the presence of amplitude scintillation is clearly visible on the C/N0 (important increase of its variance) and on the S4 (augmentation). Phase scintillation is also clearly identified by strong peaks in the sigma phi plot.

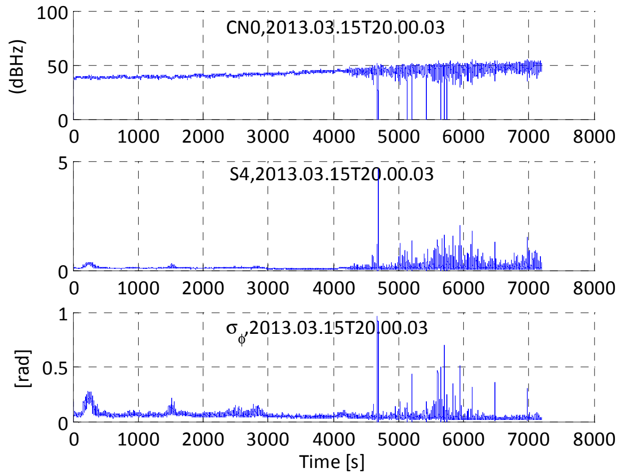

Fig. 8. PRN31 intentaneous C/N0, S4 and σ_{φ}values

Using sp3 precise ephemeris, site location and the estimated pseudo-range and Doppler by the software receiver, the PR and Doppler error has been estimated. The following figure shows the obtained PR and Doppler error for the PRN31.

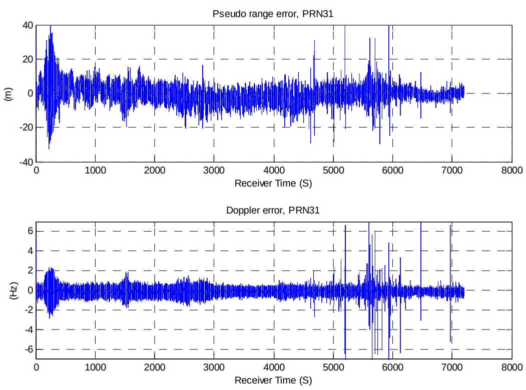

Fig. 9. PRN31 PR (up) and Doppler (Down) errors

From this figure, it seems that amplitude scintillation has not a strong impact on PR and Doppler estimation accuracy since the error variance seems quite stable from the period without scintillation (1st hour) to the period with scintillation. However the impact of phase scintillation seems more aggressive both on Doppler and pseudo range as confirm by Fig. 10 that shows a closer look on a period with and without phase scintillation. Phase scintillation, clearly visible on the Doppler error produces a significant increase of the pseudo-range error (up to 30 meters in this example) and even a loss of tracking (5650th second).

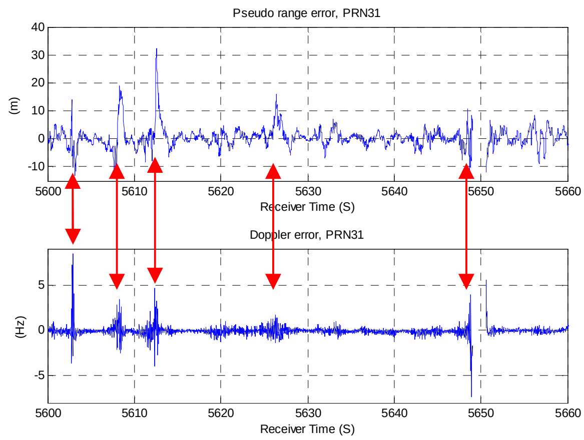

Fig. 10. PRN31 : Zoom on PR and Doppler errors

However, by averaging the Doppler error on 10 seconds sliding windows (Fig. 11), the high frequency noise is filtered and an impact of the amplitude scintillation now appears, even if it is small (about 0.05 Hz standard deviation increase). Thus, finally, amplitude scintillation creates a small low-frequency noise on the Doppler estimate while phase scintillation creates high frequency and large error but is limited in time. This behavior is not particularly observed on the pseudorange error (Fig. 12).

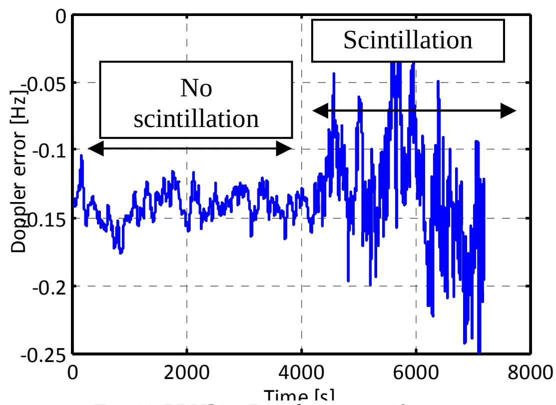

Fig. 11. PRN31 – Doppler error – 10s average

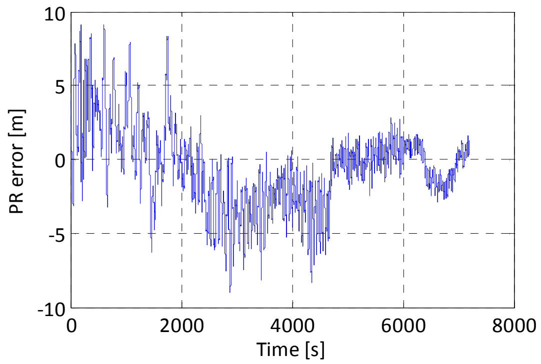

Fig. 12. PRN31 – PR error – 10s average

To understand more in detail the impact of scintillation on the GNSS signal processing Fig. 13 and Fig. 14 show the phase and code discriminators outputs. These figures confirm that only phase scintillation has a significant impact on observables.

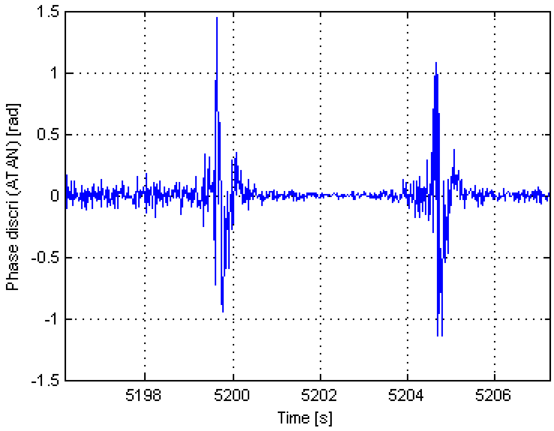

Fig. 13. PRN31: ATAN Phase discriminator

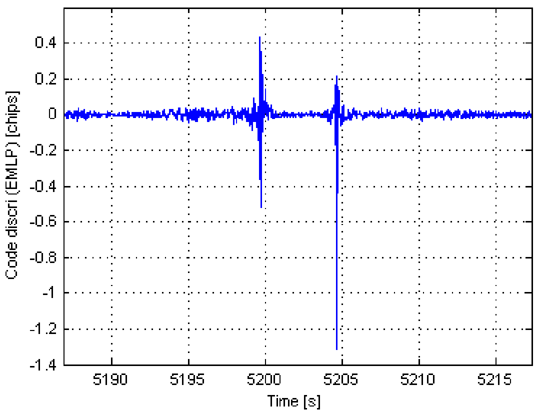

Fig. 14. : PRN31: EMPL Code frequency discriminator

The small impact of amplitude scintillation is quite surprising when looking at the C/N0 variation and on the correlator output. Indeed as shown on the following figures the impact on the correlator output seems very important. It is visible on the prompt correlator amplitude (Fig. 15) that becomes significantly noisier suddenly and also on the 3D correlation function which is 'quiet' without scintillation (Fig. 16) and very disturbed during amplitude scintillation (Fig. 17).

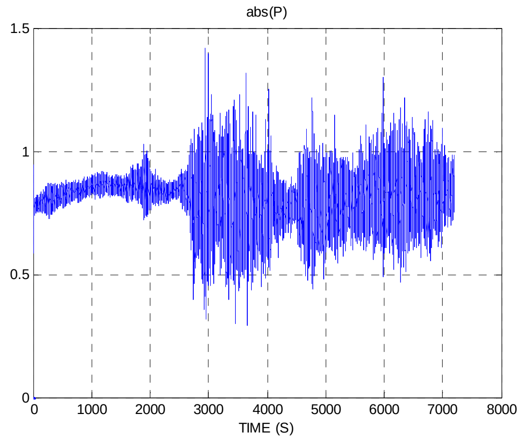

Fig. 15. Promp correlator amplitude

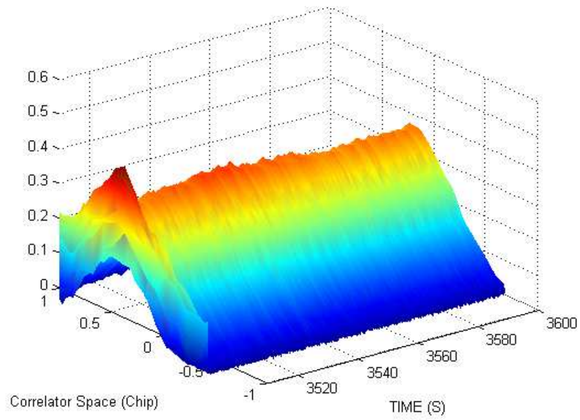

Fig. 16. : PRN31 Correlation function in absence of scintillation

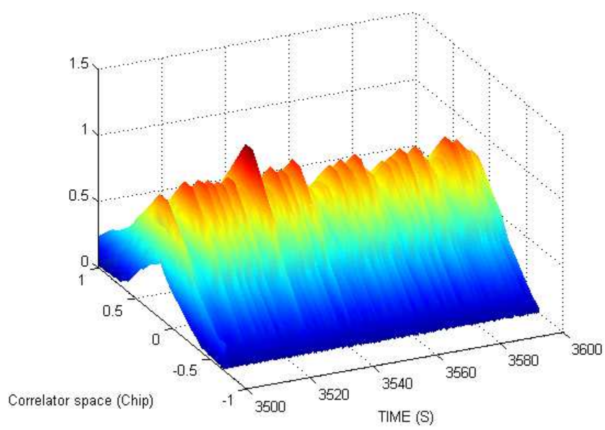

Fig. 17. : PRN31 Correlation function in presence of amplitude scintillation

However if we look on Fig. 18 showing a closer view on the Early, Prompt and Late correlators outputs during amplitude and phase scintillations, it appears that phase scintillation produces a strong drop to almost zero in the correlator amplitude. Amplitude correlation induce also quick variation of the correlators amplitude but this variation is consistent on all the correlators and thus well handheld by the discriminator normalization.

This statement explains why only phase scintillation appears to be a real problem for tracking, even if stronger amplitude scintillation event may eventually be more impacting.

In addition it is important to note that phase scintillation, by destructing the phase continuity of the signal prevent also the receiver to demodulate the navigation message. However it can be seen that the phenomenon is quite short (less than 1 seconds) and that consequently the impact on the demodulation is not so important (especially if correcting code are used).

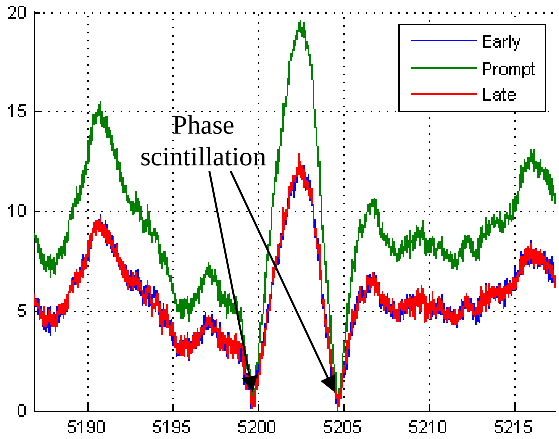

Fig. 18. Early, Late and Prompt correlator ouputs during Amplitude and Phase Scintilliation

B. *Loss of locks due to scintillation*

The ratio between the number of loss of lock and the number of S4 events has been computed to observe the impact of scintillation on tracking robustness. This statistic has been obtained by processing the 20 days of data.

This ratio as a function on the couple {S4, C/N0} is shown on Fig. 19. This plot gives information about which S4 values are critical for tracking. When a C/N0 is between [32 34] dBHz, the tracking loss of lock is possible without scintillation. However, we can observe that moderate scintillation effect (S4>0.35) increase the lost tracking probability. When the C/N0 is between [34 38] dBHz, the lost tracking was observe only in presence of moderate scintillation (S4>0.4). Last, when the C/N0 is higher than 40dBHz, we do not observe tracking loss, although strong scintillation (S4>0.6) event occur. Thus, the tracking loss is due to a combination of high S4 value (>0.4), and low C/N0 (<40dBHz).

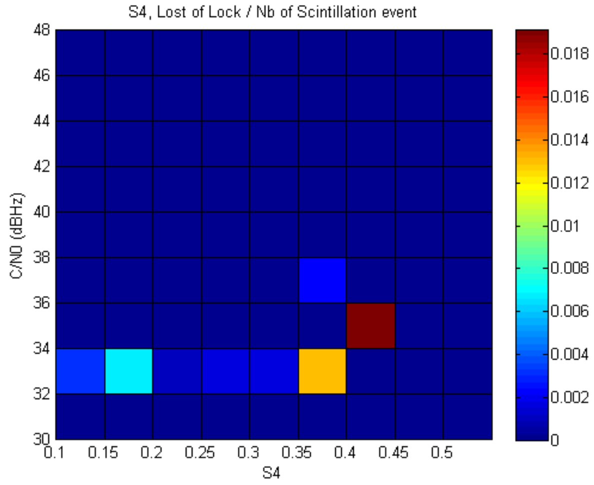

Fig. 19. Ratio Loss of lock (LoL) / Nb of scintillation event per C/N0-S4 slot

It is important to note that the loss of lock (LoL) occurrence will depend of the receiver LoL detection algorithm. For example Fig. 20 shows the code lock (up) and phase lock (down) indicators [2] used in our processing. It can be seen that these indicators are clearly impacted by the scintillation but a simple averaging on 1 second (in black) is sufficient to limit the LoL.

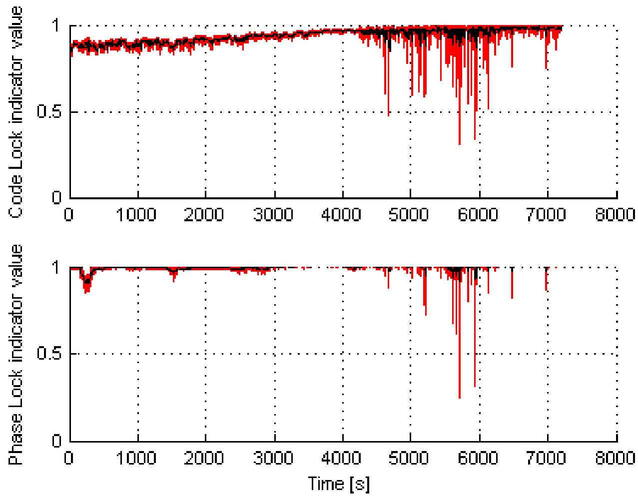

Fig. 20. Code (up) and phase (down) lock indicator @ 50 Hz – 1 second average in black

C. *Impact of scintillation on bi-frequency measurements*

To observe the impact of scintillation on bi-frequency observables of the receiver, PR and Doppler on L1 and L2 (L2C signal) are be compared. The following figures shows the Doppler difference (Fig. 21 and Fig. 22) and the PR difference (Fig. 23, Fig. 24 and Fig. 25) using the appropriate factor to take into account ionosphere (the PR difference in multiplied by $(L2^2-L1^2)/L2^2$ to get the ionosphere delay on L1). These figures concern PRN29 (only amplitude scintillation) and PRN31 (amplitude and phase scintillation); 10 seconds averaging windows is used to reduce noise.

For the PRN29 the impact of amplitude scintillation on Doppler difference is clear (Fig. 21), even if it is significantly higher for the PRN31 (Fig. 22) where phase scintillation is also present. This means that the relation between Doppler frequencies on L1 and L2 is not valid during scintillation.

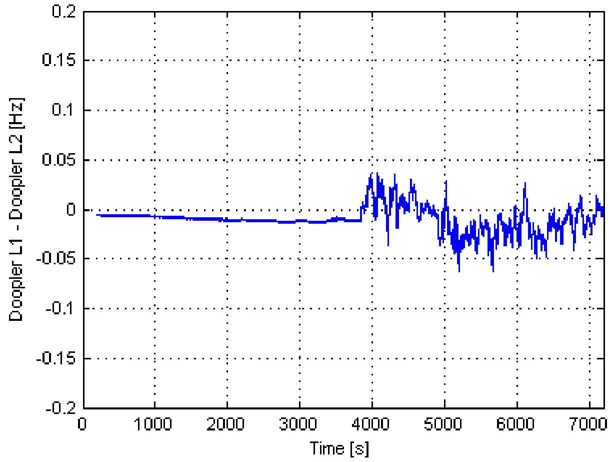

Fig. 21. Bi-frequency Doppler difference – PRN29

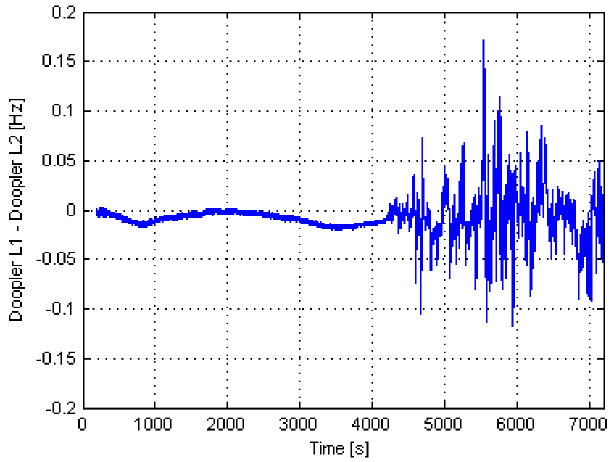

Fig. 22. Bi-frequency Doppler difference – PRN31

The impact on pseudorange is more complicated to analyze. Indeed, on one hand the L1 ionosphere delay of PRN29 (Fig. 23) seems impacted by scintillation since its evolution change suddenly when the scintillation starts. However it is hard to say if this change correspond to the actual evolution of the ionosphere (in which case it will be a good think) or this evolution is not related to an actual iono delay (in which case iono-free measurement would become erroneous).

On the other hand this behavior is not encountered on the PRN31 ionosphere delay (Fig. 24) that seems not impacted by scintillation. However its low elevation during the first hour (under 30°) induces strong oscillations of the ionosphere delay (may be due to multipath) that prevents to draw definitive conclusions.

However by looking more closely to epochs with phase scintillation a clear impact is observable on the estimation of the ionosphere delay. Again this kind of sudden change in the iono-free measurement, could impact the precision of bi-frequency receiver.

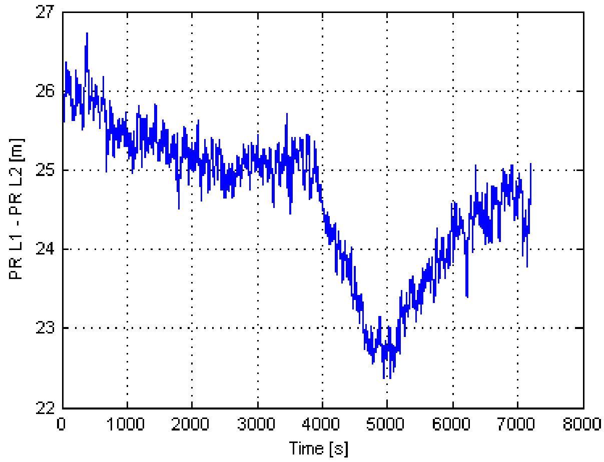

Fig. 23. Bi-frequency PR difference (ionosphere delay on L1) – PRN29

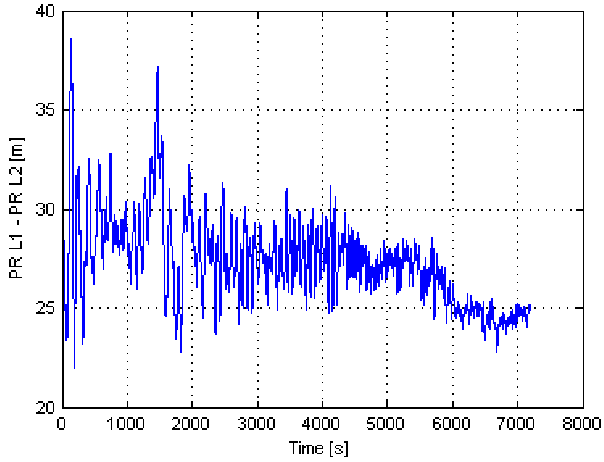

Fig. 24. Bi-frequency PR difference (ionosphere delay on L1) – PRN31

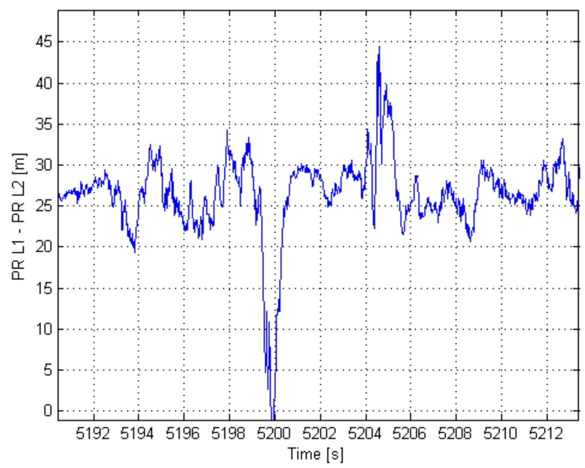

Fig. 25. Bi-frequency PR difference (ionosphere delay on L1) – Not averaged (50 Hz measurements)– PRN31 – During phase scintillation

V. CONCLUSION

This article presents an analysis of the impact of ionosphere scintillation on GNSS receiver processing.

For that purpose, in the frame of the ESA MONITOR project, raw GNSS signal has been collected in Cape Verde during a period around 2013 vernal equinox, using a bitgrabber based on two USRP2 (L1 and L2 frequencies).

The signal has been then post-processed using a GPU GNSS software receiver, developed by Thales Alenia Space France and allowing fast replay of the recorded signal and access to intermediate observable of a GNSS receiver such as correlator outputs.

The impact of scintillation on observables has been assessed on a particular day with strong scintillation activity. This analysis showed that phase scintillation is more impacting than amplitude scintillation, producing large errors on the pseudorange and Doppler estimates, preventing correct data demodulation and sometimes inducing loss of lock. However the duration of phase scintillation appears to be very short (less than one second), counter to amplitude scintillation that last several tens of minutes. This former has a more limited impact, and induce a small additional low frequency noise to the on Doppler estimate.

A loss of lock analysis has shown that impact of scintillation on loss-of-lock is limited but more important when C/N0 is low and S4 high. The tracking lock indicator are very sensitive to scintillation (as C/N0 estimator) and consequently their setup (averaging time, threshold) has a significant importance in the occurrence of loss-of-lock.

Finally, the impact on scintillation on bi-frequency measurements has been studied using L1 and L2C processing. It appears, by looking at the Doppler difference between L1 and L2, that scintillation destruct the phase coherence between L1 and L2 signal. The impact on code delay seems more similar to classical ionosphere delay even if this need to be confirmed

ACKNOWLEDGMENT

The authors thank the European Space Agency for funding this work, conducted in the frame of the MONITOR project.

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