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MEASUREMENT OF THE GEOMAGNETIC FIELD IN THE IONOSPHERE USING RADAR METHODS

A new method for measuring the geomagnetic field in the ionosphere by the integrated use of vertical sounding radar (ionosonde) and incoherent scatter radar, its capabilities and features of the technical implementation, as well as the first results of an experimental test are considered.

Key words: geomagnetic field, ionosphere, incoherent scatter radar, ionosonde.

Introduction. Currently, measurements of the geomagnetic field (GMF) in the ionosphere are realized at altitudes of flight of the Earth artificial satellites [1]. Currently, measurements of the geomagnetic field (GMF) in the ionosphere are realized at altitudes of flight of the Earth artificial satellites [1]. At first, the magnetic studies, which proved the presence of ionosphere sources, originative the changes of the GMF, have been carried out by the third Soviet satellite in 1958 [2].

However, measurements of the GMF in the ionosphere by satellites have the following weaknesses:

1. Area of the ionosphere near the ionospheric peak and below is practically beyond the observation zone due to short life of satellites in the specified area. At the same time, one can expect the greatest GMF variations associated with ionospheric currents just in this area.

2. Continuous monitoring of GMF in a fixed region of space is impossible due to the movement of satellites, making it difficult to study the temporal variations in GMF.

3. Simultaneous and continuous measurement of the characteristics of the ionosphere and magnetosphere in the area above IS radar is practically impossible. This reduces the possibility of studying magnetosphere-ionosphere coupling.

Thus, the topical problem is to develop methods for measuring the GMF in the region near the ionospheric peak and below.

To investigate the interaction of the magnetosphere and ionosphere, it is desirable to carry out combined in time and space measurement of the magnetosphere and ionosphere parameters.

Such measurements can be performed using the method developed at Institute of Ionosphere [3] and described below.

The method allows measuring the vertical component of intensity of the GMF in region near the ionospheric peak under ionospheric observatory by the integrated use of vertical sounding radar (ionosonde) and incoherent scatter (IS) radar.

Purpose is to consider the possibility of measuring the geomagnetic field at the dense ionosphere altitudes.

Method for measuring GMF in the ionosphere. The Faraday effect is used to measure GMF by IS radar. The effect appears that, when the radio wave passes through the magnetized ionospheric plasma from the radar up to a height h and backwards, its polarization ellipse is rotated by an angle

$$\Phi(h) = k\int_0^h H(l)N(l)dl\,, \tag{1}$$

where k =0,0594$\cdot f_0^{-2}$, f_0 is operating frequency, $N(h)$ is the electron density, and H is the longitudinal component of the GMF intensity.

In accordance with (1) and the mean value theorem there is in a specified height interval $[h_1, h_2]$ such height h_x , for which

$$\delta(h_x) = \Phi(h_2) - \Phi(h_1) = kH(h_x)\int_{h_1}^{h_2} N(h)dh\,. \tag{2}$$

Thus, we have from (2):

$$H(h_x) = \frac{\delta(h_x)}{kN_M I}\,, \tag{3}$$

where

$$I = \int_{h_1}^{h_2} F(h)dh \tag{4}$$

$F(h) = \dfrac{N(h)}{N_M}$ is normalized to the maximum height profile of the electron density.

As seen from (3), if we measure the Faraday effect, the normalized profile and maximum of the electron density, we can calculate the intensity of the GMF at a certain height within a specified interval of heights.

For measuring the Faraday effect, transmitter radiates a signal with linear polarization and we carry out reception of the left and right circular polarization components. At the same time, optimal algorithm of estimate formation is of the form [4]

$$\hat{\Phi}(h) = \frac{1}{2}arctg\left[\frac{r_{c1s2}(h) - r_{c2s1}(h)}{r_{c1c2}(h) + r_{s1s2}(h)}\right], \tag{5}$$

where r_{c1s2}, r_{c2s1}, r_{c1c2}, r_{s1s2} are estimates of the cross correlations of the signal quadrature components at the receiver outputs.

To determine the $F(h)$ function using the IS radar, the signal power $P(h)$, electron $T_e(h)$ and ion $T_i(h)$ temperatures are measured, and then we calculate and normalize a function

$$N(h) = CP(h)h^2\left(1 + \frac{T_e(h)}{T_i(h)}\right), \tag{6}$$

where C is any constant. N_M is measured using ionosonde.

As it is necessary to radiate a long pulse with circular polarization for $T_e(h)$ and $T_i(h)$ measurement, we proposed to use the sound signal, consisting of the first pulse with circular polarization and the second pulse with linear polarization [1]. The first pulse has long duration to ensure the accuracy of temperature measurement, and the second pulse has short duration to ensure high correlation between ordinary and extraordinary waves, as well as high resolution of IS signal for power measurement.

Thus, we obtain the estimate

$$\hat{H}(h_x) = \frac{\hat{\delta}(h_x)}{k\hat{N}_M\hat{I}}, \tag{7}$$

where $\hat{H} = H + \varepsilon_H$, $\hat{\delta} = \delta + \varepsilon_\delta$, $\hat{N}_M = N_M + \varepsilon_N$, $\hat{I} = I + \varepsilon_H$, ε_δ, ε_I, ε_H, ε_N are errors of measurement.

Estimation of the method accuracy. Assuming smallness of ε_δ, ε_I, ε_H, ε_N measurement errors and under condition of absence of their cross-correlation, we obtain on basis of (7) a formula for the relative variance of measurement error of the longitudinal component of the GMF intensity at the height h_x

$$\frac{\sigma_H^2}{H^2} \approx \frac{\sigma_\delta^2}{\delta^2} + \frac{\sigma_N^2}{N^2} + \frac{\sigma_I^2}{I^2}, \tag{8}$$

where σ_δ^2, σ_N^2, σ_I^2 are variances of δ, N_m, and I measurement.

The error due to uncertainty of the height h_x can be significant in case of strong GMF change within the altitude range $\Delta = h_2 - h_1$ and high requirements to accuracy of binding measured GMF intensity to the height.

If we represent a law of change in the GMF intensity within this altitude range as Taylor series and confine oneself to linear approximation

$$H(h) \approx H_0 + \frac{1}{2}\gamma(h - h_0), \tag{9}$$

where H_0 – GMF intensity at the height $h_0 = \frac{h_1 + h_2}{2}$, we obtain

$$\frac{\sigma_H^2}{H^2} \approx \frac{\sigma_\delta^2}{\delta^2} + \frac{\sigma_N^2}{N_M^2} + \frac{\sigma_I^2}{I^2} + \frac{\beta^2}{H^2}, \tag{10}$$

where $\beta = \gamma \frac{I_1}{2I}$, $I_1 = \int_{h_1}^{h_2} F(h)(h - h_0)dh$.

The height profile of the electron density can be approximated by the function

$$F(h) \approx F(h_0) + a(h - h_0) + b(h - h_0)^2. \tag{11}$$

Then

$$\frac{\sigma_H^2}{H^2} \approx \frac{\sigma_\delta^2}{\delta^2} + \frac{\sigma_N^2}{N_M^2} + \frac{\sigma_I^2}{I^2} + \left(\frac{\gamma}{H}\frac{a(\Delta h)^2}{12F(h_0)}\right)^2. \tag{12}$$

We assume that the variance $\sigma_\delta^2 = 2\sigma_\Phi^2(1 - r)$ makes the main contribution to the variance (12). Here σ_Φ^2 is the variance of the error of the parameter Φ, and r is the cross-correlation of errors for the heights h_1 and h_2, which depends on the amplitude-frequency response of the receiver.

We can show that the Cramér–Rao bound for the variance σ_Φ^2 under optimal measurement algorithm (5) is defined by formula

$$\sigma_\Phi^2 = \frac{\left[1 - \rho^2 + \left(\frac{1}{q_2} + \frac{1}{q_1}\right) + \frac{1}{q_1 q_2}\right]^2}{4M\rho^2\left\{1 - \rho^2 + \frac{1}{2q_2} + \frac{1}{2q_1}\right\}}, \tag{13}$$

where ρ is the coefficient of correlation between the ordinary and extraordinary waves, M is the number of processed sounding cycles, q_1 and q_2 are the signal-to-noise ratio at the receiver outputs. The values $\sigma_\Phi = \sqrt{\sigma_\Phi^2}$ for the case of M=5800 (accumulation during a 15-min session) are presented in Table 1.

Table 1 – Standard deviation of error in measurement of the angle of the polarization ellipse rotation

	$q_1 = q_2 = 2$	$q_1 = q_2 = 4$	$q_1 = q_2 = 10$	$q_1 = q_2 = 50$
ρ = 0.5	0.022	0.017	0.014	0.012
ρ = 0.7	0.0165	0.012	0.009	0.007
ρ = 0.9	0.0126	0.008	0.005	0.004

Such potential accuracy allows expecting the fact that measurement errors in intensity of GMF can be comparable with its disturbances during geomagnetic storms.

Results of experimental test of the method. Some results of the first test of the described method for measuring GMF are presented below. In this case, the one channel of the transmitter and one of two orthogonal antenna dipoles were used to emit linearly polarized waves. When sampling a signal, we used a step in height Δ=4550 m. Because of the small step, the integral (4) for the *i*-interval of heights was calculated by the formula

$$I(h_{xi}) = 0{,}5\Delta\left[F(h_{1i}) + F(h_{2i})\right]. \tag{14}$$

Parameter Φ was determined according to the algorithm (5). The signal power was determined for the echo signal from the short pulse by equalizing the receiver gains, subtraction of the noise power from the signal plus noise power, accounting gain of antenna switches with gas-filled dischargers for each segment of the radar sweep, and summing the results.

Dependence of vertical component of intensity of GMF on a height, got at watching 15 minutes presented on Fig. 1.

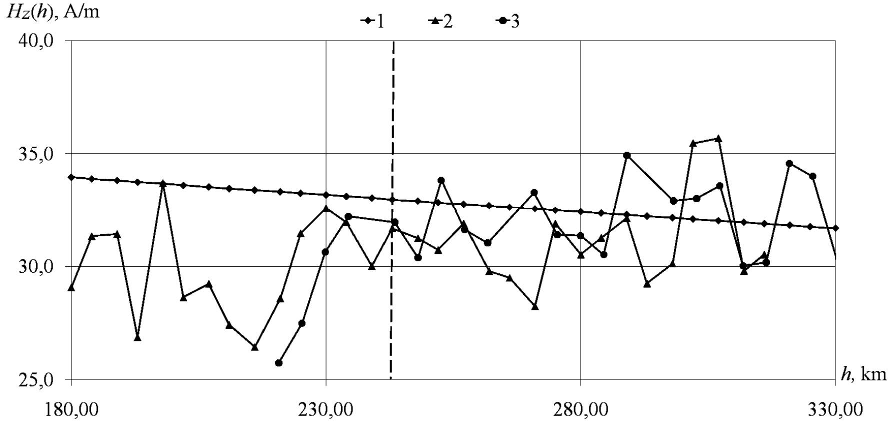

Fig. 1 – Intensity of H_z-component of geomagnetic field.
Local time in Kharkiv 13:20–13:36 (12.11.2012).

Curve 1 corresponds to the DGRF/IGRF Geomagnetic Field Model of [5], and curves 2 and 3 got experimentally. Curve 2 got with the use of temperatures in accordance with the model of IRI-2007 [6], and curve 3 – with the use of the temperatures measured by IS radar. A stroke vertical marks the height of a maximum of ionizing.

Apparently, in area of high concentration (230-300 kilometers) the measured values are near to the model.

It is of interest that the size of the measured intensity on the average a bit increases with a height, unlike the DGRF/IGRF model. In principle, such effect can be caused by the error of measuring of temperatures. A calculation was therefore produced with the use of model of temperatures of IRI-2007, that confirmed the effect of increase of vertical component of intensity with a height. This fact requires additional research. However it is known that GMF in an ionosphere can have noticeable local differences from the accepted models [1, 2].

Conclusion. Theoretical estimation and experimental test indicate that it is possible to measure the vertical component of the GMF intensity in the ionosphere by the proposed method with a relative root mean square error of a few percent. We can further improve the accuracy of these measurements, in particular due to the following:

– correction of errors due to errors in setting the polarization of the antenna;

– improving the signal-to-noise ratio by using two channels of the transmitter for formation of the sound signal with linear polarization;

– use of the polarization modulation of the sound signal, which allows to measure the electron and ion temperatures simultaneously with the signal polarization (Faraday rotation measurement).

Finally, we can evaluate quality of the GMF measurement using IS radar and ionosonde after optimization of equipment and measurement algorithms, and also the analysis of experimental data with the use of a sufficiently large statistical material.

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Рассмотрен новый способ измерения геомагнитного поля в ионосфере путем комплексного использования радара вертикального зондирования (ионозонда) и радара некогерентного рассеяния, его возможности и особенности технической реализации, а также первые результаты экспериментального испытания.

Ключевые слова: геомагнитное поле, ионосфера, радар некогерентного рассеяния, ионозонд.

Розглянуто новий спосіб вимірювання геомагнітного поля в іоносфері шляхом інтегрального використання радару вертикального зондування (іонозонду) і радару некогерентного розсіяння, його можливості й особливості технічної реалізації, а також перші результати експериментального випробування.

Ключові слова: геомагнітне поле, іоносфера, радар некогерентного розсіяння, іонозонд.