Analysis of the PLL phase error in presence of ionospheric scintillation

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Abstract

The functioning of standard phase locked loops (PLL), including those used to track GNSS signals, is based on a linear approximation valid in case of small phase errors. Such an approximation represents a reasonable assumption in most of the propagation channels. However, in presence of a fading channel the phase error may become large and the PLL is expected to operate in a non-linear regime. As PLLs are generally designed and expected to operate in their linear regime, whenever the non-linear regime comes into play, they will experience a serious limitation in their capability to track the corresponding signals. The phase error and the performance of a PLL embedded into a commercial multi-constellation GNSS receiver was analysed in the presence of ionospheric scintillation. The limitation of the linear approximation becomes evident for a scintillation level given by $S_4 \geq 0.6$. The limitations posed by a fading channel consist of an increased phase dynamics together with power fading. The presence of fading on the signal power causes the absorption of the propagating energy in such a way that the PLL is forced to lose lock, irrespective of the phase dynamics.

1 Introduction

The tracking of satellites signals is usually based on a phase locked loop (PLL). This applies to typical Global Navigation Satellite Systems (GNSS) receivers, which are often characterised by the combination of a PLL with a DLL (delay lock loop) and/or a FLL (frequency lock loop) to improve the tracking capability in case of stresses (i.e., deviations of the signal from its nominal phase) [1].

Typically, the performance of a PLL has to be evaluated in the presence of noise and Doppler phase shift due to the movement of either the receiver and/or the satellite. Most importantly, the level of the noise will characterise the typical error in the phase estimate. Such an error is described by means of the standard deviation of the PLL phase error and is called phase jitter [1].

The values of the phase jitter may provide an insight on the performance of the PLL in the presence of whatever noise source. Standard treatments only consider white gaussian noise as a deteriorating factor affecting the phase error within the PLL. Very few attempts have been made in the case of a fading channel [2].

The most important aspect to notice is that the description of the PLL performance in the presence of a fading channel is significantly different from the description where only white gaussian noise is present. Whenever the fading starts to become large the PLL functioning will shift from the linear to the non-linear regime. To date, the most notable attempt to evaluate the non-linear PLL behaviour is described in [3].

The behaviour of a PLL embedded into a typical commercial GNSS receiver was analysed in the presence of ionospheric scintillation events. The objective was to gain detailed evidence of the limitations of the PLL performance during ionospheric scintillation events.

2 Phase error analysis

A Septentrio PolaRxS was used to analyse PLL performance under the effects of an ionospheric scintillation event. The ionospheric scintillation event was characterised by means of experimental data collected at a typical low latitude station during disturbed conditions. The experimental data consisted of raw intensity and phase for all the PRNs in view at a given instant. Scintillation indices were calculated in postprocessing and used to identify the most suitable

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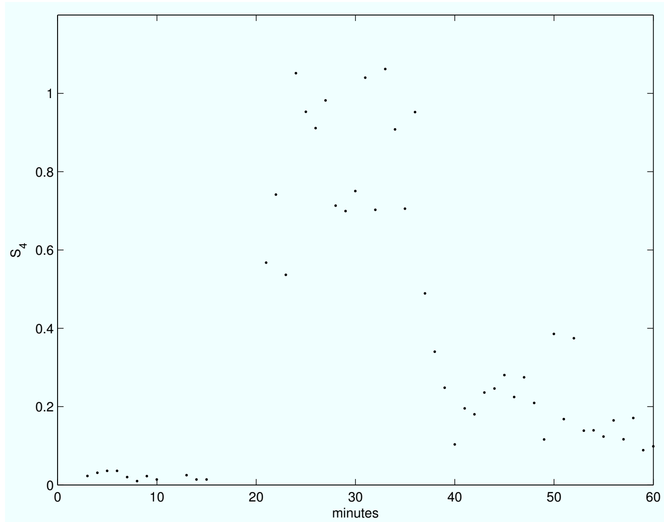

Figure 1: The input perturbations according to the scintillation index S_4.

event for the evaluation of the PLL performance. The most suitable event was characterised by an initial 20 minutes of very low scintillation activity ($S_4 \leq 0.1$), 20 minutes of moderate to strong scintillation ($0.6 \leq S_4 \leq 1$) and 20 minutes of low scintillation activity ($S_4 \leq 0.2$), as shown in Figure 1.

The signal perturbations (in both intensity and phase) corresponding to such a scintillation scenario were then extracted from the experimental data by essentially separating the high frequencies of interest from the low frequencies fluctuations in the received signal. Then, the signal perturbations were suitably ingested into a Spirent GSS8000 signal simulator, which simulated the nominal signals of the PRNs of interest together with the perturbations in input. The effects on a commercial receiver were recorded by using the Septentrio PolaRxS receiver, which is able to record post-correlated I/Q samples at 50 Hz sampling rate. Scintillation indices and phase error statistics were then calculated by using this type of raw data.

An example of the results is shown in Figure 2. The upper plot shows the estimate of the received signal intensity (at 50 Hz sampling rate) throughout the simulated scintillation event. The second plot (from the top) shows the phase error (at 50 Hz sampling rate) during the simulated event. The third plot shows the standard deviation of the phase error (averaged over one minute intervals) and is intended to provide a measure of the phase jitter in real time during the simulated fading event. The bottom plot shows the lock time on L1 throughout the event. The example in Figure 2 refers to a PLL configuration in which the bandwidth was $15Hz$, the threshold in the lowest deviation from the nominal C/N_0 was $-20dB - Hz$ and the pre-detection integration time was $10ms$. On the other hand the example shown in Figure 3 refers to a PLL configuration in which the only difference from the previous configuration was the bandwidth, this time set to a value of $10Hz$.

It can be noticed that the PLL loses lock on L1 only once for a PLL bandwidth of $10Hz$, while the loss of lock occurs twice when the bandwidth is increased to $15Hz$. This appears somehow inconsistent with the common assumption that the PLL bandwidth should increase to capture increased signal dynamics. A more careful analysis, however, reveals that this result is absolutely sound. The increase of the PLL bandwidth implies an increase in the level of the noise (white gaussian) to be considered as a whole. As a result, the total C/N_0 is decreased and, depending on the threshold on the minimum C/N_0 to be tracked, it will determine a loss of lock or not.

As mentioned before, the most important aspect to be noticed is that in the presence of fading the problem is not simply one of a faster signal dynamics. The most crucial aspect is that, in the presence of an increased signal dyanimcs, intensity fading does occur, causing the signal level to weaken. The weakening of the signal (in this particular case due to the absorption of the transmitted energy by ionospheric electron density structures) causes the C/N_0 to lower and the PLL to eventually lose lock.

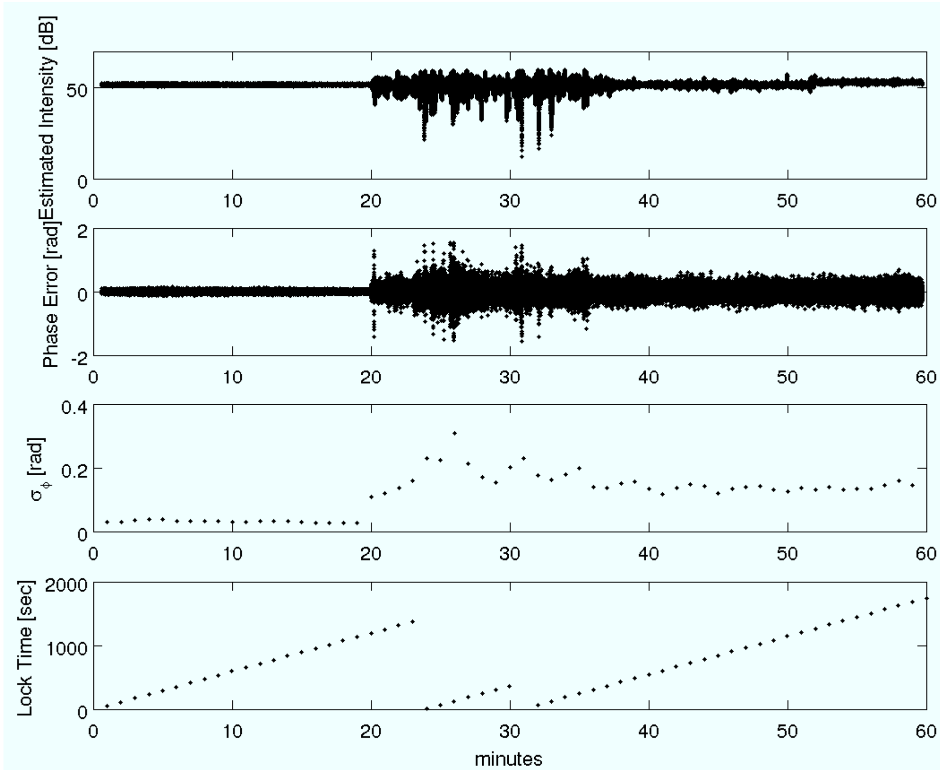

Figure 2: The PLL performance with a bandwidth of $15Hz$.

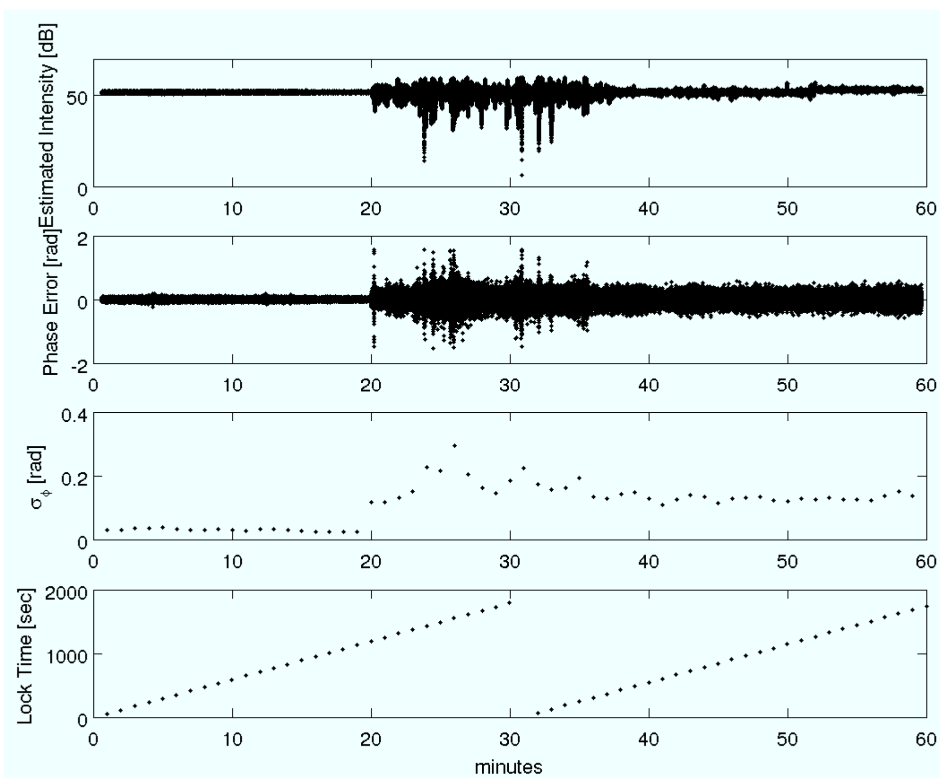

Figure 3: The PLL performance with a bandwidth of $10Hz$.

3 Conclusion

The results indicate that the description of the behaviour of a PLL in the presence of fading due to ionospheric scintillation requires a significantly deeper description than what usually encountered in the literature. The approach cannot be based only on the presence of white gaussian noise, but has to include signal fading. Further analyses will be carried out to define such a deeper description.

4 Acknowledgments

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5 References

1. E. D. Kaplan and C. Hegarty, *Understanding GPS: Principles and Applications*, Norwood, MA, Artech House, 2006.

2. M. K. Simon and M.-S. Aluoini, *Digital communication over fading channels*, Hoboken, NJ, Wiley and Sons, 2005

3. A. J. Viterbi, ”Phase-Locked Loop Dynamics in the Presence of Noise by Fokker-Planck Techniques”, *Proceedings of the IEEE*, 1963, pp. 1737-1757.