The impact of magnetic storms on GPS receiver performance

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Abstract. During the past decade, geodetic measurements have been greatly improved through the use of space geodesy techniques based on the global positioning system (GPS). The GPS allows for precise surveys, where centimetre-level accuracies may be obtained through differential carrier phase-based positioning algorithms. GPS positioning techniques often rely on the availability of dual-frequency data for formation of ionosphere-free and widelane observables (in the case of ambiguity resolution). While GPS positioning results generally provide adequate accuracies for several precise positioning applications, users may experience degraded positioning accuracies over the next few years. Of particular concern are ionospheric phenomena called magnetic storms, which are characterized by an increased spatial decorrelation of ionosphere range delays and scintillation effects at low and high latitudes. During such events, degradations in differential positioning accuracies are observed, and availability of the L2 observations may be limited through loss of signal lock. The magnitude of such effects is estimated during a global magnetic storm event, and a performance comparison of two survey grade receivers is conducted. This storm is representative of the activity at solar maximum and several years beyond.

Key words: Positioning – GPS – Ionosphere – Scintillations

1 Introduction

The ionosphere is a dispersive medium, in which radio frequency signals are refracted by an amount dependent on the given signal frequency and the electron density, resulting in a range error

\[ I = \pm 40.3 \frac{\text{TEC}}{f^2} \] (in metres) \hspace{1cm} (1)

where TEC denotes the total electron content integrated along a 1-m² column along the signal path (el/m²), \( f \) is the signal frequency (Hz), and \( + \) (–) denotes the group delay (phase advance). The dispersive nature of the ionosphere allows direct calculation of the absolute TEC, if range measurements are available on two separate frequencies

\[ \text{TEC} = \frac{1}{40.3} \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)^{-1} (P_1 - P_2 - b_t - b_s) \hspace{1cm} (2) \]

for the case of a dual-frequency GPS receiver, where \( f_1 = 1575.42 \text{ MHz} \) (herein referred to as L1) and \( f_2 = 1227.60 \text{ MHz} \) (herein referred to as L2). \( P \) denotes the pseudorange observable, and \( b_t \) and \( b_s \) are receiver and satellite interchannel bias terms, respectively. For convenience, the TEC is usually expressed in units of TECU \((10^{16} \text{ el/m}^2)\), where 1 TECU translates to 0.16, 0.27 and 0.21 m range delay for the L1, L2 and widelane observables, respectively. TEC estimates derived using Eq. (2) are corrupted by noise and multipath effects, which are typically of the order of 1–5 TECU RMS. More precise estimates of the TEC can be obtained as follows:

\[ \text{TEC} = \frac{-1}{40.3} \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)^{-1} \\
\times (\Phi_1 - \Phi_2 - \lambda_1 N_1 + \lambda_2 N_2 - b'_t - b'_s) \hspace{1cm} (3) \]

where \( \Phi \) represents the ambiguous carrier phase range and \( N \) represents the carrier phase ambiguity (in cycles). The ambiguities must be known in order to calculate absolute TEC using Eq. (3). Ambiguous phase ranges are useful, however, in deriving information about relative variations in TEC, provided that the ambiguities and biases remain constant over time

\[ \text{TEC} = \frac{-1}{40.3} \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)^{-1} (\Phi_1 - \Phi_2) \hspace{1cm} (4) \]

Such TEC estimates have a relative accuracy of better than 0.10 TECU RMS, and can be used to analyse...
relative spatial and temporal variations in TEC. The magnitude of TEC depends on slant path through the ionosphere, such that slant TEC values are three times larger at elevation angles of 5°, versus vertical TEC (at 90° elevation).

For precise carrier phase-based positioning applications, double-difference techniques are employed to reduce ionospheric range errors and resolve carrier phase ambiguities. Typically, large-scale gradients in TEC result in differential ionosphere range delays (L1) of the order of 1–2 ppm (Parkinson and Enge 1996). TEC gradients can be significantly larger, however, in both the high-latitude auroral region and the low-latitude equatorial anomaly region (Skone and Cannon 1998; Wanninger 1993) during a magnetic storm event. In some cases, it is possible to reduce ionosphere residuals by using stochastic modelling techniques (Odijk 2000) and/or a regional network approach (Liao and Gao 2000). Such techniques may not be sufficient, however, if small-scale structures in TEC are present and cannot be resolved. In such cases, the enhanced differential range errors can limit ambiguity resolution, particularly for real-time applications.

GPS receiver tracking performance can also be degraded during such storm events (Knight et al. 1999; Nichols et al. 1999). Rapid phase variations (phase scintillations) cause a Doppler shift in the GPS signal, which may exceed the bandwidth of the phase lock loop (PLL), resulting in a loss of phase lock (Leick 1995). Additionally, amplitude fades can cause the signal-to-noise-ratio (SNR) to drop below receiver threshold, resulting in loss of code lock. These effects have a larger impact on tracking loops employing codeless and semi-codeless technologies (to extract the encrypted L2 signal) versus full code correlation. In particular, codeless and semi-codeless tracking loops experience losses of 27–30 and 14–17 dB, respectively, with respect to full code correlation, and are therefore more susceptible to the effects of amplitude fading. The L2 PLL also employs a narrower bandwidth (~1 Hz, compared with ~15 Hz for L1) to eliminate excess noise, and is therefore more susceptible to phase scintillations. Availability of the L2 signal is particularly important for positioning applications that require formation of widelane and/or ionosphere-free observables.

The magnitude and frequency of such scintillation effects, and enhanced gradients in TEC, are well correlated with the solar cycle, which peaked during mid-late 2000. These effects are also often associated with specific magnetic storm events – activity which tends to peak several years before and after the solar maximum. The largest, most intense events generally occur several years after the solar cycle maximum (i.e. 2001–2003). In order to quantify the expected impact on GPS precise positioning applications over the next few years, this paper focuses on a representative magnetic storm event which took place in 1998. The global impact of this event is characterized by the magnitude of spatial gradients in TEC and receiver tracking performance.

### 2 Magnetic storm phenomena

Prior to considering TEC variations, scintillation effects and associated limitations in differential positioning, it is necessary to discuss specific features of the global ionosphere, and the nature of magnetic storm disturbances. A brief description of various phenomena is included in this section. For distinction, the effects are classified by latitude region.

#### 2.1 Low-latitude equatorial region

The magnetic storm is generally observed in low-latitude magnetic field variations, and is often associated with a mid- and low-latitude event referred to as an ionospheric storm. These storms are characterized by variations in TEC, and have a direct impact on GPS applications. The ionospheric storm consists of three phases: a positive phase lasting a few hours (during which the TEC increases from background levels), a main phase lasting a day or more (during which TEC values are well below background values), and a recovery phase of several days. Such TEC signatures are observed at both middle and low latitudes (Huang and Cheng 1991).

One feature of the low-latitude ionosphere, which may be enhanced during a magnetic/ionospheric storm, is the equatorial, or Appleton, anomaly. This anomaly consists of two maxima in electron density, located approximately 15° north and south of the magnetic equator. The southern maximum is pictured in Fig. 14. The daily equatorial anomaly generally begins to develop around 0900–1000 local time, reaching its maximum development at 1400–1500 (cf. Huang and Cheng 1991). In periods of solar maximum, however, the anomaly may peak at ~2100 local time, and gradients in TEC are considerably larger at this ‘second diurnal maximum’. Patches of small-scale irregularities in electron density can develop in the post-sunset anomaly (cf. Aarons et al. 1983) – a source of intense scintillation effects. Scintillations have been observed to peak at approximately 2100 local time, with maximum intensity near the anomaly peaks (±15° dip latitude) (Basu et al. 1988).

#### 2.2 High-latitude auroral region

High-latitude storm activity can also be present during a magnetic storm, in the auroral region. The auroral oval (Feldstein and Starkov 1967) is typically located between 60 and 65° dip latitude (low activity), with an average width of 5–7° (Rostoker and Skone 1993). Auroral regions include much of Canada and Alaska, in addition to parts of Russia, Scandinavia and Northern Europe. These regions are characterized by enhanced energetic electron precipitation, which results in optical emissions commonly known as the aurora borealis or Northern Lights.

This phenomenon is a feature of the magnetospheric substorm, where associated irregularities in electron density lead to scintillation effects (cf. Aarons 1982).