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Origin of high-frequency TEC disturbances observed by GPS over the European mid-latitude region

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ABSTRACT

High-frequency variability of the ionospheric Total Electron Content (TEC) can strongly affect precise positioning with GNSS. The occurrence rate as well as the amplitude of such disturbances has been extensively studied over the last decade. Mainly, one can distinguish disturbances due to space-weather events and the others, qualified as "quiet-time" as they are observed during quiet geomagnetic conditions. The latter, which represent more than 75% of the total number of disturbances over mid-latitudes, are then divided into two categories: the Winter Daytime (WD) and the Summer Nighttime (SN). The first category, representing the bulk of quiet-time disturbances, corresponds to classical Medium-Scale Traveling Ionospheric Disturbances (MSTIDs), that are the result of the interaction of gravity waves and the ionospheric plasma. On the other hand, SN disturbances are generally understood as non-classical MSTIDs of electrical origin. The paper investigates the origin of these two types of disturbance based on GPS measurements, ionospheric soundings and wind speed data at a tropospheric level. If one cannot exclude the solar terminator as a potential source of gravity waves responsible for WD events, it is thought that the major contribution comes from the lower atmosphere. More precisely, tropospheric jetstream is considered as the favorite candidate for daytime MSTIDs. Turning to SN disturbances, our analysis reveals that they are related to spread-F phenomenon, linked to the appearance of sporadic E-layers. The related instabilities are responsible for field-aligned irregularities in the F-region, which are thought to be responsible for noise-like fluctuations of the GPS TEC observed during SN events.

1. Introduction

Modern life relies on an increasing number of technological systems based on Global Navigation Satellite Systems (GNSS). During their propagation through the ionospheric plasma, GNSS signals are delayed and deflected due to variations of the electron density along the satellite-to-receiver path. The ionospheric variability, or more precisely the variability of its Total Electron Content (TEC), constitutes an important threat for positioning applications requiring a high-accuracy level. This variability, which will further be referred to as "ionospheric disturbances", arises from various physical phenomena, linked directly or not to solar activity. More particularly, energetic phenomena at the Sun's surface or inside the corona are responsible for the so-called space weather events. Directed towards the Earth, phenomena such as solar flares, radio bursts or Coronal Mass Ejections (CMEs), might become geoeffective and disturb the plasmaspheric–ionospheric system. Because the number of observations of the Sun and of the heliosphere is continuously increasing (e.g. ACE, SOHO, SDO, and STEREO spacecrafts), solar originating phenomena are more and more precisely described and understood. For example, the detection of geoeffective events is nearly instantaneous and the computation of their trajectory into the interplanetary medium allows us to predict their effects on Earth. With a given accuracy level, it is therefore possible to forecast the arrival of an incoming CME with an accuracy better than ten hours (Taktakishvili et al., 2010; Gopalswamy et al., 2001). However, if space weather events are the origin of large amplitude ionospheric disturbances, their impact on navigation remains quite limited as their occurrence is strongly related to solar conditions. Indeed, a recent study (Wautelet, 2013) showed that the yearly proportion of ionospheric disturbances having a space weather origin varies between 0 (during solar minimum) to about 25% (solar maximum), which represents a small fraction of all disturbances observed with GNSS. Therefore, given their rather predictive character and their low occurrence rate, the present paper will focus on ionospheric disturbances observed by the Global Positioning System (GPS) which are not linked to space weather events and whose occurrence is more difficult to predict. They will further be referred to as "quiet-

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time disturbances". Let us precise that such disturbances do not especially correspond to "Q-disturbances" discussed in Mikhailov et al. (2007, 2007, 2009) as the latter are related to NmF2 disturbances observed by ionosondes during extremely quiet geomagnetic background, while our disturbances are detected in the Total Electron Content (TEC) after detrending the effects of space and time gradients. In addition, the time scale of one hour used to detect Q-disturbances is very different from the 30 s sampling rate of GPS data used in our analysis.

The aforementioned work of Wautelet (2013) consists in a climatological study of quiet-time disturbances using ten years of GPS data in Belgium, processed by the detection algorithm developed in Warnant and Pottiaux (2000). Based on dual-frequency GPS observations at a sampling rate of 30 s, the processing algorithm uses the so-called Geometric-Free (GF) combination and a high-pass filter to isolate high-frequency ionospheric variability for each GPS satellite in view from a single station. Let us stress that only high-frequency variations of the TEC are detected by the algorithm, so that the effects of natural, recurrent TEC gradients are not taken into account. This is also valid for the effect of tidal or planetary waves which exhibit much longer periods than the 15-min interval used in the algorithm. The method has then been validated and updated by Wautelet (2013) who conducted a ten year climatological study of ionospheric disturbances based on three Belgian stations. Results of this study show that between 75 and 100% of the detected disturbances correspond to quiet-time irregularities which can be divided into two main recurrent patterns. On one hand, Winter Daytime (WD) disturbances correspond to classical Medium-Scale Traveling Ionospheric Disturbances (MSTIDs) exhibiting properties matching the results obtained in the literature (Hernandez-Pajares et al., 2006; Tsugawa et al., 2007): amplitude of about 10% of the TEC background, maximum occurrence during the autumn and winter months between 8 A.M. and 4 P.M. and the absence of correlation with geomagnetic activity. WD disturbances represent more than 50% of the yearly disturbances during moderate and high solar activity periods, with a maximum of 77%. During solar minimum, this proportion drops to 31%. On the other hand, Summer Nighttime (SN) disturbances exhibit a variable amplitude, sometimes exceeding 25% of the TEC background. The latter are generally observed around 8 P.M. during summer months, but are much less numerous than WD disturbances. Their number is rather stable with solar activity (a few %) but their yearly proportion, i.e. the proportion of SN with respect to other types of disturbances computed on a yearly basis, seems to be anti-correlated with solar activity. Their related TEC time derivative (called Rate of TEC, or RoTEC) time series exhibit either wave cycles indicating the presence of Traveling Ionospheric Disturbances (TIDs) or present a noise-like pattern that cannot be attributed to TIDs and whose origin is still uncertain.

The knowledge of the physical processes at the origin of such ionospheric disturbances is of primary interest as they will allow us to forecast their occurrence and their effects in terms of TEC perturbations. The present paper aims to investigate the different mechanisms that can be the origin of the observed WD and SN disturbances, based on existing theories. The starting point is the different processes suggested by the scientific literature, like the generation of Atmospheric Gravity Waves (AGWs) by the solar terminator or the lower atmosphere. Firstly, Section 2 describes briefly the methodology used to detect ionospheric disturbances using GPS observations. Next, Section 3 investigates the origin of WD disturbances while Section 4 refers to SN disturbances. At last, the results are summarized in Section 5 where some research perspectives are proposed.

2. Methodology

From a 10 years GPS dataset over Belgium (2002–2011), we extract all quiet-time disturbances and investigate their origin, according to their type (WD or SN). The algorithm used is described in Warnant and Pottiaux (2000) and Wautelet (2013) but the geomagnetic filters used in this paper have been slightly modified. Indeed, it has been chosen to select very quiet events in terms of geomagnetic conditions, in the same manner as for Q-disturbances (Mikhailov et al., 2007). The filter used is the following one: all Kp values must be lower than 2 for the previous 24 h. Overall, 2026 WD and 154 SN events have been extracted from our dataset. Let us recall that such events correspond to disturbed 15-min periods in terms of TEC variability between a given satellite and the observing station. This means that some events observed from different satellites located close to each other may be related to the same physical phenomenon. To each ionospheric event is associated an Ionospheric Pierce Point (IPP), which is defined as the intersection between the satellite line of sight and the ionospheric shell. The latter is a simple model of the ionosphere used for GPS studies in which all electrons of the ionosphere are supposed to be contained in and which is located at an altitude of 400 km.

Fig. 1 shows the IPPs related to all the detected WD and SN disturbances. Location of these two types of structures is quite different, as WD ones are mostly observed south from the station at low and middle elevation while SN ones are observed at high elevation. Moreover, as already mentioned, one can observe that WD irregularities are more numerous than SN ones.

The origin of WD irregularities is investigated in Section 3 based on two important mechanisms proposed by the literature: generation in situ by the solar terminator and generation in the lower part of the atmosphere by meteorological events. To study the influence of the solar terminator, a comparison of occurrence time has been performed: solar terminator would be considered as a TID source if a WD event is observed simultaneously with the sunrise or sunset. Next, the influence of tropospheric phenomena is assessed by a spatial correlation analysis between jetstream regions and the location of the disturbance: jetstream can be the source of the AGW if the WD event is observed within a cone centered on high speed wind regions. For that purpose, the atmospheric dataset ERA-INTERIM is used, which provides wind speed vectors at a given pressure level. More details concerning the mechanisms and the methodology will be supplied in Section 3.

The origin of SN irregularities has been analyzed using ionospheric soundings located close to IPPs (Section 4). Dourbes ionosonde (South of Belgium) has been chosen to support the hypothesis that sporadic E-layers and/or associated spread-F phenomena can be the source of the observed disturbances. Like for WD events, more detailed explanations about the methodology lie in the dedicated section.

3. Origin of winter daytime disturbances

Daytime MSTIDs, also called classical MSTIDs, are understood as the signature of AGWs into the ionospheric plasma, the latter playing the role of a passive tracer. They have a maximum occurrence rate around 1200 LT and propagate equatorwards (Hernandez-Pajares et al., 2006) or south–south-eastward (Tsugawa et al., 2007; Kotake et al., 2006). They occur mainly during autumn and winter months and exhibit a positive correlation with solar activity. Horizontal propagation speed lies between 100 and 400 m/s and their associated wavelength ranges from 100 to 350 km; the related period is larger than 12 min. Daytime MSTID