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High-resolution lightweight dual-frequency aircraft synthesized aperture radar for remote-sensing of the Earth: implementation experience and development prospects

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Abstract. A prototype of a dual-frequency aviation synthetic aperture radar station for remote sensing of the Earth, suitable for use on light-engine and unmanned aerial vehicles, is described. The system's concept, main technical solutions, and results achieved in the creation of onboard equipment are considered. The results of flight tests of the SAR prototype carried out in 2019 are presented. The characteristics of the radar survey are described. Possible ways of further development of the system are discussed.

1. Prerequisites for the creation of a new remote-sensing radar system and its concept

The key quality of synthesized aperture radar (SAR) systems of Earth remote-sensing (ERS) is their informativity [1]. The need for a new aviation SAR became clear with the expansion at the end of 2015 of the World Conference on Radio Communications dedicated to the remote-sensing portion of the spectrum in the X-band from 600 to 1200 MHz [2], since the sounding signal with a double-spread spectrum is able to double the radar image's spatial resolution. Looking ahead, we note that one of the directions of development of this system is aimed at increasing the information content by measuring the polarization properties of the probed earth covers.

Another important development trend in aviation SARs is the development of the use of unmanned aerial vehicles to solve several practical problems by the government of the Russian Federation. An example of developments in this direction is the Taiga Project *for the* creation of a pilot UAV operation area that is being implemented in the Tomsk Region with the participation of the Russian Foundation for Applied Research on the initiative of the Tomsk Region Administration [3 -5]. State University of Control Systems and Radioelectronics (TSUCSR) and Micran JSC Research and Production Company are participating in this project.

SAR is one of the main subjects of the Research Institute of Precision Instruments (RI PI, Moscow, Russia), one of the leaders in the space industry in Russia [6]. In addition to the traditional field of space AFAR, traditional for the research institute, since the 1990s, the development of aviation SAR has been carried out. The basis of the concept of experimental “compact” SARs is the separation of shooting and processing, as in space systems, the installation of SAR antennas in the cabin and their operation via the aircraft's windows [6]. The "compact" system was created in the early 2000s in cooperation with RI PI (algorithms and software, system integrator), Mikran (microwave electronics) and other organizations. By the end of 2015, the development of "compact" SAR was completed by the introduction of an on-board navigation system having micro-navigation features that allowed it to be successfully installed on a helicopter [7].

This paper presents the results of a project on the development and study of a new dual-frequency radar station for remote-sensing of the Earth designed to be used on light-engine and unmanned aircraft platforms [8-10].

2. Main goal of development, technical requirements for the system, main problems of technical implementation

The main objective of the project was to create two prototypes of dual-band remote-sensing SAR operable on the light-engine aircraft vehicle (LAV) of an unmanned aircraft (UAV) that should improve the quality of synthesized SAR radar images, characterized by the limiting spatial resolution of not more than 0.3 m in the X-band and 0.5 m in the L-band, as well as having a mass of not more than 12 kg per set of on-board radar equipment of each range (excluding on-board computers). It was important to carry out separate flight tests of both SAR samples.

The spatial resolution of the oblique range is increased by expanding the signal bandwidth up to 1000 MHz in the X-band (respectively, up to 0.3 - 0.15 m) and up to 300 MHz in the L-band (respectively, up to 0.5 m), and azimuth permissions – an increase in the number of coherently processed pulses (an increase in the synthesis time).

An increase in spatial resolution results in the decrease of the radiometric resolution, one of the main parameters of radar images in the analysis of spatially distributed objects. For aviation applications of SAR, where the signal / noise ratio usually is large, this drawback is not critical. It is possible to achieve an increase in the target contrast radar in this case due to an increase in SAR energy by raising the average radiation power (increasing the pulse power of the signal and / or reducing the signal duty cycle) and increasing the antenna gain.

The flight modes of the aircraft – the SAR carrier, were limited in height within the range from 0.1 to 6.0 km above the earth's surface, the maximum flight altitude above sea level – 6 km, in speed – in the range from 80 to 400 km / h, by change of aircraft speed not more than 5%, by acceleration not more than 0.1g (0.98 m / s^2) in each direction, by accuracy of maintaining the angular orientation of the aircraft by roll, drift and pitch angles not worse than ± 2 °.

The following parameters of the radar survey were set: the maximum size of the monitoring area is 30 x 30 km^2; the maximum size of the capture band in each radar channel is 8 km, the interval of angles of sight in the vertical plane is 25 - 75º, the interval of working ranges is 1000 ... 10000 m.

The system was designed to contain an airborne segment and a ground segment. The onboard segment of the SAR included transceivers and antennas of the X- and L-bands, two on-board computers and a navigation receiver with micro-navigation functions. The ground segment of the SAR consisted of a remote-sensing data processing center.

The energy potential of the SAR was mainly determined by the power of the probing signal, since the directivity characteristics of the antennas are associated with the spatial resolution of the SAR and the noise figure of the receiver cannot be reduced arbitrarily. In both frequency bands, a complex radio-pulse signal with an intrapulse chirp was used. In our case, the maximum radio pulse duration was set to 60 μs, and the minimum duty cycle – 20. The maximum pulse output power at the antenna input was set to at least 250 watts.

There is an obvious contradiction between the need to increase the energy potential and the equipment weight limitations. Considering the need to rebuild all SAR units due to the expansion of the width of the sounding signal spectrum (transceivers, digital processing equipment and the generation of radar signals and antennas), this project can be called a completely new design.

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3. Basic technical solutions

The need to simultaneously solve the conflicting tasks of increasing the energy of SARs while expanding the spectrum width of the probing signal with mass limitations has led to the application of new technologies in SARs. We shall consider the technical features of the main components of SAR. The frequency-generating scheme was chosen by direct conversion with a vector quadrature modulator and a microwave carrier quadrature demodulator, as the most wide-band [8].

Several antennas have been developed for SAR. In the X-band, a small-sized light (650 g) mirror antenna was developed (figure 1, left) and an antenna with a cosecant beam pattern (figure 1, right). The dimensions of the compact antenna are 142 x 256 x 167 mm. Its weight is 650 g.

Figure 1. Appearance of X-band SAR antennas. Lightweight reflector antenna (left) and a cosecance pattern antenna (right).

Figure 2 on the left shows the shape of the beam in the elevation (E-) plane of the X-band cosecant antenna. The same figure on the right shows the vertical polarized L-band antenna.

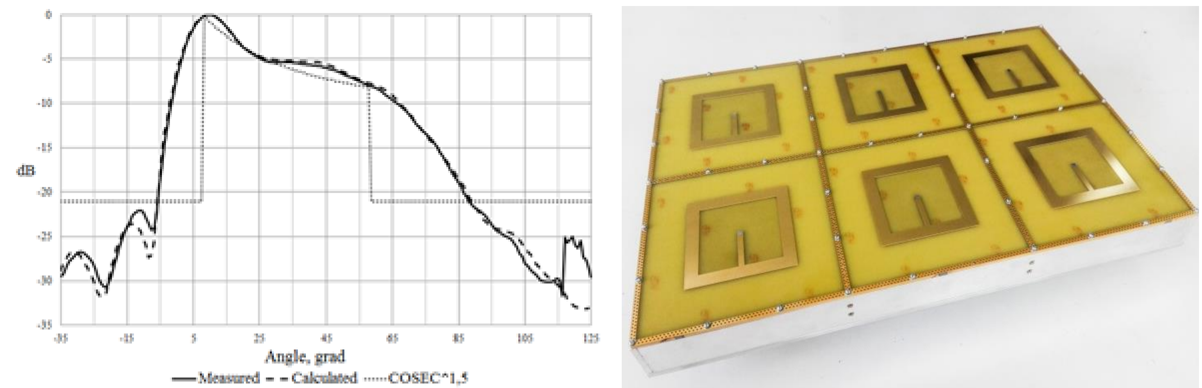

Figure 2. Directivity characteristics of antenna m with cosecant beam pattern (left). Appearance of antenna of the L-band vertical polarization (right).

The powerful output stages determine the mass of the onboard microwave transceivers. The reduction in mass and dimensional indicators is ensured by the use of output GaN transistors in the output stages of transmitters of both ranges. The X-band transmitter has a block-modular design, and is built according to the scheme of summing the power of many small-power cascades [9]. The L-band transmitter has a single-stage cascade on one powerful GaN transistor.

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The PCA digital core was implemented on the basis of industrial computers in the 6U horizontal CompactPCI form-factor (supplier of RTSoft JSC, Moscow), equipped with DSP expansion modules (supplier of Instrumental Systems JSC, Moscow) [10]. Figure 3 on the left shows the appearance of a unified on-board computer. The on-board computer software was fully developed by RI PI specialists.

The new navigation receiver allowed to determine the coordinates at a rate of 50 counts / sec with an accuracy of 3.3 mm SD, as well as the drift angle. Sensors include a miniature 3V gyroscope, a 3D accelerometer and a 3D magnetometer (compass). Figure 3 on the right shows the appearance of the navigation receiver board with micronavigation features.

The ground-based radio hologram focusing system was a high-performance laptop with an 8-line processor having 64 GB of RAM. The software was also developed by RI PI specialists.

Figure 3. Appearance of a unified on-board computer with expansion modules (left) and an on-board navigation receiver with world navigation functions (on the right).

4. Flight tests of SAR ERS models and the achieved performance of the SAR prototype

The flight tests were carried out using the laboratory airplane Il-18D board #7 5713 (Mir airline LLC) in late June - early July 2019 at the Ukhta and Petrozavodsk airport and on a flight between them. Figure 4 shows the onboard SAR ERS equipment in the flying laboratory cabin.

Figure 4. SAR ERS equipment in the flying laboratory cabin: X-band left, L-band right. Digital cores on top of transmitters.

On the first SAR model, the minimal target limit resolution (0.3 and 0.5 m) was achieved, equipment defects were found, and more than 100 high-quality radar images were obtained. Figure 5 shows the X-ray and L-band radar data from Petrozavodsk obtained during summer flights.

During the second test involving flights at Talagi Airport (Arkhangelsk) at the end of November 2019, a second SAR model was tested with two versions of the SAR on-board equipment software. With

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the first version of the software on the Arkhangelsk - Naryan-Mar - Arkhangelsk flight, the results obtained in the summer were confirmed, the absence of problems identified in the summer with L-band equipment was recorded, and the radar aerial survey was conducted from a height of 6 km.

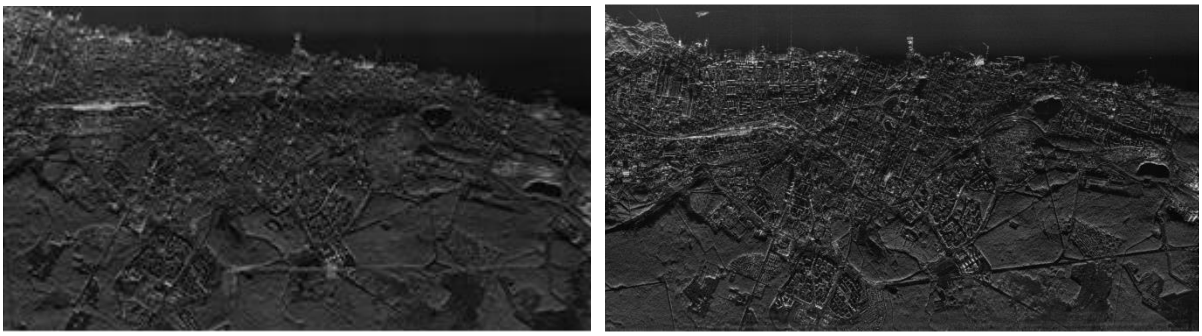

Figure 5. Radar images of Petrozavodsk obtained during flight tests of the first SAR prototype in the summer of 2019: X-band (left) L-band (right).

During the second part of the flights with new software, the expected maximum resolution of 21 cm in the X-band was reached. An example of radar images from the second flight test is shown in figure 6. When examined in detail, the image of railroad tracks (figure 6, right) contained a collection of reflections from the heads of crutches of rail fastenings having a hemi-spherical shape. The SAR resolution (21 cm) allowed us to observe this feature.

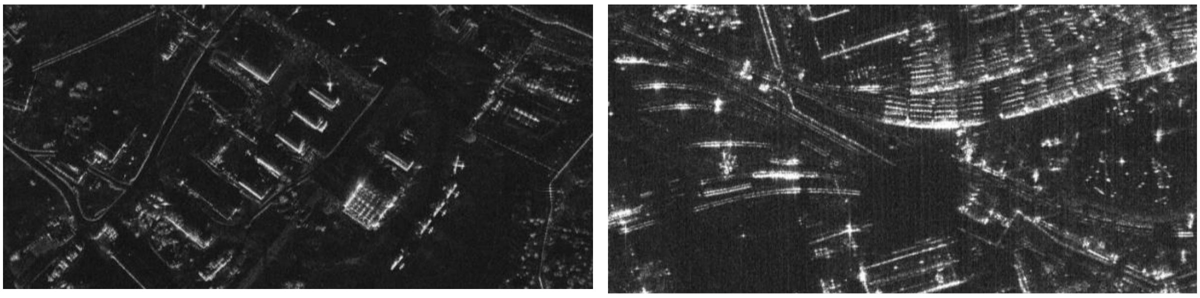

Figure 6. Fragments of radar images obtained during the tests of the second SAR prototype in winter 2019 Naryan-Mar, An-2 parking lot (top) X-band, signal spectrum width 600 MHz resolution 27 cm. Severodvinsk, railway station (bottom): X- range, signal width 1 GHz. 21 cm resolution.

The achieved main indicators of the new SAR partially exceeded the design requirements: the limiting resolution in the X-band was 0.21 m (in the L-band 0.5 m), the mass of the L-band equipment was 8.4 kg (in the X-band 12 kg) , and the swath width was 8.4 km.

5. Prospects for further development of the system

A prototype RSA ERS for light-engine and unmanned aircraft was created and tested.

The main prospect for the development of this SAR, in addition to design improvements aimed at reducing size and weight, is in further increasing its information content. Besides a small expansion of the probing signal spectrum width from 1000 to 1200 MHz, the reserve for this mainly consists in switching from a scalar to a vector-probing signal, which will allow to extract information on the polarization properties of each element of the radar image.

The technical implementation of the correct estimation of a mono-static backscattering matrix (BSM) of a fluctuating radar object was studied in the early 1990s by European researchers [11] and scientists from Russia who subsequently developed a rigorous theory [12]. Simultaneous estimation of all BSA elements will require the development of more complex on-board equipment. However, the current level of technology achieved when creating our prototype aviation SAR will allow creating a polarimetric SAR from already-developed microwave and digital units.

The relevance of the completed project has markedly increased: at the time of writing of this article, it became known that the Taiga Federal Project had been launched in the Tomsk Region [13]. Therefore, the second direction of development – the creation of a more compact version of the SAR with preservation of resolution, but with a reduced flight ceiling (and hence a reduced maximum range), may also become relevant.

6. Conclusion

A prototype SAR ERS for light-engine and unmanned aircraft was created and tested twice.

By the time of writing of this article (six months after the completion of the research), contracts between Micran and RI PI with customers had been started.

In terms of the totality of indicators, the SAR ERS prototype is one of the best in Russia that closely resembles the best samples of foreign production, surpassing them in the swath width when shooting with the maximum spatial resolution.

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