International Journal of Electronics and Applied Research (*IJEAR*) **2014, vol. 1, issue 2, 39-60**
Published Online December 2014 (*http://eses.co.in/journal.php?journal)* ISSN NO: 2395-0064

The Ionosphere Effects of the Chelyabinsk Meteoroid Explosion

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Abstract

The data of transionospheric sounding by signals from the GPS cluster satellites in the zone of explosion of the Chelyabinsk meteoroid have been analyzed. The analysis has shown that the explosion had a very weak effect on the ionosphere. The observed ionosphere disturbances were asymmetric with respect to the explosion epicenter. The signals obtained were compared both in shape and in amplitude with the known surface explosions for which the diagnostics of the ionosphere effects had been made by radio techniques. Ionospheric effects in the form of acoustic-gravity waves (AGW) produced by 500-600 tons TNT explosions on the ground are detected with confidence both by vertical sounding and by GPS techniques. This allows us to suggest that the reported equivalent of the meteoroid explosion was obviously overestimated. The experiments on the injection of barium vapor (3.3 kg) carried out under similar conditions in the terminator zone revealed the response of the ionosphere in variations of the critical frequencies of the layer at a distance of 1500-2000 km (AGW with a period of 5-10 min). The absence of such ionosphere effects in the remote zone at 1500-1700 km from the epicenter of the bolide explosion in the case under discussion also makes us feel doubtful about the estimated explosion equivalent.

Key words: *Explosion; Meteoroid; Ionosphere; AGW*

1. Introduction

An important role in the dynamics of the ionosphere belongs to the wave processes, which occur in all its regions, at any time of the day, and in all seasons. A direct comparison of the theory of wave disturbances in the ionosphere with experimental data is possible if we know the site and time of action of the wave source, e.g., when the waves are generated as a result of the impact of powerful explosions on the ionosphere or are triggered by a strong earthquake. A considerable amount of experimental evidence of the response of the ionosphere to atmospheric and surface explosions (mainly industrial and nuclear) is available [Blanc E, 1985]. Thus, after the explosions produced at the heights of 60 and 40 km, respectively, within the frames of the "Teak" and «Orange» programs [Sorokin and Fedorovich,1982; Adushkin et al, 1994], geophysical stations in the Pacific reported ionosphere effects and geomagnetic disturbances lasting about tens of minutes at distances from 10^3 to 10^4 km from the explosion point.

It is also well known that surface explosions trigger wave effects in the ionosphere both in the near and remote zones. A radio propagation experiment with the use of GPS signals [Fitzgerald T.J, 1997] was carried out to study the response of the ionosphere to the 1.5 kt open-mine explosion. The ionosphere effects were recorded by five GPS receivers at distances of 50-200 km from the explosion center. The disturbance was only detected by the satellite-receiver pairs, in which the satellite was located to the south-west of the explosion (anisotropy of the ionosphere response). It started 10-15 min after the explosion and lasted for about 30 min. The amplitude of the disturbance was $3*10^{14}$ m^{-2} (0.03 TECU). Another explosion [Calais E et al, 1998] near New-Mexico (2 kt) caused a response, which was recorded after 585 s (δTEC=0.15 TECU) by one satellite and after 600 s (δTEC = 0.07 TECU) by another. When recording signals from a geostationary satellite at a frequency of 137 MHz (Faraday rotation), only the northern of the two receivers detected the effect. A series of experiments – MASS [Gohberg M.B , 1983; Kozin and Saifutdinov, 1988; Kitov and Gokhberg, 1992] were carried out to analyze the impact of ground explosions on the ionosphere and to simulate interactions in the lithosphere-atmosphere-ionosphere system. The equipment was located both close to the explosion center (shock wave recorders, seismographs, optical devices) and at distances of dozens and hundreds of kilometers (magnetometers, devices for acoustic and radio physical measurements). The most detailed measurements were taken during the 260 tons TNT explosion produced on 28.11.81 in the vicinity of Alma-Ata. The Doppler shift of the 4.9 MHz sounding signal reflected at the altitude of 200 km revealed the ionosphere response 8-9 min after the explosion.

All said above shows that the response of the ionosphere to hundreds of tons TNT ground-level explosions is reliably recorded by radio techniques, and the anisotropy of the ionospheric effects is clearly revealed.

The bolide explosion in the atmosphere is a very rare phenomenon, which is particularly important to studying the impacts on the ionosphere from below (atmospheric sources). The phenomenon under discussion (meteorite intrusion) is also interesting from the point of view of verifying the available theoretical concepts of ionosphere disturbances caused by such sources.

On 15 February 2013 at approximately 9:22 local time (UT+6h), the people in Kurgan, Tyumen, Sverdlovsk and Chelyabinsk regions witnessed the flight of a bright bolide. Many video cameras recorded the phenomenon. The flight ended with an explosion over Chelyabinsk, which was observed from the ground as a bright flash followed by a powerful shock wave. In this work, we are making an attempt to reveal the effects in the ionosphere and to compare them with the known facts and model representations.

2. Parameters of the meteoroid explosion and background conditions (terminator, map, geomagnetic conditions)

2.1. Meteoroid parameters and explosion characteristics.

On February 15, NASA published the first data on the meteoroid based on the analysis of observations of infrared tracking stations. Before entering the Earth atmosphere, the object had about 17 meters in diameter, the mass up to 10000 tons and had been moving at a speed of 18 km/s. 32.5 s after entering the atmosphere it collapsed completely and released energy equal to about 500 kilotons TNT. According to NASA, this body was much larger than the Sikhote-Alin meteorite, and was the largest since the fall of the Tunguska meteorite in 1908. According to the estimates given in [http://www.utro.ru/articles/2013/02/20/1102314.shtml; http://ru.wikipedia.org/wiki/], the explosive power was much smaller – 100-200 kilotons.

The Czech astronomers studied the records of the tracking cameras and reconstructed the meteorite trajectory in the atmosphere [Borovicka et al, 2013; http://astronomia.udea.edu.co/chelyabinsk-meteoroid]. According to their data, the meteorite body entered the atmosphere at a speed of 17.5 km/s. The brightest burst occurred over the point with the co-ordinates 54.836° N, 61.455° E at the height of 31.73 km. At the height of 25.81 km, the body began to slow down, its speed decreasing to a few km/s.

On March 1, NASA reported specified data [Le Pichon et al, 2013] on total luminosity of the super-bolide, which was $E_0 = 3.75\ 10^{14}$ J, or 90 kt. Then, the empirical formula for the total explosion energy yields $E = 8.2508 \cdot E_0^{0,885}$, which is 440 kt. From the same data, the bolide velocity at the time of maximum brightness was 18.3 km/s. The event occurred at 54.8° N, 61.1° E at the height of 23.3 km at 03:20:33 Greenwich time. Assuming the mean density to be 3.6 g/cm^3, the mass and characteristic dimensions of the bolide were, respectively, 11000 tons and 18 meters.

2.2. The state of the ionosphere and geomagnetic conditions.

Calculations show that by the time of explosion of the bolide, the Sun over the Moscow-Chelyabinsk highway was below the horizon. The dip angle for Moscow was 7.5 degrees, and the terminator was at the height of 200 km. Figure 1 illustrates the state of the ionosphere at the time of intrusion in TEC (IONEX technology). The dashed lines mark the longitudes of Chebatkul (the shadow at a height of 500 m) and Moscow (the shadow at a height of 195 km).

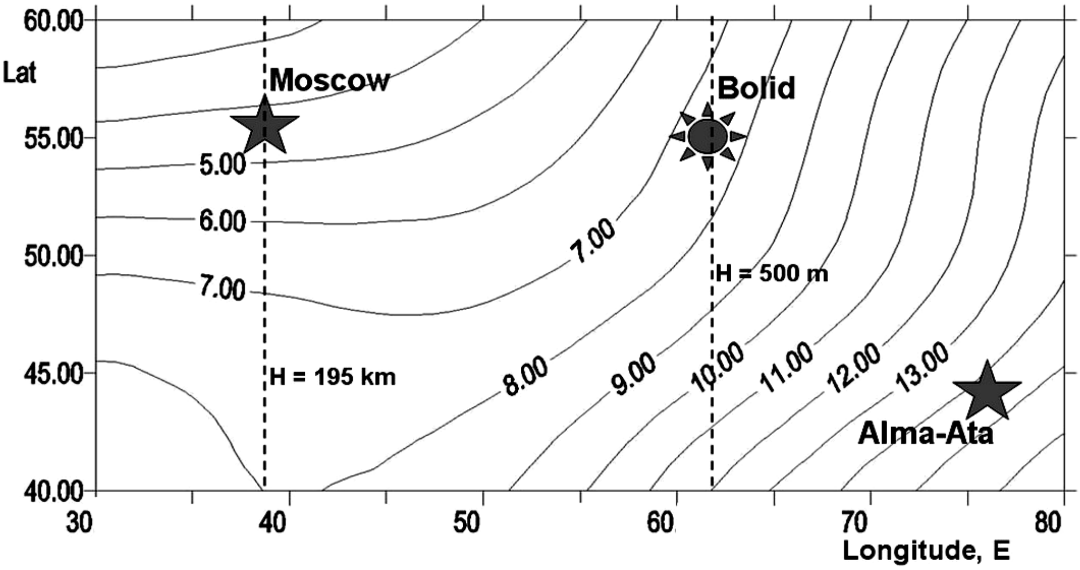


Figure 1: The position of the shadow (dashed line) in the terminator zone and TEC distribution in the ionosphere before the bolide explosion (03 UT).

As seen from the TEC distribution map Figure 1, the ionosphere was mainly quiet (undisturbed), which enabled the search for wave-like disturbances both in the intrusion zone and in remote regions. In this case, a certain analogy can be seen with the 1991 experiments on the injection of barium carried out within the CRRES program (see below): the disturbance (AGW) was propagating westward (to Moscow) in the terminator zone through the lighted ionosphere. The distance was about 1500 km.

According to the Intermagnet network data, the geomagnetic field at the time of the explosion was weakly disturbed. The geomagnetic field H component at Arti (56.43°N; 58.57°E) are plotted in Figure 2.

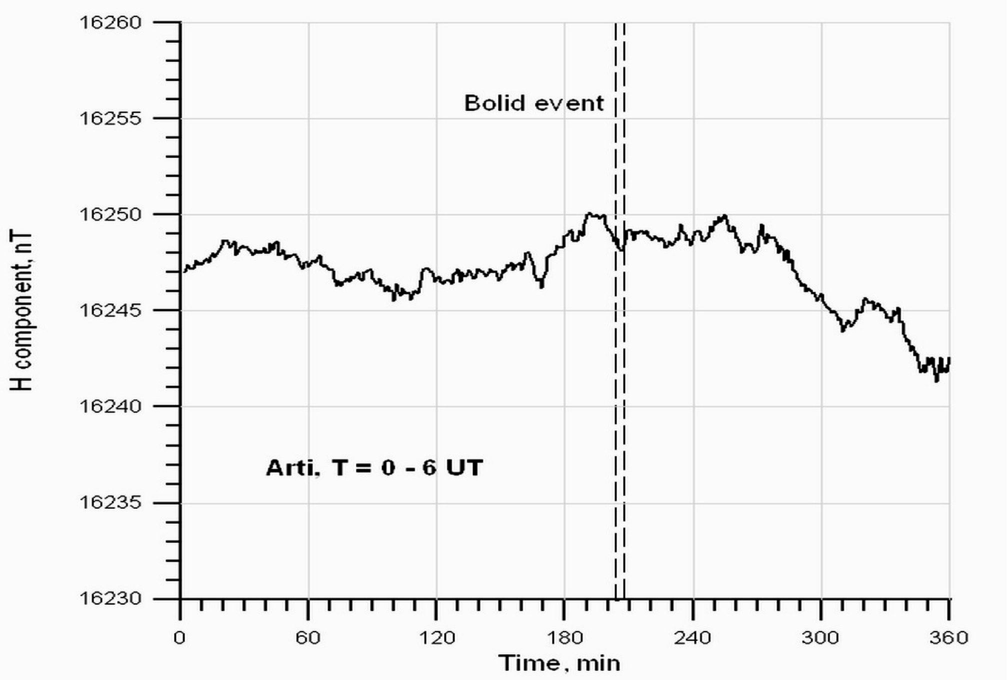


Figure 2: Geomagnetic field horizontal components (ARTI Observatory). The explosion time is marked with dashed line.

3. The method of analysis of GPS signals and experimental results

Given below are the results of the analysis of transionosphere sounding carried out using GPS signals before and after the bolide explosion in the Chelyabinsk region at 03:20:33 UT. Data from the Arti, Obninsk, and Alma-Ata stations are taken into account. The analysis is mainly focused on the Arti GPS data obtained in the vicinity of the explosion epicenter.

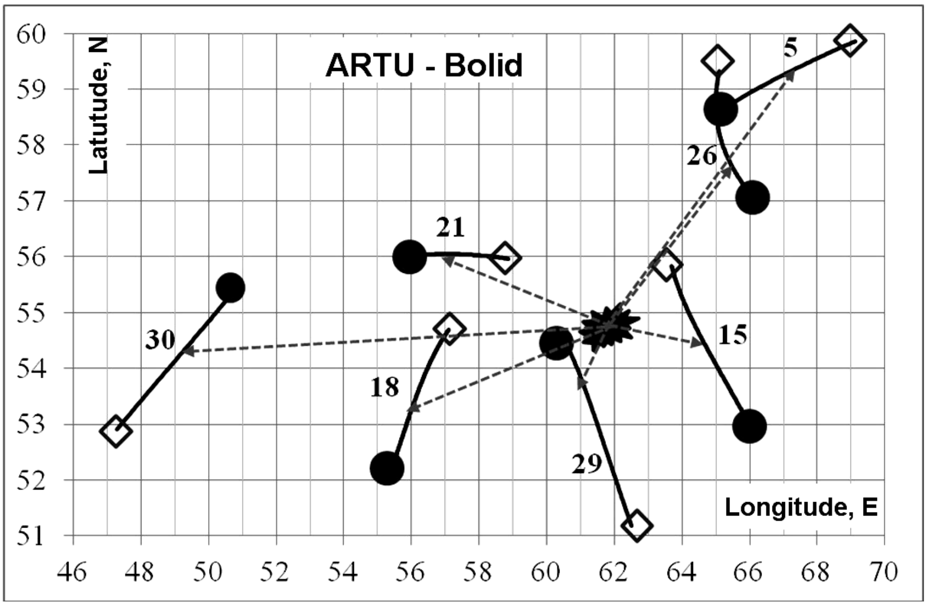


Figure 3: The tracks of the ionospheric points for all satellites observed at the Arti station, whose data were used to analyze wave disturbances.

Table I lists the initial and final co-ordinates of the tracks for the satellites that were in the zone of expected ionosphere effects. Figure 3 represents the tracks of the ionospheric points for GPS satellites in geographical co-ordinates in the time interval 3.0-4.0 UT. The beginnings of the tracks are marked with filled circles and the ends, with squares. The position of the registration point (Arti) virtually coincides with the end of the track for satellite N 21. The dashed arrows show the position of subionospheric points at the time of the bolide explosion. For the most remote satellites N 5 and N 30, the observations ended at 3.5 UT. Table I gives the explosion time and co-ordinates as recorded at the IRIS/USGS seismic network.

Table I

Explosion time and co-ordinates as recorded at the IRIS/USGS seismic network.

GPS	**3 UT**	**4 UT**	**θ – elevation angle**
N 18	**52.3N/55.3E**	**54.7N/57.1E**	**28.6-53.5**
N 15	**53.1N/65.9E**	**55.8N/63.7E**	**23.4-40.6**
N 26	**57.0N/66.2E**	**59.3N/65.1E**	**29.9-32.0-27.9**
N 21	**56.1N/56.0E**	**56.0N/58.9E**	**51.0-74.6**
N 29	**54.5N/60.5E**	**51.2N/62.5E**	**49.3-21.8**
N 30	**55.5N/50.8E**	**53.0N/47.2E**	**28.4-15.6**
N 5	**58.5N/64.9E**	**59.9N/69.1E**	**31.2-18.9**
Bolide	**55.1N/61.4E**	**3.34 UT**	

In monograph [Afraimovich and Perevalova, 2006] it is shown that a ground-level explosion is expected to produce a quasi-circular disturbance in the ionosphere at the level of F2 maximum (see Figure 9 below), which propagates from the center of the “secondary” source (at a height of 300-350 km) in all directions at speeds in the range of 300-1000 m/s, while the very disturbance in TEC is mostly N-shaped. Let us compare these results with the response to the bolide explosion.

3.1. Assessment of the parameters of the ionosphere response to the bolide explosion

The parameters of the ionosphere response to the explosion were determined by radio occultation method along the Earth-satellite path. The application of this method is described in detail in

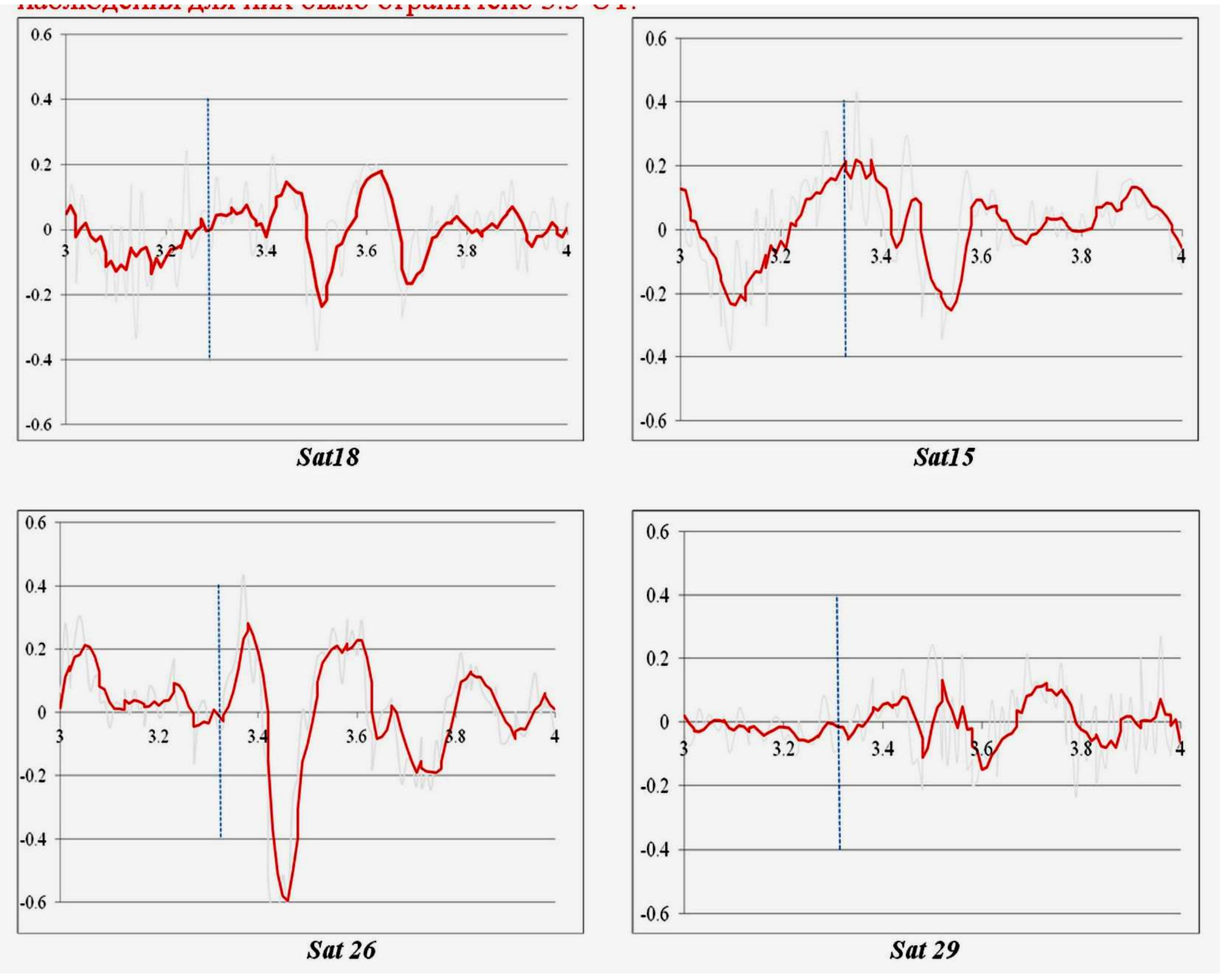
[Andrianov and Smirnov,1993; Andrianov et al, 2001]. The TEC parameters were determined using the code and phase measuring data obtained with the receivers of GPS network stations.

The ionosphere parameter most sensitive to external factors is the rate of change of the total electron content or its increment on the observed time interval. For regular GPS stations, this time interval is usually 30 s. The results of calculations (in TECU/s units) for the satellites listed in Table 1 obtained from equation

$$DTEC(t) = \frac{1.81}{T}\{\lambda_1[\Phi_1(t) - \Phi_1(t-T)] - \lambda_2[\Phi_2(t) - \Phi_2(t-T)]\}$$

are represented in Figure 4. Here, T = 30 s is the observation time, λ_1 and λ_2 are the wavelengths of the signals of navigation satellites, and Φ_1 and Φ_2 are the phase measurements for the aforementioned wavelengths; 1TECU = 10^{16}m^{-2}.

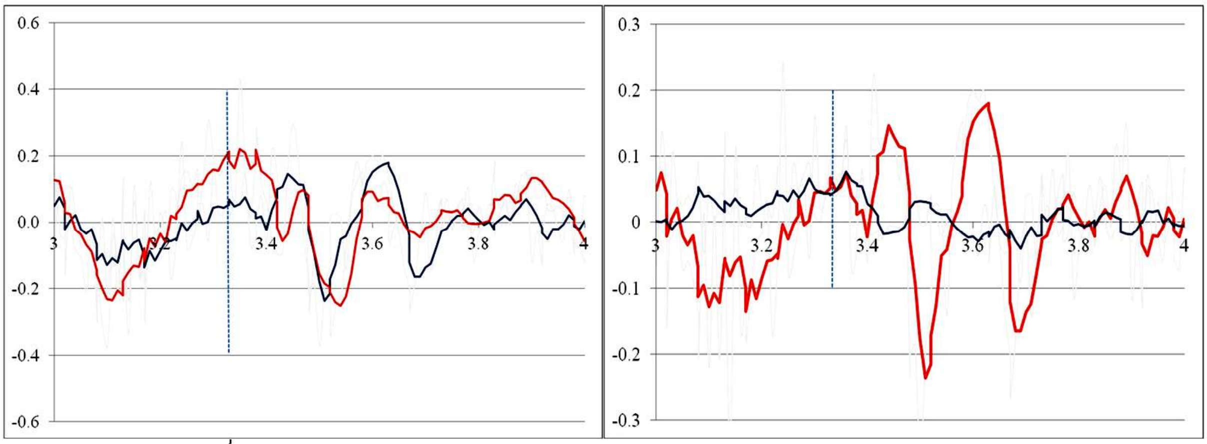
Figures 4-5 represent TEC variations as recorded by the satellites, the tracks of the subionospheric points for which are shown in Figure 3. The vertical dashed line marks the time of the bolide explosion. The plots represent data smoothed over five points. The initial data are



Sat18 **Sat15**

Sat 26 **Sat 29**

Figure 4: The disturbance in the ionosphere (TEC). Ordinate - TECU*100/s, abscissa - time UT, hr.



Sat 15@18 ***Sat 18@21***

Figure 5: The disturbance in the ionosphere (TEC).

shown with dimmed colors. The trend is removed by subtracting the approximating polynomial values. The time of the records corresponds to the position of the satellites (see Table 1 for co-ordinates). It is obvious that the disturbance in the ionosphere differs from what one might expect to see. The disturbances recorded by different satellites also do not coincide differing both in shape and in amplitude. Satellites N 5 and N 30 did not detect variations that could be attributed to the explosion, because the observation time for these satellites was limited to 3.5 UT (approximately 9 min after the explosion).

When analyzing data from satellites N 15 and N 18 obtained under the seemingly identical conditions (distance from the epicenter, direction of the subsatellite points in the ionosphere, etc.), one can see differences in the amplitude and other parameters of the disturbance. For convenience of the comparison, the results for these satellites are represented in Figure 5. The disturbances recorded by both satellites coincide in general. In the time interval under examination, the angular velocity of the satellites with respect to the navigation receiver was 0.3 deg/min for satellite N 15 and 0.42 deg/min for satellite N 18. Between these satellites, there was the track of satellite N 29, which differed from the former ones by the opposite motion of its point in the ionosphere. The disturbance recorded by satellite N 29 also differed both in amplitude and in shape. During the explosion, the ionospheric point of this satellite was closest to the epicenter (about 100 km) and apparently fell into the zone where the secondary source of the ionospheric response was arising.

Satellite N 26 recorded a noticeable reduction of noises. The rate of change of the total electron content reached its absolute maximum six minutes after the explosion. According to preliminary estimates, the change in the maximum vertical value of TEC was 0.24 TECU (see also Figure 11). It should be noted that, in the time interval from 3 to 4 UT, the satellite elevation angle changed insignificantly (by a total of 4 deg) when passing the traverse point (30-32-28 deg). In fact, the ionosphere was scanned only in the azimuthal direction at a nearly constant altitude. Perhaps, the effect of the explosion was most pronounced at a particular altitude and, therefore, satellite N 26 was able to observe a clearer disturbance pattern. The other satellites performed both azimuthal and vertical scanning of the ionosphere. Note also that the explosion occurred at the sunrise when the electron density increases and background wave disturbances are generated.

Figure 5 represents for comparison the data from satellite N 21 at elevation angles of 61-75 deg and the aforementioned satellite N 18. One can see that the data from satellite N 21 do not reveal any disturbance that could be interpreted as an explosion effect. It should be emphasized that the position of satellite N 21 was most favorable for detecting ionospheric effects caused by the bolide explosion. The ionospheric point did not virtually move making it possible to observe the signal undistorted by reciprocal motion of the ionospheric point and disturbance.

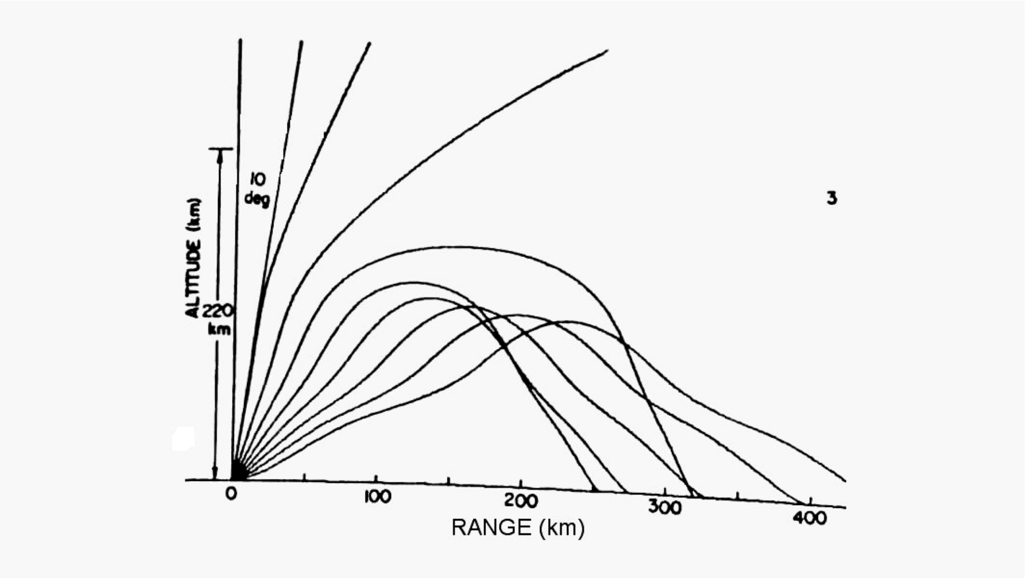


Figure 6: Model ray tracing of the acoustic disturbance under experimental conditions.

Thus, if the wave vector of the disturbance is assumed to be horizontal, the aspect orthogonality condition ($\gamma \leq 90°$, see the next Section) for satellite N 21 is fulfilled with excess and, accordingly, the amplitude of the recorded signal must be maximal (in the given cluster of GPS satellites). This signal could serve as a reference disturbance, which propagating isotropically from the region over the explosion must have the same shape under the same observation conditions.

As a result of the above analysis, we should note a distinct asymmetry of the ionospheric response to explosion at the F2 level. The small amplitude of this disturbance compared to the other known events suggests that the explosion had a complex structure and the reported TNT equivalent (30-500 kt) is inadequate. Besides the asymmetry of the signals recorded in the horizontal plane in the vicinity of the epicenter of the secondary source [Afraimovich and Perevalova, 2006], it was found that the shape of the response in TEC differed significantly from the expected classical N-shape (e.g., see Figures 7 and 10).

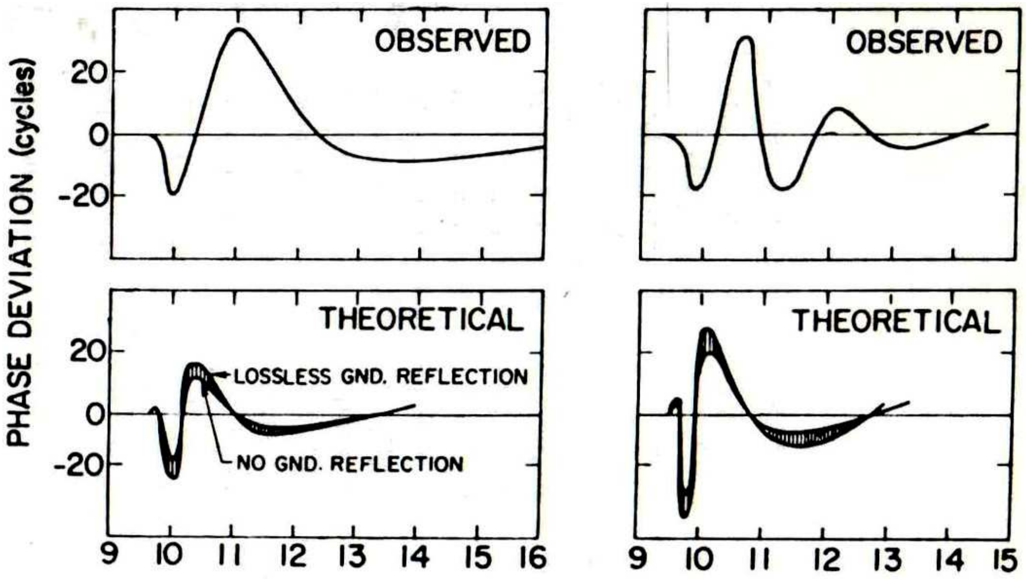


Figure 7: Comparison of the calculated and experimental shapes of the wave disturbance.

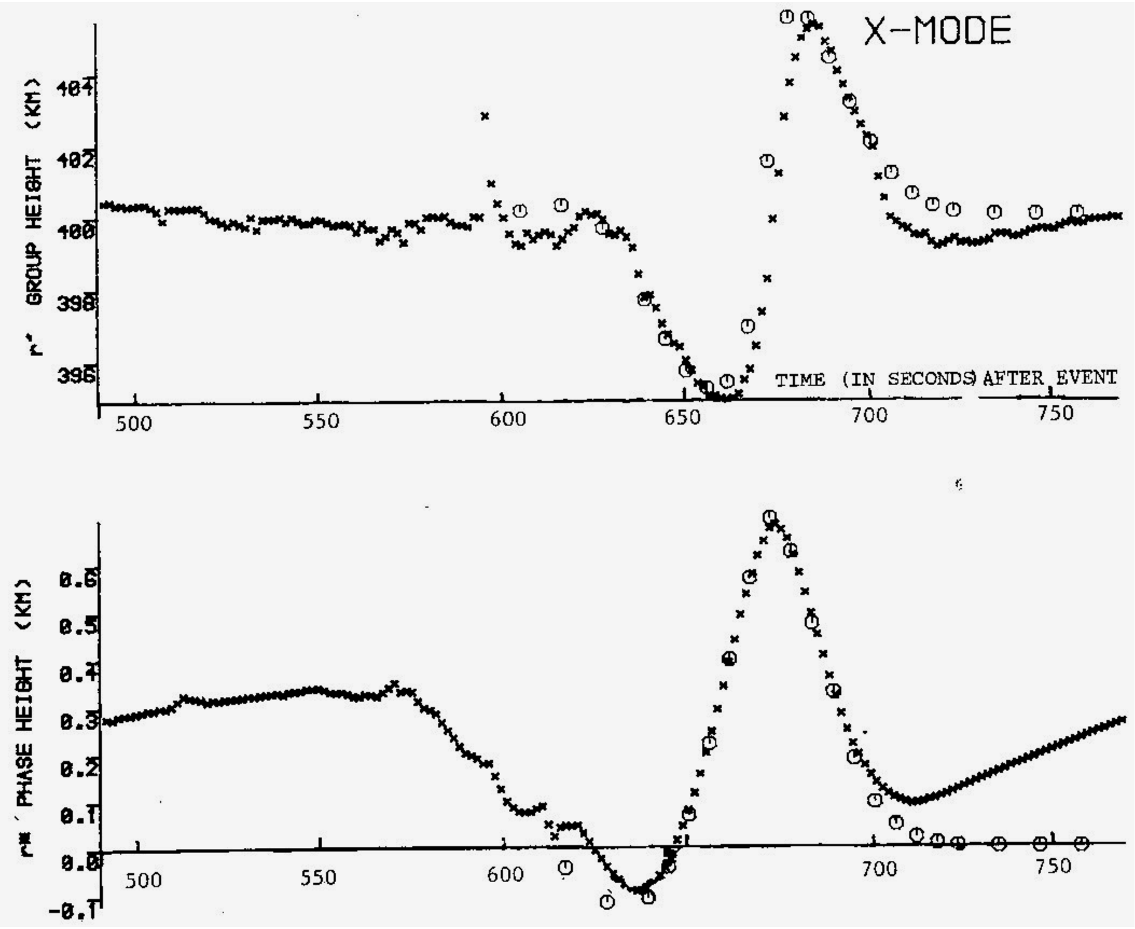


Figure 8: Variations in the ionospheric response parameters (fragment of a figure from [18])

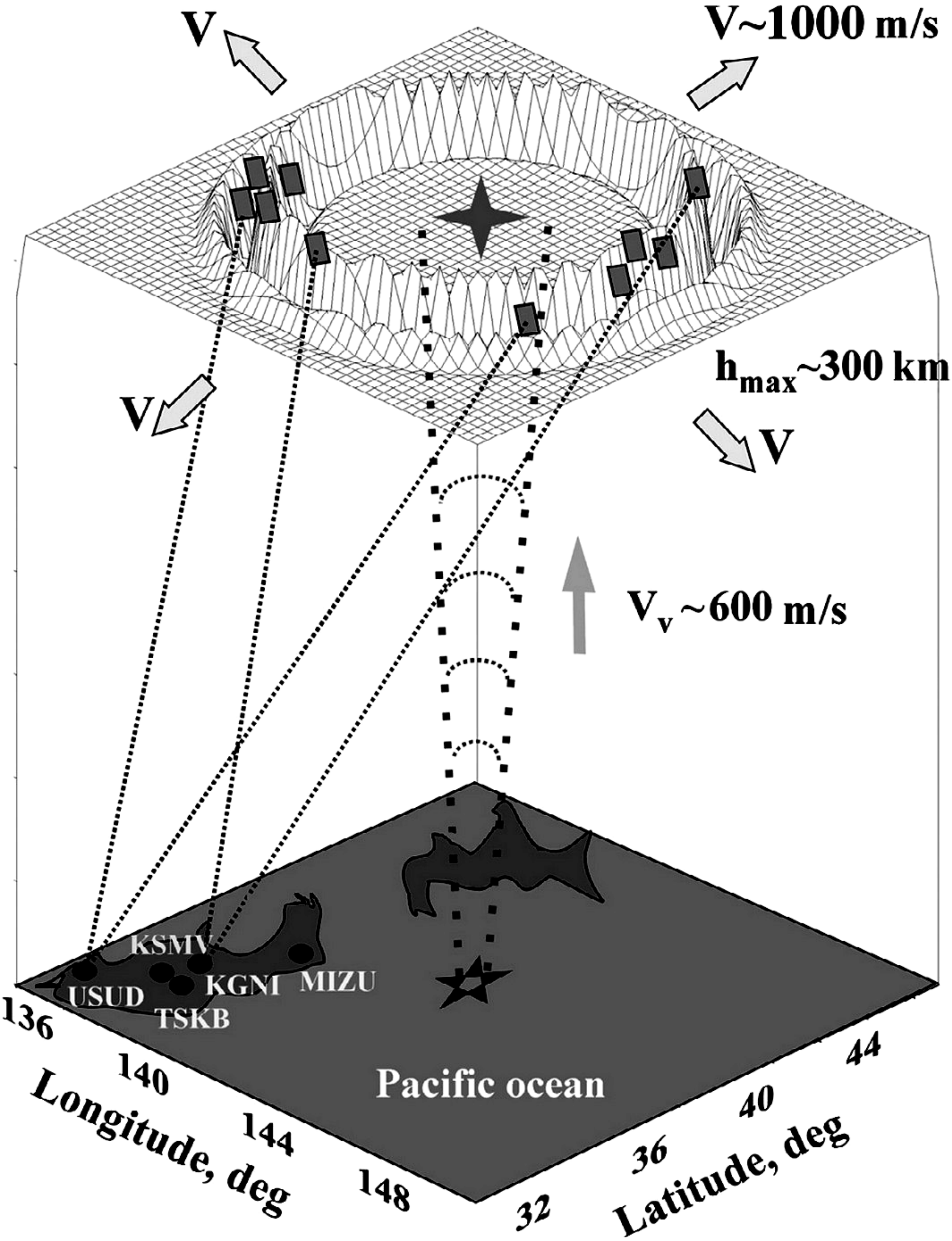


Figure 9: The scheme of generation and detection of the acoustic shock [14] during the earthquake of 25.09.2003 at Hokkaido. The epicenter is marked with an asterisk, the position of the "secondary" source - with a cross; GPS stations - with dots, and the ionospheric points for the particular satellites – with rectangles.

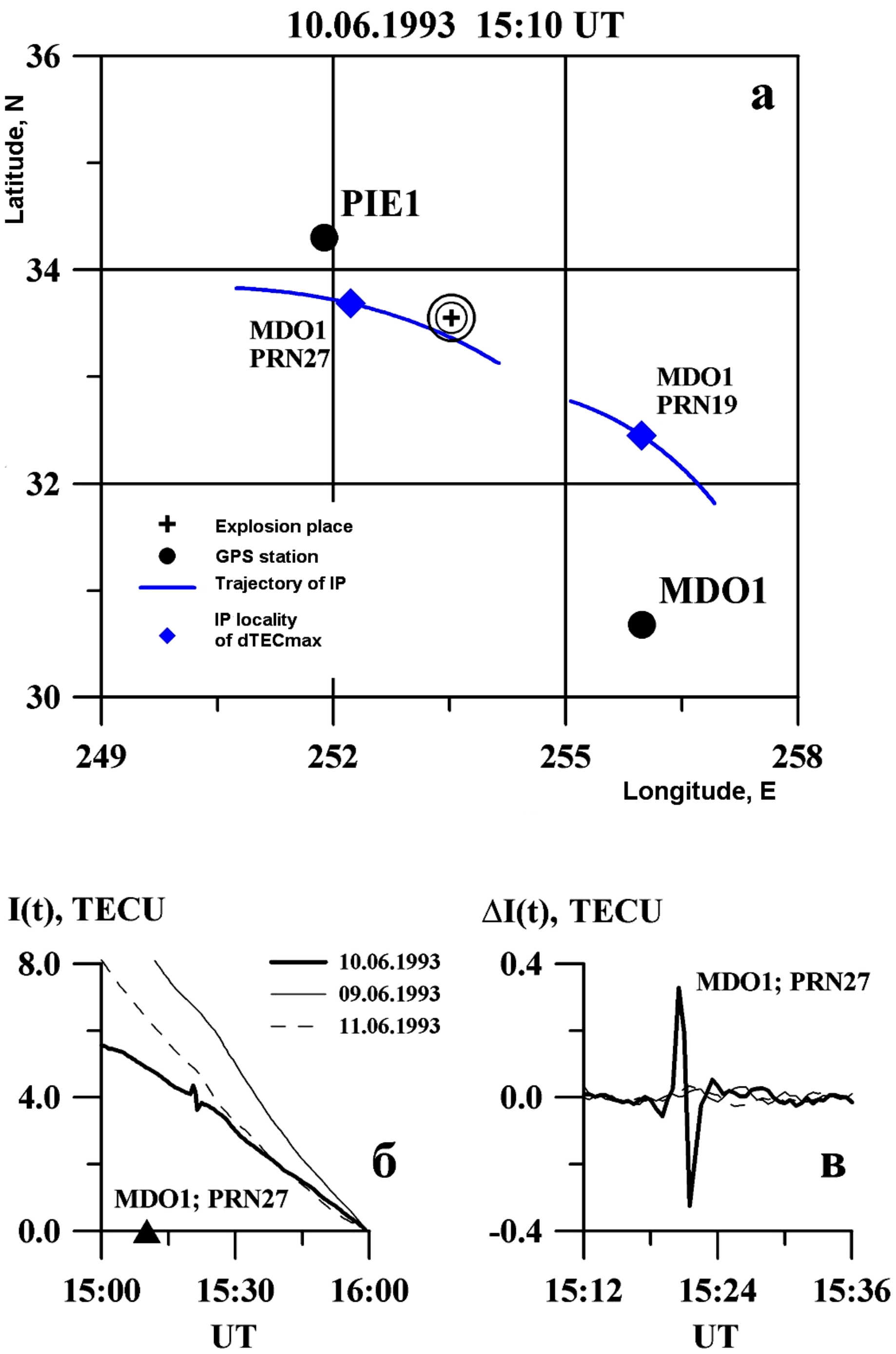


Figure 10: The geometry of TEC measurements and variations during a 2 kt surface explosion.

3.2. Distortion of the wave disturbance (see the track positions).

The difference in the shape and amplitude of the ionospheric response to the explosion recorded by different satellites can be explained using the results of the analysis described in [Afraimovich et al, 2000] and in monograph [Afraimovich and Perevalova, 2006].

Firstly, it is necessary to take into account the effect of the satellite motion on wave disturbances in the total electron content. The velocity, w, of the ionospheric point for GPS is comparable with the phase velocity of wave disturbances: at the height h_{max}=350 km and the elevation angle of 30° at mid latitudes, w≈100 m/s. Therefore, when calculating the absolute value of the disturbance velocity from GPS data, one should make allowance for the shift of the “receiver-GPS” beam relative to TID in the ionosphere. Besides, the satellite motion has to be taken into account when determining the TID oscillation frequency Ω, since the measured TEC variation rate Ω' does not coincide with Ω owing to the Doppler frequency shift:

$$\Omega' = \Omega - \mathbf{K} \cdot \mathbf{w}$$

Secondly, the amplitude of the TEC wave disturbances displays well-pronounced aspect dependence. The maximum amplitude is observed for those TIDs, whose wave vector $\mathbf{K}$ is perpendicular to the “receiver-satellite” direction, i.e. when:

$$\mathrm{tg}(\theta) = -\cos(\alpha_S - \alpha)/\mathrm{tg}\theta_S$$

where α and θ are, respectively, the azimuth and elevation angle of the TID wave vector, $\mathbf{K}$. If the azimuth α is known, one can find the elevation angle θ and the total velocity vector of TID ($V = V_h \cos\theta$) using the above expression. The aspect effect shifts the disturbance maximum along the time axis, which can lead to errors in determining the TID velocity if the latter is calculated from the time delay. Therefore, the primary task in recording and analyzing TID is to assess the aspect conditions along the trajectory under examination. For this purpose, it is necessary to calculate the angle $\gamma(t)$ between the vector $\mathbf{K}$ and the “receiver-satellite” line of sight.

$$\cos\gamma = \cos\theta_S \cos\theta \cos(\alpha_S - \alpha) + \sin\theta_S \sin\theta$$

The expressions given above allow us to thoroughly analyze the resulting shape of the signal for all satellites. The estimates made as a first approximation taking into account the aspect conditions and Doppler effect have revealed no apparent contradictions between the observed shape of TEC variations and the delay relative to the explosion time. E.g., the records from satellites N 15 and N 18 show virtually complete coincidence.

The interpretation of data from satellite N 21 seems to require that the wind velocity at these heights was taken into account. As shown by experimental data and theoretical calculations, the wind in the F2 layer is usually directed from the day (lighted) side of the planet to the night side through the pole. The wind on the night side has a speed as high as 200—300 m/s, while on the day side it slows down to 50-100 m/s because of a large number of charged particles. Then, the absence of a clearly pronounced effect could be the result of velocity addition. On the other hand, Figure 5 suggests that a signal, though very weak, probably does exist (a variation is noticeable at the proper time) and is in anaphase with the signal of satellite N 18. All this is the subject for further analysis.

4. Discussion (model approximations and experiments, facts, and effects)

4.1 Observation of the ionosphere response by vertical sounding techniques

Barry et al. were the first to report in 1966 the appearance of sound waves in the ionosphere in the HF radio band after a ground explosion equivalent to 500 tons TNT [Barry et al, 1966]. The linear theory of acoustics cited in that work claimed that a large surface explosion (hundreds of tons TNT) was bound to produce a pressure wave of a few per cent in the atmosphere at a height of 200 km above the explosion. Such an effect must be detected by the oblique-incidence radio sounding, since a disturbance of neutrals changes the density of electrons in the ionosphere.

Radio measurements carried out during a 500 tons TNT surface explosion with two ionospheric probes spaced by about 200 km symmetrically relative to the explosion center (in the geomagnetic meridian plane in the region of Sheffield, Alberta) corroborated this hypothesis. Measured were the disturbance onset time, the shape, and the intensity of AGW. The observed phase path variation was close to the prediction. The amplitude and duration of the disturbance were 100 rad and 2 min, respectively. Figure 6 (from [Berry et al, 1966]) illustrates the model ray tracing of acoustic disturbance under experimental conditions. It is shown that the main disturbance is concentrated within an angle of ± 10 degrees from the vertical (the calculation was carried out at 10-degree steps). This means that a disturbance in the ionosphere was to be expected over the explosion point within the spot affected by the acoustic wave. The theoretical radio disturbance was then calculated taking into account the real geometry and the parabolic model ionosphere fitted to the real profile. Figure 7 represents a fragment of the calculated shape of the wave disturbance for two polarizations of the sounding wave compared to the experimental one.

Paper [Pitteway et al, 1985] provides data on the ionospheric effects detected after a 600 tons TNT ground explosion. The recording method was based on the Doppler measurement of HF signal reflected from the disturbed spot in the ionosphere over the explosion. Observations of the ionosphere were made with a Dinasonde at ten fixed frequencies (from 2.20 MHz to 11.51 MHz) at a distance of 90 miles to the south. The radiation at 11.51 MHz was reflected from the ionospheric F2 layer at an altitude of 280 km. The Dinasonde was supplied with four dipole receiving aerials, which made it possible to localize echo-signals in the north-south and east-west planes, to record the polarization parameters, phase path, and Doppler velocities and, in particular, to reconstruct variations in the rate of change of the reflection altitude.

As a result, an ionospheric disturbance was reliably recorded about 10 min after the explosion. Figure 8 shows by way of example the data obtained for the ordinarily polarized wave: effective height (height variation, upper panel), phase path (center), and Doppler velocity (lower panel). With correction for the initial tilt of the ionosphere, we obtain a good agreement between the experimental parameters and those calculated from radio tracing model (circles in the figure).

The above examples suggest that an explosion in the atmosphere at a height of 25-30 km (the probable height of the bolide explosion, see Section 2) must produce a very strong effect detectable by up-to-date radio occultation method using the signals from GPS cluster satellites. This issue is discussed in the next Section.

4.2 Transionosphere GPS sounding of TEC disturbances caused by a pulse-like ground-based source.

At present, the generally recognized model of artificial disturbance caused by ground-level explosions and earthquakes is as follows (see monograph [Afraimovich and Perevalova, 2006] and references therein). An underground seismic point source generates a spherical elastic wave. Its appearance on the surface can be compared with a strong blow, which makes parts of the rocks successively rise and sink back. This is accompanied by excitation of acoustic gravity waves in the atmosphere. The intensity and spectral composition of the generated AGW display a strong dependence on the zenith angle. The directional pattern of the acoustic signal propagating from the surface is very narrow – less than 5º. Therefore, the AGW reach the ionospheric heights in a narrow sector of the zenith angles (see Figure 9).

During the earthquake of 25.09.2003 in Japan, it was experimentally established [Afraimovich and Perevalova, 2006] that the source of artificial disturbances of TEC in the ionosphere is not the epicenter, but a region over the epicenter at the height of the ionosphere F2 layer (Figure 9). It was also shown that the secondary source in the ionosphere is “switched on” 8-9 min after the main shock. The mean vertical velocity at which the acoustic disturbance propagates from the epicenter to the secondary source is close to the sound velocity C=650 m/s averaged in the height range h=100÷400 km. Thus, the experiment corroborated the theoretical model of generation of the ionospheric disturbance described above. As noted earlier, it is also true for the explosions and earthquakes.

The same work provides an analysis of TEC disturbances (as recorded by GPS network) after a ground-level explosion. Figure 10 in [Afraimovich and Perevalova, 2006] represents the geometry of measurements and variations of TEC during the 2-kt surface explosion produced on 10.06.1993 at New Mexico (USA). The disturbance had a shape typical of an acoustic shock wave with a period of about 180s. The TEC oscillation amplitude of the order of 0.3 TECU exceeded significantly the intensity of TEC fluctuations on the “background” days 09.06.93 and 11.06.93. It was noted that the shape, amplitude, and oscillation period of the TEC disturbance (N-type) observed during the explosion were very similar to those recorded during earthquakes.

Thus, the bolide explosion in the atmosphere equivalent to hundreds of kilotons TNT could be expected to cause a quasi-circular disturbance in TEC in the near zone with the amplitude of at least several TECU. Going back to our results, let us demonstrate the most intensive response of the total electron content of the ionosphere to the bolide explosion recorded by radio occultation method with the use of signals from the GPS network satellites (Figure 11).

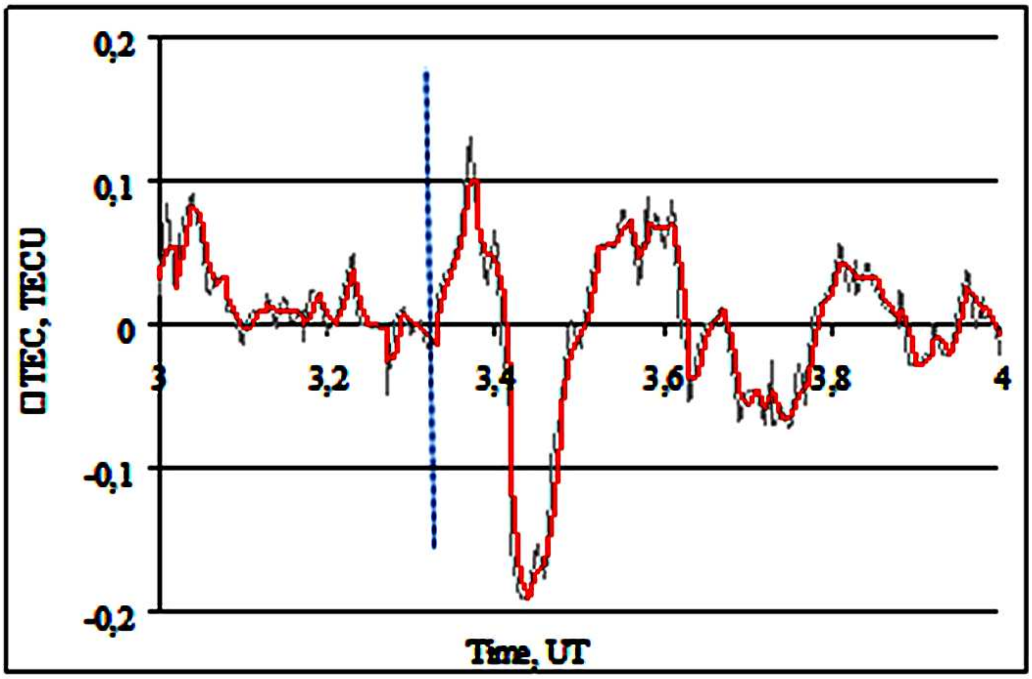


Figure 11: The maximal ionospheric response to the bolide explosion as recorded by satellite N 26.

One can see that the maximal response was about 0.3 TECU. Comparing this value with the effect of the ground-level explosion described above and taking into account that the bolide explosion occurred at a height more than 10-15 km, we can draw a conclusion that the equivalent of the Cheliabinsk meteoroide was evidently less than 2 kilotons TNT.

4.3. Remote ionosphere response to pulsed injections performed within the frames of the CRRES Program

The previous sections deal with the response of the ionosphere to ground-level explosions recorded in the vicinity of the epicenter in the form of AGW. Wave-like ionospheric disturbances are also detected in the remote region (at 1000 km and farther) where they appear as a result of propagation of the inner gravity waves (IGW) (see review [Afraimovich and Perevalova, 2006]. Let us consider by way of example the wave disturbances (WD) recorded in the ionosphere at a distance of 1500-2500 km during the series of CRRES (USA) experiments in 1991 [Bernhardt P. A, 1992]. The results of the spectral analysis of an artificial WD in the ionosphere caused by the pulsed injection of barium vapor at a height of 400-500 km along the perigee parts of the experiment trajectories are given in [Oraevsky, 1995]. Vertical sounding of the ionosphere over Havana (Cuba) revealed pulsations of the critical frequency (f_0 F2) and the height of reflection at the maximum of the ionospheric F2-layer at significant distances (see Table II) from the injection point.

Table II

The main conditions and results of the experiments.

Date	Time UT	Height (km)	α (deg)	ΔT (min)	DF2 (km)	D_{lit} (km)	V_{mean} (m/s)	Experiment
19.07	8: 37	441	19.3	99	2142	642	361	G-09
22.07	8:38	411	21.7	103	2409	909	390	G-11a
25.07	8: 37	478	13.1	75	1454	—	323	G-11Ь

Notes: D_{lit} is the length of the sunlit part of the trajectory and α is the central angle corresponding to the length of the great circle arc along the WD propagation trajectory.

In analogy with our case, the source was in the same position relative to the solar terminator (the explosion occurred in the already-lit atmosphere/ionosphere), and the propagation of disturbance in different directions had to depend on the length of the path in the day- and nighttime ionosphere, which was found in the CRRES experiments.

Figure 12 shows the spectrogram of experiment G-11b (see Table II), in which the wave disturbance was propagating only in the nighttime ionosphere, and its mean velocity was minimal. The abscissa is the oscillation period; the ordinate is the universal time UT. It was found that the delay ΔT of the wave-like response in the ionosphere relative to the pulse injection (the appearance of spectral component with a period of 6-10 min – upper scale) corresponds to the velocity of the wave disturbance in the range of 323-390 m/s and depends on the particular injection conditions.

One can see from the Table II that, in each experiment, the effective disturbance velocity in the terminator zone correlates with the length of the sunlit part of the trajectory from the injection point to Havana: the longer the path the higher the mean velocity.

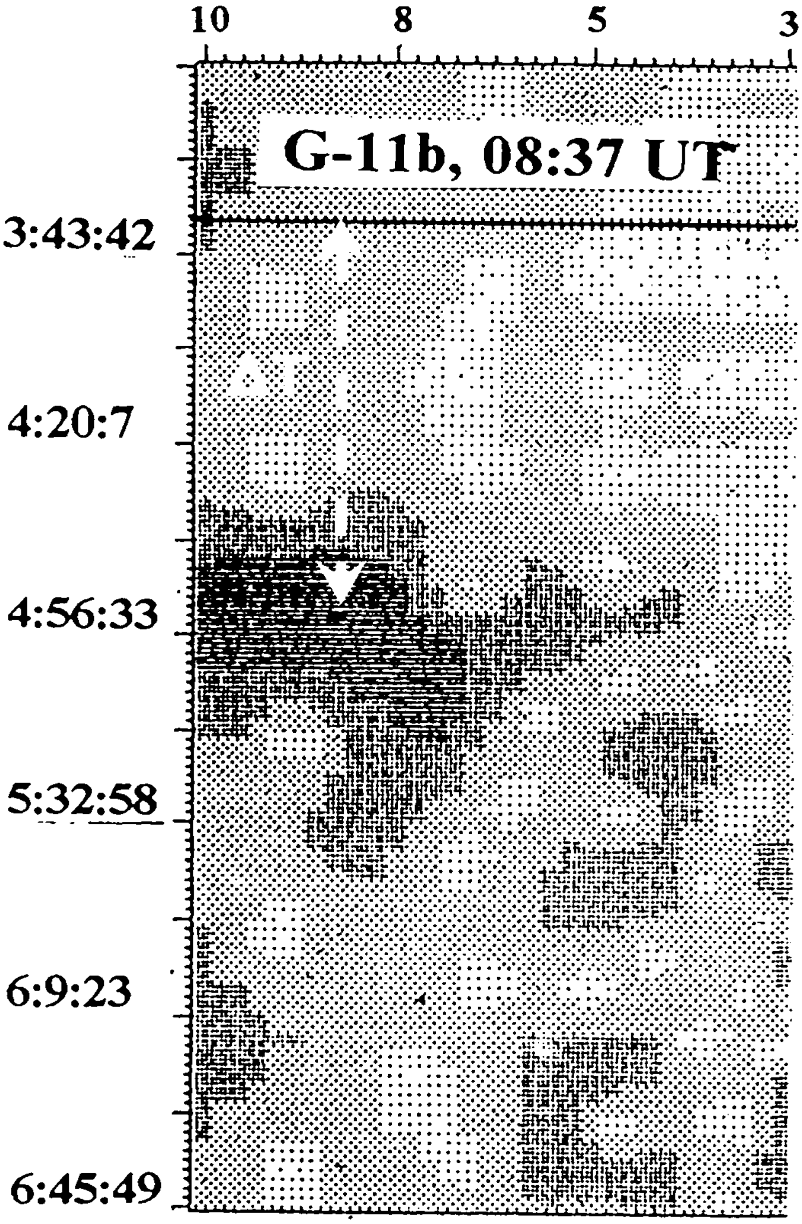


Figure 12: Variation spectrum of the critical frequency f0 F2 (ΔT is the delay of WD packet relative the barium CRRES injection).

The disturbance under discussion was compared with other WD excited by earthquakes, high-altitude explosions, and solar terminator. It was shown [Oraevsky, 1995; Ruzhin et al, 1998] that even a small amount of barium vapor (3.3 kg) injected into the ionosphere at orbital velocity in the terminator zone may effectively generate the spectral component of natural WD (with a period more than 5-10 min) recorded at a distance of 1500-2500 km.

In our case, a point similar to Havana in the CRRES Program could be Moscow. The estimates show that at the time of explosion of the bolide in the dayside atmosphere, the Sun in

Moscow was below the horizon. The dip angle was 7.5 deg and, accordingly, the terminator was at a height of 200 km. The wave disturbance was propagating westward, to Moscow in the terminator zone through the daytime ionosphere; i.e., the conditions were similar to those of experiment G-11b (see Table II). The distance was also about 1500 km (see Figure 1 for TEC values at the moment of intrusion). At the velocities obtained in the CRRES experiments for the terminator zone (see Table II), the disturbance was to be expected in Moscow after 83-98 min and in Alma-Ata, after about 100 min. Taking into account the reported intensity of the bolide explosion (300-500 kt TNT), the disturbance could (and had to) reach both Moscow and Alma-Ata. The absence of anomalies (disturbances in the remote zone) again raises questions concerning the equivalent and/or structural features of the explosion.

5. Conclusion

The paper provides a review of ionospheric effects caused by explosive phenomena of natural and anthropogenic origin at different heights in the atmosphere and on the ground.

The analysis of the event of the morning of June 30, 1908, when a large fire ball flew over central Siberia (the Yenisei basin) from the south-east to north-west showed that it had much in common with the Chelyabinsk meteoroid. The event of 1908 ended with an explosion over an uninhabited area in taiga. It was established [Bronshten V, 2000; Vasil'yev N.V, 2004] that the explosion occurred in the air at a certain height (5-15 km according to different estimates) and was hardly point-type, so one could only speak of the projection of coordinates of a particular point, which is called the epicenter. Different methods of determining the geographical coordinates of this point yield different results. The Chelyabinsk meteoroid also appeared over Siberia in the morning (around 7 am local time) flying from the south-east to north-west. Within seconds, there were more than three explosions (i.e., all disturbances had non-point source). The worldwide network stations recorded both seismic and acoustic signals. Until now, the data on the bolide trajectory, as well as the coordinates (that are particularly important for estimations and simulation), height, and exact time of the explosion differ significantly.

The results of the analysis, such as moderate ionospheric disturbances in the near zone, their pronounced asymmetry about the epicenter of the explosion, as well as the absence of the classical N-type bipolar response corresponding to the acoustic shock (AS) make us doubt the accuracy of the estimated explosion equivalent and raise questions concerning the mechanisms of generation of acoustic shock and ionospheric disturbance at supersonic motion and explosion of a bolide in the atmosphere. These are the formation of a shock front, spectral filtering, propagation and transformation of the shock energy, the trajectory of radial distribution of the acoustic pulse energy in the terminator zone, generation of the “secondary” source in the ionosphere, and, finally, the model and structure of the primary source, i.e., the explosion itself (series of explosions) in the atmosphere.

At the velocities of propagation of ionospheric disturbance in the terminator zone obtained in the CRRES experiment (see Table II), the response in the remote zone was to be expected after 83-98 min for Moscow and after about 100 min for the Alma-Ata region. The absence of the anomalies (disturbances in the remote zone) also raises question about the equivalent estimate or/and peculiar structure of the explosion. It should be noted that to correctly interpret experimental data on the unique phenomenon of the Chelyabinsk meteoroid, we must take into account processes in the terminator zone, the AS source geometry and temporal characteristics, the state of the atmosphere and ionosphere and the geomagnetic field orientation over the observation point, and, in particular, the specifics of the method of transionospheric sounding with the use of GPS network signals.

References

Adushkin V.V., Gorelyi K.I., Kudryavtsev V.P. The asymmetry of effects of atmospheric nuclear explosions in the ionospheric F-region. *Geomagn. Aeron*. 34, 1, 79 , 1994.

Afraimovich E.L., Kosogorov E.A., Palamartchouk K.S., Perevalova N.P., Plotnikov A.V. The use of GPS arrays in detecting the ionospheric response during rocket launchings. *Earth Planets and Space.* 52, 11. 1061-1066, 2000.

Afraimovich E.L., Perevalova N.P. GPS-monitoring of the Earth upper atmosphere. Irkutsk, *GU NC RVH VSNC SO RAMN*, 480, 2006.

Andrianov V., Alpatov V., Pimenov A., Romanovsky Y., Smirnov V., Shemelov V. The investigation of the ionospheric variability by the radio translucence method. *Advances in Space Research*. 27, 6-7, 1327-1331, 2001.

Andrianov V.A., Smirnov V.M. Determining the height profile of electron density of the Earth ionosphere from two-hour measurements of AES radio signals. *Radio Engineering and Electronics,* 38, 7, 1326-1335, 1993.

Barry H., Griffiths L. J., Taenzer J. C. H.F. Radio Measurements of High-Altitude Acoustic Waves from a Ground-Level Explosion. *J. Geoph. Res.*, 71, 4173-4182, 1966.

Bernhardt P. A. Phys. Fluids, B 4(7), 2249-2256, 1992.

Blanc E. Observations in the upper atmosphere of infrasonic waves from natural or artificial sources: A summary. *Annales Geophysicae*, 3, 6, 673-688, 1985.

Borovicka, J., Spumy, P., and Shrbeny, L. Trajectory and orbit of the Chelyabinsk superbolide. *Electronic Telegram Central Bureau for Astronomical Telegrams, IAU* 3423, 2013.

Bronshten V. Tunguska meteorite: history of investigations, 312, 2000. ISBN: 590127304.

Calais E., Minster B.J., Hofyon M.A., Heldin M.A.H. Ionospheric signature of surface mine blast from GPS measurements. *Geophys.J.Int*., 132, 101-202, 1998,

Fitzgerald T.J. Observation of TEC perturbations in GPS signals caused by a ground level explosion. *J.Atm.Terr.Phys*., 59, 7, 829-834, 1997.

Gohberg M.B, Strong acoustic wave action. Active experiment in space. *ESA Symp. Alpbach,* 99-110, 1983.

http://astronomia.udea.edu.co/chelyabinsk-meteoroid

http://ru.wikipedia.org/wiki/

http://www.utro.ru/articles/2013/02/20/1102314.shtml

Kitov I.O., Gokhberg M.B. Determining acoustic energy from a sub-surface source from the data of vertical ionospheric sounding. *Notices of the Acad. of Sci*., 234, 5, 982-985, 1992.

Kozin I.D., Saifutdinov I.A. A “fast response” of the ionosphere to a shock wave. *Geomagn aeron*., 28, 4, 681-683, 1988.

Le Pichon A., Ceranna L., Pilger Ch., Mialle P., Brown D., Herry P. Russian Fireball largest ever detected by CTBTO infrasound sensors. *Geophysical Research Letters*. 2013; DOI:10.1002/grl.50619

Oraevsky V.N, Ruzhin Yu. Ya. Depueva A.Kh., Perez H., Lurdes P. Orbital barium CRRES injection - effective source of ionospheric wavelike disturbances. *Adv.Space Res.* 15. 12. (12)127-(12)130, 1995.

Pitteway M. L. V., Rickel D. G., Wright J. W., Al-Jarrah M. M., Modelling the ionospheric disturbance caused by an explosion on the ground., *Geophysicae,* 3, 6, 695-704, 1985.

Ruzhin Yu. Ya., Depueva A.Kh., Lurdes Palasio. Acoustic Gravity Wave Generation during the Barium CRRES injection Experiments. *Magnetospheric Research with Advance Techniques*. 111-115, 1998.

Sorokin V. M., Fedorovich G. V. The physics of slow MHD-waves in ionospheric plasmas, *Moscow: Energoizdat*, 1982.

Vasil’yev N.V. Tunguska meteorite. Cosmic phenomenovn of summer 1908. *Russian Panorama*, 368, 2004. ISBN 5-93165-106-3

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