Comparison of Propagation Losses in THz and Optical Non-Line-of-Sight Imaging

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***Abstract*—We investigate the propagation losses in terahertz (THz) non-line-of-sight (NLoS) imaging and compare the performance to the optical counterpart. NLoS imaging exploits the multiple reflections of electromagnetic waves from surrounding surfaces to reconstruct the geometry and location of hidden objects. THz and visible/infrared radiations are attractive for NLoS imaging due to the short wavelengths and practical apertures that can support this non-conventional imaging. However, the scattering mechanisms vary significantly and determine the quality of the reconstructed images. This work compares for the first time the free-space path loss and rough surface scattering losses of a simple THz and optical NLoS imaging topology. Because specular reflections are dominant in THz scattering while optical systems suffer from strong diffuse scattering, THz NLoS imaging systems can receive considerably stronger backscattered signals.**

Keywords—NLoS imaging; THz; rough surface scattering

I. Introduction

Non-line-of-sight (NLoS) imaging can enable novel applications, including first response and rescue missions, detection for hidden traffic/pedestrians, and autonomous navigation in a crowded environment. Besides, it could also be beneficial in wireless communications and simultaneous localization and mapping (SLAM) applications [1]. THz imaging has been recently proposed as an attractive method for NLoS [2]. Common building materials appear as mirrors in the THz spectrum and allow image reconstruction with low computation resources and compact hardware. Additionally, THz waves can provide images under low visibility conditions (e.g. fog, smoke, dust) and allow high spatial resolution due to short wavelengths while using practically sized apertures.

Current NLoS imaging systems use either the microwave or visible/infrared spectrum [3]. At microwave frequencies, most common materials are semitransparent, edge diffractions become stronger and images are easily cluttered due to strong multi-reflection propagation. Additionally, due to the relatively long wavelength, poor image resolution allows only object detection rather than anatomical details of the hidden scene. On the contrary, visible and infrared light have very short wavelengths (<1 μm), which enables high spatial resolution imaging. However, most surfaces exhibit wavelength-comparable roughness that results in loss of spatial coherence of the reflected waves. Additionally, visible light suffers from large free-space path loss.

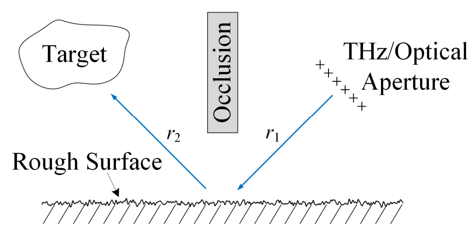

Fig. 1 Non-line-of-sight imaging using scattering from a rough surface.

In this work, we compare the loss mechanisms of optical and THz imaging NLoS systems and we show that diffuse scattering is also a dominant loss mechanism in optical NLoS systems for typical building materials. To accurately analyze wave scattering on rough surfaces, the appropriate computational methods are needed.

II. Rough Surface Scattering in the THz and Optical Spectrum

We assume that the imaging systems form pencil beams to scan indirectly the NLoS objects, as it would happen if a regular camera is used to image the object through a perfect mirror. Although this model is not an accurate representation of current NLoS optical systems, we use it as the benchmark reference. The Kirchhoff approximation [4] has been a reliable analytic method to calculate the scattered fields from a finite rough surface. It uses two parameters to account for the surface roughness: the root-mean-square (RMS) height (σ) and the correlation length (L). However, the Kirchhoff approximation will only be accurate if the correlation length of the rough surface is much larger than the wavelength of the incident waves. Thus, it is widely used in optics, but cannot be applied to the THz regime. As measured in [5], the correlation lengths of wallpaper and plaster samples are L = 0.29 mm and L = 0.18 mm, respectively, and they both are comparable to the wavelength at 300 GHz (λ = 1 mm).

On the other hand, the numerical estimation of rough scattering is computationally expensive for electrically large surfaces. Therefore, we estimate THz scattering using 2D models (in WIPL-D) such that rough surfaces become rough lines. To ensure the same scattering environment with optical waves, we generate rough lines with the same roughness statistics as in the 2D surfaces. To compare scattering from two different surfaces, the assigned rough line statistics are σ = 0.1

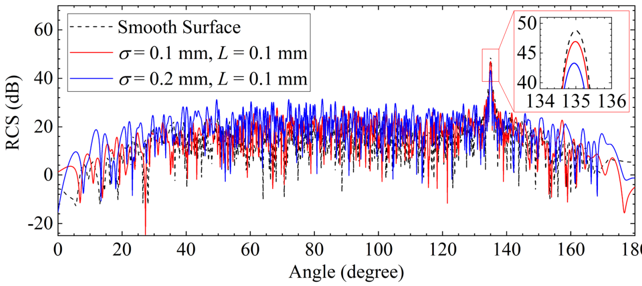

Fig. 2 Computed RCS patterns of two rough surfaces. *Inset*: detail at the angle of the specular reflection.

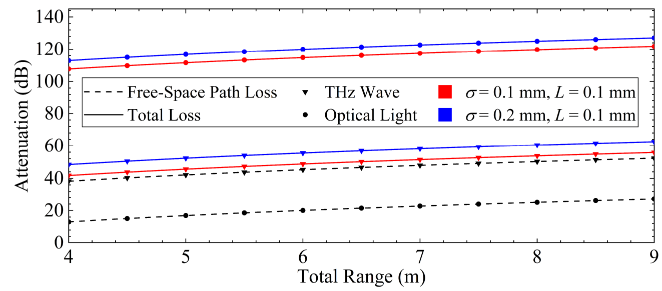

Fig. 3 Comparison of signal attenuation in mono-static THz and optical NLoS imaging systems.

mm, $L = 0.1$ mm and $\sigma = 0.2$ mm, $L = 0.1$ mm, respectively (the second surface is rougher than the first one). Fig. 2 shows the bi-static radar cross section (RCS) for 15 cm-long, perfect electric conductor (PEC) lines. Because the lines are illuminated with a plane wave at 45 degrees, we also computed the RCS for a smooth surface (dashed line) and found that edge diffraction is considerably smaller than diffuse scattering. As expected for the THz spectrum, the RCS exhibits a peak at 135 degrees.

III. Total Loss Estimation

The main loss mechanisms in NLoS systems are free-space path loss and diffuse scattering on rough surfaces. In this analysis, we omit material losses and loss mechanisms due to aperture efficiency. We assume the simple mono-static NLoS imaging scenario of Fig. 1, where we use the reflection from a wall to image an occluded object. If the wall surface is flat and well-polished ($\lambda >> \sigma$), then free-space propagation loss will be dominant. Therefore, signal loss in the round-trip propagation can be determined by the radar range equation [6]:

$$\frac{P_r}{P_t} = \sigma \frac{G^2}{4\pi}\left[\frac{\lambda}{4\pi R^2}\right]^2 \quad (1)$$

where P_r and P_t are the receiving and transmitting powers, respectively, λ is the wavelength, $R = r_1 + r_2$, σ is the RCS of the target, and G is the gain of the aperture.

As an example, we consider a THz ($\lambda_{THz} = 1$ mm) and an optical ($\lambda_{optical} = 550$ nm) imaging system staring the wall at 45 degrees angle, 3 m distance ($r_1 = 3$ m). As such, the gain for respective apertures of $d^{THz} = 10$ cm and $d^{optical} = 1$ cm is calculated by $G = (\pi d/\lambda)^2$. We assume that the target is a PEC sphere with a radius of $a = 5$ cm, which is much larger than both λ_{THz} and $\lambda_{optical}$. Thus, its RCS is the same for both systems and is calculated by $\sigma = \pi a^2$ [7]. As such, the free-space propagation loss for this target at distances of $1 < r_2 < 5$ m from the wall is depicted in Fig. 3 (dashed lines). We notice that the loss for the optical system is considerably lower compared to the THz system due to the large difference in aperture gain.

To estimate the losses due to diffuse scattering, we need to calculate the scattering area on the wall. If the NLoS image is formatted by a collimated scanning beam, the illuminated area on the wall will be the projection of the beam width at the corresponding position. For relatively small r_1, we assume the beam width to be approximately equal to the imaging aperture. As such, for the THz system, the illuminated length on the 1D surface is approximately 15 cm. Then, the scattering loss is calculated by the difference of the scattered signals from the smooth and rough surfaces. According to Fig. 2, we estimate the scattering loss to be 3.5 dB when extrapolated to 3D scattering on a rough surface with $\sigma = 0.1$ mm, $L = 0.1$ mm. It increases to 10.2 dB for $\sigma = 0.2$ mm. On the other hand, for the optical system, the illuminated area on the rough surface is calculated to be 111 mm^2. Then, using the Kirchhoff model [4], the two rough surfaces have a scattering loss of 94.7 and 99.9 dB, respectively.

Finally, the total loss can be calculated by adding up the free-space propagation and scattering losses, as shown in Fig. 3. We note that the optical system has a significantly higher total loss (> 60 dB).

IV. Conclusion

By comparing the mono-static THz and optical NLoS imaging systems, we showed that THz systems have a much lower total loss. In addition, current THz technologies enable 2D transceiving antenna arrays. So, high-gain beamforming can be operated using a large 2D array aperture. However, in optics, lenses are needed to implement high-gain emitters, thus the structures are 3D, which increases the complexity. Therefore, we can take advantage of the relatively strong specular reflection of THz incident waves to implement high-resolution, low-loss NLoS imaging systems.

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