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SAR TOMOGRAPHY FOR SHORT RANGE APPLICATIONS USING MIMO GROUND BASED NOISE WAVEFORM SAR

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SAR tomography based upon MIMO concept with channels time-division is described. Preliminary results of its experimental validation using Ka-band ground based noise waveform SAR are presented. Two different linear synthetic apertures have been used for both transmitting and receiving antennas oriented in vertical and horizontal directions, respectively. Range resolution in SAR tomography is determined by power spectrum width of the transmitted signal, while its cross-range resolution is defined by both 2D aperture dimensions and working wavelength.

Keyword: noise radar, noise waveform SAR, SAR tomography, antenna with pattern synthesizing.

INTRODUCTION

Tomographic 3D imaging of partially transparent scenes may be implemented, for instance, via generation of a series of 2D images as cross-range slices at different range bins which is possible to implement when applying both a high resolution radar and 2D aperture synthesis for each range bin. Earlier we have demonstrated implementation 3D tomographic imaging of a laboratory room interior using Noise Radar Technology [1, 2] and 2D real aperture synthesis [3].

The paper is devoted to investigation and implementation of millimeter wave band SAR tomography technique based upon Multiple-Input-Multiple-Output (MIMO) principle with time-division of signals in transmit/receive (Tx/Rx) channels. We briefly describe MIMO operational mode for 2D aperture synthesis which has been implemented with the help of Ka-band (36.5 GHz) ground based noise SAR and Antenna with Beam Synthesizing [3, 4]. In the following section the algorithm for 3D image generation using data acquired in MIMO SAR mode is given schematically. The last section of the paper is devoted to description of the results of outdoor experiments on 2D and 3D imaging of realistic scenes.

1. MIMO GROUND BASEDNOISE SAR

The principle of tomographic 3D imaging consists in illumination of an object of interest with a wideband signal enabling high enough range resolution and in formation of 2D aperture for providing cross-range (angular) resolution required. Dielectric materials in the scene, 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 sampled we can vary its delay and thereby perform range focusing. This enables generation of 2D images (tomographic slices) for every range bin inside transparent object in the scene. In this way, application of noise waveform with wide enough power spectrum bandwidth enables layer-by-layer visualization of a semitransparent scene and, therefore, generation of its tomographic 3D image. Noise SAR [1, 2, 5] transmits random signals and assures coherent reception of the scattered waves that provides information on their amplitude and phase. Noise waveform with a variable power spectrum width enables controlling the radar resolution along the range, which is the 3rd coordinate of the tomographic image. The range resolution is defined by the power spectrum bandwidth as follows: $c/2B$, where c is light propagation velocity.

Usually, for 2D aperture synthesis mechanical motion of Tx and/or Rx antennas over a planar synthetic aperture is performed with transmission and reception of signals, at the equidistant grid nodes. Positioning system for such 2D movement may be complex and expensive. We suggested generation of virtual 2D synthetic aperture via moving of both Tx and Rx antennas along orthogonal directions. 2D scan is done in the following way: Tx antenna takes its first position, and Rx antenna performs SAR scan along horizontal path. After that, Tx antenna is displaced to another position along vertical path, and a new SAR scan is performed by the Rx antenna. Every scan of the Rx antenna enables generation of a 2D image in the plane of Rx synthetic aperture. For different Tx antenna positions, those images will contain information on phase shift of the signal due to movement of the Tx antenna phase center. The information may be used for cross-range (angular) compression.

In this way, application of MIMO 2D aperture synthesis and noise waveform that give both angular and the range resolutions, enables tomographic 3D imaging described in the sections below.

2. ALGORITHM FOR TOMOGRAPHIC SAR IMAGING

Tomographic SAR under consideration has separated Tx and Rx antennas with beam synthesizing. Phase center (radiator/receiver) of the antenna can be moved along its aperture. Radar returns are sampled during data acquisition, when varying radiator / receiver positions for scene imaging. We suppose that Tx radiator phase center was placed at N positions along its aperture. At each of these positions, radiator of the Tx antenna did not move when transmitting continuous waveform (CW) noise signal. Part of the transmitted signal was coupled, sampled and used as a reference signal, while Rx antenna phase center was sequentially placed at M positions along Rx antenna aperture, where the radar returns have been received during the integration time. Both the reference and the received radar return are down converted, sampled and saved in on-board memory. We assume that every record of both the reference and the radar returns contains L samples. This gives two 3D arrays of samples: $S_{m,n,l}$ for the reference signal $X_{Ref}(t,r_R,r_T)$ and $C_{m,n,l}$ for the radar returns $X_{RR}(t,r_R,r_T)$, where r_T and r_R are coordinates of SAR Transmit and Receive antenna, respectively; $m = 1...M$, $n = 1...N$, $l = 1...L$.

The first step in the signal processing is a standard one for the SAR imaging: so called range compression, which gives range profiles. The profiles are related to every realized combination of the Tx and Rx radiator/receiver positions. This can be done via estimation of cross correlations between the received signals and the reference signals. In case of noise radar the intermediate frequency (IF) copy of the transmitted signal $X_{Ref}(t,r_R,r_T)$ is to be used as the reference function:

$$R(\tau,r_T,r_R) = \frac{1}{T}\int_{\tau}^{T+\tau} X_{Ref}(t,r_T,r_R)X_{RR}(t,r_T,r_R)dt\ ,$$

where τ is mutual delay between the reference signal and the radar returns, acquired when signal propagating from transmitter towards a scene point and back to the receiver:

$$\tau = \tau(r,r_R,r_T) = \left\{|r - r_T| + |r - r_R|\right\}/c\ ,$$

which is the function of the coordinates r of the point of interest and the Tx/Rx antennas positions: r_T, r_R. The cross-correlation is estimated in frequency domain. The range resolution may be improved using adaptive algorithms, designed for such signal processing [6, 7].

The second step in the signal processing is the angular compression. It can be done either separately for azimuth and elevation planes, or alternatively, as a single procedure. The idea of the angular compression can be explained as follows. We choose a point of interest in the scene. If a target is present at this point, it will leave responses in the range profiles acquired at all the antenna positions. Both compensation of the phase shifts acquired by signals when propagating towards the point and back to every position of Rx receive antenna and further summation of the radar returns will result in a peak, if the target really existed in the point of interest. In this way, the resulting value, assigned to the 3D pixel is:

$$I(r) = \frac{1}{L_T L_R}\iint\limits_{L_T L_R} R[r_T,r_R,\tau(r,r_T,r_R)]e^{i\omega\tau(r,r_R,r_T)}dr_T dr_R\ ,$$

where ω is circular carrier frequency of RF signal.

This equation may be rewritten in discrete form:

$$I(r) = \sum_{m=1}^{M}\sum_{n=1}^{N} R_{m,n,\tau}e^{i\omega\tau(r,m,n)}\ . \qquad (1)$$

Eq.(1) enables formation of tomographic SAR image and its cross section along any plane provided proper transformation of the coordinates. Known properties of sounding signal enable application of detection rule to the generated images [8, 9]. Note that the approach (1) properly modified enables generation of the images with multistatic passive system, as well [10, 11].

Thus 2D aperture synthesis in combination with range resolution capability of wideband noise signals gives a possibility of performing tomographic SAR images in both active and radiometric modes. Usage of random waveform gives such benefits as absence of range ambiguity and improving immunity against external electromagnetic interferences, providing high EMC performance [1–5].

3. TOMOGRAPHIC SAR IMAGING

Tomographic SAR imaging experiments have been carried out using Ka-band (36 GHz – 36.5 GHz) Ground Based Noise Waveform (GB NW) SAR [4]. Noise CW with 480 MHz band width and 1 mW transmit power was used as a sounding signal. Special type of millimeter wave antennas, the antenna with pattern synthesizing [3], was used for both 2D and tomographic SAR imaging (Fig. 1).

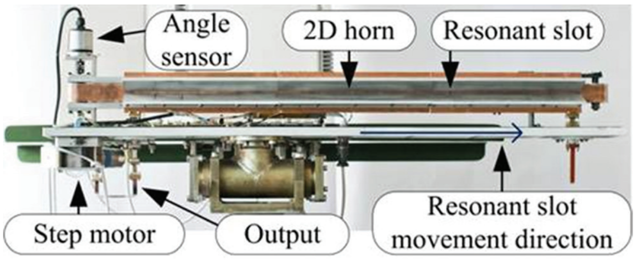


Fig. 1: Ka-band Antenna with Pattern Synthesizing

In those antennas, a vertically oriented half-lambda transmit/receive slot antenna moves along a real aperture when transmitting/receiving signals. One antenna of that type has been oriented vertically for the random signal transmission while another antenna with pattern synthesizing was fixed horizontally for the radar returns reception (Fig. 2).

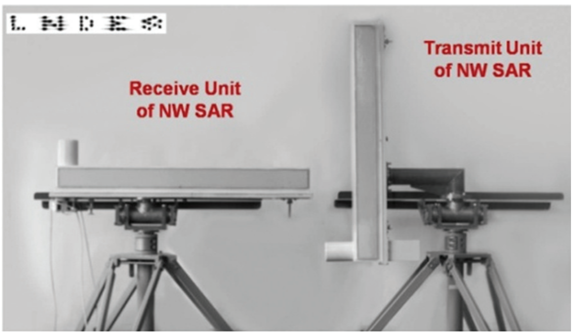


Fig. 2:Ground Based Noise Waveform SAR for MIMO mode with time division of Tx and Rx channels

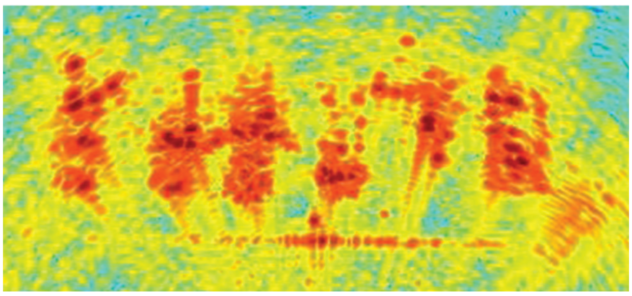
Each antenna has synthetic aperture length of 0.7 m, which defined angular resolution in elevation and azimuth. Further application of 1D or 2D aperture synthesis along with range compression technique enables generation of 2D SAR images and 3D images, respectively. In this way, the designed experimental setup allowed obtaining coherent images in vertical transmit and horizontal receive (VH) cross-polarization MIMO mode.

Radar returns and reference signals were down converted to IF band and sampled with a fast analog-to-digital converter (ADC) from GaGe Company. The ADC has two 1 GHz instant pass-band channels with 1Gs/s sampling rate and 8 bit depth resolution. The sampled radar returns and reference signals are processed in a PC using the above algorithm (1). Dynamic range of the generated images reaches 42 dB which is determined by 7 bit effective depth resolution of the ADC.

The first measurements were carried out inside the LNDES laboratory room with concrete walls, ceiling and floor. A polyethylene sphere covered with aluminum foil was placed in the middle of the room. The sphere was used as the reference target. At the same time, inside the room there were several laboratory tables with electronic devices and equipment, PCs, metal chairs and multiple metal objects. The measurements allowed validating the suggested tomographic SAR method. In particular, they have shown that both range and angular resolutions obtained are in a good agreement with their theoretical expectations.

Series of outdoor imaging experiments was carried out using the same Ka-band GB NW SAR equipment [5]. Noise CW with 480 MHz band width and 300 mW transmitted power was used as a sounding signal. The area for tomographic SAR imaging contains some vehicles and radars, shown in Fig. 3, *a*. Fig. 3, *b* shows SAR image of the scene where we may observe good identification of all targets.

a



b

Fig. 3. Photo of the scene (*a*) and its SAR image (*b*)

Fig. 4 shows 2D slice of the tomographic image along the planes inclined by 10 deg., 20 deg. and 30 deg. It is seen that unlike the first SAR picture, which contains images of all vehicle and also concrete step in the front of the scene, the second picture shows only image of the vehicles without concrete step, while the third image shows only radar antenna reflector. These results clearly illustrate capability of the MIMO Noise SAR to generate tomographic SAR images.

Multiple reflections from all the neighboring created a harsh condition for precise phase preserving measurements. However application of Noise signals with wide enough power spectral density and coherent reception of the noise radar returns enabled performing both radar coherent imaging and millimeter wave tomography in harsh conditions.

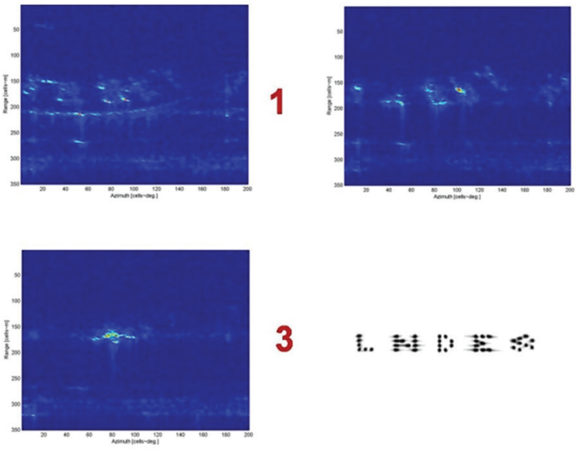


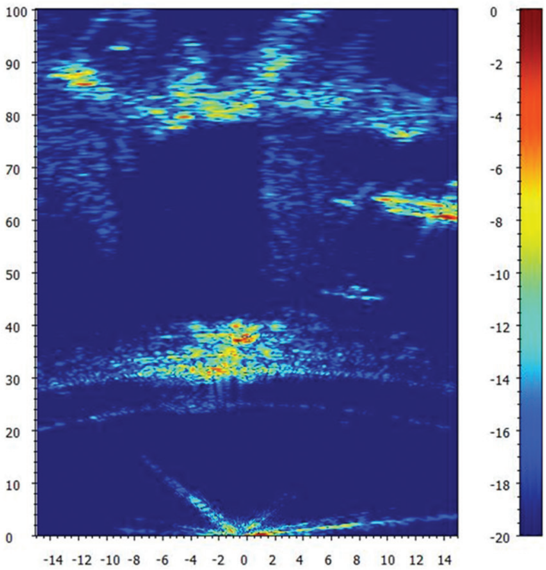
Fig. 4. Azimuthal slices in 3D image of the scene of fig. 2 for three different elevations: 1 – about 10 deg.; 2 – about 20 deg. and 3 – about 30 deg.

Another tomographic SAR imaging experiment was carried out with the help of different GB NW SAR configuration shown in Fig. 5. This SAR has only one transmit antenna and has ability to rotate in elevation plane around horizontal axes of the receive antenna. It has been deployed in the window of a room at the 5th floor of a building (20 m height) to image the yard shown in the Fig. 6, *a*. In this way, transmit antenna was changing its position along an arch and illuminating the scene.

Fig. 5. Ground Based Noise Waveform SAR with horn transmit antenna

Fig. 6, *b* shows one of SAR images of that scene. The image was for –10 deg. elevation angle. Bright area in the middle of the SAR image relates to reflections from pine trees, which also made well pronounced shadow behind them. After that shadowed area, the SAR was able to receive signals reflected by the building in the left side of the scene and far group of trees.

a



b

Fig. 6. Photograph of the yard (*a*) and its SAR image (*b*)

Finally, the bright spot in the right side of the SAR image is due to reflections from the main building. Collected data for different elevation angle give a possibility to generate SAR images in elevation plane. The latter enables generation of 3D SAR images as well. Range and angular resolutions obtained are in a good agreement with their theoretical values.

CONCLUSIONS

Tomographic SAR imaging based upon MIMO concept, Aperture Synthesis and Noise Radar Technology has been considered experimentally and validated experimentally. We have carried out experiments on generation of 3D images, using Ka-band continuous waveform noise radar [5] and two antennas with pattern synthesizing [4]. In these experiments, we have shown both generation of 3D images and capability of focusing the scene targets responses in 3D space, using the proposed approach. The method enabled implementation of Noise SAR Tomography which is promising in many applications, in particular, for homeland security; covert detection of terrorists inside and outside buildings; and others.

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References

[1] *K.A. Lukin.* Noise Radar Technology // Telecommunications and Radio Engineering, Vol. 55, No. 12. – P. 8–16, 2001.

[2] *K.A. Lukin.* Noise Radar Technology: the Principles and Short Overview // Applied Radio Electronics, Vol. 4, No. 1. – P. 4–13, 2005.

[3] *K.A. Lukin et. al.* 2D and 3D imaging using S-band noise waveform SAR // Proc. of the 3rd International Asia-Pacific Conference on Synthetic Aperture Radar (APSAR-2011). – P. 1–4, 2011.

[4] *K.A. Lukin.* Sliding Antennas for Noise Waveform SAR // Applied Radio Electronics, Vol. 4, No.1. – P. 103–106, April 2005.

[5] *K.A. Lukin, et al.* Ka-band Bistaic Ground-Based Noise Wavefom SAR for Short-Range Applications // IET Proc. Radar Sonar & Navigation, Vol. 2. – P. 233–243, August 2008.

[6] *K. Lukin, P. Vyplavin, V. Palamarchuk, O. Zemlyaniy, V. Kudriashov, S. Lukin.* Capabilities of noise radar in remote sensing applications // Proc. of the IEEE Tyrrhenian Workshop on Advances in Radar and Remote Sensing (TyWRRS 2012). – P. 10–17.

[7] *V. Kudriashov.* A modified maximum likelihood method for estimation of mutual delay and power of noise signals by bistatic radiometer // C. R. Acad. Bulg. Sci., Vol. 68, No. 5. – P. 631–640, January 2015.

[8] *D. Tarchi, K. Lukin, J. Fortuny-Guasch, A. Mogyla, P. Vyplavin, A. Sieber.* SAR imaging with noise radar // IEEE Transactions on Aerospace and Electronic Systems, Vol. 46, Iss. 3. – P. 1214–1225, July 2010. DOI: 10.1109 / TAES.2010.5545184

[9] *V.V. Kudriashov.* Non-stationary Random Wiener Signal Detection Criterion Variants for Case of Monostatic Reception // Proc. of the 7th Balkan Conference in Informatics, Article No. 30. – P. 1–4, 2015. DOI: 10.1145 / 2801081.2801089.

[10] *K.A Lukin, V.V Kudriashov, P.L Vyplavin, V.P Palamarchuk, S.K Lukin.* Coherent radiometric imaging using antennas with beam synthesizing // International Journal of Microwave and Wireless Technologies, Vol. 7, Spec. Iss. 3-4. – P. 453–458, June 2015. DOI: http://dx.doi.org/10.1017 / S1759078715000550

[11] *V. Kudriashov.* Non-Stationary Random Wiener Signal Detection with Multistatic Acoustic System // Proc. of the Fourth International Conference on Telecommunications and Remote Sensing, ICTRS 2015. – P. 49–53, 2015.

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РСА томографія на основі наземного MIMO шумового РСА 8-мм діапазону / К. Лукін, П. Виплавін, В. Паламарчук, С. Лукін, А. Шелехов, М. Заец, К. Васюта // Прикладна радіоелектроніка: наук.-техн. журнал. – 2015. – Том 14. – № 3. – С. 257–261.

Описана РСА томографія, заснована на концепції MIMO радарів з часовим поділом каналів. Дві лінійних взаємно ортогональних антени з синтезуванням діаграми спрямованості були використані як передавальна і приймальна антени, орієнтовані у вертикальному та горизонтальному напрямках, відповідно. Роздільна здатність за дальністю в РСА томографії визначається шириною спектра потужності переданого сигналу, а його роздільна здатність в поперечному напрямку визначається розмірами апертур антен і робочою довжиною хвилі. Представлені попередні результати її експериментальної перевірки з використанням наземного шумового РСА 8-мм діапазону.

Ключові слова: шумовий радар, наземний шумовий РСА, РСА томографія, антена з синтезуванням діаграми спрямованості.

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Описана РСА томография, основанная на концепции MIMO радаров с временным разделением каналов. Две линейных взаимно ортогональных антенны с синтезированием диаграммы направленности были использованы в качестве передающей и приемной антенн, ориентированных в вертикальном и горизонтальном направлениях, соответственно. Разрешающая способность по дальности в РСА томографии определяется шириной спектра мощности передаваемого сигнала, а его разрешающая способность в поперечном направлении определяется размерами апертур антенн и рабочей длиной волны. Представлены предварительные результаты ее экспериментальной проверки с использованием наземного шумового РСА 8-мм диапазона.

Ключевые слова: шумовой радар, наземный шумовой РСА, РСА томография, антенна с синтезированием диаграммы направленности.

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