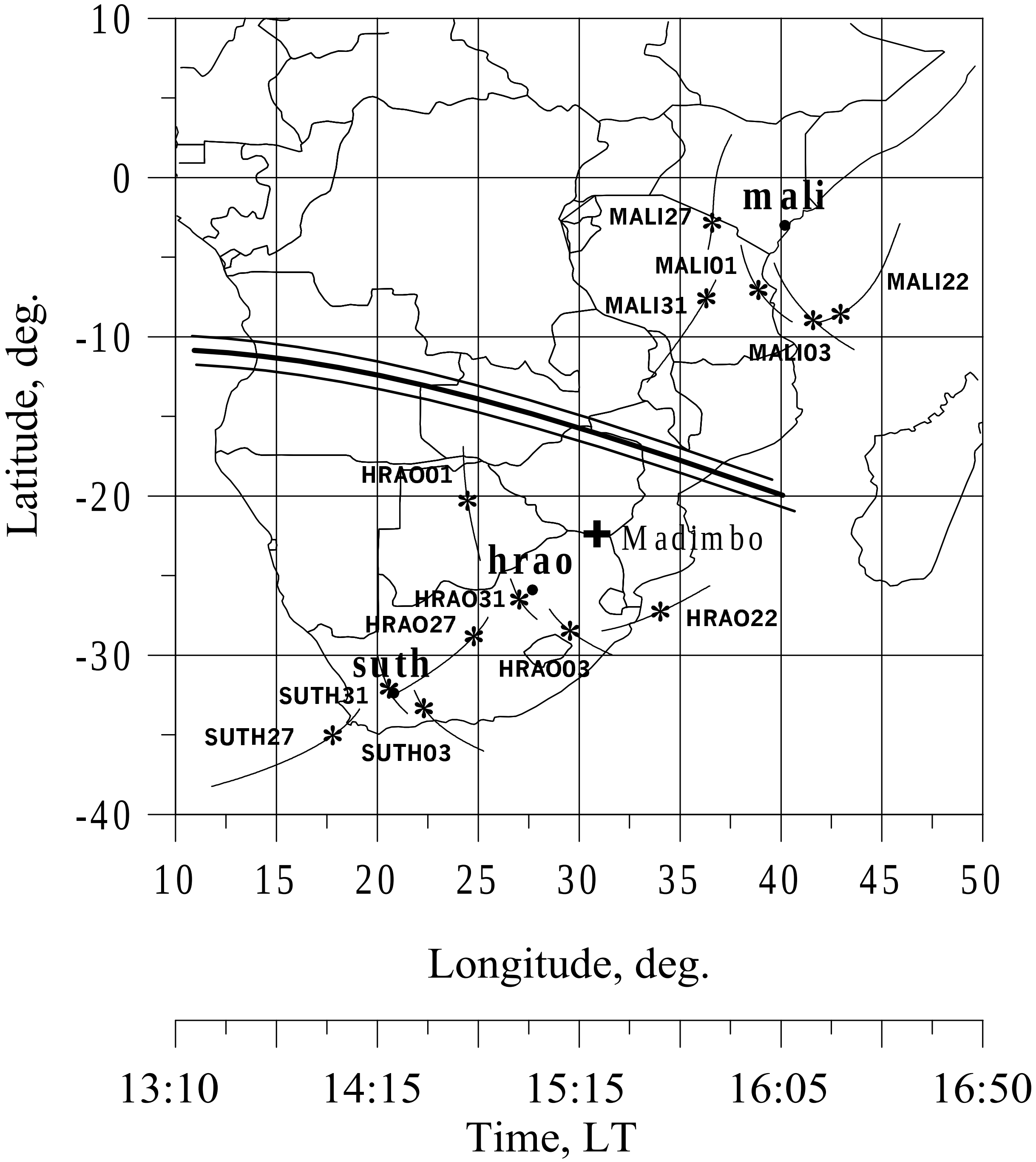

Fig. 1: Schematic map of the Moon's shadow along the surface in Africa. The heavy line shows the centerline of the eclipse at the ground level, and thin line show the southern and northern boundaries. The location of the reference ionospheric station Madimbo (22.38°S; 30.88°E) is shown by the heavy cross symbol. Heavy dots correspond to the locations of the GPS stations used in the analysis; their geographic coordinates are presented in Table 1. Numbers for the longitudes of 10°, 20°, 30°, 40° and 50°E correspond to the local time of eclipse totality at ground level. The snowflake symbol shows the location of the subionospheric point at the time of a maximum TEC response.

N	Data	Location	Method used	Parameters	Results			Reference	Note
					τ, min	A	ΔT, min		
	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, $0.7\text{-}1\times10^{12}$ 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; $0.7\text{-}1\times10^{12}$ 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; $\sim$0	11×10^4 cm^{-3}; 0.5-1.5 Hz	40-120; 120	*Boitman et al.*, [1999]	15 min; 20 sec
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- $-2.3\times10^{17}m^{-2}$; $0.2\text{-}1\times10^{12}m^{-3}$	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 sec
9	August 11, 1999	Europe	GPS	TEC	4-16	0.1-0.3 TECU	32-62	*Afraimovich et al.*, [2001]	100 St, 30 sec
10	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
11	August 11, 1999	Europe	GPS	TEC	-	-	-	*Feltens,* [2000]	60 St, 2h

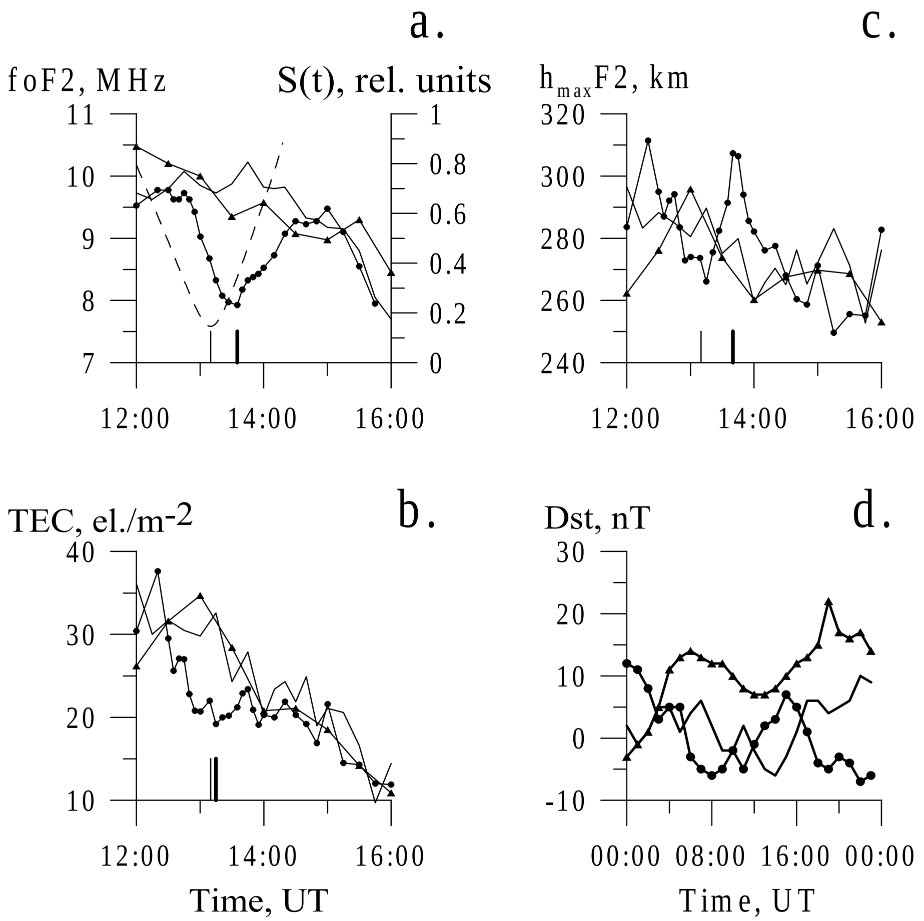

Fig. 2: The variations of ionospheric parameters over the time interval 12:00 - 16:00 UT on June 21 and on the background days of June 20 and 22, 2001, using the data from station Madimbo - panels a, b, c. Solid curves with dots correspond to the variations in critical frequencies f_0F2 (panel a), TEC (panel b), and the heights of the F2-layer maximum (panel c) for June 21, 2001 (from here on the heights of the F-region and higher altitudes are implied). Solid curves and solid curves with triangles show the variations of the parameters f_0F2, TEC, and h_mF2 for June 20 and 22, 2001, respectively. The dashed curve on panel a shows the geometrical function of eclipse S(t) obtained for ionospheric station Madimbo during 12-14:22 UT. The onset time of the phase of totality (13:10 UT) at 300 km level at the station's location is shown by a thin vertical line (panels a, b, c). The thick vertical line (panels a, b, c) correspond to the time of a minimum of the f_0F2, TEC, h_mF2, respectively. Panel d shows the Dst-variations for June 20 (solid curve), June 20 (solid curve with dots), and June 22 (solid curve with triangles) 2001.

Table 2: Statistics of experiments

PRN	SLAT, deg.	SLON, deg.	t_{min}, h:min	A, TECU	ΔT, min	τ, min
HRAO (25.89°S; 27.69°E)						
1	-20.30	24.47	13:29	-0.815	53	28
3	-28.47	29.55	13:14	-0.723	30	13
13	-25.73	22.90	13:03	-0.879	60	9
22	-27.27	34.03	13:24	-0.682	49	13
27	-28.81	24.78	13:30	-0.503	41	34
31	-26.49	27.03	13:13	-0.850	47	14
SUTH (32.38°S; 20.81°E)						
27	-35.04	17.79	13:09	-0.523	39	37
31	-32.99	20.97	13:00	-0.693	59	21
MALI (2.99°S; 40.19°E)						
31	-7.05	38.88	13:39	-0.640	67	10

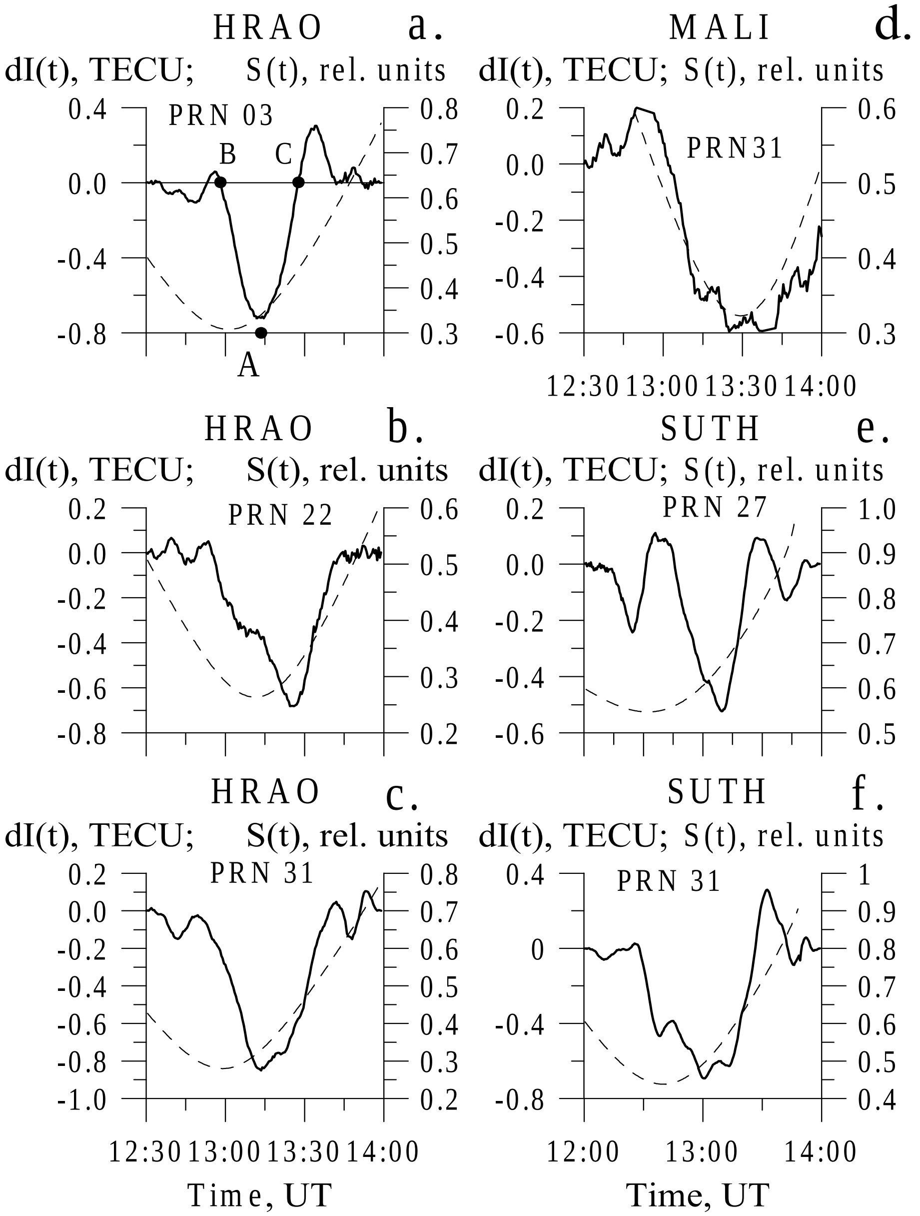

Fig. 3: The filtered variations of TEC $dI(t)$ for HRAO stations for satellite N03 (PRN03) - panel a; HRAO (PRN22) - panel b; HRAO (PRN31) - panel c; MALI (PRN31) - panel d; SUTH (PRN27) - panel e; and SUTH (PRN31) - panel f for June 21, 2001 (heavy lines). These panels also show the geometrical eclipse functions $S(t)$ (dash lines) at 300 km altitude calculated for the corresponding subionospheric points. The filtered variations resemble in their form a triangle whose vertex (point A) corresponds to the time, at which a minimum TEC value is attained. The value of dI_{min} itself can serve as an estimate of the amplitude of the TEC response to eclipse, and the time interval between the times of intersection of the dI=0 line (points B and C) can serve as an estimate of the response duration ΔT.

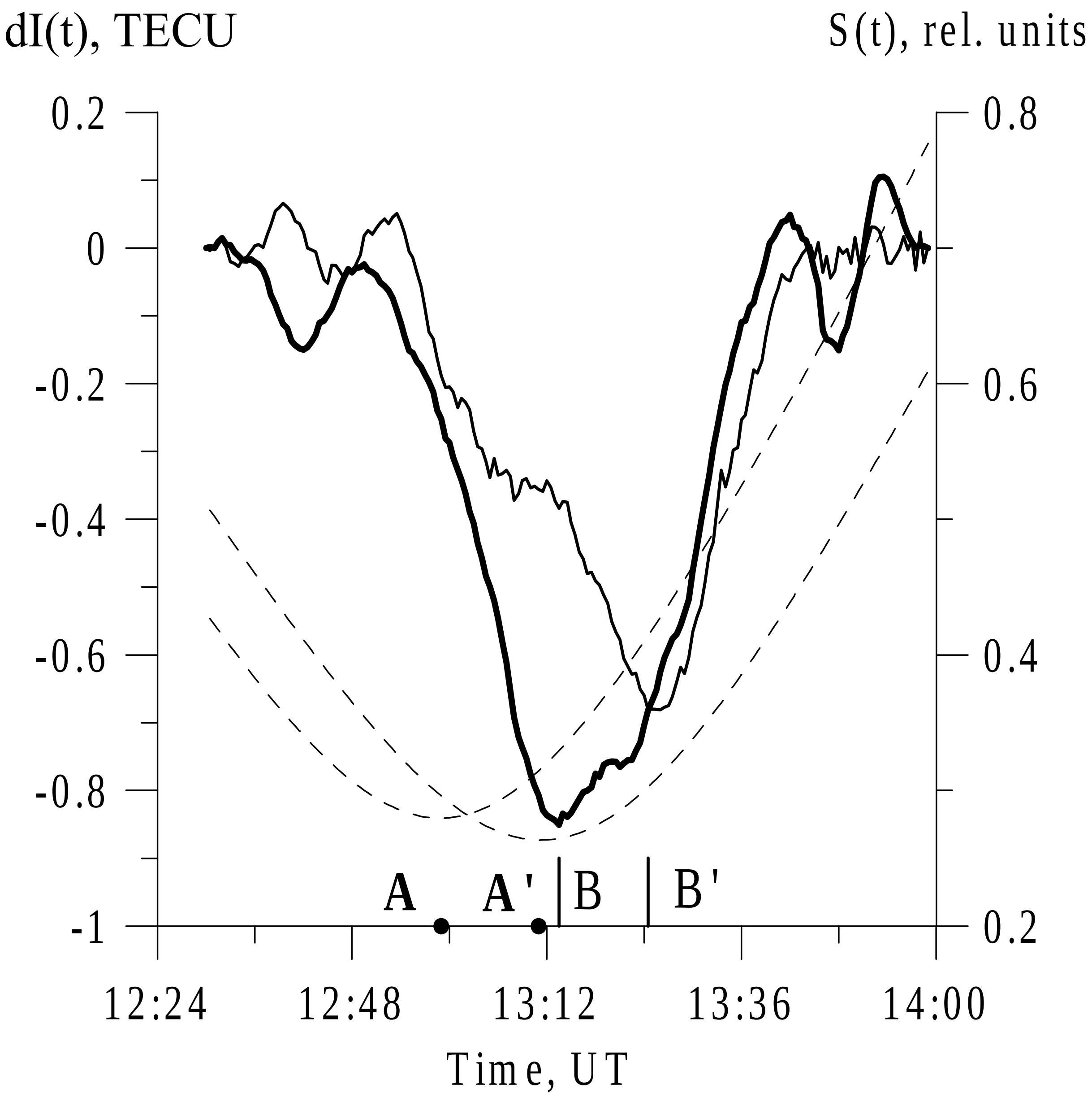

Fig. 4: The $dI(t)$ - variations for different subionospheric points of station HRAO: PRN22 - thin solid line, and PRN31 - thick solid line separated by 7° in longitude. As is evident from the figure, the responses to eclipse for the subionospheric points PRN22 and PRN31 are quite similar both in their form and in amplitude, but the delay of the response increases with longitude. A thin dashed line and a thin dashed line with dots in figure plot $S(t)$ for HRAO (PRN22) and HRAO (PRN31), respectively. The points **A** and **A**$'$ for GPS station HRAO (PRN31) correspond to the time of totality and the time of a minimum of the $dI(t)$, respectively. The points **B** and **B**$'$ for GPS station HRAO (PRN22) correspond to the time of totality and the time of a minimum of the $dI(t)$, respectively.

Ionospheric response to the total solar eclipse of June 21, 2001 as deduced from the data from the African GPS network

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Short title: IONOSPHERIC RESPONSE TO THE TOTAL SOLAR ECLIPSE OF JUNE 21, 2001

Abstract. We discuss the measurements of the main parameters of the ionospheric response to the total solar eclipse of June 21, 2001. This study is based on using the data from three stations of the global GPS network located in the area of the totality band in Africa. This period was characterized by a low level of geomagnetic disturbance (the Dst-index varied from -6 to 22 nT), which alleviated greatly the problem of detecting the ionospheric response to eclipse. An analysis revealed a clearly pronounced effect of a decrease (depression) of the total electron content (TEC) for all GPS stations. The delay between the smallest value of the TEC with respect to eclipse totality was 9-37 min. The depth and duration of the TEC depression were 0.5-0.9 TECU and 30-67 min, respectively. The results obtained in this study are in good agreement with earlier measurements and theoretical estimations.

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 nightside 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 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 TECU (Total Electron Content Units), 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,* 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 ΔT=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-on-Amur-Yakutsk, Khabarovsk-Yakutsk, Yakutsk-Tomsk, Magadan-Tomsk, Irkutsk-Tomsk, and Thushima-Tomsk. According to the data obtained using OIS, τ = 6-20 min, A = 0.5-1.5 Hz (for short paths) and 2.3-3 Hz (for long paths), and ΔT=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} of the diurnal variation of TEC [*Melbourne et al.,* 1994].

A large body of data of analysis of the ionospheric response to total solar eclipse was obtained using the GPS [*Afraimovich et al.,* 1998; *Afraimovich et al.,* 2001; *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 4 to 16 min, A ranges from 0.1 to 3 TECU, and ΔT varies between 32 and 75 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 eclipses of March 9, 1997 and August 11, 1999, *Afraimovich et al.,* [1998, 2001] used the variations in total "oblique" electron reflection and the "vertical" TEC value, respectively. The study of the ionospheric response to the August 11, 1999 total solar eclipse is based on using the data from about 100 GPS stations located in the neighbourhood of the eclipse totality phase in Europe.

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 hours) as well as the parameter ΔT derived from analyzing earlier work (1-1.5 hour) 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 behaviour 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.

In this paper the method of detecting the ionospheric response to solar eclipse, reported in *Afraimovich et al.* [2001], is used to estimate the main parameters of the ionospheric response to the total solar eclipse of June 21, 2001.

2. The geometry and general information of total solar eclipse June 21, 2001

The total solar eclipse of June 21, 2001 began in the South Atlantic Ocean 400 km to the south of Uruguay. The Moon's shadow made its first contact with the surface at 10:35 UT. The eclipse duration at that point was 2 min 6 s. Within two subsequent hours the shadow was moving along the surface of the South Atlantic Ocean. Totality occurred at 12:04 UT at the point with the coordinates 11.25°S; 2.75°E and lasted for 4 min 56 s. The velocity of the Moon's shadow along the surface averaged 1.2 km/s. For 2 h 56 min (duration of the total solar eclipse), the Moon's shadow traveled a distance of about 12000 km.

Figure 1 presents the schematic map of the movement of the Moon's shadow along the surface in Africa (based on using the data from *Espenak and Anderson* [2001]). The heavy line shows the centerline of the eclipse at the ground level, and thin line show the southern and northern boundaries. The location of the reference ionospheric station Madimbo (22.38°S; 30.88°E) is shown by the heavy cross symbol. Heavy dots correspond to the locations of the GPS stations used in the analysis; their geographic coordinates are presented in Table 1. Numbers for the longitudes of 10°, 20°, 30°, 40° and 50°E correspond to the local time of eclipse totality at ground level.

In this paper we have confined ourselves only to analyzing the area from the western coast of Africa to the point with the coordinates 19.95°S; 40.07°E, where the phase of totality was observed at 13:25 UT (16:09 LT). Thus the eclipse effect in the region under investigation took place for the conditions of the dayside summer ionosphere.

Fig. 2d shows the Dst-variations for June 20 (solid curve), June 20 (solid curve with dots), and June 22 (solid curve with triangles) 2001. This period was characterized by a low level of geomagnetic disturbance (within -6 - 22 nT), which alleviated greatly the problem of detecting the ionospheric response to eclipse.

3. The ionospheric response by eclipse from date of ionospheric station Madimbo

First we consider the variations of ionospheric parameters over the time interval 12:00 - 16:00 UT on June 21 and on the background days of June 20 and 22, 2001, using the data from station Madimbo - Fig. 2a, b, c. Solid curves with dots correspond to the variations in critical frequencies f_0F2 (panel a), TEC (panel b), and the heights of the F2-layer maximum (h_mF2) for June 21, 2001 (from here on the heights of the F-region and higher altitudes are implied). Solid curves and solid curves with triangles show the variations of the parameters f_0F2, TEC, and h_mF2 for June 20 and 22, 2001, respectively. The dashed curve on panel a shows the geometrical function of eclipse S(t) obtained for ionospheric station Madimbo during 12-14:22 UT.The geometrical function of eclipse $S(t)$ represents a part of the solar disk area that is not occulted by the Moon's shadow, and is expressed in fractions of this area in arbitrary units. To calculate the geometrical function of eclipse, we developed a special program which can be used to calculate S(t) at any heights. The mathematical apparatus that was used in preparing this program, was described in a large number of publications [e. g., *Mikhailov,* 1954].

The onset time of the phase of totality (13:10 UT) at 300 km level at the station's location is shown by a thin vertical line (Fig. 2a).

The eclipse effect is most clearly distinguished in the variations of critical frequencies f_0F2, the greatest difference of which from background values on June 20 and 22 at the time of a minimum (13:35 UT, thick vertical line in Fig. 2a) was 1.5-2 MHz. The delay between the times of totality and a minimum f_0F2 was 25 min (the time resolution of the data from the ionospheric data used in this study, is 5-15 min).

The delay τ between the times of a minimum f_0F2 and a minimum of the function S(t) for ionospheric station Chilton during the total solar eclipse of August 11, 1999 was 4 min [*Afraimovich et al.,* 2001] (time resolution 4 min).

The difference of τ for the total solar eclipses of June 21, 2001 and August 11, 1999 seems to be caused by the different time resolution used in the analysis of the f_0F2, as well as by the different distance of ionospheric stations in latitude from the band of totality.

The eclipse effect on other parameters (the TEC value obtained using the data from ionospheric station Madimbo to the height of the f_0F2 layer maximum and using the ionospheric model above this maximum, as well as the height of the h_mF2 - Fig. 2b, c) is not as clearly pronounced as in the case of f_0F2. According to the TEC data, $\tau =$ 5 min, and for h_mF2 we have $\tau = 30$ min.

Similar results (for f_0F2) of measurements at the ionospheric station were obtained during the solar eclipse of September 23, 1987 in South-East Asia [*Cheng et al.,* 1992].

4. The process of GPS–network data and results of analysis of ionospheric effect by total solar eclipse of June 21, 2001

We now describe briefly the sequence of procedures of processing the GPS data. Primary data include series of the "oblique" value of TEC $I(t)$, as well as the corresponding series of values of the elevation $\theta(t)$ measured from the ground, and of the azimuth $\alpha(t)$ of the LOS to the satellite measured eastward from north. These parameters are calculated using our developed program CONVTEC which transforms RINEX-files [*Gurtner,* 1993], standard for the GPS system, received via the Internet. The series of values of the elevation $\theta(t)$ and azimuth $\alpha(t)$ of the LOS to the satellite are used to determine the location of subionospheric points. In the case under consideration these results were obtained for elevations $\theta(t)$ larger than 45°.

The snowflake symbol in Fig. 1 shows the location of the subionospheric point at the time of a maximum TEC response.

Variations of the "oblique" TEC $I(t)$ are determined on the basis of phase measurements at each of the spatially separated two-frequency GPS receivers using the formula from [*Afraimovich et al.,* 1998]:

$$I_0 = \frac{1}{40.308}\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}[(L_1\lambda_1 - L_2\lambda_2) + const + nL] \qquad (1)$$

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).

The series of values of the elevation $\theta(t)$ and azimuth $\alpha(t)$ of the LOS to the satellite were used to determine the location of subionospheric points and to transform the "oblique" TEC $I_0(t)$ to the corresponding value of the "vertical" TEC using the technique described in [*Klobuchar,* 1986]:

$$I = I_0 \times cos\left[arcsin\left(\frac{R_z}{R_z + h_m} cos\theta\right)\right] \tag{2}$$

where R_z is the Earth's radius, and $h_m = 300$ is the height of the equivalent thin shell.

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 60 min which is fitted for each TEC sampling. The selection of the time window from 40 to 60 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 June 21, 2001 (the largest value of Dst did not exceed 12 nT) the amplitude of TEC background variations was far below the amplitude of the TEC response to the eclipse.

Fig. 3 presents the filtered variations of TEC $dI(t)$ for HRAO stations for satellite N03 (PRN03) - Fig. 3a; HRAO (PRN22) - Fig. 3b; HRAO (PRN31 - Fig. 3c; MALI (PRN31) - Fig. 3d; SUTH (PRN27) - Fig. 3e; and SUTH (PRN31) - Fig. 3f for June 21, 2001 (heavy lines). These panels also show the geometrical eclipse functions $S(t)$ at

300 km altitude calculated for the corresponding subionospheric points. Onset times of minima t_{min} of the $dI(t)$ series are presented in Table 1. In Table 1 the following symbols are used: PRN - satellite number; SLAT and SLON - latitude and longitude of the subionospheric point, respectively; A - minimum value of $dI(t)$-variations; ΔT - response duration; and τ - delay between minima of the $dI(t)$ and $S(t)$ series.

It is evident from Fig. 3a, the filtered variations resemble in their form a triangle whose vertex (point A) corresponds to the time, at which a minimum TEC value is attained. The value of dI_{min} itself can serve as an estimate of the amplitude of the TEC response to eclipse, and the time interval between the times of intersection of the dI=0 line (points B and C) can serve as an estimate of the response duration ΔT.

Such $dI(t)$ variations are characteristic for all the GPS stations and satellite numbers 1, 3, 13, 22, 27 and 31 listed in Table 1. That the above-mentioned satellites were chosen for the entire set of GPS station was dictated by the fact that for these satellites a maximum value of the elevation θ of the LOS to the satellite, for the time interval 13:00-14:00 UT, exceeded 45°, which minimized the possible error of transformation to the "vertical" TEC value as a consequence of sphericity.

For comparison, Fig. 4 presents the $dI(t)$ - variations for different subionospheric points of station HRAO: PRN22 - thin solid line, and PRN31 - thick solid line separated by 7° in longitude. It is evident from the figure, the responses to eclipse for the subionospheric points PRN22 and PRN31 are quite similar both in their form and in amplitude, but the delay of the response increases with longitude.

A thin dashed line and a thin dashed line with dots in Fig. 4 shows that $S(t)$ for

HRAO (PRN22) and HRAO (PRN31), respectively. The points **A** and $\mathbf{A}'$ for GPS station HRAO (PRN31) correspond to the time of totality and the time of a minimum of the $dI(t)$, respectively. The points **B** and $\mathbf{B}'$ for GPS station HRAO (PRN22) correspond to the time of totality and the time of a minimum of the $dI(t)$, respectively. The use of satellites PRN22 and PRN31 for the HRAO station was dictated by the fact that the paths of these satellites lie in about the same latitude range (Fig. 1). It is evident from Table 1 that the longitudinal dependence of the time of a minimum $dI(t)$ is not a monotonic function for all GPS stations in latitude from the totality band, i. e. the geophysical conditions for some of the trajectories differed drastically.

5. Conclusion

The results reported in this study are in good agreement with earlier measurements and theoretical estimations (see a review of the data in the Introduction). The principal difference of our data is the higher reliability of determination of the main eclipse response parameters caused by high space-time resolution and by improved sensitivity of detection of ionospheric disturbances using GPS.

To investigate the ionospheric response to the total solar eclipses of March 9, 1997 and August 11, 1999, *Afraimovich et al.,* [1998, 2001] used the variations in total "oblique" electron reflection and the "vertical" TEC value, respectively. 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 400 min, A ranges from 0.1 to 15 TECU, and ΔT varies between 32 and 200 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.

The TEC data for the total solar eclipses of August 11, 1999 and June 21, 2001 were processes following the technique described in the "The process of GPS–network data and results of analysis of ionospheric effect by total solar eclipse of June 21, 2001" section. The values of the parameters τ, A and ΔT, obtained by analyzing the ionospheric response to the total solar eclipses of August 11, 1999 and June 21, 2001, differ by no more than 5-21 min, 0.4-0.6 TECU, and 6-7 min, respectively. The difference of the parameters τ, A and ΔT can be explained by the difference of the geometry of the eclipses as well as by the difference of the latitude and longitude ranges.

The time constant of ionization decrease in the $F2$ maximum exceeds greatly the duration of the totality phase of eclipse, which leads to a decrease in the response amplitude. The TEC response amplitude in terms of various models were made in [*Stubbe,* 1970] and [*Boitman et al.,* 1999], also for the spring season.

The value of τ for f_0F2 about 25 min corresponded to the local time of 15:38 LT. The parameter τ for f_0F2 at the time of the total solar eclipse of March 9, 1997 varied from 9.5 to 16 min according to the data reported by *Borisov et al.,* [2000], which is in good agreement with our data.

We cannot directly compare the physical significances of the delay times τ obtained from f_0F2 observations with those obtained from TEC measurements. f_0F2 refer to a given height, namely the height of peak density. On the other hand, τ, which is height-dependent, gives a weighted value because τ is small at low heights, say, 200 km, and is large in the topside, say, 1000 km. Thus τ will vary along the GPS-Ground ray path. Since most of the TEC is above the peak the observed GPS-tau should be larger than the f_0F2-τ.

Ivelskaya et al., [1977], using simulation methods, showed that the variations of the delay time τ of a minimum local electron density $N_e(t)$ with respect to a minimum of the ion production function are: at 150 km altitude τ = 1-2 min, at 200 km - τ = 3 min, at 300 km - τ = 20 min, and above 600 km - τ = 45 min. In this paper, τ was estimated at about 3 min for 200 km altitude, and at 40 min for 300 km for 12 LT.

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