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TOMOGRAPHIC IMAGING USING NOISE RADAR AND 2D APERTURE SYNTHESIS

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Implementation of 2D aperture synthesis enables obtaining of 2D angular resolution which in combination with range resolution gives tomographic 3D images. Tomographic 3D radar images can give detailed and precise information about spatial distribution of semitransparent objects or other area of interest. Radar tomography may be realized with the help of any type of high resolution radar; however this paper is focused on *noise radar tomography*. We describe simulation of wideband noise radar operation combined with 2D aperture synthesis and present some results of tomographic SAR imaging experiments using continuous noise waveform and 2D aperture synthesis carried out in S-band.

Keywords: noise waveform, radar tomography, 3D SAR imaging, noise waveform SAR, antenna with beam synthesis.

INTRODUCTION

There are many applications of radar imaging and radar tomography. For instance, such systems can be used for intrusion detection, concealed weapons detection, monitoring of bridges, buildings, towers, etc. 3D microwave or millimeter wave imaging of partially transparent objects may be realized via generation of a series of 2D images as cross-range slices at different range gates [1] which is possible when applying a high resolution radar. Actually this technique is a combination of 2D aperture synthesis and wideband radar ranging with high enough resolution. Hereinafter, this technique will be called as *Radar Tomography* which is in agreement with general definition of the tomography. Microwave or millimeter wave radar tomography may be realized with the help of any type of high resolution radar; however in this paper we will be focused on *Microwave noise radar tomography* [2,3]. To demonstrate this capability of noise radar we have carried out computer simulation of noise radar operation in combination with 2D aperture synthesis. Indoor experiments aimed on obtaining of 3D tomographic images of a laboratory room interior have been carried out using S-band noise radar. Besides, we have shown tomographic 3D images generated experimentally and have estimated the coordinates of some strong scatterers measured from these images. Bisatic Ka-band Noise waveform SAR using antennas with beam synthesis [3,4] may be applied for tomographic imaging as well, but the related results are presented in another paper by the authors.

I. 2D IMAGE GENERATION USING NOISE WAVEFORM AND 2D APERTURE SYNTHESIS

Consider, first, simulation of 2D imaging using 2D aperture synthesis along two cross-range coordinates with the help of wideband Noise Radar. The required noise waveform with Gaussian shape of its power spectrum has been obtained from white noise sequence via application of three transformations: 1. Fast Fourier Transform (FFT), 2. Gaussian windowing in frequency domain, and 3. Inverse FFT [2,3] to obtain the required random signal in time domain.

We have simulated 2D aperture synthesis for the case of *rectangular* aperture shape. We suppose mechanical motion of transmit/receive (Tx/Rx) antenna or proper electronic switching between elements of 2D Tx/Rx antenna array. Rectangular aperture is realized via line by line scanning consisting in radiation and reception of noise signal at each discrete position of the antennas. The scene consists of point-like scatterers which don't have mutual electromagnetic interaction.

SAR imaging can be considered as matched filtration of the signals received by Rx antenna at different positions. Reference function for such filtration is obtained as a signal from a point-like scatterer placed at the point of interest. Such matched filtration can be described in spectral domain as follows. Relation for a Fourier component of the received signals from a point-like scatterer can be described as a harmonic of probing signal with factors which describe its distortions due to propagation and backscattering:

$$E_m(f,\chi_1,\chi_2)= \\ = E_0(f,\chi_1,\chi_2)\cdot\zeta(x,y,z)h(f,\chi_1,\chi_2,x,y,z), \quad (1)$$

where $E_0(f,\chi_1,\chi_2)$ is a Fourier component of the signal radiated at the antenna position described by two coordinates on the plane of the synthetic aperture (χ_1,χ_2); f is frequency; $\zeta(x,y,z)$ is reflection coefficient of the scene element with coordinates (x,y,z); $h(f,\chi_1,\chi_2,x,y,z)$ is a factor describing propagation of the signal from antenna at the position (χ_1,χ_2) towards the target with coordinates (x,y,z) and back.

Relation for estimation of the reflectivity ξ of the given point (x,y,z) of the 3D scene using matched filter concept will have the form of convolution between measured signals and theoretical return from the point-like scatterer [6]:

$$\xi(x,y,z)= \\ = \iint\limits_S \int\limits_{-\infty}^{\infty} E_{rec}(f,\chi_1,\chi_2)\cdot E_m^*(f,\chi_1,\chi_2)\,df d\chi_1 d\chi_2, \quad (2)$$

where $E_{rec}(f,\chi_1,\chi_2)$ is a Fourier component of the signal received by the radar receiver at the given antenna coordinates; S is the surface of antenna aperture, superscript * denotes complex conjugation.

Reference signal from idealistic scatterer $E_m(f,\chi_1,\chi_2)$ is to be substituted from (1) taking $\zeta(x,y,z)=1$. The propagation factor $h(f,\chi_1,\chi_2,x,y,z)$ is to be obtained from geometrical consideration of relative positions of antenna and scatterer and model of propagation. Let us denote for simplicity the coordinates of Tx/Rx antenna as radius-vector $\vec{R}_\chi$ and coordinates of the point of interest as $\vec{R}_{xyz}$. For the far zone of the antenna the propagation factor can be written as follows:

$$h\left(f,\vec{R}_\chi,\vec{R}_{xyz}\right)=\frac{P\left(\vec{R}_\chi,\vec{R}_{xyz}\right)^2 e^{-\frac{4\pi i\left|\vec{R}_\chi-\vec{R}_{xyz}\right|}{c}}}{\left|\vec{R}_\chi-\vec{R}_{xyz}\right|^2}, \qquad (3)$$

where $P\left(\vec{R}_\chi,\vec{R}_{xyz}\right)$ is pattern of the physical antenna; c is propagation velocity of radio frequency in the medium. Low variation of amplitude part of (3) enables to leave only phase part of the signal propagation factor.

When SAR antennas move with low velocity and transmitting-receiving is carried out at certain positions, it is possible to substitute integral over χ_1 and χ_2 by a sum over all antenna positions. Besides, due to the limited duration of signal, integration over frequencies can be substituted by sum over frequency spectrum components.

The cross-range resolution in both angular directions is defined by the corresponding dimensions of synthetic aperture and wavelength of the probing waveform. For simulation of 2D imaging via 2D aperture synthesis an object has been formed as a set of scattering points, which are shown in Fig. 1. The image of this object generated with rectangular scanning geometry is shown in Fig. 2.

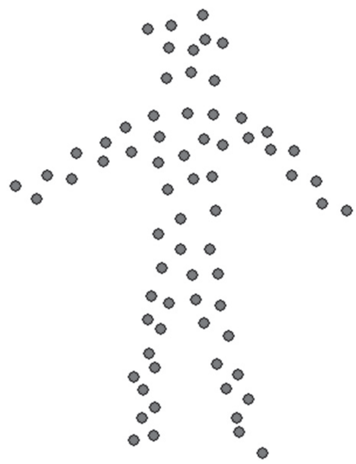

Fig. 1. 2D model formed by a number of point-like scatterers

Simulation was done for the following parameters: carrier frequency 3.6 GHz; power spectrum bandwidth 200MHz; range 1m; synthetic aperture dimensions 0.6x0.6 m; size of radar field of view 2.4x2.4m; spacing between antenna positions 2.5cm.

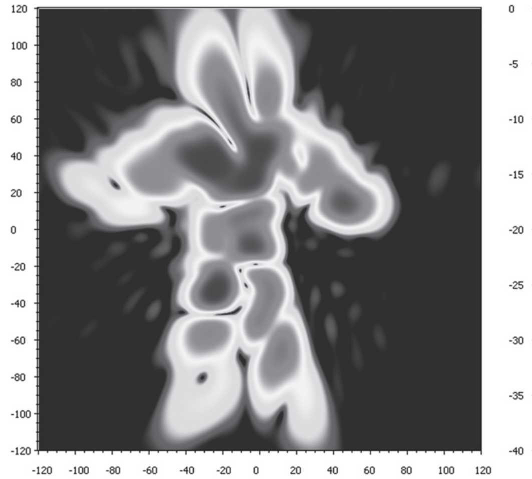

Fig. 2. 2D coherent image generated with the help of 2D aperture synthesis and noise waveform. Modeled taget is shown in Fig.1

II. 3D IMAGE GENERATION USING NOISE WAVEFORM AND 2D APERTURE SYNTHESIS

Microwaves are reflected by human body and by metals. The principle of tomographic 3D imaging consists in illumination of the object of interest with a broadband signal enabling to get high enough range resolution and in formation of 2D image for providing the angular resolution required. This is based on the fact that microwaves can penetrate through many artificial and natural media which are optically opaque. Dielectric materials such as plastics and organic materials will cause partial reflection of the waves and partial transmission so they will be seen as partially transparent. Having the reference signal we can vary its delay and thereby perform range focusing which enables generation of 2D image (tomographic slice) from certain range inside transparent object, separately. In this way, application of noise waveform with wide enough power spectrum bandwidth enables layer-by-layer visualization of a semitransparent object and, therefore, generation of its tomographic 3D image.

The Noise Radar system uses illumination by random signal and coherent detection (both amplitude and phase) of the scattered wave. Noise waveform with a variable power spectral density width enables controlling the resolution in depth of the 2D Imaging. The range resolution is defined by the power spectrum bandwidth, as

$$\Delta z = {}^{c}\!/_{2\,\Delta f},$$

where Δf is power spectrum bandwidth, c is the velocity of light.

Use of random waveform delivers such benefits as absence of range ambiguity and improving immunity against external electromagnetic interferences [1-3]. Thus imaging with 2D aperture synthesis and noise waveform enables tomographic 3D imaging through the range resolution of the wideband radar.

III. EXPERIMENT FOR INDOOR 3D SAR IMAGING

Experiment was carried out using 3.5GHz transceiver. Noise continuous waveform (CW) with 300MHz bandwidth and 20mW transmit power was used for sounding. 2D rectangular SAR scanning was implemented by moving a receive antenna on special supplement construction. Transmit antenna remained the same position during the measurements which lead to loss of half of the angular resolution but enabled to overcome high crosstalk between antennas and simplify the construction. Synthetic aperture dimensions of 0.6x0.6m defined angular resolution in both cross range axis of about 8°. Radar return and reference signals were down converted to intermediate frequency band and digitized with a 1Gs/s 8bit ADC and then processed in a PC using the proposed algorithm. Dynamic range of the generated 2D and tomographic images reaches 42dB which is determined by 7bit effective vertical resolution of the ADC.

Fig. 3 shows a picture of the experiment scenario.

Fig. 3. Scenario for tomographic 3D SAR imaging

The scheme of the experiment includes position of the SAR receive aperture and two test targets shown on the Fig. 4. The measurements were carried out in a laboratory room with concrete walls and floor. Inside the room, there were several tables with equipment, metal chairs and multiple metal objects.

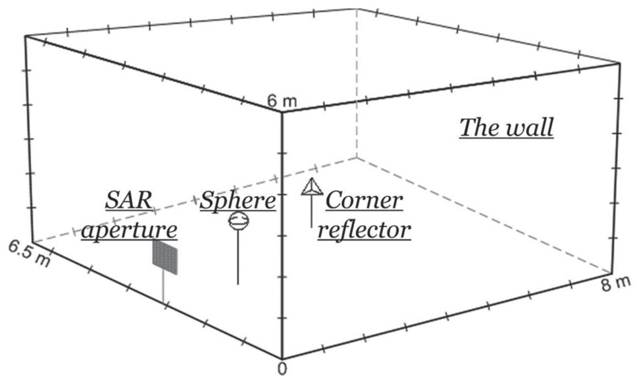

Fig. 4. Scenario for the experiment (see picture of the scene in fig. 3)

Two targets having rather strong reflectivity were placed in the radar field of view inside the room: a duralumin corner reflector and a polyethylene sphere covered with aluminum foil (Table 1). The targets positions were measured from the SAR aperture center.

Table 1

Details of the experimental setup

Features of the targets	Sphere	Corner reflector
Range, m	1.6	4.8
Cross range, m	-0.5	0.8
Elevation, m	-0.1	-0.4
Size, m	radius=0.1	length=0.3
Radar cross section, m^2	$31.4 \cdot 10^{-3}$	19.7
Size of the angular resolution cell at the distance of the target, m	0.5	1.3

Fig. 5 shows a 2D SAR image obtained using the data from these tomographic measurements (top view). The sphere and the corner reflector are clearly seen in the image. Besides, the back wall of the room, tables and chairs could be easily recognized in the image as well.

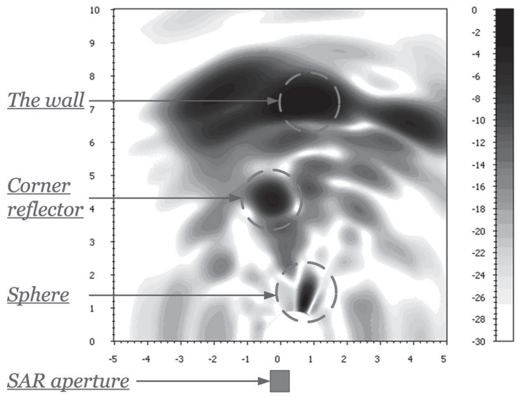

Fig. 5. 2D 'range'-'cross range' SAR image of laboratory room; top view (see picture of the scene in Fig. 3)

Fig. 6 shows vertical slice of tomographic 3D SAR image at the distance of 1.6m which corresponds to the sphere position. The target is clearly seen in the image.It has to be noted that at this distance from the radar synthetic aperture all the resolutions along all three coordinate axis (elevation, azimuth and range) are comparable (Table 1).

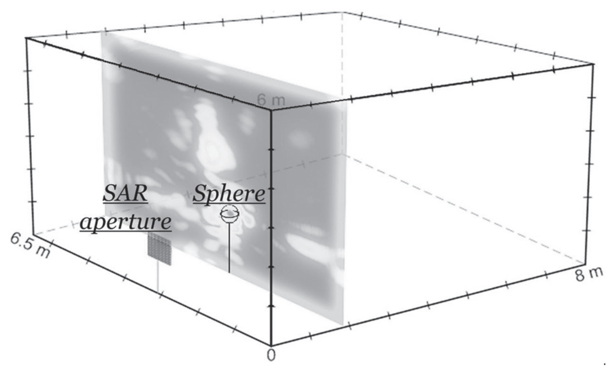

Fig. 6. Vertical slice of tomographic 3D SAR image at the distance corresponding to the sphere position

Fig. 7 shows vertical slice of tomographic 3D SAR image at the distance of 4.8m which corresponds to position of the corner reflector. The latter is also focused well. Besides, responses from chairs and tables can be also found in this image. Fig. 8 shows vertical slice of tomographic 3D SAR image at the distance of 8m which corresponds to the back wall of the room and shows strong reflection from this wall. Magnitudes of the responses are in a good agreement with the known RCS values of the reflectors. Positions of the detected peaks are in a good agreement with the placement of the radar targets (listed in Table 1). Range and angular resolutions obtained are close to their theoretical values. Application of Noise waveform and coherent reception of the radar returns enabled performing tomographic radar measurements inside the room containing high number of reflectors and, also, at the presence of multiple reflections from the walls. Experimental results have shown high repeatability of the measurements.

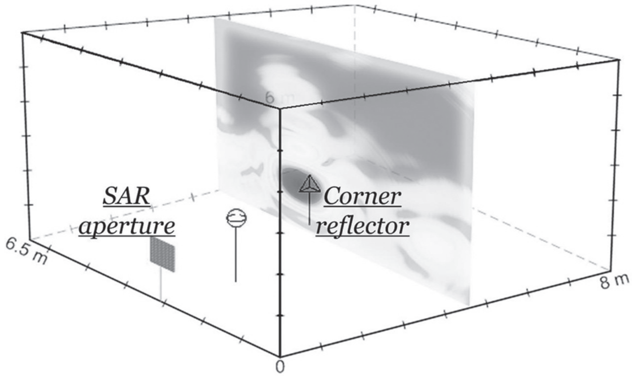

Fig. 7. Vertical slice of tomographic 3D SAR image at the distance corresponding to position of the corner reflector

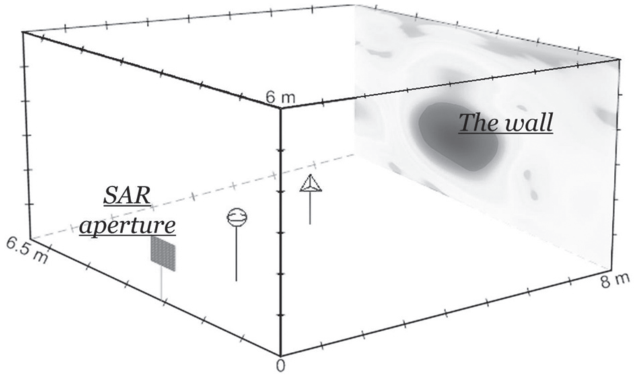

Fig. 8. Vertical slice of tomographic 3D SAR image at the distance corresponding to the back wall position

CONCLUSIONS

A method for generation of tomographic 3D microwave images based upon 2D Aperture Synthesis and Noise Radar Technology has been considered theoretically and validated experimentally.

We have carried out computer modeling of noise radar operation in 2D aperture synthesis mode. The code developed gives a possibility to simulate: (1) tomographic 3D image generation for various 2D synthetic aperture geometries; (2) simulation of the response from point scatterer and (3) perform space-time processing. Besides, this code can be used for processing of realistic radar data and for generation of tomographic 3D SAR images.

We have analyzed resolution and sidelobes of various configurations of synthetic aperture through the modeling of 1D and 2D aperture synthesis. Besides, we have carried out experiment for tomographic 3D SAR imaging using S-band (3.5 GHz) continuous waveform noise radar and 2D rectangular synthetic aperture. In these experiments we have shown possibility to generate tomographic 3D SAR images and to measure positions of strong scatterers in these images. The method is promising for many applications, in particular for homeland security and covert terrorist detection inside buildings.

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Формирование томограмм с помощью шумового радара и двумерного апертурного синтеза / К.А. Лукин, П.Л. Выплавин, В.В. Кудряшев, В.П. Паламарчук, Джонг-Мин Ли, Джонг-Су Ха, Сан-Гу Сан, Юн-Сик Канг, Кью-Гонг Чо, Бьюньг-ла Чо // Прикладная радиоэлектроника: науч.-техн. журнал. – 2013. – Том 12. – № 1. – С. 152–156.

Реализация двумерного апертурного синтеза позволяет получить двумерное угловое разрешение, которое в комбинации с разрешением по дальности позволяет формировать томографические трехмерные изображения. Томографические трехмерные изображения могут дать детальную и точную информацию о пространственном распределении полупрозрачных объектов или других зондируемых областей. Радарная томография может быть реализована с помощью любого типа радара с высоким разрешением; однако эта статья сфокусирована на *шумовой радарной томографии.* Мы приводим результаты моделирования работы широкополосного шумового радара в комбинации с двумерным апертурным синтезом и представляем некоторые результаты эксперимента по получению томографических изображений, используя непрерывные шумовые сигналы S-диапазона и двумерный апертурный синтез.

Ключевые слова: шумовой сигнал, радарная томография, формирование трёхмерных РСА изображений, шумовой РСА.

Табл. 1. Ил. 8. Библиогр. 4 назв.

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Реалізація двовимірного апертурного синтезу дозволяє отримати двовимірну кутову роздільну здатність, яка в комбінації з роздільною здатністю за дальністю дає змогу формувати томографічні тривимірні зображення. Томографічні тривимірні зображення можуть дати детальну та точну інформацію про просторовий розподіл напівпрозорих об'єктів або інших областей, що зондуються. Радарна томографія може бути реалізована за допомогою будь-якого типу радара з високою роздільною здатністю; проте ця стаття сфокусована на шумовій радарній томографії. Ми описуємо результати моделювання роботи широкосмугового шумового радара в комбінації з двовимірним апертурним синтезом і представляємо деякі результати експерименту з отримання томографічних зображень, використовуючи безперервні шумові сигнали S-діапазону і двовимірний апертурний синтез.

Ключові слова: шумовий сигнал, радарна томографія, формування тримірних РСА зображень, шумовий РСА.

Табл. 1. Іл. 8. Бібліогр. 4 найм.