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Justification of the Concept of a High-Resolution Radar with A Sparse Antenna System

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Abstract

The development of space technology necessitates the development of systems to detect various objects in outer space, such as asteroids, debris, other spacecraft and/or celestial bodies.
The paper presents the effect of counter waves, based on which a hypothesis is put forward for the development of a high-resolution radar system with a sparse antenna system.
For the presented high-resolution radar concept, image reconstructions of a satellite located at a distance of 500 and 1000 km are obtained by simulation modelling. The simulation results indicate the possibility of quantitative analysis of space object parameters.

Keywords: RADAR, sparse array, microwave imaging, microwave simulation.

1. Introduction

The first space flight inaugurated the space age, which is accompanied by the rapid development of the space industry, rocket technology is constantly improving, which allows for various interplanetary missions in space.
Space flight is a very dangerous activity, therefore, a modern spacecraft is equipped with a huge number of different sensors and instruments that complement each other, thus ensuring the safety of the flight and the success of the mission. The continuous development of space technology necessitates the placement of radars on the spacecraft to detect various objects in space, such as asteroids, debris, other spacecraft and/or celestial bodies.

2. Objective

The purpose of the ongoing research is to substantiate the concept of application of sparse antenna system radars on spacecraft for instantaneous detection of objects at long distances with high spatial resolution.

3. Methods

The standard approach of designing a radar with the required reconstruction resolution is based on determining the spatial resolution in the Fraunhofer zone (far zone) and the Fresnel zone (near zone) [1].

The boundary between the Fresnel zone and the Fraunhofer zone is called the focal distance of the wave system and is defined by the expression [2]:

$$F = \frac{2 \cdot A}{\lambda}, \quad (1)$$

where, F - focal length of the transducer, m;
A - aperture size of the wave system, m;
λ - wavelength of the probing signal, m.
The transverse spatial resolution of wave systems is determined by the expression [3]:

$$R_p = \frac{0{,}5 \cdot \lambda \cdot L}{A}, \quad (2)$$

where, R_p- is the transverse resolution of the object, m;
L - distance to the object, m.
The longitudinal spatial resolution of wave systems is determined by the expression [4]:

$$R_l = \frac{v}{(f_{max} - f_{min})}, \quad (3)$$

where, R_l - is the longitudinal spatial resolution of the object, m;
v - velocity of propagation of the sounding signal, m/s;
f_{max} - maximum frequency of theprobing signal, Hz;
f_{min} - minimum frequency of theprobing signal, Hz.
Based on the analytical dependencies (2) and (3), we conclude that it is possible to detect an object with the required spatial resolution in two ways:
- by decreasing the wavelength (increasing the frequency) of the probing signal;
- by increasing the aperture size of the antenna system.
Reducing the wavelength complicates the design of measuring and measuring equipment, because from the frequency of the probing signal 300 MHz, the wave properties of electrical signals flowing through the conductors begin to appear. The equipment for registration of microwave signals should be developed on the basis of complex architecture of microstrip structures, taking into account the peculiarities of microwave wave propagation [5].
Increasing the aperture size of the antenna system is limited by the size of the spacecraft.
For example, to detect an object at a distance of 1000 km with a resolution of 10 metres (the estimated diameter of the space object) and a frequency of 2.4 GHz would require an aperture size of 6 km.
In addition, the design of large aperture radar is complicated by the following scientific and technical problems:
- high cost due to the large number of measurement antennas;
- the difficulty of measuring the phase of the reflected radio signal by antennas located at long distances.
To solve the first scientific and technical problem, the use of sparse aperture is proposed. According to Sampling's theorem [6], in order to obtain a high-quality image, it is necessary that the distance between the radiating and measuring antennas is not more than half a wavelength in order to exclude systematic noise in the image reconstruction. However, if the required configurations of the sparse antenna system are observed, the image reconstruction quality of moving objects has high spatial resolution.
To solve the second scientific and technical problem, it is proposed to use the effect of counter electromagnetic waves [7].
The essence of this effect is based on the reversibility theorem [8], according to which, when a pair of transmitter-measurer interacts, the result of measuring the parameters of the reflected signal will be the same if the transmitter and the meter are swapped.
Consider the interaction of two Doppler radars (Figure 1).

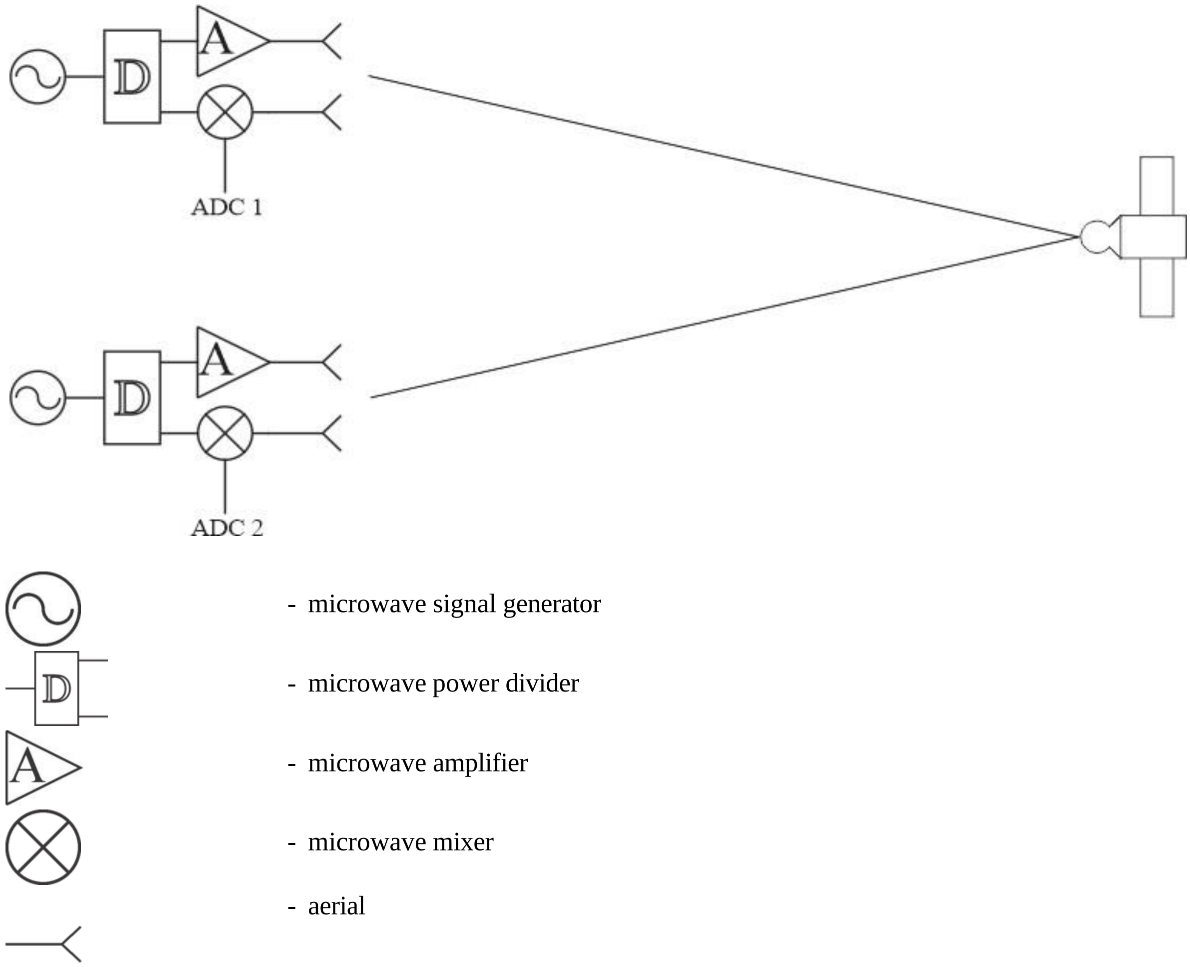


Figure 1 - Scheme of interaction of two Doppler radars

The formalisation of the effect of counter electromagnetic waves from two Doppler radars is presented in [9], in which the dependence of the phase of the electromagnetic wave reflected from the object and the intensity of intermediate signals on the first and second radar is derived:

$$\varphi = -\frac{1}{2}\left(arccos\frac{J_1^2-1-k^2}{2k} + arccos\frac{J_2^2-1-k^2}{2k}\right); \quad (4)$$

where, J_1 - is the value of the intermediate signal from the first radar;
J_2 - value of the intermediate signal from the second radar;
k - the radar gain.

The analysis of the obtained expressions for signal intensity and phase allows us to draw the following conclusions:

- knowing the values of intermediate signals from radars operating in the counterwave mode, it is possible to determine the phase and intensity of the radio radiation reflected from the object;
- the limitation on the aperture size of the antenna system is removed;
- the possibility of designing a multi-channel radar with a single transmitter.

The structure of a multi-channel radar with a single transmitter is shown in Figure 2.

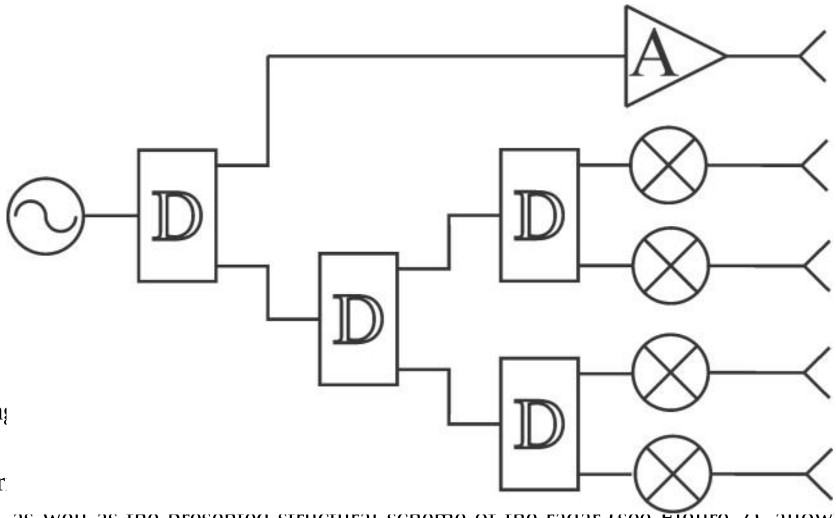
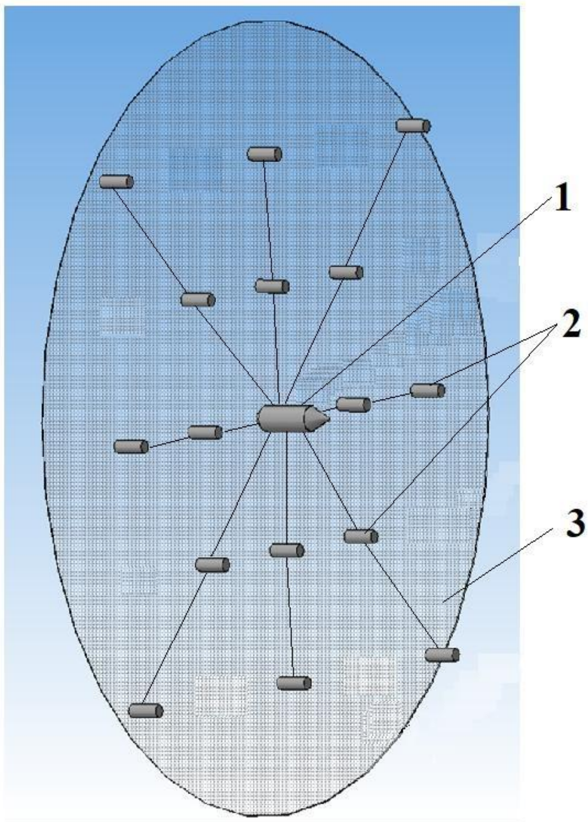


Figure 2 - Structural dia

The results obtained dur

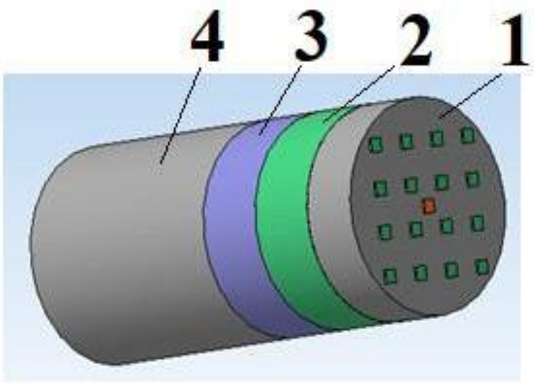
between radar modules, as well as the presented structural scheme of the radar (see Figure 2), allow us to put forward a hypothesis on the creation of a high-resolution radar system with a sparse antenna system consisting of individual radar measurement and computing modules, which are placed in a plane perpendicular to the direction of motion of the spacecraft (see Figure 3).

Each radar measurement and computing module consists of a sensor subsystem, a multichannel measurement electronics subsystem, a computing module subsystem and a wireless transmitting device. The sensor subsystem consists of one radiating antenna located in the centre and an array of measurement antennas evenly distributed in the nodes of a square grid.



1 - space object; 2 - measuring and computing radar module, 3 - radar module distribution plane
Figure 3 - Concept of a high-resolution radar system with a sparse antenna system

Figure 4 shows an example of a three-dimensional model of a 16-channel radar measuring and computing complex.



1 - antenna module; 2 - measuring module; 3 - computing module; 4 - module of radar module orientation in space

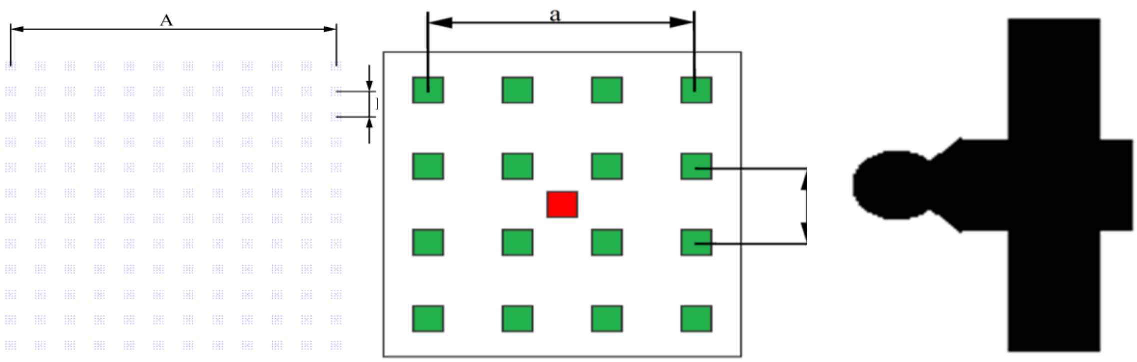
Figure 4 - Three-dimensional model of a 16-channel radar measuring and computing complex

The main probing frequency is selected to obtain information. Each radar module emits a probing monochromatic radio signal, the frequency of which is close to the fundamental frequency. When reconstructing the image using simulation modelling, the main radar emitting module is selected, relative to which the other radar modules are synchronised. The amplitude and phase of the signal reflected from the object, emitted by the first radar module, are measured. Then, using the algorithm of spatially consistent filtering, the image for the selected transmitter is calculated. Then, the second radiating radar module is selected and the other radar modules are synchronised on the basis of the counter wave method. In this way, the image reconstruction for the remaining radar modules is calculated.

The construction of the image obtained on the basis of electromagnetic waves of the microwave range is based on the application of a multistatic scheme of signal measurement, which consists in measuring the reflected wave field on the measuring plane for each transmitter.

4. Results

A simulation modelling method was used to image space objects by a high- resolution radar system with a sparse sensor system. The antenna system consisting of 144 radar modules located at a distance of 500 metres from each other. Each radar module consists of a radiating antenna and evenly distributed sensing antennas (Figure 5). The radiation frequency of the probing signal is 2.4 GHz. The satellite contour is selected as the object.



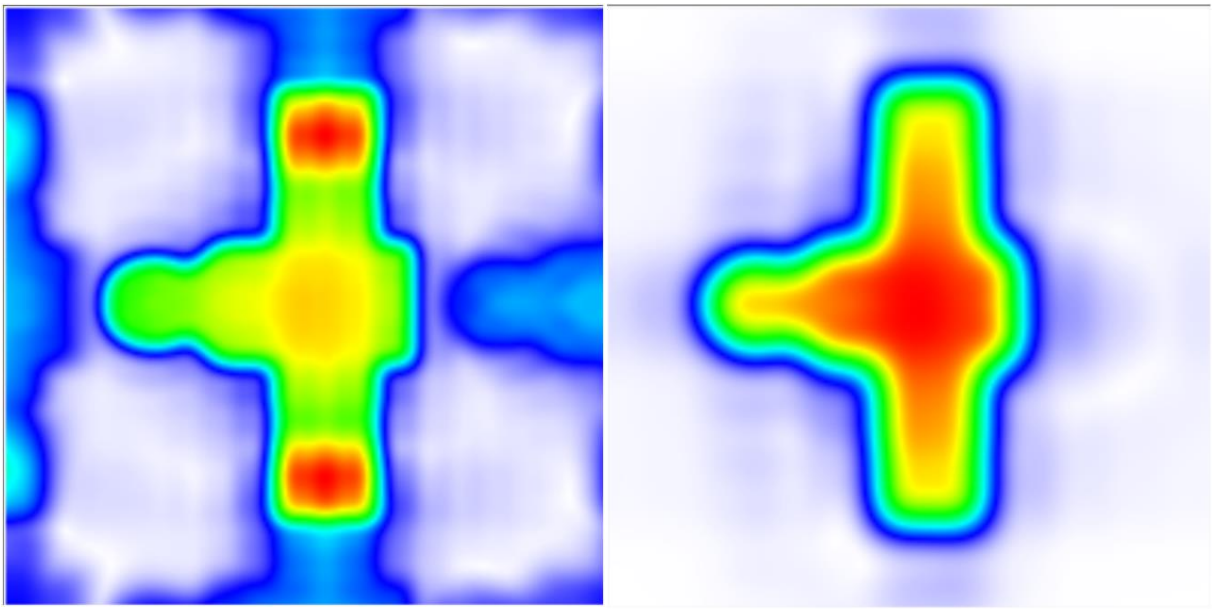
a) b) c)

a) - general scheme of the antenna system;
b) - scheme of one radar module;
c) - contour of the modelling object (space satellite)

A - the total aperture of the space object detection system;
D - distance between the radiating antennas of the radar module; a - aperture of one radar module;
d - distance between measuring antennas

Figure 5 - Parameters and object of simulation modelling

As a result of the simulation, images of the satellite at distances of 500 and 1000 km from the space object detection radar system were obtained (see Figure 6).



Distance from the antenna system to the satellite - 500 km | Distance from the antenna system to the satellite - 1000 km

Figure 6 - Reconstruction of the image of the satellite contour located at a distance of 500 and 1000 km, obtained on the basis of simulation modelling

5 Conclusions

1. Preliminary analysis of technical possibilities of instantaneous detection of objects at a long distance with high spatial resolution allowed to establish that to obtain a high-quality image it is necessary that the aperture size of the radar with a sparse antenna at the frequency of the probing signal of 2.4 GHz should be at least 6 km.

2. At carrying out of complex researches formalisation of effect of counter electromagnetic waves from two Doppler radars has allowed to establish dependence of phase of the reflected from object electromagnetic wave and intensity of intermediate signals on the first and second radar with maintenance:

- to remove restrictions on the aperture size of the antenna system;
- design possibilities for a single-emitter multichannel radar module.

3. Based on the developed structural scheme of a multichannel radar with a single transmitter, the concept of creating a high-resolution radar system with a sparse antenna system consisting of separate radar measuring and computing modules including a sensor subsystem, multichannel measuring electronics subsystems, computing module subsystems and a wireless transmitting device is proposed.

4. On the basis of simulation modelling, images of the satellite at a distance of 500 and 1000 km from the radar system for space object detection were obtained, which confirmed the hypothesis about the possibility of creating a high-resolution radar system with a sparse antenna system.

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