High-resolution experimental dual-wavelength remote sensing synthesized aperture radar: technical appearance and flight test results

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Abstract A model of new high-resolution two-wavelength aviation synthesized aperture radar (SAR) for remote sensing of the Earth, technical appearance of the system and indicators achieved are presented in the article. The technique and results of conducted flight tests of the SAR prototype as well as examples of obtained radar images are given in the work. The achieved new SAR performance at spatial resolution was equal 0.21 m and 0.5 m in X- and L-band respectively with a viewing bandwidth at a maximum resolution of 8.4 km. In the light of the development of the use of UAVs in Russia, it is concluded that the creation of a compact version of high-resolution SAR with a reduced flight ceiling and maximum range is relevant.

Keywords: remote sensing, synthesized aperture, high resolution radar, flight testing technique

1. Introduction
The information content of any radar system, and the experimental radar system in particular, is the main indicator of its quality [1]. The information content is directly related with the spatial resolution increase of the radar image generated by the synthetic aperture radar (SAR) due to the possible expansion of the spectrum of the sounding signal since 2015 [2], as well as the simultaneous remote sensing at different electromagnetic wavelengths.

In addition to the technical appearance of the new aviation dual-frequency radar station for remote sensing of the Earth, the article presents methodically important results related to its flight tests and the technical characteristics achieved during them.

2. Main goal of the project and its participants
In a successful university project carried out jointly with an industrial partner, the goal was to create an operable model of remote sensing SAR that is light enough for use in light-engine aircraft (LEA) and unmanned aerial vehicle (UAV), and at the same time to give high-quality radar images with a spatial resolution of at least 0.3 m and 0.5 m in the X- and L-bands, respectively, with weight restrictions. The most important part of the conducted research was the flight tests of the SAR model.
Spatial resolution at X-band is increased up to 0.3-0.15 m respectively by extending the spectrum width of the probing signal to 1000 MHz, and to 300 MHz in the L-band, which gives resolution up to 0.5 m. At such spatial resolution increases, the radiometric resolution decreases, this is one of the main parameters of radar image (RI) which is most important in the analysis of spatially distributed objects. For aviation applications of SAR, where the signal-to-noise ratio is usually high, this disadvantage is not critical. An increase in the target contrast RI in this case is possible due to an increase in the energy potential of the SAR by increasing the average irradiation power and SAR antenna gain.

The subject of the SAR is one of the main topics for the Research Institute of Precision Instruments (RIPI) (www.niitp.ru) – one of the flagships of the space industry in the Russian Federation. In addition to the traditional space active phased array antenna (APAA) field of interests for RIPI since the 1990s an aviation SAR has been carried out. Concept of the experimental SAR of the “Compact” family is based on the separation of the survey and processing processes, similar to space systems. The “Compact” system was created in the early 2000s in RIPI (algorithmic and software) in cooperation with SC NPF Mikran (microwave electronics) and other organizations. The development of the “Compact” SAR was finished in 2015 with the introduction of an onboard navigation system with the functions of world navigation, which allowed it to be successfully installed on a standard helicopter [3]. In recent years, many highly informative on-board SAR systems have appeared [4-7], as well as in the world as a whole, that indicates the relevance of systems of this type.

3. Technical requirements for the system and the main problems of implementation

The flight modes of the SAR carrier aircraft corresponded to modern light aircraft carriers, and were limited in altitude - in the range of 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 of 80 to 400 km/h, in the speed change of the aircraft no more than 5 %, in acceleration no more than 0.1 g (0.98 m/s²) in each of the directions, in the accuracy of maintaining the angular orientation of the aircraft in roll, drift and pitch angles no worse than ±2°.

The specified parameters are the maximum size of the monitoring area of 30×30 km²; the maximum size of the capture band in each radar channel is 8 km, the range of viewing angles in the vertical plane is 25-75°, the operating range is 1000...10000 m.

The SAR equipment is structurally divided into onboard and ground segments. The onboard segment included X- and L-band transceivers and antennas, two onboard computers, and micro-navigation equipment. The ground segment of the SAR consisted of a radar sensing data processing point, which was supposed to be mobile. This separation is associated with the performance of focusing radiogolograms not during the flight, but on the ground, because the performance of existing onboard computers does not allow processing at a speed comparable to the speed of recording primary radar image data.

The energy potential in both frequency bands was set by the requirements for the probing radio pulse signal with an intra-pulse linear frequency modulation (LFM). The maximum duration of the radio pulse was set to 60 microseconds at minimum duty cycle of 20. The maximum pulsed output power at the antenna input was set to at least 250 watts.

4. Overview of the main technical solutions determined the appearance of the new SAR

The need to simultaneously solve the controversial problems of increasing the energy of the remote sensing system while simultaneously expanding the width of the spectrum of the sounding signal with a limited mass has led to the use of new technologies in remote sensing systems. We will reveal the technical features of the main nodes of the SAR. Due to the wide relative frequency band of the probing radar signal, a direct-transform frequency-formation scheme with a vector quadrature modulator and a microwave carrier demodulator was chosen.

4.1. Antenna system of the new aviation SAR

Several antennas have been developed for the new SAR: a small-sized light (650 g) mirror antenna for X-band (fig. 1,a), and a 6-element array for L-band (fig. 1,b).
Figure 1. Appearance of SAR antennas: (a) light X-band mirror antenna; (b) L-band antenna.

The dimensions of the compact antenna are 142×256×167 mm, its weight is 650 g. The mass of the X-band antenna (Fig. 2,a) with the cosecance-square diagram is 2.5 kg. Figure 2,b shows that the shape of the antenn pattern in the angular E- (vertical) plane is close to cosec 1.5.

Figure 2. Antenna with the shape of a radiation pattern with a cosecans-square: (a) appearance; (b) directional characteristics in the vertical (E-) plane.

4.2. Receiving and transmitting microwave paths

It is the powerful output stages that determine the mass of the onboard SAR transceivers. The reduction in weight and size parameters is provided by the use of GaN output transistors in the output stages of transmitters of both bands. L-band transmitter (Figure 3) has a single output stage based on a power GaN transistor.

Figure 3. Top view of the design of a powerful output amplifier of SAR L-band (cover removed).
The X-band transmitter has a block-modular design and is built according to the power summation scheme of a set of low-power cascades.

4.3. Onboard control equipment for SAR and digital generation of radiation signals and radar response processing
The digital core of the SAR (Figure 4) was implemented on the basis of imported industrial computers in the CompactPCI design, equipped with domestic DSP expansion modules (supplier of JSC Instrumental Systems).

![Figure 4. Appearance of the unified onboard computer with installed DSP expansion modules.](image1)

![Figure 5. Appearance of the onboard navigation receiver with micro-navigation functions.](image2)

4.4. Onboard air navigation system
The new navigation receiver (Figure 5) made it possible to determine the coordinates at a rate of 50 samples/sec with an accuracy of 3.3 mm rms, as well as the drift angle. The sensors include a miniature 3D gyroscope, a 3D accelerometer, and a 3D magnetometer (compass). The software continuously solves the navigation problem of determining its own parameters using several spatial and angular coordinates in real time. The complexity of the implemented algorithms is characterized by nineteen functioning Kalman filters.

4.5. Radio hologram focusing system
It was a high-performance laptop with an 4-core 8-thread processor with 64 GB RAM. The software was also developed by specialists of the RIPI.

5. Methodological features of flight testing
Tests of SAR models were done at all stages. The main features of conducting flight tests are:
1. Testing the operation in a range of flight conditions, primarily altitudes and speeds
2. Testing the operation in different climatic (seasonal) conditions
3. Verification in the conditions of the Russian North region
4. The use of built-in tools for focusing radio-holograms to determine the characteristics of the received radar images

   Figures 6 and 7 show examples of determining system parameters such as spatial resolution (Figure 6) and the width of the capture band (Figure 7).
6. Features and results of flight tests
The tests were carried out using the IL-18D fly laboratory.

6.1. The first stage of flight tests – the summer season
Test flights were conducted in late June - early July in the surrounding area of Ukhta and Petrozavodsk airports and on flights trace between them. Figure 8 shows the onboard SAR equipment installed in the front cabin of the flying laboratory. Both antennas were located in the cabin and worked for study-reception through the windows of the aircraft.

In the first model of the SAR, the minimum target limit resolution of 0.3 and 0.5 m in the X- and
L-band was achieved, respectively, the shortcomings of the equipment were identified, and more than 100 high-quality radar images were obtained. Figure 9 shows the X- and L-band radar images of Petrozavodsk obtained during summer test flights.

![Figure 9. Radar images of Petrozavodsk obtained at flight tests of the SAR in the summer season](image)

(a) X-band; (b) L-band.

6.2. The second stage of flight tests – the winter season

During the second stage of test flights in the surrounding area of Talagi airport (Arkhangelsk) at the end of November, the model of the SAR was tested. The SAR equipment was spatially separated inside the aircraft - the X-band kit was mounted in the front cabin of the fly laboratory (Fig. 10, a), and the L-band kit in the rear cabin (Fig. 10, b) near the radio transparent door in which the antenna was installed (Fig. 10, c).

With the first version of the software, during the flights Arkhangelsk-Naryan Mar-Arkhangelsk, the results obtained in the summer season were confirmed, and aerial radar surveys were conducted at altitude of 6 km. During the second flights with the new software, the expected maximum resolution of 21 cm in the X-band was achieved. An example of radar images from the second flight tests is shown in Figure 11. It shows radar images of the Severodvinsk city in the X-band.

![Figure 10. Remote sensing equipment on board of the flying laboratory in winter season](image)

(a) X-band kit, including antenna; (b) L-band kit; (c) L-band antenna.
**Figure 11.** Radar image of the bay of Severodvinsk, November, X-band, resolution 21 cm.

AN-2 aircrafts are clearly visible at the Naryan-Mar airfield (Fig. 12, a). The images of railway tracks (Fig. 12, b), when examined in detail, were a set of reflections from the heads of the crutches of the rail mounts, which have a hemispherical shape. The spatial resolution of the X-ray diffraction system (21 cm) allowed us to see this feature.

**Figure 12.** Fragments of radar images obtained during tests of the second model of the SAR in the winter season (a) Naryan-Mar airport, An-2 parking lot, X-band, signal spectrum width 600 MHz, resolution 27 cm; (b) Severodvinsk, railway node: X-band, signal spectrum width 1 GHz, resolution 21 cm.

6.3. **The obtained results of the system**

The results are shown in Table 1.

**Conclusions**

In the course of the project, a prototype remote sensing radar for light-engine aircraft and unmanned aerial vehicle was created and tested. The achieved performance of the new SAR, characterized with maximum spatial resolution was equal 0.21 m and 0.5 m in X- and L-band respectively with a viewing bandwidth at a maximum resolution of 8.4 km. At the same time the weight of the onboard transmitters was 12 kg and 8.4 kg in both frequency bands.

By the time of writing this paper, the university project has already been continued. Two projects for industry were executed in 2020, the first project was successfully completed, the second is continued.

An important trend in the development of aviation SAR is the promotion by the Government of the Russian Federation of the use of UAVs for solving practical problems, an example is the “Taiga” project to create a pilot area for UAV operation, implemented at the initiative of the Tomsk Regional
Administration [8-10]. It becomes relevant to create a more compact version of the SAR with the same resolution, but with a reduced flight ceiling and, consequently, with a reduced maximum range.

Table 1. Obtained characteristics of the new SAR

| Content of requirements and explanations | Fact |
|----------------------------------------|------|
| In the X-band, the maximum spatial resolution is not more than 0.3 m, the spatial resolution along the inclined range (across the path line of the aircraft) and the track range (along the path line of the aircraft) at the maximum level of the side lobes in the corresponding sections of the pulse response function is not more than minus 30 dB – not more than 0.5 m. | 0.2/0.24 m |
| In the L-band, the spatial resolution is no more than 0.5 m (1.0 m). | 0.498/0.68 m |
| Monitoring tasks for objects that can be located at altitudes of up to 2 km above sea level should be carried out. | Provided h=4.5…6 km |
| Time of onboard equipment of the SAR needed to come into working condition, including check of operating. | 12 minutes |
| Maximum size of the monitoring area. | ≥ 30 x 30 km² |
| Maximum size of the capture band in each radar channel. | 8140 m |
| Range of viewing angles in the vertical plane. | 20-85° |
| Operating range. | 777-25200 м |
| Pulse power of radiation, not less than 250 W (in both bands). | 324 W(X-band)
251W(L-band) |
| Duration of the generated radio pulse. | 1-60 us |
| The frequency band of the receiver is not less than | ≥ 16 до 1000 |
| The frequency band of the receiver is not less than | 300 MHz L-band
1000 MHz X-band |

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