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Comparison of the results of ionospheric radiosounding on board the Mir manned space station with the data of ionospheric ground-based network and the Transit signal observations

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Abstract. An ionosonde installed on board the Mir manned space station (Mir) flying close to the $F2$-layer maximum offers opportunities to measure the principal ionospheric parameters. It is also interesting to compare results of ionospheric radiosounding on board of Mir with the data from the ionospheric ground-based network. The comparisons were undertaken for periods when Mir passed close to a ground-based ionosonde and also when there were no sharp changes in the ionosphere. The comparisons were performed for various times of day, for various ionospheric conditions, and for various Mir height deviations from the $F2$-layer maximum. To completely exclude methodical errors, the cases have been chosen when Mir was located directly within the $F2$-layer maximum. The height of the plasma resonance, i.e., the $F2$-layer maximum height, was determined in this case from the Mir location which is independently known from the navigation data with unusual for $N(h)$-profile calculations accuracy. The comparison of the main daytime parameters of the $N(h)$ profiles determined from Mir and from the ground-based vertical sounding station demonstrates their complete coincidence for the cases when there is no sporadic E layer in the ionosphere. However, the comparison of night-time ionograms showed that though the critical frequency is determined with the same accuracy as in the daytime, the $F2$-layer maximum height is determined with lower accuracy.

1. Introduction

The installation of an ionosonde on board the Mir manned space station (Mir), which orbited at altitudes of about 350 km meant a new qualitative step in ionospheric sounding from satellites. The orbits of all the previous satellites with onboard ionosondes were considerably higher. The Alouette 1, ISS, Cosmos 1809 and ISIS 2 flew along polar (or close to polar) circular orbits with the height of about 1000 km (the former two), 900 km and 1400 km, respectively. The orbits of Alouette 2, ISIS 1, and Intercosmos 19 (in the end of its functioning) were elliptical: 500–3000 km, 570–3550 km, and 500–1000 km, respectively. Inserting of an ionosonde directly within the region of the ionization maximum in the atmosphere became possible after conducting experiments on transionospheric sounding [*Danilkin*, 1994]. In the course of these experiments it became clear that one can obtain the main practically important ionospheric parameters (the crit-

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ical frequency, peak ionization height, and half-width of the F region) under any position of the ionosonde relative the ionospheric maximum. Moreover calculation of $N(h)$ profiles using the methods and ideas of the transionospheric sounding is also possible for any position of the ionosonde. Certainly the calculation is performed only up to the $F2$-layer maximum if the ionosonde is below it or up to the satellite height if the ionosonde is above the maximum. It is worth mentioning that, when Mir flew in the near-equatorial region, the ionosonde rather often was below the ionospheric maximum.

In the radiosounding method, a final stage of the data processing for further geophysical studies is calculation of the $N(h)$ profiles of the ionosphere. The calculation of $N(h)$ profiles under sounding from above or from below in a significant degree determines a real efficiency of this classical method. Formally, it is a solution the Volterra equation for each separate magneto-ionic components of the signal reflected from the ionosphere or some combination of such solutions. Actually, the solution process is reduced to a reverse of triangle matrixes. The solution is solitary if only one magneto-ionic component of the reflected signal is used. If there is enough information in the ionogram, simultaneous use of both components makes it possible to obtain solutions also among nonmonotonous functions. However, one can not achieve an unambiguous solution in the nonmonotonous region (as a rule, it is the "valley" between the E and F regions).

To obtain more information, polarization ionosondes began to be used [*Danilkin et al.*, 1974]. Such ionosondes register separately the ordinary and extraordinary components of the signals reflected from the ground and ionosphere. In ionograms of polarization ionosondes, there are no regions where it is impossible to read out virtual heights of the signals reflected from the ionosphere due to the polarization overlapping of the signals. The existence of such technique makes it possible to reduce the range of the solution uncertainty searching for the electron concentration parameters in the so called regions of "unobserved ionization" [*Danilkin and Vaisman*, 1997]. The latter usually means the ionization layers situated in the regions where the plasma frequencies are below either the lower limit of the sounding frequency which have traces of the reflection from the ionosphere under the sounding from below, or in the valley between the E and F regions.

Development of the method, creation of the instrumentation and conducting of space experiments on transionospheric sounding led to a development of the methods of $N(h)$-profile calculations based on solution of the Fredholm integral equations, that is (in the formal aspect) to a reverse of rectangular matrixes. The singularity of the solution is achieved in this case in the class of "monotonous equivalents." The development of the method of $N(h)$-profile derivation based on solution of the Fredholm equation extended abilities of the usual method of $N(h)$-profile derivation due to the use in calculations of the reflection from the ground, which in this terminology is merely a "double transionogram."

The orbiting height of Mir on the average corresponded to the height of the electron concentration maximum in the ionosphere. However, the ionosphere is a very changeable medium both in time and space, so during the measurements, Mir was located either above the main electron concentration maximum or below it.

Orbiting space stations have some features that make such stations attractive for carrying out ionospheric experiments. There is a permanent exchange of equipment between the station and the ground. Space vehicles from the ground are docking at the station at least once in 4 months. This provides a possibility to mend or substitute defective instrumentation. This provides also a need for special measurements of the station height and position (needed for joining of space vehicles) based on precise devices and navigation calculations with the accuracy unprecedented for ionospheric measurements. In this paper we accept the accuracy of the station height determination as 100 m; however, really it is much higher.

Registration of ionograms of the satellite sounding for the position of the ionosonde below the F-region maximum provided new possibilities for calculation of the $N(h)$ profiles in the bottomside ionosphere. These possibilities appeared due to a combination of the solutions based on the methods using radio wave reflection from the ionosphere (i.e., based on solutions of the Volterra equation) and methods used in transionospheric radio wave propagation (i.e., based on solution of the Fredholm equations). The methods developed are based on a possibility to use in the calculations at least one point at the $N(h)$ profile, the position of the point being determined from navigation satellite data with the accuracy very high for $N(h)$-profile calculations. The latter means that the entire profile is also derived with much higher accuracy.

The goal of this paper is to compare the above indicated data obtained at Mir (first of all of the critical frequency and ionization peak height) in the conditions of unprecedented accuracy in determination of the ionospheric parameter measured to the routine measurements of this (or similar by sense, for example, $N(h)$ profile) ionospheric parameters derived from the data of ground-based ionospheric stations or Transit signal receiving stations.

2. Peculiarities of Ionograms Recorded at Low-Orbiting Satellites Important for Calculation of $N(h)$ Profiles

Depending on where (below or above the F-region maximum) the satellite is orbiting, significantly different details appear in the ionograms. The examples of such ionograms registered at one orbit when Mir was crossing the ionospheric maximum downward are shown in Figure 1.

The experiments on board the Mir station have been conducted in very hard conditions for radiosounding:

The station was contaminated in the electromagnetic sense. There was many noises and interferences.

The station was rotating. Therefore the positions of the ionosonde antennas almost always were far from ideal for radiosounding.

The station dimensions were such that almost the entire

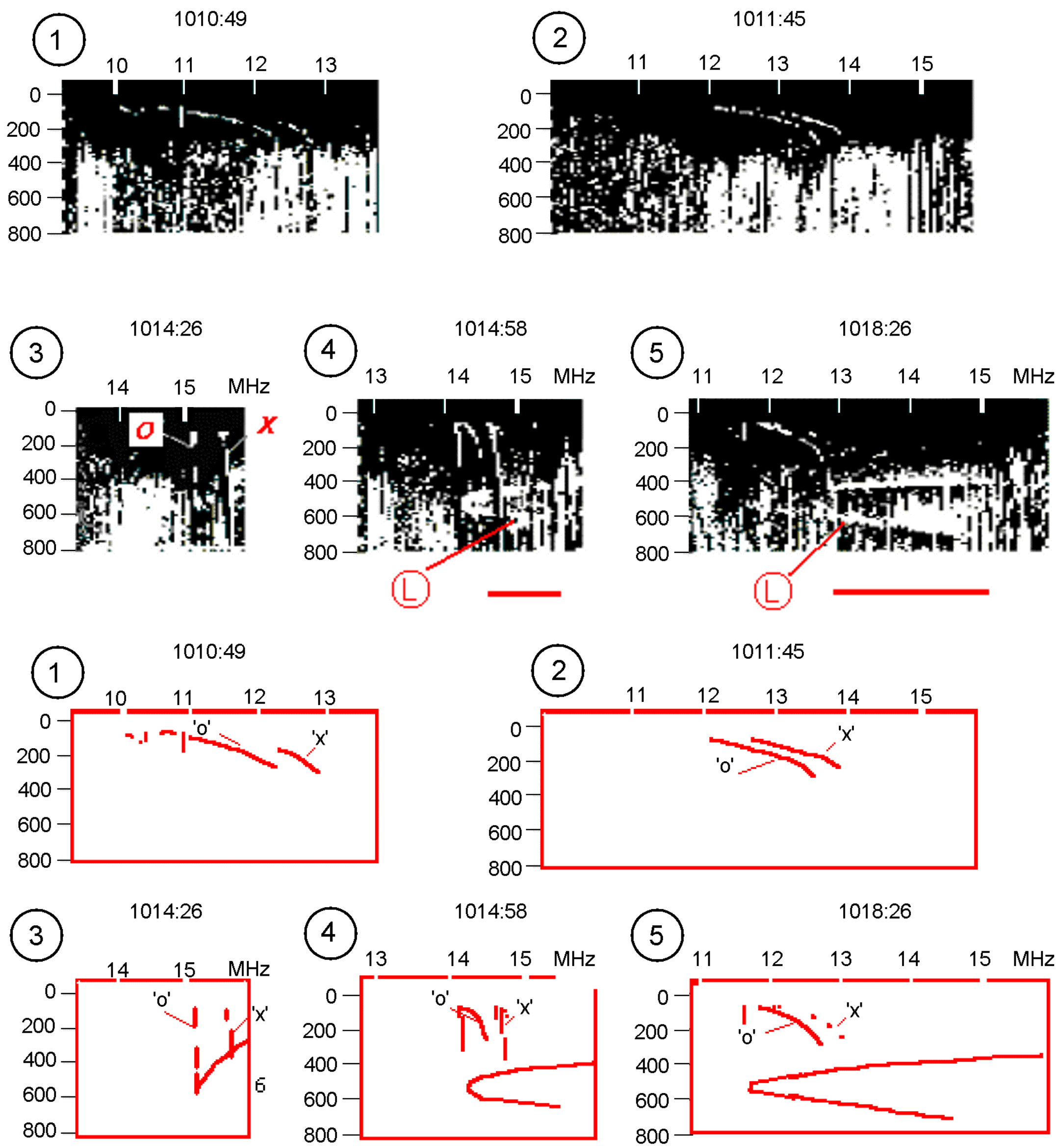

Figure 1.

station was a passive antenna for the ionosonde; however, parameters of this antenna were not known.

Under such conditions the ionograms are noisy and it is difficult to reveal the signal. That is why in Figure 1 each ionogram is accompanied by a sketch where the details considered are shown and noises and interferences are withdrawn.

The first and second ionograms were obtained when Mir was situated above the electron concentration maximum. They resemble usual topside ionograms with distinctly seen traces of the ordinary and extraordinary components reflected from the $F2$ layer.

Ionogram 3 corresponds to a rare occasion when Mir crosses the $F2$-layer maximum. The reflection trace from the maximum became almost vertical (the plasma frequency of the ordinary component vary from 15.05 to 15.1 MHz, the latter value being f_oF2, and the plasma frequency of the extraordinary component vary from 15.65 to 15.7 MHz, the latter value being f_xF2). The traces of the ordinary and extraordinary components are marked in Figure 1 by "o" and "x" respectively.

Ionogram 3 presents a good illustration of the accuracy of determination of the ionospheric peak height. The cutoff frequency of the o component is seen Also seen are the reflections of the o ray from the ionosphere. They occur almost at the same frequency and this means that Mir is located exactly within the $F2$-layer maximum. The accuracy of this measurement is high: the measured plasma frequency is $(15.1 + 0.025)$ MHz at a height of 349.1 km

Fragments 4 and 5 provide a typical example of ionograms registered on board a satellite situated below the $F2$-layer maximum. Their principal feature is the noncoincidence of the lower frequency of the sounding wave reflected from the ground with the critical frequencies of the F region: f_oF2 and f_xF2. The coincidence of the above mentioned parameters, vice versa, is the most typical feature of the topside sounding, that is, the sounding during which the ionosonde is situated higher (as a rule, considerably higher) than the electron concentration maximum in the ionosphere, and of vertical radio wave propagation. When the satellite is situated below the ionospheric maximum, the lower frequency of the reflection from the ground determines the plasma frequency of the ionosphere in the satellite location point. The trace of the reflection from the ground (unusual for topside sounding) is seen in ionograms 4 and 5. This trace makes a smooth turn at the lower sounding frequency related to the plasma frequency at the Mir location and is continued in the direction of increasing frequency (denoted by L) when the virtual distances are significantly higher those determined for a routine reflection from the ground. Such a trace is a characteristic feature of a large-scale isolated irregularity in the ionosphere situated at distances of 50–150 km from the Mir position. The frequency range in which the irregularity parameters are "ciphered" is shown by horizontal lines at the bottom of two ionograms in Figure 1. The methods of evaluation of irregularity parameters and computation process were described by *Danilkin and Kotonaeva* [2003].

Appearance of plasma resonances of higher intensity than at altitudes of 1000 km is one of the consequences of the fact that Mir is located close to the F-region maximum. It is caused by the fact that the group velocity of radio waves is close to the thermal velocities of electrons, since the group velocity of the waves is small in the vicinity of the cut off frequency. Clearly seen plasma resonances are excellent and highly precise reference points to calculate ionospheric $N(h)$ profiles.

3. Comparison of Ionospheric $N(h)$ Profiles Derived From Radiosounding Data

Depending on the ionogram character, derivation of $N(h)$ profile from ionograms presented in Figure 1 was performed on the basis of various methods of calculation described by *Danilkin and Kotonaeva* [2003].

The calculation of ionograms 1 and 2 (Figure 1) was performed from the real height of Mir to the $F2$-layer maximum height directly using the traces of o and x components reflected from the ionosphere. The results of these calculations are shown in Figure 2 by curves 1 and 2. It is worth explaining that in Figure 2 the shifts of the concentration axes are proportional to the time between the corresponding experiments. The time interval between the first two ionograms was about 1 min.

Ionogram 2 was detected at the moment when Mir orbited over a ground-based ionosonde. To calculate parameters of ionospheric irregularities capable of "returning" to the station oblique signals reflected from the ground, one should, first of all, be able to calculate $N(h)$ profiles of the bottomside ionosphere. To compare the satellite radiosounding results with the data of ground-based ionospheric stations, Figure 2 shows the $N(h)$ profile (marked by asterisk) of the bottomside and topside ionosphere published by *Pulinets et al.* [2001]. Ionograms of the ground-based ionosonde were registered at the ionospheric station of the Taiwan National Central University during the period that Mir orbited over this station.

Simultaneously, the ionograms recorded at the Mir station were transmitted (at a special frequency of 137 MHz of the onboard ionosonde) to the ground-based station and used to draw the above mentioned $N(h)$ profile. The comparison of the $N(h)$ profiles obtained at the ground-based stations and Mir shows that the heights of the ionospheric maximum calculated by the two methods coincide.

Naturally, the ground-based data (including those obtained via the 137 MHz channel) were limited by the period of observation of Mir at the ground-based station. Ionograms 3, 4, and 5 in Figure 1 were registered when Mir went behind the horizon for an observer at the Taiwan station. To provide a complete quantitative explanation of these ionograms, one had first of all to calculate the $N(h)$ profiles of the bottomside ionosphere under the Mir station.

This $N(h)$ profile is a result of calculation based on two ionograms. One was recorded in an analog regime by a ground-based receiving station in the telemetry channel at 137 MHz. The other ionogram was recorded by a ground-based ionosonde in the moment when Mir was located most close to the point over the ground-based station.

In ionogram 2 obtained at Mir, the trace of the signal reflected from the ground is absent. Therefore we can say nothing on the electron concentration profile below the $F2$-layer maximum. However, both methods of calculation gave similar results above the maximum. In the same way, there is no trace of the reflection from the ground in ionogram 1, so one can say nothing on the electron concentration profile below the $F2$-layer maximum.

In ionogram 3, Mir crosses the layer maximum. It occurs in the moment when for an observed at Taiwan Island the station was above the horizon. The trace of the reflection from the layer maximum became almost vertical and the frequency range is very small. However, since the height of the Mir is known, the error in determination of the electron concentration maximum height is absolutely insignificant and is much smaller than the error of h_mF2 determination in usual (the satellite altitude is about 1000 km) topside sounding.

The time interval between ionograms 2 and 3 is less than 4 min. About 30 s later, Mir was already much below the $F2$-layer maximum, this fact being seen in ionogram 4. There is already well seen the trace of the reflection from the ground. The $N(h)$ profile from this and similar ionograms was calculated by a combination of two methods. From Mir upward to the $F2$-layer maximum the traces of the o and x components reflected from the ionosphere were used in the same way as the ionograms considered above. Below Mir the $N(h)$ profile was derived using the distinctly seen reflection from the ground and the transionospheric sounding method [*Danilkin*, 1994].

Ionogram 5 was obtained 3.5 min after ionogram 4 and

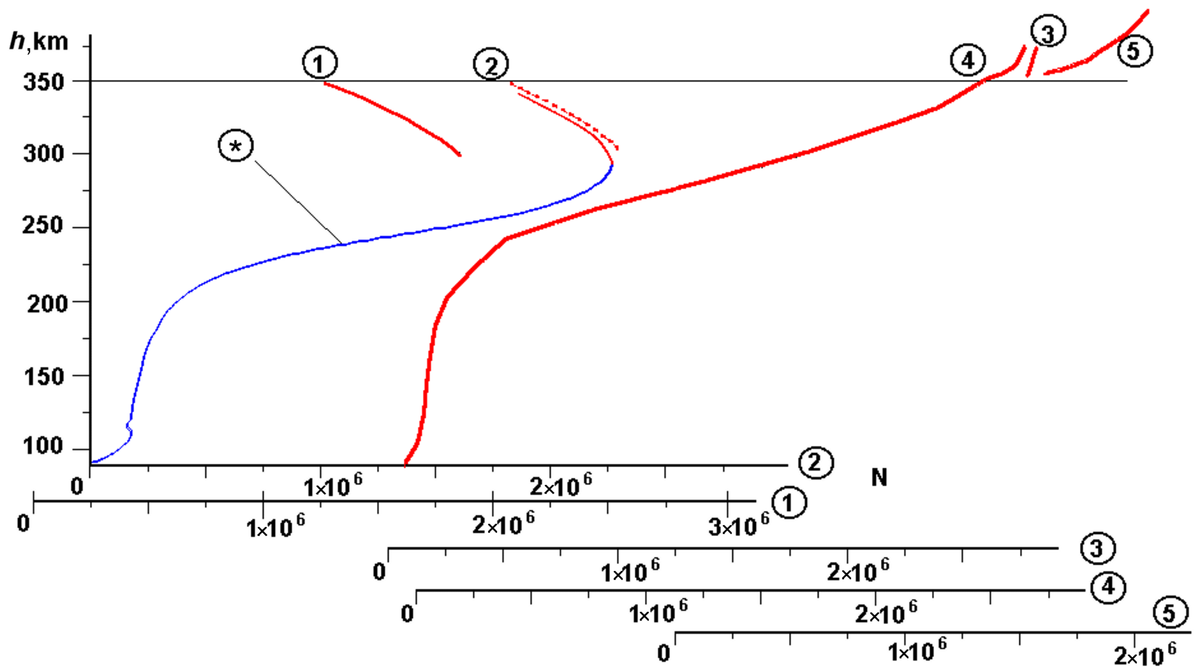

Figure 2.

does not differ considerably from the latter. Mir was located significantly below the $F2$-layer maximum. The calculated $N(h)$ profile of the bottomside ionosphere from h_mF2 to the Mir height is shown in Figure 2 (curve 5). Below Mir the $N(h)$ profile coincide with curve 4 and is not shown in the figure. The expressions "Mir is located below or above the $F2$-layer maximum" are relative. The Mir orbit height did not change considerably, so the change of the station position relative the $F2$-layer maximum manifests an increase or decrease of the layer maximum altitude. For less than 8 min of observations, the $F2$-layer maximum height along the satellite trajectory changed by about 100 km, the satellite moving to a distance of about 3800 km.

Thus, the above calculations show that combining various methods of $N(h)$-profile calculations described, one is always able to derive the electron concentration profile in the vicinity of the $F2$-layer maximum. Herewith at least part of the profile parameters will be obtained closer to the reality than in standard methods of $N(h)$-profile calculations from below or from above but from the altitude of about 1000 km.

It is widely known that inaccuracy in magnetic field dependence on altitude inputs the main error into $N(h)$-profile calculations from a height of 1000 km. The second (by its magnitude) error appears due to summation of small errors at each step of $N(h)$-profile calculation. The sounding from the Mir station has an advantage. Actually, if we know the station height with a high accuracy, we know with high precision the electron concentration at this height (for example from the cutoff frequency of the o component). Then curves showing the virtual frequency dependence on altitude are short. Therefore, moving from the cutoff frequency to the height of the maximum, we would make less errors, sounding from a height of 350 km than sounding from 1000 km.

Further comparison of the results of the $N(h)$-profile calculations from the Mir data with the profiles based on the data of ground-based vertical radiosounding was performed using the data of the vertical sounding station located (after it was moved from Slough) in Chilton near London. This station publishes vertical sounding ionograms and corresponding $N(h)$ profiles in the Internet. The choice of this station was determined by an occasional fact that orbiting over this station Mir several times was moving exactly within the $F2$-layer maximum.

The sessions have been chosen when Mir flew at a small distance over the ground-based ionosonde and there was no sharp changes in the ionosphere. The comparisons were performed for various times of day for various conditions in the ionosphere and various distance of Mir from the $F2$-layer maximum. To completely exclude methodical errors, the cases have been chosen when Mir was located directly within the $F2$-layer maximum. It is worth reminding that, when Mir is directly within the $F2$-layer maximum, only the plasma resonances and/or cutoff frequencies of this maximum, as well as traces of the reflection from the ground, are registered in ionograms. The height of plasma resonance appearance, i.e. the $F2$-layer maximum height, was determined in this case on the basis of the Mir location which is known from the navigation data with unusual for $N(h)$-calculations accuracy.

Therefore, actually we studied not the accuracy of $N(h)$-profile calculation based on the Mir data, but rather the accuracy of $N(h)$-profile calculations from the data of the accurate ground-based station as compared with the more precise profile derived from the Mir data.

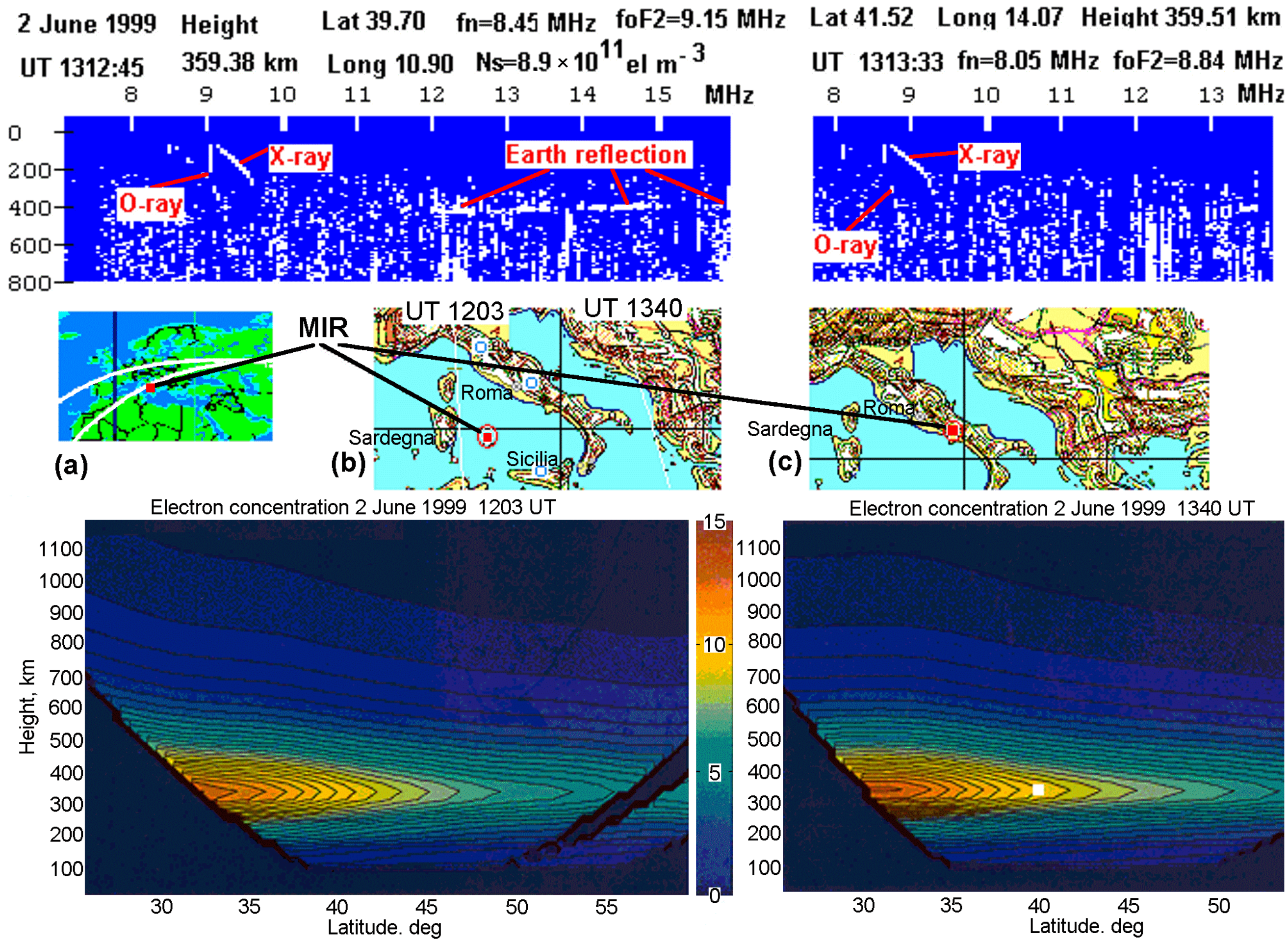

Figure 3.

The comparison of the main parameters of $N(h)$ profiles determined from Mir station and from the Chilton vertical sounding station demonstrates their complete coincidence for the cases when there is no E layer in the ionosphere. However, the comparison of night-time ionograms showed that though the critical frequency is determined with the same accuracy as in the daytime, the $F2$-layer maximum height is determined with much lower accuracy. Table 1 shows the data illustrating these differences.

4. Comparison With Transit-Signal Observations

To compare the results of ionospheric radiosounding from Mir with the data of ionospheric cuts obtained as a result of navigation satellites signal processing, one day, 31 March 1999, was chosen, when the radiosounding from Mir was conducted during 24 hours almost permanently. The comparison for other periods of time (2 and 3 June 1999, three orbits per day), when the orbits of Mir and the Transit satellites intersected in the Italian region was also made. There were obtained ionospheric cuts from the Transit-signal data along the chain of three ionospheric stations. These stations are shown in Figure 3b by blue circles on white rectangles (all indications to color correspond to the electronic version).

The results of the comparison of ionospheric parameters for one case when Mir and the Transit satellites flew over the region approximately in the same time are also shown in Figure 3. The projections to the ground of the trajectories of all the satellites and corresponding moments of time are shown in the maps in Figure 3 (middle). The Mir trajectory is shown in the large-scale map (Figure 3a). The exact positions of Mir in the above-indicated moments are shown in Figures 3b and 3c. Corresponding ionograms together with the data needed for their understanding and interpretation are shown in Figure 3 (top). Figure 3 (bottom) shows plane cuts of the ionosphere along the orbits (shown in Figure 3b by white lines with the time of flight indicated) of the navigation satellites. The lines are isolines of constant electron concentration. The scale is shown in the column in the middle of the figure. The numerals correspond to N_e in units of 10^{11} m^{-3}. The Mir data are shown by a white rectangle in the right-hand cut and demonstrate a coincidence of the measurement results. Figure 3 makes it possible for a reader

Table 1. Comparison Mir Data With Data of Night-Time Ionograms

Sounding Station	Time, UT	Critical Frequency of Extraordinary Component f_xF2, MHz	$F2$-Layer Maximum Height h_mF2, km
Chilton (London), 7 May 1999	0400	5.35	326
Mir, 7 May 1999, coordinates 51.83°N, 0.26°W	0355:32	5.34	358.3
Chilton (London), 7 May 1999	0200	5.9	368
	0230	5.7	373
Mir, 7 May 1999, coordinates 49.15°N, 0.04°E	0219:59	5.84	357.5

to evaluate, on one hand, the accuracy of the results obtained in each of the methods and, on the other hand, large difficulties in comparison of the results of such nonhomogeneous experiments. It is worth noting that a comparison of such different experiments is especially valuable for a final belief in correctness of the geophysical result.

Figure 3 demonstrates the difficulties of the data comparison for satellites flying along different orbits. It was difficult to find proper periods to compare the data. Nevertheless, on 31 March 1999, six periods were found (and five more periods on 2 and 3 June 1999) when the measurements on board both satellites were conducted in the Italian region almost simultaneously. Temporal and spatial coordinates of both satellites were different (the same for 2 and 3 June 1999), but in all cases we found a coincidence of the results obtained within the accuracy of geophysical parameters determination. No case was detected when there was a principal disagreement between the data.

5. Conclusion

It is demonstrated experimentally that an ionosonde installed on board a satellite situated in the vicinity of the $F2$-layer maximum really makes it possible to determine the principal ionospheric parameters as it has been shown earlier in the model experiment.

Combining the transionospheric methods (calculation of the $N(h)$ profile on the basis of the reflection from the ground) and standard methods of $N(h)$ calculation, one is able to derive $N(h)$ profiles of the bottomside ionosphere with the accuracy comparable to the accuracy of the $N(h)$ determination from ground-based ionosondes (and even exceeding it in some intervals of the vertical profile).

It is shown that the height of the ionospheric maximum at night is not determined correctly enough by the ground-based ionospheric stations. One may assume that if ionograms from Mir were transmitted to a corresponding ionospheric station in the zone of the Mir vision, that would have considerably improved the accuracy of $F2$-layer maximum height determination at night at all stations of the global ionospheric network.

The data of Mir and Transit satellites confirm each other mutually.

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