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Study of high-latitude ionosphere: One-year campaign over Husafell, Iceland

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ABSTRACT

This paper reports on the effects of diurnal, seasonal, geomagnetic and solar activity on GPS Vertical Total Electron Content (VTEC) measurements at a high-latitude station in Husafell, Iceland (64.7°N, 21.0°W) from March 2009 to February 2010. According to the diurnal VTEC pattern, there was generally a build-up region at sunrise (0500-1000 LT), a daytime plateau in the afternoon (1200-1400 LT), and a decay region from evening to pre-dawn (1800-0400 LT). The month-to-month analysis showed high VTEC variability, particularly in February 2010, due to an increase in solar activity. The VTEC showed a high variability during both winter and the equinoxes, with the highest value being 90%, but showed a low variability in summer. Two abnormal peaks appeared at sunrise and sunset in winter and the equinoxes. These peaks were the result of steep density gradients caused by the onset and turnoff of solar radiation. The correlation analysis yielded almost no correlation between the VTEC and geomagnetic activity but showed a high correlation with solar activity for all the seasons, particularly at night-time.

1. Introduction

The ionosphere is a part of the upper atmosphere, where free electrons are one of the main parameters that affect satellite communications. The effect can be in the phase advance and code delay of the signal that is transmitted from the satellite to the receiver on the ground, which is directly proportional to the Total Electron Content (TEC). The ionosphere varies with the local time, season, geomagnetic and solar activity. The ionospheric variations can be categorized into three regions of geographical latitude; the equatorial and low-latitude region ($+30°$ to $-30°$), the mid-latitude region ($\pm 30°$ to $\pm 60°$), and the polar and high-latitude region.

At the mid-latitude region, energetic ultra-violet and X-ray emissions from the sun play an important role in the ionization process, and this region is the best understood region having been explored the most completely. The middle latitude of the ionosphere is connected to the inner magnetosphere, which essentially rotates with the earth and so is less sensitive to external influences. The ionosphere in the low-latitude region is strongly influenced by electromagnetic forces that arise because the geomagnetic field runs horizontally over the magnetic equator.

Meanwhile, the main source of the variability of the ionosphere at high latitudes is the solar wind, which is also variable. This natural phenomenon is considerably more complex than what occurs in either the middle or low-latitude zones. The magnetic field-lines in the high latitudes are connected to the outer part of the magnetosphere and are more accessible to energetic particle emissions from the sun that produce additional ionization. This can degrade the polar radio propagation. Two important phenomena which occur at high latitudes and can degrade polar radio propagation are auroras and troughs. An aurora, which can occur within the high-latitude region, is particularly complex, while a trough of depleted ionization on the equatorward side has its own pattern of behaviour. Enhancements, generally called patches, within the polar cap can be seen during winter nights under disturbed conditions. In such conditions, the electron density in the

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F-region may be increased by as much as a factor of ten above the background, which would typically be about $10^5\,cm^{-3}$. These features lead to a more complex and dynamic ionosphere at high latitudes and offer a unique laboratory for the study of solar-terrestrial environmental connections.

It is necessary to have a better understanding of high-latitude phenomena, for example, auroral precipitation, convection, turbulence and electron content as driven by magnetospheric and solar activity. For such purposes, the GNSS sensing technique has been widely used as a powerful tool to accurately measure the ionospheric TEC (Maruyama, 2007; Bahari et al., 2011). Radio signals from GNSS satellites are propagated through the ionosphere before being received by the receiver on earth. Since the GPS signals is broadcast in two widely-spread L-band frequencies, namely channel L1 at 1557.42 MHz and channel L2 at 1227.60 MHz consisting of a code and a phase, it is possible to determine the TEC by employing differencing techniques (Bahari et al., 2011). In return, since the availability of GNSS satellites starting from the early 1990s, phase delay and pseudo-range measurements from a significant number of ground stations have become available for ionospheric research.

Most of the studies on the high-latitude ionosphere were conducted during high solar activity, such as during geomagnetic storms (Afraimovich et al., 2000; Clilverd et al., 2006; Momani, 2008; Shagimuratov et al., 2002; Tsurutani et al., 2003), auroras (Kamide et al., 2003; Fillingim et al., 2003) and solar flares (Bahari et al., 2011; Tsurutani et al., 2009). However, the characterization of the high-latitude ionospheric VTEC variation during low solar activity has rarely been studied.

This paper presents the effects of diurnal, seasonal and solar activity on VTEC variations at Husafell (64.7°N, 21.0°W (geomagnetic coordinates: 65.17°N, 66.94°E)) over a one-year period from March 2009 to February 2010, which coincided with quiet and low geomagnetic and solar activity.

2. Methods

2.1. GPS total electron content

Geodetic GPS receivers generally collect dual-frequency data at 30-second intervals, making it possible to monitor high frequency variations of the ionosphere. The oblique TEC can be obtained from delays in the GPS radio signals on L1 and L2.

TEC measurements were recorded from different GPS satellites observed at arbitrary elevations, which caused the signals to cross largely different portions of the ionosphere. In order to obtain an absolute TEC mapping, an elevation-dependent mapping function was used to convert a slanted TEC into a vertical TEC (VTEC), as described in Eq. (1). The single layer model (SLM), which assumes that all the free electrons are contained within a shell of infinitesimal thickness at an altitude, $h_{m,}$ was used to model the VTEC at specific solar-geomagnetic coordinates. The altitude was set to 450 km, corresponding approximately to the altitude of maximum electron density (Momani et al., 2008; Ya'acob et al., 2008). The elevation-dependent mapping function was defined as

$$F_I(\chi) = \frac{\mathrm{TEC}}{\mathrm{VTEC}} = \frac{1}{\cos\chi'} \text{ with } \sin\chi' = \frac{R_E}{R_E + h_m}\sin\chi \tag{1}$$

where χ, χ' are the zenith angles at the receiver site and at the ionospheric pierce point (IPP), respectively. R_E is the mean radius of the Earth, which is 6371 km, h_m is the height of the single layer above the Earth's surface, which is 450 km, and VTEC is the vertical TEC (TECU)

2.2. Instrument setup and data processing

The GPS receiver station was installed at Husafell, Iceland in September 2008 by the Institute of Space Science (ANGKASA), UKM. The station was located at the geographical coordinates of 64.7°N, 21.0°W (geomagnetic coordinates: 65.17°N, 66.94°E). The aim of this installation was to fulfil the demand to have a low-cost system to collect continuous GPS measurements to study the ionosphere over a high-latitude region and its connection to the equatorial region (Bahari et al., 2011). The system consisted of a high-precision 24-channel, dual-frequency GPS Leica 1200 receiver, a Leica AT504 choke-ring antenna and a notebook with Spider software for data logging. It was located at a distance of about 135 km from Reykjavik, the capital city of Iceland. The GPS receiver was set to track GPS signals with a one-second sampling period and the cut-off elevation angle was set to 15° to maintain the quality of the data.

The data was recorded in the Receiver Independent Exchange (RINEX) format (Gurtner and Estey, 2012), and was processed using the Bernese GPS Software (BGS) version 5.0 in the Bernese Processing Engine (BPE)'s Precise Point Positioning (PPP) mode. In the BGS, the PPP is known as a special application of the zero difference processing, where it relies on precise orbit and clock information for deriving precise site coordinates and receiver clock corrections independently for each analysed station. This technique is based on un-differenced code and phase observations, and allows the generation of a VTEC map at a single station. The PPP method is based on the assumption that the GPS orbits in an earth-fixed frame and that GPS clock corrections are fixed at some predetermined values, which allow the generation of an ionospheric VTEC map at a single station (Zumberge et al., 1997). The PPP method uses both the carrier phase and the pseudo range in data processing. The carrier phase is used to smooth the noisy pseudo range. When applied to single-receiver data, the resulting accuracies are comparable to what is obtained when data from all receivers are simultaneously reduced, thus reducing computational costs as compared to the conventional Double Difference (DD) method (Ge et al., 2008; Abdullah et al., 2008).

In order to evaluate the seasonal variability of the GPS data at Husafell, the VTEC relative standard deviation was calculated by using Eq. (2) (Forbes et al., 2000; Rishbeth and Mendillo, 2001; Mendillo et al., 2002; Bilitza et al., 2004). The standard deviation was used in this analysis due to the fact that it is a good measure for describing the average deviation from the monthly mean.

$$\mathrm{VTEC}_{\mathrm{std}} = \frac{e}{u} \times 100[\%] \tag{2}$$

where e is the standard deviation over 1 month of values measured during a particular hour of the day and u is the monthly mean.

3. Results

To study the VTEC variations with the local time, seasons, solar activities and geomagnetic conditions, the GPS measurements from March 2009 to February 2010 that had been recorded at Husafell were analysed. In the analyses, the diurnal VTEC variation, VTEC median and its variability during different seasons and the dependence on geomagnetic and solar activity were investigated.

3.1. Diurnal VTEC variation

Fig. 1 shows the month-to-month diurnal VTEC over the period starting from March 2009 to February 2010. The daily VTEC measurements were plotted against the local time (LT), where LT