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Discussion paper: Macroscale ionospheric irregularities registered by the Mir onboard ionosonde

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[1] A joint consideration of the anomalous ionograms registered on board Mir space station (and interpreted as ionospheric irregularities with sharp lateral gradients) and macroirregularities of the ionosphere detected by ground-based ionosondes. A hypothesis is proposed and analyzed that these irregularities detected by two principally different methods have a seismogenic nature. *INDEX TERMS:* 2439 Ionosphere: Ionospheric irregularities; 2494 Ionosphere: Instruments and techniques; 7215 Seismology: Earthquake parameters; *KEYWORDS:* Satellite radiosounding; Ionospheric irregularities; Earthquakes.

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1. Introduction

[2] In spring 1999 the manned space complex Mir with an onboard automatic ionospheric station (AIS) was orbiting at heights of about 330–350 km. Abilities of radiosounding almost directly from the maximum of the $F2$ layer had been studied earlier in the experiments on board the Intercosmos 19 and Cosmos 1809 satellites. A possibility of determining various ionospheric parameters and derive $N(h)$ vertical profiles has been demonstrated in these experiments [*Danilkin*, 1994; *Danilkin and Vaisman*, 1997]. Orbiting at southern latitudes, Mir often was moving below the main maximum of the electron concentration in the ionosphere.

[3] Among the ionograms registered in this period [see *Danilkin*, 2001], there are a large number of ionograms containing anomalous signals (AS). Currently, there is only one noncontroversial explanation coordinated with the entire volume of data of these traces in ionograms of oblique satellite sounding [*Danilkin and Kotonaeva,* 2002]. This explanation claims that the traces appear as a result of the oblique reflection of radiowaves within a large range of frequencies and then (or before) of the return of all radiowaves into the transmission point due to sharp gradients of the electron concentration in the ionosphere. Later, it was found that these gradients are lateral walls of stable singular macroirregularities with very specific properties [*Kalinin and Sergeenko*, 2002].

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2. Anomalous Signals While Radiosounding From Altitudes Below the F-Region Maximum (h_mF)

[4] Ionograms with AS were registered under various geophysical conditions and in different regions of the globe. Table 1 provides information on AS ionograms registered on board Mir.

[5] To describe the event thoroughly, Table 1 contains several groups of AS on various days when ionograms of this type have been registered. On 31 March 1999 a diurnal series of observations was conducted from 0949 UT to 0930 UT on the following day. This group is shown to demonstrate the quantitative side of the phenomena. During the period mentioned, six groups of ionograms of the type described were observed (see Table 1). They were predominantly observed in the latitude range from 20°S to 20°N. However, Mir sometimes was below the $F2$-layer maximum even orbiting at high latitudes. Case 8 in Table 1 provides information on such a case. Cases 9 and 10 are shown to illustrate especially long periods of observations of the ionograms con-

Table 1. Information on AS Ionograms Registered on Board Mir

Case	Time of Observation, UT	Geographical Coordinates Latitude, Longitude — Beginning	Geographical Coordinates Latitude, Longitude — End	Mir Height, km
		10 March 1999		
1	0401:13–0403:13	−20.36, −67.99	−26.18, −73.25	361
		31 March 1999 to 1 April 1999		
2	1655:48–1702:44	−24.03, −82.08	−2.97, −65.66	344
3	1830:17–1835:36	−14.95, −97.7	−0.07, −86.87	344
4	2004:15–2306:55	−7.17, −115.15	1.12, −109.27	345
5	2304:46–2307:22	−14.39, −167.01	−6.39, −161.09	344
6	0213:14–0217:26	2.94, 159.02	15.87, 168.55	345
7	0513:39–0514:41	−4.68, 107.15	−1.47, 109.42	344
		21 April 1999		
8	0524:03–0524:51	51.61, 68.33	51.81, 73.50	346
9	0714:26–0718:26	15.12, 125.41	2.81, 134.45	350
		5 May 1999		
10	1803:53–1806:49	−44.37, 56.29	−37.87, 68.13	372
11	1808:41–1808:57	−33.12, 74.49	−32.41, 75.34	369
12	1936:07–1939:35	−43.14, 35.56	−35.01, 48.83	370
		6 May 1999		
13	1825:44–1830:32	18.02, 115.83	31.82, 128.98	354
		2 June 1999		
14	1935:53–1936:41	35.05, 65.06	32.95, 67.69	352

sidered. These cases show that the region forming the extra trace is extended in space and is a structure of the global scale. Figure 1 shows a typical ionogram of this series of AS.

[6] One can see that Mir is located below the ionospheric maximum. The trace of reflection from the ground is fairly typical for the topside sounding signals [*Pulinets and Benson*, 1999]. However, its lowest frequency is equal not to the ionospheric critical frequency (as it always takes place at topside sounding) but to the plasma frequency in the vicinity of Mir, the latter fact being the strongest confirmation of the Mir location below the layer maximum height. It should be noted that the equality of the frequency of the inflection point of the reflection from the ground to the plasma frequency in the vicinity of Mir is also confirmed by the plasma resonance denoted in Figure 1 by the number 1. Very short traces of the reflection from the ionosphere above Mir are also seen: z, o, and x are the reflection traces of the z, ordinary, and extraordinary components, respectively. The group delay of AS is slightly larger than that of the signals reflected from the ground. The frequency range of AS registration is higher than the $F2$-layer critical frequency in the place of Mir location (range B in Figure 1). In such situations the hypothesis on the presence of large-scale irregularities of the electron concentration (with horizontal dimensions $l > 10^3$ km) in the region of the main maximum makes it possible to consider the typical features of AS in the scope of the "triangle" (or "returning" from the *Danilkin* [1994] terminology) trajectories concept. AS are formed because of the refraction of signals of different frequencies at the sharp lateral electron concentration gradient of the ionospheric irregularity. This refraction precedes or follows the oblique reflection of the signals from the ground and returning of the signals to the point of the Mir location. The calculations in the scope of the solution of the problem of fitting parameters of such irregularities of the simplest form to provide coincidence of the calculated and observed group delays of AS have shown a presence of sharp positive gradients of the electron density. On the whole, the entire spectrum of ionograms with AS indicates to very large dimensions of the irregularities. All the above-said makes reasonable a comparison of the macroirregularities detected in the experiment in question to the corresponding macroirregularities described by *Kalinin and Sergeenko* [2002] and *Kalinin et al.* [2001].

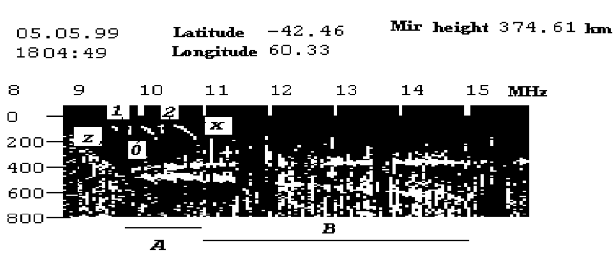

Figure 1. Ionogram with anomalous signals.

3. Ionospheric Macroirregularities Caused by Earthquakes According to Data of the Ground-Based Chain of Ionospheric Stations

[7] The experimental data obtained at the chain of the ground-based ionospheric stations (GIS) are analyzed below. The stations were located along the part of the Mir orbit where AS were registered. The hypothesis (first proposed by *Kalinin and Sergeenko* [2002]) is considered that prior to strong earthquakes, macroscale irregularities (of the very kind which according to *Danilkin* [1994] is able to explain a formation of AS) may be formed in the vicinity of the earthquake epicenters. Such interpretation of the data of *Kalinin and Sergeenko* [2002] and *Kalinin et al.* [2001] requires a detailed comparison of the features of the orbit motion of Mir to the motions of the irregularities at the $F2$-maximum height caused by this or that earthquakes in the days of AS registration.

[8] Figure 2 shows the $\delta f_o F2(t)$ dependencies for three GIS (designated by the first letters of the places of their location). The observations indicate to the presence of travelling singular macroirregularities. The lower abscissa (letter E) refers to the epicenter region, the three lower abscissas refer to three stations. The vertical shift is proportional to the distance from the GIS to the epicenter. Time is counted for all four abscissas from the moment 0000 UT on 29 April 1999 (vertical line). From each of the upper three abscissas the value of the relative variation $\delta f_o F2(t)$ of the critical frequency measured by the corresponding GIS is counted. The scale is shown as a stretch in the middle of the right-hand side of Figure 2.

[9] The earthquake moment is shown by a cross. Solid circles correspond to three positive "pulses" closest to the earthquake. For Darwin they are prior the earthquake and for Ahmedabad and Roma they are after the earthquake. The middles of the pulse bases projected to the abscissa are shown by solid circles. According to the theory of *Kalinin and Sergeenko* [2002], the dashed line shows the motion with a velocity of $V \approx 900$ m s^{-1} of an object having been formed 12 hours prior to the earthquake and shifted during 21 hours to a distance of 18,000 km. It should be noted that according to *Kalinin et al.* [2001] the relative variability of the irregularity shape in the vicinity of its center is well modeled by the $1/\cosh x$ function, x being the shift from the center.

4. Ionospheric Macroirregularities Observed Jointly by Satellite and Ionospheric Ionosondes

[10] Figure 3 shows the information on this experiment in the part of the global map in Mercator projection. (left, bottom) There are three fragments (three ionograms) illustrating by bright marks at the frequency-distance (f, D) planes the signals detected by the ionosondes on board Mir on 29 April 1999 in a complete analogy to Figure 1. (left, top)

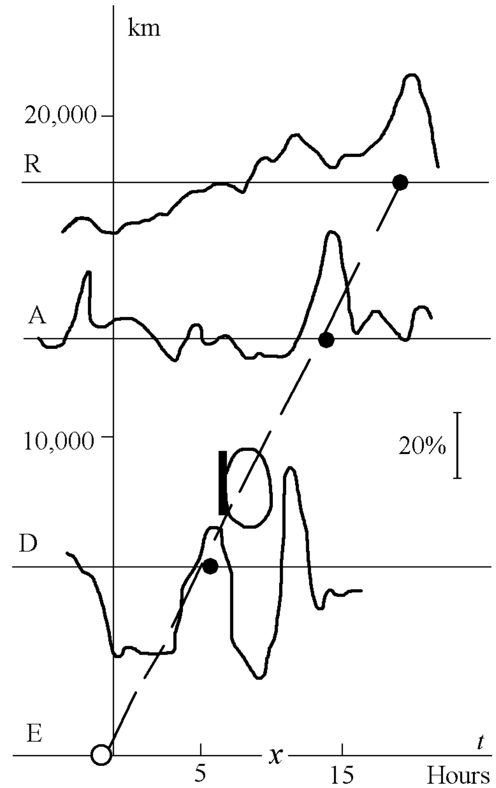

Figure 2. Trajectories of Mir and macroscale irregularity registered by ground-based ionosondes.

The Mir coordinates of fragment I. The date and time are shown in the left, bottom corner. The time is so called "winter Moscow" and goes ahead of UT by 3 hours. The track caused by the reflection from the ground is shown in the (f, D) plane by red points in the first ionograms and by white line without points in the second and third ionograms. The AS tracks are designated by green points. The position of the irregularity is shown by green oval. The part where Mir registered anomalous signals is marked by thick vertical line. The GIS locations at Darwin, Ahmedabad, and Roma are shown by circles with the corresponding letters in Figure 3 (fragment II). The dashed curve DD′ (the arc of a great circle passing through the epicenter and Roma) is the approximate trajectory of the irregularity motion. The GIS, which in proper time detected no positive "pulses" in $\delta f_c(t)$ are shown by the circles with minus sign. This is assumed to be an indication of the absence of the irregularity related to the earthquake. Those are GISs (in the westward order) located in Petropavlovsk, Tomsk, Novosibirsk, Ashkhabad, and Moscow. No positive pulses has been registered by GIS in England and Holland. This shows that soon after passing over Roma the irregularity ceased its existence. Comparing the SS′ and DD′ trajectories, one can see that the anomalous signals were observed by the onboard ionosonde exactly when the Mir trajectory passed along the irregularity edge. In Figure 3 this fact is illustrated by the green semioval with green dashes within.

[11] The dashed SS′ curve in fragment II shows the part

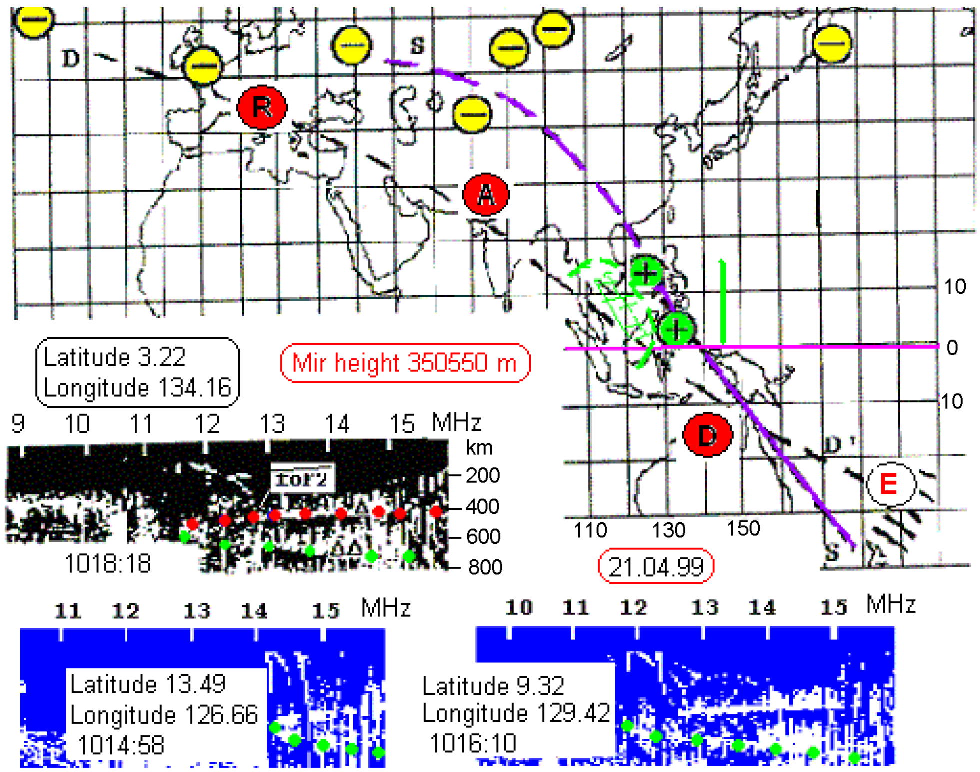

Figure 3. Map with trajectories of Mir and irregularity motion and the ground-based ionosondes which registered or did not register the irregularity.

of the great circle which is a projection of the Mir orbit on the globe. The position of the Mir station during the registration of the ionogram presented in fragment I is marked at the SS′ projection by a circle with a cross. The circle is located nearly in the middle of the solid stretch aligned from Philippines to New Guinea Island. This very stretch corresponds to the period of AS observation. *Danilkin* [1994] was the first to publish ionograms of an onboard ionosonde with AS. He suggested that the AS were due to the interaction of the signals transmitted by the onboard ionosonde to positive macroscale irregularities of the electron concentration. Sufficiency of this assumption was illustrated by the calculations of "return" AS trajectories under corresponding choice of the irregularity parameters. The irregularity parameters and arrival angles to the ground (generally speaking, they can be different for different frequencies) were chosen in such a way that the calculated virtual distances "fell" on the AS track. There appear at least two questions concerning the AS registered by the ionosonde on board Mir. First, why AS are not registered at every ionogram? Actually, the stretch containing the circle with a cross and corresponding to the periods of anomalous signal registration presents only a small part of the Mir trajectory shown in Figure 3 (fragment II) by dashed curve SS′.

[12] Second, how in general irregularities with the horizontal dimension above 10 Mm can be formed in the ionospheric $F2$ region? The answers to both these questions are in the hypothesis proposed for the first time and substantiated by *Kalinin and Sergeenko* [2002]. According to this hypothesis, in the ionospheric $F2$ region 10–15 hours prior to a strong earthquake, there are formed in the vicinity of the epicenters macroscale irregularities which then travel horizontally to distances up to 20 Mm.

[13] One should check whether the synchronism condition was fulfilled for any of the earthquakes on 20–21 April 1999. The place and time of the earthquake should fulfill the following conditions. Counting time from the moment 10–15 hours prior to the earthquake and accepting the irregularity velocity of about $V_r \sim 10^3$ km h^{-1} out of the epicenter, the irregularity should come to the place where the Mir ionosonde has registered AS to the time of the registration. For the date in question (21 April 1999) and the preceding date, the number of potentially "suitable" earthquakes (with $M > 5$) is not large. There are five of them, and all of them have occurred in the vicinity of Australia. However, the first four earthquakes have occurred too "early." Even if we assume that from each of the earthquakes the irregularity moved with a velocity of V_r directly to the point ($\varphi = 3.22$; $\lambda = 134.16$), these earthquakes should have reached the point earlier than at 0715 UT. The synchronism condition is fulfilled only for the earthquake (with $M = 5.6$) which took place at 1108 UT on 21 April 1999 northeastward from New Zealand. All the following earthquakes occurred too "late."

[14] The epicenter if this earthquake is marked by a circle with a letter E in Figure 3 (fragment II). It is of a principal importance that the motion of the irregularity formed before this earthquake has been registered by the ground-based ionosondes in Darwin (at the north of Australia, the

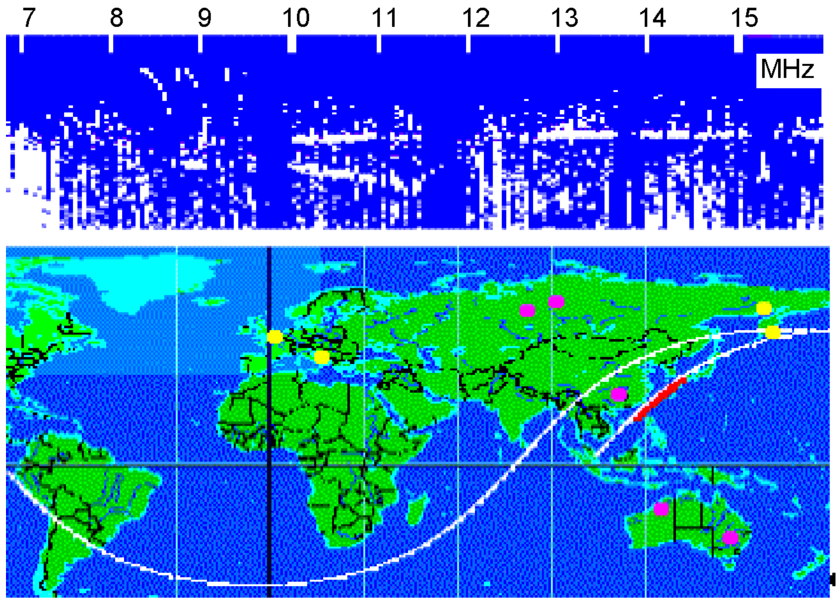

Figure 4. (top) Ionogram typical for the given irregularity. (bottom) Mir trajectory and ground-based ionosondes which registered or did not register the irregularity.

circle with a letter "D" in Figure 3 (fragment II), Ahmedabad (India, the circle with a letter "A"), and Roma (the circle with a letter "R"). All these ground-based ionosondes were registering the critical frequency of the ionospheric $F2$ layer (f_oF2). The dependence of f_oF2 on time was recalculated into the relative variations of f_oF2 using the well-known method [*Gaivoronskaya et al.*, 1971].

[15] It is worth repeating that (see Table 1) well-pronounced AS were registered on board Mir fairly often. Figure 4 shows one more case of joint observation of AS (on board Mir) and the motion of the same irregularity induced by the earthquake and registered at the ground-based ionospheric stations. In the same way as in Figure 3, here the ground-based stations which registered the passage of the irregularity are marked by red. The station not registering this passage are marked yellow. Contrary to Figure 3, in this case some sort of an opposite motion of Mir and the irregularity is observed. Nevertheless, the picture is nearly the same as in Figure 3. The latter may be explained by the fact that Mir moves considerably faster than the irregularity.

[16] Here we succeeded to choose among many earthquakes those what generated irregularities which "in time" came to the region of anomalous signal registration.

5. Conclusion

[17] The authors consider the analysis performed as a confirmation of two independent hypotheses. The suggestion on triangle trajectories is confirmed by the fact that in a "proper moment and proper place" there appear positive irregularities preceding corresponding earthquakes. On the other hand, joint consideration of the observations at the ground-based stations and on board Mir makes it possible to state that the irregularities preceding earthquakes are detected by two independent methods. The irregularity parameters agree well with the data of 38 cases of macroirregularity detection described earlier. Finally, the data obtained may be considered as an independent confirmation of the hypothesis that an irregularity has "sharp" edges. The earlier results of tomography processing of the data of navigation satellites [*Kunitsin et al.*, 1995] also indicated this fact.

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References

Danilkin, N. P. (1994), Transionospheric radiosounding, *J. Atmos. Terr. Phys., 56,* 1423.

Danilkin, N. P. (2001), The results of the satellite radio sounding of the ionosphere in the vicinity of the F-layer maximum, *Int. J. Geomagn. Aeron., 2,* 173.

Danilkin, N. P., and N. G. Kotonaeva (2002), The features of ionospheric radiosounding performed using the "Mir" manned space station, *Radiophysics* (in Russian), *6,* 473.

Danilkin, N. P., and G. M. Vaisman (1997), Positioning of satellite ionosondes for global ionospheric monitoring, *Geomagn. Aeron.* (in Russian), *37,* 191.

Gaivoronskaya, T. V., N. P. Sergeenko, and L. A. Yudovich (1971), Deviation of the F-region critical frequencies from median values, in *Ionospheric Disturbances and Their Influence on Radiocommunication,* p. 55, Nauka, Moscow.

Kalinin, Yu. K., and N. P. Sergeenko (2002), Moving singular macro-scale irregularity generated in the ionosphere a few hours before a catastrophic earthquakes, *Dokl. Akad. Nauk* (in Russian), *387,* 105.

Kalinin, Yu. K., A. A. Romanchuk, and N. P. Sergeenko (2001), Nonlinear interactions of macro-scale irregularities in the ionospheric plasma, *Geomagn. Aeron.* (in Russian), *41,* 196.

Kalinin, Yu. K. (1995), Methods and algorithms of ray radiotomography for ionospheric research, *Ann. Geophys., 13,* 1242.

Pulinets, S. A., and R. F. Benson (1999), Radio-frequency sounders in space, in *Review of Radio Science 1996–1999,* edited by W. R. Stone, p. 711, Oxford Univ. Press, New York.

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