

Effects of the Chelyabinsk Meteoroid Entry at the Ionosphere

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Abstract

The transitionospheric sounding by signals from the GPS cluster satellites carried out in the zone of explosion of the Chelyabinsk bolide 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 Earth surface explosions. Ionosphere effects in the form of acoustic-gravity waves (AGW) produced by 260-500 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.

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 [1-3]. A series of experiments – MASS [3] were carried out to analyze the impact of ground explosions on the ionosphere and to simulate interactions in the lithosphere-atmosphere-ionosphere system. 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 ionospheric response 8-9 min after the explosion. It is example that the response of the ionosphere to hundreds of tons TNT ground-level explosions is reliably recorded by radio techniques.

The bolide explosion in the atmosphere is a very rare phenomenon, which is particularly important to studying the impacts on the ionosphere from below. The phenomenon under discussion (meteorite intrusion) is also interesting from the point of view of verifying the available theoretical concepts of ionospheric 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. On March 1, NASA reported specified data [4-5] on total luminosity of the super-bolide, which was $E_0 = 3.75 \cdot 10^{14}$ 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. For the first time since the establishment of the IMS infrasound network, multiple arrivals involving waves that traveled twice round the globe have been clearly identified [6]. A preliminary estimate of the explosive energy using empirical period-yield scaling relations gives a value of 460 kt of TNT equivalent. Many video cameras recorded the phenomenon. 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. 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 14 degrees, and the terminator was at the height of 200 km. Fig. 1 illustrates the state of the ionosphere at the time of intrusion in TEC (IONEX technology). The dashed lines mark the longitudes of Chebarkul lake (the shadow at a height of 500 m) and Moscow (the shadow at a height of 195 km). As seen from the TEC distribution map (Fig. 1), the ionosphere was mainly quiet (undisturbed), which enabled the search for wave-like disturbances both in the intrusion zone and in remote

regions. According to the Intermagnet network data, the geomagnetic field at the time of the explosion was weakly disturbed. Given below are the results of the analysis of ionospheric radio observations carried out using GPS signals before and after the bolide explosion in the Chelyabinsk region at 03:20:33 UT. Data from the Arti, Ochninsk, and Alma-Ata GPS net stations are taken into account. The analysis is mainly focused on the Arti (56.43°N; 58.57°E) data obtained in the vicinity of the explosion epicenter. Fig. 2 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. In monograph [7] 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 Fig. 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.

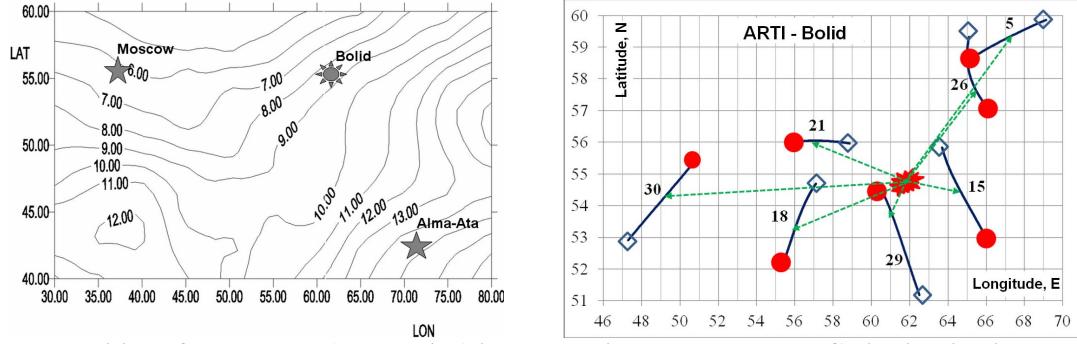


Fig. 1. The position of the shadow (dashed line) in the terminator zone and TEC distribution in the ionosphere before the bolide explosion (03 UT).

Fig. 2. The tracks of the ionospheric points for all satellites observed at the Arti station, whose data were used to analyze wave disturbances.

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

The parameters of the ionospheric response to the explosion were determined by the radio translucence method along the Earth-satellite path. The application of this method is described in detail in [8]. The TEC parameters were determined using the code and phase measuring data obtained with the receivers of GPS network stations. The ionospheric 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 all satellites obtained from equation

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

are represented in Fig. 3. 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 that wavelengths; $1 \text{TECU} = 10^{16} \text{m}^{-2}$.

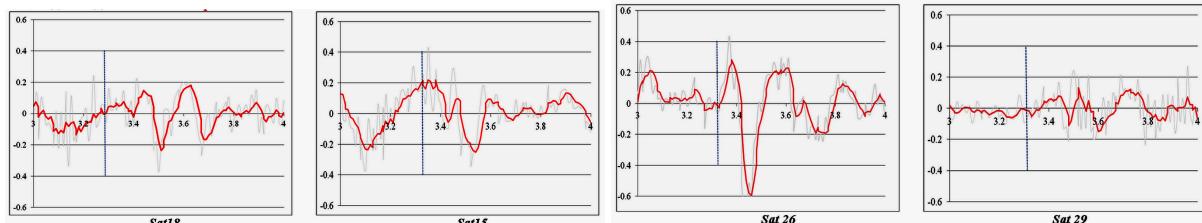


Fig. 3. The disturbance in the ionosphere (TEC). Ordinate - TECU*100/s, abscissa - time UT, hr.

Figs. 3 represent TEC variations as recorded by the satellites, the tracks of the subionospheric points for which are shown in Fig. 2. The vertical dashed line marks the time of the bolide explosion. The plots represent data smoothed over five points. The initial data are 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. 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. 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 Fig. 6). 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.

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. Thus, if the wave vector of the disturbance is assumed to be horizontal, the aspect orthogonality condition ($\gamma \leq 90^\circ$) 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 [7], it was found that the shape of the response in TEC differed significantly from the expected classical N-shape (e.g., see Figs.6).

4. Discussion. Model approximations and experiments

At present, the generally recognized model of artificial disturbance caused by ground-level explosions and earthquakes is as follows (see monograph [7] 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 5°. Therefore, the AGW reach the ionospheric heights in a narrow sector of the zenith angles.

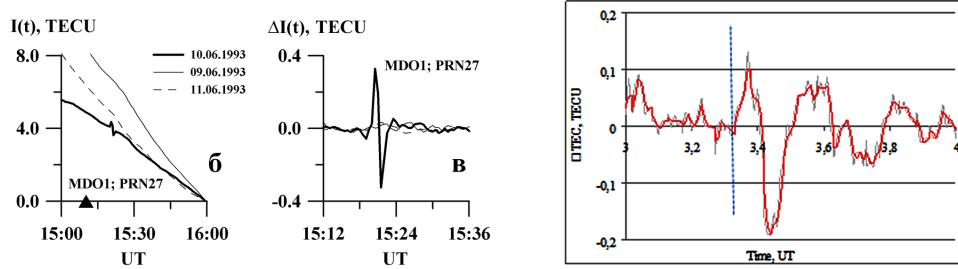


Fig. 4. The TEC variations during a 2 kt surface explosion (left panel) and Cheliabinsk meteoroid (right).

The same work provides an analysis of TEC disturbances (as recorded by GPS network) after a ground-level explosion. Fig. 4 (left) [7] represents 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 180 s. 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 (Fig. 6, right). One can see that the maximal response was about 0.24 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 meteoroid was evidently less than 2 kilotons TNT.

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 14° and, accordingly, the terminator was at a height of 200 km. The expected wave disturbance was propagating westward, to Moscow in the terminator zone through the daytime ionosphere. The distance was about 1500 km (see Fig. 1). At the velocities for the terminator zone, 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 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.

6. References

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