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Solar eclipse effects in the ionosphere observed by continuous Doppler sounding

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Abstract

The ionospheric response to the solar eclipses of 20 March 2015 above the Czech Republic, 9 March 2016 above Taiwan, and 26 February 2017 above South Africa was studied. A distinct bipolar pulse was observed in ionospheric Doppler shift measurements above the Czech Republic (Central Europe) and above Taiwan (Eastern Asia). It is a local phenomenon clearly related with changes of electron density in the ionosphere induced by the passage of the Moon shadow above the measurement sites. The solar eclipse in Taiwan was rather small, with a maximum obscuration of 0.22. Yet, it obviously influenced the ionosphere on time scales above 100 min. The solar eclipse in South Africa occurred shortly before sunset and it is likely that ionospheric effects were masked by gravity waves generated by the evening solar terminator.

Keywords: Ionosphere; Solar eclipse; Ionospheric Doppler sounding

1. Introduction

Solar eclipses occur two or three times a year on average (https://eclipse.gsfc.nasa.gov), a significant part of them above oceans or other remote/inaccessible places with a limited or non-existent observation infrastructure. Thus, whenever eclipses occur above locations with favourable conditions for observations from the ground, they are understandably in the spotlight. A large number of studies of the solar eclipse impact on the ionosphere have been carried out over the years, both modelling (e.g. Le et al., 2009; Muller-Wodarg et al., 1998; Roble et al., 1986; Vertogradov and Vertogradova, 2016) and observational (e.g. Chen et al., 2011; Cheng et al., 1992; Farges et al., 2003; Hoque et al., 2016; Jakowski et al., 2008; Jones et al., 2004; Mosna et al., 2017; Salah et al., 1986; Stankov et al., 2017; Tsai and Liu, 1999; Verhulst et al., 2016).

The travelling Moon shadow induces the cooling of the atmosphere which results in changes in the pressure field and hence in the wind direction (Muller-Wodarg et al., 1998). The sharp decrease of the ionizing radiation causes the depletion of the ionospheric plasma density (e.g. Jakowski et al., 2008; Rishbeth, 1968). For example, a substantial reduction of the total electron content (TEC), as large as 50%, was observed during the solar eclipse of 20 March 2015 (Hoque et al., 2016; Stankov et al., 2017).

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The ionospheric response in the lower ionospheric layers D, E, and F1 differs from that in the F2 layer. In the lower ionosphere, the electron distribution is determined by photoionisation and recombination processes while in the F2 region the plasma transport plays an important role (Cheng et al., 1992; Jakowski et al., 2008; Rishbeth, 1968; Verhulst et al., 2016). In mid-latitudes, the downward plasma diffusion influences electron distribution. In the equatorial ionisation anomaly (EIA) region, the plasma transport is governed by the equatorial ExB drift and by the fountain effect resulting in the upward plasma drift at the magnetic equator during the daytime and in the horizontal plasma motion towards geomagnetic latitudes of 15° north and south.

Jakowski et al. (2008) and Mosna et al. (2017) report an increasing time delay of the ionospheric response with an increasing altitude in observations of the ionospheric response to the solar eclipses of 3 October 2005 and 20 March 2015. Delays of about 20–25 min with respect to the obscuration function were reported in the F2 region in European mid-latitudes (Jakowski et al., 2008; Verhulst et al., 2016). Tsai and Liu (1999) found a short response time of 0–30 min near the magnetic equator and the delay of 90–120 min at 12°N in the TEC measurements. Le et al. (2009) expect the response delay of 2 min in the E and F1 region, similar in all latitudes. Taking into account the eclipse geometry when analysing the ionospheric behaviour during eclipses and interpreting the eclipse effects is of crucial importance (Stankov et al., 2017). Thus, considering the actual eclipse geometry at ionospheric heights is much more important for the analysis than at the commonly referenced Earth' surface.

The motion of the Moon shadow generates gravity waves. Farges et al. (2003) identified two wave sources in the thermosphere and in the stratosphere or in the troposphere during the eclipse of 11 August 1999. Jones et al. (2004) reported a considerable wave activity in the Doppler recordings during the eclipse of 11 August 1999. The wave back-azimuths were consistent with the motion of the shadow along the path of totality. Jones et al. (2004) further described a long period change in the electron density distribution produced by the cut-off of the ionizing radiation flux and by the subsequent recovery after the maximum obscuration.

We studied and compared the effects of solar eclipses observed in the ionosphere by the continuous Doppler sounding at three different locations, in Central Europe, East Asia, and South Africa during the eclipses of 20 March 2015, 09 March 2016, and 26 February 2017.

2. Methods and data

2.1. Ionospheric data

Ionospheric Doppler shift measurements are based on the continuous transmission of a radio wave of a stable known frequency and the reception of the wave after its reflection from the ionosphere. The frequency shift between the transmitted and the received radio wave is extracted. The detailed description of the principles of the ionospheric Doppler sounding is given in Chum et al. (2010).

The big advantage of the Doppler sounding of the ionosphere during the solar eclipses is the continuity of the signal which enables very detailed observations of the time development of the ionospheric response to the eclipse. The disadvantage is the complicated interpretation of the measurements.

The reflection height of the Doppler sounding wave varies in time since the sounding is performed on a stable frequency. The Doppler shift measurement in itself does not contain the information about the reflection height of the sounding wave. Therefore, it is convenient to place the sounding system in the vicinity of an ionosonde. A limited number of sounding frequencies is transmitted by the Doppler sounding system and thus the examined altitude range is limited.

Observations of the ionospheric behaviour during the solar eclipses at three different locations in the world are analysed. The Doppler sounding systems are located in the Czech Republic (geographic coordinates 50°N 14°E), in Taiwan (24°N 121°E), and in South Africa (34°S 19°E).

All the employed Doppler sounding systems are of the same type. The sounding system consists of one receiver and three transmitters arranged in a triangle (Figs. 1–3, right panels). The distance of the transmitters from the receiver is 8–90 km in the Czech Republic, 45–125 km in Taiwan, and 96–182 km in South Africa. The point of the signal reflection from the ionosphere is for simplicity sake assumed in the middle between the transmitter and the receiver. The frequencies of the transmitted signals are mutually shifted by 4 Hz, so the signals received from the three sounding paths can be distinguished. The sounding is performed on the single frequency of 6.57 MHz in Taiwan and on the single frequency of 3.59 MHz in South Africa. In the Czech Republic, three sounding frequencies are transmitted; on the analysed eclipse day of 20 March 2015, measurements of sufficient quality were only available on the sounding frequency of 4.65 MHz.

The measured data are visualized in the Doppler shift spectrograms (Chum et al., 2009). Then, Doppler frequency shifts as a single-valued function of time are estimated separately for each of the sounding paths. The fitting procedure is automatic with consequent manual corrections. The fitted data are stored with the sampling period of 12 s.

The Doppler sounding systems in the Czech Republic and South Africa are collocated with Digisondes (Reinisch et al., 2005); thus reflection heights of the Doppler sounding wave can be obtained directly from ionograms. The information about reflection heights of the Doppler sounding wave was unfortunately not available in Taiwan.

Ionospheric drift measurements are carried out by the Digisonde at Pruhonice observatory, Czech Republic once