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Implications of Ionospheric Scintillation for GNSS Users in Northern Europe

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Extensive ionospheric scintillation and Total Electron Content (TEC) data were collected by the Institute of Engineering Surveying and Space Geodesy (IESSG) in Northern Europe during years of great impact of the solar maximum on GNSS users (2001–2003). The ionospheric TEC is responsible for range errors due to its time delay effect on transionospheric signals. Electron density irregularities in the ionosphere, occurring frequently during these years, are responsible for (phase and amplitude) fluctuations on GNSS signals, known as ionospheric scintillation. Since June 2001 four GPS Ionospheric Scintillation and TEC Monitor receivers (the NovAtel/AJ Systems GSV4004) have been deployed at stations in the UK and Norway, forming a Northern European network, covering geographic latitudes from 53° to 70° N approximately. These receivers compute and record GPS phase and amplitude scintillation parameters, as well as TEC and TEC variations. The project involved setting up the network and developing automated archiving and data analysis strategies, aiming to study the impact of scintillation on DGPS and EGNOS users, and on different GPS receiver technologies. In order to characterise scintillation and TEC variations over Northern Europe, as well as investigate correlation with geomagnetic activity, long-term statistical analyses were also produced. This paper summarises our findings, providing an overview of the potential implications of ionospheric scintillation for the GNSS user in Northern Europe.

KEY WORDS

1. GNSS. 2. Ionosphere. 3. Scintillation. 4. TEC.

1. INTRODUCTION. Signals from Global Navigation Satellite Systems (GNSS), such as GPS and the proposed European system Galileo, pass through the ionosphere before reaching users on the Earth. Activity in the Sun has a direct influence on the Earth's atmosphere and during the peak of the 11 years solar cycle causes increased levels of variability in the Total Electron Content (TEC) of the ionosphere. This can disturb the signals, in an effect known as ionospheric scintillation, and is most likely to occur in equatorial and auroral regions. It can affect

GNSS receivers in a number of ways, from degradation of accuracy (through range errors) to the loss of signal tracking. Required levels of accuracy and availability may not be met during the occurrence of scintillation, compromising positioning and navigation in general, and in particular safety critical applications, such as the precision approach phase of flight (civil aviation). Scintillation occurrence and its effects have received special attention worldwide, however it is generally recognised that further research is required.

When studying the morphology of GPS phase fluctuations at high latitudes, Aarons (1997) noted that phase fluctuation activity has a daily pattern mainly controlled by the motion of the receiver location into the auroral oval. The auroral oval is the region where *aurora borealis* or *northern lights* are observed. Scintillation is expected to occur when the signal path intercepts the auroral oval. Movement of high-density plasma from the sub-auroral region on day-side into the polar cap is the mechanism proposed by many authors (e.g. Fukui et al, 1994, Rodger et al, 1994, Valladares et al, 1994) to explain ionospheric irregularity development. The auroral oval expands equatorward with increasing magnetic activity. During magnetic quiet periods, scintillation occurs when the signal intercepts the auroral oval, which has the largest latitudinal extension at magnetic midnight. During long quiet periods the auroral oval contracts to very high latitudes and phase fluctuation activity decreases.

The IESSG study started late in 2000. It was a comprehensive exercise involving the collection of long term GPS ionospheric scintillation and TEC data and analyses of effects on GPS users, carried out during the solar maximum. Amongst the results, an analysis of the occurrence of high levels of scintillation on a day of enhanced geomagnetic activity showed that for nearly 2% of the time, two satellites may be affected simultaneously (Rodrigues et al, 2003). If this enhanced activity leads to receiver loss of lock on these satellites an immediate impact to users is geometric degradation. Crucially, however, when only 4 or 5 satellites are in view, the loss of two satellites ultimately represents a 50% loss of availability. Considering that this can be aggravated by receiver dynamics, this is the scenario most likely to pose a serious problem for the user community in Northern Europe; especially those involved in safety-critical applications. Furthermore, Space Based Augmentation Systems (SBAS) reference stations may be adversely affected. These stations track the GPS satellites using dual frequency receivers with the aim of computing and disseminating ionospheric delay corrections. This service may be seriously compromised when data from either or both of the GPS signals (L1 or L2), are not available due to satellite loss of lock, as both are necessary to compute the ionospheric delay. This is the case of the European Geostationary Navigation Overlay Service (EGNOS), which must provide coverage to Northern Europe.

2. SCINTILLATION AND SATELLITE LOSS OF LOCK.

In the case of GPS receivers, strong amplitude scintillation may cause the received signal to drop below a threshold that may lead to loss of lock. Strong phase scintillation may cause the frequency Doppler shift in the signal carrier to exceed the receiver's Phase-Lock-Loop (PLL) bandwidth and loss of phase lock may be observed. A measure of the intensity of amplitude and phase scintillation may be given by the widely used S4 and σ_φ indices, which the IESSG network has been continuously recording. The S4 index is the standard deviation of the received signal power normalized to the average signal power and the phase scintillation index (σ_{φ}, also referred to as sigma-phi) is estimated from measurements of phase variance, in the case of our receivers at every 1, 3, 10, 30 and 60-seconds interval, based on 50-Hz sampling rate measurements of L1 carrier phase. Both phase and amplitude scintillation contribute to the RMS phase tracking error in the output of the PLL. It is when this RMS error exceeds a threshold that loss of lock may occur (Conker et al, 2003, Knight and Finn, 1998).

Scintillation occurrence at high latitudes seems to be mostly correlated with geomagnetic activity. Klobuchar (2002) suggests that amplitude scintillation on the L1 GPS frequency does not seem to be a significant concern for auroral regions. Indeed if the levels of scintillation suggested by Hegarty et al, (2001) are used as reference, moderate to strong amplitude scintillation would occur only when the S4 index on the L1 reaches about 0·6 (moderate) and 0·9 (strong). Statistics drawn from our data (Rodrigues et al, 2003), considering every day of 2002, reveal that occurrence of levels of S4 over 0·5 rarely exceeded 1% of the time on any particular day at Hammerfest (70° N geographic latitude), our Northern most (most auroral) station. Phase scintillation however poses a greater concern. Our statistics for 2002 reveal levels of phase scintillation significantly higher than amplitude scintillation, with moderate to strong values on Hegarty's scale (0·3 for moderate and 0·6 for strong) occurring during more than 5% of the time on many days.

The jitter introduced by phase scintillations affects the carrier tracking loop more significantly than the code tracking loop due to the much shorter wavelength of the carrier. In addition the narrower bandwidth of the code loop improves its immunity to amplitude scintillations (Knight et al, 1997). However, as carrier aiding of the code loop is present in every GPS receiver (Knight et al, 1997) one may also assume that loss of carrier lock is shortly followed by loss of code lock (Knight and Finn, 1998). GNSS users in auroral regions should therefore be more concerned with phase scintillation or a combination of phase and amplitude scintillations, and in particular during geomagnetic storms.

Skone et al, (2001) found that strong scintillations can degrade receiver tracking performance at both equatorial and high latitude regions, with greater impact on the L2 signal. Techniques used to track the L2 carrier normally lead to a reduction in the signal to noise ratio. Also, both amplitude and phase scintillations affect more adversely the L2 frequency due to inverse frequency scaling of scintillations (Rino, 1979). Knight and Finn (1998) showed that a wider bandwidth PLL increases the tolerance to phase scintillation and decreases the tolerance to amplitude scintillation, meaning that the GPS L2 frequency may suffer more effects from phase scintillations than L1.

In our study we confirmed many of these results, as reported in Moore et al (2002a and 2002b) and Rodrigues et al (2003). Figure 1(a) shows a typical example of loss of lock correlated with increase in scintillation levels at our monitoring station in Bronnoysund (geographic latitude 65° N). Although these scintillation monitors were specially developed for continuous operation during strong scintillation conditions, other cases such as that of Figure 1(a) were found in our study, indicating the potential impact in the tracking performance of conventional GPS receivers. Further to this, on a number of occasions loss of lock was observed only on the L2 signal, as shown in Figure 1(b).

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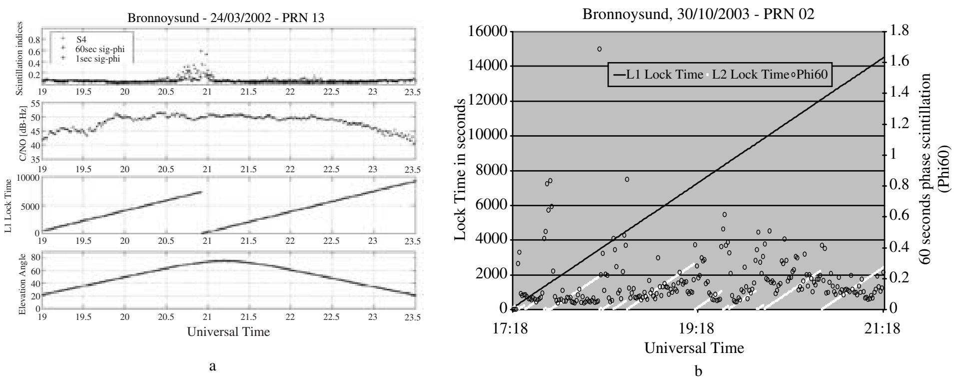

Figure 1. (a) Loss of satellite lock on L1 (break in the L1 lock-time, third plot from top) associated with scintillation occurrence, PRN 13; (b) Loss of satellite lock on L2 (breaks on the white line), associated with scintillation occurrence (Phi60, or 60 seconds σ_φ), PRN 02.

In the situation of Figure 1(b), although a user relying solely on the L1 C/A code for positioning would not be affected, the computation of the ionospheric delay by a L1/L2 user would be severely disrupted. Also affected would be a SBAS reference station, committed to continuously contribute dual frequency data to the computation of ionospheric corrections for dissemination to users. Although figure 1(a) shows that not very high values of Phi60 align with loss of lock on L1, in figure 1(b), despite the Phi60 index reaching higher values, L1 lock time (dark line) does not present a break (the very high outlier value of 1·7 in Figure 1(b) however might have been caused by phase variance miscomputation by the receiver firmware, which occasionally occurs). One must consider that receiver tracking loops are designed to minimise the error between the input phase and the estimated phase at the output of the PLL, which feeds the receiver processor, and that the receiver performance is in all likelihood associated with the magnitude of this error. The scintillation indices are average values measured at the input of the receiver PLL and alone do not provide sufficient information regarding the actual instantaneous values of phase and amplitude fluctuations that will affect the receiver performance, and therefore can only give an indication of forthcoming problems. Receiver tracking models (such as those of Conker et al, 2003) must therefore be considered in conjunction with these indices to accurately account for the influence of scintillation on the output error of the PLL.

To illustrate the performance of conventional GPS receivers under scintillation conditions we show in Figure 2 the time series of the percentage of data loss on the L2 for two common receiver types commercially available. That was during the period from 4th to 8th of November of 2001, when significant ionospheric disturbances were observed at magnetic latitudes as low as 50° N in the European longitude sector. The Ashtech ZXII semi-codeless and the Trimble 4000 SSI codeless receivers of Figure 2 are permanently installed respectively at Lerwick (LERW) and Sumburgh Head (SUMB), both in Northern UK, with similar geographic latitudes (about 60° N), in the transitional region between mid and high latitudes. At the peak in the figure, at the early hours of 6 November, the codeless receiver presents up to 50% of L2 data loss. It is known that the L2 tracking on codeless receivers is more susceptible

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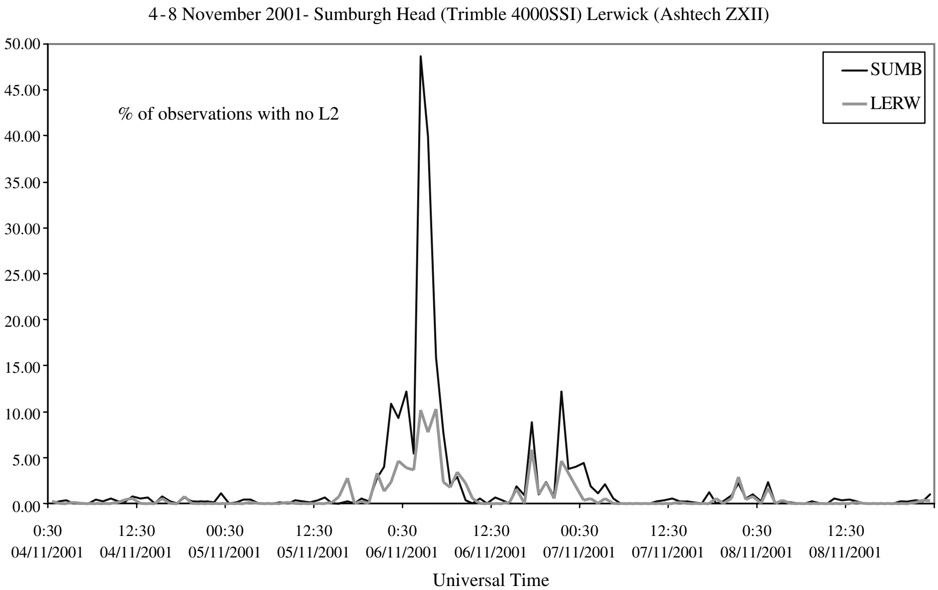


Figure 2. L2 data loss for codeless (Trimble 4000SSI) and semicodeless (Ashtech ZXII) receivers at similar latitudes during high geomagnetic activity.

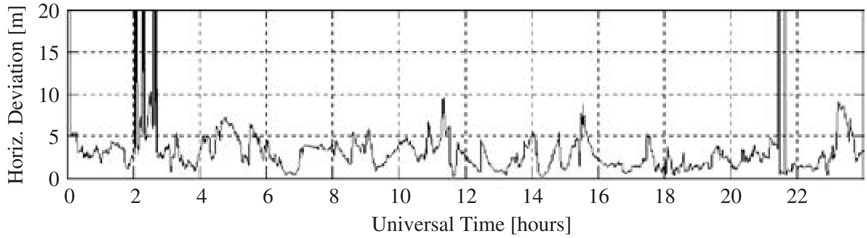
to degradation than on their semicodeless counterparts, our results confirming the findings of previous studies (e.g. Skone et al, 2001).

Analyses aiming to investigate further these two receivers' performances were conducted by screening their respective RINEX files for the occurrence of missing L1 or L2 phase data. Results revealed that during the peak of the storm on the 6 November, L1 or L2 data from up to 7 satellites was not present on some occasions, with the codeless receiver being more severely affected. The semicodeless receiver presented only one instance when phase data from 7 satellites was missing, although on some other occasions phase data from up to 4 satellites had been lost. However, analyses performed on other ionospherically disturbed days presented lower degrees of impact on GPS phase and code tracking.

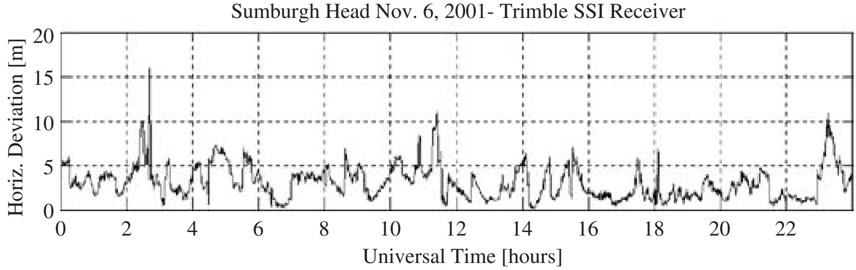
Finally, dynamic conditions, which are not included in the examples discussed herein, may also contribute to the receiver's loss of lock. Furthermore, Kintner et al. (2001) have pointed out that when the velocity of the ionospheric pierce point of a moving receiver and the velocity of the scintillation pattern match, the probability of loss of lock increases because the tracking loop cannot track through the long time scales. The ionospheric pierce point is the point where the path satellite/receiver penetrates a *screen* situated about 350 km above the Earth's surface. For most modelling purposes it is assumed that all free electrons in the ionosphere are concentrated within that screen of infinitesimal thickness. This case of a moving GPS receiver applies for example to receivers used in civil aviation, a critical application and a driver of scintillation research.

3. GNSS USER ACCURACY DEGRADATION.

3.1. *C/A code stand-alone positioning*. Rodrigues et al (2003) indicate that GPS phase based applications in Northern Europe would suffer more effects from



a



b

Figure 3. Horizontal positioning errors from C/A code stand-alone solution: (a) at Lerwick (Ashtech ZXII receiver) and (b) at Sumburgh Head (Trimble 4000SSI receiver).

ionospheric scintillation than code-based applications. In that paper examples were given where no significant accuracy degradation in C/A code positioning convincingly correlated with enhancement on scintillation levels could be observed. Figure 3 represents the time series of horizontal errors from a stand-alone C/A code solution for the same two receivers of the previous section, located at Lerwick (a) and Sumburgh Head (b), respectively. No ionospheric correction was applied. These time series refer to the rather severe geomagnetic storm of 6 November 2001 and show that the errors compare without significant difference for the two receivers, except for the spikes in Figure 3(a) for the Ashtech receiver. These spikes relate to epochs when the receiver lost lock on certain satellites and abnormal pseudorange values were written in the RINEX file, leading to large positioning errors. It is also noticeable, by comparison with Figure 4(a), that these occurrences correlate in time with an enhancement in phase scintillation levels given by the Phi60 index.

Figure 4(a) shows the scintillation indices for all satellites in view at our Nottingham monitor on the same day when, due to the severity of the ionospheric disturbance, high phase scintillation values were observed even at mid-latitudes. It is also interesting that the S4 index does not show significant increase throughout the day. These results confirm that: amplitude scintillation seems to be of less concern than phase scintillation; code based positioning is not notably affected by scintillation and that loss of lock does seem to be the main concern. Figure 4(b), however, presents an example of analysis of degradation in stand-alone C/A code positioning accuracy occurring during a period of time when high values of phase scintillation were observed, 14:00 to 24:00 UT, on 30 October 2003. On that day the 3-hourly K planetary geomagnetic activity index, Kp, reached 9 during the time

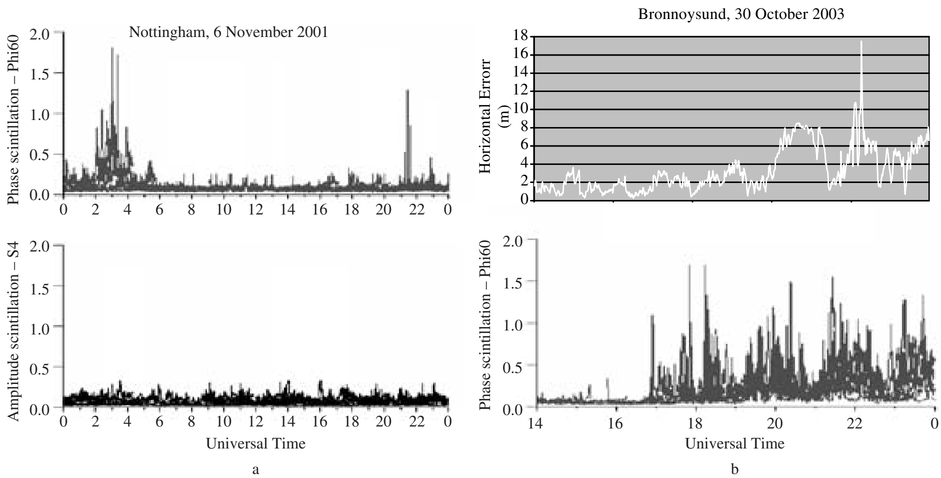


Figure 4. (a) Phi60 and S4 indices measured by GSV4004 receiver at Nottingham, 6 November 2001; (b) Horizontal positioning errors from C/A code stand-alone solution and Phi60 values measured at Bronnoysund, 30 October 2003, both with GSV4004 receiver.

sectors 18:00/21:00 and 21:00/24:00 UT (the Kp value of 9 indicates extremely high geomagnetic activity). Our scintillation monitors are dual frequency receivers that can also record GPS code and carrier phase data, so that corresponding RINEX files can be obtained. The top plot in Figure 4(b) represents the time series of horizontal errors at our monitoring station Bronnoysund, from an epoch-wise point positioning solution from the corresponding RINEX file and using C/A code pseudoranges alone, again with no ionospheric correction model applied. The errors in the plot have been 'normalised' – the actual horizontal error has been divided by the HDOP (Horizontal Dilution of Precision) of each epoch – so that the effect of the satellite geometry is neutralised, allowing a meaningful comparison between epochs. The bottom plot shows the Phi60 index recorded for all satellites in view by the same receiver. The S4 index time series for the same period of time did not show any appreciable increase and is not presented herein.

A first glance at Figure 4(b) suggests that position degradation occurs concurrently with an overall increase in phase scintillation levels (no correlation could be seen with the values of S4). However, an attempt to mitigate the effects by using the actual Phi60 values of individual satellites to de-weight the range observations proved ineffective. Indeed, when comparing the values of the Phi60 index (average of all satellites in view) with the corresponding epoch-wise position errors (i.e. at every 60 seconds), no significant mathematical correlation was found (correlation coefficient of 0·46). As the average Phi60 value for all satellites in view might not accurately represent the scintillation conditions at every individual epoch (only a few satellites might have been affected by strong scintillation due to localised irregularities) we also investigated correlation of the maximum Phi60 value for every epoch with the positioning errors. This however resulted in an even weaker correlation, with a coefficient of 0·32.

As no ionospheric correction model was used, the conclusion is that the observed accuracy degradation is rather due to enhancement in the background TEC observed during that time, which is not accounted for in the solution. This enhancement is

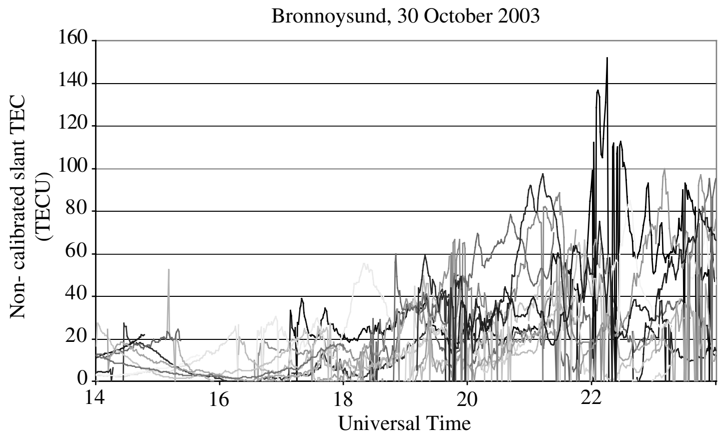
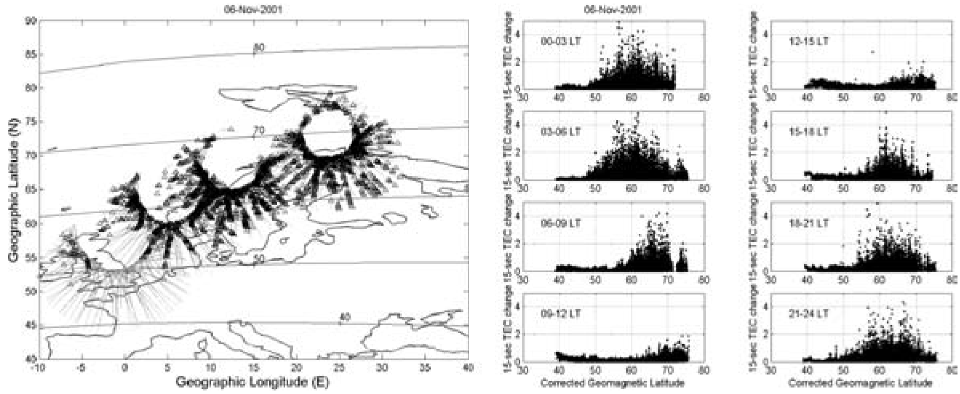


Figure 5. Non-calibrated slant TEC values measured by GSV4004 receiver at Bronnoysund.

confirmed in Figure 5, the time series of (non-calibrated) slant TEC values for all satellites in view measured at Bronnoysund. It is also worth noting that in a situation of TEC enhancement such as this the application by the user of empirical ionospheric models would most probably be ineffective. For instance, the ionospheric model broadcast within the GPS navigation message (the Klobuchar model) would not improve positioning accuracy, as it models the local night-time ionosphere by a constant value which would not account for these sudden and localised effects.

3.2. *Differential GPS*. Differential GPS (DGPS) relies on the spatial correlation between reference and user stations, implying that the error induced by the ionosphere sensed at the reference station is the same as at the user location. During geomagnetic storm events, however, fast TEC changes and ionospheric gradients are frequently observed, which may lead to the spatial decorrelation of the ionospheric error and therefore to consequential effects on DGPS positioning.

Figure 6(a) shows a map of Northern Europe on which ionospheric pierce points at an ionospheric height of 350 km for the four IESSG scintillation monitors are plotted. Triangles indicate where 15-sec TEC changes larger than 1 TECU were observed. The plots in Figure 6 refer to a worst case scenario (the storm of 6 November 2001). Under those circumstances significant TEC changes were observed at latitudes as low as Nottingham's (approximately 53° N geographic). Figure 6(b) shows the values of TEC changes plotted against magnetic latitude. The representation in 3-hour (local) time sectors highlights the expansion of the disturbed ionosphere during evening and night-time hours and its contraction during daytime. This is a good example of the extension of the ionospheric disturbances during high geomagnetic activity. TEC changes larger than 1 TECU were observed at geomagnetic latitudes as low as 50° N, which might be regarded as the southern boundary of the transitional region between the disturbed auroral region and the quiet mid latitude region. We also verified in our study that during days of moderate to high activity fast TEC changes can be observed at geomagnetic latitudes as low as 55° N and, more importantly from the DGPS user point of view, TEC gradients may also be fairly visible.



a b

Figure 6. 15-sec TEC changes measured by the IESSG network for the severe magnetic storm of 6 November 2001 (Kp values = 9−9−7 5 5+7−6+6+). In (a), △ indicates TEC changes larger than 1 TECU. In (b) TEC changes are plotted against magnetic latitude.

In Moore et al (2002b) implications arising from the above issues are discussed and the effect of north-south horizontal ionospheric gradients on DGPS positioning accuracy is investigated. When comparing the 2 drms errors from an (approximately) north-south oriented baseline with those from an (approximately) east-west oriented baseline in the UK, during the disturbed period between 4–8 of November 2001, a degradation of about 30% in the horizontal positioning accuracy was observed, demonstrating the potential effect of spatial decorrelation due to TEC gradients under extremely adverse ionospheric conditions. The 2 drms for the whole period (5 days) was 3·50 m for the north-south baseline and 2·66 m for the east-west counterpart. These errors are well below specified DGPS errors, normally about 10 m 2 drms. The north-south baseline in that example is about 359 km in length, between permanent stations Flamborough and Girdleness (central to northern UK latitudes), so that effects for DGPS users in shorter baselines, and in particular under less demanding ionospheric conditions, should be only marginal. This was also verified in our study.

3.3. *Carrier phase positioning*. Carrier phase data from the 30 October 2003 was analysed aiming to investigate possible accuracy degradation on carrier phase positioning potentially related to ionospheric scintillation. On that day significant enhancement in Phi60 (phase scintillation) values was observed even at our mid-latitude station in Nottingham (Figure 7a). The increased levels began quite markedly during the night time hours, with values changing from low during the day to moderate and high.

In order to assess whether this sudden enhancement in scintillation conditions could lead to any effect on carrier phase based positioning, the 24 hours RINEX file of our scintillation monitor was split in 2 hours sessions for processing. Processing was carried out using IGS (International GPS Service) precise orbits and three IGS permanent stations with data available in the region. A network was formed with the four stations and we then solved for the coordinates of our scintillation monitor. The observable was the ionosphere corrected L1 double difference carrier phase. Our analyses were conducted, respectively for each of the 2 hours sessions. In Figure 7(b)

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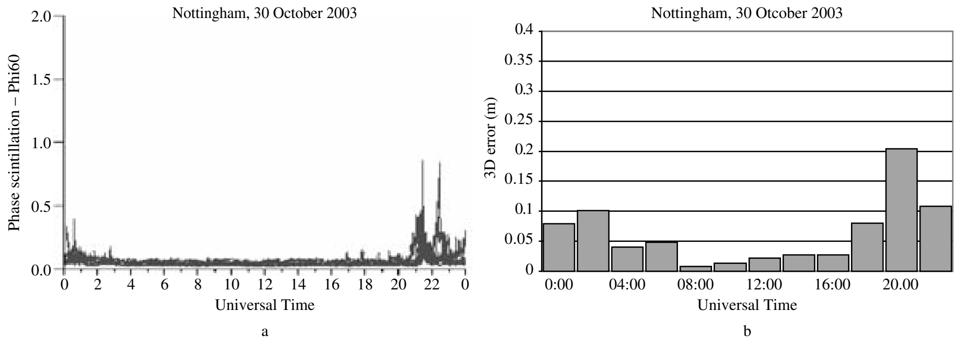

Figure 7. GSV4004 receiver at Nottingham, 30 October 2003: (a) measured Phi60 for all satellites in view and (b) 3D errors for 2-frequency carrier phase data processing of 2 hours sessions.

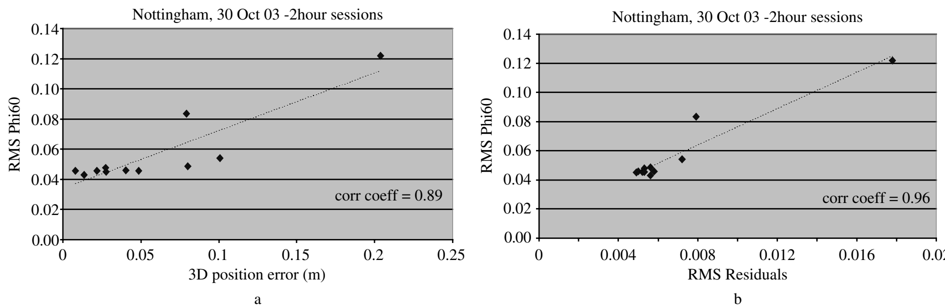

Figure 8. GSV4004 receiver at Nottingham: (a) correlation between RMS Phi60 values and 3D position error for every 2 hours session and (b) correlation between RMS Phi60 values and RMS residuals for every 2 hours session.

we show the 3D errors obtained for each processing session. The network formed for the processing was consistently repeated throughout all sessions. Resulting coordinates were compared with accurate ground truth coordinates. Temporal correlation with phase scintillation values recorded on the same day by the monitor may be visualised when comparing Figures 7(a) and 7(b).

For a more realistic and accurate evaluation of the influence of the observed phase scintillations on the accuracy of the coordinates, the RMS of the Phi60 values of all satellites in view for every 2 hours session was computed. The plot in Figure 8(a) shows the correlation between these RMS values and the 3D errors for each session. This comparison results in a correlation coefficient of 0·89, demonstrating the influence of phase scintillation on our monitor's performance. A computed trend line was added to the plot for visualisation of the correlation. Clearly, as scintillation levels were high over most of Northern Europe during that time, it is not possible to infer how much degradation due to phase scintillation sensed at the IGS stations involved in the solution is present in the computed 3D error. These results can only suggest that when higher values of phase scintillation were observed in Nottingham higher degradation in the coordinates computed with carrier phase data from the scintillation monitor was observed. In Figure 8(b) we confirm the correlation of phase scintillation with measurement noise at Nottingham. We compared the RMS of the

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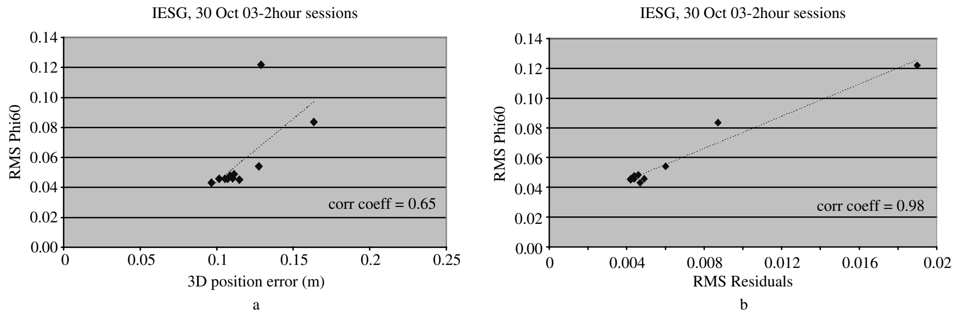

Figure 9. Ashtech ZXII receiver at Nottingham: (a) correlation between RMS Phi60 values and 3D position error for every 2 hours session and (b) correlation between RMS Phi60 values and RMS residuals for every 2 hours session.

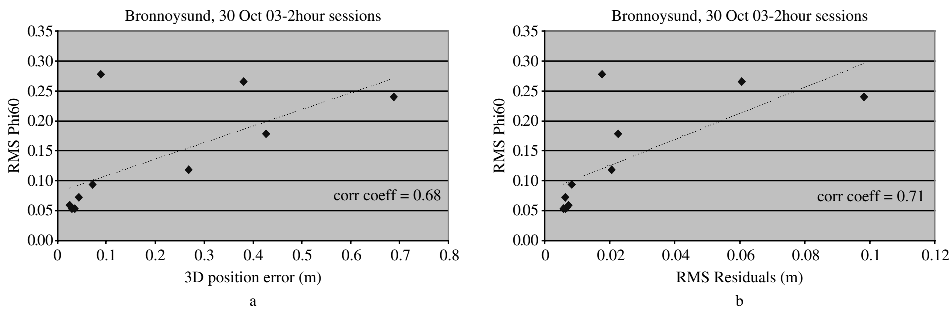

Figure 10. GSV4004 receiver at Bronnoysund: (a) correlation plot between RMS Phi60 values and 3D position error for every 2 hours session and (b) correlation plot between RMS Phi60 values and RMS residuals for every 2 hours session.

Phi60 values with the RMS of the residuals for each 2 hours session solution. A coefficient of 0·96 confirmed the strong correlation.

An additional analysis was conducted involving data from a permanent Ashtech ZXII semicodeless GPS receiver (station IESG), whose antenna is located just a few meters from our scintillation monitor's at the IESSG, with accurately known coordinates. A similar processing strategy was adopted using the 24 hours RINEX file and the corresponding 2 hours sessions. Figures 9(a) and 9(b) show the results, which are respectively analogous to those of Figures 8(a) and 8(b). Comparing Figures 8(a) and 9(a) it can be seen that the scintillation monitor overall provided better positioning accuracy than the Ashtech semicodeless receiver, especially when scintillation levels were low. However when scintillation was at its peak on that day, the latter seemed to have been less affected, this being also seen by the correlation coefficient of Figure 9(a). Influence of scintillation on the RMS residuals does not show any appreciable difference between the two receivers.

Finally we analysed the performance of our monitor in Bronnoysund in a similar fashion, during the same day, i.e. 30 October 2003. Results are shown in Figures 10(a) and 10(b). Correlation between phase scintillation and performance despite not being as high as for the analyses at Nottingham, is still visible and, as the levels of the RMS Phi60 are markedly higher at that station, significantly more degradation in positioning accuracy and higher residual errors are observed. This can be seen by inspecting the scale of the plots (Figures 10a and 10b), in comparison with those of the analyses for the Nottingham scintillation monitor (Figures 8a and 8b). These findings require further investigations, but are nevertheless encouraging and give scope for the potential development of warning/mitigation mechanisms that could be based on phase scintillation indices.

4. EFFECTS ON SBAS. The aim of SBAS systems, such as EGNOS and the American WAAS (Wide Area Augmentation System), is to complement GPS (and GLONASS in the case of EGNOS) with accuracy, integrity and availability, providing navigation services suitable for safety critical applications. The Wide Area Differential (WAD) approach used in EGNOS treats each of the error components individually in order to overcome the issue of spatial decorrelation affecting the conventional DGPS technique. EGNOS WAD corrections include ionospheric grid delays (based on L1/L2 data collected at their reference stations) which the user can interpolate to compute the delay at the ionospheric pierce point of each individual satellite being tracked. In section 2 we discuss the implications of ionospheric scintillation on satellite loss of lock and in section 3.2 we refer to Moore et al (2002b) to address the implications of TEC gradients for the DGPS users in Northern Europe. Further in that paper the performance of the EGNOS ionospheric correction model during the same worst case scenario is investigated. In figure 11 we show the potential impact on user accuracy originating on problems that in all likelihood relate to strong scintillation affecting receiver tracking performance at the EGNOS reference stations.

Figure 11 shows the time series of horizontal positional errors for a 359 km DGPS baseline between permanent stations Flamborough and Girdleness in the UK, with the latter emulating a mobile user, during the storm of 6 November 2001. Position is calculated from L1 C/A code pseudoranges alone. In the top plot all satellites in view (including those without EGNOS ionospheric corrections available) at both stations were used in the solution and the EGNOS ionospheric delay corrections applied to those with corrections available. In the bottom plot only satellites with EGNOS corrections available were used. The peak at about 3:30 am in the bottom plot relates to the fact that during that particular period of time only 4 out of the 7 satellites in view had corrections available, leaving 3 satellites used in the first solution out. Apparently the larger errors arise from an unreliable least squares adjustment, based on only 4 satellites. In this situation there is no redundancy in the solution (zero degrees of freedom), leaving the estimated coordinates unchecked. By inspecting the EGNOS ionospheric grid corresponding to these epochs, it was confirmed that corrections were not provided for IGPs (Ionospheric Grid Points) to the northwest of the stations, affecting the pierce points of 3 satellites. We suggest that the missing corrections possibly relate to the inability of the EGNOS reference stations to track one or both of the GPS signals of some satellites during that particular period of time due to strong scintillation, rendering the computation of the ionospheric delays impractical. More importantly, although at mid-latitude, a user at station Girdleness (57° N geographic latitude) opting to avoid satellites not monitored by the EGNOS ionospheric grid is shown to indirectly suffer the effects of strong scintillation due to ionospheric irregularities occurring further northwards. It seems that in practice users

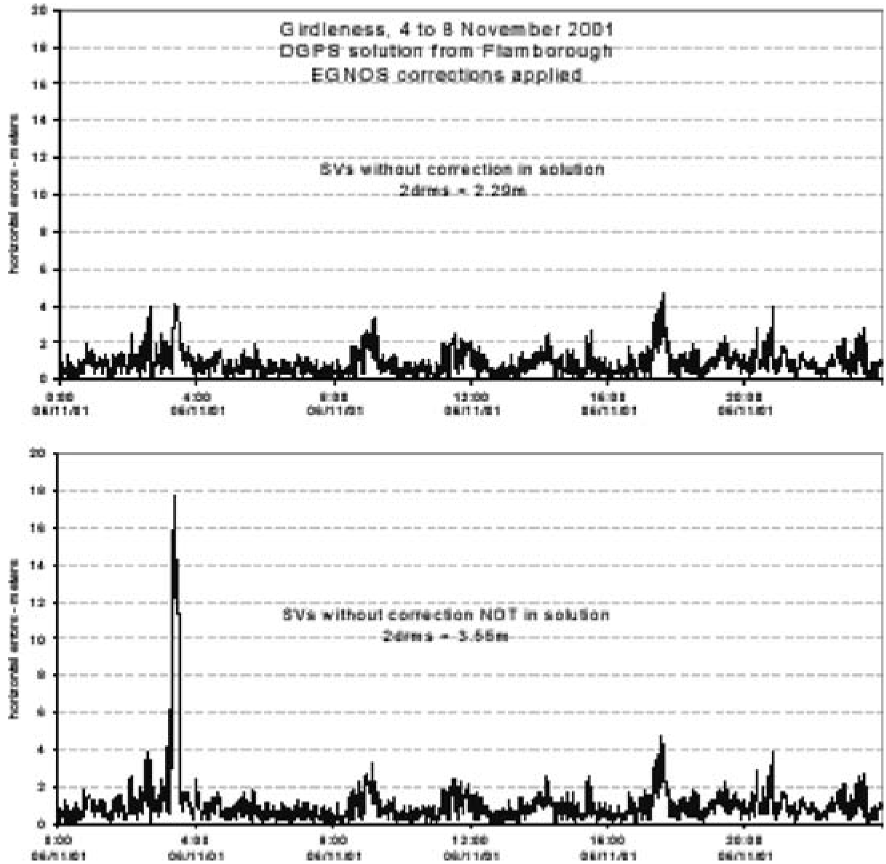

Figure 11. Potential impact of strong scintillation on EGNOS reference stations.

will not have a choice to include extra (non-monitored) satellites, as EGNOS enabled GPS receivers are expected to automatically only use satellites covered by the grid.

The main conclusion from this example is that by avoiding the use of IGPs not monitored by EGNOS, rather than protecting against accuracy degradation, the user might potentially result in obtaining even more degraded coordinates. In our study we confirmed this effect by analysing data on different days when activity in the ionosphere was significant. An example is the 30 October 2003, when we processed a DGPS baseline formed by our scintillation monitor in Bronnoysund as mobile and EUREF station Trondheim (TRDS), approximately 250 km to the south-west, as reference. In Figure 12 we show the results of the DGPS solution for the critical period between 18:00 and 24:00 UT, with the application of the EGNOS correction model and using only satellites monitored by the grid. Also shown is the number of satellites with EGNOS correction available at each epoch. The (phase) scintillation conditions at Bronnoysund can be seen from Figure 4(b).

The dashed horizontal line in figure 12 indicates the threshold of 4 satellites with corrections available, in which case the least squares solution is considered unreliable. It can be seen that in some instances during that short period of time there were less than 4 satellites with corrections available and a solution was not even possible. In a

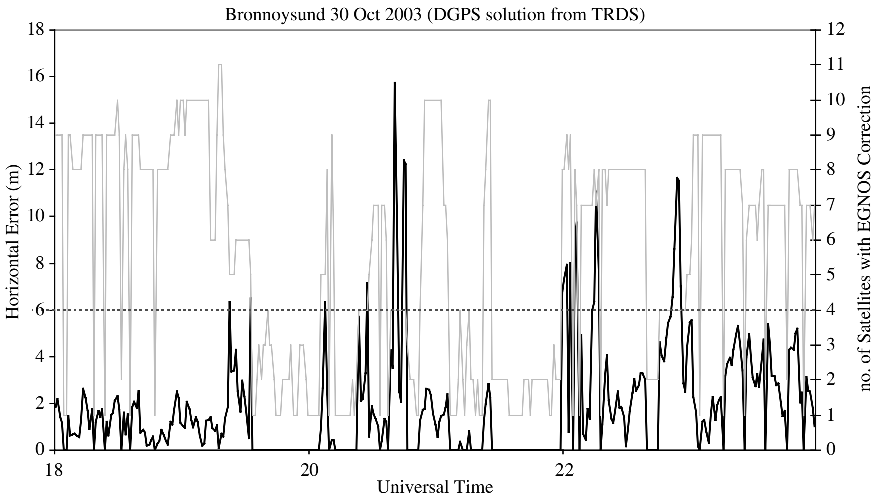

Figure 12. Availability of EGNOS corrections and C/A code stand-alone horizontal errors at Bronnoysund, on 30 October 2003. The dark line shows horizontal errors (left vertical axis) and the light line shows the number of satellites with EGNOS corrections available (right vertical axis).

few other occasions only 4 satellites had corrections available and an effect similar to that seen in figure 11 was observed. Figure 12 confirms the potential problems, arising from ionospheric scintillation, that the EGNOS user may be faced with in Northern Europe in years of high solar flux.

5. CONCLUSIONS.

Ionospheric scintillation occurring in equatorial and auroral regions can affect GNSS users, with effects from accuracy degradation to loss of signal tracking. The need for further research in this field is widely recognised. This paper presents an overview of the work undertaken at the IESSG in this area during the past three years, highlighting the implications for Northern European GNSS users. Our main overall conclusions are summarised below.

- Loss of simultaneous lock on satellites due to ionospheric scintillation is probably the most unfavourable scenario for the user community in Northern Europe, especially those involved in safety-critical applications.
- Scintillation occurrence at high latitudes seems to be mostly correlated with geomagnetic activity. Statistics for 2002 reveal levels of phase scintillation significantly higher than amplitude scintillation in Northern Europe. GNSS users in that area should therefore be more concerned with phase scintillation or a combination of phase and amplitude scintillations, in particular during geomagnetic storms.
- Losses of satellite lock correlated with phase/amplitude scintillation occurred with our specially designed GPS scintillation monitor receivers. This highlights what the potential impact of ionospheric scintillation in the tracking performance of conventional GPS receivers could be.
- Loss of lock on the GPS L1 signal correlated with the occurrence of scintillation was verified. The L2 signal is less robust to scintillation, and loss of lock on either

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of the signals has a direct implication for SBAS reference stations, as these stations must track them both in order to compute and disseminate ionospheric delay corrections to users.

- A codeless receiver exhibited up to 50% of L2 data loss during a severe geomagnetic storm and L1 or L2 data from up to 7 satellites was not present in the corresponding RINEX file in some occasions.
- As the scintillation indices are average values measured at the input of the receiver PLL they do not provide sufficient information regarding the actual instantaneous values of phase and amplitude fluctuations that will affect the receiver performance. Therefore they can only give an indication of forthcoming problems. Receiver tracking models must be considered in conjunction with these indices to accurately model the influence of scintillation on receiver performance.
- No significant accuracy degradation in GPS C/A code stand-alone positioning which was convincingly correlated with enhancement on scintillation levels could be observed. Instead, increase in horizontal positioning errors during times of occurrence of high scintillation was seen to relate to enhancement in the background TEC observed during those times.
- When comparing the 2 drms errors from a (approximately) north-south with those from an (approximately) east-west oriented baseline in the UK, during a severely disturbed period, a degradation of about 30% in the horizontal positioning accuracy was observed, confirming the potential influence of TEC gradients on DGPS positioning.
- Experiments with static carrier phase positioning revealed an increase in the measurement noise and degradation of positioning accuracy significantly correlated with increases in phase scintillation values. That was verified at mid-latitudes, for both our scintillation monitor and a permanent semicodeless GPS receiver in Nottingham (53° N geographic latitude), as well as at high latitudes, for our monitor in Bronnoysund (65° N geographic latitude). Comparing the performance of our two scintillation monitors, in Nottingham and Bronnoysund, both measurement noise and positioning accuracy were markedly more degraded at the higher latitude location of the latter.
- Missing corrections in the EGNOS ionospheric grid observed during periods of occurrence of high values of phase scintillation may relate to the inability of the EGNOS reference stations to track one or both of the GPS signals of some satellites. Users at mid-latitudes opting to avoid satellites not monitored by the EGNOS ionospheric grid were shown to indirectly suffer the effects of strong scintillation due to ionospheric irregularities occurring further northwards. This could be an issue if users do not have a choice to include (non-monitored) extra satellites in their solution.

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