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Terahertz Three-dimensional SAR Imaging Using Time- and Frequency-Domain Algorithms

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Abstract—Terahertz (THz) SAR opens opportunity for some new applications, e.g., sub-mm localization based on 3D SAR imaging, that cannot be based on the conventional SAR operating at frequency ranges below THz. For 3D THz SAR imaging, the image formation algorithms play an important role. Two 3D SAR image formation algorithms, Range Migration (RM) operating in frequency domain and Backprojection (BP) operating in time domain are considered in this comparative study. The algorithms are first used to form 3D images from simulated THz SAR data. The comparison is then based on image quality measurements such as range and cross-range resolutions, and peak sidelobe ratio (PSLR).

Index Terms—THz, SAR, algorithm, resolution, PSLR

I. INTRODUCTION

Although terahertz (THz) has been known for many decades [1], the applications are very limited and mainly used in, e.g., astronomy [2]. High-complexity and cost of the devices are challenges that prevent THz to be universally used. In addition, due to the high atmospheric absorption at the THz region [3], the propagation range is short. This limits the applications of THz.

SAR is a radar technique that synthesizes long aperture based on the movement of the radar platform. Typical SAR applications can be categorized into three groups imaging, change detection and ground moving target indication (GMTI). 3D imaging with conventional SAR is an unpopular application because forming an aperture plane with many elevation passes is a difficult task for airborne and spaceborne SAR systems.

The research on THz SAR has been emerged recently. Several novel THz SAR testbeds based on radar frontends [4]- [6] and vector network analyzer (VNA) [7]- [9] have been experimented. In [8], a VNA based testbed has been setup for the measurements at a center frequency of 275 GHz with a bandwidth of 110 GHz to investigate the resolution and quality of THz SAR images. In this frequency region, the spatial resolution of a SAR system is down to the order of mm that cannot be reached by the conventional SAR systems such as TerraSAR-X and TanDem-X. However, with limited propagation, THz SAR can aim at the indoor applications such as room profiling, material characterization, classification

and sub-mm localization in which 3D SAR imaging has advantages. With 3D SAR imaging, the short-range application such as sub-mm localization can provide the exact position of object of interest in space which is unfeasible with 2D SAR imaging. For an indoor SAR system, e.g., mounted on a drone, it is not a challenge for forming an aperture plane with many elevation passes.

With THz SAR data cube obtained from measurements, 3D images of the monitored space can be reconstructed using 3D SAR image formation algorithms. Applying the same categorization used for 2D SAR imaging, the 3D SAR image formation algorithms can be divided into two groups: time domain and frequency domain. For time domain algorithms, the reflecting radar signals in time domain are projected on a defined plane based on radar range calculations. For frequency domain algorithms, the spectrum of reflecting radar signals is mapped into the spectrum of a defined image based on the so-called Stolt interpolation. High image quality and low complexity are always objectives for any algorithm.

The paper gives a comparison between the uses of the time- and frequency-domain algorithm for THz 3D SAR imaging. Two 3D SAR image formation algorithms, Range Migration (RM) operating in frequency domain and Backprojection (BP) operating in time domain are considered in this comparative study. The algorithms are first used to form 3D images from simulated THz SAR data. The comparison is then based on image quality measurements such as range and cross-range resolutions, and peak sidelobe ratio (PSLR).

The rest of the paper is organized as follows: Section II discusses about the 3D indoor SAR geometry. The considered 3D SAR image formation algorithms are briefly presented in Section III. Section IV provides the simulations results for the comparison purposes. Section V summarizes the concluding remarks.

II. 3D INDOOR SAR GEOMETRY

Consider a 3D indoor SAR geometry sketched in Fig. 1. The radar aperture is arranged in a planar array which is a combination of a set of linear apertures. There are M linear apertures (x - direction) and each linear aperture has also N aperture positions (y -direction). The total number of aperture positions is therefore $M \times N$. The aperture step in both x - and y - directions are set in the principle that the pulse repetition

Fig. 1. 3D indoor SAR geometry.

frequency (PRF) must not be less than two times the maximum Doppler frequency.

Assume that there is a SAR system mounted on a platform, e.g., drone. The platform starts at the coordinate $(-x_0/2, -y_0/2)$ and flights along the first linear aperture in x - direction before move to next linear aperture so that the last coordinate of the platform is $(x_0/2, y_0/2)$. The zigzag flight path of the platform is defined by $(x_p(t_x, t_y), y_p(t_x, t_y))$ changing with respect the cross-range times t_x and t_y .

A scatterer is placed symmetrically in front of the aperture. The reflection from the object $s(t_x, t_y, \tau)$ will be recorded at each aperture position and is expressed by

$$s(t_x, t_y, \tau) = A \exp \left\{ j2\pi\nu_c \left(\tau - \frac{2r(t_x, t_y, \tau)}{c_0} \right) + j\pi\kappa \left(\tau - \frac{2r(t_x, t_y, \tau)}{c_0} \right)^2 \right\} \quad (1)$$

where A is amplitude depending on radar cross section, τ is fast time referring to the wave propagation, c_0 is the speed of propagation, ν_c is the center radar frequency and κ is the chirp rate. The radar range $r(t_x, t_y, \tau)$ in (1) is estimated by

$$r(t_x, t_y, \tau) = \sqrt{(x_p(t_x, t_y) - x_t)^2 + (y_p(t_x, t_y) - y_t)^2 + z_t^2} \quad (2)$$

where (x_t, y_t, z_t) is the scatterer's coordinate. If the data measured at each aperture position is stored in a 3D matrix, the dimensions of the data will be $M \times N \times P$ where P is the number of range samples. Hence, we obtain a data cube after a 3D indoor SAR measurement.

III. 3D INDOOR SAR IMAGE FORMATION ALGORITHM

Transforming an indoor SAR data cube to 3D SAR image can be carried out in both time- and frequency domain leading to two groups of algorithms. In this section, we present two 3D SAR image formation algorithms, Range Migration (RM) operating in frequency domain and Backprojection (BP) operating in time domain.

A. Backprojection

Global Backprojection (GBP) algorithm has been known as the basic of the time-domain algorithms. The principle of GBP is the superposition of the reflecting radar signals with respect to the radar ranges. The ranges are calculated for all aperture positions and all image pixels defined in an image space. The most convenient way is to define an image space in the space (ξ, η, ζ) where ξ - and x - axes are coincide, and η - and y - axes are coincide. In this case, the range ρ is calculated by

$$\rho = \sqrt{(\xi - x_p)^2 + (\eta - y_p)^2 + \zeta^2} \quad (3)$$

For single image pixel, we need to calculate the range $M \times N$. The value of the image pixel (ξ, η, ζ) is given by

$$\iota(\xi, \eta, \zeta) = \sum_x \sum_y s\left((x, y), \frac{2\rho}{c_0}\right) \quad (4)$$

where the sums perform the superposition of the reflecting radar signals with respect to the calculated ranges.

For a 3D image, the number of image pixels is K^3 . This leads to a huge number of operations ($\propto M \times N \times K^3$) to form a 3D SAR image using GBP. In the special case where $M = N = K$, we can say that the number of operations required by 3D GBP is proportional to N^5 resulting in to very long processing time.

A solution for long processing time is to use the fast versions such as fast backprojection (FBP) using the concepts: subimage and subaperture [10]. A set of adjacent image pixels in ξ -, η - and ζ - directions belonging to the defined image space forms a subimage whereas a planar subaperture is formed by a set of the adjacent aperture positions in both x - and y - directions. We assume that the aperture plane is equally divided into L subaperture while the image space is equally divided into K subimages. The mathematical expression for the subdata formed with the data of the l -th subaperture for the k -th subimage is

$$\tilde{s}_{l,k}\left(\tilde{x}_l, \tilde{y}_l, \frac{2\tilde{\rho}_{l,k}}{c_0}\right) = \sum_x \sum_y s\left((x, y), \frac{2(\rho_k - \Delta\rho_k)}{c_0}\right) \quad (5)$$

where $(\tilde{x}_l, \tilde{y}_l)$ is the center of the subaperture, the distance between the aperture positions belonging to the l - subaperture to the center of subimage $(\tilde{\xi}_k, \tilde{\eta}_k, \tilde{\zeta}_k)$ is calculated by

$$\rho_k = \sqrt{(\tilde{\xi}_k - x)^2 + (\tilde{\eta}_k - y)^2 + z^2} \quad (6)$$

The shift in time (fast time) with respect to the center of the k -th subimage for forming subdata is represented by the term $(2\Delta\rho_k)/c_0$ in (5), where

$$\Delta\rho_k = \rho_k - \sqrt{(\tilde{\xi}_k - \tilde{x}_l)^2 + (\tilde{\eta}_k - \tilde{y}_l)^2 + \tilde{\zeta}_k^2} \quad (7)$$

The square rooted term in (7) is the distance from the center of the l -th aperture to the center of the k -th subimage. The number of the subdata is given by the number of subapertures times the number of subimages, i.e., $L \times K$. The value of

the image pixel (ξ, η, ζ) is given belonging to k -th image is estimated by

$$\iota_k(\xi, \eta, \zeta) = \sum_{l=1}^L \tilde{s}_{l,k} \left((\tilde{x}_{l,k}, \tilde{y}_{l,k}), \frac{2(\tilde{\rho}_{l,k} + \Delta\rho)}{c_0} \right) \quad (8)$$

where $\Delta\rho = \rho - \tilde{\rho}_{l,k}$ with ρ is given by (4). This procedure will be repeated for all K subimages. The 3D SAR image is finally retrieved by a combination of K subimages.

Equation (8) is an approximation of (4) and the phase error caused by this approximation depends on the values L and K . To limit the phase error $\Delta\phi \leq \pi/8$, L and K are selected so that

$$\frac{d_L d_K}{\rho} \leq \frac{\lambda}{4} \quad (9)$$

where λ is the radar wavelength, d_K denotes the maximum dimension of the subimage space (diagonal of cube) and d_L denotes the maximum dimension of the subaperture plane (diagonal of rectangle).

Forming 3D SAR images using FBP helps to reduce the number of operations with a factor of $\sqrt{N}$ in comparison to GBP.

B. Range Migration

The proposed processing scheme for the 3D RM algorithm is similar to a processing scheme for 2D range migration algorithm [11]. The differences come the 3D input and the 3D output leading to the modifications of the reference function and the interpolation. Because the 3D RM algorithm operates in frequency domain, in the first processing step, the SAR data cube (1) in time domain is transformed to the frequency domain using 3D fast Fourier transform (FFT). The bulk compression is implemented by multiplying the spectrum of SAR data cube with the conjugate complex of the reference function

$$S(f_x, f_y, \nu) = \exp \left\{ -\frac{j\pi\nu^2}{\kappa} - \frac{j4\pi z_t}{c} \sqrt{(\nu_c + \nu)^2 - \left(\frac{f_x c}{2\delta_x} \right)^2 - \left(\frac{f_y c}{2\delta_y} \right)^2} \right\} \quad (10)$$

where f_x, f_y and ν are cross-range frequencies and radar signal frequency, respectively. The reference function (10) is also derived from (1) based on the method of stationary phase. We can see that the different between the reference functions used for 2D and 3D is only the last term inside the squared root term in (10). It relates to the extra dimension given by the data cube in comparison to the data matrix.

For mapping the bulk-compressed data cube in frequency domain into 3D image spectrum, a 3D interpolation, that is similar to Stolt interpolation in 2D, is required. The relationship between the radar signal frequency ν_τ and the wavenumbers (k_ξ, k_η, k_ζ) , i.e. the $\omega - k$ relationship, can be shown to be

$$\omega = \frac{c_0}{2} \sqrt{k_\xi^2 + k_\eta^2 + k_\zeta^2} \quad (11)$$

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Frequency span	220GHz–330GHz
Minimum range	2m
Aperture step in x - direction	0.002 m
Aperture step in y - direction	0.002 m
Aperture positions in x - direction	101
Aperture positions in y - direction	101
First aperture coordinates	(−0.1, −0.1)
Last aperture coordinates	(0.1, 0.1)
Scatterer's coordinate	(−0.02, −0.02, 1.98) (0.00, 0.00, 2) (0.02, 0.02, 2.02)

where $\omega = 2\pi\nu$ is the angular frequency of the radar signal. A remark is that the $\omega - k$ relationship for 3D interpolation is also similar to the one for 2D interpolation. The difference is the middle term inside the squared root of (11) that relates to the extra dimension.

The $\omega - k$ relationship (11) indicates that the values $S(f_x, f_y, \nu)$ belonging to the 3D isosceles trapezoid will be interpolated into a new 3D space limited by two concentric spheres and a cone with the apex angles are given by the integration angles of the system. A 3D SAR image $\iota(\xi, \eta, \zeta)$ is retrieved by transforming the interpolated data $\mathcal{I}(k_\xi, k_\eta, k_\zeta)$ into image domain using a 3D inverse Fourier transform.

Unlike the time domain algorithms, the number of operations required the frequency domain algorithms in general is directly proportional to the dimension of data cube $M \times N \times P$ and this is also the dimension of a 3D SAR image.

IV. SIMULATION RESULTS

The main parameters for the simulations are summarized in the upper part of Table I. The frequency span for the simulations 220GHz – 330GHz are chosen by the parameters of the experimental THz indoor testbed [8] and [9]. With this frequency span, the fractional bandwidth is $B/f_c = 0.4$ and larger the limit for ultrawideband ($B/f_c \geq 0.25$). Therefore, the simulated system can be seen to be an ultrawideband system. The sampling frequency is selected by $\nu_s = 2\nu_{\max} = 660\text{GHz}$, where $\nu_{\max}$ is the maximum radar signal frequency.

The lower parts of Table I provides the supplement parameters for the simulations. The second part is with the information on platform coordinates and the last part is with the coordinates of the scatterers in the simulated SAR scene. The aperture step and the number of aperture positions in x -direction are selected by $\Delta l_x = 2 \times 10^{-3}$ and $M = 101$, respectively. The aperture step and the number of aperture positions in y -direction are simply selected identically to the ones in x -direction, i.e., $\Delta l_y = 2 \times 10^{-3}$ and $N = 101$. The aperture lengths are therefore 0.2m for both x - and y -directions. The corresponding integration angles are $2\theta_{\max} \approx 5.72^\circ$.

Fig. 2. Slices $\iota(\xi, \eta, [-0.02 \ 0 \ 0.02])$, $\iota(-0.02, \eta, \zeta)$ and $\iota(\xi, -0.02, \zeta)$ of 3D SAR image formed with FBP.

The SAR scene is simulated with three scatterers symmetrically placed in front of the aperture plane. The scatterers are the point-like scatterers placed at three different positions in space. The dimensions of simulated SAR data cube are given by $M \times N \times P = 101 \times 101 \times 1321$.

A. 3D image formation with FBP

The 3D image space is created symmetrically surrounding the center object, i.e., the object with the coordinates $(0.00, 0.00, 2)$. The element spacing in ξ , η and ζ is selected equally and by two times the sampling range, i.e., $c_0 \tau_s = 4.54 \times 10^{-4} \text{m}$, where $\tau_s = 1/(2\nu_{\max})$ is the range sampling time. With the number of space elements $N^3 = 256^3$, the 3D SAR image covers a space of about $0.12 \times 0.12 \times 0.12 \text{ m}$.

If we select $L = 400$, i.e., a subaperture is formed with 5 aperture positions in x -direction times 5 aperture positions in y -direction, the maximum dimension of the planar aperture will be given by the diagonal, i.e., $d_L = 5 \times 2 \cdot 10^{-3} \times \sqrt{2} \leq 1.5 \cdot 10^{-2} \text{ m}$. The condition (9) gives the limit $d_K \leq 3 \cdot 10^{-2} \text{ m}$. With this limit of the diagonal of the subimage space, the length of each edge is limited by $< 1.8 \cdot 10^{-3} \text{ m}$. If we select the length edge by $32c_0\tau_s \approx 1.45 \cdot 10^{-3}$, (9) gives a phase error $\Delta\phi < \pi/12$. In this case, it is understood that the subimage space is defined by $32 \times 32 \times 32$ pixels and the number of subimages is $K = 512$. To further reduce the processing time for the 3D fast backprojection algorithm, we can even select a subimage space, e.g., $64 \times 64 \times 64$ pixels. The length edge is therefore $64 \times c_0\tau_s \approx 2.91 \cdot 10^{-3}$ so that the maximum phase error $\Delta\phi < \pi/6$. The number of subimages is only $K = 64$.

Armed with these algorithm parameters, we form the 3D SAR image with $L = 400$ subapertures and $K = 512$ subimages with the phase error $\Delta\phi < \pi/12$. The zoomed-in slices of the 3D SAR image is given in Fig. 2 considering the slices $\iota(\xi, \eta, [-0.02 \ 0 \ 0.02])$, $\iota(\xi, 0.02, \zeta)$, and $\iota(0.02, \eta, \zeta)$. All scatterers are seen to be well focused and placed at the correct positions.

Fig. 3. Slices $\iota(\xi, \eta, [-0.02 \ 0 \ 0.02])$, $\iota(-0.02, \eta, \zeta)$ and $\iota(\xi, -0.02, \zeta)$ of 3D SAR image formed with RM.

B. 3D image formation with RM

Forming a 3D SAR image using the processing scheme of the RM algorithm is straight forward. The main issue is the implementation of 3D interpolation. After bulk compression, the scatterer associated with the range z_t , i.e., in the middle of the SAR scene, should be focused. However, the other scatterers beyond this range are still unfocused and an interpolation is required to focus them. The bulk-compressed data cube is defined in the intervals

$$\begin{aligned} -\frac{\pi}{\Delta l_{x,y}} &\leq k_{x,y} \leq \frac{\pi}{\Delta l_{x,y}} \\ \frac{4\pi\nu_{\min}}{c_0} &\leq k_r \leq \frac{4\pi\nu_{\max}}{c_0} \end{aligned} \quad (12)$$

whereas the 3D image spectrum is defined in a new space (k_ξ, k_η, k_ζ) . The wavenumbers $k_{\xi,\eta} \equiv k_{x,y}$ while

$$-\frac{2\pi\nu_s}{c_0} \leq k_\zeta \leq \frac{2\pi\nu_s}{c_0} \quad (13)$$

where ν_s is the sampling frequency.

The values inside the 3D isosceles trapezoid whose the parallel sides are parallel to the x - y plane and will be defined by the planes $4\pi\nu_{\min}/c_0$ and $4\pi\nu_{\max}/c_0$. For the sampling frequency given by $\nu_s = 2\nu_{\max}$, then the new 3D space for interpolation will be limited by two concentric spheres of radii $4\pi\nu_{\min}/c_0$ and $4\pi\nu_{\max}/c_0$, and a cone of slant length $4\pi\nu_{\max}/c_0$ and apex angle $2\theta_{\max}$, where $2\theta_{\max}$ has been known as the integration angles of the system.

A perfect 3D interpolation will be a 3D complex sinc interpolation with high complexity. A simpler way to implement 3D interpolation is to upsample the bulk-compressed data cube and then to use a nearest neighbor interpolation. Upsampling the bulk-compressed data cube leads also to high computational cost as the dimensions of the data cube is proportional to the power of three of the oversampling rate. Figure 3 shows the slices $\iota(\xi, \eta, [-0.02 \ 0 \ 0.02])$, $\iota(-0.02, \eta, \zeta)$ and $\iota(\xi, -0.02, \zeta)$ of the 3D SAR image formed with the RM

TABLE II
MEASUREMENT AND ESTIMATION.

Axis	Resolution			PSLR		
	RM $\times 10^{-3}$ [m]	FBP $\times 10^{-3}$ [m]	Diff. [%]	RM [dB]	FBP [dB]	Diff. [dB]
ξ	4.83	4.82	0.2	14.3	14.3	0
η	4.83	4.82	0.2	14.3	14.3	0
ζ	1.21	1.21	0	13.2	13.3	0.1

algorithm. All scatterers are seen to be well focused and placed at the correct positions.

C. Comparison

The cuts $\iota(\xi, 0, 0)$, $\iota(0, \eta, 0)$ and $\iota(0, 0, \zeta)$ on the slices given in Fig. 2 and Fig. 3 are provided in Fig. 4, where the quality image measurements can be performed. It should be highlight that the cuts $\iota(\xi, 0, 0)$, $\iota(0, \eta, 0)$ and $\iota(0, 0, \zeta)$ relate to the point target in the middle of the simulated SAR scene. These cuts are the impulse responses of the target in ξ -, η - and ζ - directions. The SAR geometry is symmetrical in both ξ - and η -, the cuts in these directions should be identical. According the definition of the subimages, the mainlobe of this target impulse response is distributed into four subimages, i.e., not completely inside a subimage. This ensures that the effects caused by the phase error on this target are maximum for the FBP case. The measured values including spatial resolutions and peak sidelobe ratios (PSLR) are summarized in Table II. The resolutions are given by the -3 dB widths of the mainlobes while the values of peak sidelobe ratios can be found directly from the first sidelobes due to the normalization with the maximum intensity.

As shown in Table II, the measured values are almost identical. The differences calculated using the relative error concept are much less 1%. These differences might be caused by upsampling for plot and, therefore, can be ignored. The measured results indicate that the 3D FBP and RM algorithms work well with SAR data simulated at the THz frequencies.

V. CONCLUSION

Two 3D SAR image formation algorithms, RM operating in frequency domain and FBP operating in time domain were considered in a comparative study in this paper. The simulation at THz frequency range results showed that the algorithms work well with simulated THz SAR data. The point-targets in the 3D images formed by the algorithms were well focused and at the correct positions. The comparison between two algorithms has based on image quality measurements including range and cross-range resolutions, and peak sidelobe ratio (PSLR). The measured results are almost identical indicating that both algorithms can be used for 3D indoor THz SAR.

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Fig. 4. Cuts $\iota(\xi, 0, 0)$, $\iota(0, \eta, 0)$ and $\iota(0, 0, \zeta)$ of the 3D SAR images.

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