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The results of the satellite radio sounding of the ionosphere in the vicinity of the *F*-layer maximum

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Abstract. The first experimental results of the radio sounding of the ionosphere from the satellite orbits lying below the F-region maximum are presented. It is shown that (as it has been predicted earlier on the basis of numerical simulation) the ionograms obtained under different conditions always make it possible to determine the main ionospheric parameters used for radiocommunication. For the illustration sake the principal features of the ionograms of such type for various geophysical conditions are presented. Details in the ionograms which have never been observed before in the ionospheric experiments on the topside radiosounding of the ionosphere are shown and an explanation of their origin is given. In some cases shown in this paper part of the ionograms was not fully explained.

Introduction

Danilkin and Vaysman [1997] suggested earlier that to determine the principal ionospheric parameters used in radiocommunication (the critical frequency of ionosphere f_oF2, height of maximum of the electron density in the ionosphere h_mF2, and parameter qF characterizing the half-thickness of the F layer in some approximation), the radiosounding may be conducted practically from any height. If the ionosonde is located above the maximum of the F layer, usual ionograms which are well known and described in literature [*Pulinets and Benson*, 1999] and for which determination of the above-mentioned parameters causes no problems, are obtained. The only difference is a considerably shorter length of the vertical part of the $h'(f)$ curve (the dependence of the virtual depth of the radio wave reflection on the frequency). For the illustration sake Figure 1 shows such ionogram obtained in Rostov-Don in the regime of the analog reception on a portable antenna [*Danilkin and Ivanov*, 1999]. Registration of the amplitude of the signal reflected from the ionosphere and Earth is a visible difference of the ionograms obtained in the analog reception regime. The color (here and below the reference to the color is for the online version of the paper) corresponds to various amplitudes and changes from red to violet while the amplitudes change from higher to lower.

Location of the ionosonde at heights below or within the electron density maximum in the F region presents evidently the most difficult case which had no experimental verification before the Mir experiment. Conducting the experiments on the ionosphere radiosounding on board the orbital complex (OC) Mir provided a good chance to check this statement in the real conditions. During the experiments (August 1998–June 1999) OC Mir was at heights of about 340–360 km. Moving in the region of middle latitudes, it was, as a rule, above the ionosphere maximum and moving in the region approximately from 30°S to 30°N, OC Mir rather often moved below the F-region maximum. This paper describes the ionograms obtained in these conditions and their preliminary analysis.

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1. The Principal Considerations and Elements of the Modelling

The principal features typical for the radiosounding from a satellite flying below the F-layer maximum only slightly

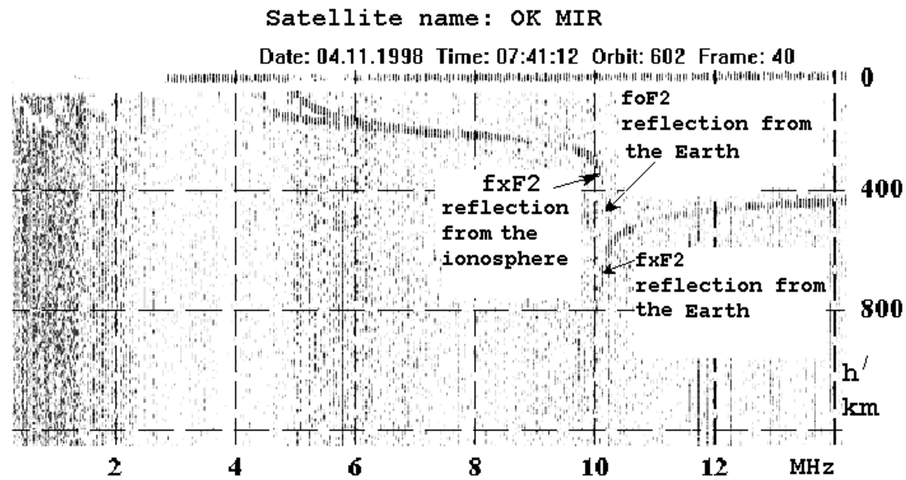

Figure 1. Ionogram obtained on November 4, 1998 at 0741 (orbit 602): 1. F_xF2 determined by the reflection from the ionosphere; 2. f_oF2 determined by the reflection from the Earth; 3. f_xF2 determined by the reflection from the Earth.

differ from the cases when the ionosonde flies at a height of about 1000 km. It should be only remembered that the deviations of rays from the vertical under the upward motion of a wave packet (the satellite is below h_mF2, that is in the bottomside sounding) occurs in the same way as under the downward motion (topside sounding) in the magnetic meridian plane but in the opposite direction. In these cases the ordinary and extraordinary rays will be deviated northward and southward, respectively. In the situation under consideration, the satellite is in the plasma with higher electron concentration. Therefore the frequency ranges in which the conditions for propagation of three main magneto-ion components are fulfilled will be shorter. The initial frequencies (frequency cutoffs) are determined from the same conditions as for the topside sounding [*Pulinets and Benson*, 1999; *Scannapieco and Ossakov*, 1976]:

$$f_Z = \frac{\sqrt{4f_N^2 + f_H^2}}{2} - \frac{f_H}{2}$$

where f_Z is the slow extraordinary mode, f_N is the fast ordinary mode, the cutoff frequency being equal to the local electron plasma frequency,

$$f_X = \frac{\sqrt{4f_N^2 + f_H^2}}{2} + \frac{f_H}{2}$$

where f_X is the fast extraordinary mode.

The group velocity of the waves near the cutoff frequencies is small and therefore there appear effective conditions (the group velocity is close to the thermal velocities of the electrons) for occurrence of plasma resonances at the plasma frequencies of the region where the satellite is located.

The noncoincidence of the lowest frequency of the sounding radio wave reflection from the Earth with the critical frequency f_oF2 of the F region is the main principal difference of the low-orbital ionograms (that is, ionograms obtained when the satellite was below the F layer maximum). The coincidence of the parameters indicated is the most prominent feature of the topside sounding (that is, radio sounding by the ionosonde located above (as a rule, considerably) the electron density maximum in the ionosphere) and vertical propagation of the sounding radio waves. In the case when the satellite is located below the electron density maximum of the F region, the lowest frequency of the reflection from the Earth determines the plasma frequency of the ionosphere at the OC Mir location. Figure 2 shows the calculated expected ionogram and the rays forming some of its components in the case when only one reflection from the Earth is registered.

The calculated expected ionograms have very typical form and, processing the satellite ionograms, the above-mentioned difference (lower value of the lowest frequency reflected from the Earth as compared with the critical frequency of the ionosphere) may serve as a reliable criteria of the ionosonde location above or below the F region maximum. This difference is seen in all ionograms shown below and obtained during the sounding from the Mir station. The effect is visually seen in Figure 2. It should be noted also that the critical frequencies determined from the ionosphere reflection (rays 1, 5, and 9), from the ionosphere-Earth reflection (rays 3 and 7), and from the ionosphere–Earth–ionosphere reflection (rays 4 and 8) coincide.

Analyzing the ionograms one should bear in mind that the disposition of rays 3, 4, 7, and 8 is strictly determined by the disposition of rays 2 and 6 and 1, 5, and 9. Actually, any virtual depth, for example, for the ordinary component in the range from f_n to f_oF2 reflected only from the ionosphere (ray 1) is defined by the relation

$$h'_1(f) = \int_{h_s}^{r} \mu'(f, f_n, f_h)dh$$

where μ' is the group refraction index, h_s is the height of

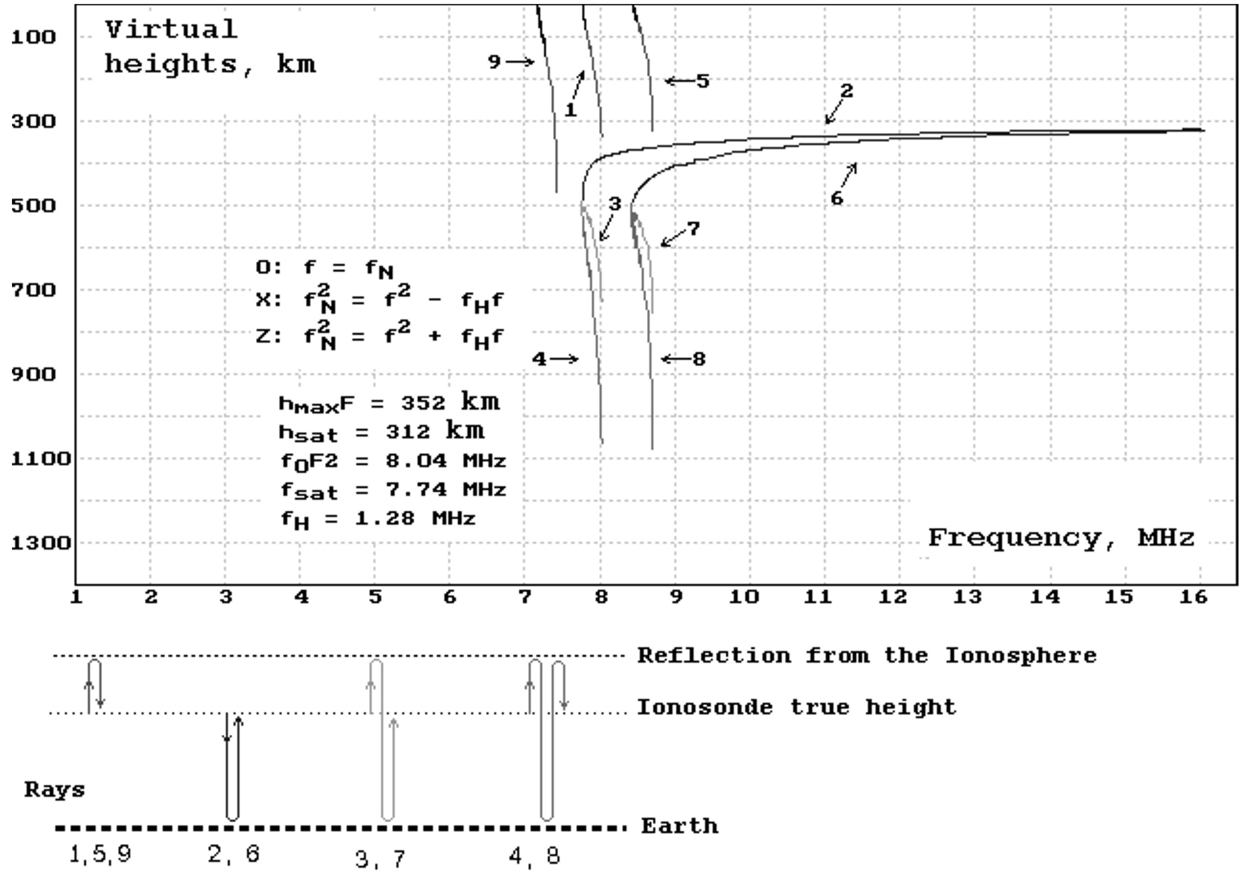

Figure 2. The modelled ionogram. The traces 1–9 correspond to the rays shown at the bottom diagram.

the satellite, r is the reflection height of a wave of the given frequency, f, f_n, and f_h are the working, plasma, and gyro frequencies, respectively, at the this height. Under reflection from the Earth the virtual depth from the satellite to the Earth (h_E) at the given frequency is determined (ray 2) as

$$h_2'(f) = \int_{h_E}^{h_s} \mu'(f, f_n, f_h) dh$$

Now the disposition of ray 3 is determined by the sum of rays 1 and 2 at each frequency. Similar consideration is correct for the extraordinary component and rays with a double reflection from the ionosphere.

2. Results of Observations and Their Preliminary Analysis

Although the first ionograms obtained during the ionosonde operation from heights below the F region maximum confirmed the main relations presented above, they showed however that the situation is much more complicated. Figure 3 (the left-hand panel) shows an example of the ionogram which confirms the numerical simulation shown in Figure 2 (color arrows show the o, x, and z components reflected from the ionosphere, green and red points show the reflection from the Earth and from the Earth and ionosphere, respectively). One can distinctly see that the virtual depth of the lower track is actually the sum of the virtual depths of two upper tracks for both components within the accuracy the measurements. Plasma resonances are almost always observed at the cutoff frequencies for all three magneto-ionic components.

2.1. Ionograms With an Additional "Lower" Track

Besides the ionograms which confirm the model ionograms predicted, there is a considerable number of ionograms in which the lower track behaves principally different from the predicted one. It is not a sum of two upper tracks and, which is especially important, it is continued considerably further than the critical frequency and often reaches the end of the frequency range used. The right-hand panel of Figure 3 illustrates this case. Here the ionosonde is situated slightly below the layer maximum, the fact being confirmed by very narrow tracks of the reflection from the ionosphere of all three components of the magneto-split signal. The track

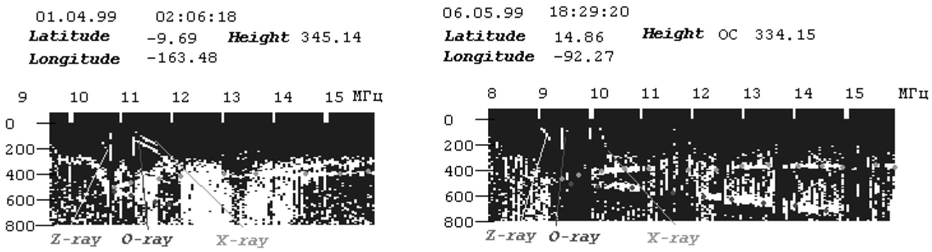

Figure 3. Ionograms registered on April 1, 199 at 0206:18 (left panel) and May 6, 1999 at 1829:20 (right panel).

of the reflection from Earth is also distinctly seen (the same colors are used as in the left-hand panel). Situated below is the second well-seen track which stretches in frequency much further than f_oF2, the latter being easily determined from the reflection from the ionosphere. We shall conventionally call tracks of the considered type as a "lower track".

The number of ionograms with the lower track exceeds the quantity of "correct" ionograms and the former were obtained under different geophysical conditions and in various parts of the Earth. Table 1 presents information on the ionograms with the lower track obtained on board OC Mir.

For a proper description of the phenomenon considered, Table 1 shows three groups (3 various days) in which ionograms of the considered type were observed. A daily series of observations was carried out on March 31, 1999 since 0949 UT till 0930 UT of the next day. This group is shown to illustrate the quantitative side of the phenomenon. During this time 6 groups of ionograms of the type described were observed, the corresponding data being shown in the top part of Table 1 (lines 1–6). They were observed mainly in the latitudinal belt from 20°S to 20°N. However at high latitudes the satellite also sometimes was below the F-layer maximum. Line 7 shows information about such case. Lines 8 and 9 illustrate particularly long periods of observation of the ionograms considered. The latter fact demonstrates that the region forming the extra track is very vast spatially and is a structure of the global scale.

To understand the physical nature of the phenomenon in question we consider a sequence of ionograms which arises when the satellite moves from his position above the F-region maximum to the position below the maximum. The observations on April 21, 1999 were chosen for the consideration. During 12 minutes of the station flight, an increase of f_oF2 from 8 to 15 MHz occurs smoothly enough before the first frame of Figure 4. Figure 4 shows four successive ionograms (registered through unequal time intervals) along the OC Mir trajectory and southward from the Taiwan Island (frames 567–582). The reflections of various components of the magneto-split signal and resonances at the plasma frequencies in the vicinity of the Mir station for the ordinary and extraordinary rays are seen in all ionograms.

The receiving station of ionograms from OC Mir in the analog regime and the station of the vertical sounding of the ionosphere operated in the Taiwan Island at this time. The comparison of the data of the ground-based and satellite sounding showed their full conformity in determination of the critical frequency and height of the ionosphere maximum [*Pulinets et al.,*]. At this orbit while the station moved equatorward there occurred an increase of the ionosphere maximum height and the station found itself below

Table 1. Ionograms With the Lower Track

No.	Moscow time of observation (UT+3)	Beginning Geographic coordinates Latitude	Beginning Geographic coordinates Longitude	End Geographic coordinates Latitude	End Geographic coordinates Longitude	Height of the OC Mir
			March 31, 1999–April 1, 1999			
1	1655:48–1702:48	−24.03	−82.08	−2.97	−65.66	344
2	1830:17–1835:36	−14.95	−97.7	−0.07	−86.87	344
3	2004:15–2306:55	−7.17	−115.15	+1.12	−109.27	345
4	2304:46–2307:22	−14.39	−167.01	−6.39	−161.09	344
5	0213:14–0217:26	+2.94	+159.02	+15.87	+168.55	345
6	0513:39–0514:41	−4.68	+107.15	−1.47	+109.42	344
			April 21, 1999			
7	0524:03–0524:51	+51.61	+68.33	+51.81	+73.50	346
8	0714:26–0718:26	+15.12	+125.41	+2.81	+134.45	350
			May 6, 1999			
9	1525:44–1533:12	+18.02	+115.83	+38.66	+138.07	354

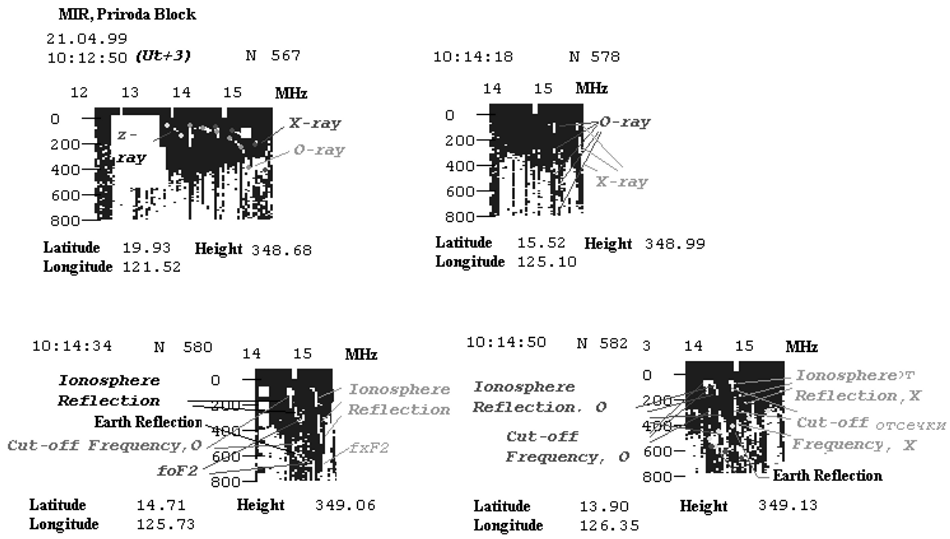

Figure 4. A sequence of ionograms registered on April 21, 1999.

this height. Figure 4 presents successive phases of this process. Frame 567 shows that the station is still above the maximum. Frame 578 shows that the station passes the maximum. That is manifested very clearly by practically vertical reflection tracks of both components of the signal.

Frame 580 shows the first ionogram in which one can distinctly see that the station is already below the maximum of the layer. The track of reflection from the Earth and ionosphere is already well seen here in full conformity with the model-predicted ionogram in Figure 2. To let the reader see the real signals the artificial color points emphasizing the author's idea are not shown in this fragment of the ionogram. In the next frame 582, where the reflections from the Earth (yellow points) and from the Earth and ionosphere (red points) are already fully developed, the real signals are underlined by the above-mentioned colors.

The track of the reflection only from the Earth, from the Earth and ionosphere, plasma resonances at both components, coincidence of the sums of the virtual heights which was mentioned above, and so on are seen in this fragment. Until this ionogram all occurs in absolute conformity with the model predictions.

However further on occurs something unexpected. Already in the ionogram in Figure 5 (frame 583) one can clearly see that the track of the reflection from the Earth and ionosphere is continued in the frequency further than f_oF2, and the principle of the sum of the virtual depths is not fulfilled. Frames 588, 603, and 608 show further development of this process. A fast decrease of the critical frequency occurs and at this background the lower track is seen well for several megahertz (about 3 MHz in frame 588, that is, about 60 soundings at fixed frequencies and about 2 MHz in frame

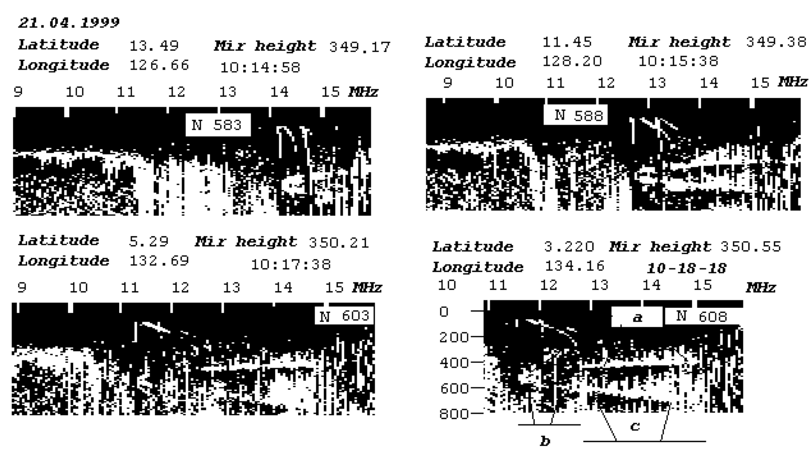

Figure 5. A sequence of ionograms registered on April 21, 1999.

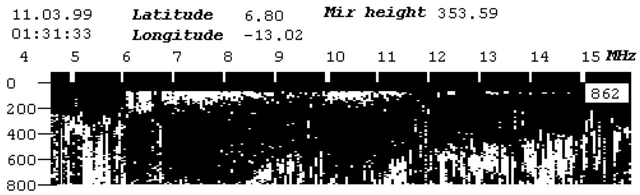

Figure 6. An ionogram registered on March 11, 1999 at 0131:33.

603, that is, about 40 soundings). Figures 3–5 and Table 1 provide information about this phenomenon.

2.2. Ionograms With "Upper Track"

Ionograms presented in this section have been obtained in the conditions when the ionograms themselves do not indicate the disposition of the satellite, that is, it is not clear whether the satellite is below or above the maximum of the ionosphere. However this can be found from the events preceding and following the phenomenon in question. The corresponding analysis shows that this phenomenon arises both below and above the F-region maximum.

Figure 6 (frame 862) shows the ionogram typical for the case considered. The horizontal track in a wide range of the plasma frequencies of the ionosphere, by virtual depth beginning almost at once after "opening" of the ionosonde receiver, is seen in the ionogram. The reflections from the plasma frequencies between 6 and 15 MHz with the density of reflections irregular over the range are seen here. Conventionally we call this type of reflection in ionograms as an "upper track". The most typical features of the upper track are the absolute absence of group delays and minimum possible virtual depth of the reflection.

The ionograms where the upper track is present are observed almost at all latitudes of the Mir station orbit, however, the predominant range of their appearance lies from 20°S to 20°N. Almost in a half of all cases the event described covers one or at the most two ionograms. In these cases the upper track in the succession of ionograms appears suddenly and also suddenly disappears.

In the second half of the cases of the upper track occurrence it arises in a chain of successive phenomenon. Figure 7 shows a typical situation. One can see that the upper track appears (frame 480) in the conditions when the station is below the F layer maximum height. It is evident from the lower track which is also distinctly seen in this ionogram. Further on it "develops" (frame 482) and covers a vast region of the sounding frequencies (from 5 to 16 MHz), the reflection density being lower than in the previous figure. In the frame 486 one can see again a group delay and therefore the end of the phenomenon.

Sometimes the upper track is observed long enough. For example, on March 10, 1999 it was observed during 584 seconds or 73 frames. The station flew more 2500 km during this time. The upper and lower frequencies and also the track "density" were changing considerably, the upper frequency sometimes crossing the upper limit of the ionosonde measurement range (15.95 MHz).

Figure 8 shows one more typical (that is, repeated more than once) example of a "developing" upper track. Before its appearance the group delay of the extraordinary component is sharply increased. It is worth noting that the first ionogram of this cycle (frame 364) was registered when the OC Mir was above the h_mF2 height. The last ionogram (frame

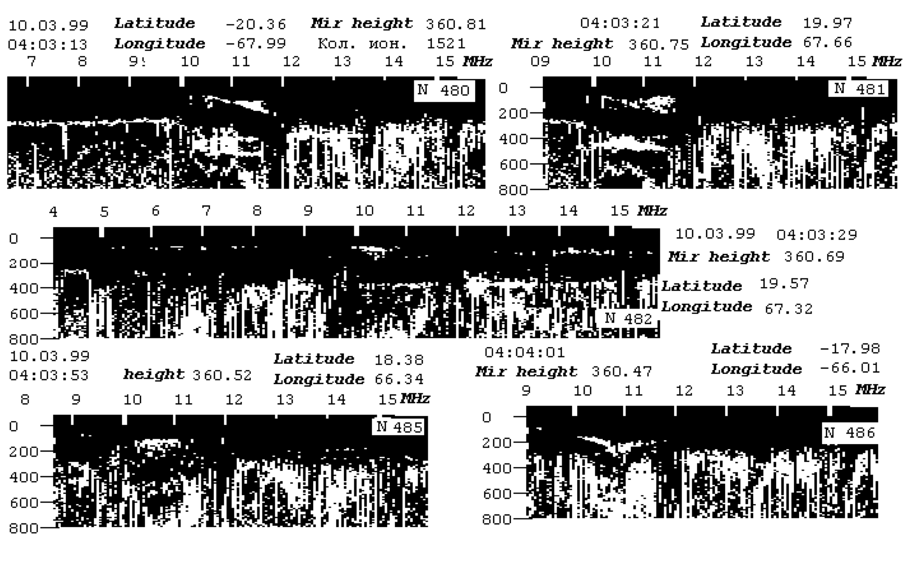

Figure 7. A sequence of ionograms registered on March 10, 1999.

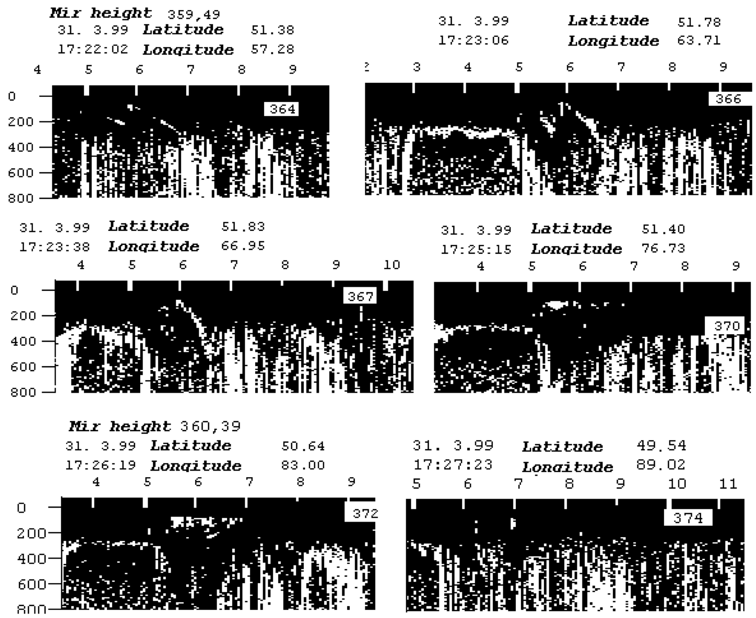

Figure 8. A sequence of ionograms registered on March 31, 1999.

374) corresponds to the station position almost within the F layer maximum. In this case the upper track was observed during approximately one minute, that is, the dimension of the corresponding region was about 300 km.

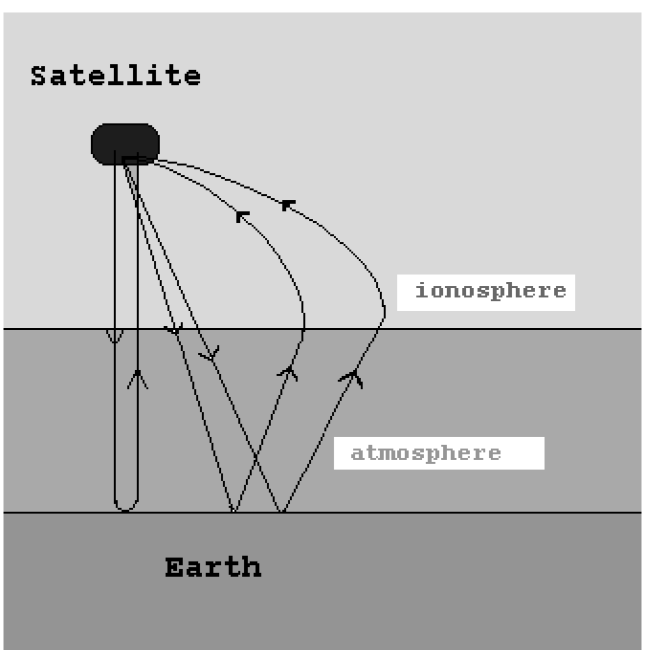

Figure 9. The scheme of possible ray paths.

3. Discussion on the Experiment Conduction Conditions and Conclusion

Analyzing possible explanations of the appearance of the lower track in the ionograms the author supposed that the lower track is the result of an oblique reflection of radio waves from the Earth and "lateral" reflection of radio waves from the ionosphere, when the wave "returns" to the satellite due to a strong gradient of the electron concentration situated aside the gravitational vertical. Figure 9 shows this case conventionally. Possible explanation of the appearance of this track as a result of only the lateral reflection from steep gradients of the electron concentration present in the equatorial "trough" seems less probable. The matter is that the lower track arises always as a continuation of the reflection from the Earth at its low-frequency end. This reflection can not arise without reflection from the Earth.

The author thinks that, discussing physical causes of the appearance of the upper track, two hypothesis should be considered. The first one deals with the well known at equatorial latitudes "bubbles" [*Kelley et al.,* 1976; *Scannapieco and Ossakov,* 1976], that is, the formations where considerable decreases of the electron concentration are observed within some region. In this case the range of the plasma frequencies observed indicates the gradient of the electron concentration increase at the boundary of the bubble.

The second possible cause is a scatter of radio waves at some extremely thin and steeply-gradient layer of the electron concentration. Sometimes such layers occur and give reflections of the type of a sporadic E layer at heights of 100–150 km [*Piggot and Rawer,* 1977].

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