Analysis of Surface Roughness with 3D SAR Imaging at 1.5 THz

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***Abstract*—The expansion of the synthetic aperture radar (SAR) to the emerging THz spectrum has enabled a new era of applications in the areas of automobile, security, non-destructive testing, and material characterization. Thanks to the sub-mm wavelength, extraction of material surface properties is possible and of significant interest for the THz SAR applications. The properties define the surface scattering behavior, which is relational to the applied frequency. This study focuses on surface classification. We evaluate the scattering behavior of a rough surface and a smooth surface at 1.5 THz based on a SAR processing sequence that is introduced in this paper. First, we form the 3D SAR images of the metallic objects and then evaluate the surface properties based on the variation in the energy reflected by the object's surface.**

I. INTRODUCTION

SYNTHETIC aperture radar (SAR) is a remote sensing technique developed in the 1950s for defense applications. Since then, the SAR technique has been adopted in a variety of applications such as environmental monitoring and meteorology [1]. State-of-the-art SAR commercial applications primarily utilized microwave spectrum below 30 GHz, which provides a long sensing range and high penetration depth but is limited with spatial resolution. It is common knowledge that the spatial resolution is proportional to bandwidth and center frequency. The Terahertz (THz) spectrum can provide much higher spatial resolution. Despite the high free space path loss and atmospheric attenuation, the THz spectrum is suitable for short-range SAR applications [2] and widely explored in the areas of automobile, security, indoor profiling, and non-destructive testing (NDT).

Focusing on NDT and indoor environment profiling, the extraction of surface roughness of examination objects is of significant interest. For example, in NDT applications, the roughness parameter is used in the standardization procedure or surface quality assessment. In indoor profiling with SAR, the surface roughness defines the intensity of the object in the SAR image. A smooth object reflects higher energy due to the dominated specular reflection. Based on the roughness property, the SAR trajectory can be synthesized for efficient mapping. Besides, the roughness parameter can be utilized for hidden object imaging by the exploitation of diffuse [3] and specular reflections. Similarly, based on the roughness parameter, a map-assisted THz indoor wireless communication can be realized, where the material information is required to establish non-line-of-sight (NLOS) links [4]. Hence, the surface roughness is a vital parameter for various applications.

Therefore, in the work the extraction of surface roughness is explored at 1.5 THz with the SAR technique. In electromagnetic field theory, the surface roughness can be categorized with the Rayleigh criterion and Fraunhofer criterion [5], where the estimation of the standard deviation of target surface irregularities Δh is required. At 1.5 THz with an incident angle $\theta_i = 0°$, a surface is considered electrically rough if $\Delta h > 25$ µm in the case of the Rayleigh criterion and the Fraunhofer criterion is fulfilled with $\Delta h > 6.25$ µm. For precise measurement of Δh in μm accuracy, bulky devices such as profilometer are used which is limited in terms of scalability, portability, and mobility. Whereas in this work, the roughness evaluation is based on the surface profiles extracted from the 3D SAR imaging. The futuristic miniaturized THz chips [2] can be deployed in a realistic mobile environment. However, due to the current unavailability of commercial THz radar chipset at 1.5 THz, a vector network analyzer (VNA) based testbed is employed in this work. The testbed is suitable for experimental evaluation and validation.

The remaining of the paper is organized as follows. Section II presents the measurement setup. In section III, the results about surface roughness based on 3D SAR imaging are presented. Lastly, in Section IV, a conclusion along with an outlook is provided.

II. MEASUREMENT SETUP

A monostatic geometry for SAR 3D imaging is shown in Fig. 1, where electromagnetic (EM) wave radiation direction is along the x-axis. A radar synthesizes a 2D aperture along azimuth and elevation directions or y- and z-axis, respectively. The coordinate of the radar is marked by $P_{u,v}$, where u and v represent the aperture coordinates that coincide with the y- and z-axis. At each aperture position in the 2D scanning track, the EM waves are transmitted impinging the object located at a reference distance R_{ref} and backscattered waves are captured.

In this work, the measurement setup is composed of a VNA coupled to a frequency extender mounted on a two-axis motorized stage to form the 2D aperture. The low-frequency signal is up-converted by the frequency extender into the desired spectrum of 1.1-1.5 THz, which provides a bandwidth of 400 GHz. A horn antenna with a diameter of 1.1 mm is connected to the extender waveguide flange. The implemented

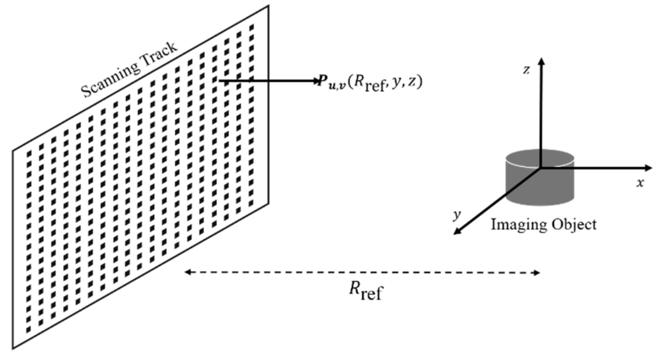

Fig. 1. SAR 3D imaging geometry

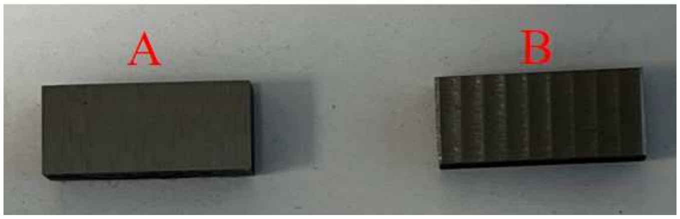

Fig. 2. Picture of smooth (A) and rough (B) imaging objects.

configuration can provide a range resolution of 0.375 mm and azimuth/elevation resolution of 0.55 mm is achievable. A detailed description of the testbed and signal processing is available in [6]. In this work, two metallic objects or samples, A and B are considered at $R_{\text{ref}} \approx 48$ cm. Sample A surface is relatively smoother than B as A has an average roughness of 1.6 µm. Whereas, B average roughness is 12.5 µm. Moreover, sample A is obtained from its workpiece via a plain grinding process and sample B is the result of horizontal milling.

III. Results

With the employed testbed, reflection coefficients S_{11} are captured in the frequency domain and the 3D image is reconstructed using the *Backprojection* algorithm [2], [6]. Based on the SAR 3D image cubes, the surface is visualized with the maximum intensity projection estimation along the range direction. For both samples, a high-resolution THz image is generated as shown in Fig. 3, where Fig. 3 (top) represents the smooth sample A and the rough sample B image is Fig. 3 (bottom). The SAR image of a smooth surface shows a high degree of continuity due to the dominant specular reflection. For the surface B, the SAR image shows a discontinuous pattern due to the diffuse scattering.

For further evaluation, the azimuth profiles along the y-axis are estimated and presented in Fig. 4 (top-left) and (top-right) for samples A and B, respectively. The azimuth profile for the smooth objects is nearly flat with a variation of ~4 dB. The source of variation could be the misalignment in the SAR geometry to form $\theta_i = 0°$. In comparison to the smooth surface, the azimuth profile of the rough objects shows much higher variation in the order of 15 dB. Such scattering behavior is also present in both azimuth and elevation profiles, which can be

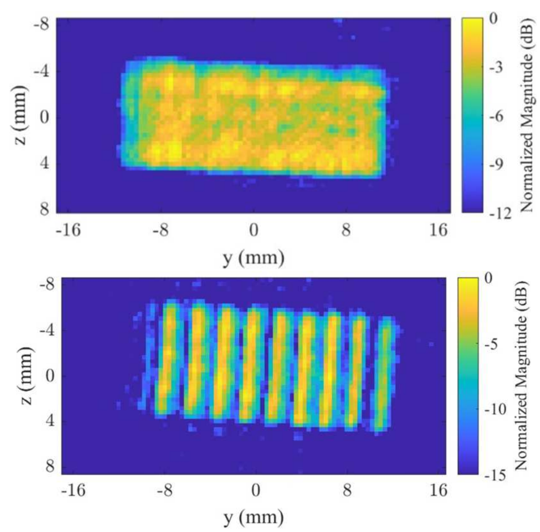

Fig. 3. SAR image of (top) A and (bottom) B samples

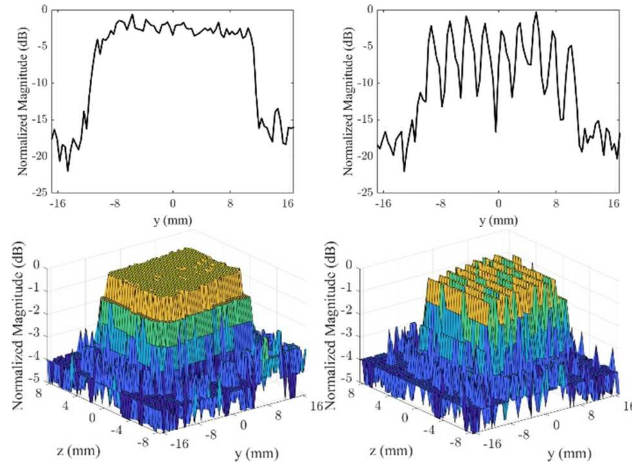

Fig. 4. Azimuth profiles of samples (top-left) A and (top-right) B, and surface plots including both azimuth and elevation profiles of samples (bottom-left) A and (bottom-right) B.

seen with the 3D surface plot present in Fig. 4 (bottom-left) and (bottom-right) for samples A and B. Here, a threshold of 4 dB is applied for compensation of the misalignment. Besides, the threshold can be adapted in consideration of phase variation, and spatial resolution. The plots in Fig. 4 define clearly the relative degree of roughness. The variation and discontinuity increase with the roughness. Hence, the considered smooth and rough objects can be classified with the THz SAR imaging.

IV. Conclusion

The paper presented the analysis of surface properties in terms of roughness at 1.5 THz with consideration of smooth and rough surface samples. Although, the roughness average differs in µm range, the variance in the scattering behavior is observed in the generated 3D SAR images of the samples. Based on the proposed method with MIP image acquisition and further deriving the azimuth and elevation profiles, the surfaces can be classified. Besides, if the average roughness is in the range of spatial resolution, more surface parameters such as root mean square height and skewness can be extracted from SAR 3D cube, and it will be addressed in future publications.

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