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A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held at the P L Kapitza Institute for Physical Problems on 22 April 1998. Three reports were presented at this session:

(1) **Shteĭnshleĭger V B, Dzenkevich A V, Manakov V Yu, Misezhnikov G** S (The Moscow Scientific Research Institute of Instrument Engineering, Moscow) "On overcoming the destructive effect of the ionosphere on the resolution of VHF transionospheric radar for remote sensing of the Earth";

(2) **Braginskiĭ V B** (M V Lomonosov Moscow State University, Physics Faculty, Moscow) "Decoherence and quantum measurements in a laser interference gravity-wave observatory";

(3) **Lozovik Yu E** (Institute of Spectroscopy, RAS, Troitsk) "Phase diagram and superfluidity of excitons and magnitoexcitons in double quantum dots".

An abridged version of the first report is given below.

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On overcoming the destructive effect of the ionosphere on the resolution of VHF transionospheric radar for remote sensing of the Earth

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Modern space-borne synthetic aperture radars (SAR) generate microwaves in the centimeter or decimeter wavelength ranges. Therefore they are unsuitable for detecting natural and some other objects hidden under the vegetation cover or in the subsurface layer of the Earth. Meanwhile these data are required to solve various economical and ecological problems.

The attenuation of radiowaves in the vegetation cover and especially in the subsurface layer of the Earth as well as backscattering of the waves from the vegetation cover are much less pronounced in the meter-wave range than in the microwave range. However, the use of these advantages of the meter-wave range in SAR requires radars of high enough resolution (of the order of several wavelengths) to reduce the backscattering from resolved elements of the objects on the terrain to a sufficient extent.

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As is shown in this connection [1], there is an optimal wavelength $\lambda_{\rm opt}$ at which the SAR capacity to detect objects (hidden under the vegetation cover or in the subsurface layer of the Earth) against the background of reflections from the terrain is maximum. For practically important cases the value of $\lambda_{\rm opt}$ is in the range of meters. Thus, for example, at the wavelength $\lambda = 2.5$ m and resolution $\sim 3\lambda$ one can safely detect an object with an effective scattering area 8 m^2, lying at a depth of 16 m beneath the Earth's surface in dry sand and at a depth of 1.5 m in wet sand (wetness 8%). While at the wavelength $\lambda = 0.6$ m and resolution 3λ a similar object can be detected only if its effective scattering area exceeds 60 m^2.

The desired high resolution can be attained in an aircraft SAR operating in the meter-wave range. However, it can hardly be achieved in a space-borne SAR of the same wave range because of the destructive influence of the ionosphere. Thus, phase distortions caused by dispersion of the rf pulse in the ionosphere may decrease the slant range resolution of a space-borne SAR operating in the range of 2 – 3 m down to $\sim$ 100 m [2].

On account of fluctuations of the phase of a signal during the interval of aperture synthesis (because the electron concentration is inhomogeneous in the ionospheric SAR-beam trace), the azimuth (cross-range) resolution of a space-borne SAR operating in the 2 – 3 m range, may be impaired up to several hundreds of meters [3]. Such low resolution, both in azimuth and slant range, appears inadequate for many practically important applications of the technique for remote sensing of the Earth.

The authors of [1, 4] demonstrated the possibility of overcoming these harmful effects and improving the resolution of a space-borne VHF SAR by adaptive processing of the signals received at the radar output. In this report we present the results of the semifull-scale modelling treatment using actual data obtained by an aircraft VHF SAR, actual records of ionospheric phase fluctuations of VHF signals as well as experimental data on ionospheric dispersion.

When a rf pulse passes through the ionosphere, it is subject to polarization and phase (due to phase dispersion) distortions, decreasing the SAR slant range resolution. If the emitted rf pulse has a circular polarization, the polarization distortions are negligible [2], therefore we will assume that the SAR receives rf pulses with circular polarization and will only allow for phase dispersion.

We suggest that the emitted signal is a rf pulse with intrapulse linear frequency modulation (LFM, or chirp), whose envelope is Gaussian, with deviation B during the pulse time T, mean frequency f_0, baseline $BT \gg 1$ and the chirp rate $\mu = 2\pi B/T$ (the chirp rate may be either positive or negative).

In the high-frequency approximation, the phase shift φ of the signal in the ionosphere proper can be presented as a Taylor power series in $\Omega = 2\pi(f - f_0)$, where f is the frequency, so that

$$\varphi = \varphi_0 + \varphi_0'\Omega + \varphi_0''\frac{\Omega^2}{2!} + \varphi_0'''\frac{\Omega^3}{3!} + \ldots \tag{1}$$

Here we introduced the notation

$$\varphi_0' = 1.34 \times 10^{-7} f_0^{-2} N_\Sigma;\ \varphi_0'' = -4.28 \times 10^{-8} f_0^{-3} N_\Sigma;$$
$$\varphi_0''' = 2.04 \times 10^{-8} f_0^{-4} N_\Sigma\,. \tag{2}$$

The quantity N_Σ is equal to the total number of electrons in the twice passed beam trace whose cross section is 1 m^2; the maximum value is $N_\Sigma \approx 10^{18}$ m^{-2}.

Dispersive phase distortions determined by second-order and higher terms of the series (1) can be compensated for in receiving the pulse if the phase characteristic of the dispersion filter (compressing the LFM signal) in the receiver or the reference function of digital compression are adjusted not with the emitted signal but with the received one which has passed through the ionosphere.

In the first approximation taking into account only the second-order phase distortions in Eqn (1), the group time delay τ in the adjusted filter will be written as

$$\tau \approx t_F - \left[\frac{1}{\mu} - |\varphi_0''|\right]\Omega = t_F - D_F\Omega\,, \tag{3}$$

where t_F is a frequency-independent time delay, $D_F = 1/\mu^*$ is the filter dispersion coefficient, and μ^* is the chirp rate of the received LFM signal.

Thus, for example, in the VHF range at the carrier frequency $f = 120$ MHz ($\lambda = 2.5$ m), the first approximation holds good up to the deviation $B_1 \cong 15$ MHz; the second approximation, which allows for third-order distortions as well, holds good up to the deviation $B_2 \cong 30$ MHz. In these approximations, the resolution is $\Delta r_1 \approx 15$ m and $\Delta r_2 \approx 7.5$ m, respectively.

Since it is impossible to know N_Σ *a priori* with the desired pinpoint accuracy, one should self-adjust the parameters of the dispersion filter (coefficients of the reference function in digital processing) using an appropriate criterion for assessing the quality of compressed signals at the output of the processing system. The dispersive distortions of the SAR signal phase should be compensated together with fluctuation distortions of the phase at the aperture, i.e. the compensation should be two-dimensional with regard to the slant range and azimuth.

The compensation of azimuth phase distortions caused by ionospheric fluctuations (i.e. one-dimensional compensation) with the use of an algorithm for phase-gradient autofocusing (PGA) [5] is dealt with in Refs [1, 4].

Below we consider simultaneous compensation of both dispersion and fluctuation distortions, i.e. two-dimensional compensation of ionospheric distortions.

For the sake of definiteness, we restrict ourselves to only the second-order term in Eqn (1), accounting for dispersion distortions. Using *a priori* data on N_Σ, we suppose that there are n dispersion filters (n reference functions in digital processing) with various values of the dispersion coefficient D_F (3) for a rf pulse compressed with respect to slant range.

For each D_F out of n values, the SAR LFM signal is compressed with respect to slant range and azimuth. Then the optimal $D_F = D_{\rm opt}$ is selected. One way to select $D_{\rm opt}$ is the following: azimuth distortions due to the phase fluctuations (see Ref. [1]) are initially compensated for by conducting some operations inherent in the PGA algorithm. Then the value $D_F = D_0$, for which the total intensity of the most intense signals over all range channels [1] has a maximum, is selected from the available n values of the dispersion coefficient D_F. If the intervals between the values of D_F correspond to large phase jumps, then after the above-indicated procedure D_F is somewhat varied around D_0 and eventually one selects the value of D_F at which the total intensity peaks. This realization corresponds to the optimal value $D_F = D_{\rm opt}$.

Then for the selected optimal value $D_F = D_{\rm opt}$ one compensates for azimuth distortions of the phase fluctuations in the ionosphere, as described in [1].

Another way to compensate for dispersive phase distortions studied in this report is as follows. After determining D_0 (see above), one may not vary D_F but reduce the dispersion distortions using slant range PGA algorithm, by analogy with the azimuth PGA algorithm described in [1].

In compensating the azimuth phase fluctuations using PGA algorithm it is important to know the size of the region of spatial invariance of the phase error, i.e. the size of the region on the terrain of which all points have the same phase error (with an accuracy to the admissible small value $\delta\varphi$). We gave in Ref. [1] a formula to calculate the size of this region.

In the semifull-scale experiment presented below we use radar images and digital data for actual complex signals obtained by an aircraft SAR 'Imark' operating at the wavelength $\lambda \cong 2.5$ m [1]. The slant range resolution of this SAR was about 15 m, the azimuth resolution comprised 8 – 10 m, the width of the emitted pulse $T = 6.4$ μs, and the LFM deviation was $B = 10$ MHz.

Assuming the resolution of this SAR to be similar to that of a hypothetical space-borne SAR operating in the same wave range (the height of the orbit is 600 km), the time of aperture synthesis in both SARs appears approximately the same.

In the digital data obtained by the aircraft SAR we introduced (in the frequency range) dispersive phase distortions of the radio signal corresponding to the second-order term in Eqn (1) with maximum phase shift at the spectrum edge $\Delta\varphi \approx 50$ rad (at the given bandwidth this corresponds to a widening of the short pulse by ~ 6 μs).

Azimuth phase distortions caused by ionospheric fluctuations were corrected as in Ref. [1], by recording a coherent signal at frequency 137 MHz from a satellite with orbit $H = 1000$ km, recounted for the SAR with the orbit $H = 600$ km. The root-mean-square value of 'fast' phase fluctuations was around 3.2 rad.

The experimental study of the two-dimensional compensation described above included the following stages.

First, the signals were compressed in the frequency range with respect to azimuth and slant range for nine values of the dispersion coefficient D_F, uniformly overlapping the possible dispersion distortions in the ionosphere.

Then the aperture was synthesized in all the range channels for each magnitude (out of 9) of the slant range compression. The synthesis was performed by a harmonic algorithm [1].

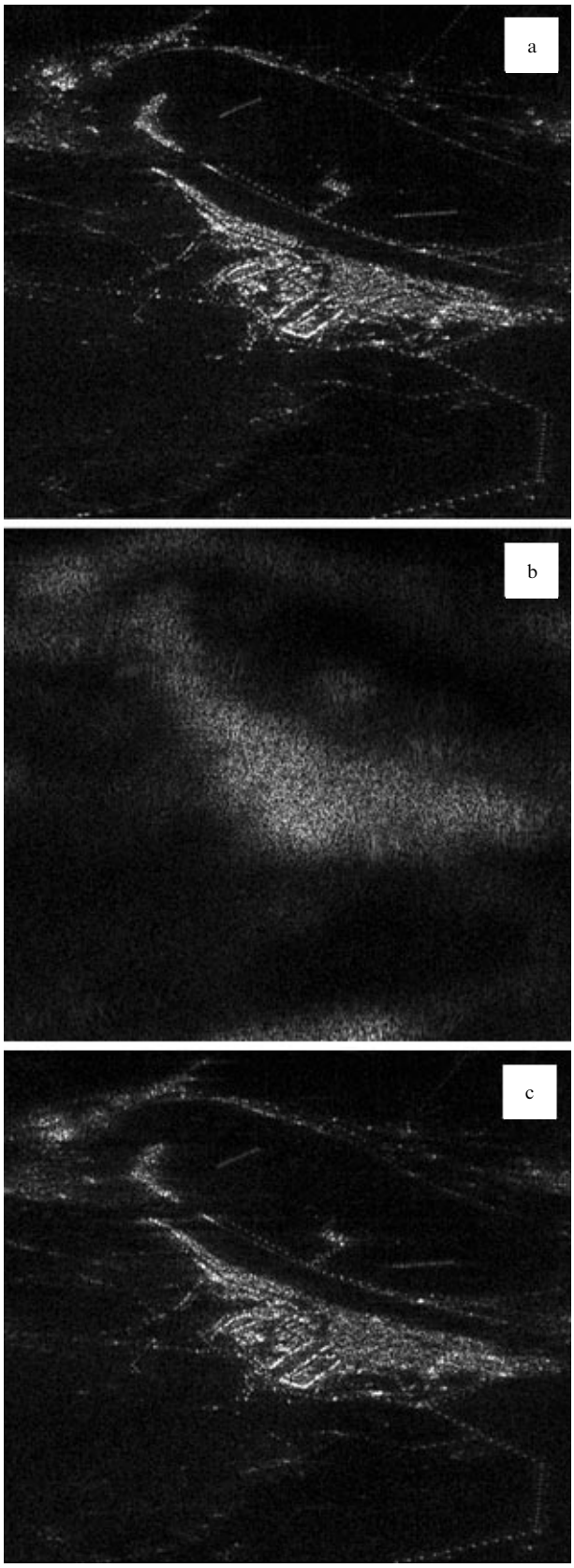

Figure 1. Radar images of a city region: (a) with no ionospheric distortions; (b) after introduction of dispersion and fluctuation phase distortions in the ionosphere; (c) after the two-dimensional adaptive compensation of the distortions.

Then the optimal slope $D_{\rm opt}$ of the reference function was determined, as described above.

The two values of D_F (D_1 and D_2) closest to the optimal value were selected from the set of nine values used, according to the above-indicated criterion.

The interval between the chosen values D_1 and D_2 was divided into three parts, and then a value of D_F, satisfying the above criterion of the maximum of total intensity, was selected from four values lying in the range from D_1 to D_2. This was the optimal value $D_{\rm opt}$.

For the adopted variant of slant range compression at $D_F = D_{\rm opt}$, we performed azimuth autofocusing using the PGA algorithm, as described in Ref. [1].

Figure 1 shows radar images of a city region obtained by this treatment. Figure 1a corresponds to the initial radar image produced with the SAR 'Imark' at a wavelength of 2.5 m, while Fig. 1b presents the radar image after introducing dispersion and fluctuation phase distortions in the ionosphere. Figure 1c demonstrates the radar image after the two-dimensional adaptive compensation of the distortions. The images in Fig. 1a and Fig. 1c differ little from each other.

Some radar images were also obtained using a second above-described method of compensation of dispersion distortions by phase-gradient autofocusing with respect to slant range. The images obtained by the two methods are quite similar. However, the quality of radar images obtained by direct application of slant range PGA algorithm with no preliminary sorting of values of the dispersion coefficient D_F for determination of D_0 was worse than for those obtained after sorting out as indicated.

Conclusions

The results obtained testify to the efficiency of the suggested two-dimensional adaptive compensation of ionospheric dispersion and fluctuation distortions of space-borne VHF SAR signals. This offers possibilities for remote sensing of the Earth with a transionospheric VHF SAR possessing increased ability to penetrate through the vegetation cover and subsurface layer of the Earth. Designing such a SAR will enable a number of important ecological and economical problems to be solved.

References

1. Shteĭnshleĭger V B et al. *Radiotekh. Elektron.* **42** 725 (1997)
2. Enert P, in *Colloque Intern. Radar Int. Conf.* "*Radar 94*" (Paris, 1994) p. 512
3. Kretov N V et al. *Radiotekh. Elektron.* **37** 90 (1992)
4. Shteinshleiger V et al., in *Europ. SAR Conf.* "*EUSAR-96*" *Record* (Kenigswinter, 1996) p. 321
5. Wahl D et al. *IEEE Trans. Aerosp. Electr. Syst.* **30** 827 (1994)