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Development of Diagnostic Capabilities of the Irkutsk Incoherent Scattering Radar

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Abstract—A description of the incoherent scattering radar of the Institute of Solar-Terrestrial Physics, Siberian Branch of Russian Academy of Sciences is given. New diagnostic capabilities attained as a result of modernization are described. The types of measurements are considered to be performed using this facility when studying the upper atmosphere of the Earth and the near-Earth space.

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1. INTRODUCTION

Incoherent scattering radars (ISRs) are being used in ionospheric studies for more than four decades, still remaining the most informative ground-based instruments for diagnostics of the upper atmosphere. All this time their technology develops continuously, separate ISRs become more perfect, and, in spite of complexity and high costs, their network becomes wider. The following advances in perfecting the diagnostic capabilities of operating radars are recognized as promising [7]: provision for flexibility and diversity of the methods of off-line data processing thanks to retaining the maximum possible amount of source information; improvement of spatial resolution and extension of the altitude range of ionospheric measurements by way of using complicated signals optimized for particular tasks; enhancement of the capabilities for studying the spatially inhomogeneous structure of the ionosphere owing to application of antennas with special capability of electron scanning and interference measurements. At the moment, over the world as many as 10 IS radars operate, each of which being unique in its design and methods of diagnostics. Included in this number is the only radar in Russia: the Irkutsk Incoherent Scattering Radar (IISR) [1]. At the present time, new methods of signal processing have been developed at IISR and new types of observations have been promoted, which requires a substantial modernization of receiving, detecting, and controlling systems of the radar.

2. AIMS AND DIRECTIONS OF MODERNIZATION

The IISR represents a monostatic pulse radio location station with frequency scanning. Its on-peak power reached with two transmitters is up to 3.2 MW. The pulse-repetition rate is 24.4 Hz, and the duration of a sounding pulse is from 70 to 900 μs. The range of working frequencies of the radar is 154–162 MHz, while the antenna power gain is about 35 dB. The design and arrangement of transmitting and antenna-feeder systems, as well as the structure of the complex of receiving and recording equipment that existed before 2006, are described in detail in paper [1]. The progress of diagnostic capabilities of the IISR at the new stage was associated with radical modernization of the entire complex of controlling, receiving, and recording devices, as well as means of signal processing, in order to use the potentialities of the radar and specific features of its antenna design as fully as possible.

The main task of modernization was to provide for the following capabilities of the radar.

1. To measure parameters of the ionosphere plasma in several direction simultaneously, in order to study its spatially inhomogeneous structure.

2. To measure simultaneously, without loss of necessary accuracy, powerful signals from spacecraft or coherent echo (CE) against the background of weak signals of scattering on thermal fluctuations of plasma.

3. Programmed control over the shape of the directivity diagram (DD) of the radar and conductance of interferometric measurements.

4. Improvement of the spatial resolution by way of using optimal sounding signals and extending the altitude range of ionospheric measurements owing to elimination from the radio location sweeping of signals from local objects.

5. Recording on storage media the full amount of real time data of sounding in order to provide a user for a choice of the method of off-line processing depending

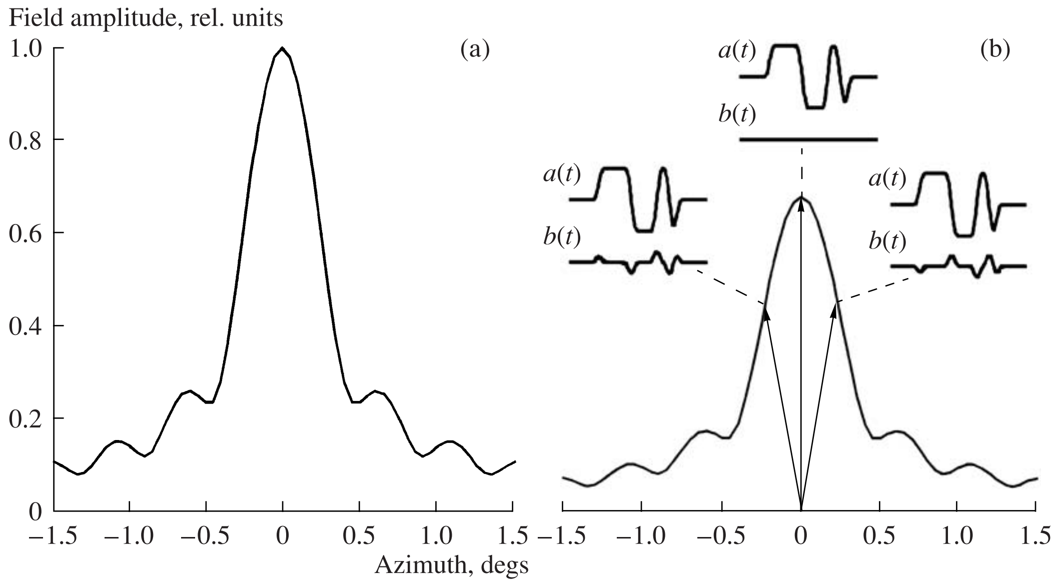

Fig. 1. The antenna directivity diagram in the azimuth plane: (a) DD cross section in the azimuth plane; (b) variation of a signal shape when a target deviates from the DD center in the azimuth plane.

on particular problems solved, and processing of a large data array of ionosphere and satellite sounding in the real time mode.

Realization of thus formulated problems has required to create a new controlling and receiving-recording complex (CRRC) which includes a multichannel receiving device, a digital system of synchronization and formation of operating frequencies, a system of automatic phase adjsting of the transmitters, a quick response device of signal recording and radar control, and a distributed computing system of off-line processing of sounding data in the real time mode.

3. TYPES AND METHODS OF MEASUREMENTS

Capabilities of the antenna system. The DD of the radar antenna along the lengthwise axis (azimuth direction in the antenna coordinate system) is formed by a extended linear array of slot radiators and has a width of about 0.5° (Fig. 1a). The IISR is a radar with frequency scanning, i.e., its current azimuth $\varepsilon(f)$ is determined by the operating frequency. In this case, if an observed space object (SO) is located at angular distance $\varepsilon(f)$ from the DD center, then distortions appear in the received signal in the form of additional phase modulation (quadrature of $b(t)$ in Fig. 1b) whose amplitude in the first approximation is proportional to $\Delta\varepsilon$ and the shape corresponds to the derivative of the envelope of an emitted signal. A special technique was developed allowing one, based on the analysis of the amplitude of distortions in the received signal, to diminish an error of determining the target azimuth down to a few angular minutes.

Along the antenna's transverse axis (elevation angle direction in the antenna coordinate system) the radar DD is formed by adding in space the signals of two independent half-horns. Each half-horn has a rather broad DD (Fig. 2a) and high accuracy of determination of the angular coordinate of a location object can be achieved only with the interference method. As a result of performed technological modernization of the IISR, a possibility has appeared to record signals independently in each half-horn of the antenna and to measure a phase shift between them. The phase-elevation characteristic of the antenna was measured experimentally by observing such powerful cosmic source as radio galaxy Cygnus-A in the passive mode of cyclic scanning [4]. The resulting phase characteristic is shown in Fig. 2b. The slope of the phase characteristic of the IISR antenna is 16 electric degrees per one degree of the elevation angle, which ensures a high accuracy of measuring the elevation angle.

Determination of parameters of the ionosphere plasma. This is the basic type of IISR measurements [1]. Diagnostics of the ionosphere by the IS method is based on the radiolocation equation connecting the averaged spectrum of received signal with the spectrum of thermal fluctuations of the ionosphere plasma. Multi-parameter adjustment of these spectra is a complicated problem, often having no unambiguous solution. It is important to have a possibility of reducing the number of parameters in which the adjustment is made and to eliminate possible sources of errors. The new system of recording IS signals that retains the raw data of sounding gives a possibility of flexible and efficient application of different methods in off-line processing, of changing the time of data accumulation (from 40 s for the dayside lower ionosphere to 1 h in the night at 1000 km), and of elimination of coherent signals and interference from the ionosphere data. In particular, the

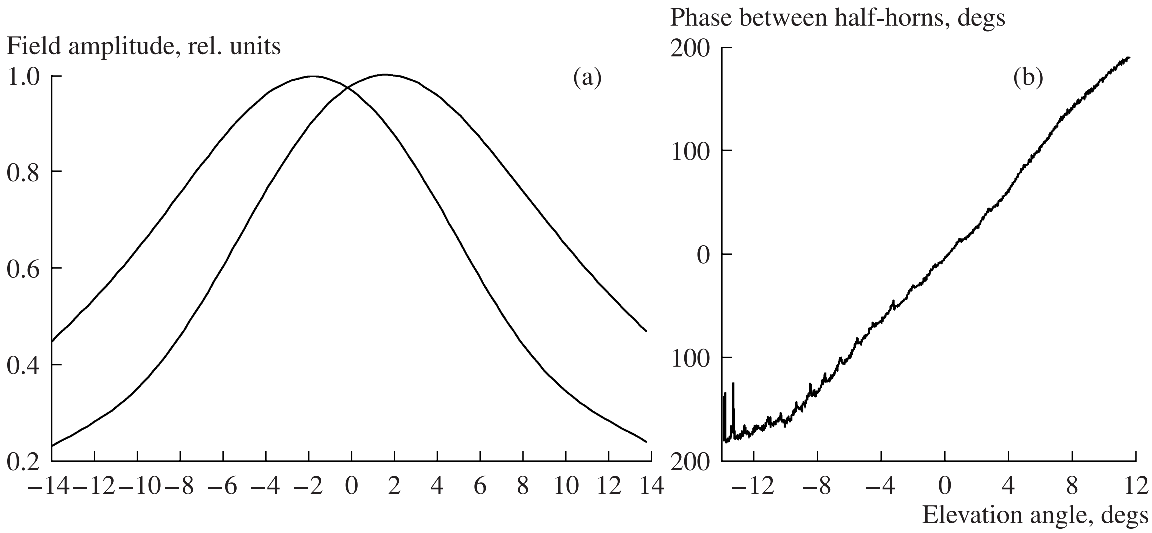

Fig. 2. The antenna directivity diagram in the plane of the elevation angle.

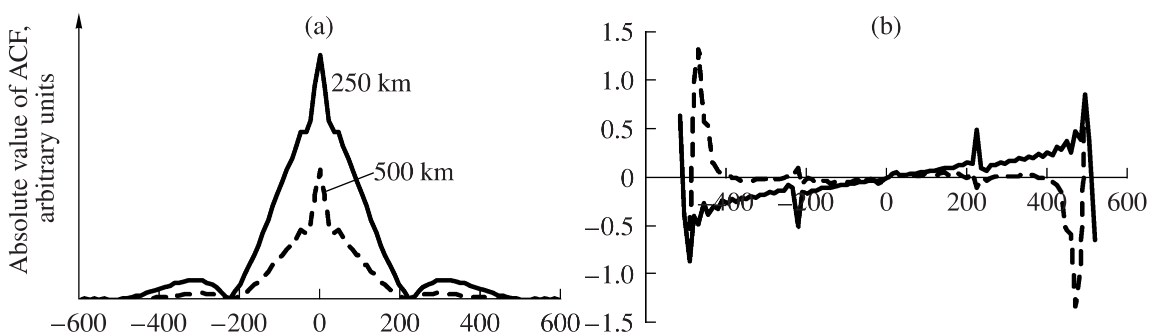

Fig. 3. Experimental auto-correlation function of IS signal averaged over 1000 realizations.

recording system allowed us to introduce a new method of determining the drift velocity of the ionosphere plasma. In usual practice of the IS method the Fourier transform of the IS spectrum (its autocorrelation function, ACF) is applied for this purpose. It is believed [6] that in the first approximation the plasma drift velocity can be determined, irrespective of other parameters, as an inclination angle of the ACF phase. This technique of determining the drift velocity using linear regression gave a large error at the IISR. It was established that nonlinearity of the phase characteristic of ACF due to asymmetry of the spectrum of IS signals (Fig. 3) was the main source of this error. At small values of the asymmetry coefficient and Doppler shift of the spectrum frequency their contributions to the ACF phase are additive and can be successfully separated in the context of the same method of linear regression. Processing of the experimental data has shown that the modified algorithm allows one to reduce several times the variance of determining the plasma drift velocity. Determination of these parameters by an independent method simplifies the problem of further fitting the spectra of IS signals, which, in turn, improves the accuracy of determining other parameters of plasma. Application of the new methods allows one to get basic characteristics of the ionosphere plasma virtually throughout the entire ionosphere thickness under various helio- and geophysical conditions. An example of the results of such measurements on September 11, 2005 is presented in Fig. 4.

Detection of anomalously strong CE signals. This type of observations is not new for the IISR [2]. These powerful signals are received by the side lobes of the radar DD from the northern direction, where the perpendicularity condition is met for the geomagnetic field lines and the emission direction. Origination of CE is associated with the development of plasma instabilities during strong geomagnetic events. A special regime of observations (with continuous scanning in a given frequency band) is used in order to localize the CE source and to study its aspect angle characteristics. Figure 5 presents an example of observation of a CE on November 10, 2004 at 10 frequencies in the frequency band

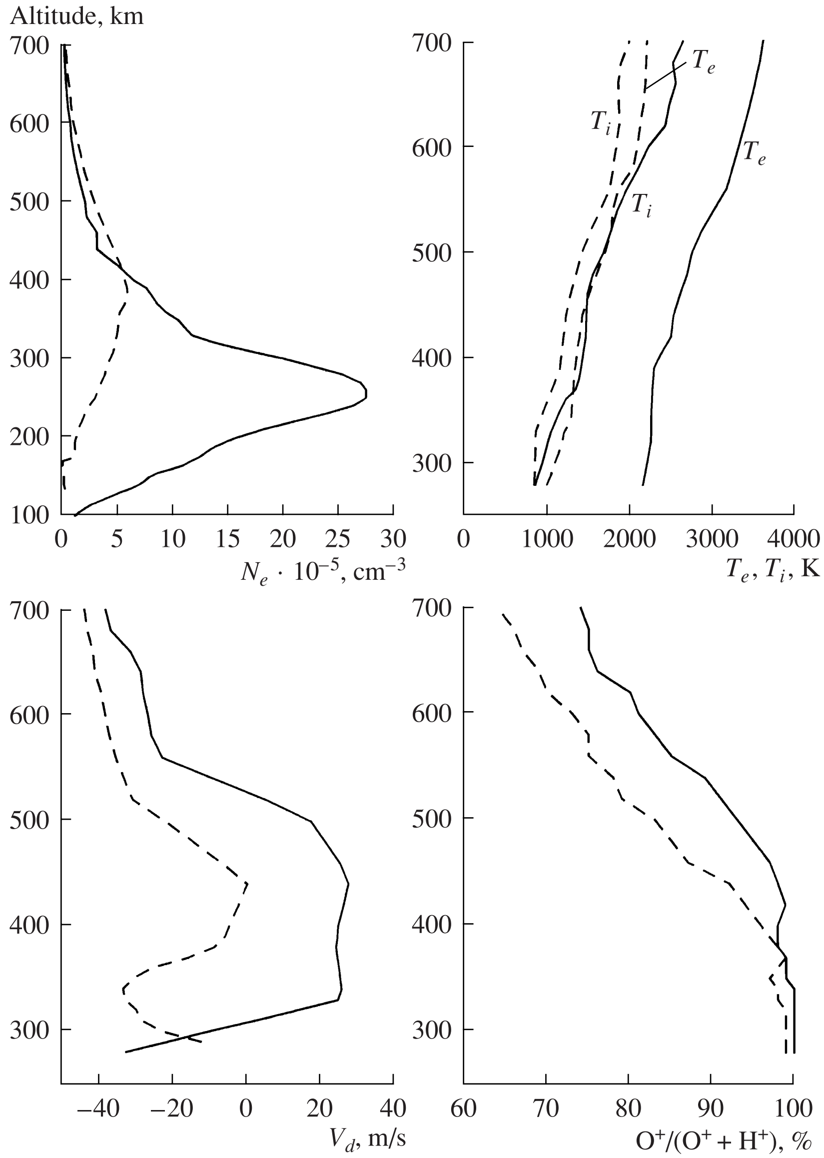

Fig. 4. Altitude profiles of the ionosphere parameters, solid and dashed lines represent dayside and nightside values, respectively.

from 159 to 160 MHz, Figs. 5a and 5b representing, respectively, the temporal dynamics of the CE and its power as a function of distance.

Investigation of space-time characteristics of MII. Based on the new capabilities of the IISR attained as a result of modernization and on inclusion into the analysis of the data of accompanying instruments, a method of determining space and time characteristics of traveling ionosphere disturbances (TID) was developed. In order to study TID it was suggested to join the data of three facilities of the radio-physical complex of the Institute of Solar-Terrestrial Physics of Siberian Branch of Russian Academy of Sciences: IS radar, ionosonde DPS-4, and LFM ionosonde (the regime of slightly inclined sounding) which form together an interferometer with a base of about 100 km, allowing one to determined parameters of TID of various scales. The method suggests the use of the data on the entire altitude profile of electron density, the capability of the IISR to get electron density profiles simultaneously in several directions (lying in the plane of scanning) being used in this case. A new method of cross-correlation measurements of the total vector of TID velocity [5] was developed and verified experimentally. Figure 6 presents the altitude profiles of electron density disturbances in the band of periods from 1 to 4 h as measured on September 11, 2005 by ionosonde (Fig. 6a), by the IISR along the normal to the antenna aperture (Fig. 6b, frequency 154 MHz), and by the IISR along the magnetic field line (Fig. 6c, frequency 158 MHz). The day selected for this illustration is outstanding among regular observations by its large amplitude of disturbances

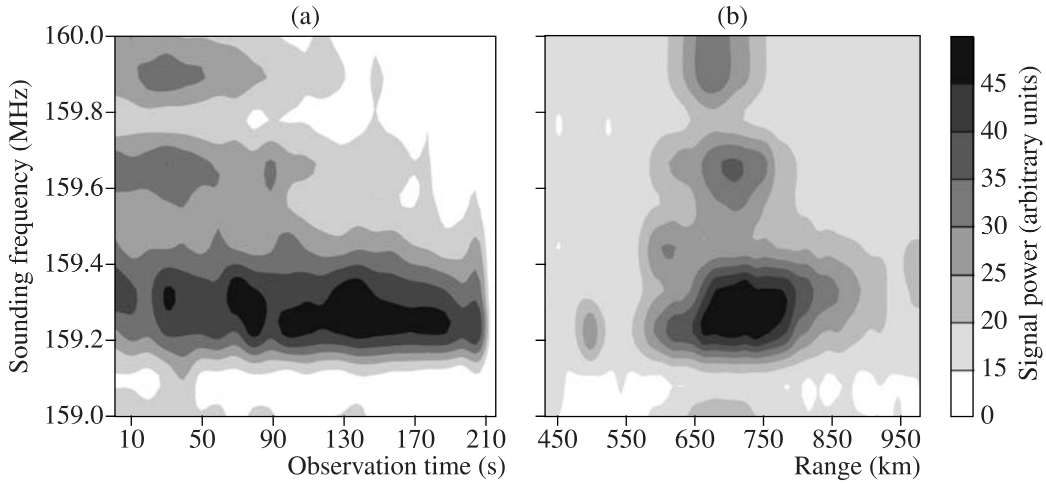

Fig. 5. Investigation of spatial characteristics of coherent echo with the IISR.

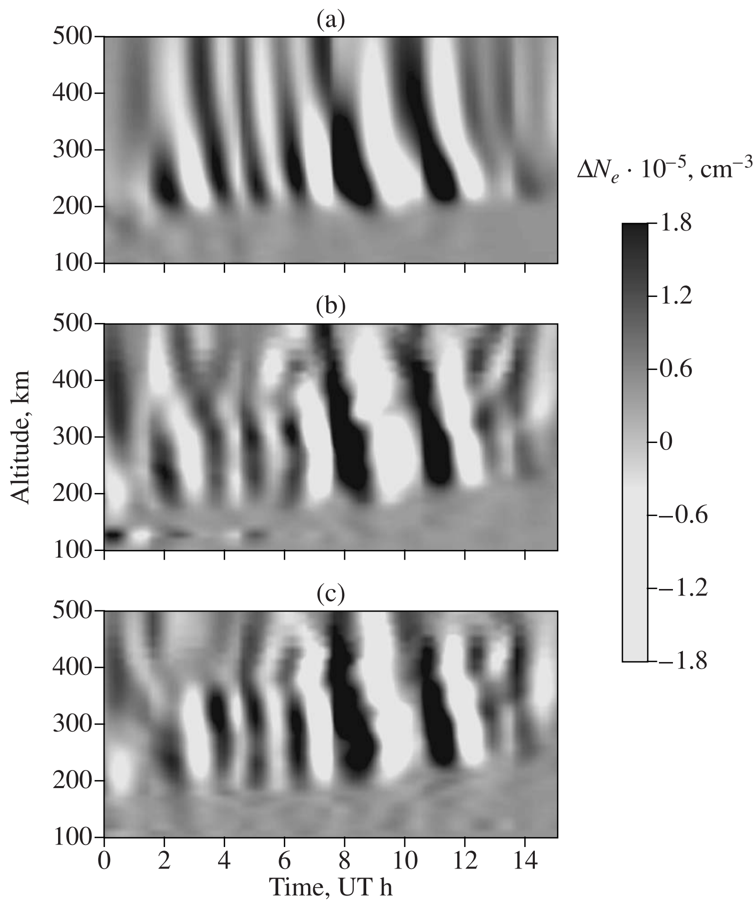

Fig. 6. Altitude profiles of disturbances of the electron density.

reaching more than 30% of the background density on the interval from 8 to 12 h of UT. The altitude-time structure of disturbances in Fig. 6 corresponds to the character of propagation of internal gravity waves in the upper atmosphere of the Earth.

Observations of space objects. They allow one to solve a number of interesting research problems, such, for example, as studying the effects produced in the ionosphere by operating engines of spacecraft on the orbital flight segment. Space objects are observed by the IISR in the capture–tracking regime. The following characteristics are measured in each cycle of sounding: distance R to a space object, radial velocity V_R, azimuth angle ε, elevation angle γ, and the amplitude of reflected

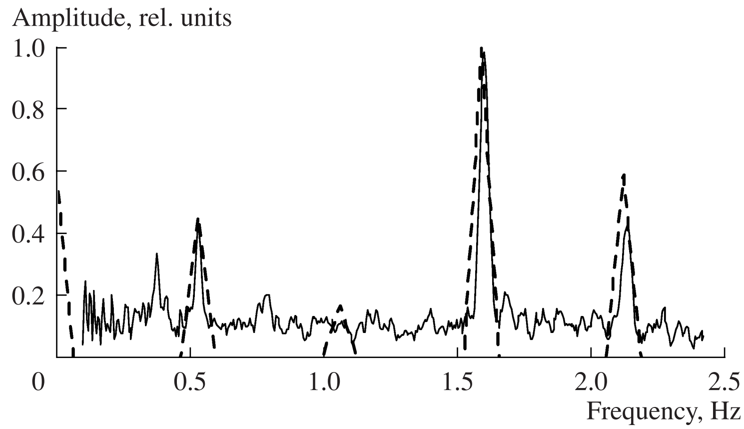

Fig. 7. Investigation of dynamics of amplitude variations of radio location signal from the *EGP* satellite, solid and dashed lines represent the experimental spectrum of signal amplitude dynamics and the signal spectrum in the two-point model, respectively.

signal. At sufficiently high signal-to-noise ratio (S/N > 10) typical mean root square deviations of measured parameters are as follows: for R, V_R, ε and γ they are equal to 100m, 10 m/s, 5 angular minutes, and 7 angular minutes, respectively.

Non-coordinate information obtained with the IISR plays an important role. In some cases the analysis of reflected signal amplitudes allows one to classify objects according to their reflectivity and to keep an eye on variations of the effective scattering surface area of objects depending on their aspect angle. Interesting results were obtained analyzing dynamics of the amplitude of radio location signal from the *EGP* geodetic satellite. This amplitude was unusual by its fast and strong variations. The spectral analysis has shown that the nature of these fluctuations is not of noise character. The spectrum has prominent frequencies and is stable from one passage of the given satellite to another, the ratios of amplitudes at these frequencies, as a rule, remain constant. In paper [3] it is shown that the model of two connected reflecting points spaced by a distance of $l = 2$ m (diameter of the satellite) is most suitable for description of such a behavior of radio location signal. The model allows one to connect the spectrum of signal fluctuations with the parameters of rotation of the *EGP* satellite by the following relationship:

$$\alpha = \arcsin\left(\frac{\lambda}{4\pi \cdot l}\arccos(J_0 - 2J_2 + 2J_4 - \ldots)\right),$$

where λ is the emission wavelength; $J_0, J_2, J_4 \ldots$ are the amplitudes of resonance frequencies in the spectrum of amplitude dynamics of the receiver signal. The experimental spectrum of fluctuations presented in Fig. 7 corresponds to the rate of spacecraft rotation 0.25 Hz at an angle of inclination of the rotation axis $\alpha = 85°$.

CONCLUSIONS

As a result of modernization, the Irkutsk ISR is transformed into a coherent multi-purpose radar with program control. The task of widening the diagnostic capabilities of the IISR was solved by putting into operation the radar's controlling and receiving-recording complex (CRRC), developed on the basis of present-day digital technologies. The high-precision digital multi-channel radio receiver with wider dynamic range, spectral band, and automatic control of through characteristics has become the key element of the CRRC.

The wider dynamic range and coherence of the radar allow us to isolate weak noise-like IS signals on the background of strong coherent signals reflected from mountains and scattered by plasma instability waves. This makes it possible to determine the ionosphere parameters by the IS method for altitudes of the middle and lower ionosphere (90–150 km), inaccessible before due to reflections from the mountains. This also gives a possibility to measure sharp and deep variations of the amplitudes of coherent echoes and to conduct measurements of IS signals simultaneously with parameters of coherent echoes and signals from spacecraft.

Widening of the frequency band allows one to improve the radar's spatial resolution in the ionosphere studies (to 1.5–3 km and a few tens of kilometers for the lower and upper ionosphere, respectively) by using complex coded signals and the correlation method of their processing. The accuracy of determining the distance to space objects can also be improved.

The increase of the number of receiving channels allows one to control the directivity diagram in the elevation angle, to realize the ionosphere inrferometric measurements, and to improve the accuracy of determining the spacecraft motion parameters.

The modern system of recording the IISR signals ensures storage and processing of 45 GB of data per day.

As a result of putting the CRRC into operation, potential capabilities of basic equipment of the Irkutsk radar are realized, and its parameters and diagnostic capabilities for performing effective studies in planned fundamental and applied research are substantially improved.

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