Characterisation of Ionosphere Scintillations
PLL and DLL Errors at Receiver Level

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Abstract

This paper presents an analysis of loss of lock probabilities and positioning errors obtained at equatorial regions due to scintillations on GPS links. This analysis has been conducted with help of a numerical scintillation model. Some elements of comparisons with measurements are moreover presented.

1. Introduction

Scintillations on signals transmitted through the ionosphere may reach in some cases 30 dB peak to peak for the intensity and greatly affect consequently the service provided either for telecommunications or navigation applications.

In this paper, we focus on navigation applications and GPS receivers. A numerical model has been used to estimate the level of fluctuations for all PRNs seen from a particular ground station located in equatorial regions. The analysis has been conducted at post sunset hours, corresponding to the highest scintillations occurrence and for two days: one with a high value of the solar spot number (SSN) and the second with a low value of the SSN. This directly impacts on the level of scintillations. The budget link and the intensity (s4) and phase (σ_ϕ) fluctuations levels have been calculated for each PRN.

The receiver characteristics are then considered to obtain the PLL and DLL standard deviations at receiver level. The probability of loss of lock can be estimated from the knowledge of this PLL standard deviation and of the budget link. They both are calculated by the model. This can easily be extended to obtain the number of satellites simultaneously locked out.

The positioning error depends on the quality of the distribution of the constellation which directly influences the Dilution of precision (DOP). The DOP value increases when links are lost and especially when several of them are lost simultaneously. This analysis is also presented.

2. Comparisons Model – Measurements

GISM, the model used in this study, is a mixed climatological / physical model [1]. It allows to calculate mean errors and scintillations due to propagation through the ionosphere. Mean errors are obtained by a ray technique using the values of the ionosphere electronic density. This last is obtained with NeQuick model [2] which is included in GISM. The line of sight being determined, the fluctuations are calculated in a second stage using a multiple phase screen technique.

The comparisons with GPS links measurements have been done for two days [3], one with a high value of the SSN : 200 and the other with a low value : 85. All the PRNs have been considered. The cumulative probabilities are presented below for these two days. Measurements are in blue and GISM results are in green.

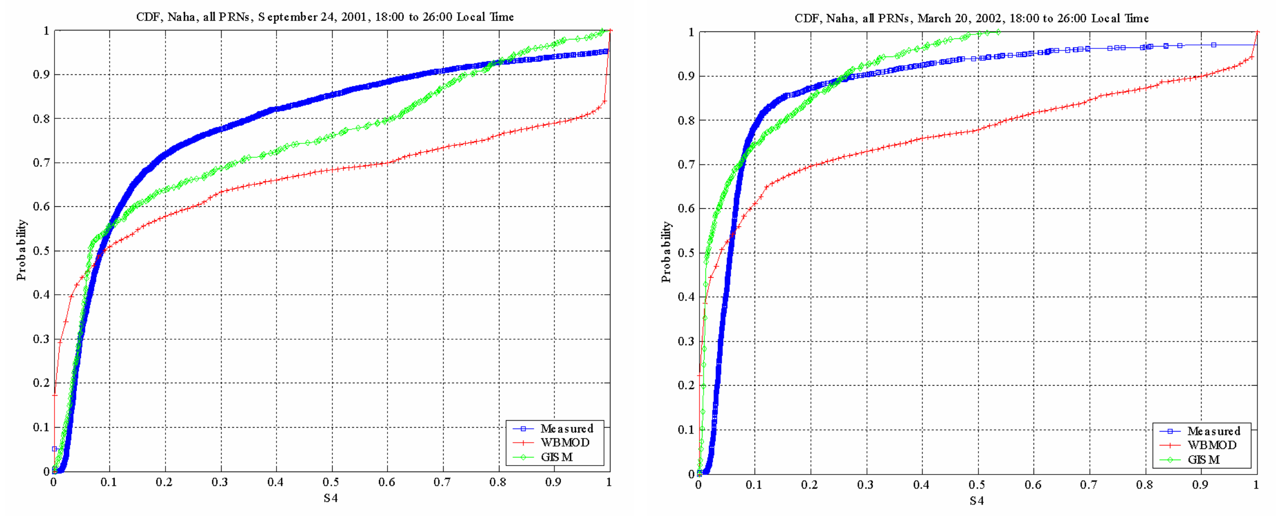


Figure 1 : comparison between GISM results and measurements. Left curve SSN = 200 ; right curve SSN = 85

3. Scintillations at receiver level

3.1 GPS Receiver Architecture

A GPS receiver is a spread spectrum receiver, requiring several essential parts for acquisition, tracking and extracting useful information from the incoming satellite signal. It can be broadly divided into three sections: the RF Front-end (RFF), Digital Signal Processing (DSP) and the Navigation Data Processing (NDP). The RFF and the DSP sections generally consist of various hardware modules, whereas the NDP section is implemented using software. Figure 2 shows a simple block diagram of a typical single frequency GPS receiver with major interfaces and input/output signals of the essential blocks.

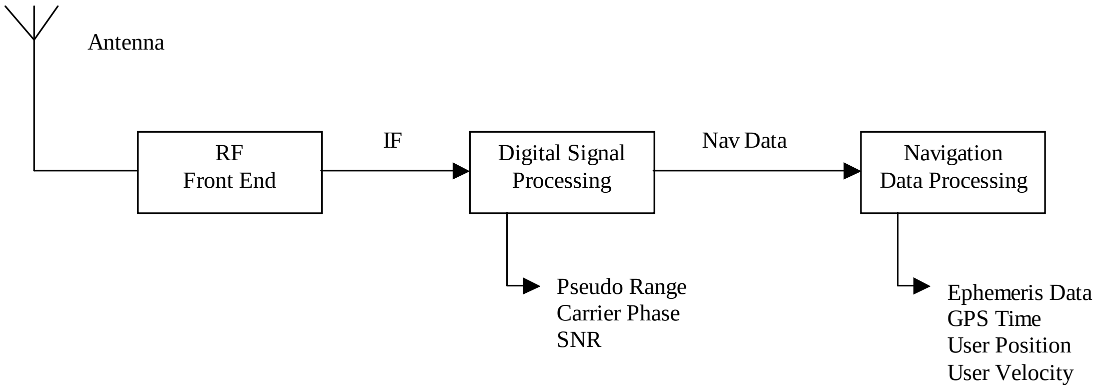


Fig. 2 : Block diagram of a generic GPS receiver

The DSP performs the acquisition and tracking of the GPS signal. Traditional signal demodulation such as those used for FM or AM cannot be used for spread spectrum signals such as GPS because the signal level is below the noise level. Instead, the signal must be coherently integrated over time so that the noise is averaged out, thereby raising the signal above the noise floor.

Any GPS receiver locking up on a GPS satellite has to do a two-dimensional search for the signal. The first dimension is time. The GPS signal structure for each satellite consists of a 1023 bit long pseudo-random number (PRN) sequence sent at a rate of 1.023 megabits/sec, i.e. the code repeats every millisecond. To acquire in this dimension, the receiver needs to set an internal clock to the correct one of the 1023 possible time slots by trying all possible values. Once the correct delay is found, it is tracked with a Delay Lock Loop (DLL).

The second dimension is frequency. The receiver must correct for inaccuracies in the apparent Doppler frequency. Once the carrier frequency is evaluated, it is tracked with a Phase Lock Loop (PLL). Figure 3 shows an extremely simplified PLL/DLL architecture. A more precise description of the GPS signal processing can be found in [4].

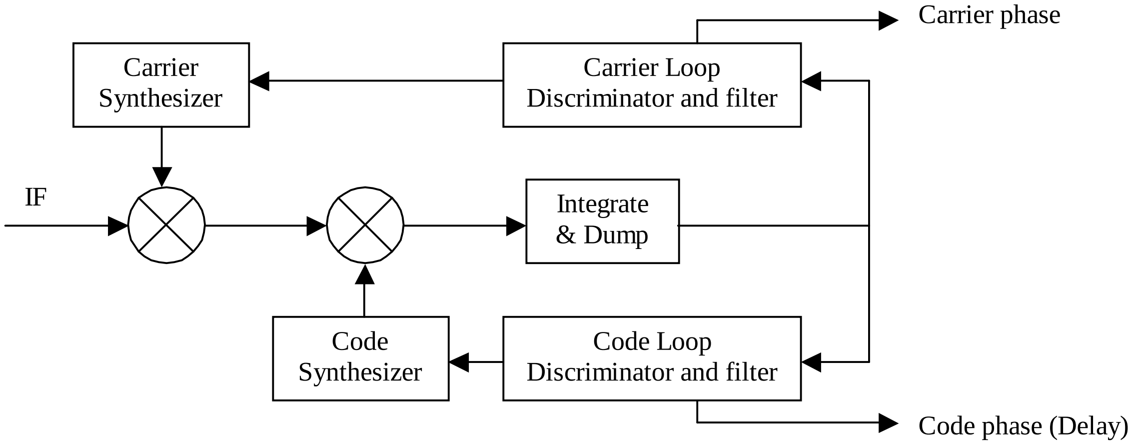


Fig. 3 : Simplified GPS Digital Receiver Channel

3.2 Phase Noise at Receiver Level

When the receiver is unable to track the carrier phase, the signal is lost. Loss of lock is directly related with PLL cycle slips. To evaluate the occurrence of cycle slips, the tracking error variance at the output of the PLL as to be considered. Following [5], this variance is expressed as a sum of three terms :

$$\sigma_{\Phi}^2 = \sigma_{\Phi S}^2 + \sigma_{\Phi T}^2 + \sigma_{\Phi, osc}^2 \tag{1}$$

where

$\sigma_{\Phi S}$ is the phase scintillation

$\sigma_{\Phi T}$ is the thermal noise

$\sigma_{\Phi,osc}$ is the receiver oscillator noise (0.122 rad) [5]

The phase variance scintillation at the output of the PLL is given by [5] :

$$\sigma_{\Phi S}^2 = \int_{-\infty}^{\infty} \left|1 - H(f)\right|^2 S_{\Phi}(f)\, df \tag{2}$$

where $S_{\Phi}(f)$ is the PSD of phase scintillation. Figure 4 shows a phase scintillation spectrum obtained with GISM. $\left|1 - H(f)\right|^2$ is the closed loop transfer function of the PLL and depends on k, the loop order, and fn, the loop natural frequency. Its expression is given by (3). Typical values are k = 3 and fn = 1.91 Hz.

$$\left|1 - H(f)\right|^2 = \frac{f^{2k}}{f^{2k} + f_n^{2k}} \tag{3}$$

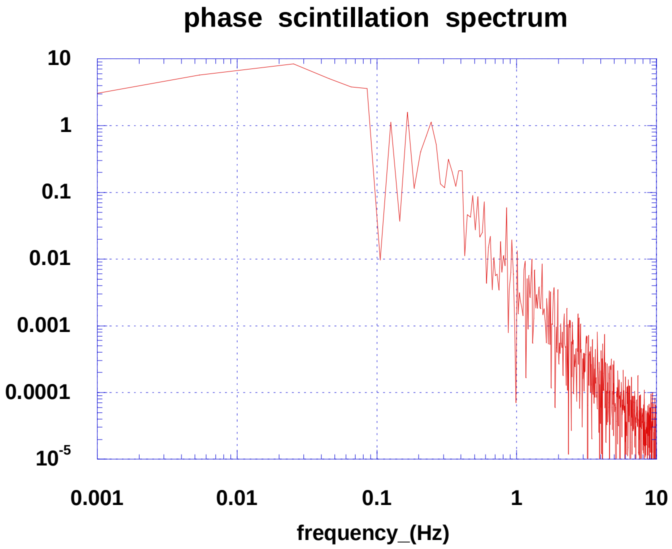


Fig. 4 : PSD of phase scintillation computed with GISM

When there is no scintillation, the standard thermal noise tracking error for the PLL is :

$$\sigma^2_{\Phi T} = \frac{B_n}{(c/n_0)}\left[1+\frac{1}{2\eta\ (c/n_0)}\right] \tag{4}$$

where c/n0 is the signal to noise ratio (SNR), Bn is the receiver bandwidth, and η is the predetection time. For airborne GPS receiver, Bn = 10 Hz and $\eta = 10$ ms. Amplitude scintillation alters the SNR and increases the thermal noise tracking error. According to [5], in presence of scintillation characterized by S4 index, thermal noise tracking error is given by :

$$\sigma^2_{\Phi T} = \frac{B_n\left[1+\frac{1}{2\eta\ (c/n_0)\ (1-2\,s_4^2)}\right]}{(c/n_0)\ (1-s_4^2)} \tag{5}$$

Equation (5) needs the evaluation of the SNR. The GPS link budget can be expressed in dB as following :

C / N0 = P0 + Gt + Gr - Propagation losses - Insertion Losses - N0 (6)

where P0 is the emitted power, Gt and Gr are respectively the emitter and the receiver antenna gain, and N0 is the receiver noise density. Therefore, the SNR appears to be depending on the elevation angle as shown in figure 5.

Equations (5) and (2) can be used with (1) to compute the PLL tracking error variance. Figure 6 is a comparison of this variance vs C/N0 for S4 = 0.7 and S4 = 0.5. Loss of lock is highly probable for values above the 15° threshold. Therefore a receiver is able to tolerate scintillation if the C/N0 is above a minimum value. This minimum is 26 dB for S4 = 0.5 and 32 dB for S4 = 0.7.

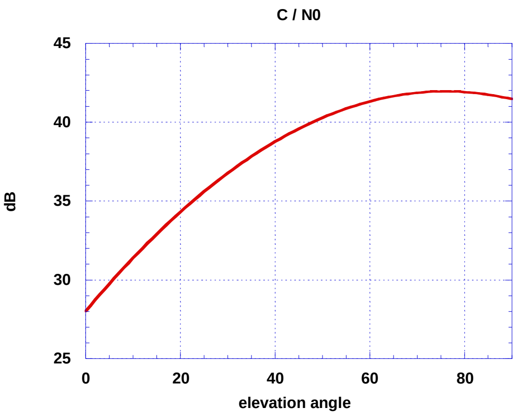


Figure 5 : C/N0 vs elevation angle without scintillation for a GPS link

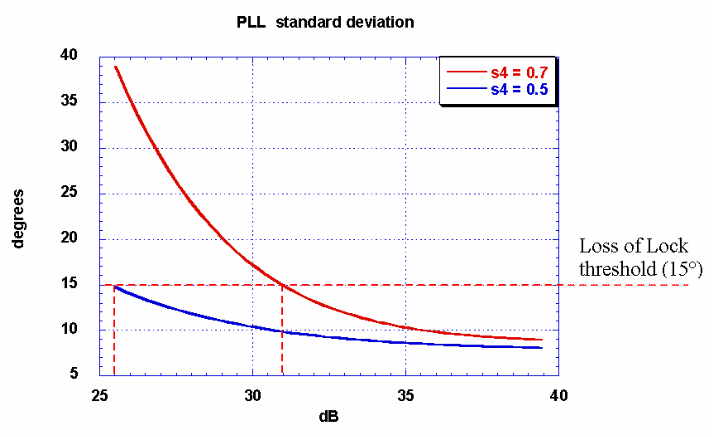


Figure 6 : PLL standard deviation vs C/N0

3.3 Loss of Lock Probability

Thermal noise appears to be the essential contribution to PLL tracking error. It is the unique S4 dependent term in (1) and the influence of S4 is obvious in fig. 6. A study of amplitude scintillations is detailed in [5] and leads to (5). We will present here another approach of amplitude scintillation effects on thermal noise.

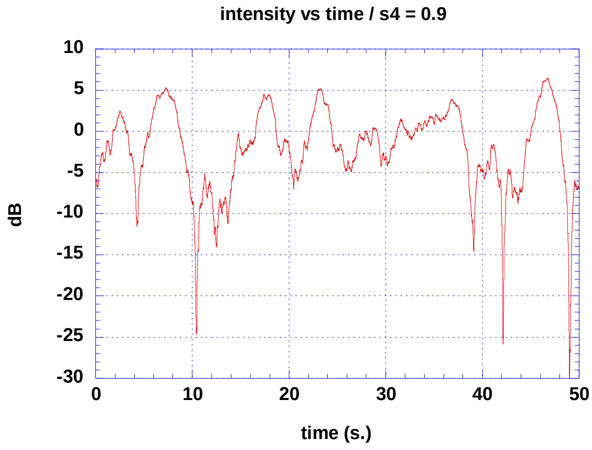


Figure 7 : Scintillation intensity vs time computed with GISM

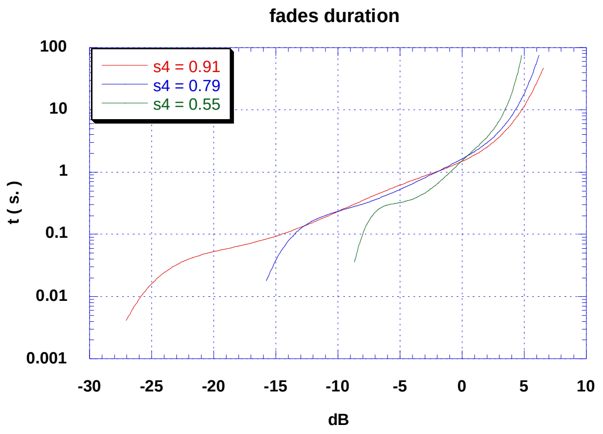


Figure 8 : fades duration vs fade depth

Figure 7 shows a typical signal amplitude under severe scintillation conditions (S4 = 0.9). The corresponding fade duration always exceeds the pre integration duration time. As a consequence it corresponds to a degradation of the SNR at receiver level :

$$C/N = C/N0 + Is(\text{in dB}) \tag{7}$$

or, with the fractional form :

$$c/n = c/n0 * Is \tag{8}$$

where Is is the scintillation intensity. Its mean value is 1 and it has a Nakagami distribution characterized by S4.

Equation (4) is modified to take the fading into account :

$$\sigma^2_{\Phi T} = \frac{B_n}{(c/n_0)\ Is}\left[1 + \frac{1}{2\eta(c/n_0)\ Is}\right] \tag{9}$$

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 (9). 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 SNR. It can be noticed that links with high SNR are quite robust. On the contrary, links with low values of SNR are likely to be lost.

GISM has an integrated GPS satellite trajectory generator. It has been used use to simulate a whole day (24th September 2001) over Naha (Japan, latitude = 26° geographic, 15° magnetic). All visible satellites were used to compute an average probability of loss of lock. The result is 0.21 %. In other words, each satellite was 0.21% of the time locked out during that day.

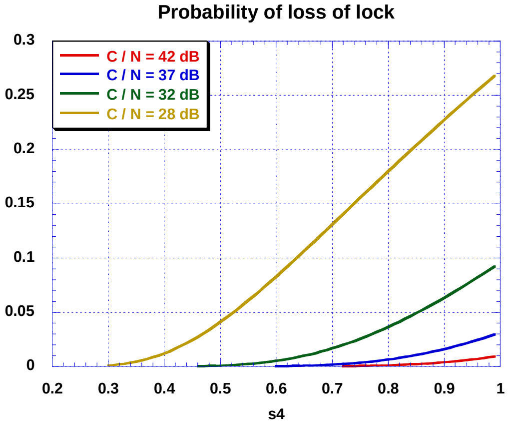


Figure 9 : Probability of loss of lock vs s4 for 4 values of the SNR

3.4 Positioning Errors

In most cases, scintillations doesn't affect all visible satellites. If the number of satellites is above 4 then a standard receiver should be able to provide navigation information. However, the number of satellites and their positions affect the positioning precision. The Dilution Of Precision (DOP) is usually used to quantify this precision. The DOP is related to the geometrical distribution of the visible constellation. The scheme on figure 10 shows how the DOP is related to the satellites positions. The DOP is used to derive the positioning error (σ_p) from the User Equivalent Range Error (UERE) :

$$\sigma_p = DOP * UERE \tag{10}$$

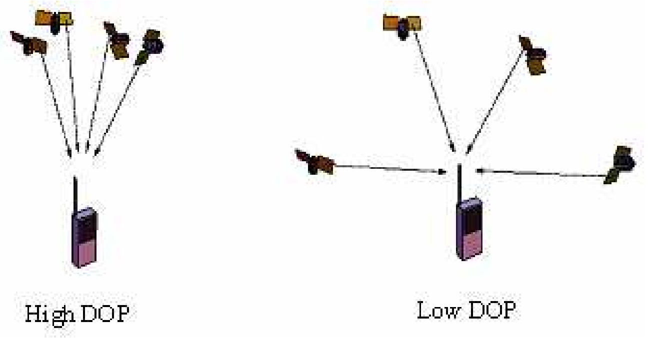
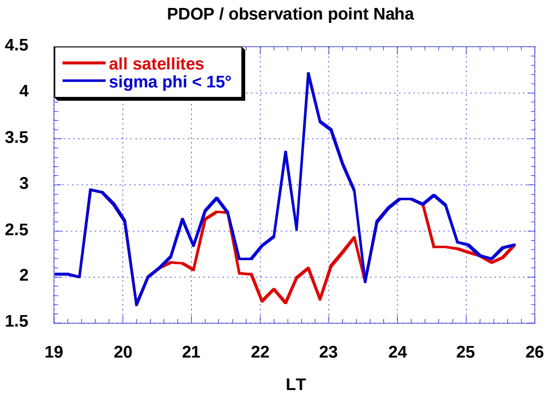


Figure 10 : DOP and constellation

GISM was used to compute all scintillation parameters for each GPS satellite visible from Naha (Japan). The tracking error was derived from these parameters and from typical receiver characteristics. Satellites with tracking error above the 15° threshold were ignored for the DOP evaluation. Figure 11 presents the resulting DOP, compared with the DOP of the unaffected constellation. In worst cases, the DOP during scintillation can be twice as high than under normal conditions.



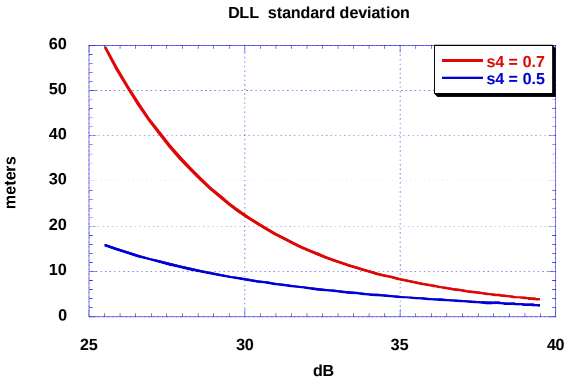


Figure 11 : DOP at Naha under scintillation conditions computed with GISM

Figure 12 : DLL tracking error vs C/N0

Even if the signal emitted from a GPS satellite isn't lost, it can alter the position precision. One of the DLL functions is the measurement of the delay between the code carried by the GPS signal and the receiver internal clock. This delay is an estimation of the time needed by the GPS signal to reach the receiver. The receiver is then able to compute the distance of the satellite. Errors in this estimation are collected in the UERE. To take into account the scintillations, we have to consider the DLL tracking errors. The DLL can be studied like the PLL to evaluate its tracking error variance in degrees. The UERE due to scintillations can then be deduced with a product with the chip length (equal to 293 m for L1 [5]). The results are shown in Fig. 12. These results seem to show high degradation of the UERE. It must be combined with Fig. 6 : satellites with high DLL tracking errors have also high PLL tracking errors and therefore they might be considered as lost and don't contribute to the UERE.

The combination of both effects is presented in Fig. 13. Satellites with PLL tracking errors above 15° were considered invisible for the DOP calculation. All other links with visible satellites were used to compute a mean UERE contribution due to scintillation.

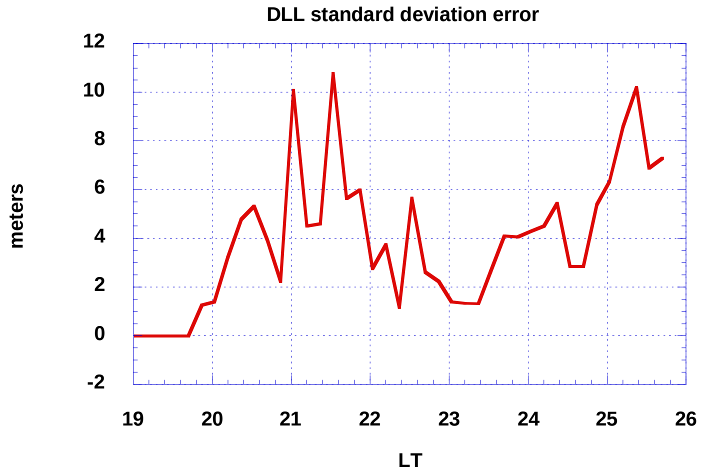
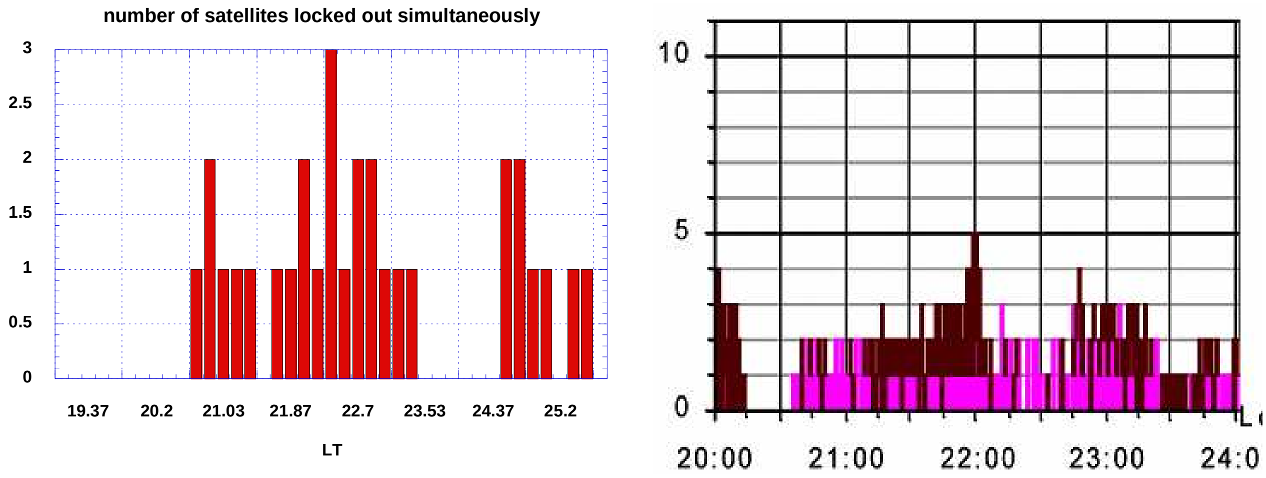


Figure 13 : Positioning error at Naha (Japan) under scintillation conditions, computed with GISM

3.5 Simultaneous Loss of Lock

Taking the 15° criteria for loss of lock threshold, the links with such a phase standard deviation level have been selected. This gives the number of satellites simultaneously locked out. The result is reported on figure 14a. Three satellites may be lost simultaneously in a few cases which correspond to the highest values of the DOP. As a comparison, the measurements results are presented on figure 14b [6]. Locked out links are in brown. Strong scintillations are in pink. Quite similar results are obtained. Three satellites are locked out simultaneously in some cases and even 4 in extreme cases.



a) GISM results b) measurements [6]

Figure 14: number of satellites locked out simultaneously

4. Conclusion

As presented in the first section, the model developed gives results in reasonable agreement with measurements. The way to include the relationship between scintillations and PLL and DLL errors at receiver level has been presented together with the probability of loss of lock calculation.

Concerning the positioning error, two effects act in opposite way. Increasing s4 increases the PLL error and as has been mentioned, beyond a given threshold the link is disrupted with two consequences : the number of usable satellites in the constellation decreases. Consequently the DOP will increase. On the other hand if we average the DLL for the remaining links it will decrease and the product with the DOP will not be necessarily greater. However it is difficult to conclude due to the fact that this is highly dependent on the geometry. In general at equatorial regions, we have more than 7 satellites in view. Loosing one link is consequently of low consequence on the accuracy. It becomes more significant if we lose more than one link.

All the results presented here were computed for given receiver characteristics. It should be noticed that other GPS receivers might be more or less vulnerable to scintillation. In addition, the study can be extended to dynamic effects.

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