Global Reconstruction of the Ionospheric F-Region Structure

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Vertical structure of the ionospheric electron density profiles is characterized by the F-region peak parameters interrelated with the F2 layer topside and bottomside subpeak semi-thickness parameters and the EF valley width. Using this chain of parameters, various portions of the ionospheric structure are reconstructed under the regular perturbations and anomalous conditions depending on the illumination of the ionosphere by sunlight and on the geomagnetic field orientation. The structural parameters of the ionospheric contour of the solar terminator as well as the effects of an artificial disturbance and of the sohir eclipses at magnetic conjugate points are considered.

1 Introduction

The ionosphere comprises a part of united solar-terrestrial magnetism-atmosphere system. The ionosphere responds to variations of the other components of the system while being available for remote sensing studies from the Earth and by satellites (i.e. it can serve as an indicator of the state of the other parts of this system). To systematize the observed variation of the ionosphere, classification of parameters of an outer and inner control such as the solar short-wave radiation, effects of the neutral atmosphere and the terrestrial magnetic field is being made. The Reference Ionosphere model system, IRI\(^1\), describes the Earth’s ionospheric climate using parametrization of the main ionospheric characteristics as a function of the solar illumination, solar activity, the geographic and geomagnetic coordinates and the local time and season.

While modelling the global ionosphere one can consider it as consisting of three latitudinal zones with different physical features, viz. equatorial, mid-latitude and polar regions, with the natural bounds between these—an equatorial anomaly and the main ionospheric trough\(^2\). A lot of attention has been given in the literature both to development of these zonal models and to their boundary regions, and a certain amount of success has been reached in their synthesis into global ionospheric models. Given below is one more important feature of the global ionospheric structure—connecting of all the above zones, the ionospheric belt of the solar terminator inducing many disturbances in a regular behaviour of the ionosphere\(^3\).

In the region of solar night-day terminator at the Earth’s surface a large temperature gradient is created, which, thanks to the heat exchange, yields an inhomogeneity in the atmosphere\(^4\). With the planet’s rotation the inhomogeneity moves with great speed which at the latitudes from the equator to ±40° even reaches the supersonic velocity. As a result, atmospheric gravity waves are produced the frequencies of which are harmonics of diurnal rotation. Their upward propagation has the salient feature of amplitudes growing inversely as square root of the atmospheric density which serves as a source of mixing the atmosphere. These inner gravity waves are always present in the ionosphere at the belt of solar terminator\(^5,6\).

Work has been done earlier in regard to configuration of the Earth’s shadow determining proportions of day to night conditions in the upper atmosphere decreasing with height\(^7,8\). Details of illumination of the winter polar ionosphere at different heights as given below allow us to understand better the peculiarities of the polar ionospheric structure under near twilight conditions specific to all the global ionosphere at the solar terminator region. However, the pure geometry of the solar terminator at the Earth’s upper atmosphere does not yield actual image of its ionospheric contour. This height distribution of electron density structure is studied using empirical models and results of the vertical-incidence sounding data analysis.

An important consequence of passing the solar terminator through the ionosphere is a regular redistribution of the ionospheric structure. This is revealed for example in an increased variability of the ionosphere during dawn-dusk periods\(^8\), maximum of the ionospheric scintillations occurring when orientation of the solar terminator is coinciding with geomagnetic field line direction\(^9\) and so on.
When tackling the regular redistribution of the ionosphere structure under different solar and geomagnetic activity conditions one should distinguish (a) a quiet state and (b) disturbances in the ionosphere. Both the states are under the control of the outer inducing parameters—the Sun, neutral atmosphere and terrestrial magnetic field which in turn are either under quiet or disturbed conditions. But in the ionospheric behaviour there are events specific only to its own activity when the ionosphere is disturbed while the outer controlling parameters can be either quiet or disturbed ones. Such anomalous phenomena should be attributed to the effects of solar eclipses and artificial manmade disturbances. Examples of redistribution of electron density profiles under such conditions are considered below.

Actually, the regular restructuring of the ionosphere can be characterized by analyzing variations of physical semi-thickness of the topside and bottomside sub-peak F2 region and the EF valley width depending on the main F-region peak ionization parameters. These parameters are presented below.

2 F-region Peak Parameters as Functions of Illumination of the Ionosphere by the Sun at Different Latitudinal Zones

Altitude of the Sun over horizon (zenith angle $\alpha$) affects the optical radiation reaching a given level in the atmosphere. The relevant conditions of ionization depending on the optical wavelength under different conditions of sunlight are given in literature. Latitudinal variation of solar zenith angle has the maximum of $\alpha = 180^\circ$ in winter hemisphere at latitudes of $\pm 23^\circ$, decreasing towards the poles. The minimum $\alpha = 0^\circ$ is observed obviously at midday summer hemisphere latitudes of $\pm 23^\circ$, then increasing towards the poles. As a result specific conditions occur between $\pm 23^\circ$ of latitudes near equator and above the polar regions at latitudes more than $\pm 67^\circ$ where illumination differs from midlatitude ionosphere.

Proportion of night to day conditions at the different ionospheric heights is determined by area of true nighttime cone of the Earth's shadow. With increasing height this obscured area relative to the total day and night sides area of the ionosphere is gradually decreasing, remaining percentage being 37% at the level of 300 km, 26% at 1000 km, etc. Additional lightened time at the height of 300 km as compared to the surface level ($90^\circ \leq \alpha \leq 108^\circ$) for the Northern hemisphere is presented in the top of Fig. 1; the same picture is valid for the Southern hemisphere shifted by half-year in the months. It is evident from Fig. 1 that this additional lightened time at latitudes below $\pm 40^\circ$ slightly varies during a year—within 1 to 2 hr during dawn and dusk. When passing to higher latitudes one should notice that a change of seasons at terrestrial atmosphere should be observed at the times different from the times of beginning of the seasons at the ground level of Earth.

Thus, at latitude of Moscow (Fig. 1, bottom) at altitude of 300 km the Sun remains above the horizon during three months as in polar ionosphere: this season lasts from 7 May to 8 August. The daylight period in the summer is increased by 3 to 8 hours depending on the latitude.

On the other hand, considering illumination of the ionosphere by sunlight during nighttime one should point out an absence of continuous polar night in winter upper atmosphere as it happens at the ground surface. The dependence of illuminated hours (twilight conditions) on altitude and latitudes at the polar zone for the winter solstice is shown in Fig. 2. One can see that at the ground surface the continuous polar night is spread through all the latitudes above $67^\circ$ to the pole. With increasing height this nighttime zone quickly moves to the higher latitudes, and even after taking into account the ozone layer (dashed lines) the Earth's atmos-
Fig. 2—Latitudinal height variation of the sunlight duration for the polar upper atmosphere (Numbers at the curves indicate the height in km above the Earth's surface. Dashed lines—with ozone layer taken into account)

Fig. 3—Model distribution of the peak electron concentration in the polar F-region of the ionosphere for Northern hemisphere in December, sunspot number 160, 18 hrs UT, \( k_p = 3 \): (a) corrected geomagnetic latitude and geomagnetic time as coordinates (units \( 10^{11} \text{ m}^{-3} \)), Ref. 18. Hatched area—nightside at altitude of 300 km; and (b) latitudinal variation along the midday-midnight magnetic local time: curve a—Ref. 18, curve b—model IRI-CCIR (Refs 1, 20)

A general pattern of the global distribution of the F-region peak density\(^{19}\), and the peak height\(^{20}\) \( (Z_mF_2) \) is shown in Fig. 4. These models present latitudinal and longitudinal variations of the peak controlling parameters, with orientation of the geomagnetic field, local time (solar zenith angle), hemisphere (North-South), season and solar activity taken into account. In this multiparametric space the empirical data are summarized as a superposition of analytical functions and provided with a software. Fig. 4 shows the global and regional features of the peak parameters such as equatorial anomaly, ionospheric contour of the solar terminator, and diurnal and latitudinal variations in the state of the ionosphere.

3 Regular Redistribution of the Ionospheric Structure by the Solar Terminator

Appreciable decrease of the diurnal variation values of the F-region peak height is observed near the solar terminator passing during dawn and dusk (solar zenith angle \( x = 80 \) to \( 90^\circ \)) as compared with nighttime and daytime values\(^{11,12}\). This is shown in the sketch of Fig. 5 where the F2 layer peak altitude is given around the Earth: \( Z_mF_2 = Z_D \) at the dayside, \( Z_mF_2 = Z_N \) at the nightside cone of the Earth's shadow, and the lowered height \( Z_mF_2 = Z_T \) presents a belt of terminator. This phenomenon fixed in the chosen system of coordinates related to the Sun as shown in Fig. 5 is moving virtually through the ionosphere along with the diurnal rotation of the Earth, inducing redistribution of the electron dens-
Fig. 4—Three dimensional global representation of the peak electron density (left) and the main peak height (right) of the F-region.

Fig. 5—F-region peak height over the Earth in the sun-oriented system of coordinates shows decrease at the belt of solar terminator as compared with daytime ($Z_D$) and nighttime ($Z_N$) values.

Fig. 6—Diurnal relation of the EF valley width of the F2 layer sub-peak semi-thickness remaining invariant for all latitudes, seasons and levels of solar activity as a function of the solar zenith angle. [Data for two levels of solar activity (minimum—1976, maximum—1980) for three seasons: viz. winter $\circ/\bullet$, equinox $\Delta/\Delta\bullet$, summer $\Delta/\Delta\bullet$ are used.]

When the peak height is decreased, the EF valley is 1.7 times wider than the F2 layer semi-thickness by night and the EF valley of 10-30 km wide by noon comprises 0.3 of the F2 layer semi-thickness.

It is important to note that close to the dawn terminator the peak height and density are both decreased in the F-region. In the dusk sector such decreases are less pronounced or are not observed at all especially at the low latitudes, whereas passing of the evening terminator induces increased scintilla-
tion of radio waves, appearance of the post-sunset equatorial anomaly and other signs of increasing the effects of inhomogeneities in the ionosphere. In the other characteristic zones of the ionospheric structure – the main ionospheric trough and equatorial anomaly – changes in the peak height and density in the F-region are of opposite nature.

Examples of latitudinal sections of the daytime averaged values of the F2 layer critical frequency and height are given in Fig. 7 to demonstrate longitudinal features of equatorial anomaly. Also, the dashed hatched portions are three longitudinal zones of a “spot” structure of the ionosphere along the longitude axis as obtained from the same topside sounding data. Actually, the zones of enhanced and reduced electron concentration as compared with the background values (“spots” at the maps of the F2 layer critical frequency – see, for example, Ref. 29) refer to the peaks and troughs of the latitudinal variation of $N_{m}F2$ given in Fig. 7. Opposite changes in the height and peak density are clearly evident in Fig. 7 as well as different character of both types of curves at the different longitudinal zones.

Comparison of orientation of the solar terminator in the month of May with direction of the geomagnetic lines of force indicates that the dawn and dusk sides of terminator for the longitude of 90°E are closest to the directions of the magnetic field lines; this is just the case when the maximum amplitude of latitudinal variation of $N_{m}F2$ is observed in Fig. 7 which corresponds to the most pronounced zones of the spots in the ionosphere. Under winter solstice such a pattern should be observed at longitude of 300°E. Relative orientation of solar terminator and geomagnetic field lines slowly varies day by day with season and that is why typical spots of ionospheric structure are retained for some time and can be observed from the satellite data averaged over a number of days.

In the diurnal variation of the F2 layer critical frequency at low and middle latitudes, the dawn minimum is clearly seen which has been extensively studied in the ionospheric research. Considering passing through the ionosphere of the night-to-day boundary at different altitudes this can be compared with an actual response of the ionosphere to transition from shadow to light using data of vertical-incidence sounding. Fig. 8 shows annual variation of the time of the dawn $f_{0}F2$ minimum occurrence at the stations of Moscow and Alma-Ata during high (1980) and low (1976) solar activity. Solid lines indicate time of the terminator passing at the Earth’s surface ($x = 90°$) and at the atmospheric height of 300 km ($x = 108°$). All the curves clearly testify a response of the ionosphere to sunrise near $x = 90°$ during summer but shifting it to $x = 108°$ by winter. This comparatively small delay of the $f_{0}F2$ dawn minimum as compared to sunrise at the ionospheric heights in winter can be explained by analysis of the magnetically-conjugate ionosphere conditions. The dashed lines in Fig. 8 shows times of sunrise at the ground and in the ionospheric heights at the magnetically-conjugate points for Moscow and Alma-Ata. The observed dawn $f_{0}F2$ minimum times are seen to be affected by both the illumination of the ionosphere both at the point of observation and at conjugate point – the annual variation is a result of both the components of illumination. The arrows indicate those times when illumination in both the conjugate points is almost the same – they point out the orientation of terminator being closest to orientation of magnetic field lines connecting this pair of the conjugate points, so that just at this time one should expect an increased disturbance in the ionosphere.

4 Response of the Magnetically-Conjugate Ionosphere to Artificial Manmade Disturbance and Solar Eclipses

Experiment of chemical “ionospheric-hole-make” (water-hole) has been carried out with Spacelab-2 at pre-sunrise winter ionosphere over Hobart, Australia, with water vapour release on 4 Aug. 1985, at 1700 hrs UT (geographic latitude 39.4°S, longi-
Fig. 8—Times of the dawn minimum of the F2 layer critical frequency from the ionograms at Moscow and Alma-Ata at high (1980) and low (1976) solar activity (Solid lines: sunrise at the ground $x = 90^\circ$, and at altitude of 300 km, $x = 108^\circ$; dashed lines: sunrise for the two stations at magnetically-conjugate points).

At the point of the water vapour release over Hobart, the decrease of the local electron concentration by 0.2 MHz of $f_{\text{F}}$ should induce the most pronounced changes above or below the F-region peak as it has been pointed out at the similar mission over the incoherent scatter station Millstone-Hill. Such “hole” in the pre-sunrise winter ionosphere over Hobart should be compensated by pre-sunrise heating of this region with photoelectrons from the continuously illuminated conjugate summer zone.

Fig. 9 shows the results of electron density profile calculations using the procedure published elsewhere from the data over Magadan for the quiet background days of 2, 3, and 5 Aug. 1985, as well as for the main day of 4 August. Here the F2 layer peak height and the height of the base of the F-region at the semi-thickness corresponding to $N_{0.5} = 0.5 N_{0.5}$ are given. A decrease of the ionospheric heights is observed during the water-hole experiment as compared with the background days. The ionosphere “went down” at the conjugate point to the release zone, and this phenomenon continued for about 1 hr at the level of the main peak and about 2 hr at the sub-peak F-region. Probably, the duration of reconstruction of the ionosphere to a regular state is attributed to processes of slow refilling of the plasma resources under the dawn conditions of minimal ionization, and the lowering of the whole thickness of the F2 layer is connected with the plasma flow for filling the “hole” at the place of man-made disturbance of the ionosphere.

Note that the critical frequencies at ionograms of station Magadan did not show any significant variation so that an effect of response could be only detected when the complete calculations of electron density profiles have been carried out.

If such local short-term action onto the ionosphere induces appreciable redistribution of the electron density profile structure at the magnetically-conjugate zone then the similar or even more pronounced effects should be observed during natural phenomena such as the solar eclipses when the...
source of ionization is cut off completely or partially and the shadow of it is passing through the ionosphere with a supersonic speed over large regional surface in the terrestrial atmosphere under all conditions from sunrise to sunset.

The analysis of the solar eclipse of 30 June 1973, has been carried out in a combined experiment with the data of rocket measurements and ionograms of vertical-incidence sounding, and the ionospheric behaviour has been studied in detail under these conditions. Some results of these observations are presented in Fig. 10(a) from the time of totality of the eclipse (curve 1) observed at geographic latitude 17°N, longitude 28.2°W and during 1 hr afterwards. The electron density profile at the totality of eclipse is approaching the shape of a nighttime profile though the event was observed in the morning hours (solar zenith angle 50°). The most appreciable variations have been observed in the interlayer EF-region where the electron concentration decreased by a factor of 10 as compared with the control days, while the decrease near the F2 layer peak was by a factor of 4. With a set of the profiles of Fig. 10(a) a long sink of the electrons is evident, but with analysis of the peak height alone the full picture is not clear; in profile 4 the peak height increased sharply and the general variations of $Z_m$, $F2$

parameter demonstrates a wave-like oscillation. At the same time, analysis of the whole ionospheric electron density profiles revealed a sink of large inhomogeneity from the topside ionosphere (curves 4 and 5).

Assuming that such an inhomogeneity can come from the conjugate region in the ionosphere, the data of vertical-incidence sounding for the solar eclipse of 23 Oct. 1976, have been analyzed from the chain of the ionospheric stations (Alma-Ata, Ashkhabad, Karaganda, Tomsk, Magadan), these stations being set at the magnetically-conjugate area for the band of the eclipse in the Southern hemisphere [Fig. 10(b)]. The most appreciable variations of the peak parameters of the F2 layer have been observed at station of Karaganda (Fig. 11) as compared with median (M) and values of the control day of 24 Oct. 1976. On the ionograms for the eclipse day the condition “R” has been marked which means impossibility to estimate the F2 layer peak parameters. The electron density profile calculations [Figs 10(b) and 11] made it possible to determine with the help of the peak extrapolation the critical frequency, peak height and the level of the F2 layer semi-thickness ($Z_m$). The arrows at the bottom of Fig. 11 indicate moments of the start, maximum phase and the end of the solar eclipse at magnetically-conjugate point (geographic coordinates 32.3°S, 81.4°E, at Karaganda 49.8°N, 73°E).

The critical frequency at Karaganda is seen to decrease during the eclipse at the conjugate zone, then become less than the median values near the
Fig. 11—Variation of critical frequencies (bottom) and the height at the F-region peak and semi-thickness level (top) at the magnetically-conjugate zone (Karaganda) during the eclipse of 23 Oct. 1976 and for the controlling day 24 Oct. 1976 (solid lines); and for the 5-day median (M) during 21-25 Oct. 1976.

totality and recover to regular values after about 2 hr of the eclipse end. The peak height and the F2 layer sub-peak semi-thickness (top) have shown a downward trend from the moment of totality which has been recovered after about 2.5 hr of the eclipse termination.

The electron density profile during the totality of eclipse (curve 1 in Fig. 10(b)] has shown increase for all the heights of the F-region without increase of the peak electron density, and after 15 min of the end of eclipse an increase of the peak height and density was observed for about 30 min [profile 4 in Fig. 10(b)] as compared with background values (see Fig. 11) which then drooped. This latter stage can be assumed to be a source of formation of a large inhomogeneity near the F-region peak in the magnetically-conjugate region such as has been observed at the eclipse zone during the event of 30 June 1973 [Fig. 10(a)].

Fig. 12—Observations along the longitude of 25°E of the spatial structure of topside ionospheric F-region from the satellite Interkosmos-19 data during the total solar eclipse of 16 Feb. 1980.

The spatial behaviour during the solar eclipse of 16 Feb. 1980 has been observed near the equator at longitude of 25°E with Interkosmos-19 satellite. Latitudinal variation of electron concentration after about 30 min of the totality at the F-region peak and in the topside ionosphere as well as the peak density in the control days of 13 and 19 Feb. 1980 are shown in Fig. 12 (Ref. 41). The total eclipse band at this longitude was placed at the geomagnetic latitude $\phi_m = -5^\circ$ where the maximum electron density in the latitudinal variation and the minimum of the peak height of the F2 layer have been observed. Apart from the daytime equatorial anomaly which was observed during the control days (solar zenith angle 25-35°), at the eclipse day a typical nighttime variation of ionization has been obtained at the equatorial zone as a counter-phase to the daytime equatorial anomaly. Also, the opposite variation of the peak height and density is seen on the eclipse day. Minima of electron concentrations and maxima of the height refer to the magnetically-conjugate points along the meridian which confirms interrelations of response of these regions of the ionosphere to the solar eclipse.

The same eclipse during evening hours has been observed at Gauhati, India (latitude 26.2°N, longitude 91.75°E) as in the above cases, near the totality of eclipse a rise of the whole electron density profile has been observed in the F-region and then its sink to regular diurnal variation. The main redistribution of the ionospheric structure has been pointed out at the sub-peak heights with the F1 layer being clearly pronounced near the totality. During
these observations, appearance of the atmospheric gravity waves has been obtained owing to the solar eclipse which can be also related to the dusk terminator approaching the point of observation.

5 Conclusion

The given examples of reconstruction of the ionospheric structure during the natural and manmade disturbances, the most regularly observed twice-a-day events when the solar terminator passes the Earth's atmosphere, indicate a possibility and necessity of their further detection using the ground-based and satellite-borne observations. In so doing it is not sufficient to study only the peak parameters—electron density and height. Many effects can be detected just with complete analysis of electron density profiles the calculations of which, from the available vertical-incidence observational data of soundings, should help in the diagnostics and modelling of the ionosphere.

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References

4 Krasnopolsky V A, Physics of the atmospheric emissions of the planets and comets (Nauka, Moscow, USSR), 1987, 304.
19 Suvorov V V & Teltsov M V, Geomagn & Aerion (USSR), 19 (1979) 444.
29 Atlas of Ionospheric Critical Frequency (foF2) Obtained from Ionosphere Sounding Satellite-b Observation, Parts 1-4 (Radio Res Labs, Tokyo, Japan), 1979-83.
33 Efizarniev Yu N, Seasonal-latitudinal variations of the cyclic increase of foF2 in Electrodynamics and radio wave propagation (Tomsk, USSR), No. 2 (1982), 3; also in Ionospheric Research (WDC-B, Moscow, USSR), No. 26 (1978) 47.
Indian J Radio & Space Phys, Vol. 17, October 1988

40 Chasovitin Yu K, Gulyaeva T L & Khryukin V G, Physica Solarterrestrial (Germany), No. 7 (1978) 89.