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SCIENTIFIC AND TECHNICAL SUBSTANTIATION OF THE PARAMETERS OF THE RADIOLOCATION DEVICE FOR THE DETECTION OF PROHIBITED ITEMS

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Abstract. *The paper presents a scientific and technical substantiation of the parameters of the radar device, which allows to detect and visualize forbidden objects by means of electromagnetic radiation of the microwave range. A model of a multistatic scheme for measuring waves reflected from an object based on the holographic method is developed. A software complex of simulation modeling of radar device operation has been developed, by means of which reconstructions of object images for different configurations of sparse sensor subsystems of the radar device have been obtained. An optimal configuration of the sparse sensor subsystem was selected by the method of peak signal-to-noise ratio analysis, for which a multi static hologram was modeled and a reconstruction of the metal rod image was generated. The reconstruction of the metal rod image obtained as a result of simulation modeling has a recognizable contour, which confirms the prospect of developing an experimental prototype of a radar device for detecting prohibited objects.*

Keywords: microwave imaging, holography, multi static array, detection of prohibited items, visualization.

1. Introduction

Places of mass gatherings require special measures to ensure safety. This is due to the fact that mass events involve large numbers of people, which may be associated with security threats due to unlawful actions of certain groups of people. To reduce the surprise factor from the use of various types of prohibited items, it is necessary to use technical systems to detect the presence of prohibited items hidden under clothing or in any hand-held items, such as bags [1].

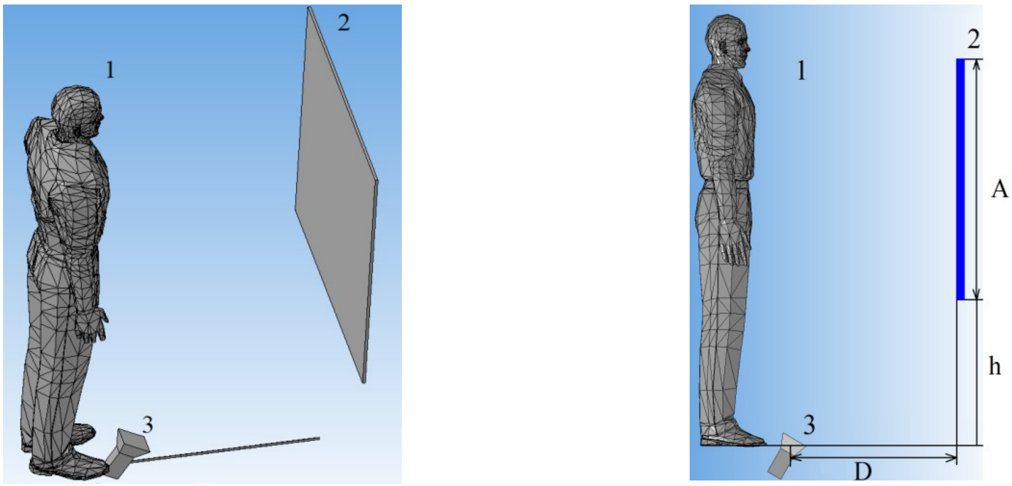
Prohibited items to be detected are traditionally made of durable materials that have a high reflection coefficient for electromagnetic waves: metal, plastic, rubber, ceramics, and others. [2].

The radio wave method of object detection is promising in terms of in formativeness, safety and non-contact action in the process of scanning various objects. Based on the radio wave method, research is underway to develop inspection systems that allow remote detection of prohibited objects [3,4].

Currently created means of remote detection and visualization of prohibited items, based on radio waves have a rather high price, which is one of the factors limiting their widespread use. Based on the above, it can be stated that the development of an affordable radar device that allows remote detection of hidden prohibited items is an urgent scientific and technical task that requires research.

In the presented work, a scientific and technical justification of the parameters of a radar device for the detection of forbidden objects by means of a holographic method of image acquisition using a multi static measurement scheme is proposed [5,6].

The concept of radar device application is as follows: the object of inspection is installed at a certain distance from the sensor subsystem, which is an array of measuring and radiating antennas evenly distributed in the plane of the sensor subsystem (Figure 1).



a *b*

a - general view of the arrangement; b - side view; A - aperture size of the sensor subsystem; D - distance from the base of the sensor subsystem to the reference source; 1 - detection object; 2 - sensor system; 3 - reference source

Fig 1. Location of the detection object in relation to sensor system and reference source.

The reference source is installed opposite the sensor subsystem in such a way as to ensure a high stable level of the reference signal over the entire measuring plane. Radiators of the sensor subsystem in turn irradiate the object with electromagnetic wave of the microwave range. As a result of interaction between the wave reflected from the object and the reference source, a hologram is formed, which is registered by the measuring antennas of the sensor subsystem [7].

For most prohibited items, the most common place to carry prohibited items is the torso area. It is in this area that the best authorization should be concentrated. The average height of a person is 1.7 meters, but occasionally people with a height of about two meters are encountered, so the maximum dimensions of a person are assumed to be 2 meters.

In [8], studies of spatial resolution depending on aperture parameters and location of the object of inspection relative to the sensor subsystem were carried out, and rational parameters of the radar device for human inspection for the presence of prohibited items were scientifically substantiated (Table 1).

Table 1. Rational parameters for inspection of a person up to two meters tall.

Parameter name	Minimum value	Maximum value
Distance to the object, m	L = 0,6 м	L = 1 м
Aperture size of radiolocation device sensor subsystem, m	D = 1 м	
Height of radiolocation device sensor subsystem center, m	J = 1 м	

The presented location of the sensor subsystem relative to the scanning object allows its inspection with a resolution in the range from half-length to 0.9 wavelength. One of the main criteria in the process of creating a radar device for the detection of prohibited items is for the assembly of the system to select according to certain parameters the necessary components with operating frequency up to 6 GHz and wavelength of 50 mm.

2. Formulation of the problem

The research task of designing a radar device for the detection of prohibited objects is to find its best configuration that combines a rational ratio between the quality of the received image and the technical characteristics of its subsystems. The standard approach of designing sensor subsystems is based on the fact that the distance between neighboring radiating and measuring antennas should be no more than half a wavelength of radiation, which provides a high-quality image [9]. However, the design of such a sensor subsystem is not economically feasible due to the high requirements for the measurement electronics and computing module.

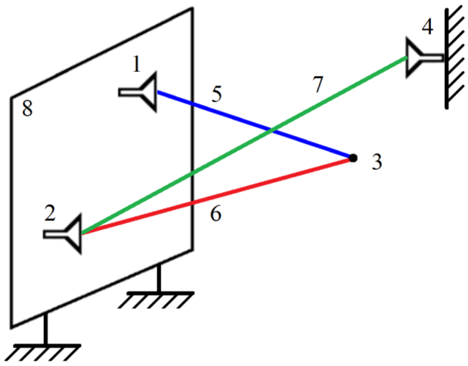
The main advantage of wave systems based on a multi static sensing scheme is that the reconstruction algorithm is robust to the aperture sparsity of the sensor subsystem. This means that it is possible to use a sensor subsystem in image computation where the distance between the emitting and measuring elements of the sensor subsystem is greater than half the wavelength of the sensing signal.

The use of a sparse sensor subsystem will result in the appearance of systematic noise in the image reconstruction [10]. However, despite the presence of systematic noise, the image quality can remain at the required level, sufficient for detection and unambiguous recognition of the forbidden object, at different coefficients of the sensor subsystem sparse.

In view of the existence of many combinations of parameters and configurations of the radar device, the task of searching for rational parameters by experimental methods is quite laborious, so in this case the method of simulation modeling is the most effective [11].

3. Model Development

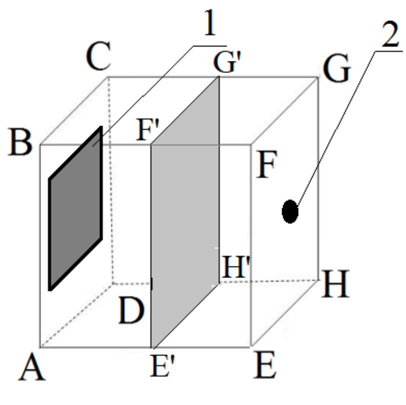
To analyze the influence of sensor subsystem parameters on the quality of image reconstruction, a spatial diagram of one transmitter-receiver pair of sensor and reference source subsystems was initially drawn (Figure 2).



1 - transmitter; 2 - receiver; 3 - reflection point; 4 - reference source;
5 - wave path from the transmitter to the reflection point; 6 - wave path from the reflection point to the receiver; 7 - wave path from the reference source to the receivers; 8 - measurement plane of reflected signals

Fig 2. Spatial diagram of one pair “transmitter - receiver” sensor subsystem of the radar device.

In the process of forming the simulation area, which is bounded by the cube ABCDEFGH with an edge equal to 1 m, the sensor system 1 (see Figure 3) was located on the face ABCD. In the center of the EFGH face there is an object 2 (see Figure 3) of scanning, for which analytical studies with the help of simulation were performed.



1 - location of the sensor subsystem; 2 - location of the modeling object

Fig 3. Simulation modeling area.

The flat image of the scanning object for simulation modeling is a two-dimensional array of 256 x 256 points, each of which of the simulation object has two states:

1 - 100% reflection;

2 - 0% reflection.To control the noise level of image reconstruction we will use the peak signal-to-noise ratio (hereinafter referred to as PSNR) [12]:

$$\mathrm{PSNR} = 20\lg\left(\frac{\mathrm{MAX}}{RMS}\right), \tag{1}$$

where, MAX – maximum value of the reconstruction intensity;

RMS – the standard deviation of the image reconstruction [13].

$$RMS = \frac{1}{\mathrm{X}\cdot\mathrm{Y}}\sum_{i=o}^{X-1}\sum_{j=0}^{Y-1}\left(I_0(i,j) - \mathrm{I}(i,j)\right)^2, \tag{2}$$

where, $I_0(i,j)$ - image reconstruction obtained by the sensor subsystem with the distance between neighboring emitters and receivers equal to half wavelength, two-dimensional array;

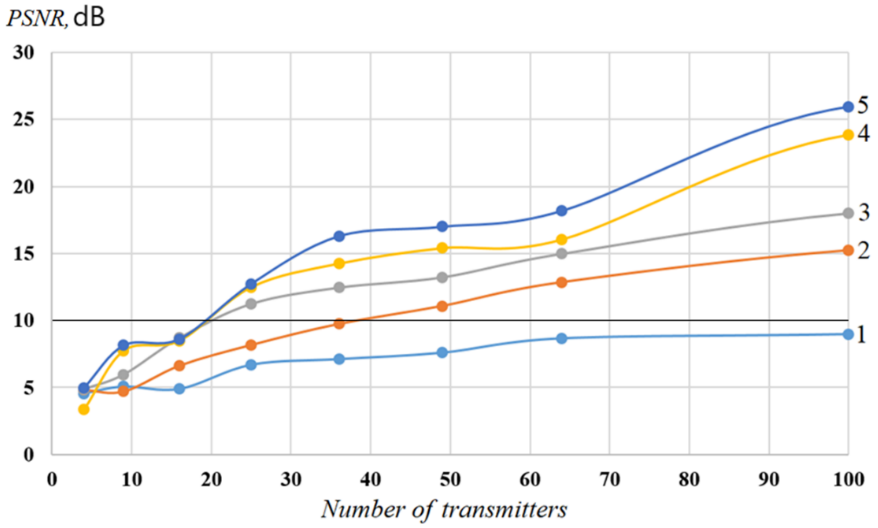
$I(i,j)$ - image reconstruction obtained by a sparse sensor subsystem with the distance between neighboring emitters and receivers exceeding half a wavelength, two-dimensional array;

i, j - coordinates of the image point, pixel;

X, Y - length and width of the image reconstruction, pixel.

4. Results of simulation modeling

Using the simulation software package, the influence of the rarefaction coefficients of transmitters and receivers in the sensor subsystem was investigated of the sensor subsystem of the radiolocation device on the PSNR of the image reconstruction (Figure 4).



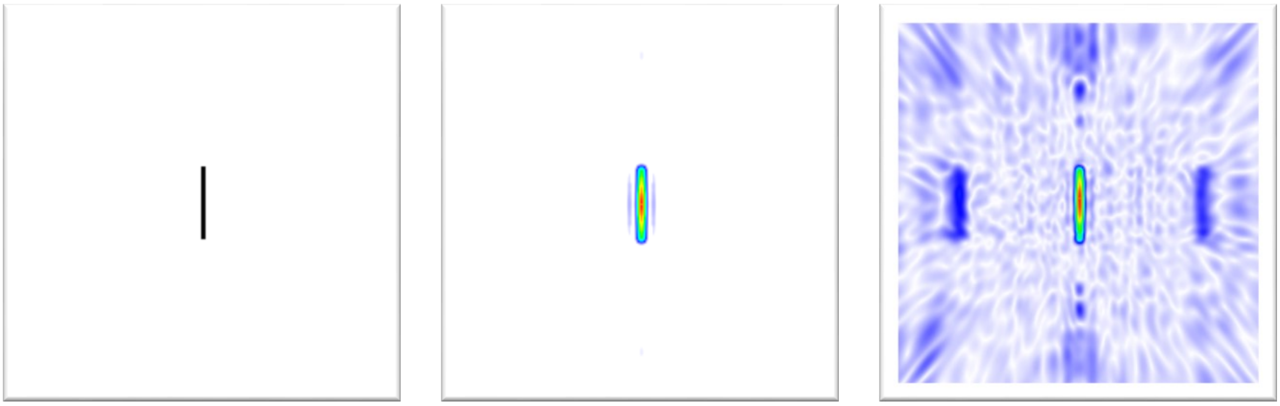
1 - PSNR for 144 receivers; 2 - PSNR for 196 receivers; 3 - PSNR for 256 receivers;
4 - PSNR for 324 receivers; 5 - PSNR for 400 receivers;

Fig 4. Plots of peak signal-to-noise ratio as a function of the number of transmitters in the sensor system.

As a criterion for selecting the configuration of the sensor subsystem we will use the value of peak signal-to-noise ratio equal to 10 dB. Such peak signal-to-noise ratio will allow to detect, unambiguously recognize and classify the object as forbidden.

Further parameters of the sensor subsystem are selected based on the principle of minimizing the number of measurement channels.

As a result of optimization, a sensor subsystem configuration consisting of 49 emitting and 196 measuring channels was selected. Simulation modeling was performed for the selected sensor subsystem configuration, and the contour of a metal rod with a length of 500 mm and a diameter of 20 mm was used as a modeling object (Figure 5-A). As a result of the simulation, image reconstructions were obtained for a full sensor subsystem consisting of 1600 emitters and 1600 receivers (Figure 5-B) and a sparse sensor subsystem consisting of 49 emitters and 196 receivers (Figure 5-C).



A B C

A - modeling object; B - image reconstruction for sensor subsystem with C

Fig 5. Modeling object and its image reconstruction depending on the number of measurement channels.

5. Conclusions

As a result of this study, the possibility of developing an affordable radar device for detecting hidden prohibited objects using a sparse sensor subsystem has been confirmed.

For different configurations of sparse sensor subsystems, the simulation modeling of radar device operation was carried out. Dependences of the peak signal-to-noise ratio depending on the sparse aperture configuration are obtained.

An optimization strategy based on the requirements of image reconstruction quality equal to 10 dB and minimization of the number of measurement channels is formed.

As a result of the optimization, a sensor subsystem consisting of 49 transmitters and 196 receivers is selected, with:

- aperture equal to 1 m;
- center of the sensor subsystem placed at a height of 1 m;
- distance to the scanning object equal to 1 m.

The reconstruction of the image of the metal rod obtained as a result of simulation modeling has a recognizable contour, which confirms the possibility of developing an experimental prototype of the radar device for the detection of prohibited objects, despite the existing noise.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Zhantlessov Y.Zh.: conceptualization, project administration; Smakova N.S.: investigation, validation;
Gruzin V.V.: Methodology; Formal analysis; Togusov A.K.: investigation; Jusupbekov T.Kh: research strategy; Zhantlessov Z.Kh: mathematical model concept.
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References

1. Harmer S., Cole S., Bowring N., Rezgui N., Andrews D. (2012) On body concealed weapon detection using a phased array. *Progress in Electromagnetics Research*, 124, 187 – 210, DOI:10.2528/PIER11112105.

2. Yermakhanova A., Kenzhegulov A., Meiirbekov M., Samsonenko A., Baiserikov, B. (2023) Study of radio transparency and dielectric permittivity of glass- and aramid epoxy composites. *Eurasian Physical Technical Journal,* 20(2(44), 70–78. DOI: 10.31489/2023No2/70-78.

3. David M. Sheen. (2015) Noise analysis for near-field 3D FM-CW radar imaging systems. *Proceedings of the SPIE,* 9462. DOI: 10.1117/12.2180032.

4. Corredoura P., Baharav Z., Taber B., Lee G. (2006) Millimeter-Wave Imaging System for Personnel Screening: Scanning 10^7 Points a Second and Using No Moving Parts. *SPIE Passive Millimeter-Wave Imaging Technology*, 62110B.DOI: 10.1117/12.669664.

5. Sheen D.M. (2013) Sparse multi-static arrays for near-field millimeter-wave imaging. *2013 IEEE Global Conference on Signal and Information Processing,* Austin, TX, USA, 699-702, DOI:10.1109/GlobalSIP.2013.6736987.

6. Sherif A. (2013) *Electronic Microwave Imaging with Planar Multistatic Arrays.* Faculty of Engineering Friedrich-Alexander - Universitaet Erlangen - Noernberg for the doctoral degree Doctor of Engineering. - Erlangen. - 226 p. https://www.researchgate.net/profile/Sherif-Ahmed-5

7. Zhantlessov Zh.Kh, Gruzin V.V., Zhantlessov Y.Zh. (2017) Object scanning method. *Patent for invention № 32026.* National institute of intellectual property. Astana, Kazakhstan 31.03.2017.

8. Zhantlessov Y.Zh. (2020) *Justification of parameters and development of hardware-software complex of radio- and acoustic tomography of static objects*. National Defense University of the Republic of Kazakhstan. Astana, 2020. 151 p. [in Russian], For official use.

9. Zhuravlev A., Razevig V., Rogozin A., Chizh M. (2023). Microwave Imaging of Concealed Objects With Linear Antenna Array and Optical Tracking of the Target for High-Performance Security Screening Systems. *IEEE Transactions on Microwave Theory and Techniques,* 71 (3), 1326-1336, DOI:10.1109/TMTT.2022.3217593.

10. Muhammad A. E., Martin G., Edward J., Martin O'H. (2013) Artifact Removal Algorithms for Microwave Imaging of the Breast. *Progress In Electromagnetics Research,* 141, 185-200. http://dx.doi.org/10.2528/PIER13052407.

11. Shumakov D.S., Tu S., Nikolova N.K. (2015) Fast quantitative microwave imaging based on measured point spread functions and inversion in real space. *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting.* Vancouver, BC, Canada, 687-688. DOI: 10.1109/APS.2015.7304730.

12. Yang X. (2018) *Signal processing for microwave imaging systems with very sparse array*. Doctoral Dissertation. Missouri University of Science and Technology. 116 p. https://scholarsmine.mst.edu/doctoral_dissertations/2733

13. Zhang B., Hong W., Wu Y. (2012) Sparse microwave imaging: Principles and applications. *Sci. China Inf. Sci.*, 55, 1722–1754. DOI: 10.1007/s11432-012-4633-4.

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