IONOSPHERIC EFFECTS OF THE AUGUST 11, 1999 TOTAL SOLAR ECLIPSE AS DEDUCED FROM EUROPEAN GPS NETWORK DATA

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ABSTRACT

We present the results derived from measuring fundamental parameters of the ionospheric response to the August 11, 1999 total solar eclipse. Our study is based on using the data from about 70 GPS stations located in the neighbourhood of the eclipse totality phase in Europe. The key feature of our data is a higher reliability of determining the main parameters of the response to eclipse which is due to high space-time resolution and to the increased sensitivity of detection of ionospheric disturbances inherent in the GPS-array method which we are using. Our analysis revealed a well-defined effect of a decrease (depression) of the total electron content (TEC) for all GPS stations. The depth and duration of the TEC depression were found to be 0.2-0.3 TECU and 60 min, respectively. The delay τ between minimum TEC values with respect to the totality phase near the eclipse path increased gradually from 4 min in Greenwich longitude (10:40 UT, LT) to 18 min at the longitude 16^0 (12:09 LT). The local time-dependence of τ that is revealed in this paper is in agreement with theoretical estimates reported in (Stubbe,1970).

INTRODUCTION

Experimental observations of the ionosphere at the time of solar eclipses provide the source of information about the character of behaviour of the various ionospheric parameters. The main parameters of the ionospheric response are the value of the delay τ with respect to the eclipse totality phase, as well as its amplitude A and duration ΔT. Almost all publications devoted to the study of the ionospheric response to solar eclipses present estimates of these parameters (see review by Cohen, 1984). A knowledge of these values makes it possible to refine, in terms of the respective aeronomic ionospheric models, the time constants of ionization and recombination processes at different heights in the ionosphere (Stubbe, 1970). But a large body of experimental data do not permit us to make any reliable estimates of the basic parameters of the ionospheric response.

The development of the global navigation system GPS and the creation, on its basis, of extensive networks of GPS stations (which at the November of 2000 consisted of no less than 757 sites), the data from which are placed on the INTERNET, open up a new era in remote sensing of the ionosphere. A unique opportunity to exploit the potential of the GPS network was provided by the total solar eclipse of August 11, 1999. For this period of time, the INTERNET made available the data from at least 100 GPS stations located in Western and Central Europe within and near the totality path.

The objective of this paper is to determine the basic parameters of the ionospheric response to the August 11, 1999 total solar eclipse using these data. Figure 1a shows a schematic map of the path of the Moon's shadow crossing parts of Western and Central Europe (the data from Espenak, 1999). The centre line of eclipse at ground level is shown as a thick line, and thin lines correspond to the southern and northern boundaries. The symbols + and • designate the locations of GPS stations - their entire set. The symbols + correspond to the near zone. The location of ionospheric station Chilton (RAL) is shown by ★. Numbers for the longitudes 10^0 W, 0^0, 10^0 E, 20^0 E, 30^0 E, 40^0 E designate the local time for these longitudes.

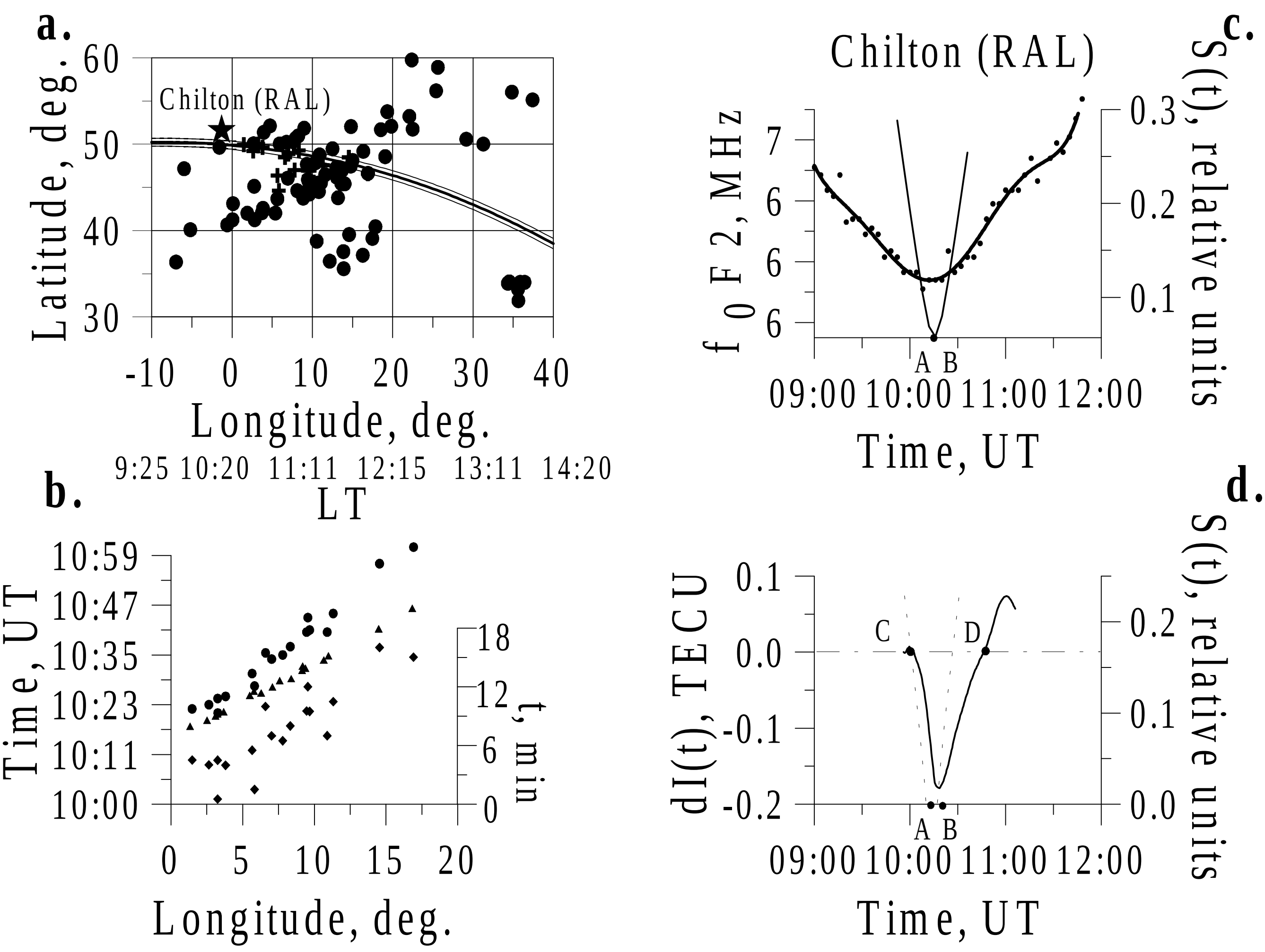

Fig.1: a) Schematic map of the Moon's shadow sweeping through parts of Western and Central Europe; b) Longitudinal dependence of the time position of minima of the curve dI(t); c) Dots designate the variations of critical frequencies f_0F2, measured on August 11, 1999 at station Chilton (RAL). Thick curve correspond to the same values, but smoothed with the time window of 60 min. This panel plots also the geometrical function of eclipse at 300 km altitude, S(t), calculated for the subionospheric point of PRN 14 - the thin line. Minimum values of S(t) and f_0F2 correspond to the points A and B in this figure. The points A and B coincide because of small scale of the figure and small value of time delay between them; d) Filtered variations of the total electron content dI(t) for station HERS (PRN 14) for August 11, 1999 - the thick line. This panel plots also the geometrical function of eclipse at 300 km altitude, S(t), calculated for the subionospheric point of PRN 14 - the dashed line. Minimum values of S(t) and f_0F2 correspond to the points A and B in this figure. The time interval between the times of intersection of the dash-dot line dI=0 (points C and D) can serve as an estimate of the duration of the response ΔT.

In this paper we confine ourselves to analysing only to a region of Western and Central Europe from the coast of southern England to the point with coordinates 56.03^0 N, 37.2^0 E, where the totality phase was observed at 11:20 UT (14:20 LT). Thus the solar eclipse effect occurred for the conditions of the daytime summer ionosphere. The period under consideration was characterized by a low level of geomagnetic disturbance (Dst - variation from -10 to -20 nT), which simplified greatly the problem of detecting the ionospheric response of eclipse.

RESULTS OF OBSERVATIONS

The f_0F2 - variations, measured at ionospheric station Chilton (RAL) at time intervals of 11 min, are presented in greater detail in Figure 1c (heavy dots). The thick curve connecting these dots is an approximating one for these values. This panel plots also the geometrical function of eclipse S(t) at 300 km altitude (thin line), calculated for station Chilton. The geometrical function of eclipse S(t) represents a portion of the solar disk area that is not occulted by the Moon's shadow, and is expressed in fractions of this area on a per-unit basis. For calculating the geometrical function of eclipse, we have developed a special program which enables S(t) to be calculated at any height (calculations in this study were performed for the heights of subionospheric points). The mathematical apparatus that was used in writing this program, is described in a large number of publications, to cite an example (Michailov, 1954). Minimum values of f_0F2 and S(t) correspond to the points A and B in this figure. The respective delay τ between the time of a minimum of f_0F2 and of the function S(t) is close to 11 min in this case. The points A and B coincide because of small scale of the figure and small value of time delay between them. We now give a brief account of the sequence of procedures used in processing the GPS data.

Input data are represented by series of “oblique” values of TEC I(t), as well as by the corresponding series of elevations $\Theta(t)$ measured from the ground, and azimuths $\alpha(t)$ of the line of sight to the satellite measured clockwise from the northward direction. These parameters are calculated by our developed CONVTEC program by converting the GPS-standard RINEX-files from the INTERNET (Afraimovich et al., 1998). Series of elevations $\Theta(t)$ and azimuths $\alpha(t)$ of the line of sight to the satellite are used to determine the location of subionospheric points. In the case under consideration, all results were obtained for larger than 45^0 elevations $\Theta(t)$. With the purpose of eliminating variations of the regular ionosphere, as well as trends introduced by the satellite's motion, we employ the procedure of eliminating the trend by preliminarily smoothing the initial series with the time window in the range from 40 to 100 min which is fitted for each TEC sampling. Such a procedure is also required for a clearer identification of the ionospheric response of eclipse which is characterized by a relatively small amplitude (see below) under the presence of space-time TEC variations that are not associated with the eclipse. The selection of the time window from 40 to 100 min when removing the trend is reconciled with the expected duration of the ionospheric response. The determination accuracy of the time of the TEC response extremum at the chosen values of the time window was sufficiently high (not worse than 1 min). The reason is that under the conditions of the magnetically quiet day of August 11, 1990 (the largest value of Dst did not exceed -11 nT) the amplitude of TEC background variations was far below the amplitude of the TEC response to the eclipse.

Figure 1d presents the filtered variations of TEC dI(t) for GPS station HERS for PRN 14 during August 11, 1999 (thick line). This panel plots also the geometrical function of eclipse at 300 km altitude (dashed line), S(t), that is calculated for the subionospheric point of GPS satellite PRN 14. A minimum value of S(t) corresponds to the point A in the figure. As is apparent from this figure, the form of the filtered variations is similar to a triangle whose vertex (point B) corresponds to the time at which the TEC attains its minimum value. The value of dI_{min} itself can serve as an estimate of the amplitude of TEC response to eclipse, and the time interval between the times of intersection of the dash-dot line dI=0 (points C and D) can serve as an estimate of the duration of the response ΔT.

Particular interest was provoked by the study on the F-region dynamics at the time of eclipse, and by the correlation between the changes of S(t) and TEC. Of practical interest is the delay between the S(t) and dI(t) minima. The corresponding delay τ between the times of the minimum of dI_{min} and of the function S(t) in this case was found to be 11 min, which coincides with the estimate of τ for ionospheric station Chilton. The response amplitude in this case was close to 0.18×10^{16} el m^{-2} (TECU), and the response duration as 46 min. Such dI(t) - variations are characteristic for all GPS stations and satellite PRN 01 and PRN 14. The choice of the same satellites, PRN 01 and PRN 14, for the entire selected set of GPS stations was dictated by the fact for these satellites a maximum value of the elevation Θ of the line of sight to the satellite exceeded 45^0 for the time interval 10:00-12:30 UT, which reduced to a minimum the possible error of conversion to the “vertical” value of TEC as a consequence of the sphericity.

The mean value of τ for the entire set of stations is 16 min, while for the stations in the near zone this value is 7 min. The mean value of the amplitude A=0.3 TECU for all stations and A=0.1 TECU for the near zone. The width of the TEC trough for the far and near zones ΔT = 60 min, on average. It is evident in Figures 1c, d that the TEC and f_0F2 variations have identical forms for the time interval 9:00-12:00 UT. Such a picture is accounted for by specific (i.e. atypical of the usual conditions) photochemical processes (Boitman et al., 1999; Huang et al., 1999), as well as by electrodynamic processes (Tsai and Liu, 1999) which are taking place over the time interval under consideration.

Figure 1b presents a longitudinal dependence of the time position t_{min} of minima of the curves dI(t) for subionospheric points lying in the immediate vicinity of the eclipse band (PRN 1 and PRN 14) - heavy dots. Shaded symbols Δ designate the variations of the totality phase of eclipse at 300 km altitude for subionospheric points as a function of longitude. Shaded symbols ◊ correspond to delay times between maximum of the geometrical function of eclipse and a minimum in TEC. It was found that the delay τ increases gradually from 4 min at the Greenwich longitude (10:23 UT, LT) to 18 min at the longitude of 16^0 (12:09 LT).

CONCLUSIONS

The key feature of our data is a higher reliability of determining the main parameters of the response to eclipse which is due to high space-time resolution and to the increased sensitivity of detection of ionospheric disturbances inherent in the GPS-array method which we are using. Also, due regard must be had to the fact that the distinctive property of the eclipse under consideration was a relatively small response amplitude, which required special filtering of the TEC series. The reason is that, unlike a number of eclipses for which more-or-less reliable data were obtained, this eclipse occurred in the summer season characterized by only moderate differences of the daytime and night-time ionization. The linear recombination coefficient β undergoes serious changes over a diurnal period of time (Akasofu and Chapman, 1974), with the mean values and the amplitude of such changes depend on the concentration of the molecular component of neutral gas. This property of the recombination term explains some of the properties of the diurnal variations in electron density in the F2-layer maximum.

The form and amplitude of the electron density variation during the daytime depend on: a) the initial (predawn) value of the molecular ion density in the atmosphere; and b) on the concentration of the molecular component of neutral gas. The initial conditions produce an effect on the morning growth rate of electron concentration, and the concentration of molecular gases determines amplitude (at noon) values of the recombination coefficient. The recombination rate in the morning hours is determine by the residual rate of molecular ions which remains at the level, to which the layer minimum is cause by the diffusion to come down before the sun-rise. Consequently, the initial morning values of β depend, among other factors, on the duration of the night. The summer conditions are characterized by a high number density of molecular ions throughout the entire diurnal period of time. This accounts for the slow increase in electron concentration in the morning, and for its minor changes over the course of the daytime. It is also vital to note that the time constant of a decrease in ionization in the F2 maximum exceeds substantially the duration of the totality phase of eclipse, which leads also to a decrease in response amplitude.

The local time-dependence of τ that is revealed in this paper is in agreement with theoretical estimates reported in (Stubbe, 1970). The value of τ for f_0F2, approaching 6 min, corresponded to 13:40 LT.

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