

Quasi-optical array radar method for obtaining four-dimensional radio images

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A quasi-optical array radar method has been developed for obtaining four-dimensional radio images. In the presented method, angular coordinates of an object are determined by using a quasi-optical lens, in the focal plane of which an array receiver is located, while the distance to the object and its radial velocity are determined by the frequency-modulated continuous-wave radar technique. The workflow of the developed method is demonstrated in the operation of a fabricated 94 GHz radar system. The proposed method advantage over its analogues is a simpler way to determine the object angular coordinates and, as a result, a less complex design and more affordable fabrication procedure.

Keywords: array radar, quasi-optical system, frequency-modulated continuous-wave radar, four-dimensional radio image, millimeter waves.

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Millimeter waves are used in radar because they enable achieving high resolution with maintaining high penetration power of the probing signal. Most of millimeter-wave radars provide measurement of no more than three characteristics of the detected object, e.g., radial coordinate, one of the angular coordinates, and radial velocity [1]. Measuring each additional characteristic of the object not only allows obtaining its more complete description, but also increases the probability of distinguishing this object against the background of other objects or noise [2]. In this regard, increasing the number of radar-measurable characteristics is an urgent task.

All the currently known millimeter-wave radars use for obtaining 4D radio images the multiple input and multiple output (MIMO) method [3]. Such radars are capable of obtaining 4D radio images at distances of up to ~ 300 m [2,4,5], which is used in vehicle driver assistance systems. These systems are also in demand at short distances (up to 1 m), when they are used in gesture recognition [6]. An attractive aspect of the MIMO method is the possibility of creating transmit-receive arrays with a large number of virtual elements and significantly lower number of physical elements. This reduces the radar's cost and makes it preferable to other solutions (e.g., phased array radars). Nevertheless, 4D imaging radars are not yet widely used, first of all because they do not meet the economic feasibility requirement.

This paper is devoted to examining an alternative approach to creating a millimeter-wave array radar for obtaining 4D radio images, which is based on an analog method for image formation along angular coordinates. In the described system, the image formation along angular coordinates is performed by using a quasi-optical lens [7]: the signal power distribution in the lens focal plane

matches the distribution of reflectors over the scene. The distances to objects and their velocities are determined by the continuous-wave frequency-modulation radar technique. The use of the quasi-optical image formation method is the main feature distinguishing the proposed approach from the MIMO method. In the MIMO method, to get an image along the angular coordinates, it is necessary to measure the received signal phase difference between the array elements, and this should be done for a great variety of transmitted signals [8]. In the proposed method, phase distribution of the received signal is detected in passing through the quasi-optical lens; this simplifies both the system technical implementation and signal processing algorithms.

The developed method for obtaining 4D radio images is illustrated in Fig. 1. The millimeter wave oscillator generates a continuous frequency-modulated signal whose power is divided into two parts. The first part is directed into the space to be studied, while the other one is fed directly to the array receiver (reference signal). An object (or objects) in the probed space reflects incident energy in different directions. A part of energy is reflected towards the quasi-optical lens which focuses it in the focal plane. Each point of the focal plane corresponds to the direction from which the reflected energy comes. The reflected signal is mixed with the reference signal in each sensing element.

The signal frequency modulation, as well as the frequency shift due to the Doppler effect, leads to that the reflected signal frequency differs from the reference signal frequency, which gives rise to a beat frequency signal at the mixer output. Distribution of the beat frequency signal amplitude between the array elements corresponds to the objects' distribution over angular coordinates in the space under study. Data on the radial coordinate and velocity is obtained

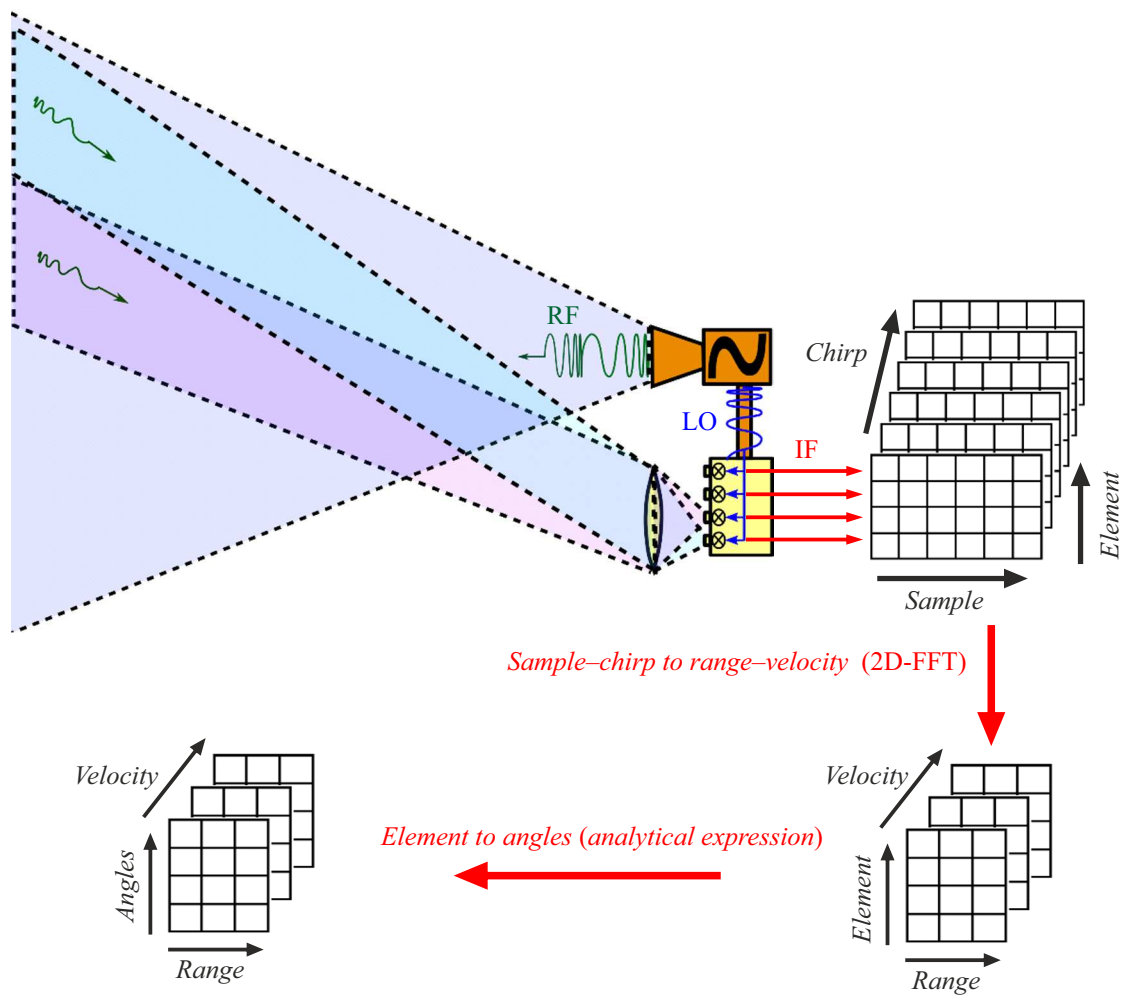


Figure 1. An illustration of the proposed method for obtaining 4D radio images.

by analyzing the phase of the beat frequency signal in accordance with the continuous-wave radar method [9].

As initial data for obtaining a 4D radio image, there are used segments of the beat frequency signal in a time interval including several periods of the probe signal modulation for each array element: $U_{l,m,n}$, where $l = 0, \dots, L-1$ is the array element number, $m = 0, \dots, M-1$ is the modulation period number, $n = 0, \dots, N-1$ is the count number. Later on, a two-dimensional fast Fourier transform (2D-FFT) is performed over variables m and n [10]; as a result, we obtain the beat frequency signal amplitude distribution over radial coordinate R and velocity V : $U_l(R, V)$. Next, using analytical expressions in accordance with rules of geometric optics, azimuth angle φ and elevation angle ε are assigned to each array element l . Finally, obtain $U(\varphi, \varepsilon, R, V)$. To find the 4D radio image projection onto the required coordinate plane, the squared amplitudes are summed over the other two coordinates.

The proposed method was demonstrated by using a previously developed 94 GHz radar prototype with an array receiver consisting of 8×8 elements [11]. The array receiver mixer is created based on a low-barrier Schottky

diode mounted in a bow-tie slot antenna. The radar's angular resolution which depends on the lens parameters is 3 deg. The used frequency modulation parameters were as follows: deviation of 443 MHz, period of 9 ms. To obtain a radio image, a signal 10 modulation periods (90 ms) long was analyzed with the sampling frequency of 250 kHz. At the given probing signal parameters, the range resolution was 17 cm, speed resolution was 1.8 cm/s.

In the course of experiment, probing was performed for a space region containing two objects mutually arranged as shown in Fig. 2, *a*. As the moving object, a spherical reflector with effective scattering area of 1 m^2 was used (object 1); as the stationary object, there was used an M6 metal stud (object 2). The spherical reflector was mounted on a linear displacement module on which it moved at the preset speed of 4.3 cm/s by 10 cm back and forth. The objects were located at the same distance from the radar (accurately to the range of spherical reflector motion) and had identical angular coordinates. 4D radio images projected onto various planes are shown in Figs. 2, *b–g*. As shown in Figs. 2, *b–d*, the objects are indistinguishable if their velocities are unknown. To identify whether there

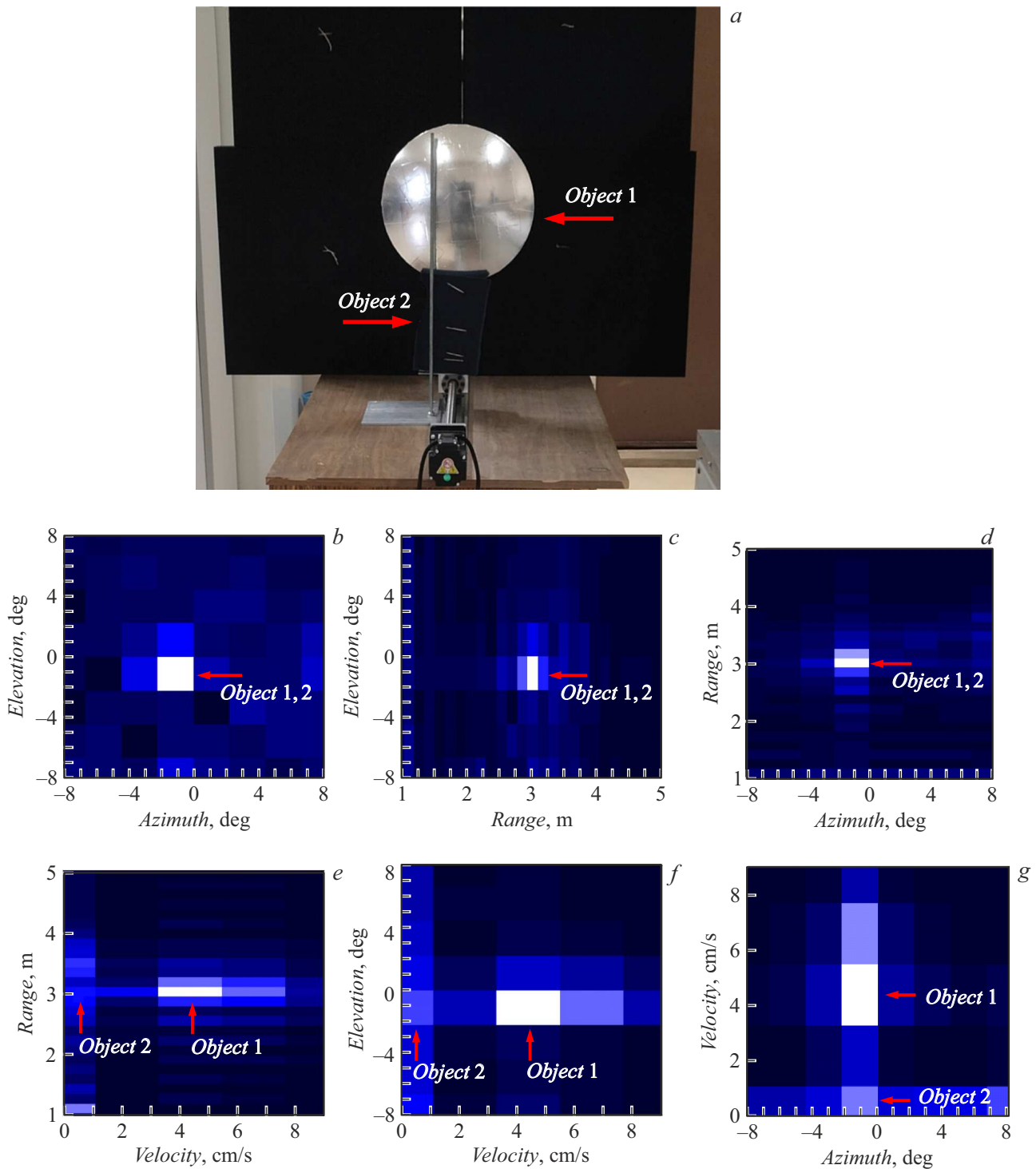


Figure 2. *a* — a photo of the spherical reflector (object 1) and threaded stud (object 2); *b–g* — radio images of the spherical reflector and threaded stud projected onto different planes.

are two objects rather than one, it is necessary to use information on their velocities (Figs. 2, *e–g*).

Thus, the use of the method for obtaining 4D radio images expands capabilities of the millimeter-range quasi-optical array radar. Moreover, the proposed method not only increases the probability of distinguishing objects against

other objects, but can also help solve the problem of identifying the useful signal against the background of low-frequency noise including that associated with detecting the reference signal power. This enables an increase in the array receiver sensitivity and, hence, an increase in the radar energy potential.

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Conflict of interests

The authors declare that they have no conflict of interests.

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