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Analysis of the PLL phase error in presence of simulated ionospheric scintillation events

B. Forte[1,2]

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[1] The functioning of standard phase locked loops (PLL), including those used to track radio signals from Global Navigation Satellite Systems (GNSS), is based on a linear approximation which holds in presence 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 However, in presence of a fading channel the phase error may become large, making the linear approximation no longer valid. The PLL is then 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 typical PLL embedded into a commercial multiconstellation GNSS receiver were analyzed in presence of simulated ionospheric scintillation. Large phase errors occurred during scintillation-induced signal fluctuations although cycle slips only occurred during the signal re-acquisition after a loss of lock. Losses of lock occurred whenever the signal faded below the minimum C/N_0 threshold allowed for tracking. The simulations were performed for different signals (GPS L1C/A, GPS L2C, GPS L5 and Galileo L1). L5 and L2C proved to be weaker than L1. It appeared evident that the conditions driving the PLL phase error in the specific case of GPS receivers in presence of scintillation-induced signal perturbations need to be evaluated in terms of the combination of the minimum C/N_0 tracking threshold, lock detector thresholds, possible cycle slips in the tracking PLL and accuracy of the observables (i.e. the error propagation onto the observables stage).

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1. Introduction

[2] 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 characterized 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) [*Kaplan and Hegarty*, 2006].

[3] The possibility to assist the PLL demodulation in presence of deteriorated signal levels was investigated in several instances [*Chiou et al.*, 2004; *Khan et al.*, 2009; *Lian et al.*, 2005; *Mao*, 2007; *Sun et al.*, 2010; *Ward*, 1998].

[4] Typically, the performance of a PLL is well evaluated in presence of particular stresses on the incoming phase (which include the case of a relative motion between the transmitter and the receiver). In the typical description of a PLL a zero-mean white Gaussian noise is usually considered as well. Most importantly, the noise level as well as the amount of stress will characterize the final 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 (see *Kaplan and Hegarty* [2006] for examples of typical phase jitter figures corresponding to first, second and third order loops). The phase jitter is meant to be the ensemble standard deviation in the presence of a zero-mean white Gaussian noise process [*Van Trees*, 1971]. The PLL in presence of zero-mean white Gaussian noise represents the optimum signal demodulator as it provides the maximum a-posteriori estimate and the minimum mean square error [*Van Trees*, 1971]. In presence of a fading channel (i.e., a propagation channel where the phase disturbances stem not only from a zero-mean white Gaussian noise but from scattering and absorption of the transmitted energy somewhere along the propagation path), such as Rayleigh or Rice, the PLL might not provide the optimum solution. A formal proof of such a conjecture seems to the author still missing to date.

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[5] The values of the phase jitter characterize the performance of the PLL in the presence of any noise and disturbance source. Standard treatments only consider white gaussian noise as a deteriorating factor affecting the phase error function within the PLL. Very few attempts have been made in the case of a fading channel [*Simon and Aluoini*, 2005].

[6] 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 behavior is described in *Viterbi* [1963]. In that particular case, the exact solution for the phase jitter in the non-linear regime was calculated by solving the Fokker-Planck equation assuming a simple first order loop ($F(s) = 1$). The calculation appears far more complicate when higher order filters are assumed (as in the case of typical PLL within GNSS receivers).

[7] The behavior of a PLL embedded into a typical commercial GNSS receiver was analyzed in presence of simulated ionospheric scintillation events. The analysis described here focused on the use of a Spirent signal simulator to test the PLL performance of a GNSS multifrequency multi-constellation receiver in presence of simulated scintillation events. Previous studies attempted at analyzing the overall performance of typical GPS dual frequency receivers, by implicitly testing their tracking capabilities [*Morrissey et al.*, 2004; *Van Dierendonck et al.*, 1999; *Ganguly et al.*, 2004]. Some analyses tried to simulate scintillation-like signal perturbations by using a numerical approach while others extracted the signal perturbations from real data measured in correspondence of a particular scintillation event [*Van Dierendonck et al.*, 1999].

[8] The performance of typical PLLs and DLLs implemented within GNSS receivers was also tested in a statistical sense by calculating the intensity and phase scintillation contribution onto the overall phase jitter [*Hegarty et al.*, 2001; *Conker et al.*, 2003; *Knight and Finn*, 1998; *Knight et al.*, 1998]. This method was coded into a model [*Conker et al.*, 2003] capable of predicting the total phase jitter of a given PLL and/or DLL in presence of scintillation.

[9] All the mentioned analyses focused on the description of the conditions leading to cycle slips by modeling scintillation-induced signal fluctuations by means of zero-mean white Gaussian noise. Nevertheless, in the specific case of GNSS receivers other parameters may come into play, for example the minimum C/N_0 tracking threshold.

[10] The objective of the analysis presented here was to avoid any modeling of the phase jitter and subsequent assumptions in deriving results such as those in *Conker et al.* [2003] and *Humphreys et al.* [2010a, 2010b] and to evaluate the phase error in presence of scintillation-induced fading. The analysis focused indeed on the use of correlated I/Q samples output from a GNSS receiver particularly modified in order to provide this type of output directly from the PLL section of each signal being tracked. The I/Q samples were used to evaluate the PLL phase error in correspondence of signal fading imposed by scintillation-induced signal perturbations. Subsequently, the phase jitter was also calculated. The scintillation events were simulated by means of perturbations extracted from real data measured at L band by means of a dual frequency receiver sampling at 50 Hz rate. The high frequency signal fluctuations corresponding to a particular real scintillation event were superposed to the nominal signals simulated by a GSS8000 GNSS simulator (Spirent GNSS signal simulators, http://www.spirent.com/Positioning-and-Navigation.aspx, accessed on 6 March 2011). The corresponding perturbed signals were then recorded afterwards and the phase jitter analyzed.

2. The Simulation Scenarios

[11] A GSS8000 GNSS simulator (Spirent GNSS signal simulators, http://www.spirent.com/Positioning-and-Navigation.aspx, accessed on 6 March 2011) was used to simulate nominal signals (classical and modernized signals) from both GPS and Galileo during simulated scintillation event. In order to simulate realistic signal fluctuations in correspondence of ionospheric scintillation events, real experimental data were used. The experimental data were collected by using dual frequency GNSS professional receiver, particularly modified in order to sample estimated intensity and phase of incoming radio signals at a 25 Hz rate (N. Jakowski, private communication, 2009). The data output from that receiver consisted of estimates of signal levels and carrier phases at a 25 Hz sampling rate and were extracted after the tracking section in analogy with typical GPS scintillation monitors [*Van Dierendonck et al.*, 1993]. The experimental data used to define the signal perturbations to be superposed onto nominal simulated GNSS signals were isolated in an interval where neither losses of lock nor cycle slips occurred. Entangled with those signal perturbations was the reconstruction effect imposed by the Topcon receiver itself (this would be true for any type of scintillation monitors used, as well). In extracting signal perturbations from real experimental data a fundamental assumption needs to be made. The signal perturbations were assumed to be weakly affected by the reconstruction process happening in the Topcon receiver used to measure the data during the scintillation events. A more complete way would indeed be to record the entire signal at IF stage before the correlation filters leading to lock acquisition, as attempted for instance in *Humphreys et al.* [2010a]. The signal at IF stage would be more representative of the real features characterizing it during its propagation up to the receiving antenna. Unfortunately, the IF signal needs to be passed through a tracking algorithm in order to distinguish individual PRNs, as *Humphreys et al.* [2010a] did in building their empirical scintillation library. Hence, the assumption about tracking filters effects on scintillation-induced signal perturbations was necessary and reasonable at the same time, as previously done in *Morrissey et al.* [2004]. The objective here was to understand the behavior of the phase error in the non-linear regime in presence of realistic and reasonable scintillation-induced signal fluctuations.

[12] The dataset referred to a campaign run at Bandung (geographic latitude 6.9°S, geographic longitude 107.6°E, magnetic dip ≈ −16.5°) by using a Topcon unit (N. Jakowski, private communication, 2009). The 25 Hz sampled signals were spectrally processed in order to separate high from low

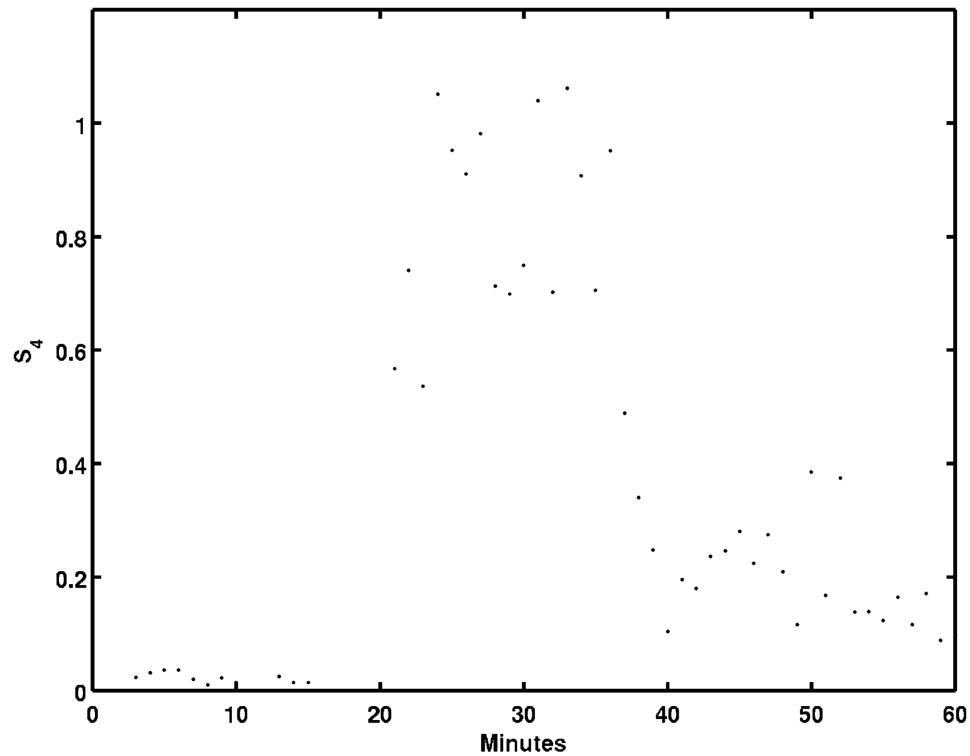


Figure 1. The input perturbations according to the scintillation index S_4.

frequencies component. The high-frequency components were used as perturbations to be superposed to nominal GNSS signals within the signal simulator. The isolation of high-frequency components from experimental data was done in total analogy to similar signal processing performed within standard GPS scintillation monitors [*Van Dierendonck et al.*, 1999]. The signal perturbations were superposed to the nominal signal generated in the simulator by means of a user command defined (UCD) file. The simulator used an update rate of 100 Hz to merge the perturbations onto the nominal signals. The simulated nominal signal level was set to default values of −130 dBm for GPS L1C/A and L2C and −127.9 dBm for GPS L5. In case of L1C/A, for instance, the nominal signal level originated an average $C/N_0 \approx 45$ dB − Hz in the receiver. The signal simulator produced typical GNSS signals which were fed into the receiver antenna input. Consequently, the signal underwent a typical sampling within the receiver used passing through RF, IF and tracking stages. The signal simulator was connected onto a Septentrio PolaRxS receiver characterized by programmable tracking bandwidths, pre-detection integration times and C/N_0 tracking thresholds. In the present analysis the pre-detection integration time was constantly set to 10 ms while the tracking threshold was constantly set to $C/N_0 = 20$ dB − Hz. The PLL used in this particular type of receiver was a third-order loop based on an arctangent discriminator function. The Automatic Gain Control (AGC) and the adaptive tracking loop functions were disabled throughout the tests presented here.

[13] I/Q signal samples at the PLL output were sampled at 50 Hz, in order to calculate scintillation indices and statistics connected with them. By using 50 Hz I/Q samples the phase error (at the same rate) experienced by the PLL at each instant was indeed calculated. This value represent the overall phase jitter which includes ionospheric scintillation and satellite motion only. Multipath and tropospheric effects were indeed neglected.

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

[15] The signal perturbations extracted from this particular experimental event were then superposed to all simulated PRNs in view. Each simulated PRN in view was affected by the same signal perturbations, suitably scaled according to the wavelengths considered (L1, L2, and L5), as previously assumed in *Morrissey et al.* [2004] for instance. The scaling on the phase was accomplished by keeping the ratio between different wavelengths considered. On the other hand, the scaling on the intensity was accomplished by assuming a dependence on the wavelength of the tye $S_4 \propto f^{-1.5}$, which is a reasonable assumption for typical low latitudes conditions and low scintillation levels [*Yeh and Liu*, 1982; *Rastogi et al.*, 1990]. The particular scaling adopted to perturb both the intensity and phase of nominal GNSS signals was based on a conservative assumption. The actual scintillation levels

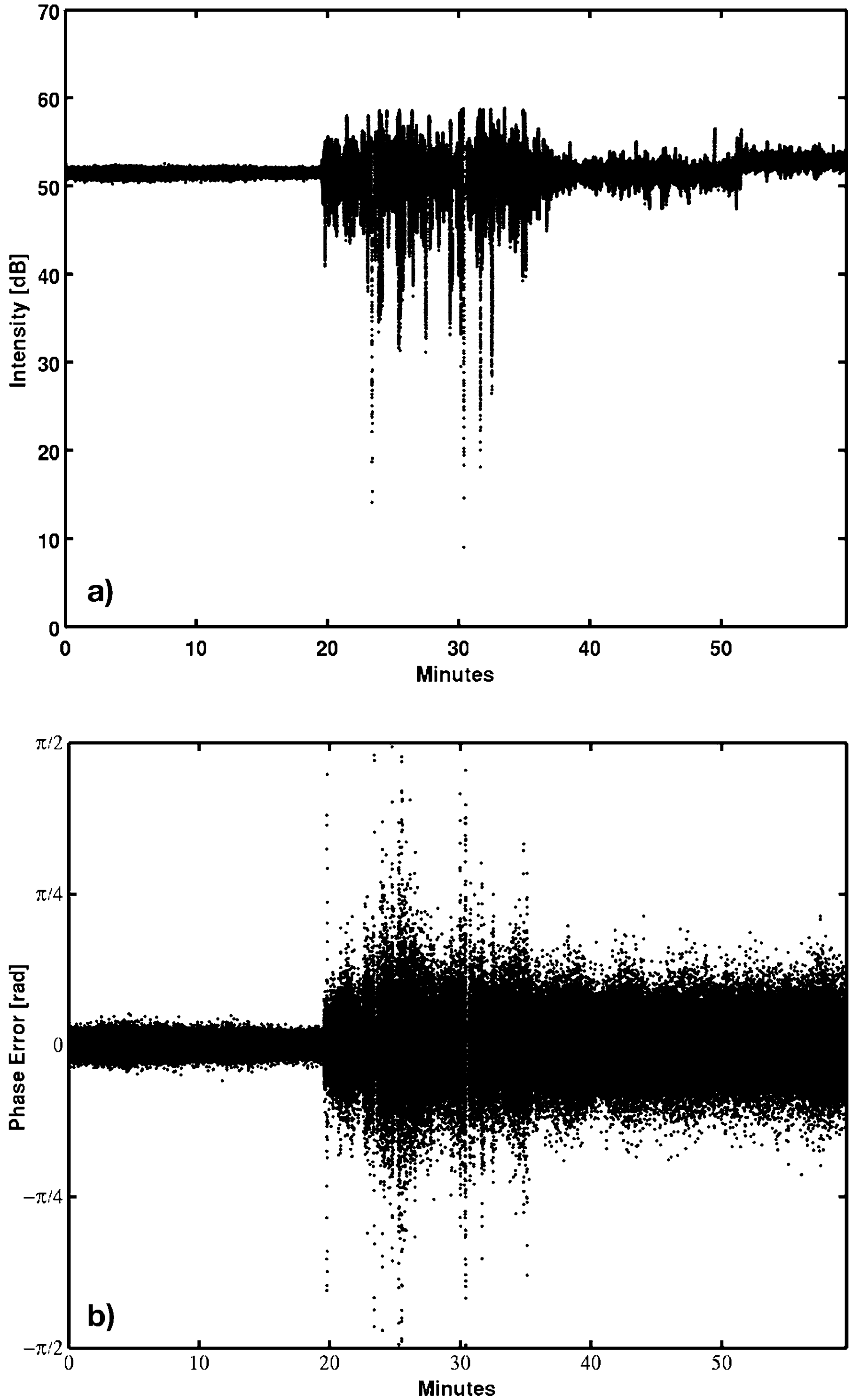


Figure 2. (a–e) GPS L1C/A with a PLL bandwidth of 15 Hz. (f–j) GPS L1C/A with a PLL bandwidth of 10 Hz. (k–o) GPS L1C/A with a PLL bandwidth of 20 Hz.

simultaneously appearing on L1, L2 and L5 would probably be higher for wavelengths longer than L1. The point here was indeed to try and see how the tracking capability of the particular receiver considered was modified or affected by signal perturbations of this type. The exercise can indeed be refined afterwards.

[16] The GNSS signals considered in this study were GPS L1C/A, GPS L2C, GPS L5, and Galileo L1. The signal perturbations were extracted from experimental data sampled at 25 Hz rate on GPS L1C/A and superposed onto the nominal signals by using a 100 Hz update rate

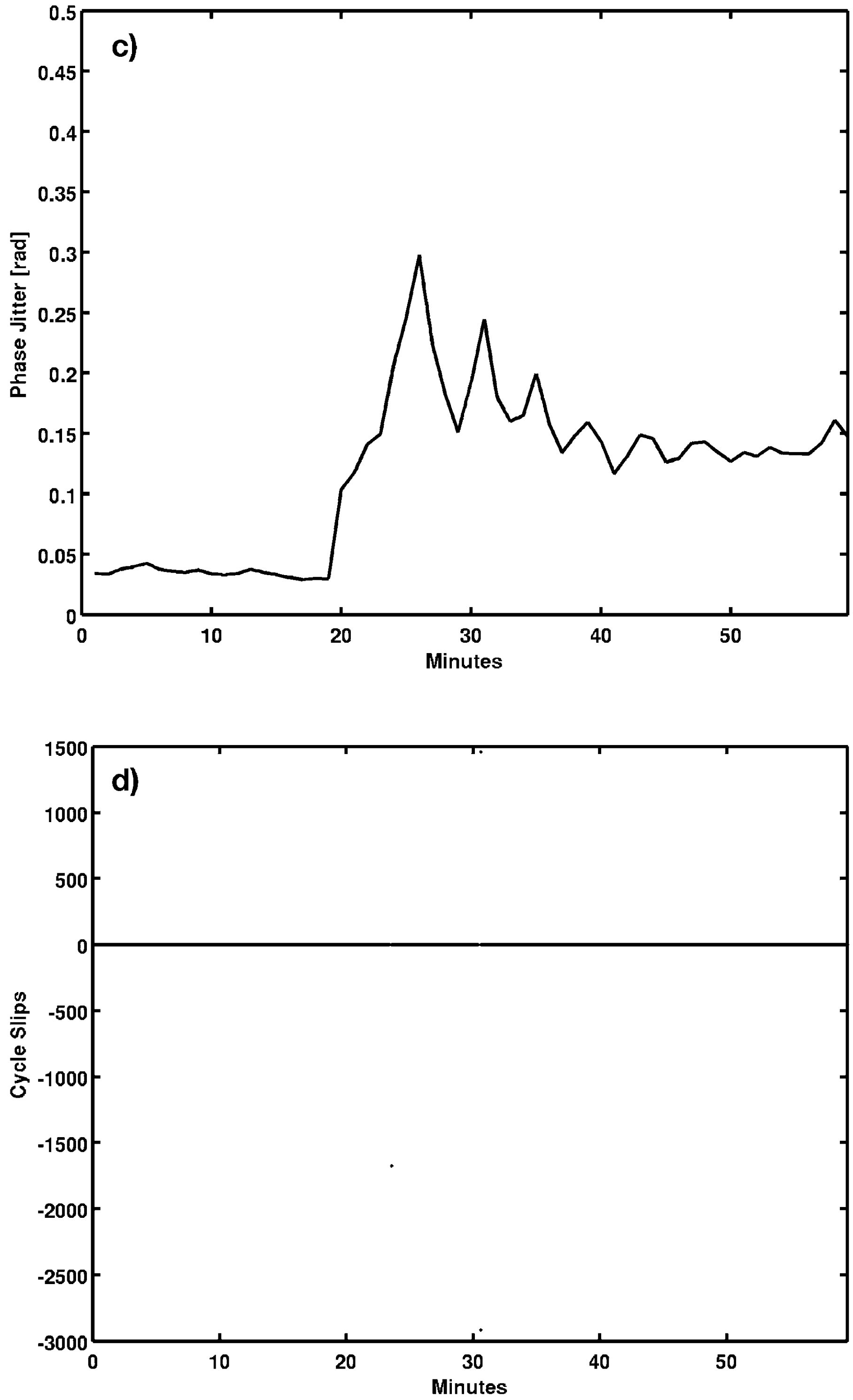


Figure 2. (continued)

within the Spirent simulator. Usually, GPS scintillation monitors sample at a 50 Hz rate [*Van Dierendonck et al.*, 1993]. However, scintillation induced signal fluctuations occupy a small portion of that spectral window being the typical Fresnel frequency of the order of 10^{-1} Hz at low latitudes and 1 Hz at high latitudes for GPS satellites for typical small-scale effects [*Forte and Radicella*, 2002]. Hence, a 25 Hz sampling rate is already enough to catch signal fluctuations originated by small scale plasma density

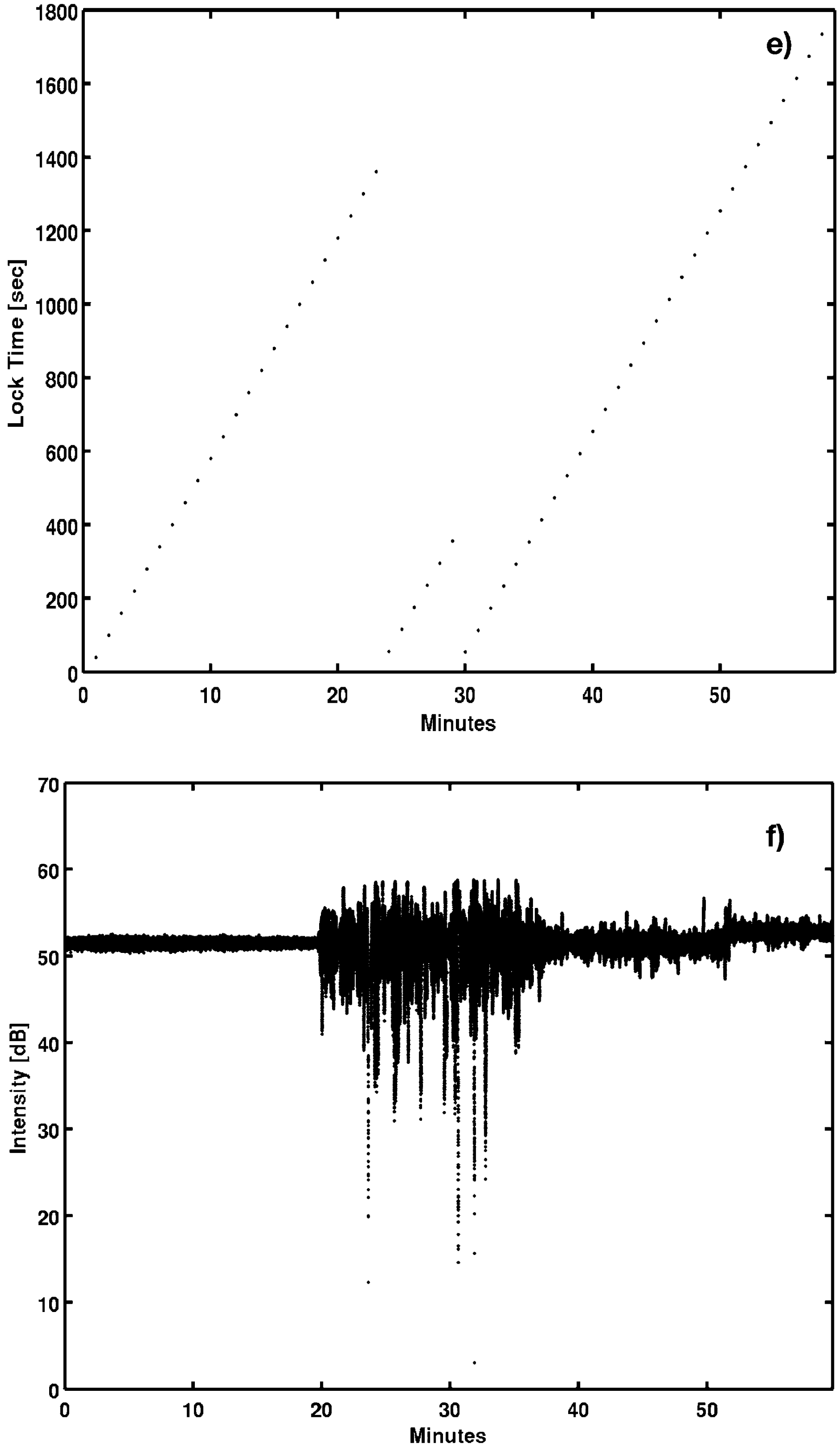


Figure 2. (continued)

irregularities, as previously demonstrated for instance in *Forte* [2005].

[17] The original signal perturbations were adapted onto the different GNSS signals wavelength by taking into account a simple frequency scaling for both intensity and phase components. This operation introduced a sort of amplification of the original fades, which was common on all the signals (including L1C/A). The most important aspect

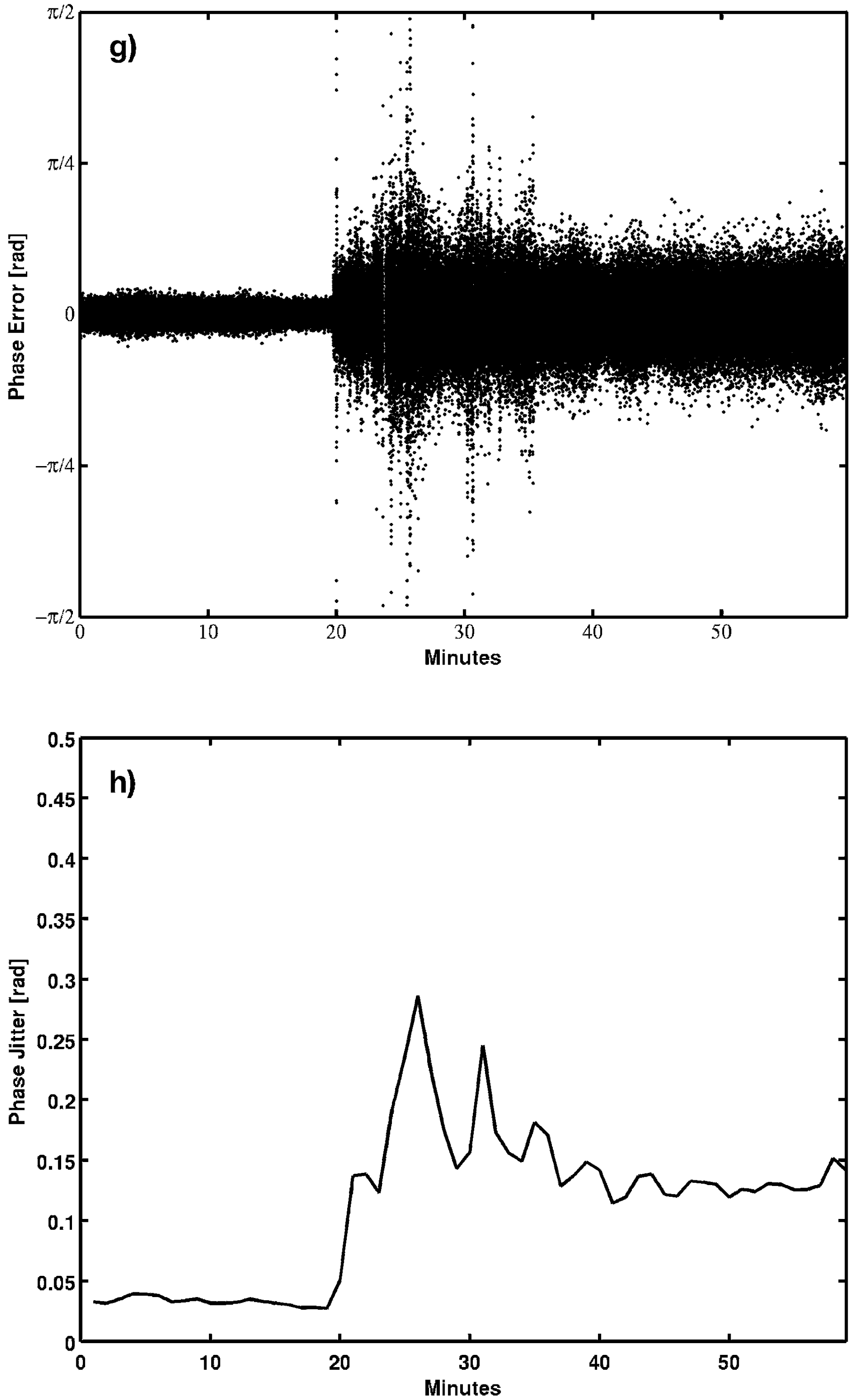


Figure 2. (continued)

was indeed to understand the ultimate conditions leading to loss of lock within a given receiver by close inspection of the phase error. In such a case, amplified fades would mimic the extreme fades to be encountered at low latitudes during solar maximum conditions, still maintaining a timescale similar to what measured in the field. The timescale of scintillation-induced signal perturbations may well change during real conditions. However, such a change is expected to remain well within the PLL bandwidth values considered in the present analysis. In any case, deep fades connected with strong scintillation events may not always be connected with a change in the timescale, as such a change would strictly depend on the geometry [*Kintner et al.*, 2001] as well as on

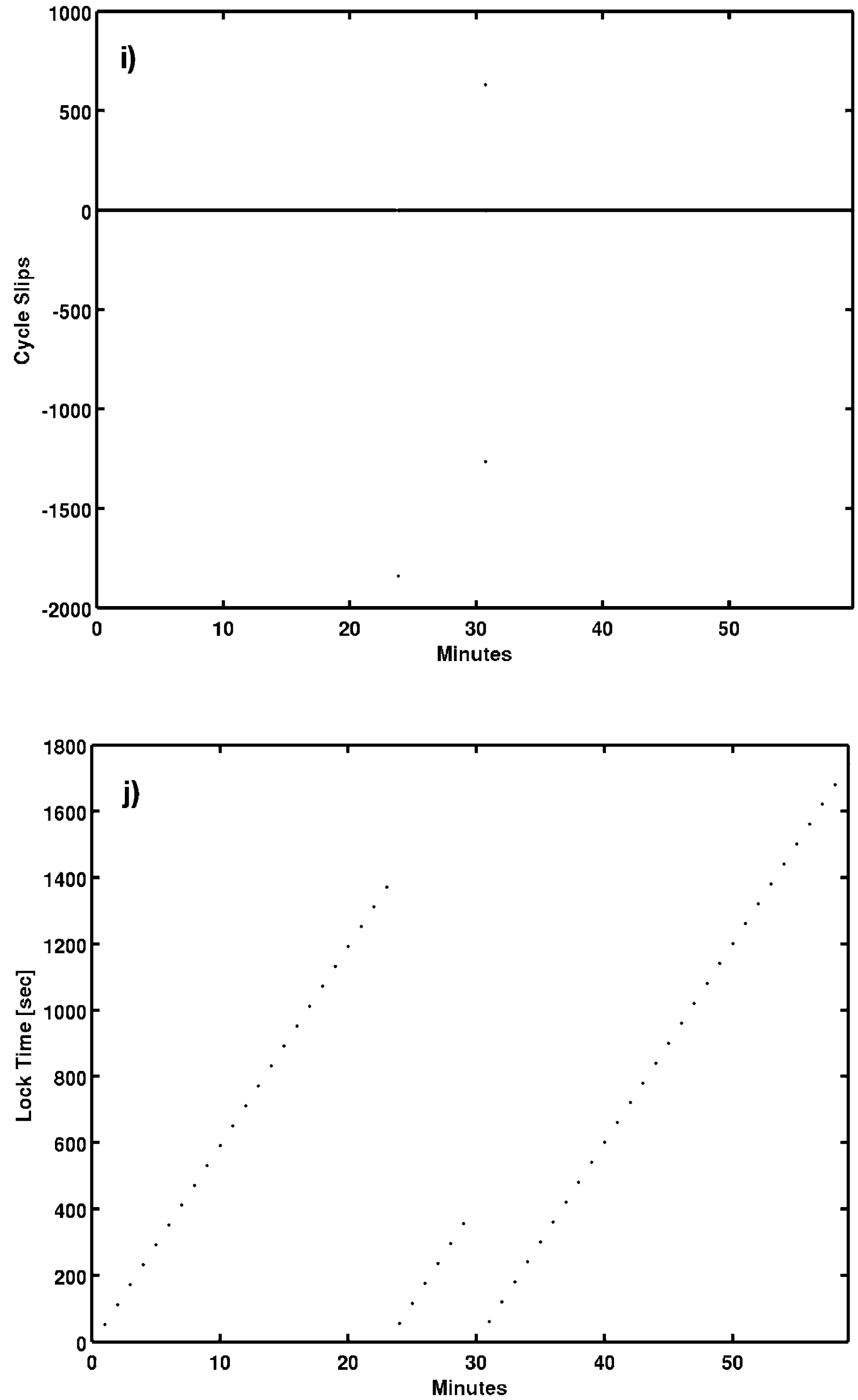
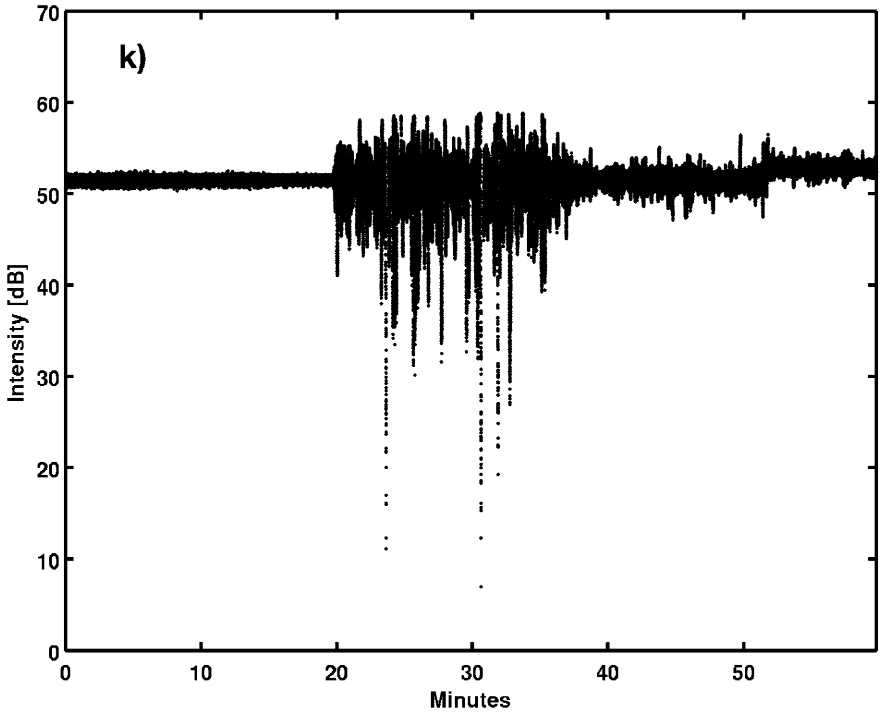


Figure 2. (continued)

the scattering mechanism behind the observed scintillation fades.

3. Phase Error Analysis

[18] The overall results are shown in Figures 2 (corresponding to the signal GPS L1C/A), 3 (GPS L2C), 4 (GPS L5), and 5 (Galileo L1). Figures 2a–2e correspond to a PLL bandwidth of 15 Hz (almost the default value in typical commercial receivers), the minimum C/N_0 tracked equal to 20 dB-Hz, and the pre-detection integration time equal to 10 ms. Figures 2f–2j correspond to the receiver setting in which the PLL bandwidth was fixed to 10 Hz, the minimum C/N_0 tracked was fixed to 20 dB-Hz, while the



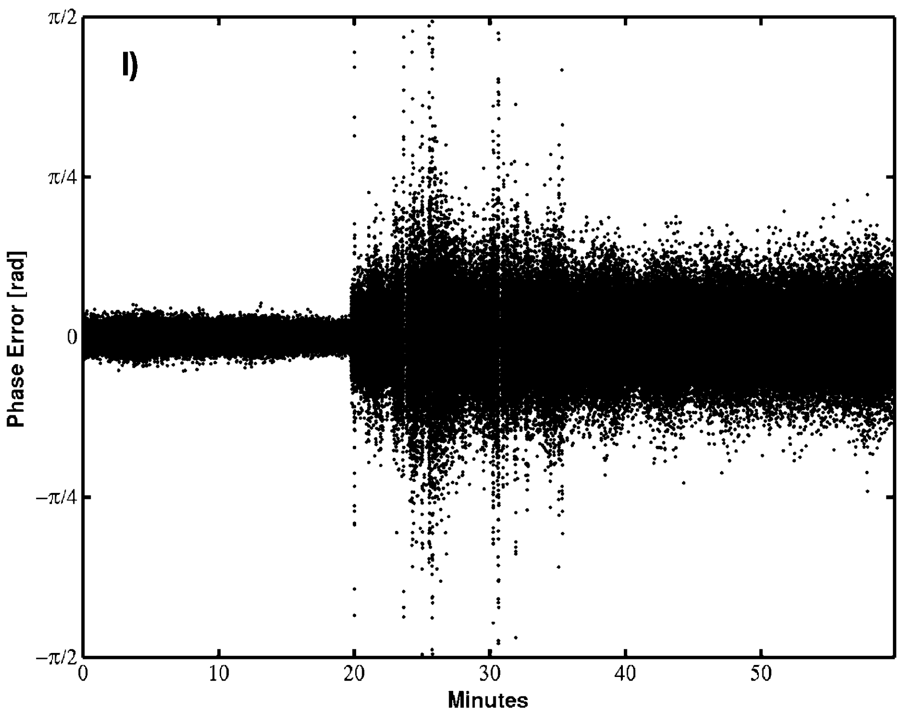
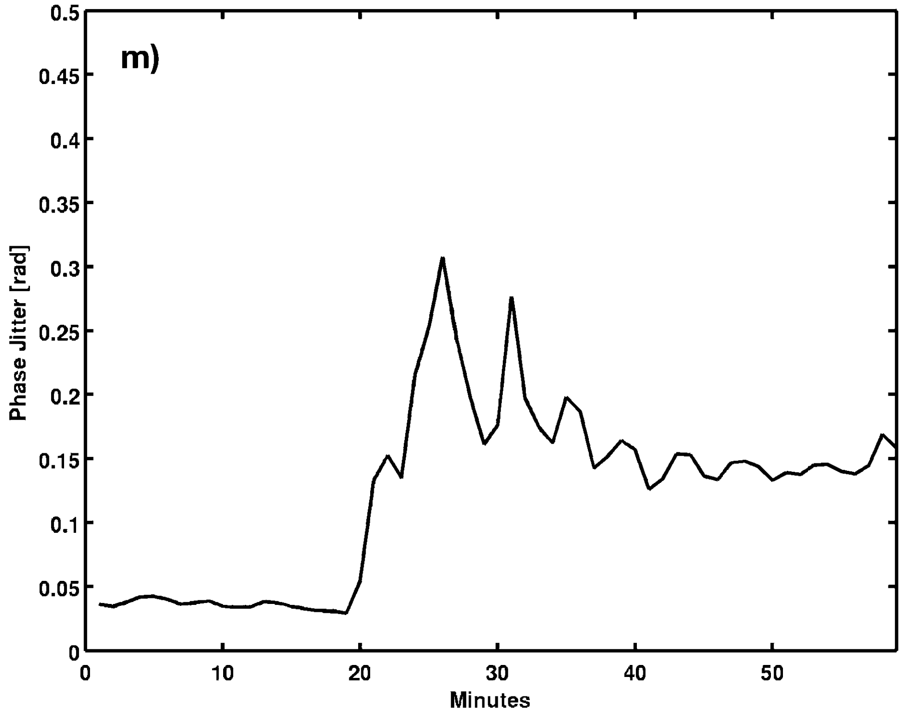


Figure 2. (continued)

pre-detection integration time was fixed to 10 ms. Figures 2k–2o refer to the receiver setting in which the PLL bandwidth was fixed to 20 Hz, the minimum C/N_0 tracked was fixed to 20 dB-Hz, while the pre-detection integration time was fixed to 10 ms.

[19] On the other hand, Figures 3–5 refer to the receiver setting in which the PLL bandwidth was fixed to 15 Hz, the minimum C/N_0 tracked was fixed to 20 dB-Hz, while the pre-detection integration time was fixed to 10 ms.

[20] In Figures 2–5 the sets of plots contain the same information but for different signals. Figures 2a, 2f, 2k, 3a, 4a, and 5a show the estimate of the received intensity (as calculated directly from I/Q samples at 50 Hz rate) expressed in dB as a function of time throughout the duration of the



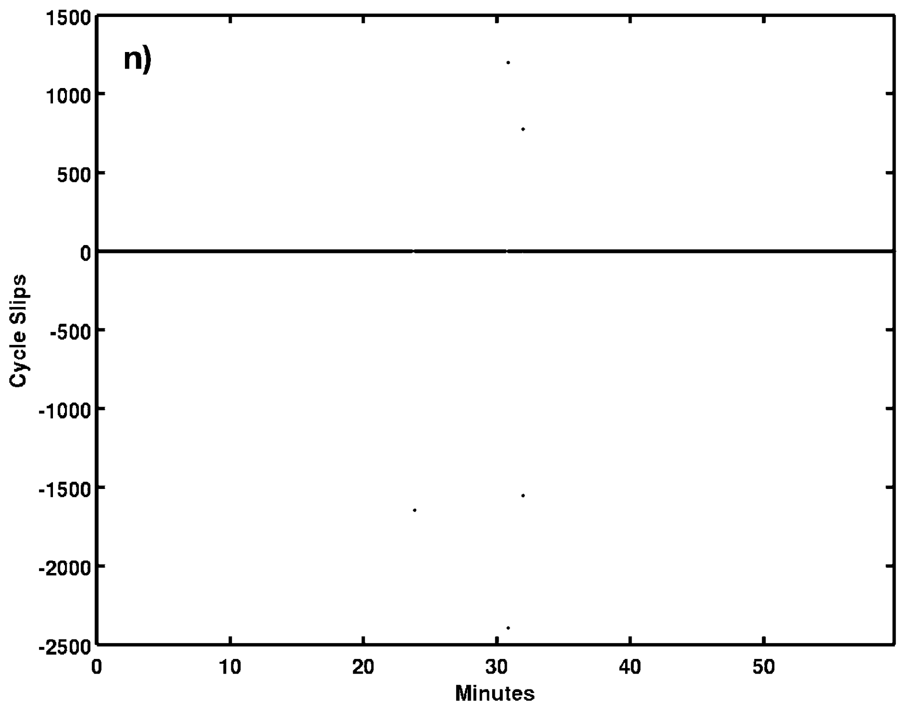


Figure 2. (continued)

simulated scintillation event. Figures 2b, 2g, 2l, 3b, 4b, and 5b show the phase error (as calculated directly from I/Q samples at 50 Hz rate) expressed in radians as a function of time throughout the duration of the simulated event. Figures 2c, 2h, 2m, 3c, 4c, and 5c show the phase jitter (i.e., the standard deviation of the phase error, averaged over 1 minute intervals, taking into account all non-missing points) expressed in radians, as a function of time. Figures 2d, 2i, 2n, 3d, 4d, and 5d show the occurrence of cycle slips (as deduced from the received carrier phase by using the triple difference method) as a function of time. Finally, Figures 2e, 2j, 2o, 3e, 4e, and 5e show the lock time (output from the receiver) cumulatively summed over 1 minute intervals as a function of time.

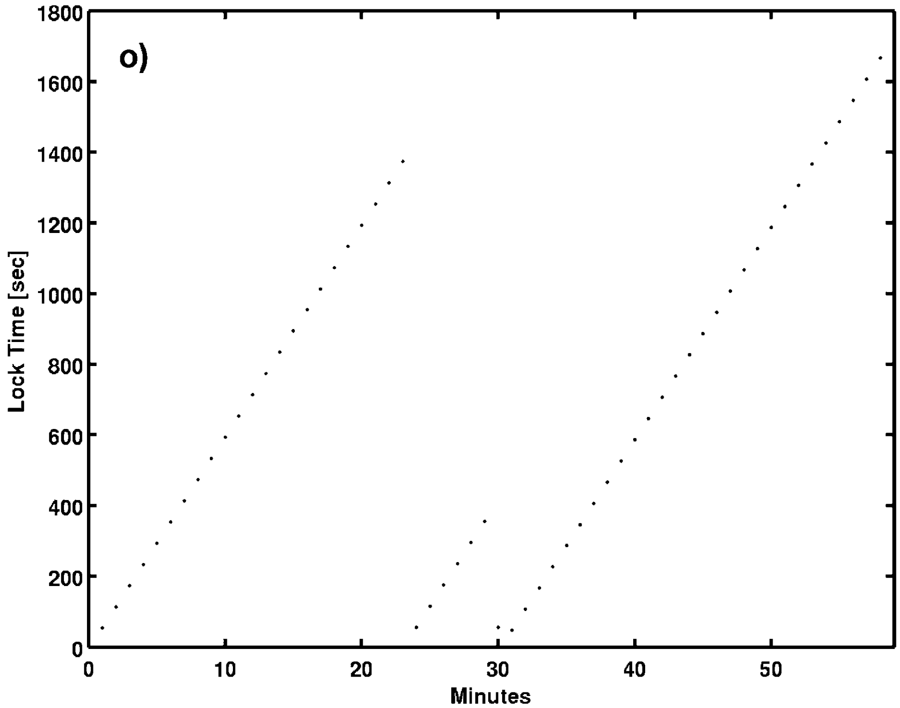


Figure 2. (continued)

[21] The phase jitter was calculated over one minute periods by using all available I/Q samples in that particular minute. If no loss of lock occurred in a particular minute all the 3000 samples (at a 50 Hz rate) were used in the calculation of the standard deviation. If one or more losses of lock occurred the phase jitter was based on all available I/Q samples between consecutive losses of lock in that particular minute.

4. Discussion

[22] The intensity of the perturbed signals as measured by the receiver throughout the simulated scintillation event appeared to behave in a similar way for all the signals considered (see Figures 2a, 2f, 2k, 3a, 4a, and 5a). The signal GPS L2C appeared to be overall on a lower intensity probably as a result of different amplification factors as compared to the other signals. As a result, the signal GPS L2C suffered more throughout the simulated event. Slight differences were observed when changing the PLL bandwidth in correspondence of the deepest fading peaks due to thermal fluctuations across the simulated events.

[23] The phase error (Figures 2b, 2g, 2l, 3b, and 4b) increased with the signal perturbations (Figures 2a, 2f, 2k, 3a, 4a, and 5a) in response to increasing scintillation levels (Figure 1). The increase in the phase error subsequent to the increase in the scintillation level was not uniform, as it can be noticed by comparing the phase error plots relative to L1C/A, L2C, L5, and Galileo L1. In some cases (L1C/A, L5, Galileo L1) the phase error intensified in a neighborhood of minute 30 (the all simulated event lasted 60 min in total, see Figure 1), while in others (L2C) the phase error intensification occupied a broader interval around minute 30. This discrepancy in the phase error response was due to an overall lower received power on the signal GPS L2C as compared with all the other signals. The lower intensity proved to suffer more of the fading process throughout the simulated event, giving rise to phase error values generally larger than those observed on the other signals (see phase error plots in Figures 2–5). Overall, the scintillation-induced signal perturbations recorded by the Septentrio receiver seemed reasonably correlated for all the signals considered. In particular, a higher transmitted power over L5 was apparently not enough to overcome scintillation-induced perturbations (compare for instance Figures 2 and 4), being a lower frequency still the dominant aspect. This aspect was recently confirmed by experimental measurements conducted at high latitudes [*Peng et al.*, 2011]. The analysis described here agrees with and is in support of the understanding of the findings shown in *Peng et al.* [2011].

[24] For all the signals (i.e., in all different tracking schemes) the largest value reached by the phase error was about $\pm\pi/2$ rad (see phase error plots in Figures 2–5) throughout the whole simulated scintillation event. It means the phase error was in a neighborhood of $+\pi/2$ rad or $-\pi/2$ rad, with $\pi/2$ rad representing the limiting value which can be achieved. Whenever the phase error exceeds this particular value a cycle slip has to occur in response to a phase error larger than what the tracking loop could cope with. Large phase errors occurred in several circumstances during the simulated event on all the tracking channels. The first time (around minute 20) corresponded to the beginning of the perturbations superposed onto the nominal signal. Likely, this phase gradient caused an abrupt increase in the phase error pushing it toward the edges of its domain. The phase error stabilized afterwards in presence of anyhow low

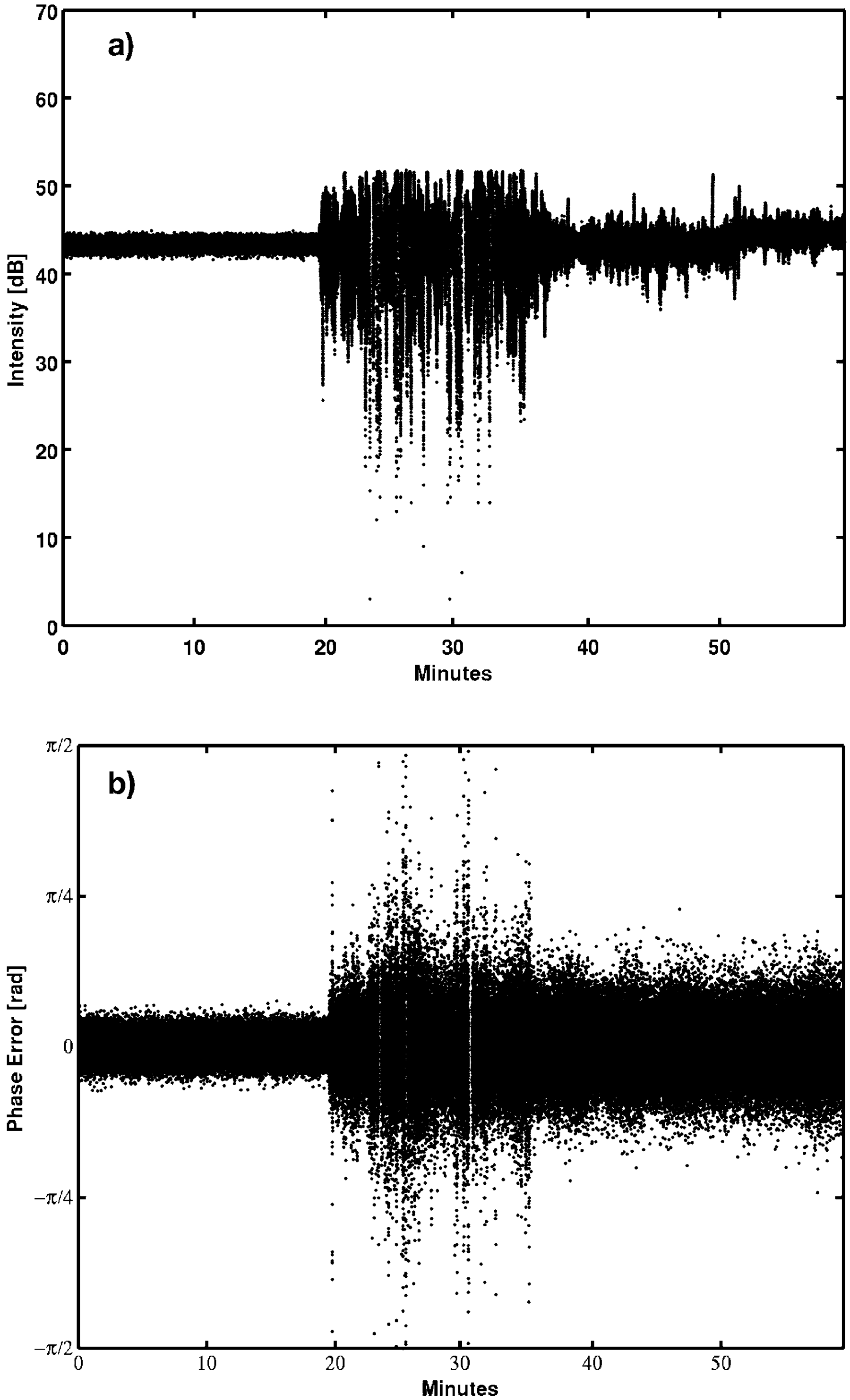
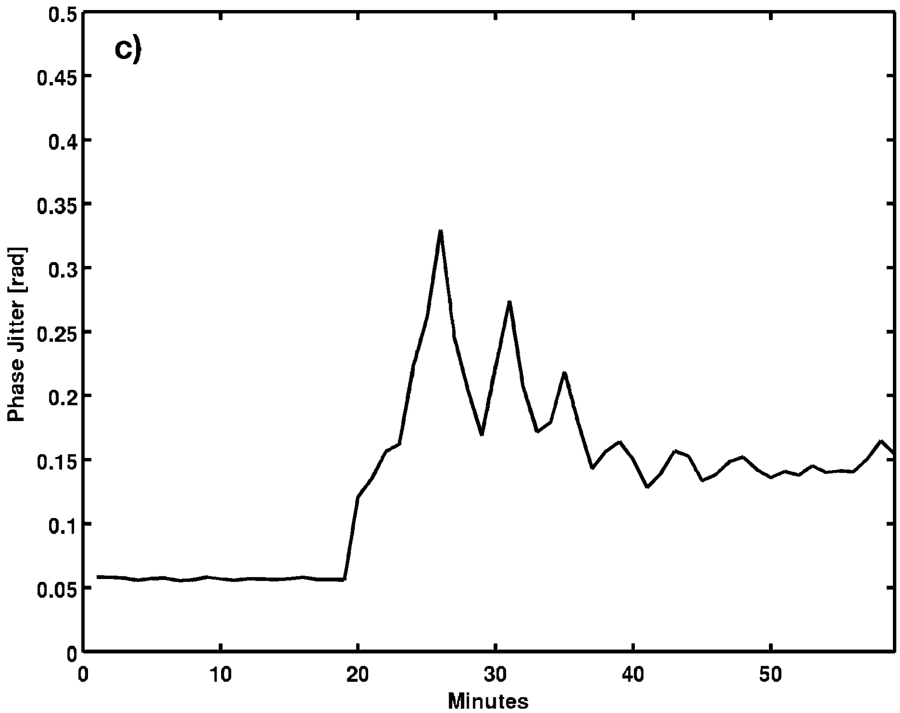


Figure 3. GPS L2C with a PLL bandwidth of 15 Hz.

scintillation levels. As the scintillation level increased (reaching its peak around minute 30, see Figure 1) the occurrence of large phase errors increased. Overall, the probability of occurrence of large phase errors and, subsequently, cycle slips was highest during high scintillation levels (which is expected).

[25] The tendency shown by the phase error is summarized in the phase jitter (Figures 2c, 2h, 2m, 3c, 4c, and 5c). In this case, the phase jitter accounts for thermal noise purely within the receiver, satellite motion, and ionospheric scintillation only. The phase jitter maximized between minutes 20 and 30 in correspondence of the strongest signal



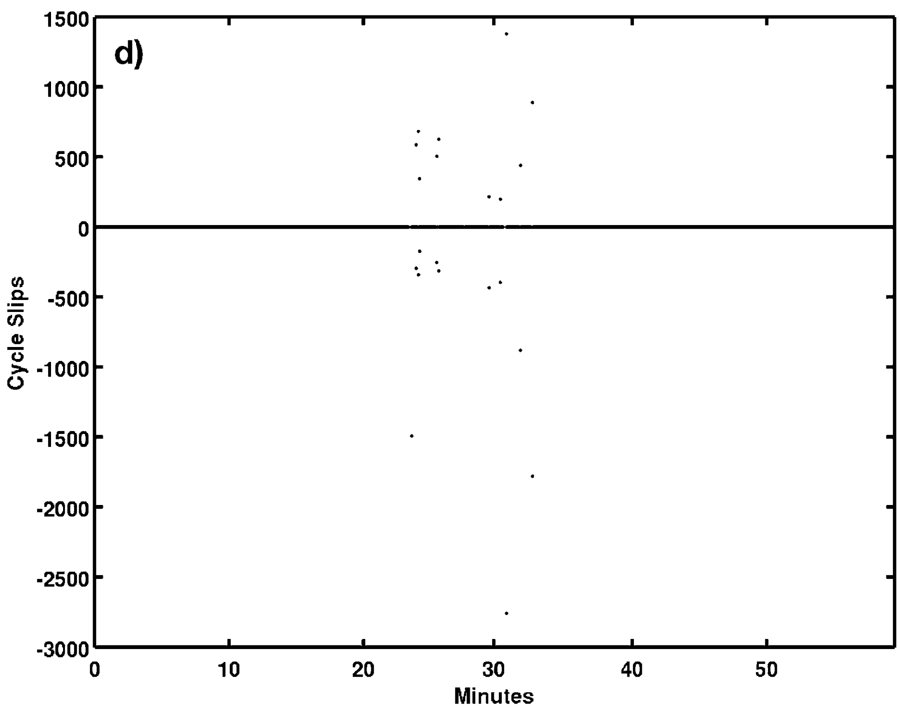


Figure 3. (continued)

perturbations due to the selected scintillation event (see Figure 1). The phase jitter showed to be ≤0.3 rad even during the strongest scintillation conditions (see phase jitter plots in Figures 2–5).

[26] The description and functioning of the PLL is most of the time based on the approximation of a small phase error (i.e., phase error ≈0), in which the equation describing the loop is linear. This approximation holds whenever the phase jitter is less than 0.5 rad for generic loops [*Van Trees*, 1971] or less than 0.26 rad for Costas loops [*Knight and Finn*, 1998]. The phase jitter shown in Figures 2–5 never exceeded such a limiting value in view of the linear approximation considered. In presence of strong scintillation the PLL is expected to migrate from the linear to the non-linear regime,

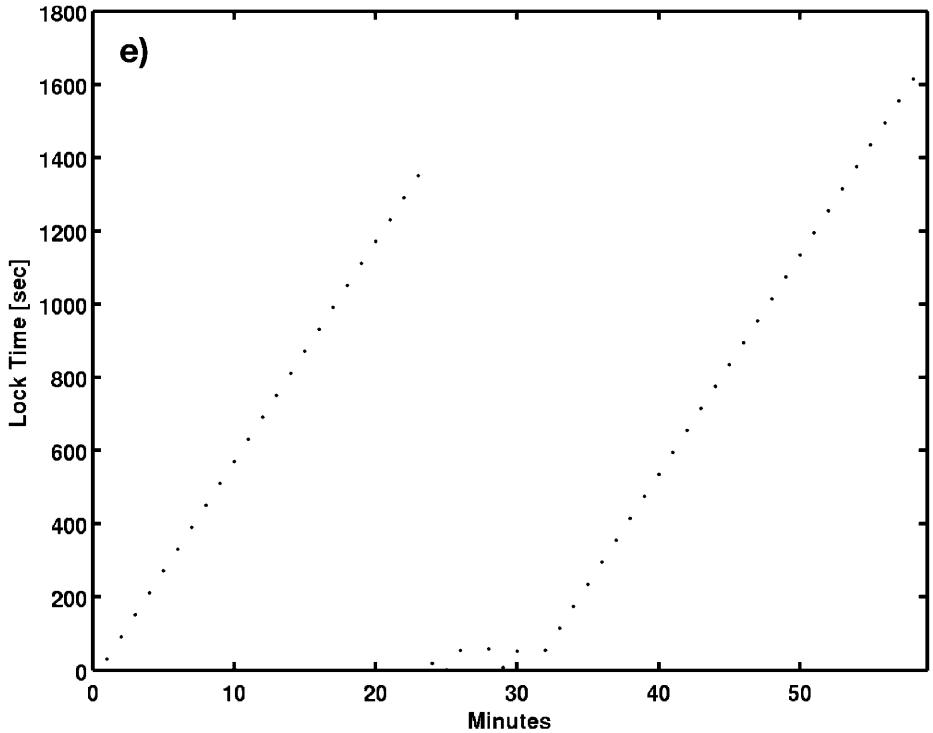


Figure 3. (continued)

the theoretical analysis of which has to be approached in a statistical sense.

[27] The distinction between linear and non-linear regimes is evident from the plots showing the phase error (values in a neighborhood of the limiting edges of its domain $\pm\pi/2$ rad) rather than from the phase jitter plots (≤ 0.3 rad) in correspondence of scintillation-induced fading. The PLL attempted to find a solution even in presence of the strongest signal perturbations (between minutes 20 and 30) where the linear approximation is evidently uncorrect. This is accomplished by paying a price such as a larger error (lower accuracy) in the phase estimate.

[28] Large phase errors occurred in several circumstances throughout the simulated events, where the phase error showed values in a neighborhood of its validity domain (i.e., around $\pi/2$ rad or $-\pi/2$ rad). Cycle slips did not occur in all those cases though, but only during the re-acquisition process after a loss of lock. This can be noticed by comparing the plots showing the phase error, the cycle slips and the lock time in Figures 2–5. In particular, the lock time (in seconds) on all signals is shown in Figures 2e, 2j, 2o, 3e, 4e, and 5e. The comparison between Figures 2a, 2f, 2k, 3a, 4a, and 5a and Figures 2e, 2j, 2o, 3e, 4e, and 5e clearly showed that the signal was lost whenever it faded below the minimum C/N_0 allowed (in this case 20 dB-Hz). The loss of the signal lock was entirely driven by the value of the C/N_0 being tracked at a given instant. The fading in the C/N_0 due to ionospheric scintillation weakened the incoming signal by forcing the receiver to declare a loss of lock. Whenever a loss of lock verified, the phase error showed to be around the edges of its domain following the re-acquisition process. The phase error reached the edges of its domain even in cases where a loss of lock was not declared, simply because the C/N_0 was not below the minimum tracking threshold (in this case 20 dB-Hz). However, the large phase errors were caused by the strongest signal fluctuations, both on the phase and on the intensity of the received signal. Those large phase errors were caused by an increased (or spectrally broader) phase dynamics as well as by an increased intensity dynamics and fading. If the signal was above the C/N_0 threshold the PLL was able to find a solution to the tracking and demodulation problem (even though the phase error was in a neighborhood of $+\pi/2$ rad or $-\pi/2$ rad). The optimum demodulated phase came with a larger error though (see phase jitter plots). The random walk the phase was subject to during the whole simulated event was not enough to declare neither cycle slips nor losses of lock. The loss of lock and consequent cycle slips due to signal re-acquisition occurred only when the signal intensity faded below the C/N_0 tracking threshold.

[29] Different C/N_0 tracking thresholds (and, consequently, different lock detector thresholds) would imply a different performance of the lock time. C/N_0 tracking thresholds higher than 20 dB-Hz would imply more losses of lock (and subsequent cycle slips), while lower thresholds would imply less losses of lock. A different response to the same scintillation-induced signal perturbations is likely for receivers utilizing different tracking thresholds (e.g., in lock detectors). This was previously shown in great details in *Groves et al.* [2000], where three receivers with different tracking conditions (i.e. bandwidths and thresholds) showed a different response to the same scintillation events. In that analysis the response seemed to be driven by the combination of the tracking bandwidth used (which defines the noise

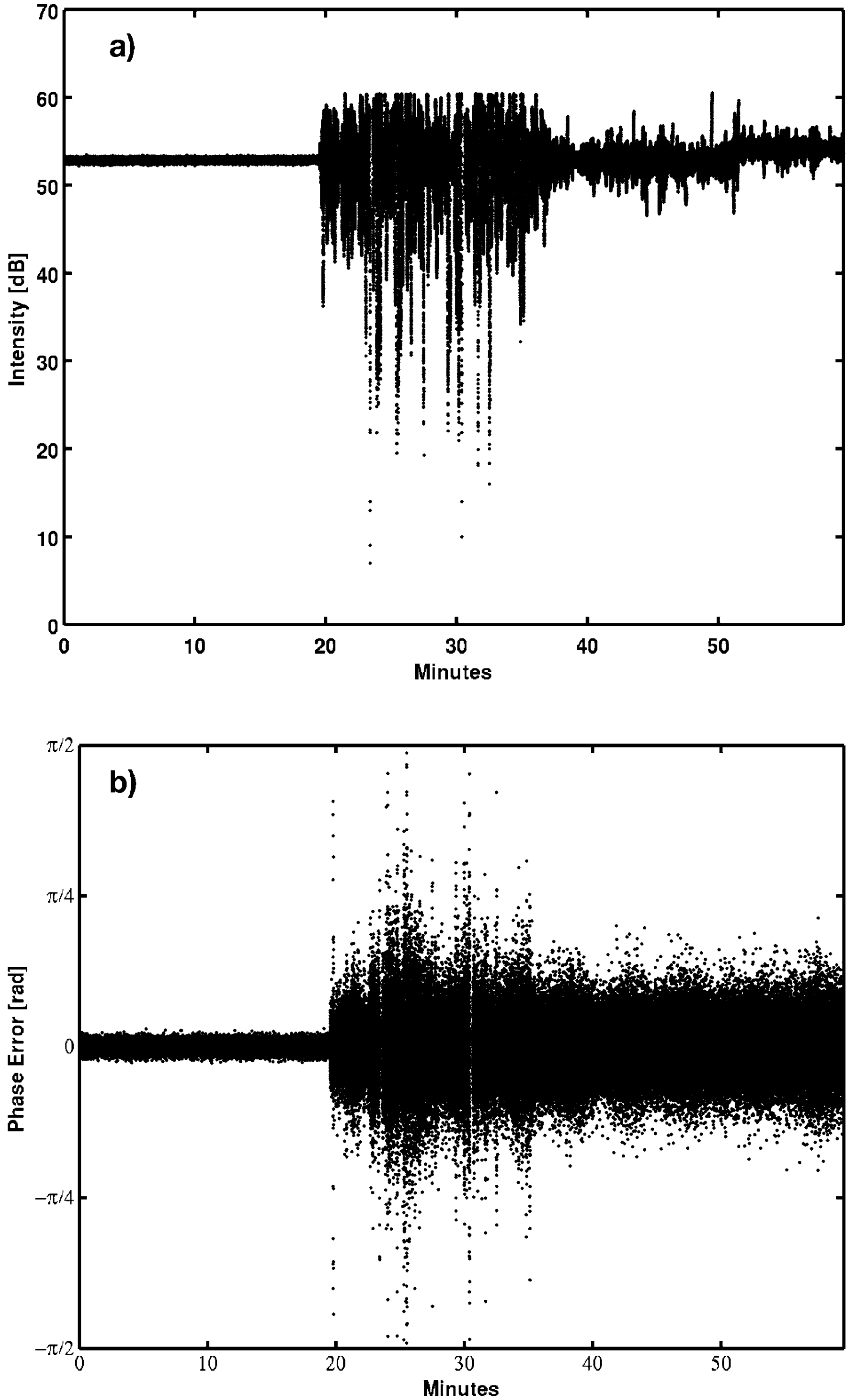


Figure 4. GPS L5 with a PLL bandwidth of 15 Hz.

variance) and the C/N_0 tracking threshold [*Groves et al.*, 2000]. The present analysis offered a view on a closer detail (i.e. the phase error) consistent with the results shown in *Groves et al.* [2000].

[30] There was neither a clear impact nor an improvement in changing the bandwidth of the tracking loop. This is evident from the comparison of Figures 2a–2e, 2f–2j, and 2k–2o, corresponding to a bandwidth of 15 Hz, 10 Hz and 20 Hz, respectively. Overall, it can be noticed as the broadening of the phase error values increased with increasing bandwidth due to the injection of higher levels of white noise within larger bandwidths (see phase error plots in Figure 2). Similarly, the phase jitter showed exactly the same behavior though with slightly higher values for increasing bandwidths in result of higher levels of white noise because of larger bandwidths. In terms of lock time

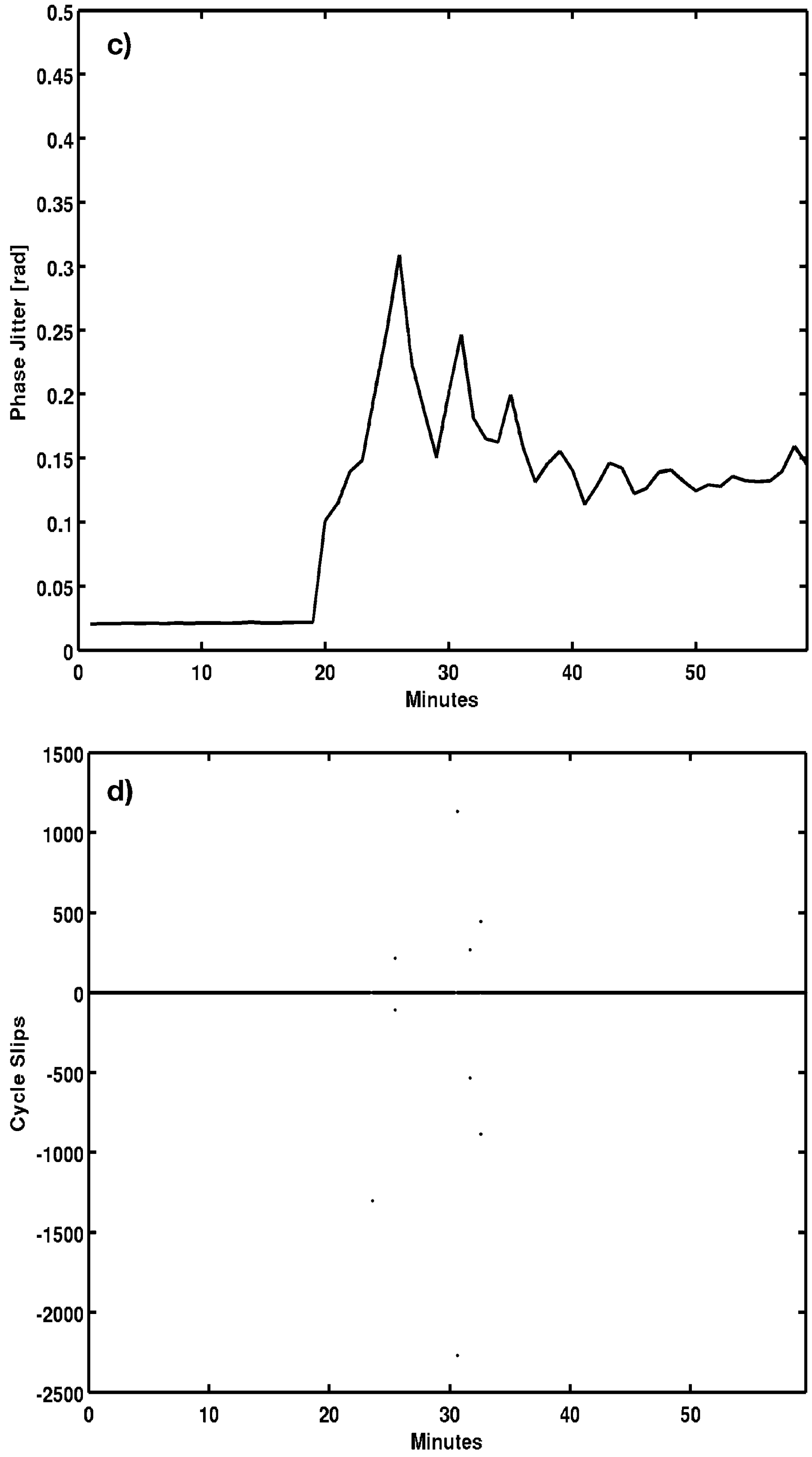


Figure 4. (continued)

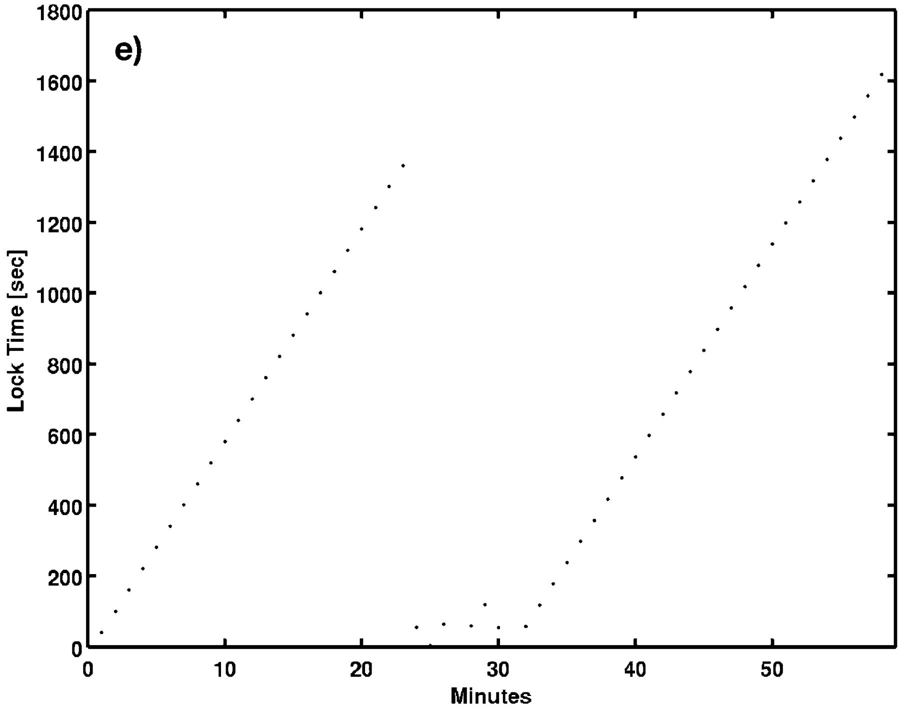


Figure 4. (continued)

and phase jitter the situation did not improve by widening the PLL bandwidth, as expected.

[31] The analysis of PLL performance in presence of scintillation-induced signal perturbations was attempted for example in *Conker et al.* [2003] and *Humphreys et al.* [2010a, 2010b] in the specific case of GPS receivers. Usually, this type of analyses are based on the statistics provided by the phase jitter, as standard deviation of the phase error which is supposed to be calculated over an ensemble. The former analysis was based on theoretical calculations based on general PLL concepts and applied to the GPS case, while the latter was characterized by a comprehensive summary of general results in the field of PLL studies applied to the specific GPS case. As an example, the analysis in *Conker et al.* [2003] predicted a mean time to lose lock for a phase jitter of ≈0.21 rad of about 1 min being this interval overall decreasing for increasing phase jitter values. This condition was not capable of describing the results obtained in the present analysis, as the loss of lock was uniquely dictated by the signal fading below the tracking threshold allowed in the receiver used, with no tracking problems for phase jitter values of ≈0.2rad (see Figures 2–5). The PLL behavior is indeed driven by the phase error, while in *Conker et al.* [2003] the phase jitter was estimated by assuming linearity of the tracking loop corrupted by zero-mean white noise only. In such a way, theoretical representations of the phase jitter are not representative of the actual behavior of a PLL and the conditions leading to cycle slips or losses of lock. On the other hand, the non-linear description in presence of fading was attempted in *Simon and Alouini* [2005] but the results effectively reduced to previous findings related to the non-linear behavior in presence of zero-mean white Gaussian noise [*Viterbi*, 1963].

[32] *Humphreys et al.* [2010a, 2010b] deduced similar predictions on the basis of an extensive scintillation data library. In their case, the mean time between cycle slips was between 5 sec and 10 sec for an average phase jitter of ≈0.26 rad, which appeared in contrast with the results shown in Figures 2–5 where cycle slips were observed only during the re-acquisition process after a loss of lock in presence of the same phase jitter value. Those losses of lock only occurred in correspondence of signal fading below the allowed C/N_0 tracking threshold. Hence, the analysis contained for example in *Humphreys et al.* [2010a, 2010b] though quite extensive was not capable of describing the cases shown in Figures 2–5. As previously found out in *Groves et al.* [2000], the performance of GPS-specific PLL seems to be indeed receiver dependent, where the usual PLL phase error is coupled with the minimum C/N_0 tracking threshold. It is this combination to drive the receiver performance in presence of scintillation-induced signal perturbations (or similar fading). Of course, the optimum choice of the C/N_0 tracking threshold depends on the accuracy needed in the estimate of the observables.

[33] The conditions driving the PLL phase error (for the specific case of GPS receivers) in presence of non-linearity due to scintillation-induced signal perturbations will need to be evaluated in terms of the combination of the minimum C/N_0 tracking threshold, lock detector thresholds, possible cycle slips in the tracking PLL and accuracy of the observables (i.e. the error propagation onto the observables stage). The analysis of a fading channel rather than simply corrupted by zero-mean white Gaussian noise would allow to further understand the mechanisms leading to cycle slips not depending on the C/N_0 tracking threshold. Overall, this would allow an advancement in the understanding of

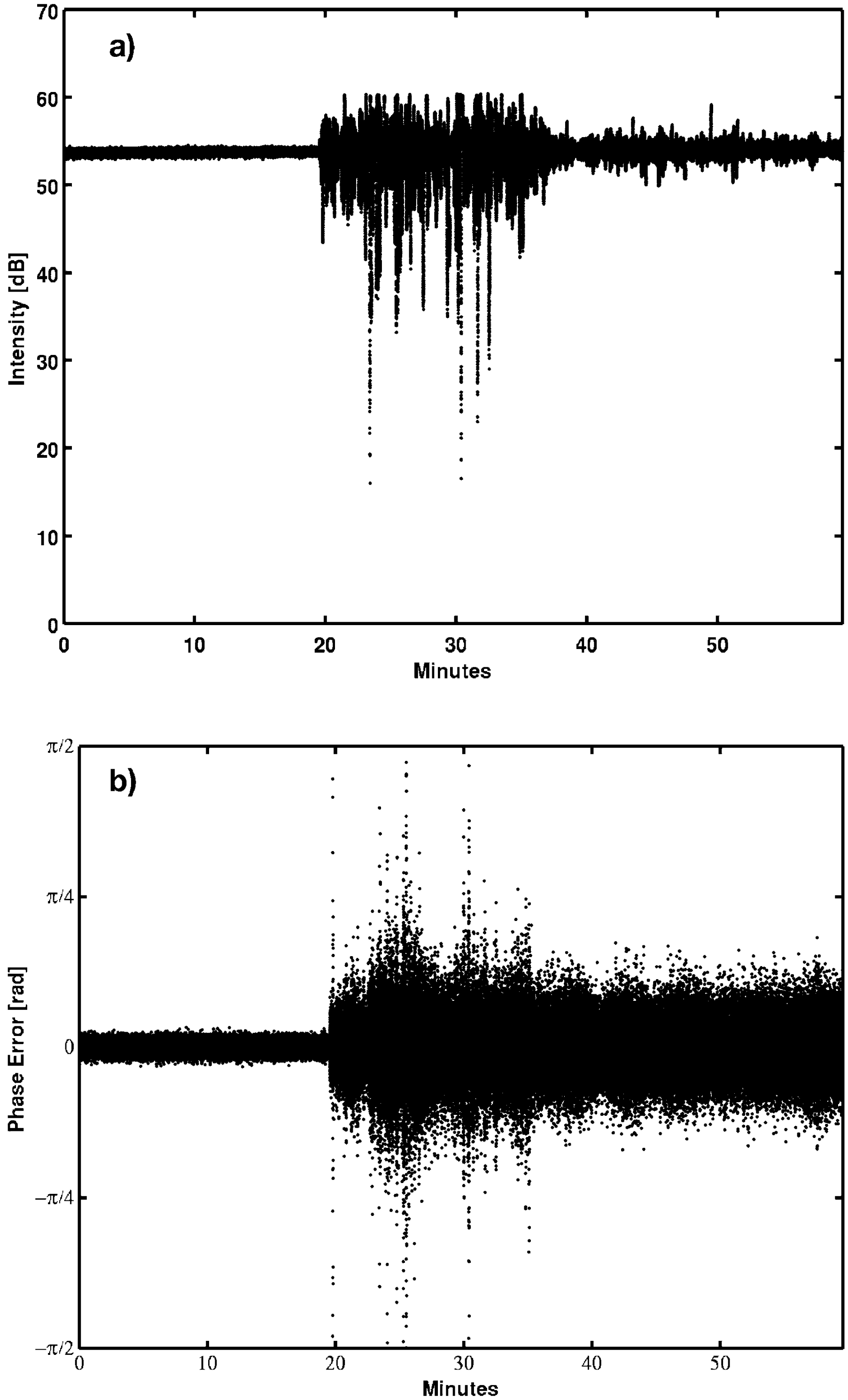


Figure 5. Galileo L1 with a PLL bandwidth of 15 Hz.

possible improvements into the robustness of GNSS receivers in presence of ionospheric scintillation. The present analysis allows to further understand experimental evidences in *Groves et al.* [2000] and *Peng et al.* [2011], for instance, while previous analyses such as those in *Conker et al.* [2003] and *Humphreys et al.* [2010a, 2010b] showed limitations in this direction (e.g., fading channel not properly modeled or receiver-dependent figures for the mean time between cycle slips).

5. Conclusion

[34] Ionospheric scintillation events were simulated by extracting fast frequency components from experimental data of interest and superposing them onto nominal signal

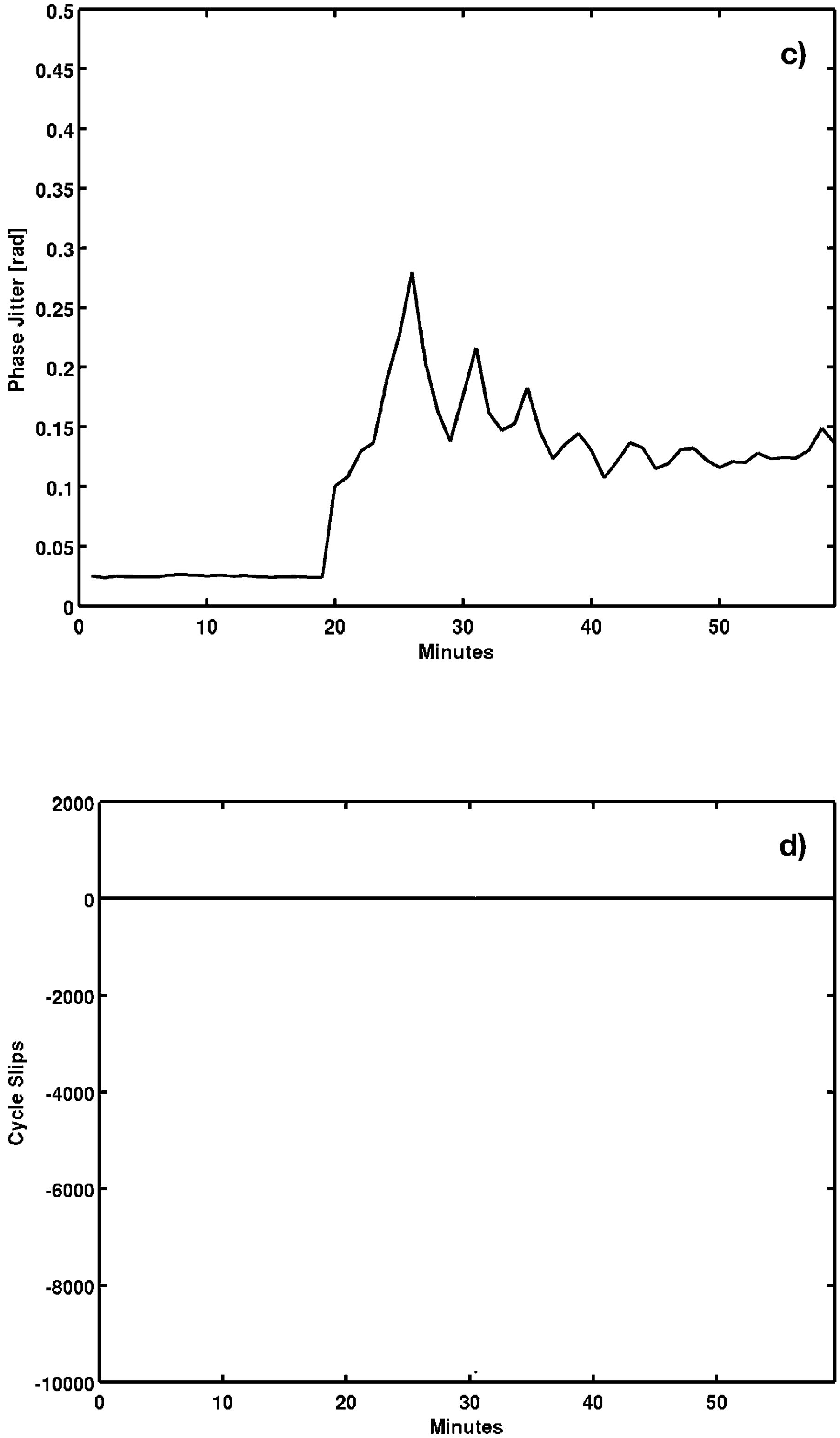


Figure 5. (continued)

generated by a GNSS signal simulator. The signals were recorded through a typical multifrequency GNSS receivers, particularly modified to output correlated I/Q signal samples. Following a loss of lock cycle slips occurred following the re-acquisition process. No improvement was made by changing the bandwidth of the tracking loop. The problem is not connected to faster phase dynamics only, but critically affected by the presence of fading which weaken the signal power to be detected. The bandwidth corresponding to scintillation induced signal fluctuations is indeed of the

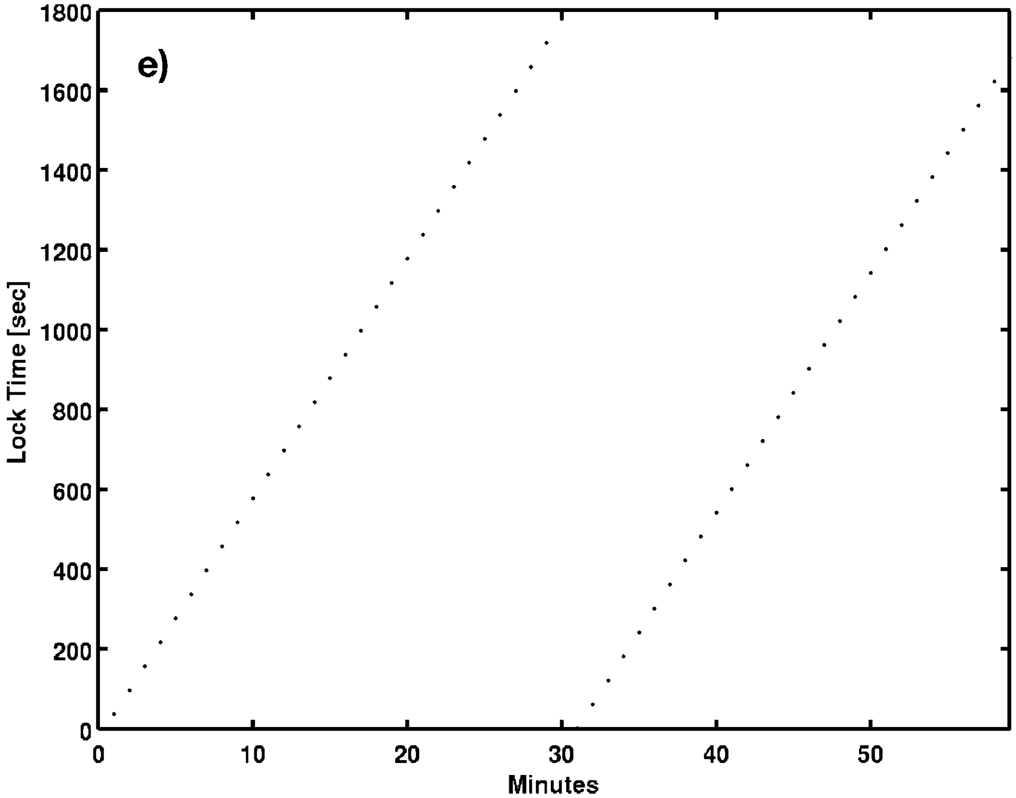


Figure 5. (continued)

order of 1 Hz in presence of weak scintillation and may occasionally extend to about ≤10 Hz in presence of strong scattering [*Humphreys et al.*, 2009; B. Forte, Analysis of strong ionospheric scintillation events measured by means of GPS signals at low latitudes during disturbed conditions, submitted to *Radio Science*, 2011]. This sort of signal dynamics is well affordable by the PLL bandwidths considered here and usually employed in GNSS receivers.

[35] The results indicated that the description of the behavior of a PLL in presence of fading due to ionospheric scintillation might possibly require a 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 and non-linearity. The performance of the PLL phase error in the specific case of GPS receivers in presence of scintillation-induced signal perturbations depends on the combination of the minimum C/N_0 tracking threshold, lock detector thresholds, and possible cycle slips in the tracking PLL. Such a combination is expected to have an impact on the accuracy of the observables (i.e. the error propagation onto the observables stage).

[36] L5 and L2C proved to be weaker than GPS or Galileo L1 owing to a lower transmission frequency. A higher transmitted power on L5 did not seem to properly balance the effect of increased scintillation-induced perturbations related to a transmission frequency lower than L1.

[37] The situation is expected to be worse when observing real data from the open sky. In real configurations, indeed, the differences would be due to the combination of ionospheric absorption, tropospheric absorption, multipath, antenna patterns, absorption in the antenna cable (varying with its length), use of splitters, different gains and thresholds within different receivers. The combination of all those factors would in principle deteriorate the C/N_0 to a larger extent than in the simple simulated cases analyzed here. The presence of larger data gaps associated with losses of lock during extreme fading conditions would become more likely.

[38] Further analyses will be carried out in order to refine the general description of PLL used in GNSS receivers in view of the evidences obtained here.

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