Ionospheric slab thickness: analysis and monitoring applications

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Abstract

Based on long time series of vertical incidence sounding and GPS TEC observational data, analyses have been made on both climatological and storm-time patterns of the ionospheric slab thickness behavior, such as the pre-dawn and post-sunset enhancements and the correlation with plasma scale height. Particular attention will be given to the variations during active geomagnetic conditions. Potential applications of these analytical results and present-day monitoring capabilities will be discussed as well. Ionospheric slab thickness monitoring, when available in real time and for several suitable locations in a region of interest, can be used for detecting and eventually predicting the propagation features of ionospheric disturbances. A local monitoring system has been developed by RMI Belgium to provide better real-time ionospheric characterization and understanding of the local ionospheric dynamics at Dourbes (50.09°N, 04.59°E). The feasibility of establishing an operational system for broad mapping of the ionospheric slab thickness over Europe is being investigated.

Introduction

The ionospheric slab thickness (τ) is defined as the ratio between the total electron content (TEC) and the F2-layer peak electron density (N_mF_2). Alternatively, τ is the depth of an idealized ionosphere which has the same electron content as the actual ionosphere but uniform electron density equal to the maximum electron density of the actual ionosphere. The slab thickness measurements offer substantial information on the shape of the electron density profile and, via TEC, on the level of ionospheric ionization in general (Stankov et al., 2003). Also, the slab thickness value contains, by virtue of its relation to the vertical plasma scale height, implicit information on the neutral and ion gas temperatures. Thanks to the regular and reliable Global Positioning System (GPS) measurements of TEC, valuable information can be obtained for the plasma distribution and various other dynamic processes occurring in the Earth's ionosphere-plasmasphere system. For example, sharp changes in slab thickness can be attributed to physical processes such as plasma uplifting, enhanced plasma fluxes from/to the plasmasphere, etc. (Titheridge, 1973; Furman and Prasad, 1973; Davies, 1991; Buonsanto, 1999; Stankov, 2002; Gulyaeva, 2003).

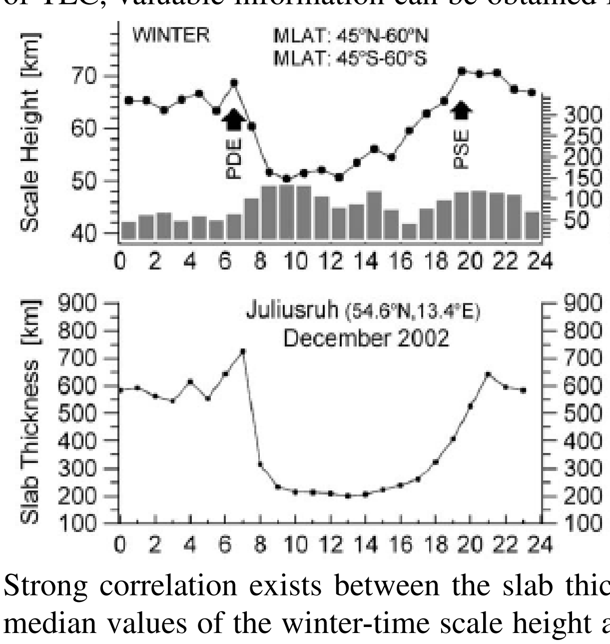

Fig.1. Comparison between the diurnal behavior of the plasma scale height and the slab thickness at middle latitudes during winter. Slab thickness calculated at the site of ionosonde station Juliusruh (54.61°N, 13.41°E) using f_oF_2 measurements from the local digisonde and TEC measurements from the IGS.

Strong correlation exists between the slab thickness and plasma scale height (Fig.1). For example, median values of the winter-time scale height are plotted together with corresponding slab thickness

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estimations at the site of the ionosonde station Juliusruh (54.61N, 13.41E) which is in the middle latitude belt. As seen from the figure, the correlation is very strong. It is important to mention here that independent measurements have been used for computing the slab thickness - TEC is obtained from the International GNSS Service (IGS) measurements and N_mF_2 is derived from ionosonde measurements. Interestingly, our previous calculations show that such winter-time behavior, of both Hsc and τ , is preserved for low solar activity levels as well. It is clear from the results that during quite-time conditions the slab thickness is correlated with the plasma scale height, whereas under disturbed conditions, the compression/expansion of the electron density profile is controlled mainly by dynamic forces such as neutral winds and electric fields. Most of the mechanisms determining the plasma scale height are valid for the slab thickness behavior as well (Stankov and Jakowski, 2006).

Climatology of the ionospheric slab thickness variability

It has been found that the slab thickness shows appreciable diurnal, seasonal, spatial, solar and geomagnetic activity variations.

The diurnal variations of the slab thickness during low solar activity are characterized with higher night-time values while the opposite occurs during solar maximum. The night-time values are higher during all seasons in middle latitudes, while during summer at low and high latitudes night-time values are higher (Davies and Liu, 1991; Goodwin et al., 1995; Jayachandran et al., 2004).

The slab thickness exhibits a pronounced pre-dawn enhancement (PDE). The magnitude of this increase is larger in low latitudes than in middle latitudes (Bhonsle et al., 1965; Davies and Liu, 1991). It is attributed to low values of N_mF_2 rather than be an increase in TEC. The pre-dawn increase is a phenomenon closely related to the maintenance of the night-time F layer and can sufficiently well be explained by the lowering of the ionospheric F layer immediately before sunrise to regions of greater neutral density, leading to increased ion loss due to recombination. The effect is believed to be particularly strong in the bottom-side ionosphere includes the density peak. As a result, the decrease in N_mF_2 and the bottom-side density is much faster than the topside ionosphere where the loss rate is lower and thus, an enhancement occurs. In addition, plasmaspheric fluxes can also play a role in the increase. There exists also a post-sunset (PSE) enhancement in the slab thickness which origin is still not well understood. Both, the PDE and PSE peaks are regular features appearing during solar minimum in all seasons and latitudes, while during solar maximum they are still preserved for high and low latitudes but not for middle latitudes (Jayachandran et al., 2004). Kouris et al. (2004) report that, due to the hysteresis effect between TEC and $(f_oF_2)^2$, the mid-latitude pre-noon slab thickness values are substantially higher than the afternoon values.

In general, the slab thickness variations increase with solar activity during all seasons. However, in some regions, e.g. at low and equatorial latitudes, the median daytime value of the slab thickness seems to be poorly correlated with the solar activity index $S_{10.7}$ (Chuo, 2007). At these latitudes, the mean daytime values remain more or less constant for both low and high solar activity. At higher latitudes, the slab thickness may stay unchanged during low solar activity; but during high solar activity appear to increase in step with the increasing solar flux values (Jayachandran et al., 2004). For the equatorial region, Klobuchar et al. (1991) calculated a slab thickness peak of about 510 km during solar maximum conditions and, during solar minimum conditions, a corresponding peak in the range of 460 - 560 km depending on the drift conditions. The pre-dawn enhancement is reported to be well pronounced during the solar minimum, gradually disappearing during the ascending part of the solar cycle, and reappearing during the solar maximum particularly during the winter season. (Minakoshi and Nishimuta, 1994).

Although the magnetic activity does not appear to have any significant influence on the τ variations at equatorial and low latitudes (Jayachandran et al., 2004; Chuo, 2007), it seems to enhance the τ values for mid-latitude during solar minimum and for high latitude during solar maximum (Buonsanto et al., 1979). A positive correlation has been detected between the monthly mean values of the slab thickness and the Ap geomagnetic index (Kersley and Hosseinieh, 1976), explained with the dependence of the neutral gas temperature on the level of magnetic disturbances.

Several studies in the northern hemisphere indicate that, generally, the slab thickness is greater in summer than in winter (Roger, 1964; Spalla and Ciraolo, 1994; Minakoshi and Nishimuta, 1994; Stankov, 2002; Leitinger et al., 2004). Observations from the southern hemisphere confirm that the day-time slab thickness is greater in summer than in winter (Titheridge, 1973; Goodwin et al., 1995). Nevertheless, there are obviously some differences. For example, Jin et al. (2007) report that, in the East Asian zone, larger day-time values are maintained during equinox while smaller values are observed in summer and winter. Moreover, two peaks appear around 10 LT and 18 LT, most distinctively in summer. Both the pre-dawn and post-sunset enhancements appear over the equatorial ionization crest area in all seasons and solar activity levels (Chuo, 2007).

There are no clear-cut trends established in the spatial variations of the slab thickness. Davies and Liu (1991) report that it is impossible to discern any geographical or geomagnetic dependence to within the data accuracy (scatter). Other observations from the southern hemisphere also indicate an absence of latitudinal dependence of the slab thickness in any season (Goodwin et al., 1995). Klobuchar et al. (1991) find that there is a region of enhanced slab thickness extending from equatorial to dip latitudes of around $\pm$ 34°. Leitinger et al. (2004) conclude from theoretical considerations that there is an increase in the slab thickness towards the dip equator when the equatorial anomaly is on. At higher latitudes, the τ diurnal ratios are found to be larger than the corresponding values from the lower latitudes, particularly during solar maximum winter and equinoxes; on the other hand, the mean winter daytime value at middle latitudes is lower compared to that in low latitudes (Jayachandran et al., 2004).

By combining vertical electron content (derived by means of the Faraday effect on the VHF signals of geostationary satellites) with peak electron density (derived from ionograms), and after neglecting solar activity, diurnal and seasonal variations, Leitinger et al. (2004) estimated that the overall mean slab thickness for Europe can be given as 230 km with a standard deviation of 50 km. For high solar activity however, an increased average around 300 km is found to be more appropriate. The overall means for the American sector are slightly higher: τ = 242 km for low solar activity, τ = 267 km for moderate solar activity, and τ = 292 km for high solar activity (Fox et al., 1991). Other longitudinal differences in the diurnal and seasonal variations of the slab thickness are reported as well (Jayachandran et al., 2004).

Slab thickness variations during geomagnetic storms

The slab thickness variations during a given geomagnetic storm depend mainly on the relative variations of TEC and N_mF_2 parameters, but also on the storm intensity and the time passed since the storm onset. An increasing slab thickness (e.g. rising TEC accompanied by constant or decreasing f_oF_2) indicates plasma uplifting - a manifestation of active electric fields that produce a vertical drift driving the plasma upwards to regions of lower ion loss (Buonsanto, 1999). Slab thickness enhancements are observed during the negative storm phases of N_mF_2 and TEC, during solar maximum (for as long as 48 hours since the storm onset) as well as during solar minimum, although with a 12–24 hour delay from the storm onset (Gulyaeva and Stanislawska, 2005). If the sudden storm commencement occurs during daytime, a positive phase in the slab thickness is seen throughout the rest of the day but on the following days a negative phase arises in the winter hemisphere while in the summer hemisphere, slab thickness shows a positive phase during the entire storm period (Titheridge and Andrews, 1967). Several case studies show that, during winter storms, the slab thickness values are consistently higher than their mean values from around local noon until midnight on the storm day and then decreasing back to the mean values (e.g. Fox et al., 1990; Mansilla et al., 1997).

As an example, presented here is the slab thickness behavior during the geomagnetic storm starting early on 10 January 1997. This is a typical winter geomagnetic storm characterized by a pronounced positive response from both the TEC and f_oF_2 parameters (Fig.2). However, the TEC response is much stronger than the f_oF_2 response, with the noon TEC values exceeding by more than 100% the corresponding monthly medians. In effect, this leads to a strong 'positive phase' in the slab thickness values throughout the day. Since the positive phase observation is initiated at night, the positive cause-effect description given above cannot be applied for the increased night-time densities. Instead, it should be attributed to downward plasmaspheric fluxes, known to be caused by the geomagnetic field compression during the storm onset phase and/or inter-hemispheric flows. Such plasmaspheric fluxes can be easily detected; for example, a high slab thickness value during night-time (cf. Fig.2D, 0200UT) is an indication of an enhanced plasma influx from above.

An operational system for monitoring the local ionospheric slab thickness has been established in Dourbes, Belgium. By having instantaneous access to European ionosonde and GNSS data, it would be possible to extend this system and provide regional mapping of the slab thickness in real time.

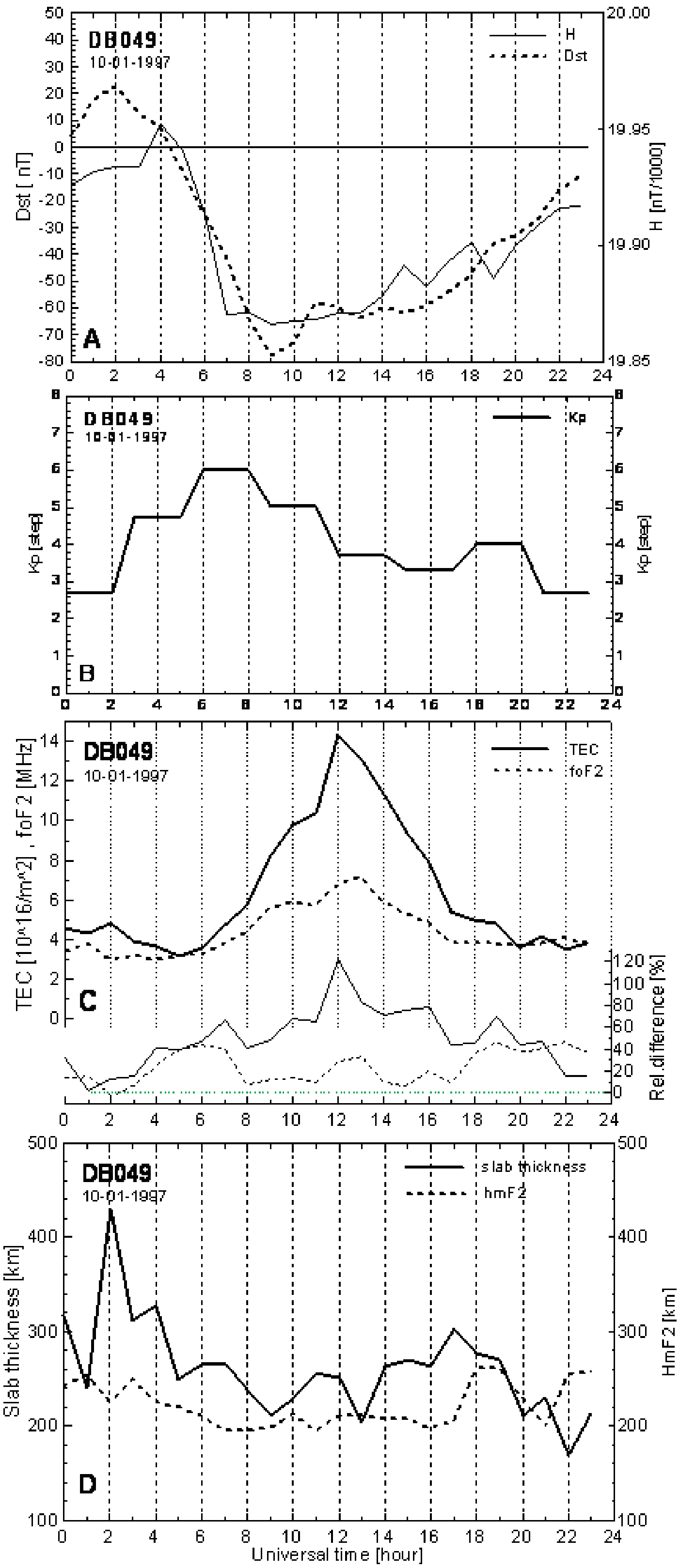

Fig.2. The ionosphere-plasmasphere response to the geomagnetic storm on January 10, 1997, as observed at the site of the Dourbes (50.09°N, 04.59°E) station (DB049). The slab thickness is plotted in Panel D.

Slab thickness monitoring, modeling, and possible applications

Several possibilities exist for utilizing the ionospheric slab thickness monitoring and modeling efforts. Some slab thickness studies have been carried out with the purpose of assessing empirical or theoretical ionospheric models (Fox et al., 1991; Gulyaeva, 2003), some have been carried out to gain more information on related ionospheric characteristics (Stankov, 2002; Stankov and Jakowski, 2006), and others have been carried out to address ionospheric effects issues (Stankov et al., 2005).

Several slab thickness models, appropriate for middle latitudes have been published during the years (Leitinger et al., 2004; and references therein). In general, these models provide a slab thickness value in the range between 170 km and 320 km for low solar activity and between 200 and 400 km for high solar activity, an increase in slab thickness with solar activity, a slight positive dependence on geomagnetic activity for non-storm conditions. For strong magnetic storm conditions, only a slight daytime increase of 10 to 30 km is envisaged.

Another recent development, closely related to the slab thickness modeling efforts, is the topside 'half-peak density height' model (Gulyaeva, 2003). Similarly to the shape of the bottom-side electron density profile, expressed via the sub-peak semi-thickness, a topside half-peak density anchor point (h05top) has been identified. In fact, h05top is the height in the topside ionosphere (i.e. above h_mF_2) where the electron density is half the F layer peak density N_mF_2 . Actually, this global empirical model provides the ratio (Rh05) of the topside half-width to the F-layer peak height, i.e. Rh05 = (h05top-h_mF_2)/h_mF_2. The model parameters are the solar local time, geomagnetic latitude, and solar activity. The model database is constructed from topside sounding measurements carried out onboard the ISIS1 (1969–1971, orbit altitude 500–3500 km), ISIS2 (1971–1980, altitude 1400 km) and Interkosmos 19 (1979–1982, altitude 500–1000 km) satellites. The database covers more than one complete cycle of solar activity, including the whole range of diurnal, seasonal and spatial variations in the vertical profile of the topside electron density.

When available in real time, over a region of interest, the slab thickness values/mapping can be used for detecting and eventually predicting the extent of an ionospheric density anomaly and its propagation characteristics. One possible application of the ionospheric slab thickness monitoring is to assist the operation of the well known ionosphere spatial gradient threat model (Luo et al., 2003).

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