Active and passive millimeter and sub-millimeter-wave imaging

Douglas T. Petkie*a, Frank C. De Luciab, Corey Castob, Paul Helmingerc, Eddie L. Jacobsd, Steven K. Moyerd, Steve Murrille, Carl Halfordf, Steve Griffinf, and Charmaine Francheg

aDepartment of Physics, Wright State University, Dayton, OH, USA
bDepartment of Physics, Ohio State University, Columbus, OH, USA
cDepartment of Physics, University of South Alabama, Mobile, AL, USA
dNight Vision and Electronic Sensors Directorate, Fort Belvoir, VA, USA
eArmy Research Laboratory, Adelphi, MD, USA
fDepartment of Electrical and Computer Engineering, University of Memphis, Memphis, TN, USA
gScience Applications International Corporation, USA

ABSTRACT

We have developed several millimeter/submillimeter/terahertz systems to study active and passive imaging and associated phenomenology. For measuring the transmission and scattering properties of materials, we have developed a dual rotary stage scattering system with active illumination and a Fourier Transform spectrometer. For imaging studies, we have developed a system based on a 12-inch diameter raster-scanned mirror. By interchange of active sources and both heterodyne and bolometric detectors, this system can be used in a variety of active and passive configurations. The laboratory measurements are used as inputs for, and model calibration and validation of, a terahertz imaging system performance model used to evaluate different imaging modalities for concealed weapon identification. In this paper, we will present examples of transmission and scattering measurements for common clothing as well as active imaging results that used a 640 GHz source and receiver.

Keywords: terahertz, imaging, active, passive, millimeter-wave, submillimeter-wave, transmission, reflection, scattering

1. INTRODUCTION

Due to the low attenuation and scattering in fabrics, clouds, fog, and dust, etc., millimeter-wave imaging has received considerable attention for the past several decades. The recent need for new personnel security screening techniques and advances in submillimeter-wave (submm) and terahertz (THz) technology have drawn attention to shorter wavelength systems that have attractive attributes over millimeter wave imagers. Shorter wavelength systems provide the opportunity to construct more compact systems while still increasing the spatial resolution of the imaging system, an extremely important consideration in developing portable imaging systems that would be able to detect concealed weapons. However, higher spatial resolution comes at the cost of greater atmospheric attenuation, limiting the stand-off ability of higher frequency systems. Standoff imagers need to operate at a frequency near an atmospheric window where absorption to due to water vapor is a minimum. These windows are nominally centered near 94, 140, 250, 350, 410, 500, 650, 850, 1035, 1350, and 1500 GHz. In addition to greater atmospheric attenuation at higher frequency1, most materials also begin to have rapidly increasing attenuation. While successful imagers have been developed in the millimeter wave region2,3, the higher regions have not been as thoroughly explored and many investigations into imaging phenomenology and system architectures are needed before submm/THz imaging systems can be successfully realized.

Development of a successful sensor imaging system relies on three fundamental components illustrated in Figure 1 and described elsewhere in these proceedings by Murrill, et al.4. Theoretical models based on fundamental physics and
engineering guide the design of a sensor system and are linked to the field performance measures of how successful the sensor is at accomplishing a specific task (i.e. detection of concealed weapons). Laboratory measurements are an integral component to efficient sensor system development as they provide empirical inputs to the theoretical models and an image archive provides a link between the theoretical model and field performance. While the U.S. Army Night Vision and Electronic Sensors Directorate and the U.S. Army Research Laboratory are developing the theoretical model discussed in Murrill, et al., our parallel effort addresses the laboratory measurements component of the submm/THz imaging system and will provide empirical transmission and scattering measurements as inputs to the model, serve to validate the modeling of images, and provide an image archive to calibrate the terahertz imaging system performance model with human perception testing.

This paper will describe the systems that are being used to perform a detailed study of millimeter and submm/THz wave imaging. It includes both active and passive imaging, with several different operating modes and frequency windows. All imaging modalities share a common raster scanned mirror system used to collect the images. These systems are all very sensitive with high spatial resolution to allow the development of an image library to further study the attributes of each modality. This library will also be used by the U.S. Army Night Vision and Electronic Sensors Directorate and the U.S. Army Research Laboratory to validate theoretical models to predict field performance of different imaging modalities. To complement the image library and to provide inputs for the model and understand the phenomenology associated with these images, the systems also provide measurements of transmission/attenuation and scattering phenomenology. For these studies, we have built a Fourier Transform Far Infrared (FTFIR) spectrometer and a scattering measurement system to study both transmission and scattering properties of various materials. The broad categories of laboratory measurements that are being carried out in this research effort are given in Table 1. The remaining part of this paper will describe details of various systems and their components along with examples of results.

### Table 1. Categories of laboratory measurements.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission and Absorption (FTFIR)</td>
<td>Active (Heterodyne)</td>
</tr>
<tr>
<td>Scattering (rotary stage scattering system)</td>
<td>Co-propagated illuminated</td>
</tr>
<tr>
<td></td>
<td>Flood-light illuminated</td>
</tr>
<tr>
<td></td>
<td>Passive (Heterodyne and Si bolometer)</td>
</tr>
<tr>
<td></td>
<td>Thermal signatures</td>
</tr>
<tr>
<td></td>
<td>Cold incoherent illuminator</td>
</tr>
</tbody>
</table>

### 2. MATERIALS AND IMAGING MEASUREMENT SYSTEMS

Because the texture scales of many objects of interest are comparable to submm/THz wavelengths, we are particularly interested in quantitative comparisons, at high spatial resolution, of the various imaging modalities and strategies that might be employed: co-propagated active, flood-light active, thermal passive, illuminated passive, etc. We are also interested in the relation of these images to the more fundamental properties of materials and their interactions with radiation. The latter will sever as inputs to the terahertz imaging system performance model and the former will provide comparison/validation/calibration of the output of the model.

#### 2.1. Properties of materials

While clothing materials are fairly transparent at 94 GHz, the loss in transmission rapidly increases for many materials between 350-1000 THz. In addition, the scale of the weaves of many materials is on the order of the wavelength of radiation in the submm/THz region, opening up the possibility of interference phenomena. To study the absorption and scattering properties of materials, the two systems described below have been constructed.
2.1.1. Scattering system

Figure 2 shows a two stage rotary scattering system. One stage positions the detector about the sample at an angle between zero and ±160° and the other stage rotates the orientation of the sample with respect to the incident radiation. In its active mode, the system makes measurements near 100, 200, 300, and 600 GHz. One lens couples the radiation beam from the source to the sample followed by another lens that couples the beam to the detector, with a beam waist located at the sample. The radius arm of the rotary stage is ~40 cm and the angular resolution is limited by the diffraction angle of the beam, which is ~4 degrees FWHM near 600 GHz. Several zero-biased Schottky-diode detectors from Virginia Diodes, Inc. and helium-cooled bolometers (hot electron InSb and Si) are used as detectors.

![Diagram of the scattering and transmission measurement system.](image)

2.1.2. Far Infrared Fourier Transform

This system utilizes an Infrared Systems Inc. liquid helium cooled silicon composite bolometer optimized for the mm/submm region. When cooled to 1.7 K by pumping on the liquid helium bath, the NEP is $1.8 \times 10^{-14} \text{W/Hz}$. It is also equipped with a filter wheel to allow the selection of 1 THz, 3 THz and 10 THz low pass filters. A globar is used as a thermal source. Off-axis parabolic mirrors are used to couple the radiation between the source/detector and the Michelson Interferometer. Either Mylar or free-standing wire grids are used for beam splitters. A stepper motor controls one of the mirrors and has a 10-μm step size with a total possible translation of ~25 cm. A fast scan is used and a one-sided interferogram is recorded. Scans are co-added to improve the signal-to-noise ratio. The entire instrument can be enclosed and purged with nitrogen gas to minimize atmospheric absorption. The design also includes motorized stages to automate the insertion and removal of samples from the beam path as well as translate samples along the beam path to minimize standing wave effects.
2.2. Imaging System

To study imaging phenomenology and develop an image library, we have constructed a single pixel imaging system. It is based on a raster scanned mirror and can be used in both active and passive imaging modes. Figure 3 shows the system set up for active co-propagated imaging. The 643.2 GHz source and heterodyne receiver share a common mirror via a 1-mil Mylar beam splitter. The 30-cm diameter, 50-cm focal length mirror is raster scanned to image the backscattered radiation from the object under study. For passive imaging, the beam splitter is replaced with a plane mirror, and an optical chopper is placed in front of the receiver. The source can also be used to illuminate the object in a static flood-light mode. The bolometer described in Sec. 2.1.2 can replace the heterodyne receiver and has a 1.2-cm aperture in front of a Winston cone that has a field of view (FOV) of ~40°. For imaging applications, variable mechanical apertures limit the FOV, and therefore the number of spatial modes collected. Cooled filters are used to define bands within the several atmospheric windows.

![Diagram of the active co-propagated heterodyne imaging system.](image)

2.2.1. Raster scanned mirror

A 30-cm diameter spherical mirror with a 50-cm focal length is mounted to a pan/tilt unit that controls the azimuth and elevation angles of the mirror during a scan. Two stepper motors drive the pan/tilt unit and are controlled by LabVIEW. The image is constructed in realtime, pixel by pixel, in a step-by-step fashion. The signal from the detector (heterodyne or bolometer) is passed through a lock in amplifier before being digitized by a 16-bit National Instruments DAQ board. The mirror is scanned in one direction to avoid any pixel registration problems and shift in alternate scans that would arise due to bi-directional scans and the lock-in time constant. To minimize aberrations, the source/receiver and object are positioned as close to the mirror’s optical axis as possible.

2.2.2. Heterodyne receiver and source

The source and the heterodyne receiver systems were purchased from Virginia Diodes, Inc. The fundamental oscillator for each system is a dielectric resonant oscillator (DRO), with 13.4 GHz being the base frequency for the source and 13.3 GHz for the receiver phase locked to a 100-MHz reference. The 319.2-GHz LO of the receiver mixes with the 643.2-GHz source signal to generate a 4.8-GHz IF signal, which is then amplified and rectified with a diode detector. The source has a 1-kHz modulation switch and the output of the receiver diode detector passes through a lock-in amplifier before being digitized.
3. TRANSMISSION AND SCATTERING RESULTS

3.1. Static clothing transmission

A variety of clothing was tested using the scattering system with both the detector and sample angles fixed at zero degrees. The mm/submm source was a Virginia Diodes, Inc. multiplier chain driven by a YIG oscillator; an InSb hot-electron bolometer was used as a detector. The frequency of the YIG oscillator was fixed near 12 GHz and multiplier blocks were attached and removed from the chain to change the frequency and characterize the transmission at 96, 192, 288, and 576 GHz. Fig. 4 presents the transmission results through a single layer of a variety clothing materials. The thickest material was the overcoat while the thinnest was the scarf, which showed the greatest and least attenuation, respectively. Also note that several dresses, marked with an asterisk in the legend, were identical material and all closely followed the same trend. Although there is some variation, the general trend is one of increasing attenuation with increasing thickness, material mass and frequency, as expected. We will further investigate the frequency/wavelength dependence of transmission over a wider and more complete range with the FTFIR system.

![Figure 4. Transmission properties of a variety of clothing.](image)

3.2. Dynamic clothing transmission

The static transmission results presented in the previous section were with the clothing material held fixed in position. In many real-time imaging applications, personnel will be moving causing their clothing to move and change orientation with respect to their body. To explore consequences of this motion, we have also investigated the dynamic transmission of clothing by slowing “waving” the clothing material to mimic the motion of clothing on a moving person. Fig. 5 shows a 30 second time interval for transmission through an overcoat at 576 GHz. The garment was held fixed for the first ~10 sec and then gently waved for the remaining 20 sec. The waving motion changed the location of the material by ~ 1 cm in the beam as well as the angle of the clothing up to ~ 20 degrees. Three trials were recorded to examine the reproducibility of the transmission fluctuations. From these trials, we can expect the transmission through certain materials to fluctuate by 5-10%, a variation similar to the ‘differences’ among the transmission losses for similar materials shown in Fig 4. Additionally, since this variation will also be present as a spatial modulation across a static target, this ‘clutter’ may present more of a limitation to imaging systems than the loss of signal intensity.
3.3. Coherent effects in clothing

In this section, we provide an example of how the incident angle of radiation with respect to the clothing changes the transmission as a result of coherent scattering. This can be one of the phenomena responsible for the variable transmission demonstrated in the sections above. Using the scattering system described in Sec. 2.1.1 and shown in Figure 2, with the detector angle fixed at zero degrees, we recorded the transmission as the sample was rotated about normal incidence. The results are shown in Fig. 6 for a scarf that was measured to have a ~95% transmission at 576 GHz. When the sample was vertically mounted such that it was flat, but not very taut, variations in the transmission of ~8% appeared with a significant dip in transmission when the scarf was oriented at -12.5 degrees with respect to the incident radiation. When the scarf was taut in the mount, more dips in the transmission were observed and the transmission varied by ~12% with symmetric features present. Under an optical comparator, the average weave spacing when the scarf was relaxed was ~0.415 mm. Stretching the scarf may slightly change the weave spacing, but more importantly, it better aligns the weaves to more efficiently scatter the radiation at certain angles, causing the observed interference phenomena.

Figure 6. Transmission through a scarf as a function of the incident angle of radiation at 576 GHz. The detector was set at zero degrees and the sample angle was varied. The scattering data was normalized to a baseline of 95% transmission that was measured at normal incidence to illustrate the percent variations as a function of angle.
4. ACTIVE IMAGING RESULTS

4.1. Active, co-propagated imaging

In this section, we provide examples of active co-propagated scans of a flat, front-surfaced aluminum mirror and a metallic toy cap gun placed in front of an optical breadboard. The optical breadboard has $1/4"$ diameter holes spaced on $1"$ centers and provides a useful calibration of both scale and spot size. In Figs 7a and 8a, scans of the active co-propagated system (Figure 3) shows interference effects due to the coherent nature of the source. In each case, a set of concentric rings similar to Newton’s Rings or an Airy Function of a Fabry-Perot cavity, are clearly evident. The angular dependence of these rings are satisfactorily fit to an Airy Function with the width of the cavity in agreement with the dimensions of the imaging system. To eliminate this coherent effect, the frequency of the source was modulated by 2 parts in $10^4$, which corresponds to a shift in the interference pattern by several fringes. The frequency of the source was modulated at a rate faster than the lock-in time constant to average the interference fringes from the images. The favorable impact of a frequency modulated source is shown in Figs. 7b and 8b. The experimental resolution shown in Fig. 8b is ~3mm, as expected of our optical system. For a 1-m aperture this image, which shows enough detail to distinguish among types of handguns, would correspond to that obtained at about 20 ft.

![Image of a flat mirror without frequency modulation](a) ![Image of a flat mirror with frequency modulation](b)

Figure 7. 640 GHz image of a flat mirror (a) without frequency modulation and (b) with frequency modulation.

![Image of a toy metallic gun without frequency modulation](a) ![Image of a toy metallic gun with frequency modulation](b)

Figure 8. 640 GHz image of a toy metallic gun placed in front of an optical breadboard (a) without frequency modulation and (b) with frequency modulation.
5. SUMMARY AND FUTURE WORK

We have built several systems to study the transmission and scattering properties of materials and an imaging system to study the quality and phenomenology of different imaging methods. Results of the transmission and scattering measurements show that below 600 GHz, a single layer of a variety of clothing transmits at least 50% of the incident radiation. Additionally, coherent scattering was shown to potentially play a crucial role in reducing transmission. Active imaging results yielded high resolution and contrast, but also showed coherent effects that can lead to fringes in the images. These coherent effects were successfully eliminated by frequency modulating the source. Based on a specified set of test targets, we are now building an image library that will use all available imaging modalities. This library, along with transmission and scattering measurements, will be used in the development of a terahertz imaging system performance model that will evaluate different imaging modalities for concealed weapon identification.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Defense Advanced Research Projects Agency (DARPA) and the Army Research Office (ARO) for support of this research, recognize and thank Dr. Mark Rosker (DARPA) and Dr. Bruce Wallace (ORSA Corp) for their programmatic and technical guidance during the course of this work, and Jenn Holt and Bryan Hren of Ohio State University for hardware and software contributions related to this project.

REFERENCES