Solar-Terrestrial Physics. 2019. Vol. 5. Iss. 4. P. 101–107. DOI: 10.12737/stp-54201914. © 2019
A.V. Podlesnyi, A.A. Naumenko, M.V. Cedrik. Published by INFRA-M Academic Publishing House
Original Russian version: A.V. Podlesnyi, A.A. Naumenko, M.V. Cedrik, published in Solnechno-zemnaya fizika.
2019. Vol. 5. Iss. 4. P. 122–129. DOI: 10.12737/szf-54201914. © 2019 INFRA-M Academic Publishing House (Nauchno-Izdatelskii Tsentr INFRA-M)

ESTIMATING ANTENNA COUPLING FACTOR FOR PROBLEM OF TOPSIDE IONOSPHERE SOUNDING FROM SPACE BY CHIRP SIGNALS

A.V. Podlesnyi
Institute of Solar-Terrestrial Physics SB RAS,
Irkutsk, Russia, pav1986@rambler.ru

A.A. Naumenko
Institute of Solar-Terrestrial Physics SB RAS,
Irkutsk, Russia, naym@iszf.irk.ru

M.V. Cedrik
Institute of Solar-Terrestrial Physics SB RAS,
Irkutsk, Russia, mark7cedrick@gmail.com

Abstract. When developing the first topside ionosphere sounding stations, the issue was debated concerning the improvement of the electromagnetic compatibility of these stations through the use of chirp signals. One of the main problems of using chirp signals was the impossibility of ensuring simultaneous operation of receiver and transmitter. The article presents the results of the use of receiving and transmitting dipole antennas for sounding the ionosphere by a chirp signal, which have a common center. Conclusions are drawn about the possibility of using such facilities for sounding the external ionosphere with hardware separation of polarizations and in the terrestrial version with orthogonal location of receiving and transmitting antennas. During tests conducted on a specially designed antenna stand, we have found that the coupling factor of transmitting and receiving antennas at mutual angles of 45° is no more than –10 dB, and the difference between coupling factors of transmitting and receiving antennas with mutual angles of 45° and 90° is ~15 dB.

Keywords: antenna coupling factor, satellite, ionosphere sounding, HF.

INTRODUCTION

The launch of the first artificial Earth satellite in 1958 opened up the possibility of investigating the electron density in the topside ionosphere, inaccessible to ground-based ionospheric stations. The importance of exploring the topside ionosphere at that time is confirmed by the launch of the Canadian satellite Alouette I with a fully-featured panoramic facility for ionospheric sounding less than four years after the launch of the first artificial Earth satellite. Alouette I was designed for pulsed topside sounding with the aid of ionospheric station (ionosonde) having an operational range from 0.45 to 11.8 MHz. The main objectives of the experiment was to determine the electron density distribution at heights above the maximum at different latitudes and at different times of the day, to study seasonal variations of the electron density, and the effect of magnetic activity and other factors on it during solar minimum. In addition, this satellite was used to analyze the VLF emission in a range from 400 Hz to 10 kHz and energetic proton, electron, and α-particle fluxes.

The success of the satellite program for exploration of the ionosphere was guaranteed by high data quality in spite of the fact that the emitting power was two orders of magnitude lower (100 W) than that of ground stations (10 kW). The major factors contributing to this proved to be shielding properties of the ionosphere, which shield satellite orbits from noise of terrestrial origin, and the low collision frequency in the topside ionosphere, which determines the low degree of absorption of radio waves when passing to a reflection point.

Despite the importance of the missions with ionospheric sounding systems for the study and diagnostics of near-Earth space, a relatively small number of such satellites were launched. One of the reasons is that due to the use of transmitters with a power of several hundred watts and large antenna array the ionosondes represent one of the most energy-intensive and largest systems composed the research instruments. The second problem is that an ionosonde generates strong electromagnetic interference for the rest of the equipment of the satellite, thus making simultaneous observations with some instruments impossible. Perhaps that is why after the completion of the Cosmos-1809 mission in 1993 there were no more missions with on-board ionosondes designed to study Earth's topside ionosphere. The installation of an ionosonde on board the Mir Space Station in 1996 can hardly be called a topside ionosphere mission because of the too low orbit, which was below the height of maximum electron density in the ionosphere in some regions of the planet. So much so that in modern papers on the study of the global ionospheric structure when simulating its topside layer the only reliable data is still the results obtained 40 years ago, for example [Klimenko et al., 2015]. Moreover, articles on reanalysis of data acquired at that time are still published [Karpachev, Zhbankov, 2017]. Not only the space weather (current state), but also the space climate (general global parameters) in near-Earth space might, however, have changed over this considerable period. Both Russian and foreign researchers understand this. The irony is that the only active space-based ionosonde is in the orbit of Mars. This instrument of the MARSIS project was launched in 2003 [Orosei et al., 2015]. This ionosonde uses a simple unmodulated pulsed signal of 5 W in the HF range for ionospheric sounding and a short broadband chirp signal for studying the surface relief and subsurface structures of Mars, i.e. in this sense Mars is more technically equipped than our home planet.

The program closest to the implementation is the Russian project of space complex "Ionosonde" [Pulinets, 2013] consisting of four instruments "Ionosphere" with on-board ionosondes LAERT and an instrument "Zond" with a complex of equipment for monitoring solar conditions. The first pair of "Ionosphere" satellites is launched into a Sun-synchronous orbit 820 km high in 2020. In 2022, the ionosonde group is supplemented with a second pair of instruments rotated relative to the first one by 180°. According to publicly available information, the pulsed ionosonde LAERT of the Ionosphere-M spacecraft was developed from IS-338 ionosondes the prototype of which, in turn, was ionosondes on board Alouette satellites. Antenna system, modes of sounding by a monopulse with a peak power of more than 100 W, frequency range, and frequency resolution have similar characteristics and work on the same principles. The LAERT ionosonde has even the archaic low-speed system of data transmission to ground stations at a frequency of 137 MHz, the necessity of which is highly questionable if there are on-board modern high-capacity storage systems and high-speed data transmission channels. The secondary problem of synchronizing the work of ground and satellite ionosondes in transionospheric sounding, this system also solved in previous missions, should currently be solved through synchronization by signals from a single source of synchronizing and clock signals from GNSS, defined in the project.

There are satellite ionosonde projects launched by the team of Reinisch B., developers of such well-known facility of ground-based ionospheric sounding as DPS-4. For example, in the late 1990s they designed an on-board ionosonde TOPAS for the Ukrainian space mission WARNING [Reinisch et al., 2001]. For this ionosonde, they developed prototypes of boards for ground tests. The instrument consisted of three orthogonal receiving antennas 10 m long, which theoretically made it possible to determine angles of signal arrival, its polarization characteristics and Doppler shifts. In this ionosonde, complementary sequences and short narrowband chirp pulses were meant to be used depending on the case. But no satellite with this ionosonde was launched.

On the website of Atmospheric & Space Technology Research Associates, LLC (ASTRA) specializing in CubeSat small spacecraft, it has been reported on a program for a satellite equipped with a 6U ionosonde [Swenson et al., 2014], i.e. with a volume up to 6 l, energy consumption up to 10 W, and weight up to 10 kg, which can probably use complex signals. Since there is no detailed information about characteristics of this spacecraft yet, we can assume that it is currently in the early stages of development.

Nevertheless, none of the known teams have announced that they worked at installation of the ionosonde using a continuous chirp signal in a satellite and made any estimates for this purpose.

SETTING OF THE PROBLEM

It should be noted that, for example, when developing Alouette satellites in 1965 the possibility of using continuous chirp signals was explored. Then it was observed that the use of chirp signals for sounding (signals with swept frequency and continuous emission) in ground-based two-position instruments can significantly reduce the peak voltage, provide a high signal-to-noise ratio, and simplify the design of the output stage of ionosonde amplifiers. At that time, the practical implementation of such systems in topside sounding was considered impossible for the following reasons:

- complexity of designing chirp signal generators;
- inability to provide simultaneous operation of receiver and transmitter, and hence the need for antenna switches;
- difficulty in building a compact system of preliminary data analysis and preparing it for transmission via telemetry channels [Jackson, Warren, 1969].

The development of digital radio systems and chirp signal processing theory made it easy to build such compact systems of generation and processing of chirp signals [Ivanov et al., 2003]. The development of the compact systems of data preprocessing and transmission via telemetry channels is also out of question today. The use of antenna switches providing the pulse mode is, however, still problematic. This problem may be solved by installing separate receiving and transmitting antennas in one instrument. On the one hand, it is clear that the level of electromagnetic interference of the transmitter, determined by the antenna coupling factor, will be very high; on the other hand, the use of modern technologies and software defined radio (SDR) enables us to identify desired signals against the background of very intense noise and ensure the work of the receiver during operation of the transmitter [Podlesnyi et al., 2014]. The antenna coupling factor is inverse to the damping factor between the antennas and is determined from the relation

$$R_{\mathrm{SW}} = 10\log\left(P_{\mathrm{rec}} / P_{\mathrm{tran}}\right), \tag{1}$$

where P_{tran} is the power at the transmitting antenna input, and R_{rec} is the power at the receiving antenna output. The coupling factor of antennas can be found in various ways, e.g., through a theoretical analysis using empirical formulas derived from experimental and theoretical modeling, or from an experiment. The theoretical analysis and empirical formulas can generally be applied when antennas are in the far field and there is a possibility of mathematical simulation of regular body radio wave diffraction. For example, sometimes in such cases the aircraft is approximated by a cylinder of infinite length, although it is a more complicated body of final length. The theoretical estimate of the coupling factor when continuous chirp signals are used to study the topside ionosphere is complicated by specific features of antenna systems of satellite ionosondes. Satellite antenna systems as compared to ground systems are severely limited by structural arrangement, size, and distance between transmitting and receiving antennas. This fact makes it difficult to estimate the antenna coupling factor through simulation because the antennas are in the near field. To estimate the electromagnetic interference level between the antennas, which directly sets requirements for characteristics of the receiving path and limits the maximum applicable signal power, therefore requires special experiments.

The advantage is that, as experience of the use of pulsed ionosondes indicates, the desired signal power for topside sounding is lower at least 100 times than that for ground instruments. The long experience of operation of the ionosonde of vertical and oblique sounding by a continuous chirp signal with an emitting power of ~5 W (Ionosonde-MS) the results of operation of which under difficult conditions are reported, say, in [Polekh et al., 2016], allows us to take the required power of sounding signal to be less than 10 W for the ground instrument using chirp signals. Hence the estimated sufficient power for a space-based ionosonde transmitter will be only 0.1 W (+20 dBm) with a root-mean-square effective voltage of 2.24 V per a load of 50 ohms. If the coupling factor of receiving and transmitting antennas is less than –10 dB, the effective voltage at the output of receiving antennas will be ~700 mV, which fits into the scale of voltages of existing high-speed ADCs and suggests that the proposed measurement scheme is valid.

ANTENNA SYSTEMS OF SATELLITE IONOSONDES

The antenna system of the ionosonde installed in Alouette II consisted of two crossed vibrators 23 m and 73 m long. The 73 m vibrator was used for a range 1–5 MHz; the 23 m one, for a range 4.5–15 MHz [Franklin, Maclean, 1969]. This approach is also applied in MARSIS, whose operational range is 0.1–5.5 MHz. This frequency range is divided into sections 1 MHz wide, each using its own antenna matching network with a dipole of respective size [Jordan et al., 2009].

As an antenna a simple thin vibrator is generally utilized; the main differences are in its length and deployment mode. The Alouette II's antenna was made of beryllium bronze alloy with shape memory effect. A strip of this alloy was wound onto a drum and slowly unwound from it, curling into its performed shape to form a thin tube. The MARSIS dipole is made of foldable composite tubes, which incorporate a hinge design. When deployed, the antenna is a dipole. Dipoles of the LAERT ionosonde in “Ionosphere” satellites are planned to be made in the form of foldable composite antennas.

STAND CONFIGURATION

The wide use of symmetric dipoles as receiving and transmitting antennas of satellite ionosondes is the reason for choosing these very antennas rarely utilized in ground-based facilities for in-situ testing. Besides geometry, an additional constraint for the antenna system is the continuous signal radiation with frequency tuning, which eliminates the use of adjustable antenna tuners and requires the use of separate antennas for receiving and transmitting. Continuous operation also complicates the frequency switching of the antenna systems, therefore one antenna system for the entire frequency range was used in the tests. Given this, the 72 m dipole with a load on the broadband balun 1:16 BR-800-16 manufactured by Radial was used as the basis for the stand. On the one hand, antennas with such a length of the elements have already been used in existing instruments; on the other hand, a longer dipole facilitates the effective work of the antenna system in a lower range. A 4 mm^2 gauge copper wire was utilized as material for manufacturing the dipoles.

As noted above, the use of a continuous chirp signal requires at least two dipoles — receiving and transmitting. Because of the relatively small size of the spacecraft as compared to the size of the antennas, we can suppose that the dipole centers are located in almost the same place and the only available degree of freedom is the angle between them. From elementary considerations it is clear that the larger is the angle, the less significant is the coupling factor. Of greatest practical interest are, therefore, measurements at maximum available divergence angles. In the minimum configuration, they may be represented by orthogonal receiving and transmitting dipoles. When using two orthogonal receiving dipoles for hardware separation of ordinary and extraordinary waves, the transmitting dipole can be placed at an angle of 45° to them (Figure 1). The in-situ simulation of the satellite ionosonde antenna system was carried out using three dipoles located in a plane parallel to the ground, at a height of ~6 m. The whole structure was mounted to a reinforced concrete mast 21 m high in the center and six auxiliary metal masts 6 m high along the edges of the dipoles. The two dipoles are orthogonally oriented; the third is located at an angle of 45° to them. This system allowed us to measure coupling factors of the orthogonal dipoles and the dipoles placed at an angle of 45°. The external view of the stand is shown in Figure 2. The receiving and transmitting equipment of the model ionosonde was in the vehicle UAZ standing under the center of the antenna system.

The standing wave ratio (SWR) measured in a range 2–30 MHz using a panoramic antenna analyzer Anritsu S332E is plotted in Figure 3. For this antenna, SWRs below 4 in the upper part of the band and below 9 in its lower part are very worthy values. The measurements have revealed the absence of apparent SWR dependence on the presence of additional dipoles; therefore we do not present the measurement results for each of the three dipoles.

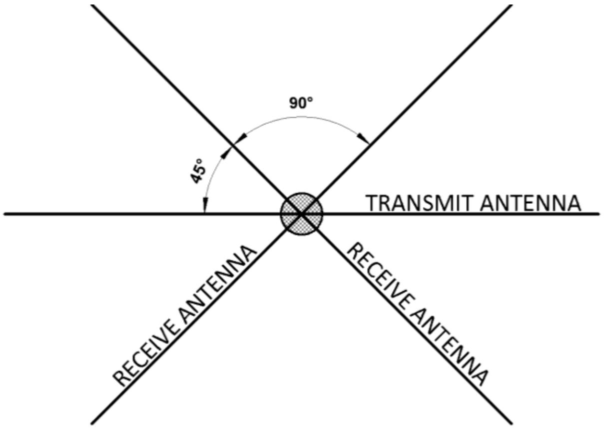

Figure 1. Position of antennas with hardware separation of polarizations

Figure 2. Stand: general view (left); central part at the point of intersection of the dipoles (right)

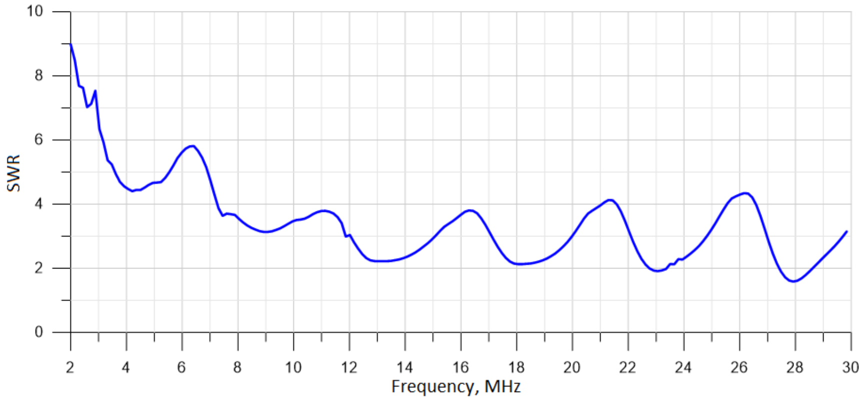

Figure 3. SWR of one of the dipoles at the stand

DESCRIPTION OF THE EXPERIMENT AND RESULTS

The dipole antenna above the conducting shield, represented by the dipoles being a part of the stand, is well described in various textbooks and manuals. When the length of a vibrator is less than a quarter wavelength, such an antenna has a pronounced vertical lobe, but the gain decreases rapidly with increasing wavelength. When the length of a vibrator is greater than a quarter wavelength, the dipole antenna pattern breaks up into lobes, the number of which is larger, the shorter is the wavelength. For the testing, we have made experimental measurements along differently oriented oblique sounding (OS) paths. The relative orientation of the paths and the tested dipole antenna are shown in Figure 4.

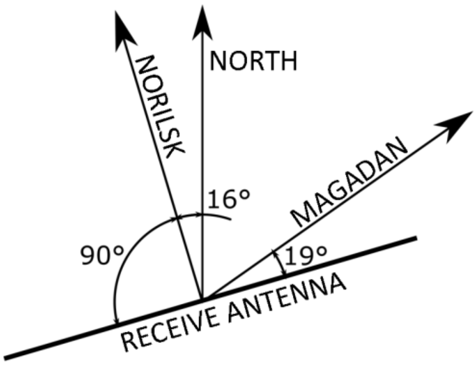

Figure 4. Orientation of the dipole tested in the OS mode at the stand

The comparison between ionograms from the dipole antenna and results from the delta antenna as part of the ionosonde (the ionosonde's receiving antenna is a triangle in the plane perpendicular to the ground, with a base of 36 m, a height of 7 m, and feeding in the center of the lower side) shows the appearance of low horizontal angle lobes in the upper part of the operational range (see Figure 5 *b*, *c*).

To test the hypothesis on the use of continuous chirp signals for topside sounding, we have carried out pilot sessions of vertical sounding, using both the horizontal dipole at the stand and the delta antenna of the vertical ionosonde located at a distance of ~200 m from the stand.

The sounding was made in the frequency range 2–15 MHz with a frequency sweeping rate of 1 MHz/s. The resulting IQ component samples from the output of the chirp signal receiver were processed using the standard software of primary chirp data processing to obtain ionograms (Figure 6) with a frequency step of 40 kHz and a height step of 1.25 km. When constructing ionograms, we corrected phase distortions of a signal, using a correction filter, threshold detection and elimination of localized radio station noise, automatic adaptive determination of noise level, and elimination of the apparent height range 0–80 km (in this range during vertical sounding is the signal of electromagnetic interference providing no useful information). Figures do not show the inconclusive part of the 8–15 MHz frequency range.

The IQ component samples were also used to obtain the coupling factor of the antennas. The coupling factor

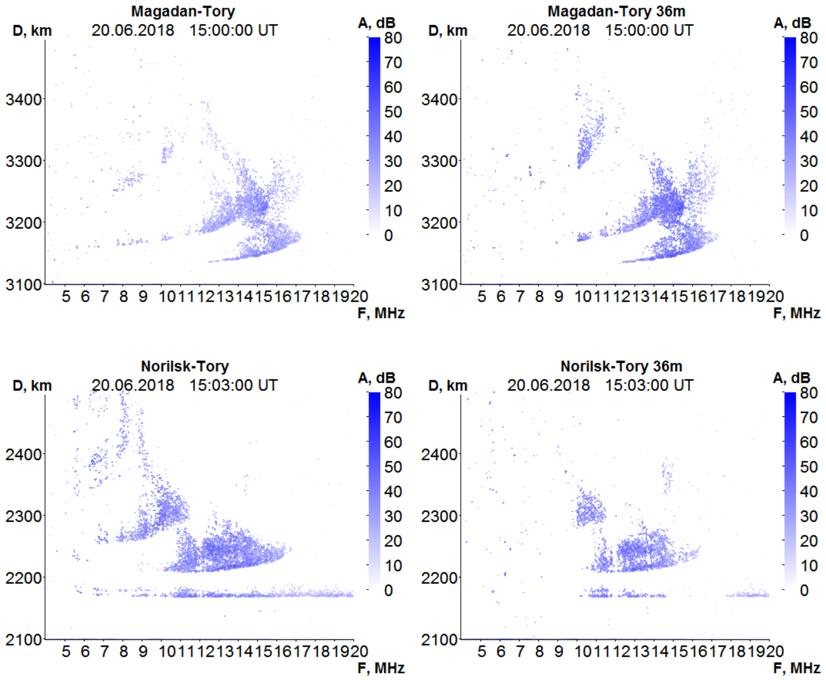

Figure 5. Ionograms obtained along oblique sounding paths Magadan–Tory (top) and Norilsk–Tory (bottom) with a vertical loop delta antenna (left) and horizontal dipole (right)

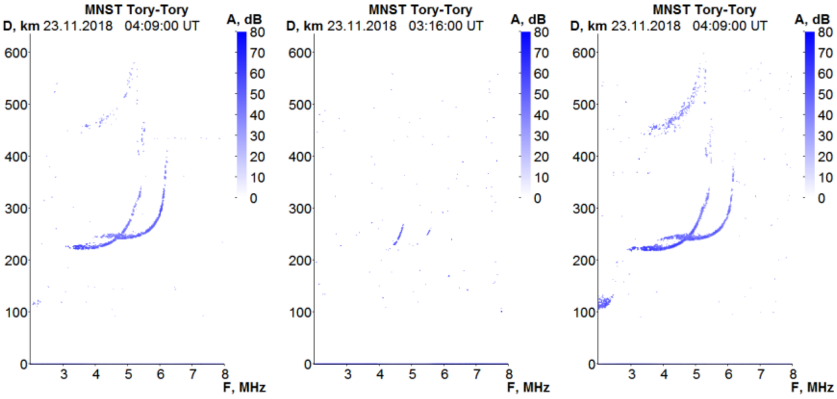

Figure 6. Ionograms from the stand (left to right): from the dipole orthogonal to the transmitting one (1 W); from the dipole at an angle of 45° to the transmitting one (0.1 W); from the delta antenna at a distance of 200 m (5 W)

was determined according to Formula (1) for each frequency in the operational range 2–15 MHz in 100 Hz increment. We can see (Figure 7) that the coupling factor of the transmitting and receiving antennas when located at an angle of 45° is substantially higher than in their orthogonal position, which limits the sounder's maximum usable power.

In particular, high coupling factors when the antennas are at the angle of 45° lead to saturation of ADC of the receiver with a transmitter power higher than 0.15 W and, accordingly, to complete inoperability of the ionosonde.

Some exact values of antenna coupling factors (Figure 7) are listed in Table.

DISCUSSION

It must be admitted that the model of the antenna system used in the experiment has some sources of systematic error. On the one hand, there is no underlying surface and masts in space. On the other hand, a real spacecraft may have dipoles of different length, thickness, and configuration. Moreover, in space long antenna systems are strongly affected by solar radiation. Due to thermal expansion of the daylight side, the geometry of long vibrators may be distorted [Mar, Garrett, 1969].

In particular, the temperature effect was one of the reasons for the fact that hinge-10 had stalled at 40° from full deployment of the 20 m MARSIS vibrator. The situation was corrected by adjusting position of the spacecraft for more uniform heating by solar radiation and by performing the correct maneuver [Douglas, Mehran, 2009].

We, however, think that the results of this work quite adequately demonstrate levels of coupling factors in such antenna systems and will be useful for develop ers of such systems. The masts and feeding cables located in the stand orthogonally to dipoles of the antenna system should not have a critical effect on its pattern, which is

Coupling factors

	Minimum value	Maximum value	Mean
Angle of 45°	–27.43 dB	–10.45 dB	–18.14 dB
Angle of 90°	–43.57 dB	–26.26 dB	–33.14 dB
Difference between 45° and 90° angles in frequency range	3.65 dB	27.19 dB	15.01 dB

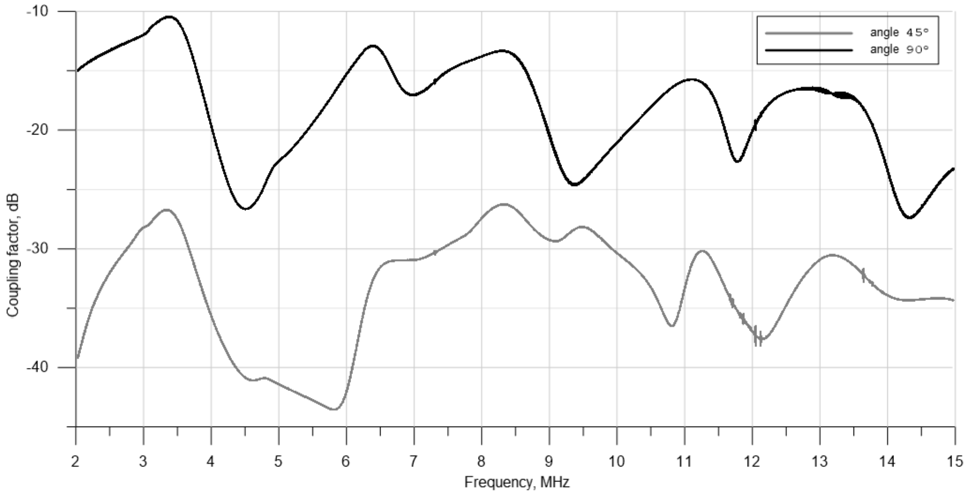

Figure 7. Coupling factors of receiving and transmitting dipoles at angles of 45° and 90°

indirectly confirmed by the vertical and oblique sounding ionograms obtained.

The satisfactory quality of the ionograms obtained when sounding Earth’s surface by a 1 W signal firstly shows that antenna gains conform to those assumed in calculation of the minimum required power for the sounding and secondly leads to a rather unexpected conclusion that it is possible to implement the ground-based facility of ionospheric sounding by continuous chirp signals with zero spacing between transmitting and receiving antennas.

The rather irregular behavior of the coupling factor over the frequency range suggests its resonant nature and that its maximum values can be reduced by ~ 5–7 dB if we vary the length of the transmitting dipole at a fixed length of the receiving one, shifting thereby antenna resonances relative to each other. But the study and, especially, the selection of these parameters require long and careful experiments.

In general, the results show that the coupling factor between the orthogonal dipoles is more than adequate, and in the case of dipoles set at an angle of 45°, the coupling factor despite approaching the threshold value of –10 dB in a part of the range has allowed values. The use of chirp signals, on the one hand, increases the complexity of the antenna system due to the need to use a dedicated transmission antenna; on the other hand, it is compensated by a decrease in the effective voltages and an increase in the spectral purity of the signal.

CONCLUSION

The results of the use of transmitting and receiving dipole antennas with a common center for ionospheric sounding by a continuous chirp signal allow us to conclude that such facilities can be used for satellite sounding of the topside ionosphere at hardware separation of polarizations and in the terrestrial version with orthogonal location of receiving and transmitting antennas. During tests conducted at a specially constructed antenna stand, we have established that the coupling factor of transmitting and receiving antennas at mutual angles of 45° is at most –10 dB, and the difference between coupling factors of transmitting and receiving antennas at mutual angles of 45° and 90° is ~15 dB.

The results were obtained using the equipment of Center for Common Use «Angara» [http://ckp-rf.ru/ckp/3056].

The work was supported by RFBR grant No. 18-35-00510-mol_a.

The work of ISTP SB RAS Geophysical Observatory, on the territory of which the studies were carried out, is performed with budgetary funding of Basic Research program II.12.

REFERENCES

Douglas S.A., Mehran M. Lenticular jointed antenna deployment anomaly and resolution onboard the Mars Express spacecraft. *J. Spacecraft and Rockets*. 2009, vol. 46, no. 2, pp. 403–410. DOI: 10.2514/1.36891.

Franklin C., Maclean M.A. The design of swept-frequency topside-sounders. *Proc. IEEE*. 1969, vol. 57, no. 6, pp. 46–82.

Ivanov V.A., Shumaev V.V., Kurkin V.I., Nosov V.E., Uryadov V.P. Chirp ionosonde and its application in the ionospheric research. Radiophysics and Quantum Electronics. 2003, vol. 46, no. 11, pp. 821–851. DOI: 10.1023/B:RAQE.0000028576.51983.9c.

Jackson J.E., Warren E.S. Objectives, History, and Principal achievements of the topside sounder and ISIS project. *Proc. IEEE*. 1969, vol. 57, pp. 861–865.

Jordan R., Picardi G., Plaut J., Wheeler K., Kirchner D., Safaeinili A., et al. The Mars Express MARSIS sounder instrument. *Planet. Space Sci.* 2009, vol. 57, iss. 14-15, pp. 1975–1986. DOI: 10.1016/j.pss.2009.09.016.

Karpachev A.T., Zhbankov G.A. Scattered reflections and multiple traces in the band of 7–10 MHz on ionograms of the Interkosmos-19 satellite. *Geomagnetism and Aeronomy.* 2017, vol. 57, iss. 4, pp. 442–450. DOI: 10.1134/S0016793217040090.

Klimenko V.V., Ratovsky K., Stepanov A., Klimenko M., Karpachev A.T. Spatial features of Weddell Sea and Yakutsk Anomalies in f_oF2 diurnal variations during high solar activity periods: Interkosmos-19 satellite and ground-based ionosonde observations, IRI reproduction and GSM TIP model simulation. *Adv. Space Res.* 2015, vol. 55, iss. 8, pp. 2020–2032. DOI: 10.1016/j.asr.2014.12.032.

Mar J., Garrett T. Mechanical design and dynamics of the Alouette spacecraft. *Proceedings of IEEE*. 1969, vol. 57, no. 6, pp. 30–46. DOI: 10.1109/PROC.1969.7134.

Orosei R., Jordan R.L., Morgan D.D., Cartacci M., Cicchetti A., Duru F. Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) after nine years of operation: a summary. *Planet. Space Sci.* 2015, vol. 11, pp. 98–114. DOI: 10.1016/j.pss.2014.07.010.

Podlesnyi A.V., Kurkin V.I., Laryunin O.A., Pezhemskaya M.D., Chistyakova L.V. Studying travelling ionospheric disturbances from near-vertical ionosphere sounding with high temporal resolution. *Proc. XXXI URSI General Assembly. Beijing, China*, 2014, GP2.27. DOI: 10.1109/URSIGASS.2014.6929806.

Polekh N.M., Zolotukhina N.A., Romanova E.B., Ponomarchuk S.N., Kurkin V.I., Podlesnyi A.V. Ionospheric effects of magnetospheric and thermospheric disturbances on March 17–19, 2015. *Geomagnetism and Aeronomy.* 2016, vol. 56, iss. 5, pp. 557–571. DOI: 10.1134/S0016793216040174.

Pulinets S.A. Prospects of satellite sounding of the ionosphere according to Ionosonde Project. *Geliogeofizicheskie issledovaniya* [Heliogeophysical Res.]. 2013, vol. 6, pp. 1–7.

Reinisch B.W., Haines D.M., Benson R.F., Green J.L., Sales G.S., Taylor W.W.L. Radio sounding in space: magnetosphere and topside ionosphere. *J. Atmos. Solar-Terr. Phys.* 2001, vol. 63, iss. 2-3, pp. 87–98. DOI: 10.1016/S1364-6826(00)00133-4.

Swenson C., Pratt J., Fish C.S., Winkler C., Pilinski M., Azeem I., et al. Topside Ionospheric Sounder for CubeSats. *AGU. Fall Meeting 2014: Abstracts*. SA43A-4102.

How to cite this article

Podlesnyi A.V., Naumenko A.A., Cedric M.V. Estimating antenna coupling factor for problem of topside ionosphere sounding from space by chirp signals. *Solar-Terrestrial Physics*. 2019. Vol. 5. Iss. 4. P. 101–107. DOI: 10.12737/stp-54201914.