2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018

The spatial structure of the equatorial anomaly in accordance with results of satellite radio sounding from altitudes below the maximum of the F2 layer

Kotonaeva N.G., Danilkin N.P.
Fedorov Institute of Applied Geophysics, Moscow, RF, http://ipg.geospace.ru/

Abstract

We consider the results of an ionospheric sounding experiment onboard the Mir space station (MSS) in the equatorial anomaly region and the specifics of the obtained ionograms.
The experiment lasted from August 1998 and to June 1999. The station was orbiting Earth at 330–400 km and 51.6° inclination. The sounder's operating frequencies were in the range from 1 to 16 MHz.

1. Introduction

The decision to place a top sounder onboard the space station was made with aim to estimate the usefulness of a permanently functioning ionosonde on the planned larger space stations.

The discovery of absolutely new, never-seen-before, types of ionograms was a completely unexpected, and pleasant, surprise for the researchers. Such ionograms were observed when the station was below the ionospheric maximum.

The ionograms obtained in the EA regions below the maximum height show traces of reflections from the upper layers of the ionosphere of both ordinary and extraordinary waves. They are caused by echoes of the radio waves, which propagate from the MSS upward, and, after reflection from the higher ionospheric layers, return back. The ionogram trace begins on the plasma frequency at the altitude of the satellite f_s f. On some ionograms, the z-wave trace was also observed, and it reached the maximum of the ionosphere too. The ground-reflected trace was also clearly visible if the wave propagated in vertical direction. A specific feature of the ionograms is the retarded lower trace (RLT) [1], a result of oblique propagation of the radio ray, its reflection from the ground and subsequent reflections (or refraction) from the horizontal heterogeneities of the ionosphere (Figure 1). The RLT is located at greater virtual distances than the ground reflection. This is a fundamentally new result of sounding from ultra-low orbits.

As one can see from the ionogram, the critical frequency f_0F2 is 10,3MHz. The lowest frequency of the ground reflection coincides with the plasma frequency at the satellite altitude $f_s = 9{,}6$ MHz . Mismatch of these frequencies is an evidence that the ionosonde is below the maximum of the F2 region. The RLT is observed up to the frequency of 15 MHz.

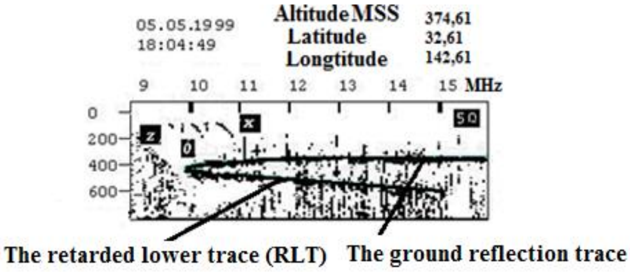

Figure 1. MSS sounder ionogram with selected traces of reflections.

Numerical experiments confirmed that the RLT is the result of propagation of the sounding rays along a series of closed-loop trajectories (Figure 2 on the left). Such propagation is possible only in the presence of horizontal electron concentration gradients.

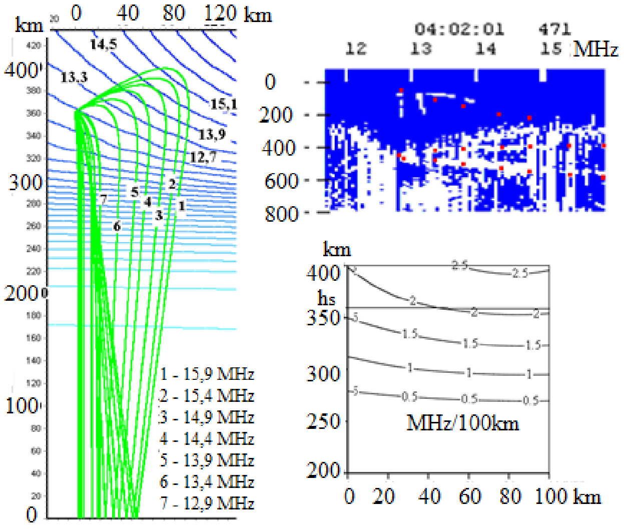

Figure 2. On the left: the trajectories of radiosounding signals (green), the frequencies of the enumerated rays are indicated below. In the upper right: ionogram 471 from March 10, 1999 with the results of numerical simulation (red dots correspond to the frequencies shown on the left). Bottom right: distribution of the horizontal gradients of the plasma frequency (MHz /100 km) in the zone of the closed-loop trajectories.

2. The eastern edge of the equatorial anomaly

The RLTs were observed in the zone of the equatorial anomaly. EA is a big natural heterogeneity in the ionospheric electron distribution with large electron concentration gradients and increased ionospheric maximum height h_mF2 . As result, when MSS crossed the crests of the equatorial anomaly, it found itself below h_mF2 . The ionograms with RLTs were usually received in series. The satellite speed is much greater than characteristic movements in the ionosphere, so when interpreting the successive ionograms we may consider the structure of EA.

The ionograms obtained on two different days but approximately in the same place and the same local time are shown in Figure 3. The local time was evening and the period between observations was 23 hours. Note the similarity of the ionograms in these two series of observations at same latitude (Figure 3 on the left).

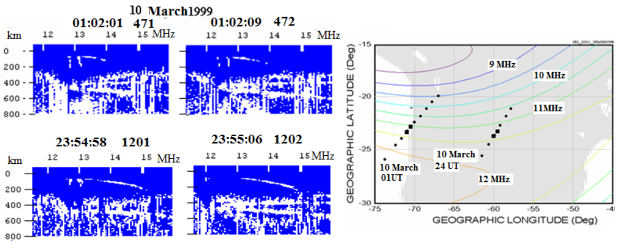

Figure 3. On the left – ionograms obtained over the region of South America on March 10 and 11. On the right are sections of MSS orbits along the background of modelled plasma frequencies at 360 km (the model is IRI-2001).

The IRI plasma frequency map, calculated for the height of 360 km is shown on the same picture. On the right side, the sounding sites for an RLT ionogram series are marked with black diamonds.

Distributions of plasma frequencies on March, 10 are shown in Figure 4. The graphs show the latitudinal regions where the RLT ionograms were obtained. The appearance of the RLT on ionograms was accompanied by a sharp decrease in the critical frequency from 15 to 8.5 MHz. The plasma frequencies decrease rate at the orbit altitude reached 0.75 MHz / 100 km.

In general, one can note that the IRI forecast is approximately correct, however, the details of the electron density fine structure – firmly determined from the experimental RLT data – can differ by 40-50% of the predicted mean.

Let us qualitatively compare the results of the MSS equatorial zone study with the studies of the total electron content (TEC) [1]. Figure 5 shows the fragments of the TEC distribution map (based on IGS data) with plotted sections of the MSS orbit.

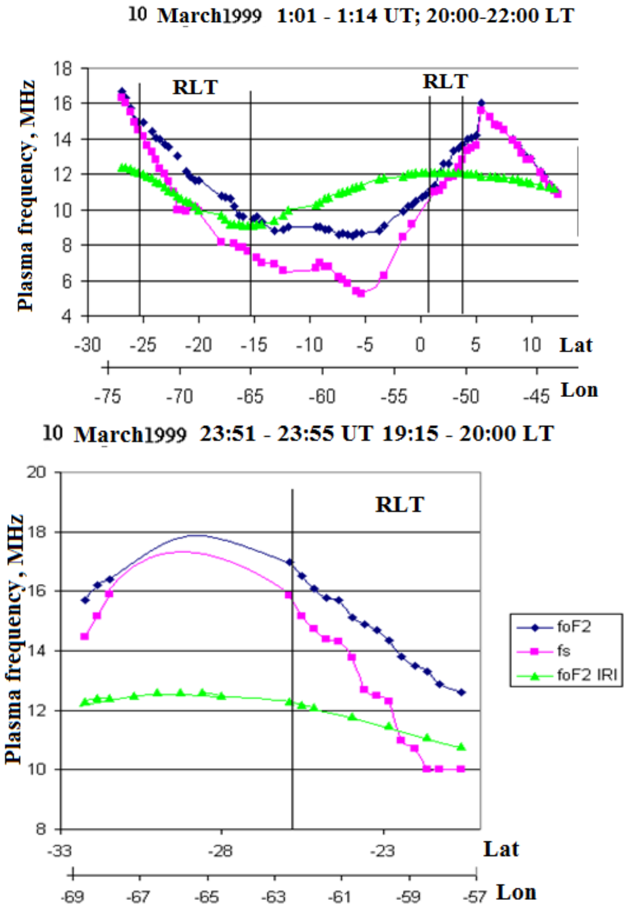

Figure 4. Distributions of plasma frequencies along the MSS orbit.

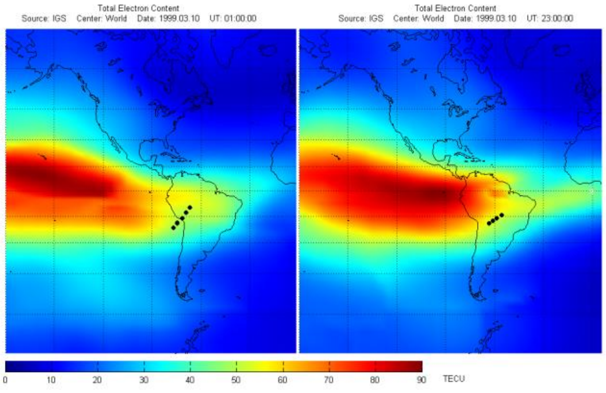

Figure 5. IGS-based TEC distribution maps with the plotted Mir trajectory: on the left - March 10, 1999 1:00 UT; on the right - March 10, 1999. 23:00 UT.

The simulation shows that smaller differences between the virtual distances of the RLT and the ground-reflection trace correlate with greater horizontal gradients in the plasma frequency. The average gradient at 360 km was 2 MHz / 100 km (Figure 2). Numerical analysis shows that the angle between lines of equal concentration and the MSS orbit in a small neighborhood is 22.5°

2. The central region of the equatorial anomaly

On March 31–April 1, 1999, a day-long session of continuous radio-sounding of the ionosphere was conducted on the Mir station. The ionograms were taken every 32 seconds. During this session, MSS ten times crossed the Equator at local noon. Traces of the orbits are plotted in Figure 6.

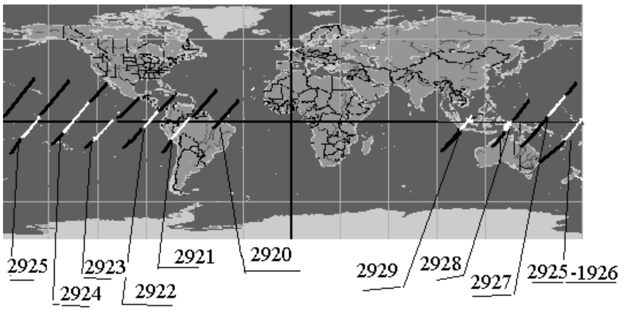

Figure 6. Traces of the MSS orbit in the equatorial zone (afternoon hours) on March 31 - April 1, 1999. The light sections are fragments of the trajectory where the RLTs were observed. Orbits are marked with their numbers.

Consider the section of the MSS trajectory from orbit 2922 with more than 7000 km length starting at 26.01ºS; 107.19ºW and ending at 19.58º N; 72.2ºW. The local time along this segment of the orbit changed from 11:30 LT to 13:50 LT. Figure 7 shows the distribution of $f_O F2$ and f_s along the orbit and, for comparison, the distribution $f_O F2$ modeled by IRI.

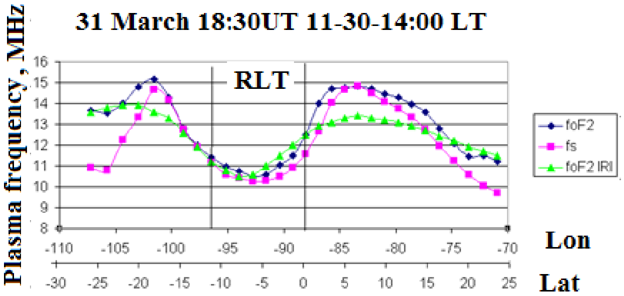

Figure 7. Distribution of f_OF2 and f_s along the Mir trajectory 31 March 1999, 18:26 – 18:40 UT; 11:30 – 13:50 LT, orbit 2922.

The variations of plasma frequencies indicate presence of regions with increased electron density on both sides of the geomagnetic equator – the crests of the EA. The projection of this part of trajectory on the TEC map is shown in Figure 8.

Let us consider the trajectory section on the next orbit 2923 on March 31 from 19:59 to 20:07 UT. The distributions of $f_O F2$ and f_s are shown in Figure 9.

RLT effect was well pronounced in the afternoon, but in many cases it was accompanied by a strong noise. The trace in most cases was short, having frequency range of no more than 2 MHz.

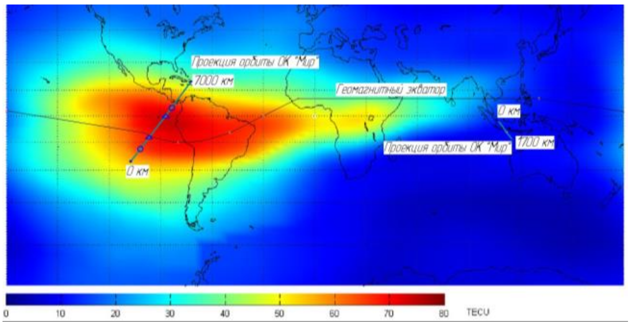

Figure 8. IGS-based TEC distribution maps with plotted MSS trajectory: 31 March, 1999.

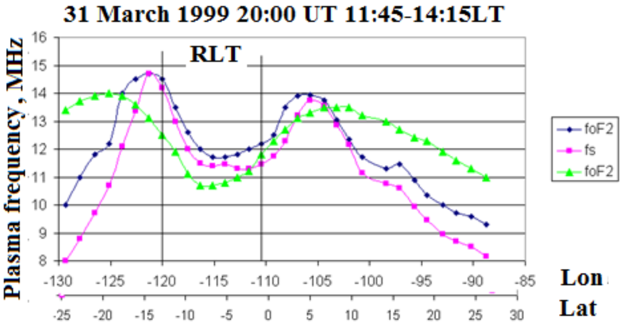

Figure 9. Distribution of f_O F2 and f_s along the *Mir* trajectory 31 March 20:00 –20: 15 UT, 11: 45-14: 15 LT, orbit 2923.

The trajectory analysis, presented in Figure 10, has shown that the gradient of the plasma frequencies was about 1.2 MHz per 100 km.

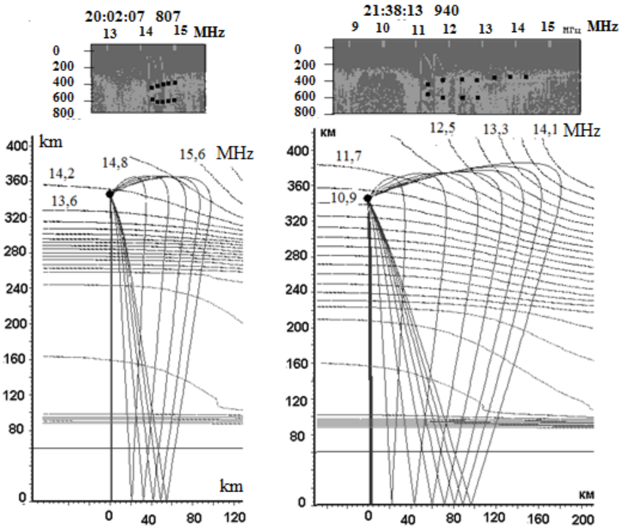

Figure 10. The trajectory analysis of the RLT ionograms from the central part of the EA. At the top are characteristic ionograms with the results of numerical simulation applied, at the bottom – a simulation of the plasma frequencies distribution and the radio ray trajectories leading to RLT appearance.

3. Midnight equatorial anomaly

On May 5, 1999, in periods 15:00 to 15:09 UT and 16:30 to 16:40 UT, the radio-sounding of the ionosphere was conducted in the Pacific and South-East Asia regions in two consecutive orbits 3472 and 3473.

Local time is 23:30 to 1:30 LT. At this time, the ionosphere of this region is characterized by the presence of only one EA crest.

Figure 11 shows the distribution of critical frequencies along the *MSS* trajectory on the given orbits.

The change in longitude for orbit 3472 section was 125° – 157° E, and for orbit 3473 it was107° – 131° E. For comparison, the distribution of IRI-modelled plasma frequencies is presented.

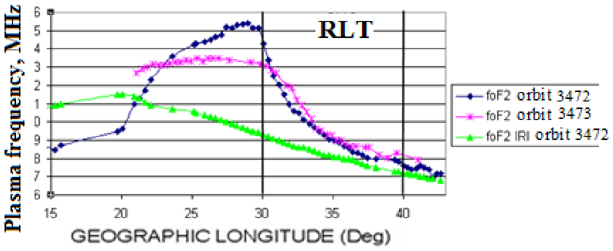

Figure 11. The distribution of f_O F2 along the *MSS* orbit on May 5, orbits 3472 and 3473, 23:00–01:30 LT

In Figure 12, the trajectory is plotted over the IGS-based TEC map. There is a qualitative coincidence of the position of the midnight EA crest and increase in the TEC along the MSS orbit.

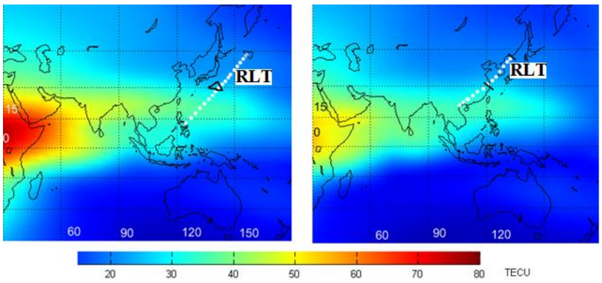

Figure 12. Maps of the IGS-based TEC distribution and *MSS* trajectory plots: on the left – May 5, 1999 1:00 UT

The data of the ionogram series were characterized by extensive RLTs. A series of ionograms with RLT is shown in Figure 13.

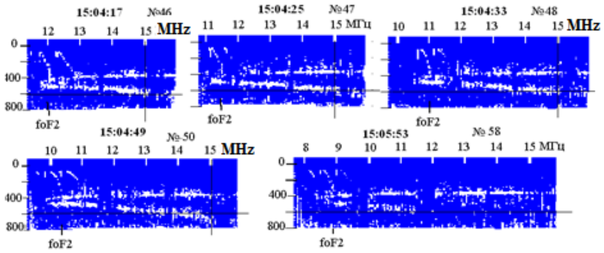

Figure 13. A series of ionograms with RLT. *MSS*, May 5, 1999, 15:04–15:06 UT, 23:00–1:30 LT

The integral average of the horizontal electron density gradient in the region of propagation of trajectories from 0 to 140 km in MHz per 100 km and the average horizontal gradient of the electron density at the distances up to 140 km from the sounder (in electron / (cm^3 km)) for each ionogram are presented in Table 1.

Table 1

№	grad $f_O F2$ MHz / 100 km	grad $N_e F2$ electron / (cm^3 km)
46	2,25	7,3×10^3
47	2,47	7,8×10^3
48	2,36	7,1×10^3
50	2,02	5,5×10^3
55	1,79	4,4 ×10^3
58	1,68	4,0 ×10^3

4. Conclusions

Top-sounding ionograms of a new type were obtained for the periods of the EA crest crossings by the Mir station sounder. The ionograms have additional extensive traces on significant virtual distances.

During the *Mir* space station experiment ionograms with RLT were received:

- in the daytime (from 11:00 - 18:00 LT) between the crests of the EA;
- in the evening (from 18:00 - 21:00 LT) on the Northern slope of the Northern crest and on the Southern slope of the Southern crest
- at midnight on the Northern slope of the EA crest.

The reason for the appearance of the RLT is the propagation of the sounding signal along an oblique trajectory that loops back to the satellite.

Причиной появления ЗНС на ионограммах стало распространение зондирующего сигнала по наклонной траектории, возвращающейся на ОК. The existence of such radio rays is due to the presence of horizontal electron density gradients in those regions of the EA where the electron concentration peak was at greater height than the MSS orbit.;

The values of horizontal electron density gradients that cause refraction of the oblique sounding rays and forcing them back to the satellite are calculated. They exceed the gradients of this parameter along the Mir orbit. And they amounted to 0.8 MHz per 100 km for the noon time (central EA), 2 MHz per 100 km for the Eastern edge of the EA, and more than 2.2 MHz per 100 km for the midnight ionosphere on the Northern slope of the EA crest.

7. References

1. N. P. Danilkin "The results of the satellite radio sounding of the ionosphere below the F-layer maximum" International Journal of Geomagnetism and Aeronomy.. .3, V. 2,. 2001, C.173-180. http://elpub.wdcb.ru/journals/ijga/v02/gai00351/gai00351.htm

2. ftp://cddis.nasa.gov/gps/products/ionex/1999/