Foliage penetrating radar imaging system

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ABSTRACT

A radar range has been constructed at the University of Massachusetts Lowell Submillimeter-Wave Technology Laboratory to investigate electromagnetic scattering and imagery of threat military targets located in forested terrain. The radar system, operating at X-band, uses 1/35\textsuperscript{th} scale targets and scenes to acquire VHF/UHF signature data. The trees and ground planes included in the measurement scenes have been dielectrically scaled in order to properly model the target/clutter interaction. The signature libraries acquired by the system could be used to help develop automatic target recognition algorithms. The difficulty in target recognition in forested areas is due to the fact that trees can have a signature larger than that of the target. The rather long wavelengths required to penetrate the foliage canopy also complicate target recognition by limiting image resolution. The measurement system and imaging algorithm will be presented as well as a validation of the measurements obtained by comparing measured signatures with analytical predictions. Preliminary linear co-polarization (HH, VV) and cross-polarization (HV, VH) data will be presented on an M1 tank in both forested and open-field scenarios.

Keywords: VHF, UHF, radar, imagery, modeling

1. INTRODUCTION

For the past twenty years, Expert Radar Signature Solutions (ERADS) under funding from the National Ground Intelligence Center (NGIC) has developed state-of-the-art scale model measurement systems to acquire radar signatures in support of a number of advanced radar applications such as automatic target recognition (ATR) systems, low-observable target evaluation, RAM development, and buried object detection. ERADS has developed fully polarimetric compact ranges at 160 GHz\textsuperscript{1}, 520 GHz\textsuperscript{2}, and 1.56 THz\textsuperscript{3} for acquisition of X-band, Ka-band, and W-band radar imagery of 1/16\textsuperscript{th} and 1/48\textsuperscript{th} scale model targets and scenes.

Detection and classification of targets obscured by foliage through the use of synthetic aperture radar (SAR) imagery is still an unsolved problem. The difficulty in detection lies in the fact that trees and other vegetation concealing a target can result in electromagnetic (EM) returns or clutter responses that are equivalent to or greater than those expected by the target itself, thereby causing false target detection. Trees act as a main source of clutter due to the dihedral ground bounce formed between the tree trunk and the ground plane.\textsuperscript{4} The ultimate goal of foliage penetration research is the development of a radar system, incorporating advanced signal processing techniques, which has the capability to accurately detect targets embedded in vegetative type clutter and to classify them through the use of an automatic target recognition (ATR) algorithm.
Application of an ATR algorithm requires the ability to correctly interpret SAR imagery to accurately classify the detected target. At foliage penetration frequencies, difficulty in this interpretation arises due to the long wavelengths required to penetrate the foliage canopy. VHF/UHF wavelengths, which are typically used to penetrate forest canopies, range between 10 meters and 10 cm. Take for example an M-1 tank which has approximate dimensions: 7.6-m x 3.6-m x 2.7-m. At VHF/UHF frequencies, the dimensions of the tank become comparable to the center wavelength. In such cases, scattering centers are not necessarily represented by a physical feature of the target. Furthermore, complex target/clutter interactions exhibiting polarimetric dependence (such as Brewster's angle) also create difficulty not only in classifying the target but in understanding exactly how the trees alone will scatter energy. In a scale model measurement system, such target-obscured scenes can be studied in a controlled manner. The data can be utilized to generate cost effective libraries of target signatures of various tactical scenarios.

Scale Model Measurement of VHF/UHF Radar Data

Scale modeling requires that the target's geometric and dielectric properties be scaled appropriately. Therefore, the complex dielectric constant of any nonmetallic component of the full scale target at the full scale wavelength must be matched to the complex dielectric constant of the corresponding scale model component at the scaled wavelength. The University of Massachusetts Lowell Submillimeter-Wave Technology Laboratory (STL) has demonstrated the technology necessary to tailor the dielectric properties of materials. Conductive coatings necessary to simulate the metallic components of the full scale vehicles have been developed as well.

2. The VHF/UHF Radar Measurement System

The X-band measurement system was based on an HP8510B network analyzer such that VHF/UHF signatures of targets could be measured by using 1/35\textsuperscript{th} scale models. Targets and scenes are mounted for measurement on motorized staging incorporating five individual motorized axes, two translational axes and three rotational axes, programmable through a system control computer. Figure 1 displays the motorized staging used in the measurement system. The translational stages are comprised of the target and calibration translation stages, used to translate the target scene and calibration object in and out of the anechoic chamber during measurements. The rotational axes are comprised of the target's azimuth and depression axes as well as a dihedral rotation stage used during calibration.

X-Band Transceiver and Polarization Controller

Figure 2 displays a diagram of the VHF/UHF measurement setup utilizing the HP8510B microwave vector network analyzer integrated with a HP8130 pulse generator and a custom microwave pulsing unit. Also shown is the Macintosh system controller running LabVIEW\textsuperscript{\textregistered} v5.1, used to communicate with the pulse generator, the HP8510B, and the indexers used to control the translation and rotation stages. The polarization control signals were generated by the National Instruments NU-Bus MIO-16E data acquisition card. The HP8510B network analyzer provides coherent measurement of scattering parameters $S_{mn}$ of two port devices as a function of frequency. Therefore, it generated a frequency swept continuous-wave (CW) signal at the transmit port $n$ and measured the response at the receive port $m$ as a function of frequency. As diagrammed in figure 2, port 2 was set up as the transmit port and port 1 as the receive port constituting an $S_{12}$ scattering measurement. This particular configuration was chosen due to the extended dynamic range of the receiver in port 1 over that of port 2.
Figure 1: Motorized staging used in VHF/UHF measurement system showing both target and calibration axes.

Figure 2: Diagram of the scale model VHF/UHF measurement setup.
The CW source provided by port 2 was then coupled to the microwave input on the pulsing unit. The microwave pulsing unit was designed to hardware gate out the undesired reflections that took place in the measurement chamber and transceiver electronics. It also provided the necessary signal routing to obtain co and cross polarization measurements. In addition, the pulsing unit allowed for increased dynamic range through the use of microwave amplification and significantly reduced measurement time. A description of hardware gating through pulsed/CW measurements can be found in 8 and 9.

Antenna Setup and Data Acquisition

The acquisition of all polarization channels was accomplished by integrating two commercially available linear polarization X-band antennae with the transceiver. Each antenna was dedicated to transmit and receive a single polarization, namely, horizontal or vertical. The pulsing unit coupled the microwave energy to the antennae, generating a pulsed/CW signal. This served to hardware gate the response from the target under measurement. The horn antennae both incorporated a dielectric lens, effectively increasing the gain. The beam propagating from both antennae was allowed to diverge and the scale model target was placed in the far field where the phase curvature of the beam approximated that of a plane wave over the extent of the target. The two antennae were set up as shown in figure 3a. Since measurements had to be performed on two different axes in the same experiment to obtain both calibration and target measurements, it was not possible to direct the antennae toward a single axis. Rather, the boresight direction of each antenna was directed to a point half way between each axis, as shown in figure 3. The bistatic angle (2.9°) between the two antennae was minimized by bringing both antennae into contact to allow approximate monostatic data acquisition. In the next generation system, a wire grid will diplex the H and V-polarization channels to permit true monostatic operation.

Since each antenna was dedicated to a single polarization, the co-polarizations (HH and VV) were measured independently through their respective antenna, establishing monostatic measurements of the co-polarizations. The cross-polarizations (HV and VH) were measured by transmitting from one antenna and receiving in the other, constituting a bistatic measurement.

After mounting and aligning the target under measurement to the desired orientation, the data acquisition program was initiated. The sequence began by obtaining a background level measurement of the chamber by moving all

![Figure 3: Antenna setup used in VHF/UHF scale model radar system.](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)
measurement pylons out of the chamber and acquiring a measurement sweep. The calibration pylon was then moved into the chamber and a measurement sweep of a flat plate, oriented normal to the bistatic angle bisector was acquired. Subsequent measurements of a dihedral corner reflector were then acquired with its seam oriented at horizontal and at 22.5° with respect to horizontal. The calibration pylon was then moved out of the chamber and the target pylon was moved in. Once the target pylon is in place, measurement sweeps of the target are acquired as a function of aspect angle. The range operator has the option to perform measurements of the target as a function of azimuth for a given depression angle or vice versa. Data is stored on the system controller’s internal hard drive on an angle by angle basis as a LabVIEW® datalog file.

**Data Pre-Processing**

Acquired data from the HP8510B was uncalibrated and subject to clutter within the hardware gate in the chamber. This raw data was then pre-processed using a program written in LabVIEW. The pre-processing procedure first calibrates the raw data utilizing the calibration measurements stored in the log file. A polarization calibration algorithm was used to calibrate the raw data set and served to linearize the systematic errors that existed in the measurement system, corrected the polarization distortions arising from the transmitting/receiving antennae and reflected the true RCS of the object under measurement. The flat plate measurement was used to linearize the measurements and provided the RCS reference. The dihedral measurements provided a reference for polarization orientation. Software range gating was then applied to the calibrated data to remove unwanted clutter within the hardware gate, such as that resulting from target staging. Software range gating also serves to improve the SNR of the measurement since noise is uniformly distributed in all range bins, while the target response is concentrated in a those range bins associated with the target.

**3. WIDEBAND ISAR IMAGERY OF POLAR FORMATTED DATA**

Wideband inverse synthetic aperture radar imaging is accomplished through by tracking the phase of scatterers as they traverse a circular trajectory. As shown in references 11 and 12, there is a Fourier transform relationship between the target reflectivity function $g(x,y)$ and the scattering function $G(f, \theta)$. Based on the measured values of $G(f, \theta)$ we wish to reconstruct $g(x,y)$ to obtain a physical interpretation of the scattering centers of the target. Images are processed over an angular aperture defined as $\theta : -\theta_a/2 \rightarrow \theta_a/2$, $\theta_a$ being the aperture of integration, using the following Fourier transform relationship:

$$g(x, y) = \int_{\theta} \int_{f} (F_x, F_y) e^{-j2\pi(F_x x + F_y y)} \, dF_x dF_y$$

(1)

The spatial frequency variables $F_x$ and $F_y$ are related to the frequency of the illuminating signal $f$ and the angle of illumination $\theta$ by:

$$F_x(f, \theta) = \frac{2f}{c} \sin(\theta)$$

(2)

$$F_y(f, \theta) = \frac{2f}{c} \cos(\theta)$$

(3)

The resolution of the images are determined by the bandwidth of the effective CW signal used in the experiment and the aperture $\theta_a$ over which the image was processed. For modest angular apertures ($\theta_a < 90^\circ$), the down range resolution $\Delta r_y$ of the processed image is given by:

$$\Delta r_y = \frac{\lambda}{2 \sin(\theta_a/2)}$$
where $B$ is the bandwidth of the experiment. The cross range resolution $\Delta r_x$ given by: \[\Delta r_x = \frac{\lambda}{4 \sin \theta / 2} .\]  

In order to preserve the total radar cross-section value of the image, the DFT sum in equation (1) must be normalized with respect to the size of a resolution cell and the actual size of an image pixel. Therefore, equation (1) becomes: 

\[
g_N(x, y) = \frac{1}{NM \Delta r_x \Delta r_y} \int F_x F_y e^{-j2\pi(F_{x+\Delta x} F_{y+\Delta y})} \]  

where, $N$ and $M$ are the number of frequency points and number of angular samples in the processing aperture, respectively. $\Delta x$ and $\Delta y$ are the image pixel dimensions and $\Delta r_x$ and $\Delta r_y$ are as given in equation (4) and (5).

4. RESULTS

4.1 Validation of Measurements using a Flat Plate

As a test to validate the performance of the RCS measurement system, measurements were obtained on a flat plate rotated in azimuth. The measurements were then compared with an analytical prediction based upon a geometrical theory of diffraction (GTD) program. Since GTD is a high frequency prediction, it was necessary to choose a plate that was sufficiently large to satisfy the high frequency requirement. However, the plate must also be uniformly illuminated by the antenna beam and is therefore limited to a maximum spot size. To satisfy both requirements an 8" x 6.165" (23.3' x 18' full scale) flat plate was used as the test plate. Figures 4 and 5 display the measured HH and VV RCS data at 286 MHz. The data were obtained by rotating the plate in azimuth and maintaining a fixed elevation angle of 0° and acquiring data over the scale model frequencies. The normal to the front surface of the plate was defined as zero degrees azimuth.

4.2 Validation of Measurements using the Slicy Model

A photograph of the Slicy at 0° azimuth is shown in Figure 8. It is composed of various basic scatterers, such as cylinders, dihedrals and trihedrals and it's RCS can be calculated by computational electromagnetic (CEM) algorithms. Monostatic RCS predictions as a function of azimuth of the Slicy in free space at a 15° depression angle were obtained from a CEM method of moments program (Carlos). Figure 6 displays the measured and predicted RCS of the Slicy in free space as a function of azimuth, at a 15° depression, at the full scale frequency 286 MHz for the HH, HV, VH, and VV polarizations. As shown in figure 6, the co-polarizations demonstrate excellent agreement with the code predictions and reasonable agreement with the cross-polarizations. This suggests that the present hybrid system, with monostatic co-polarization and slightly bistatic cross-polarization data, approximates a monostatic configuration.
4.3 Demonstration of Brewster's Angle Effect

The role of polarization in scattering is of importance when analyzing the backscatter behavior of targets. One of the most well known polarization dependent scattering phenomenon is Brewster's angle effect. According to this theory the polarization parallel to the plane of reflection experiences complete transmission at an elevation/depression angle equal to the Brewster's angle if the dielectric is lossless. The depression angle at which Brewster's angle occurs in at an air/dielectric interface is calculated from the following:

\[ \theta_B = 90^\circ - \tan^{-1}(\sqrt{\epsilon}) \]  \hspace{1cm} (7)

Figure 4: HH measurement and GTD Prediction of 23.3' x 17' flat plate rotated in azimuth at 286 MHz.

Figure 5: VV measurement and GTD Prediction of 23.3' x 17' flat plate rotated in azimuth at 286 MHz.
where \( \varepsilon \) is the dielectric constant of the ground plane. A dielectric ground plane has been constructed at STL having a measured dielectric constant of \( \varepsilon_m = 14.7 + i 1.1 \). This simulates a ground surface having moderate moisture content at VHF/UHF bands. Neglecting the loss, the ground plane used in the scale model measurements had a Brewster's angle of 14.6° depression. As an experiment to demonstrate the system's ability to analyze such effects, a large rectangular aluminum block was placed on the ground plane normal to the radar beam, effectively forming a dihedral retro-reflector with a horizontal seam. Backscatter measurements of this target configuration were acquired as a function of depression angle. The backscatter at 10 GHz is plotted as a function of depression angle for the co-polarizations in figure 7. In the case of a radar system, the vertical polarization experiences Brewster's angle and as can be seen in figure 7, the VV polarization experiences a deep null at approximately 13.5° depression, close to the predicted value of 14.6°.

### 4.4 VHF/UHF Imagery of a Tree-Obscured M1 Tank

As well as a dielectric ground plane, STL has fabricated dielectrically scaled trees, with a dielectric constant \( \varepsilon = 69 + i 10 \). These scale model trees simulate full scale trees having high water content at the VHF/UHF bands. Figure 9 displays an image of the scene target/clutter scene used in the experiment. The actual foliage (leaves, etc.) has been omitted in the scaling process under the assumption that the attenuation at this wavelength is negligible. Measurements of this scene were obtained as a function of azimuth at a 45° depression angle with and without the scale model target. It has been shown\(^\text{11}\) that imagery of the target-obscured scene at the cardinal angles provides the most backscatter from the target, therefore, imagery was generated of trees with and without the target centered at 270° azimuth and displayed in figures 10 and 11, respectively. These images were processed over the frequency band 234 – 354 MHz using a 36° angular aperture, yielding a resolution cell size of 1.25m down range by 1.02m cross range. Measurements were also obtained of the M1 unobscured on the ground plane to demonstrate how the tree clutter affected the image of the tank. These data were also processed at 270° and the generated imagery are displayed in figure 12. These images were processed using the same parameters as figures 10 and 11. Care was taken to ensure that orientation of the trees was not altered when inserting the tank into the scene. The same care was taken to preserve the orientation of the tank when removing the trees from the scene. Preserving the orientation of the objects ensured that all images were perfectly registered with one another when the imagery was generated.

As previously shown, Brewster's angle effect does in fact play a role in the target/ground plane scattering observed in this system. This phenomena can also be observed by examining the HH and VV images in figure 12. There is clearly larger return from the tank in the HH polarization than that of the VV polarization. This effect also seems to play a role in the scattering of the trees shown in figures 10 and 11. However, it is difficult to ascertain the scattering behavior of the trees. Firstly, the trees reflect a considerable amount of energy due to the dihedral they form with the ground plane. The Brewster's angle has already been demonstrated to scatter a greater amount of energy in the horizontal polarization than in the vertical. However, the vertical orientation of the trees, which according to EM boundary conditions will predominately scatter the vertical polarization, competes with the Brewster's angle effect. These competing effects have to be considered in predicting the return. In any polarimetric radar system operating monostatically, reciprocity considerations state that the cross-polarization signatures are identical. Figures 10, 11, and 12 indicate that this is true of the present system. This fact provides additional reassurance that the bistatic setup used to collect the cross-polarization measurements approximates a monostatic measurement.

### 5. SUMMARY

A prototype 1/35\(^{\text{th}}\) scale model VHF/UHF radar imaging system used to investigate scattering of targets in a forested scenario has been constructed. The accuracy of the measurement system has been demonstrated through the comparison of flat plate and Slicy measurements with computer code predictions. The system's ability to measure polarization dependant effects, such as Brewster's angle, has been established. Furthermore, the competing effects of the Brewster's angle and the vertical orientation of the trees on scattering have also been presented. The system is currently being upgraded to operate in a monostatic configuration in all channels, for acquiring fully polarimetric data.
Figure 6: Comparison of measured and Carlos MoM prediction of Slicy at 286 MHz, 15° depression angle.

Figure 7: Comparison of measured HH and VV return from ground plane/conductive dihedral at 286 MHz.
Figure 8: The 1/16th scale Slicy used for TRCS measurement comparison with CARLOS MoM prediction.

Figure 9: The 1/35th scale target/clutter scene used in VHF/UHF radar measurements.

Figure 10: ISAR imagery of tree clutter processed 234-354 MHz over a 36° aperture, 270° azimuth. Note that the cross-pol scale is 20x the co-pol scale.
Figure 11: ISAR imagery of M1 tank obscured by tree clutter processed 234-354 MHz over a 36° aperture, 270° azimuth. Note that the cross-pol scale is 16x the co-pol scale.

Figure 12: ISAR imagery of unobscured M1 tank processed 234-354 MHz over a 36° aperture, 270° azimuth. Note that the cross-pol scale is 16x the co-pol scale.
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