EGU General Assembly 2021

PROBLEM OT ENERGY TRANSFER FOR RADIO PATHS NEAR SINGLE-HOP LIMITING DISTANCE FOR LOW SOLAR ACTIVITY

[1]Barbara Atamaniuk, Barbara Matyjasiak. [1]Space Research Center. Warsaw, Poland
[2]Igor Krasheninnikov, Alexei Popov. [2]IZMIRAN. Troitsk, Moscow, Russia

Motivation

Ionograms of oblique radio sounding show a deep trough in the amplitude-frequency plots in the periods of low solar activity. This effect may have a critical influence on the systems of backup HF communication and navigation.

Our goal

Study the factors determining formation of a dip in the amplitude-frequency characteristic of HF radiation transfer.

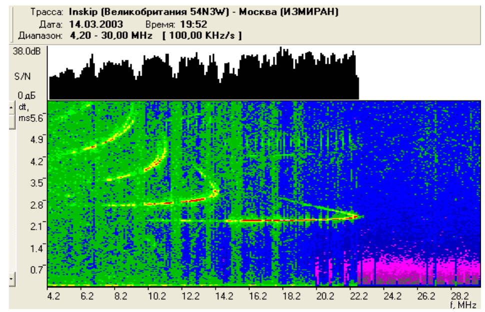
Methods

Ray optics, Appleton-Hartree theory of ionospheric plasma, COSPAR-URSI International Reference Ionosphere (IRI-2016), and radio wave propagation model Prognoz-IZMIRAN.

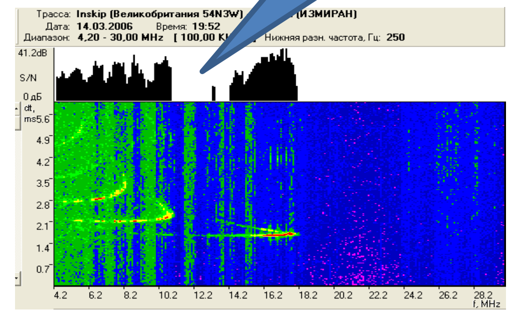
Oblique incidence sounding (OIS)

Inskip(GB)-Moscow(RU) path ~ 2500 km

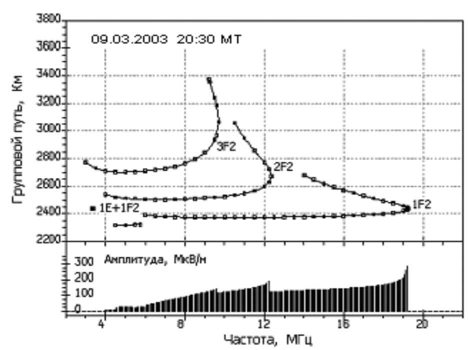
Deep though

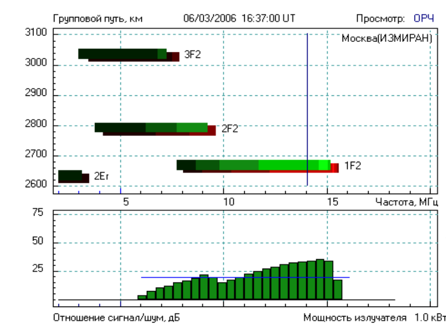


High solar activity



Low solar activity





Experiment versus numerical simulation

Conclusion

Simulation, in the framework of the extended ionosphere model IRI, shows high probability of appearing such an effect in the local day time, with a well developed regular E-layer of the ionosphere, in the periods of minimum solar activity.

EGU General Assembly 2021

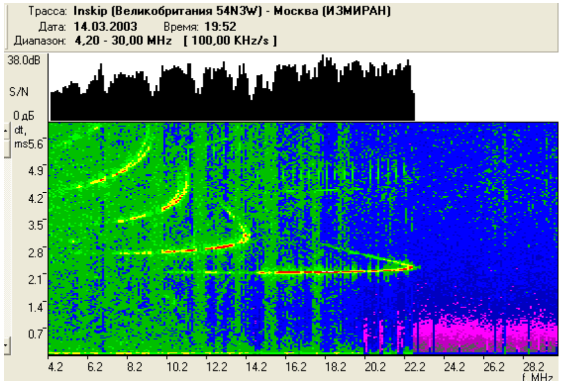
Problem of the energy transfer for radio paths near single-hop limiting distance for low solar activity

[1]Barbara Atamaniuk, 2Igor V. Krasheninnikov, [2]Alexei Popov, and [1]Barbara Matyjasiak

[1]Space Research Center, Polish Academy of Sciences, Warsaw, Poland (batama@cbk.waw.pl)
[2]N.V.Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, RAS, Troitsk, Moscow, 108840 Russia (popov@izmiran.ru)

Formation of a deep trough in the frequency dependence of the HF wave field strength at single-hop paths with distances near classical limiting distance 3000 km, at low level of solar activity, was considered. Model calculations, within the framework of the extended global ionosphere model IRI, show high probability of appearing such a situation in the local daytime, with a well developed regular E-layer of the ionosphere. Experimental results of multi-frequency radio sounding of the ionosphere, exhibiting the deep trough in frequency dependence of signal-to-noise ratio (SNR), were analyzed. It was shown that the IRI model, in principle, makes it possible to reproduce this peculiarity in the wave field energy parameters. However, in some cases of experimental data, to a large extent, it can provide only a qualitative description of this effect. Possible reasons of the quantitative discrepancy between experimental and model results are discussed.

Basing on the ionospheric radio wave modeling and experimental data, we present a physical analysis of the high frequency EM radiation transfer problem. In the periods of low solar activity there are peculiarities near the classical maximal range of single-hope radio wave propagation, leading to the formation of a deep trough in the wave field amplitude frequency dependence. The mode structure of the wave field in the ionospheric point-to-point radio wave propagation is determined by the following basic factors: terminal points positions, solar activity level, and the local time at the midpoint of the radio path.
There are two important parameters: MUF - maximum usable frequency and LUF - lowest observed (usable) frequency. The latter is the lowest frequency at which the wave field from the emitter can be physically recorded (distinguished from the background electromagnetic noise).



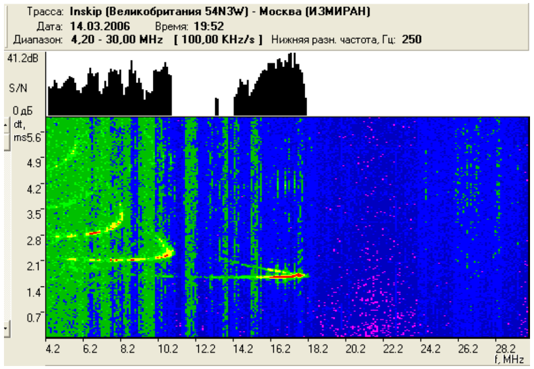


Figure shows an example of recording SNR (signal to radio noise) ionograms for the same time - 16:52 UT and day of the year - March 14, but in different years: of maximum (2003) and minimum (2006) solar activity.

NUMERICAL MODELING

We simulate two-point ionospheric radio wave propagation using the geometric optics approximation (Kravtsov and Orlov, 1980) and a standard model of the ionospheric plasma complex refractive index (Ratcliffe, 1959; Davies, 1973; Budden, 1985). For the field amplitude of each propagation mode, the solution of the transport equation has the following form:

$$A(\mathbf{r}) = \frac{A_0^0}{\sqrt{J}}\sqrt{G_t G_r}\exp\left\{-k_0\int_l \chi ds\right\},$$

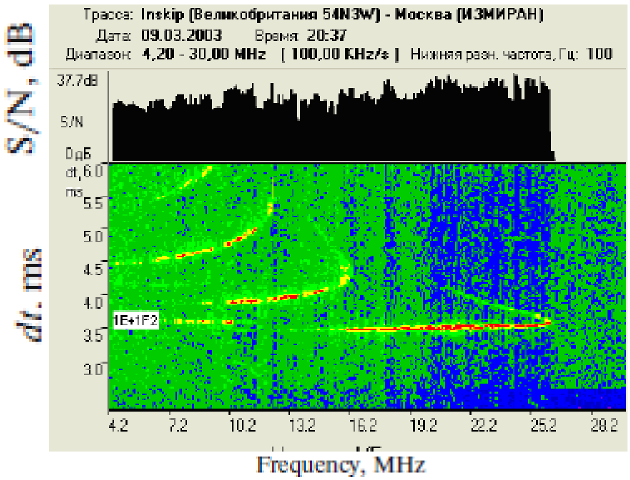
where A^0_0 is the initial value of the amplitude in mV/m at a distance of 1 km determined by radiation power in KW $A_0^0 = 245\sqrt{P_t}$ (Maslin, 1987); $J = \frac{\mu da}{\mu_0 da_0}$ is the spatial divergence of the ray tube; G_t and G_r are the antenna gain coefficients; k_0 is the wave number;

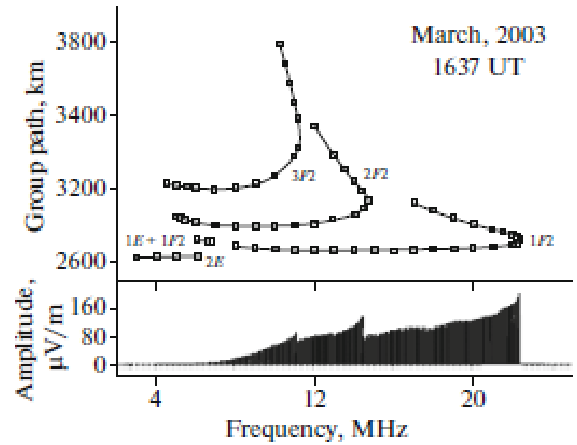
$\chi = -\frac{Z}{2\mu}\frac{\partial n^2}{\partial(Z)}\Big|_{Z=0}$ is the linear absorption coefficient;

$X = \omega_N^2/\omega^2$, $Y = \omega_H/\omega$, $Z = \nu_e/\omega$, ω_N, ω_H are the cyclic plasma and gyro-frequencies; ν_c is the effective collision frequency of electrons with neutral gas molecules and ions in the ionospheric plasma, and L is the beam path connecting the terminal points. For the isotropic case (Y = 0) and the refractive index in the Appleton–Hartree form, the attenuation coefficient has a simple formula that is convenient for understanding the physical laws of the radiation transfer:

$$\mu^2 = 1 - X,\ \chi = XZ/2\mu \quad \text{(Davies, 1973)}$$

Therefore, the linear attenuation coefficient $\chi \sim 1/\omega^3$





The figure shows a typical frequency dependence of the of the wave field power parameters at high solar activity for the Inskip (England)–IZMIRAN (Moscow) latitudinal radio path with a range of 2550 km (Krasheninnikov and Egorov, 2005). General uniformity of the field strength with frequency is clearly visible, both on the experimental recording of SNR and on the synthesized OIS ionograms.

At present, the most proven and used source of the ionospheric plasma electron density data is the global ionospheric model IRI (Bilitza et al., 2017), the input parameter of which is the level of solar activity in the form of the smoothed sunspot number (Wolf number). Subject to the 2015 reform for the determination of Wolf numbers (Clette et al., 2014), the mechanism was used to generate the optimized indices of the average monthly solar data R_m^g and F_m^g; whose maxima and the minima in the last two cycles of solar activity (Krasheninnikov et al., 2017) are presented in the Table:

Solar activity indices

Year	Month	Rms	Fms	R_m^g	F_m^g
2003	march	118.7	138.3	95.2	143.0
2006	march	27.4	81.2	24.2	82.0
2014	march	114.3	140.8	96.4	145.0
2018	march	9.9	71.9	10.5	72.0

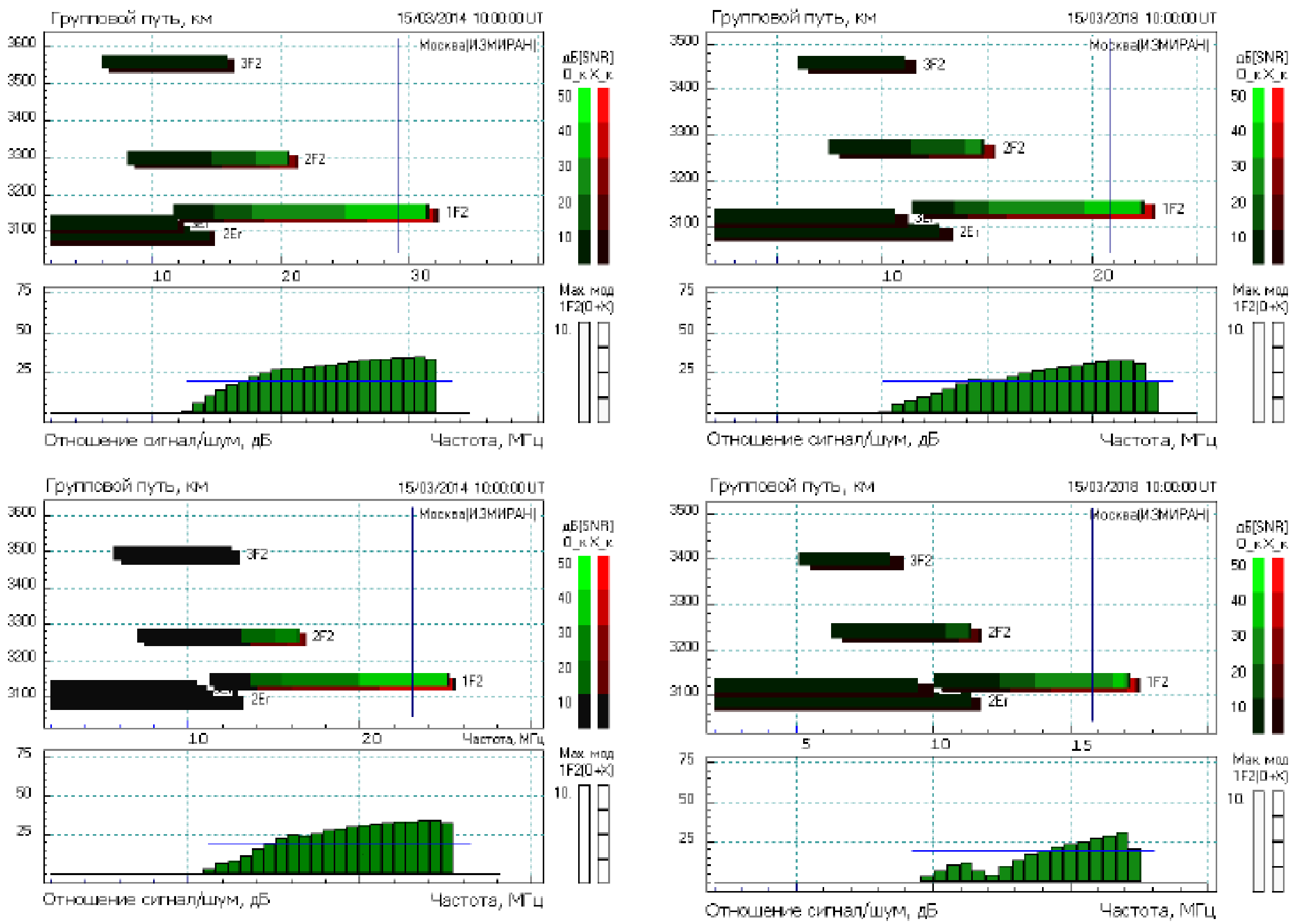
The radio paths considered had meridional and latitudinal directions with ranges of 1500, 2000, 2500, and 3000 km and a common final point of Moscow (IZMIRAN): the 2014 maximum and the 2018 minimum had the indicated monthly average solar activity parameters.

The synthesized oblique ionospheric sounding (OIS) data will be further analyzed in the form of the wave field mode structure adapted for practical forecasting of the ionospheric radio wave propagation. The ray tracing calculations were performed with the characteristics method (Lukin and Spiridonov, 1969) in an isotropic approximation of the refractive index. Based on the high degree of similarity of the magnetoionic branches of the OIS ionograms, under the condition of $X < 1$ for a fixed value of the group path, the following relation between the characteristic frequencies (isotropic *f,* ordinary and extrordinary *fo,x*) was used: (Krasheninnikov et al., 2018):

$$f^2 = f_{o,x}^2 - \frac{f_T^2}{2} \pm \left(\frac{f_T^4}{4} + f_{o,x}^2 f_L^2 \right)^{1/2}$$

where f_L and f_T are the longitudinal and transverse components of the electron gyro-frequency

$f_H = \omega_H/2\pi$ on the wave-vector direction at the midpoint of the radio path, with the layer height and arrival angles taken in the thin reflecting layer approximation (Davies, 1973). The wave energy for the frequencies *fo,x* is assumed to be distributed equally.



Frequency dependence of the HF wave mode structure (group paths) and the SNR at a range of 3000 km in the southern meridional (upper panels) direction and western latitudinal (lower panels) directions. Calculated in the IRI model at 10:00 UT, for high (*Rms* ~ 110, March 2014, left panel) and low (*Rms* ~ 10, March 2018, right panel) solar activity.

The main physical factors determining the occurrence of a trough in the frequency band of the HF radiation transfer at maximum ranges of single-hop propagation can be identified:

(a) curvature of the Earth's surface,

(b) greater influence of solar activity level on the *F*2-layer parameters, compared to the *E* layer,

(c) effect of the intermediate electron density, including the *E*–*F* transition region, on both the value of the lower boundary (Krasheninnikov et al., 1996) and the 1*F*2 mode wave field amplitude in the lower part of the trace on the OIS ionogram.

The maximum distance of the radio path D_{max} is approximately related to the reflection height by the following relation (Davies, 1973):

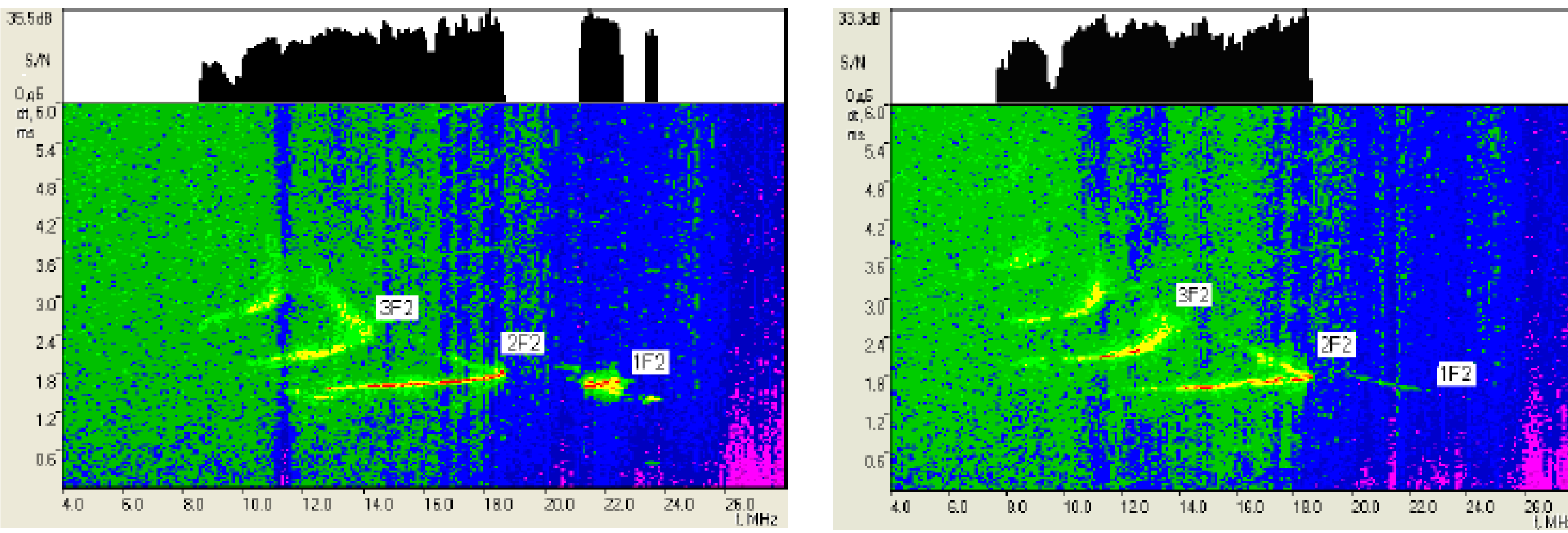
$$D_{max} = 2r_e \arccos \frac{r_e}{r_e + h}$$

where r_e is the Earth radius and h is the height of reflection above the Earth's surface.

An almost mirror reflection occurs for the *E* layer of the ionosphere, and the maximum distance is 2300–2350 km for the altitudes of 105 and 110 km. This corresponds to the simulation results and experimental data, showing the absence of the 1*Er* mode (reflection from the regular *E* layer) at a range of 2500 km. For the ionospheric *F*2 layer, this relation gives an underestimated value, since refractive reflection is already typical for it.

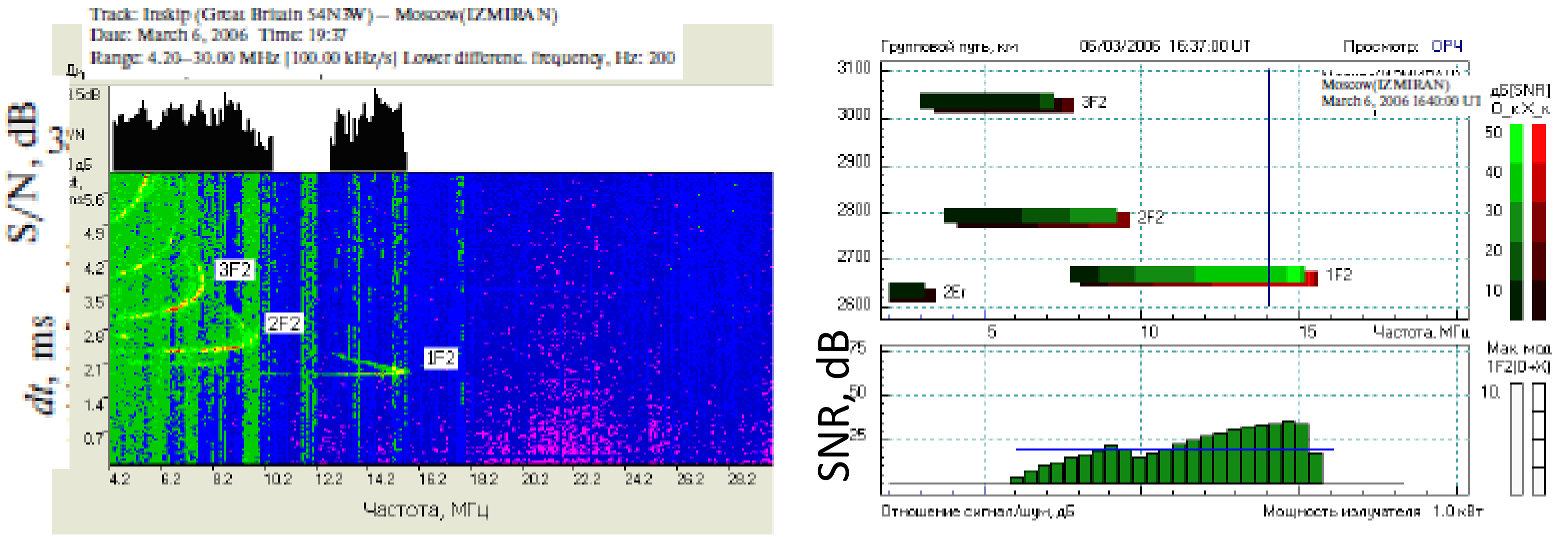
For the altitude of *hmF*2 ~ 250 km, which is typical for the daytime, the limiting range is about 3500 km. However, the real single-hop radio wave propagation extends beyond this value.

The next figures show that the 1F2 mode exists in the modal structure of the wave field when the terminal points are separated by ~4200 km, although it is formed only by the upper rays reflected at heights in the vicinity of the maximum of the F2 layer. The growing longitudinal inhomogeneity leads to the weakening of the mode 1*F*2 amplitude (right panel) due to the increasing divergence factor.

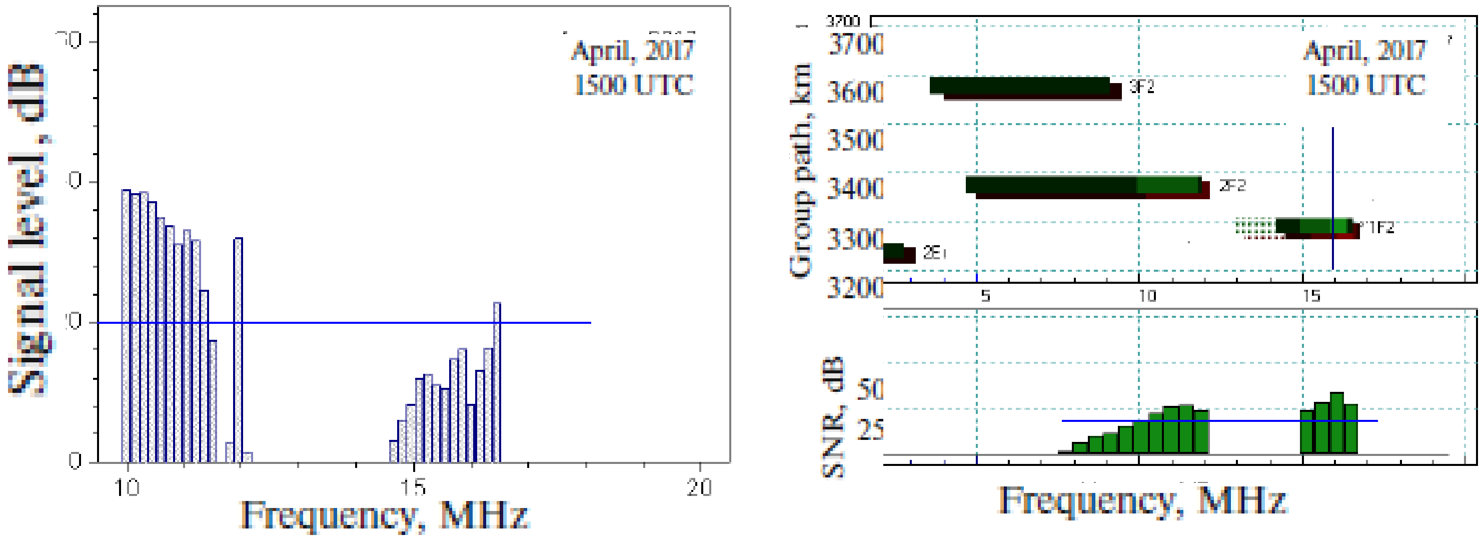


Experimental ionograms of oblique ionospheric radio sounding for a distance of Irkutsk (ISTP)–Moscow (IZMIRAN), ~4200 km. September 8, 2011, 1100 UT (left panel) and 1245 UT (right panel).

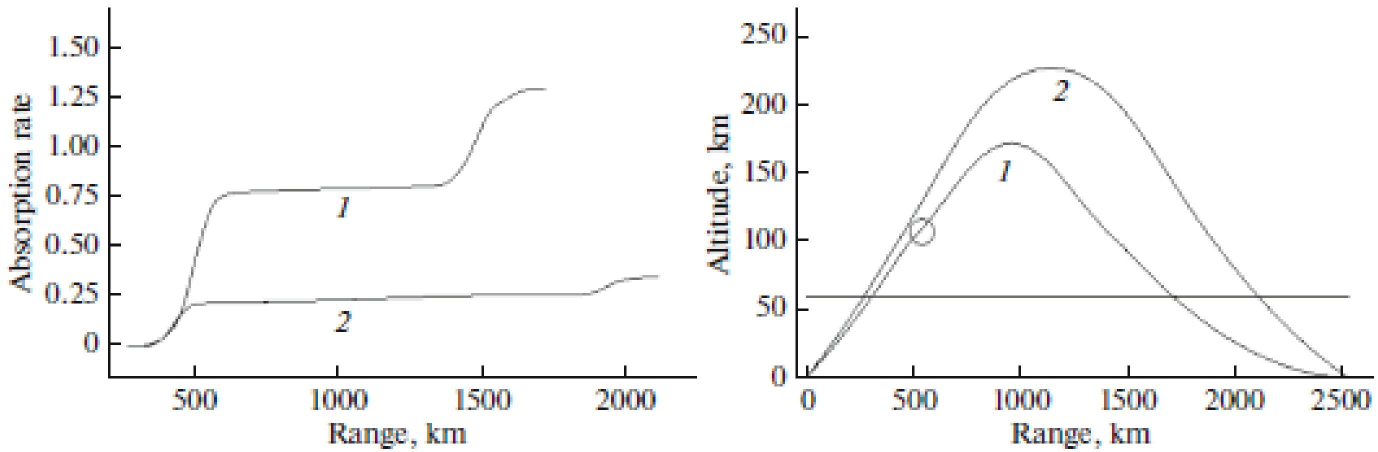
Experiment and simulation results



Frequency dependence of the wave field and signal-to noise ratio (SNR): experimental ionogram of oblique radio sounding on March 6, 2006, 16:37 UT (left panel) and a synthesized ionogram in the IRI model (right panel).



Averaged experimental results of the radio communication system operation in the frequency scanning mode within range of 10−20 MHz (left panel);
the synthesized OS ionogram, IRI model (right panel) for April 2017.



Integral absorption index (left panel) along the ray trajectories (right panel) corresponding to the minimal and maximal frequencies of 1*F*2 mode in the IRI model for the oblique radio sounding data on March 6, 2006, 16:37 UT. Local deformation of the ray trajectory for the minimal frequency, when crossing the *E* layer, can be noted.

Based on the simulation data, the formation of a more pronounced trough in the frequency dependence of the wave field amplitude requires a higher absorption of the 1F2 mode in the lower frequency range, when passing the E layer of the ionosphere. An increase in *hmE* is especially characteristic of the evening time during a period of an intensive decrease in the electronic density. Zawdie et al. (2017), using the generalized representation of the refractive index by Sen and Wyller (1960), showed the increase of the absorption in the *E* and *D* layers.

The absorption will also rise up with electron density increasing in the ionospheric *E* layer (the zenith angle of the Sun increases) as the summer season approaches. The appearance of a trough in the frequency range of the energy parameters of the wave field at single-hop passage ranges exceeding 2500 km with low solar activity will be a highly probable event for the summer months

CONCLUSIONS

The results of numerical modelling and analysis of the experimental data show that during the periods of minimum solar activity for radio paths with ranges close to the limiting range of the single-hop HF propagation in the presence of a pronounced layer E of the ionosphere, the probability of a deep trough in the amplitude-frequency dependence of the wave field significantly increases. This effect is especially typical for radio paths of the latitudinal direction during the passage of the terminator, i.e. at the maximum longitudinal inhomogeneity of the electron density of the ionospheric plasma. This feature can serve as a good indicator of the reliability of the ionosphere models, in particular, the effective frequency of electron collisions. In practical terms, it can lead, in particular, to a decrease in the reliability of the operation of ionospheric radio communication systems, due to the possible falling the operating frequencies into the energy dip band.

REFERENCES

Bilitza, D., Altadill, D., Truhlik, V., Shubin, V., Galkin, I., Reinisch, B., and Huang, X., International Reference Ionosphere 2016: From ionospheric climate to realtime weather predictions, *Space Weather*, 2017, vol. 15, pp. 418–429.

Budden, K.G., *The Propagation of Radio Waves*, Cambridge: Cambridge University Press, 1985.

Chasovitin, Yu.K., Shirochkov, A.V., Besprozvannaya, A.S., et al., Global empirical model of the distribution of electron density, temperature, and effective frequency of electron collisions in the ionosphere, *Ionos. Issl.*,1988, no. 44, pp. 6–13.

Clette, F., Svalgaard, L., Vaquero, J.M., and Cliver, E.W.,Re-visiting the sunspot number: A 400-year perspective on the solar cycle, *Space Sci. Rev.*, 2014, vol. 186, no. 1, pp. 35–103.

Krasheninnikov, I.V. and Egorov, I.B., Formation of combined modes during the ionospheric radiowave propagation, *Geomagn. Aeron. (Engl. Transl.)*, 2005, vol. 45, no. 2, pp. 227–230.

Krasheninnikov, I.V., Jodogne, J.-C., and Alberca, L.F.,Compatible analysis of vertical and oblique sounding data, *Ann. Geofis.*, 1996, vol. 39, no. 4, pp. 763–768.

Krasheninnikov, I.V., Pavlova, N.M., and Sitnov, Yu.S., IRI model in the problem of predicting ionospheric radio-wave propagation under conditions of high solar activity, *Geomagn. Aeron. (Engl. Transl.)*, 2017, vol. 57,no. 6, pp. 719–726.

Krasheninnikov, I.V., Givishvili, G.V., and Stakhanova, I.G.,Estimation of the critical frequency in the radio sounding of the ionosphere on board high-orbit spacecrafts over the arctic region, *Geomagn. Aeron.*, 2018, vol. 58, no. 5, pp. 644–650.

Kravtsov, Yu.A. and Orlov, Yu.I., *Geometricheskaya optika neodnorodnykh sred* (Geometric Optics of Inhomogeneous Media), Moscow: Nauka, 1980.

Kravtsov, Yu.A. and Orlov, Yu.I., *Caustics, Catastrophes and Wave Fields*, Berlin, Heidelberg: Springer, 1999

Kryukovskii, A.S. and Skvortsova, Yu.I., Using the theory of catastrophes for the description of the spatiotemporal structure of a frequency-modulated signal in plasma, *Elektromagn. Volny Elektron. Sist.*, 2013, vol. 18, no. 8, pp. 18–23.

Lukin, D.S. and Spiridonov, Yu.G., Using the method of characteristics for the numerical solution of the problem of radiowave propagation in an inhomogeneous and nonlinear medium, *Radiotekh. Elektron.*, 1969, vol. 14, no. 9, pp. 1673–1677.

Maslin, N. M. HF Communications. A Systems Approach. CRC Press, 1987.

Ratcliffe, J.A., *The Magnetoionic Theory and Its Applications to the Ionosphere*, Cambridge: Cambridge University Press, 1959.

Zawdie, K.A., Drob, D.P., Siskind, D.E., and Coker, C., Calculating the absorption of HF radio waves in the ionosphere, *Radio Sci.*, vol. 52, pp. 767–783. https://doi.org/10.1002/2017RS006256.