Ionosphere Scintillations and their Effect on the Positioning Errors

Y. Beniguel, JP. Adam
IEEA, France, beniguel@ieea.fr

Abstract

The earth satellite links may in some cases be affected by signal scintillations due to the propagation through ionosphere. In the case of strong fluctuations these scintillations lead to losses of lock on one or several links and to positioning errors.

1. Introduction

The signal scintillations are related to some geophysical parameters as the solar activity and the magnetic activity. They occur after sunset and may last a few hours. They develop essentially around the magnetic equator (- 20° + 20° magnetic latitude). They are more important at the equinoxes and practically do not exist during summer during summer. Several measurements campaigns have been carried out mainly in South America and India. There is actually one such measurement campaign, in the frame an ESA/ESTEC activity, with receivers in South America, Africa, Vietnam and in Northern Europe. A data base is under constitution. This will increase the knowledge on the corresponding scintillation space weather climatology.

In this paper we will review the scintillation characteristics, their probability of occurrence and their extent. We will then present an analysis of the scintillation impact on a receiver with special interest for the losses of lock and the positioning errors

2. Local time & seasonal dependency

Figure 1 below shows some results of measurements recorded in N'Djamena in may 2007. The values indicated correspond to the highest values measured during the month. The satellites seen with an elevation angle lower than 30° were not considered. The peak values correspond to medium to low scintillation levels. This is due to the low value of the solar activity which is the minimum of the solar cycle.

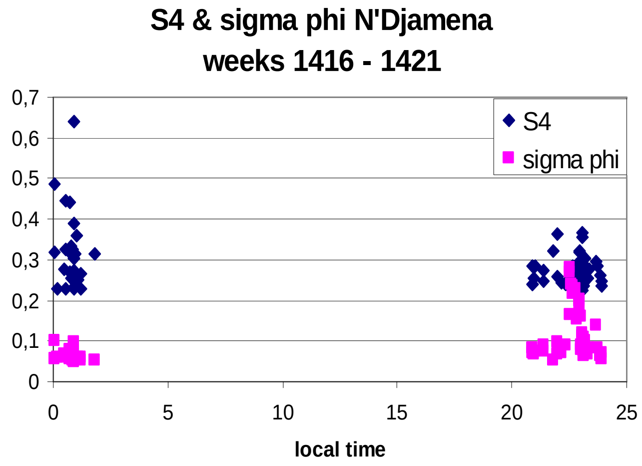


Figure 1: local time dependency in N'Djamena, Chad.

3. Spatial extent

The red crosses on the Brazil map presented on figure correspond to the locations of six scintillations receivers whose data has been made accessible to us by E. de Paula (INPE, São Paulo). Those data have been recorded in 2001, corresponding consequently to the year of solar maximum.

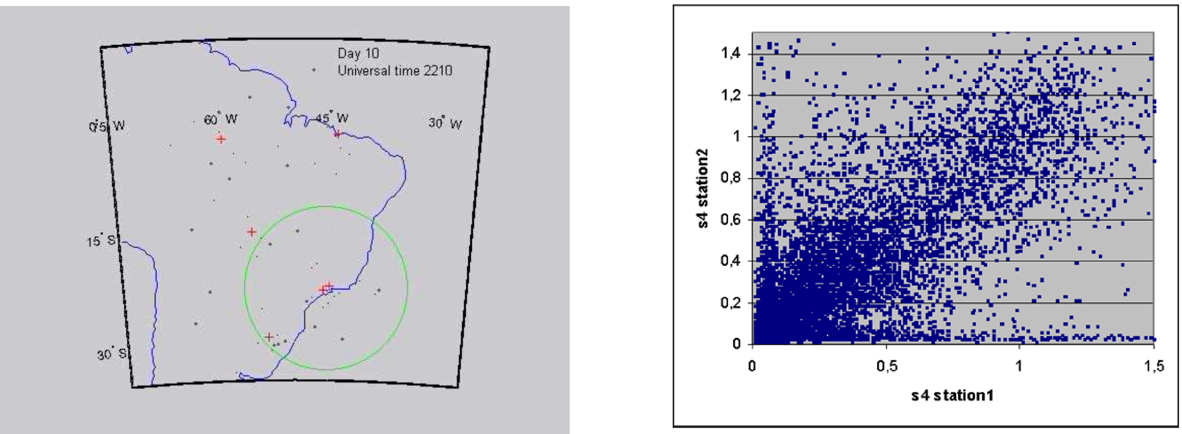
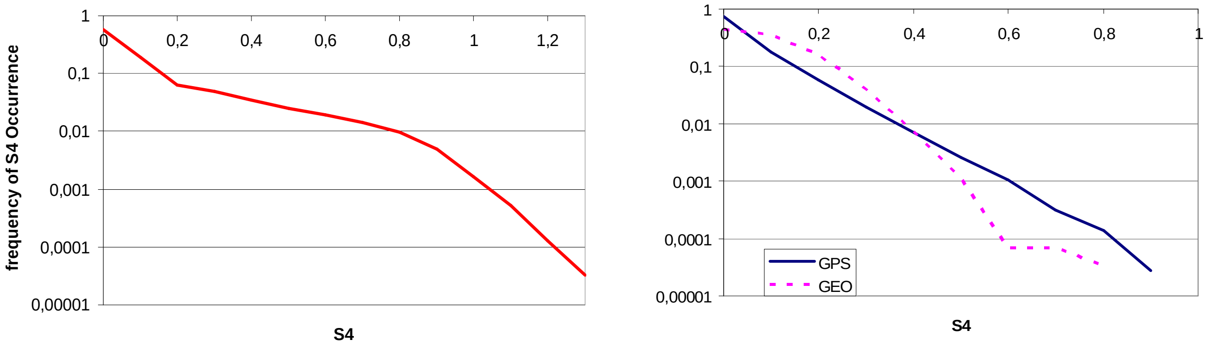


Figure 2: scintillations spatial extent measurement

One interesting feature is the fact that two stations are very close. Their distance is 100 km. It is consequently possible to calculate the correlation distance of the medium. Figure 2 presents one week of measurements of the S4 values at the two stations. The corresponding correlation coefficient is 0.8. Assuming a Gaussian variation, this leads to a correlation distance of about 175 km.

4. Frequency of occurrence of S4

The frequency of occurrence of S4 is presented on Figure 3 for two measurements data sets: the first one from São Jose dos Campos (Brazil) in 2001 and the second one from Douala (Cameroon) in 2004 (medium values for the solar cycle). In both cases, the S4 frequency of occurrence seems to exhibit a Log normal distribution. The red line (São Jose dos Campos) and the dashed line (one link with a GEO satellite recorded from Douala) have been plotted with a reduced data set on the contrary to the blue curve (GPS satellites in Douala).



a) b)

Figure 3: Frequency of occurrence of S4 in São Jose dos Campos (a) and Douala (b). Ten S4 intervals of equal width were considered. Each sample is counted in one of these intervals.

5 Analysis of signals with scintillations

The scintillation signal has to have an equivalent power spectral density (PSD). The PSD is given by the relationship:

$$\Gamma = \frac{A}{(q + q_0)^{-p}}$$

It is determined by three parameters:

- The slope p,
- The cut-off frequency $q_0 = \frac{2\pi}{L_0}$, where L0 corresponds to the bubbles correlation distance
- The threshold value A or equivalently the value at 1 Hz

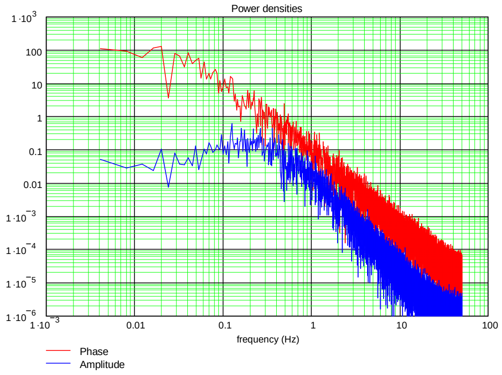
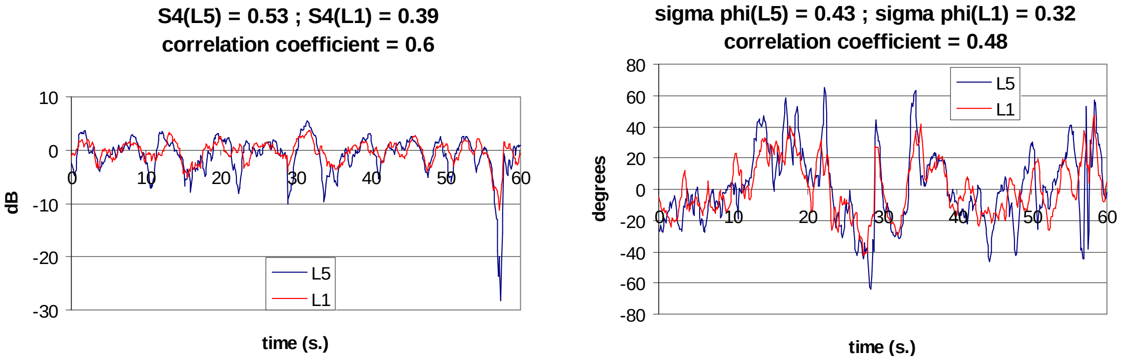


Figure 4: intensity and phase spectrum

To characterize the scintillation strength at the ground level, the S4 scintillation ratio is used. It corresponds to the intensity standard variation. Due to normalization, S4 is between 0 and 1. A value lower than .2 will correspond to low fluctuations, a value around .5 to medium fluctuations and a value greater than .7 to high fluctuations.

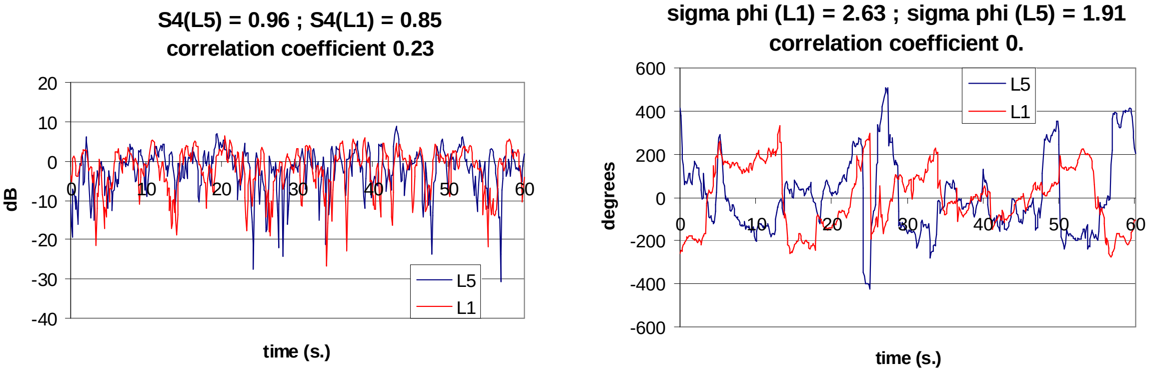
The scintillations level is frequency dependent. As a first approximation it increases with the inverse of the frequency. However the relationship is not linear. Two examples corresponding to medium scintillations are reproduced below for the phase and intensity. These plots have been produced by a model (GISM) but they are representative of the measurements.



S4(L5) = 0.53 ; S4(L1) = 0.39
correlation coefficient = 0.6

sigma phi(L5) = 0.43 ; sigma phi(L1) = 0.32
correlation coefficient = 0.48

Figure 5: phase fluctuations (medium scintillations)



S4(L5) = 0.96 ; S4(L1) = 0.85
correlation coefficient 0.23

sigma phi (L1) = 2.63 ; sigma phi (L5) = 1.91
correlation coefficient 0.

Figure 6: intensity and phase fluctuations (strong scintillations)

The simulations presented figures 5 and 6 have been obtained using the same seed for the random generator. The medium is consequently the same for the two frequencies.

The following plots present the correlation coefficient between the two frequencies and the dependency of the correlation coefficient on the frequency.

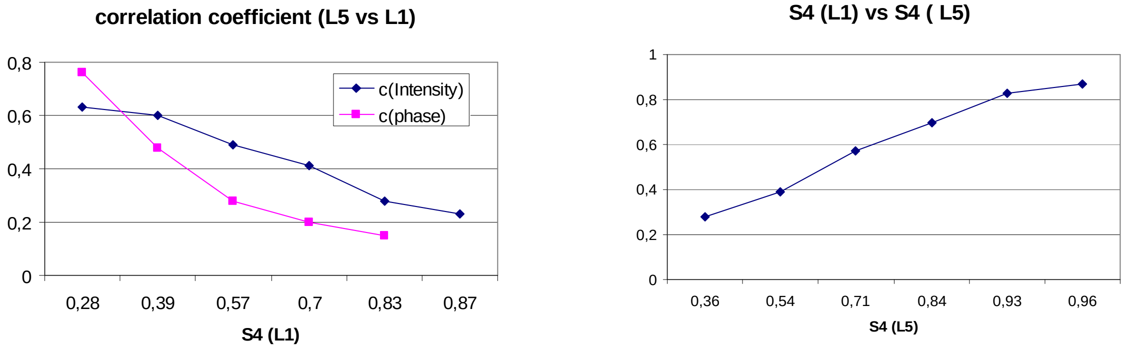
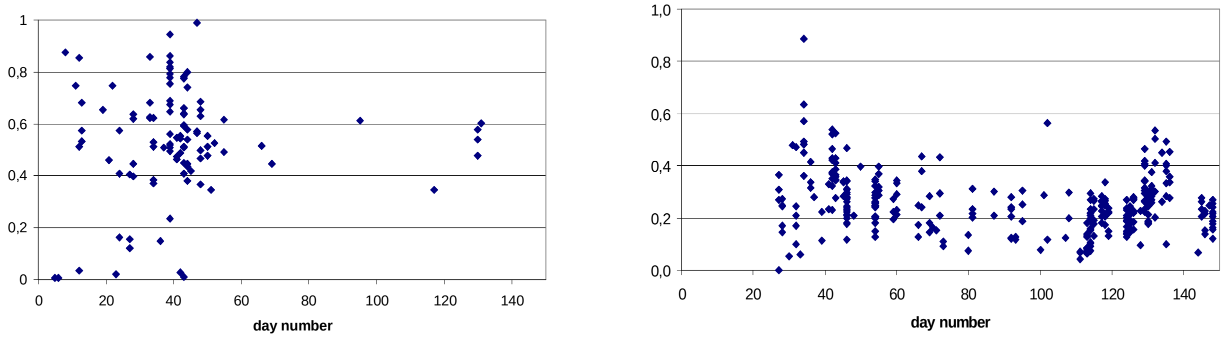


Figure 7: frequency correlation coefficient

The phase correlation coefficient drops significantly with the scintillations level. This is due to phase jumps which appear as the scintillation ratio increases. The frequency correlation exhibits a linear relationship for medium scintillations. Both values peak to 1 in the case of strong scintillations.

6. Loss of lock

This section present some results for the loss of lock from the measurements results recorded in Douala. The scintillation receiver which was used (GSV4004) provides the lock time. This value indicates how long the receiver has been locked to the carrier phase of the GPS signal. This also indicates the time of the last loss of lock and it can be used to detect this failure.

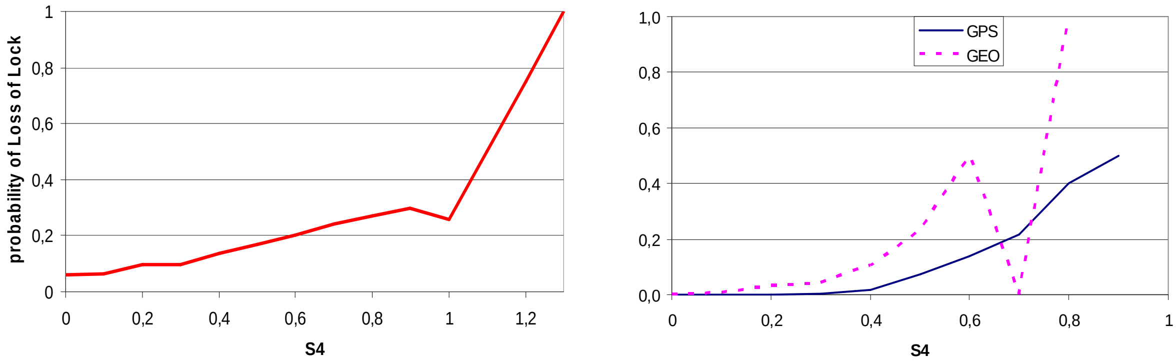


a)

b)

Figure 8: S4 before loss of lock of L1 carrier for all GPS satellites over 30° (a) and for the GEO (b). For each day, there may have several losses of lock. Only nighttime (19-24 LT) losses of lock were considered. The difference of S4 levels for GPS and GEO satellite is probably related to the signal level, which is significantly lower for the GEO.

The GEO link uses a GPS like signal with an L1 carrier. That is the reason why we have only considered the loss of lock of L1. Figure 8 presents the value of S4 before the loss of lock. It is consequently possible to estimate the probability of having a loss of lock and a given value of S4. In addition, the frequency of occurrence of S4 may also be evaluated from the samples. Therefore we can calculate the probability of loss of lock vs. the value of S4. This result is presented on Figure 9.



a)

b)

Figure 9: Probability of loss of lock, given the value of S4 in São Jose dos Campos (a) and Douala (b). For the GEO, for S4 greater than 0.6, there are not enough loss of lock occurrences to get correct statistics. This explains the discontinuity in the curve.

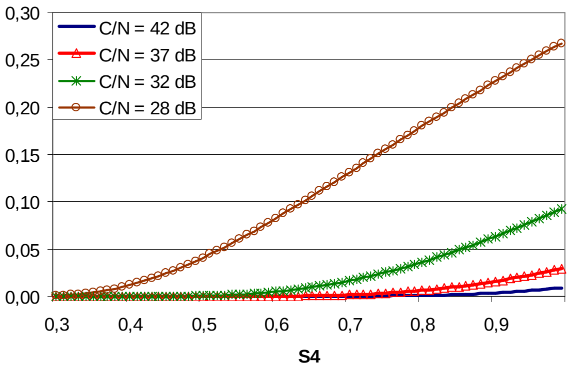


Figure 10: Probability of Loss of Lock for a typical receiver obtained with GISM scintillation model

As a comparison, the Figure 10 presents the values obtained with GISM for a typical receiver. The behaviour depending on the S4 level is the same. The differences of levels are related to different values of the receiver parameters and to the fact that curves presented on figure 9 have plotted independently of the value of C/N and correspond consequently to an average value of this ratio. The GISM model allows setting any value to these parameters.

In the GISM model, loss of lock is evaluated through the standard thermal noise tracking error for the PLL:

$$\sigma^2_{\Phi T} = \frac{B_n}{(c/n_0)\ Is}\left[1+\frac{1}{2\,\eta\,(c/n_0)\ Is}\right]$$

where Bn is the receiver bandwidth, and η is the predetection time. For airborne GPS receiver, Bn = 10 Hz and η = 10 ms. Is is the scintillation intensity. Its mean value is 1 and it has a Nakagami distribution characterized by S4.

This relation expresses the thermal noise as a decreasing function of the scintillation intensity. As a result, if $\sigma_{\Phi T}$ is above the 15° threshold then Is is below a value computed using this relation. As Is distribution is known for a given S4, the probability of occurrence of "Is < threshold" can be evaluated. The result is the probability of Loss of Lock. Figure 9 presents this probability versus S4 at given values of the C/N0. It can be noticed that links with high C/N0 are quite robust. On the contrary, links with low values of C/N0 are likely to be lost.

There are more losses of lock on the GEO link than on the GPS links (Figure 8). For the SBAS signal, the loss of lock appears at a lower value of S4. This may be due to the lower signal power provided by the GEO satellite. The receiver also provides the C/N0 value of the link. As can be seen on Figure 11, the C/N0 value is 10dB lower for the GEO satellite link.

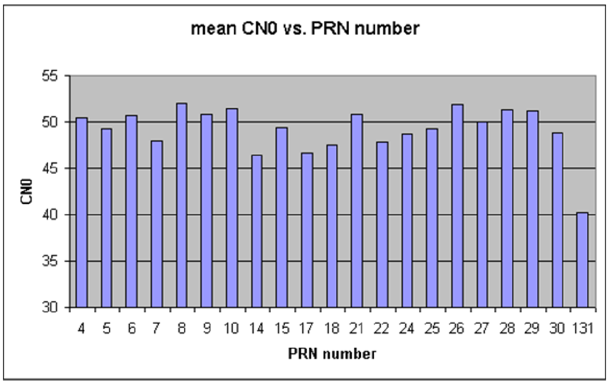


Figure 11: mean C/N0 for each satellite PRN number. PRN 131 corresponds to the GEO satellite. The GPS satellites taken into account are all seen with an elevation angle greater than 30°. The elevation angle for the GEO satellite is 28°.

7. Positioning error

The receiver used for this study is unable to record the position. To analyze the effect of scintillation on the positioning error, we have to simulate the receiver behavior affected by scintillation characterized by S4. According to [3], in presence of scintillation, the tracking variance for a DLL (in C/A code chips squared) may be expressed as:

$$\sigma_\tau^2 = \frac{B_n d}{2(c/n_0)\ (1-S_4^2)} \left[1 + \frac{1}{\eta (c/n_0)\ (1-2S_4^2)} \right]$$

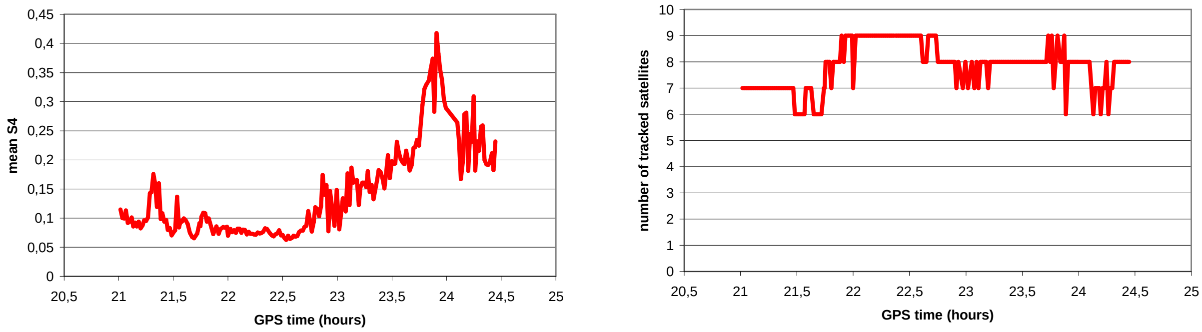
Where Bn is the one-sided noise bandwidth (typical value is 0.1 Hz) and d is the correlator spacing in C/A code chips (typical value is 1 to 0.1). η is the predetection time. The chip length is about 293 m.

To evaluate the positioning error, the following steps were performed for each tracked satellite:

- S4 is measured.
- σ_τ is deduced from S4.
- assuming a gaussian distribution characterized by σ_τ, a range error is computed.
- a Yuma file is used to evaluate the satellite position in order to fill the navigation equations.

The navigation equations are solved with these range errors to compute a positioning error.

Figure 12 presents the results of this simulation. In that example, the scintillation effects aren't significant. The mean value of S4 shows that the scintillation activity was weak. As a result, the number of tracked satellites was always high enough to mitigate the range error.



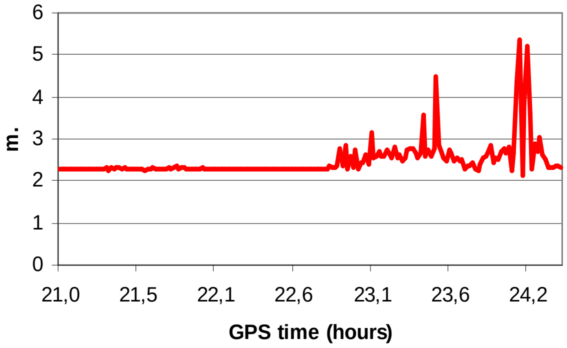


Figure 12: The first curve represents the mean value of S4 (all visible GPS satellites), it shows the scintillation activity. The second presents the number of tracked satellites. The last one corresponds to the evaluated positioning error.

7 Conclusion

A review of the scintillations characteristics and of their related climatology has been given. There are two consequences for the positioning errors. In case of strong scintillations, losses of lock may occur. This modifies consequently the DOP value. In addition the phase and intensity fluctuations create positioning errors for each one of the remaining links. The two effects are combined and degrade the accuracy of the navigation system. An approach based partly on measurements and partly on modelling has been carried out leading to errors of a few meters.

References

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