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High-resolution ionospheric observations and modeling over Belgium during the solar eclipse of 20 March 2015 including first results of ionospheric tilt and plasma drift measurements

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Abstract

The ionospheric behavior over Belgium during the partial solar eclipse of 20 March 2015 is analyzed based on high-resolution solar radio flux, vertical incidence sounding, and GPS *TEC* measurements. First results of ionosonde-based ionospheric plasma drift and tilt observations are presented and analyzed, including some traveling ionospheric disturbances caused by the eclipse. Also, collocated ionosonde and GPS measurements are used to reconstruct the time evolution of the vertical electron density distribution using the Royal Meteorological Institute (RMI) ionospheric specification system, called Local Ionospheric Electron Density profile Reconstruction (LIEDR).

Keywords: Solar eclipse; Traveling ionospheric disturbances; Ionospheric drift and tilt; Ionosonde; Digisonde

1. Introduction

Solar eclipses have long since attracted attention with the relatively rare conditions they create and, thus, the opportunities they offer for ionospheric research (Beynon and Brown, 1956). It was soon recognized that the eclipses can be particularly useful when studying the solar ionizing radiation and various effects on both the thermosphere and the ionosphere, including temperature balance, production and loss in the lower ionosphere, transport processes in the upper ionosphere, etc. (Rishbeth, 1968, 1970).

One might be tempted to think that (total) eclipse conditions can be considered the same as the night conditions, albeit short-lived. However, since the space shadowed by the Moon's passage in front of the Sun is relatively small, the decay rate of the ionosphere is not the same as during night because of the compensating effect of the ionization coming from the adjacent (sunlit) regions. This, and the fact that different eclipses occur at different locations and seasons, makes the eclipse studies quite difficult actually.

Earlier investigations of eclipse effects on the ionosphere were carried out by observing the changes in intensity of radio waves reflected from the ionosphere, followed by absorption measurements at oblique incidence on one or several frequencies (Beynon and Brown, 1956, and references therein), vertical incidence sounding (VIS) with ionosondes (Nestorov and Taubenheim, 1962), in situ measurements with rockets and satellites, total electron content (*TEC*) deduced by observing the Faraday rotation of polarization of lunar radio waves (Klobuchar and Whitney, 1965), incoherent scatter radar measurements of plasma density, temperature and drifts (Baron and Hunsucker, 1973), and – with the advancement of the Global Positioning System (GPS) technology – via GPS-based *TEC* observations (Afraimovich et al., 1998; Rashid et al.,

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2006). Simultaneous multi-instrument observations (at single and/or several locations) (Farges et al., 2001; Jakowski et al., 2008; Le et al., 2009; Chuo, 2013; Kumar et al., 2013) together with targeted modeling studies (Müller-Wodarg et al., 1998; Korenkov et al., 2002) seems to be the most efficient way of studying the complex, multifaceted nature of solar eclipses and their effects on the ionosphere.

While, initially, the efforts went on investigating the source of atmospheric ionization (electromagnetic or corpuscular radiation) and the chemical composition of the upper atmosphere (e.g. ionospheric plasma recombination rates), the interest shifted in recent years towards investigating the atmospheric gravity wave (AGW) phenomena generated by the Moon's shadow passing (at a supersonic speed) through the atmosphere (Chimonas and Hines, 1970; Davis et al., 2001; Altadill et al., 2001; Jakowski et al., 2008).

An eclipse affects all ionospheric layers although with different strength and manifestation of the effects. At lower altitudes (in the ionospheric *D* and *E* layers), the amount of ionization is governed by ion production and loss processes (photochemical equilibrium) while at higher altitudes the drift (transport) processes take precedence.

The presence of (substantial) ionospheric tilt and plasma drifts impedes the accuracy (and, in some cases, even the implementation) of some of the above-mentioned observation techniques. It is therefore important to have these (tilt and drift) measurements carried out in parallel to other measurements and considered when studying the eclipse effects.

A total solar eclipse occurred on 20 March 2015 with most of the total eclipse path located in the North Atlantic (Fig. 1). As a result, a partial solar eclipse was visible from Belgium on the same day between 8:27 UT (start, t_s) and 10:47 UT (end, t_e), with a maximum eclipse of 81.5% recorded at 09:34 UT (max, t_m).

The paper presents first results and analyses of ionosonde-based ionospheric plasma drift and tilt observations together with a reconstruction of the local vertical plasma redistribution in an unprecedented high-cadence survey.

2. Instrumentation and measurements

Spectral radio observations of the Sun are carried out by the Royal Observatory of Belgium (ROB) in Humain (50.2°N, 5.2°E). The Humain Radio-Astronomy Station (RAS) employs a radio telescope consisting of a 6-m Sun-tracking parabola with a receiver antenna placed at the focus. The instrument measures the solar radio flux (SRF) with a sampling rate of 250 ms (integrated over 6-s time periods) at pre-selected frequencies, delivering valuable information about the solar irradiance and flares.

A high-performance NovAtel GPStation-6™ is used to provide 1-s Total Electron Content (*TEC*) measurements. The receiver can track all present and upcoming Global Navigation Satellite System (GNSS) constellations and satellite signals with a maximum sampling rate of 50 Hz for each of the 120 available tracking channels.

The principal instrument used in this study is the Digisonde-4D® (Reinisch et al., 2009), installed at the RMI Geophysical Center in Dourbes (50.1°N, 4.6°E). Digisonde-4D is a state-of-the-art equipment using radar principles of remote sensing to evaluate with high-accuracy and precision the conditions of the ionospheric plasma above the station. It boasts multiple functionalities supported by a fully automated operational and database management system. It is capable of simultaneously measuring the following observables reflected (in vertical incidence) or refracted (in oblique incidence) signals from the ionosphere: frequency, range, amplitude, phase, Doppler shift and spread, angle of arrival, and wave polarization. Signal transmission is performed with two (NE-SW and NW-SE) crossed "delta" antennas of 40 m in height and reception is done with an array of four crossed magnetic dipole receive antennas in a triangular arrangement. The Digisonde is equipped with the latest versions of the computer software for automatic ionogram interpretation, ARTIST-5 (Galkin and Reinisch, 2008), and Digisonde Drift Analysis, DDA (Kozlov and Paznukhov, 2008). For the purpose of this study, the Digisonde was used to produce ionogram and drift measurements with a time resolution of 30 s. Some of the Digisonde operational settings for the eclipse campaign are listed in Table 1.

The measurements during the eclipse on 20 March 2015 were compared with the same type of measurements from a "control" (or "reference") day, 21 March 2015, when the geophysical conditions were back to normal. The sampling rate was kept unchanged during both the eclipse and control days.

3. Solar radio flux observations

The Humain RAS recorded the solar radio flux (Fig. 2) during the eclipse as the Moon was moving in front of the Sun and, again, during the same period on the control day. During the eclipse, the solar flux decreased steadily from about 08:30 UT to a minimum at about 09:30 UT before recovering to its pre-eclipse values at about 11:00 UT. The spikes on the frequency curves are caused by solar bursts (when appearing simultaneously on different curves) or by interference. Ripples are due to interference with the telescope parabola reception by the solar radiation reflected from the ground.

4. GPS-based observations of the vertical TEC

Fig. 3 shows the vertical *TEC* for the eclipse and reference days at 60-s time resolution. Similar to the critical frequency (f_oF_2, see Section 5), the reference-day *TEC* shows a straightforward linear increase, expected for this time of day. During the eclipse, *TEC* behaves similarly to f_oF_2: around 08:00 UT it starts to deviate from the reference,