PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 64 (2002) 1933–1941

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Effects of the August 11, 1999 total solar eclipse as deduced from total electron content measurements at the GPS network

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Received 13 December 2000; received in revised form 14 December 2001; accepted 4 July 2002

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 100 GPS stations located in the neighborhood of the eclipse totality phase in Europe. The eclipse period was characterized by a low level of geomagnetic disturbance (D_{st}-variation from −10 to −20 nT), which alleviated significantly the problem of detecting the ionospheric response to the eclipse. Our analysis revealed a well-defined effect of a decrease (depression) of the total electron content (TEC) for all GPS stations. The delay 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 8 min at the longitude 16° (12:09 LT). The depth and duration of the TEC depression were found to be 0.2–0.3 TECU and 60 min, respectively. The results obtained in this study are in good agreement with earlier measurements and theoretical estimates.

Keywords: Total electron content; Total solar eclipse; Ionosphere; GPS

1. Introduction

Experimental observations of the ionosphere at the time of solar eclipses provide a source of information about the character of behavior of the various ionospheric parameters. Regular ionospheric effects of solar eclipses are fairly well understood. They imply an increase of effective reflection heights, a reduction in concentration in the F-layer maximum, and a decrease in total electron content (TEC) in the ionosphere, which is typical of the transition to the night-side ionosphere (Cohen, 1984). The behavior of the above parameters can be modeled using appropriate ionospheric models (Boitman et al., 1999; Stubbe, 1970).

The main parameters of the ionospheric response include 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 make estimates of these parameters. A knowledge of these values makes it possible to refine, in terms of the respective aeronomic ionospheric models, the time constants of ionization, and the recombination processes at different heights in the ionosphere.

The statistic of measurements of these parameters according to published data is presented in Table 1 (columns 5, 6 and 7, respectively). Table 1 also includes: Date—date of the total solar eclipse; Location—geographic region where the eclipse was observed or the path for the methods recording the delay time on the VLF signal ray path between the signal reception site and the transmitting station (VLF); FDS—frequency Doppler shift on the HF ray path between the signal reception site and the transmitting stations, as well as for the method of oblique-incidence ionospheric sounding (OIS); Method—method used in the investigation; Reference—reference to publication. The Note column (column 9 of Table 1) presents the time resolution of the method used in investigating the ionospheric response to total solar eclipse, and the number of stations. The following abbreviations are used in Table 1: I—vertical-incidence ionospheric sounding; DS—differential Doppler shift; GPS—Global

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1364-6826/02/$ - see front matter
PII: S1364-6826(02)00221-3

Table 1
General information

N	Data	Location	Method used	Para-meters	Results τ (min)	A	ΔT (min)	Reference	Note
	1	2	3	4	5	6	7	8	9
1	April 19, 1958	Haringhata	I	N_mF2, h_mF2, TEC	20, 20, 40	4×10^5 cm^{-3}, 40 km, 18×10^{-11} cm^{-2}	130, 100, 72	Datta et al. (1959)	2 min
2	March 18, 1988	East Asia (7–45°N; 114–142°E)	I	f_0F2, f_0E, N_mF2	15–30, 20–30, 5–20	0.2–1.4 MHz, 0.4–0.6 MHz, 0.7–1 $\times 10^{12}$ m^{-3}	100–120, 70–120, 160–170	Walker et al. (1991)	5 min
3	September 23, 1987	Chung-Li; Chung-Li–Yosami; Lunping Observatory	I; VLF; DS	f_0F2, h_pF2; VLF; DS	28, 34; 8; 1–20	1 MHz, 30 km; 2.3 μs; 0.7–1 $\times 10^{12}$ m^{-3}	100, 50; 96; 105–140	Cheng et al. (1992)	—
4	March 9, 1997	Tomsk, Novosibirsk, Krasnoyarsk, Magadan, Irkutsk	I; OIS	h'F2, f_0F2, h'; f_D	−10–30, 9.5, −26, 6–16	25, —, —, 0.5–1.5–2.3–3 Hz	70, 50, 26; 150	Borisov et al. (2000)	1 St; 4 OIS
5	March 9, 1997	Russia, Irkutsk–Tory	OIS; FDS	N_mF2; FDS	12–20; ~ 0	11×10^4 cm^{-3}; 0.5–1.5 Hz	40–120; 120	Boitman et al. (1999)	15 min; 20 s
6	August 11, 1999	London–Troitsk, Praga–Troitsk	FDS	FDS	5–15	35–90 km	87	Cherkashin and Agafonnikov (2001)	2 FDS
7	October 24, 1995	GPS (14.6°–31°N; 121°E); Chung-Li	GPS; I	TEC; N_mF2	90–100, 80	−0.5 −2.3 $\times 10^{17}$ m^{-2}; 0.2–1 $\times 10^{12}$ m^{-3}	60–90, 240	Huang et al. (1999)	6 St, 1 St
8	March 9, 1997	Irkutsk	GPS	TEC	9–10	1–3 TECU	70–75	Afraimovich et al. (1998)	3 St, 30 s
9	October 24, 1995, March 9, 1997	South and North Asia	GPS	TEC	0–120, 0–400	−0.2–15 TECU, −0.4–14 TECU	80–200, —	Tsai and Liu (1999)	5 St
10	August 11, 1999	Europe	GPS	TEC	—	—	—	Feltens (2000)	60 St, 2 h

Positioning System; N_mF2—electron density in the F2-layer maximum; h_mF2—height of the F2-layer maximum; f_0F2—F2-layer critical frequency; f_0E—E-layer critical frequency; h_pF2—virtual height of the F2-layer; h'F2—virtual height of the lower boundary of the F2-layer; h'—virtual height at fixed plasma frequencies; f_D—frequency Doppler shift; A—signal amplitude; and St—number of stations. The Total Electron Content Units (TECU), which is equal to 10^{16} m^{-2} and is commonly accepted in the literature, will be used throughout the text.

Measurements of τ were made by analyzing the characteristics of the ionosphere-reflected radio signal at vertical-incidence soundings at a network of ionospheric stations (Borisov et al., 2000; Cheng et al., 1992; Datta et al., 1959; Huang et al., 1999; Walker et al., 1991). In the cited references, the value of τ was found to vary from 5 min (Walker et al., 1991; line 2 of Table 1) to 80 min (Huang et al., 1999; line 7 of Table 1) according to the N_mF2 data, and from 9.5 min (Borisov et al., 2000; line 4 of Table 1) to 30 min (Walker et al., 1991) according to the f_0F2 data. The amplitude A of a decrease in local electron density from 0.2 to 1×10^{12} m^{-3} (N_mF2), and from 0.2 to 1.4 MHz (f_0F2). The response duration $\Delta T =$ 100–240 min according to the data on N_mF2 and f_0F2.

To analyze the ionospheric effects from the total solar eclipse of September 23, 1987, Cheng et al. (1992) used the phase variation of the VLF signal transmitted from NDT, Yosami (34.97°N; 137.02°E), Japan, and recorded at Kaojong (24.95°N; 121.15°E), Taiwan, as well as the differential Doppler shift data from the Lunping Observatory (25°N; 121.17°E). Results of this investigation are presented in line 3 of Table 1.

Interesting results were obtained by investigating the ionospheric response to the total solar eclipse of March 9, 1997 (Boitman et al., 1999; line 5 of Table 1) and of August 11, 1999 (Cherkashin and Agafonnikov, 2001; line 6 of Table 1) using FDS and OIS (Boitman et al., 1999; Borisov et al., 2000; lines 5 and 4 of Table 1).

Boitman et al. (1999) used the following radio sounding paths: Tory (51.7°N; 103.8°E)-Irkutsk, Tory-Ulan-Ude, Tory-Krasnoyarsk, Tory-Chita (recording of FDS), and Tory-Irkutsk (OIS method). To investigate the ionospheric response to the total solar eclipse of March 9, 1997, Borisov et al. (2000) used frequency Doppler shift data obtained from soundings for the following paths: Novosibirsk–Tomsk, Krasnoyarsk–Tomsk, Magadan–Yakutsk, Komsomolsk-na-Amur–Yakutsk, Khabarovsk–Yakutsk, Yakutsk–Tomsk, Magadan–Tomsk, Irkutsk–Tomsk, and Thushima–Tomsk. According to the data obtained using OIS, $\tau = 6$–20 min, $A = 0.5$–1.5 Hz (for short paths) and 2.3–3 Hz (for long paths), and $\Delta T = 40$–150 min (lines 4 and 5 of Table 1).

Cherkashin and Agafonnikov (2001) investigated the ionospheric response to the total solar eclipse of August 11, 1999 for the following paths: London (GB)–Troitsk (IZMIRAN) with $L = 2.5$ Mm (at 12095 kHz frequency), and Prague (Czech Republic)–Troitsk (at 9520 kHz frequency). In the cited reference the value of the frequency Doppler shift was converted to the amplitude A of the variation of the reflection height (line 6 of Table 1). The values of τ and ΔT, obtained by Boitman et al. (1999) and Cherkashin and Agafonnikov (2001) using FDS are 0–15 min and 87–120 min (lines 5 and 6 of Table 1), respectively.

The development of the global navigation system GPS and the creation, on its basis, of extensive networks of GPS stations (which at the end of 2001 consisted of no less than 900 sites), the data from which are placed on the Internet Klobuchar (1997), opens up a new era in remote sensing of the ionosphere. At almost any point of the globe and at any time at two coherently coupled frequencies $f_1 =$ 1575.42 MHz and $f_2 = 1227.60$ MHz, two-frequency multichannel receivers of the GPS system are used to carry out high-precision measurements of the group and phase delay along the line of sight between the ground-based receiver and satellite-borne transmitters in the zone of reception. The sensitivity afforded by phase measurements in the GPS system permits irregularities to be detected with an amplitude of up to 10^{-3}–10^{-4} of the diurnal variation of TEC.

A large body of data of analysis of the ionospheric response to total solar eclipse was obtained using the GPS (Afraimovich et al., 1998; Feltens, 2000; Huang et al., 1999; Tsai and Liu, 1999). The values of τ, A and ΔT, derived from investigating the ionospheric response to total solar eclipses using the GPS, differ greatly (τ varies from 0 to 330 min, A ranges from 0.2 to 15 TECU, and ΔT varies between 60 and 240 min). The large scatter of the values of τ, A and ΔT is likely to be associated with the difference of the longitude and latitude ranges, over which the investigations were carried out, the season, the technique for processing the GPS data, as well as with differing geomagnetic situations.

To investigate the ionospheric response to the total solar eclipse of March 9, 1997, Afraimovich et al. (1998) used the variations in total "oblique" electron content. In examining the ionospheric effect from the total solar eclipses of October 24, 1995 and March 9, 1997, Huang et al. (1999) and Tsai and Liu (1999) analyzed the variations in "vertical" TEC. Tsai and Liu (1999) carried out their investigations near the magnetic equator; for that reason, the TEC series contain, in addition to the response to total solar eclipse, variations caused by the dynamics of the equatorial anomaly.

Feltens (2000) investigated the ionospheric response to the August 11, 1999 total solar eclipse using total electron content maps (TEC maps, line 10 of Table 1), the raw data for which are represented by TEC series obtained by means of the global network of GPS receivers. Taking into account the temporal resolution of standard TEC maps (2 h) as well as the parameter ΔT derived from analyzing earlier work (1–1.5 h) it can be concluded that such TEC maps do not secure the necessary determination accuracy of τ, A and ΔT.

Hence, a large body of experimental data do not permit us to make any reliable estimates of the basic parameters of the ionospheric response. One of the reasons for such a great difference is that different methods of measurements are used, which differ greatly by spatial and temporal resolution. However, the main reason is caused by dissimilar characteristics of the eclipse itself, by geophysical conditions of individual measurements, and by a large difference in latitude, longitude and local time when experiments are conducted.

To obtain more reliable information about the behavior of the ionosphere during an eclipse requires simultaneous measurements over a large area covering regions with different local times. Furthermore, high spatial (of some tens of kilometers at least) and temporal (at least 1 min) resolution is needed. However, none of the above familiar methods meets such requirements.

The objective of this paper is to determine the basic parameters of the ionospheric response to the August 11, 1999 total solar eclipse using GPS data from at least 100 GPS stations located in Western and Central Europe within and near the totality path.

General information about the eclipse, and a description of the experimental geometry are given in Section 2. The ionospheric response to the eclipse is discussed in Section 3 using the data from reference ionospheric station Chilton. The processing technique for the GPS network data, and results derived from analysing the ionospheric response of the August 11, 1999 solar eclipse in Europe are outlined in Section 4. Results obtained in this study are discussed in Section 5.

2. The geometry and general information of the total solar eclipse, August 11, 1999

The last solar eclipse in the 20th century began in the North Atlantic, and the path of the Moon's shadow made first landfall in south-western England at 10:10 UT; the Sun at that time was at an angle of 45° over the eastern horizon. The center line duration of total eclipse averaged 2 min, and the total eclipse was confined to a narrow corridor 103 km wide.

Fig. 1 shows a schematic map of the path of the Moon's shadow crossing parts of Western and Central Europe (the data from Espenak and Anderson (1999) were used in constructing this map). The centerline of eclipse at ground level is shown as a thick line, and thin lines correspond to its southern and northern boundaries. The location of reference ionospheric station Chilton (RAL) is marked by the symbol ★. Dots • and symbols + show the locations of the GPS stations used in the analysis. Dots •, together with symbols + are used to represent a total set of GPS stations. Symbols + form a network of GPS stations located near the eclipse path; therefore, we designated this group as the near zone. Numbers for the longitudes 10°W, 0°, 10°E, 20°E, 30°E, 40°E correspond to the local time for these longitudes.

In this paper, we confine ourselves to analyzing only a region of Western and Central Europe from the coast of southern England to the point with coordinates 56.03°N, 37.2°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 distance along the great-circle arc between the above-mentioned extreme points is about 2900 km, with the time difference of 67 min only. Hence, a distinguishing characteristic of this eclipse, was the supersonic speed of the Moon's shadow sweeping across the terrestrial surface, exceeding 720 m/s.

At ionospheric heights the totality path was travelling somewhat further south. The onset time of the totality phase for the height $h = 300$ km over Budapest is 1.3 min ahead of that at ground level. The difference in the values of the totality phases and their onset times is caused by the Sun's altitude over the horizon. At the time of the totality phase in Budapest (11:05 UT, or 14:05 LT), it was as small as 59°.

The period under consideration was characterized by a low level of geomagnetic disturbance (D_{st}-variation from −10 to −20 nT), which simplified greatly the problem of detecting the ionospheric response of eclipse.

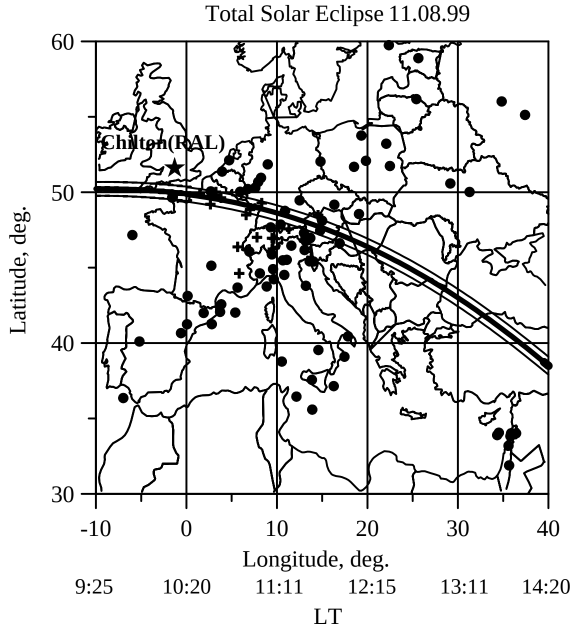

Fig. 1. Schematic map of the Moon's shadow sweeping through parts of Western and Central Europe. The center line of eclipse at ground level is shown as a thick line, and thin lines correspond to the southern and northern boundaries. The symbols + and ● designate the locations of GPS stations—their entire set (these stations were used in calculating the parameters appearing in the first line of Table 2). The symbols + correspond to the near zone (the stations of this group were used in calculating the parameters appearing in the second line of Table 2). The location of ionospheric station Chilton (RAL) is shown by ★. Numbers for the longitudes 10°W, 0°, 10°E, 20°E, 30°E, 40°E designate the local time for these longitudes.

3. The ionospheric response to the eclipse in data from the ionospheric station Chilton

First we consider the variations of critical frequencies f_0F2 over the time interval 00:00–24:00 UT on August 11, 1999 according to the data from station Chilton (RAL)—Fig. 2a. The onset time of the totality phase of eclipse in the area of station Chilton (RAL) at 300 km altitude is shown by a vertical solid line. As might be expected under the conditions of the summer ionosphere, the mean level of f_0F2 differs only slightly for the night-time and daytime. Nevertheless, a decrease of f_0F2 during the totality phase of eclipse is sufficiently clearly distinguished.

Consider the variations of ionospheric parameters for the time interval 06:00–15:00 UT on August 11, 1999, and on the background days of August 10 and 12, using the

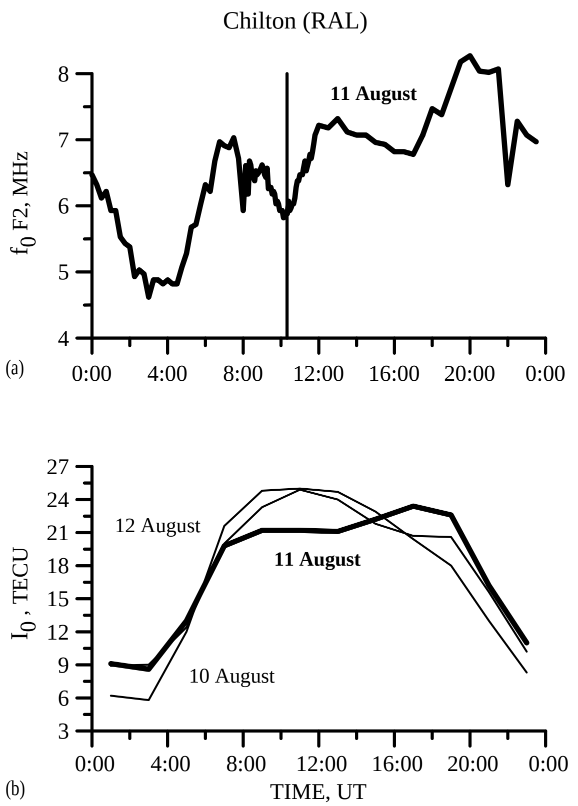

Fig. 2. (a) Variations of the critical frequencies f_0F2 over the time interval 00:00–24:00 UT on August 11, 1999 according to the data from station Chilton (RAL). (b) Variations of the absolute vertical value of TEC for the same time interval of August 11, 1999 (thick line), and for the background days of August 10 and 12 (thin lines)—see text. The onset time of the totality phase of eclipse at 300 km altitude is shown by a vertical solid line.

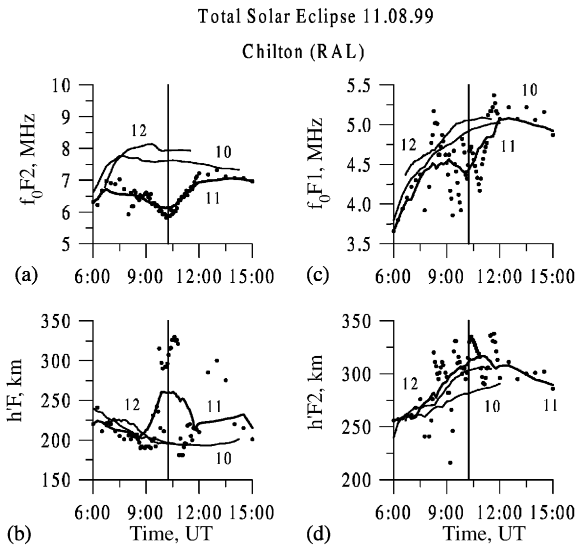

Fig. 3. Variations of ionospheric parameters during 06:00–15:00 UT on August 11, 1999 and on the background days of August 10 and 12, based on the data from station Chilton (RAL). Dots designate the variations of critical frequencies f_0F2 (panel a), f_0F1 (panel c), apparent heights h'_F (panel b), and h'_{F2} (panel d). Solid curves correspond to the same values, but smoothed with the time window of 60 min (only smoothed curves are given for August 10 and 12). The onset time of the totality phase of eclipse at 300 km altitude is shown by a vertical solid line.

data from station Chilton (RAL)—Fig. 3. Dots correspond to variations of critical frequencies f_0F2 (panel a), f_0F1 (panel c), apparent heights h'F (panel b), and h'F2 (panel d) for August 11, 1999. Solid curves plot the same values that are smoothed with a time window of 60 min. For August 10 and 12, only smoothed curves are given, with the same time window of 60 min. The onset time of the totality phase of eclipse (10:16 UT) at 300 km altitude over the station is shown by a vertical line.

The eclipse effect is most conspicuous in the variations of critical frequencies f_0F2, whose maximum difference from the background values on August 10 and 12 at the time of reaching a minimum (10:20 UT) was up to 2 MHz. On the other hand, the amplitude of a decrease of f_0F2 for the August 11 event (after the totality phase of eclipse) does not exceed 1 MHz. The eclipse effect on other parameters is not as clearly distinguished, and becomes evident only when comparing the smoothed curves. Similar results of measurements at an ionospheric station were obtained during the total solar eclipse of September 23, 1987 in south-eastern Asia (Cheng et al., 1992).

The f_0F2-variations, measured at station Chilton (RAL) at time intervals of 4 min, are presented in greater detail in Fig. 4a (heavy dots). The solid 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, calculated for station Chilton. 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 4 min in this case.

The data from the station Chilton (RAL) and from GPS station HERS nearest to it are compared in the next section.

4. The processing of GPS-network data and results of analysis of ionospheric effect by total solar eclipse of August 11, 1999

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

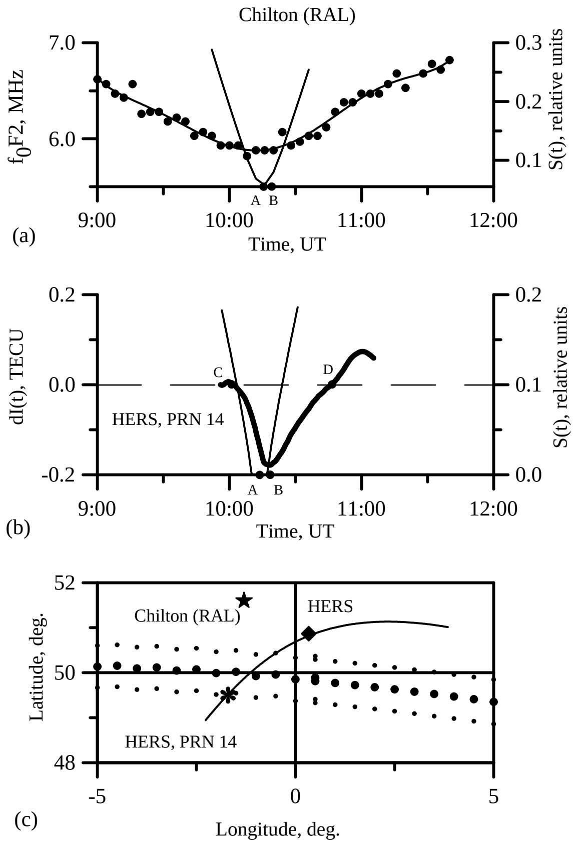

Fig. 4. (a) Values of the critical frequency f_0F2, measured on August 11, 1999 at station Chilton (RAL) at time intervals of 4 min during 09:00–12:00 UT (dots). The solid curve connecting these dots is an approximating one for these values. This panel plots also the geometrical function of eclipse at 300 km altitude, $S(t)$, calculated for station Chilton. (b) 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. (c) Experimental geometry in the area of ionospheric station Chilton (RAL)—★, and for GPS station HERS (♦). Heavy dots show the center line of eclipse at ground level, and smaller symbols · show the southern and northern boundaries. The symbol ∗ shows the position of the subionospheric point at the time of a maximum response of TEC.

program by converting the GPS-standard RINEX-files from the Internet. 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° elevations $\theta(t)$. The height of the F2-layer peak (300 km) is used to calculate the location of the subionospheric points for the entire set of GPS satellites.

Fig. 4c presents the experimental geometry in the area of ionospheric station Chilton (RAL) (★), and GPS station HERS (♦). Heavy dots • show the center line of eclipse at ground level, and smaller dots correspond to its southern and northern boundaries. The symbol ∗ shows the position of the subionospheric point at the time of a maximum response of TEC (see below).

Various methods for reconstructing the absolute value of TEC are currently under development using measurements of both phase and group delays; however, effective algorithms for an accurate solution of this problem are still unavailable for the different types of two-frequency receivers and operating modes of the GPS system. In this connection, for purposes of this paper, we limit our attention to considering only those TEC variations which were obtained from phase delay measurements by formula (Afraimovich et al., 1998):

$$I_p = \frac{1}{40.308} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} [(L_1\lambda_1 - L_2\lambda_2) + \text{const} + nL], \qquad (1)$$

where $L_1\lambda_1$ and $L_2\lambda_2$ are additional paths of the radio signal caused by the phase delay in the ionosphere, (m); L_1 and L_2 represent the number of phase rotations at the frequencies f_1 and f_2; λ_1 and λ_2 stand for the corresponding wavelengths, (m); *const* is the unknown initial phase ambiguity, (m); and nL are errors in determining the phase path, (m).

For an approximate specification of the TEC constant component I_0 at time intervals of 2 h, we made use of the Internet data on corresponding global maps of the absolute vertical value of TEC in the IONEX format (Mannucci et al., 1998)—see also Fig. 2b.

To normalize the response amplitude we converted the "oblique" TEC to an equivalent "vertical" value (Klobuchar, 1986):

$$I = I_p \times \cos\left[\arcsin\left(\frac{R_z}{R_z + h_{\max}} \cos\theta\right)\right], \qquad (2)$$

where R_z is the Earth's radius, and $h_{\max} = 300$ km is the height of the F_2-layer maximum.

Although, because of a strong horizontal TEC gradient and without regard for the sphericity of the problem, this procedure gives a very rough result, but this result is quite acceptable because all our results were obtained for larger than 45° 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.

For the purposes of illustration of the data processing procedure Fig. 5 presents the filtered TEC variations $dI(t)$ for August 11 (thick line), and for the background days of August 10 and 12, 1999 (thin lines) for station HERS for satellite N14 (PRN 14) (c), as well as for stations ZIMM

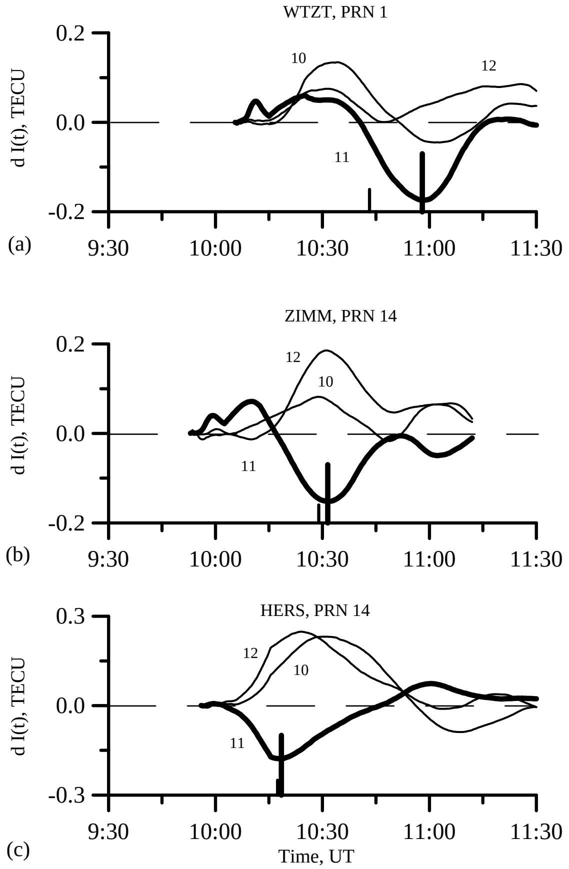

Fig. 5. Filtered variations of the total electron content $dI(t)$ for August 11 (thick line), and for the background days of August 10 and 12, 1999 (thin lines) for station HERS (a), ZIMM (b), and WTZT (c). Figures correspond to the GPS satellite numbers. The onset time of the totality phase of eclipse at 300 km altitude for corresponding subionospheric points is shown by thin vertical lines. The time of a minimum $dI(t)$ is shown by thick vertical lines.

(PRN 14) (b) and WTZT (PRN 1) (a), which are separated from station HERS, respectively, by 7° and 13° in longitude eastward. Figures correspond to GPS satellite numbers. The onset time of the totality phase of eclipse at 300 km altitude for the corresponding subionospheric points is shown by thin vertical lines. The time of a minimum $dI(t)$ is shown by thick vertical lines. As is evident from the figure, responses to the eclipse at these stations are very similar in both form and amplitude, but the response delay increases with the longitude. $dI(t)$-variations for the background days of August 10 and 12, 1999 for different stations differ substantially not only from the TEC response to eclipse but also from one another.

Fig. 4b presents the filtered variations of TEC $dI(t)$ for station HERS for PRN 14 during August 11, 1999 (thick line). This panel plots also the geometrical function of eclipse at 300 km altitude, $S(t)$, that is calculated for the

Table 2
The ionospheric parameters of total solar eclipse of August 11, 1999

N	Number of subionospheric points	A, TECU	ΔT (min)	τ (min)
1	98	0.298/0.197	62/32	16.4/14
2	19	0.193/0.081	61/36	8/4

subionospheric point of 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 line $dI = 0$ (points C and D) can serve as an estimate of the duration of the response ΔT. 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 4 min, which coincides with the estimate of τ for ionospheric station Chilton (see Section 3). The response amplitude in this case was close to 0.18 TECU, and the response duration was 46 min.

Such $dI(t)$-variations are characteristic for all GPS stations and satellite numbers 1 and 14. The choice of the same satellites, PRN 1 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° 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 first line of Table 2 presents the results of a statistical processing for the entire set of GPS stations. The second line includes only those stations which lie in the immediate vicinity of the eclipse path, within ±5° with respect to the center line (near zone). In Table 2, the values before the bar are mean values, and those after the bar correspond to the standard deviation. 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 8 min. The mean value of the amplitude $A = 0.3$ TECU for all stations and $A = 0.2$ TECU for the near zone. The width of the TEC trough for the far and near zones $\Delta T = 60$ min, on average.

Fig. 6 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 (satellites 1 and 14)—heavy dots. Symbols ▲ designate the times of totality phases of the geometrical function of eclipse versus longitude which are calculated for the subionospheric points. Symbols ♦ correspond to delay times between maximum of the geometrical function of eclipse and a minimum in TEC.

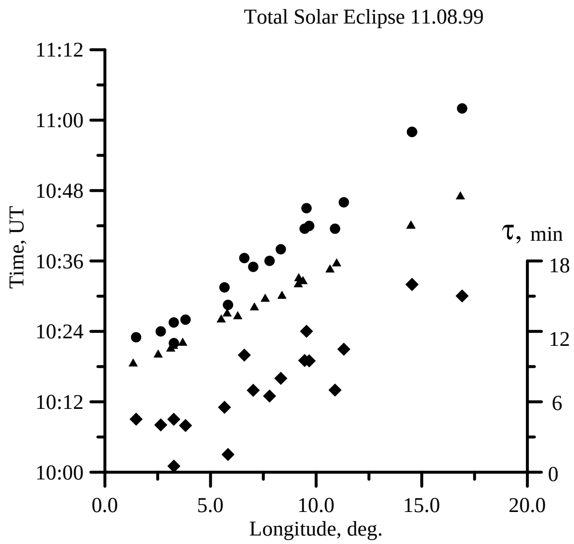

Fig. 6. Longitudinal dependence of the time position of minima of the curve $dI(t)$ for the stations in the near zone—heavy dots ●. The symbols ▲ designate the variations of the totality phase of eclipse at 300 km altitude for subionospheric points as a function of longitude. The symbols ◆ plot the longitudinal dependence of the delay τ of the TEC response $dI(t)$.

It was found that the delay τ increases gradually from 4 min at the Greenwich longitude (10:23 UT, LT) to 16 min at the longitude of 16° (12:09 LT).

5. Conclusions

Our results are in good agreement with earlier measurements (e.g. Cherkashin and Agafonnikov, 2001) and theoretical estimates (see a review of the data in the Introduction and in Table 1). 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 given 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 (see preceding Section). 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. Furthermore, in this situation the time variation of f_0F2 and vertical TEC near noon usually shows a minimum which, in essence, masks the eclipse effect (see also Fig. 2b). 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 linear recombination coefficient β undergoes serious changes over a diurnal period of time, with the mean values and the amplitude of such changes depend on the concentration of the molecular component of neutral gas (Polyakov et al., 1968). 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 determined by the residual rate of molecular ions which remains at the level, to which the layer minimum is caused 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.

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. Using modeling methods (Ivelskaya et al., 1977) showed that the variations of the delay time τ of minimum local electron density $N_e(t)$ with respect to a minimum of the ion production function are as follows: $\tau = 1$–2 min at 150 km altitude, $\tau = 3$ min at 200 km, $\tau = 20$ min at 300 km, and $\tau = 45$ min above 600 km. In this paper (Ivelskaya et al., 1977), τ is estimated, respectively, at about 3 min for 200 km altitude and 20 min for 300 km altitude for 12 LT.

Acknowledgements

We are grateful to A.V. Tashchilin and A.D. Kalikhman for their interest in this study, helpful advice and active participation in discussions. Thanks are also due to V.G. Mikhalkosky for his assistance in preparing the English version of the manuscript. Finally, the authors wish to thank the referees for valuable suggestions which greatly improved the presentation of this paper. This work was done with support from the Russian foundation for Basic Research (Grant 00-05-72026) and RFBR grant of leading scientific schools of the Russian Federation no. 00-15-98509.

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