Accurate Terahertz Three-dimensional Subsurface Imaging by Range Points Migration Method

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***Abstract*— This paper proposes the novel imaging algorithm based on the range points migration (RPM) for the terahertz (THz) subsurface three-dimensional imaging. The inherent problem in the optical lens-based THz imaging system is the depth dependency for the azimuth resolution, and it is fatal, if the depth of object is not available in such as subsurface imaging issue. This paper newly introduces the range points migration (RPM) based auto-focusing algorithm, which is suitable for general THz-time domain spectroscopic (THz-TDS) measurement. The effectiveness of the proposed method has been validated through the THz-TDS measured data.**

I. INTRODUCTION

THE three-dimensional (3-D) terahertz (THz) imaging system is much promising for the applications, such as non-destructive testing (NDT) for industrial product, or chemical compound analysis using spectroscopic feature. General THz imaging systems employ a dielectric lens for transmitter and receiver to obtain the higher azimuth resolution at the focal point, and then, could limit an effective penetration range, which guarantees a sufficient azimuth resolution. In addition, if the depth of object is unknown, a prior mechanical adjustment of dielectric lens is hardly achieved. As a promising auto-focusing signal processing, the radar approach such as synthetic aperture (SA) process has been considered in some literature [1,2]. However, the SA method could incur unnecessary responses by coherent process, such as speckle noise or grating lobe.

To overcome the above difficulty, the range points migration(RPM) method has been developed in microwave radar model [3], and the spectroscopic extended RPM has been also developed for the 3-D THz imaging issue [4]. The traditional RPM algorithm assumes the omni-directional propagation of electro-magnetic wave, and this method is advantageous when the distance between the covered surface and the sample is unknown and much longer than the focusing length. In this paper, we extend the RPM method to be suitable for the dielectric lens model to secure the imaging accuracy at any depth. The experimental validation with the THz time domain spectroscopic (THz-TDS) measurement show that the extended RPM algorithm considerably enhances the imaging accuracy compared with the traditional THz-TDS 3-D image in the case of out-of-focus data.

II. OBSERVATION MODEL

Figure 1 shows the observation model. It assumes that a target has an arbitrary 3D shape with a clear boundary. A set of transmitter and receiver is scanned on the plane. $s(\boldsymbol{L};R)$ is defined as a recorded signal, where $\boldsymbol{L} = (X; Y)$ denotes the transmitter and receiver location, and $R = ct/2$ is expressed by time t, and c is the speed of light in the air. The range points extracted from the local maxima of $s(\boldsymbol{L};R)$ are defined as $\boldsymbol{q}_i = (\boldsymbol{L}_i;R_i)$.

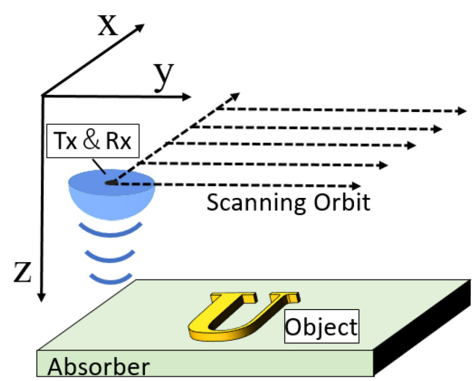

Fig. 1. Observation model.

III. RANGE POINTS MIGRATION METHOD

The RPM basically converts the observed range point as $\boldsymbol{q}_i$, that is defined as the set of antenna location and measured range, to the corresponding scattering center $\hat{\boldsymbol{p}}(\boldsymbol{q}_i)$ as:

$$\hat{\boldsymbol{p}}(\boldsymbol{q}_i) = \arg\max_{\boldsymbol{p}^{\mathrm{int}}(\boldsymbol{q}_i,\boldsymbol{q}_l,\boldsymbol{q}_m)} \sum_{j,k} g(\boldsymbol{q}_i;\boldsymbol{q}_j,\boldsymbol{q}_k) \times \exp\left\{-\frac{\left\|\boldsymbol{p}^{\mathrm{int}}(\boldsymbol{q}_i;\boldsymbol{q}_j,\boldsymbol{q}_k) - \boldsymbol{p}^{\mathrm{int}}(\boldsymbol{q}_i;\boldsymbol{q}_l,\boldsymbol{q}_m)\right\|^2}{\sigma_r^2}\right\} \quad (1)$$

where, $\boldsymbol{p}^{\mathrm{int}}(\boldsymbol{q}_i;\boldsymbol{q}_l,\boldsymbol{q}_m)$ is the intersection point among the three orbits of propagation paths, determined by the background media, and $g(\boldsymbol{q}_i;\boldsymbol{q}_j,\boldsymbol{q}_k)$ is weight function considering the sensor separation.

To the original RPM method assumes the omni-directional radiation, while the THz-TDS systems usually employs the optical lens, and then, the above wide-beam assumption is invalid. Then, this paper introduces the geometrical optics (GO) based path estimation considering the dielectric and dimensional parameters of dielectric lens, which can be calibrated by the experimental data.

A. Virtual Source and Lens Design

This section describes the virtual source for dielectric lens model for the RPM method, so that it is suitable for the optical lens measurement. Here, we assume the point source at the backside of the fixed ellipsoidal-shaped dielectric lens, as shown in Fig. 2. We also assume that the spherical wavefront radiated from the point source would incident to the bottom surface, which has also spherical shape with radius R. The radius R and the relative permittivity of dielectric lens ε is

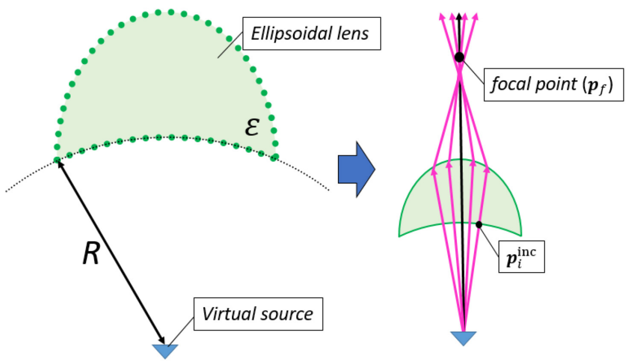

Fig. 2. Virtual source and propagation paths for each incident point $\boldsymbol{p}_i^{\mathrm{inc}}$.

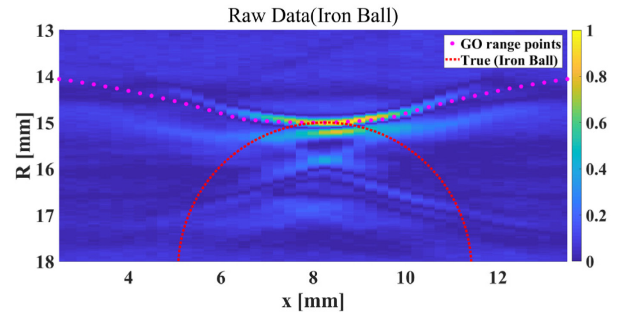

Fig. 3. Calibration data from 1/4 inch metallic ball and range points determined by GO using the optimized parameters $(\hat{R}, \hat{\varepsilon})$ = (60.4 mm, 2.1).

determined as:

$$(\hat{R}, \hat{\varepsilon}) = \arg\min_{(R,\varepsilon)} \sum_{i=1}^{N} d(\boldsymbol{p}_i^{\mathrm{inc}}, \boldsymbol{p}_f; R, \varepsilon) \qquad (2)$$

where $\boldsymbol{p}_i^{\mathrm{inc}}$ denotes the i-th incident point on spherical bottom surface of dielectric lens, and $d(\boldsymbol{p}_i^{\mathrm{inc}}, \boldsymbol{p}_f; R, \varepsilon)$ denotes the minimum distance between the focal point $\boldsymbol{p}_f$ and the propagation line from the incident point, which is determined by the Snell's law. Figure 2 shows the geometrical concept of our design.

IV. Results with Experimental Data

THz-TDS measurement system, by Spectra Design co.,ltd, is introduced, where a focal dielectric lens with diameter 34mm is set, and its focal length is 25 mm. The reflection data are obtained with a center frequency of 0.3 THz and an effective bandwidth of 0.3 THz. A photoconductive antenna(PCA) is moved along the $z = 0$ plane with 0.25mm interval. The data, when the target is located at 15 mm depth, are measured, namely, at the case of 10 mm far from the focal point. The virtual lens is assumed to be an elliptical lens, with a major axis radius of 30 mm and a minor axis radius of 17 mm. The focal point $\boldsymbol{p}_f$ is set at the 25mm from top of lens. The parameters of $(\hat{R}, \hat{\varepsilon})$ are determined in Eq. (2) by using the calibration data assumed a 1/4 inch iron ball located at 15mm depth as shown in Fig.3, where the GO-based range point estimation, using the optimized parameters $(\hat{R}, \hat{\varepsilon})$ = (60.4 mm, 2.1), is also plotted. Figure 4-(a) shows the actual metallic target, forming the alphabetical character "U". Figure 4 (b) and (c) show the 3-D images obtained by the traditional THz-TDS data and the extended RPM methods, respectively, where the reference image is acquired at the 25 mm (focal point). These figure show that while the traditional THz-TDS image suffers from the image distortion, the proposed method could compensate such distortion accurately. The cumulative probabilities of the errors within 0.2 λ (0.2 mm) are 34.5 % for the traditional THz-TDS image (Fig. 4-(b)) and 63.5 % for the proposed method (Fig. 4-(c)), respectively.

V. Conclusion

This paper proposes the novel imaging algorithm based on the RPM method for the THz subsurface three-dimensional imaging. The experimental validation with the THz-TDS measurement demonstrated that our method could achieve accurate 3-D imaging, even in the out-of-focus case.

ACKNOWLEDGMENT

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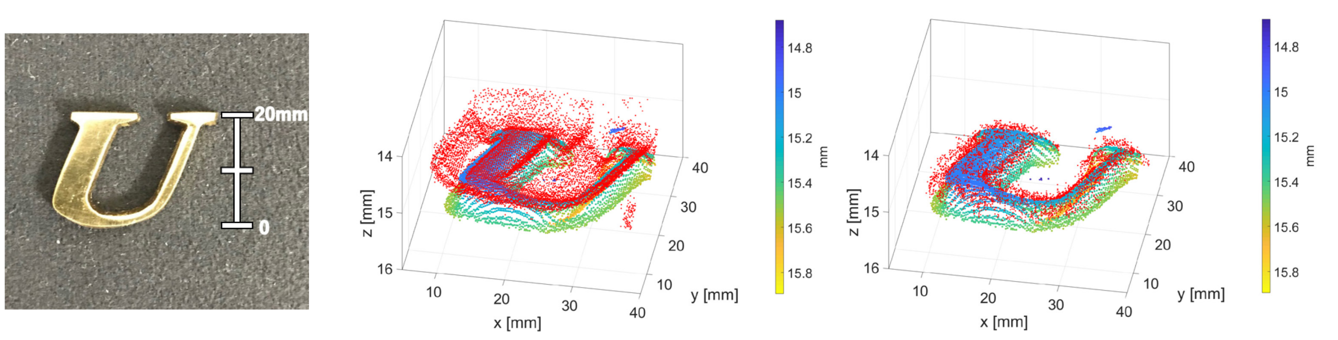

(a) (b) (c)

Fig. 4. (a): Actual target shape. (b): Traditional THz-TDS image (red dots). (c): Extended RPM images (red dots), where the reference image (color denotes the depth) is that obtained at focal point (25 far from a dielectric lens).