A 1.56 THz Spot Scanning Radar Range for Fully Polarimetric W-Band Scale Model Measurements

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Abstract

A radar transceiver operating at 1.56 THz has recently been developed to obtain coherent, fully polarimetric W-band (98 GHz) RCS images of 1:16 scale model targets. The associated optical system operates by scanning a small focused beam of swept-frequency radiation across a scale model target to resolve individual scattering centers and obtain the scaled RCS values for the centers. Output from a tunable microwave source (10 - 17 GHz) is mixed with narrow band submillimeter-wave radiation in a Schottky diode mixer to produce the chirped transmit signal. Two high-frequency Schottky diode mixers are used for reception of the V-pol and H-pol receive states, with a fourth mixer providing a system phase reference. The full 2x2 complex polarization scattering matrix (PSM) for each resolved center is obtained following off-line data processing. Measurement examples of five simple calibration objects and a tank are presented.

Keywords: Compact Range, PSM, Radar, RCS, Scale Modeling, Submillimeter-Wave.

1. Introduction

In order to effectively implement target recognition or RCS reduction a detailed knowledge of how targets, and target features, scatter radiation must be determined. Due to the large sizes of many targets of interest (i.e. tanks, airplanes, sea vessels, etc.) it is frequently costly or impractical to directly obtain the necessary signature information for a given radar wavelength regime. Thus the use of target models scaled down in physical size by a given scale factor, and illuminated with identically wavelength-scaled electromagnetic radiation, has become a proven and practical method of obtaining the radar signatures of full-size targets [1].

Recently, a spot-scanning radar range has been developed for the purpose of measuring the RCS of scaled models in three-dimensional space. This three-dimensional imaging (3DI) laser radar system at the University of Massachusetts Lowell Submillimeter Wave Technology Laboratory is a coherent, frequency agile, submillimeter-wave radar range operating at a center frequency of 1.56 THz. This system was originally designed to obtain three-dimensional target backscatter information (RCS) for a single transmit and receive polarization state of the electric field [2]. The monostatic system operates by raster-scanning a small beam of submillimeter wavelength radiation across a target. The beam diameter of approximately 12 cm FWHM at the full-size target, assuming a 1:16 scale factor, allows the resolution of individual scattering centers on the scaled model. The receive optics were configured to measure the far-field amplitude of each defined scattering center. This report discusses the improved 3DI system which is now capable of obtaining the full 4-element polarization scattering matrix (PSM) for each resolved scattering center. Theoretically, the PSM provides a complete description of the scattering properties of an object at a given frequency [3]. Such data is useful on its own or in addition to total radar cross section (TRCS) data. Compared to an equivalent full-scale polarimetric range, this system provides a cost-efficient method for studying individual scattering regions on targets of interest.

2. Overview of 3DI System Architecture

There are a number of methods by which coherent tunable sources of submillimeter-wave radiation may be obtained [2]. For frequencies above 1 THz the mixing of

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submillimeter-wave radiation with a lower frequency tunable microwave source in a Schottky contact diode has been found to provide an acceptable balance between power and tunability [2]. A description of this system is presented here, however additional detailed information regarding the 3DI system may also be found in [5].

A carbon dioxide laser operating at a wavelength of 9.56 μm and providing >90 Watts of continuous wave (CW) power, is used to optically pump two far infrared (FIR) cells each filled with 250 millitorr of difluoromethane gas (Figure 1). The pumping of the difluoromethane by this CO_2 laser transition causes the FIR lasers to emit radiation at a center wavelength of 191.84803 μm with a gain bandwidth of approximately 10 MHz. A small portion of the CO_2 radiation (~ 1 - 3 Watts) is sampled and used in a Fabry-Perot cavity-based, laser-locking scheme. The FIR lasers are identical and each individually yields >10 mW of CW radiation with one laser providing the drive signal for the transmitter and the other acting as the local oscillator (LO) common to the receivers and reference detector.

To determine the scaled radar cross section (RCS) of an object, the power of the returned signal is referenced to an in-scene object of known size. The in-scene object size is determined by comparing its scaled RCS to those of a sphere (0.67 dBsm) and a flat plate (4.87 dBsm) located in the target zone. Undesired polarization rotation in the transmitter and receivers (i.e. cross talk) is taken into account through the use of a calibration routine [5], resulting in at least 40 dB of channel isolation. All targets measured were 1/16th scale and all resolution sizes and RCS values in this paper are referred to the full-size object (i.e. 16 times and 24.1 dB above values measured in the compact range, respectively). The scaled radar frequency is 1.563 THz ÷ 16, or 98 GHz (W-band).

To enable side band generation and signal reception at THz frequencies, Schottky barrier diodes are used with anode sizes less than 1 μm in diameter. Whisker-contacted Schottky diodes are used for purposes of radiation transmission/reception, and to provide a stable phase reference to allow heterodyning (i.e. phase sensitive detection). The reason for using the whisker-contacted Schottky diodes lies in their extremely fast response time (< 1ps) which enables them to follow the phase of an incident waveform at the required frequency regime near 1.56 THz. The Schottky diode receivers were provided by the University of Virginia's Electro-physics laboratory - Far Infrared Receiver Lab.

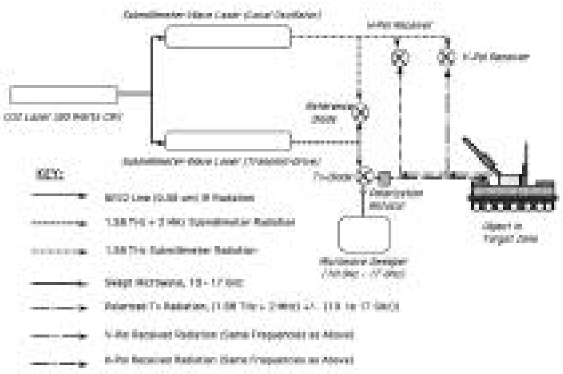

Figure 1. Simplified Schematic of 3DI System.

A portion of the LO and drive submillimeter-wave laser radiation mix together in the reference Schottky diode and the phase of the resulting downconverted radiation is used as a reference in determining the phase of the received radiation. Transmission is accomplished by mixing the drive laser in a Schottky diode (at frequency ν) with the signal from a tunable microwave synthesizer (at frequency χ) which is swept over a 7 GHz wide bandwidth starting at 10 GHz. Such a linear sweep in frequency is known as a "chirp". The result is the transmission of radiation at frequencies $\nu \pm \chi$ from this Schottky diode.

The transmitted radiation encounters two wire-grid polarizers. The first polarizer serves to define the transmit state of the radiation with the second polarizer following as a "clean-up" polarizer. Figure 2 provides a slightly more detailed view of the transmit optics in the system. Noteworthy components include the mylar splitter located just before the antenna mirror optic with the in-scene calibration object, a rotated dihedral, located behind it. A portion of the outgoing radiation passes through the splitter with the remaining radiation reflecting off of the splitter towards the in-scene dihedral. The polarization of the transmitted radiation is then rotated by twice the dihedral rotation angle and sent back through the beam splitter to be detected by the H and V polarization receivers. Transmit radiation which proceeds to the target encounters a scatterer, with the backscattered radiation being returned to the beam splitter, and reflected back towards the receivers. The reflectivity and transmissivity of the mylar beam splitter are highly dependent upon the polarization of the incident radiation. This causes the noise floors between channels to differ (typical 1:16 scale values using a 0.1 second time constant are approximately -30 dBsm for VV, -20 dBsm for HV, -33 dBsm for VH, and -28 dBsm for HH).

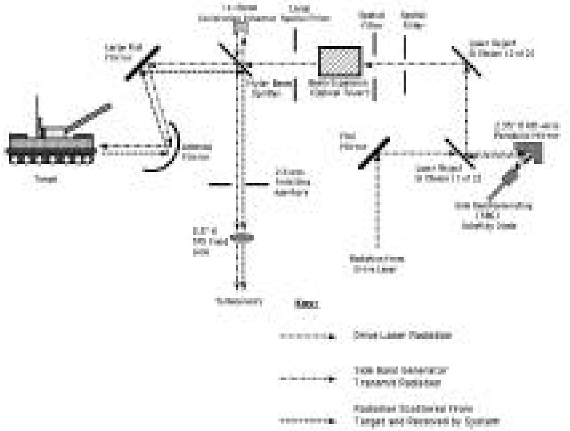

Figure 2. Schematic of 3DI System Transmit Optics.

The two Schottky diode receivers are used to determine the rate of change of phase of the received signal across the transmitted bandwidth. The receiver electronics were designed to detect and process only a single sideband, typically the lower frequency sideband, ν-χ [4]. These diodes measure the return from a scatterer located in the radar range for polarization states parallel and orthogonal to that of the transmitted signal. The range distance of the scatterer may be ascertained by taking the Fourier transform of the complex I&Q data. A benefit of this type of system is that, upon the application of the Fourier transform to the complex data, scatterers located outside of the target range will appear in different range bins than those located within the target range.

Objects for characterization are mounted on a 5-axis stage (Figure 3). The stage allows the precise positioning of the targets in aspect and depression as well as in elevation (z-axis), range (y-axis), and cross range (x-axis). The aspect, depression, elevation, and cross range axes may be controlled independently by computer. The transmitted beam is focused to a slightly elliptical spot, which is much smaller than the target itself. The target is moved across the transmitted beam while the complex (I & Q) data is collected. This collected data is stored on the computer hard drive for analysis.

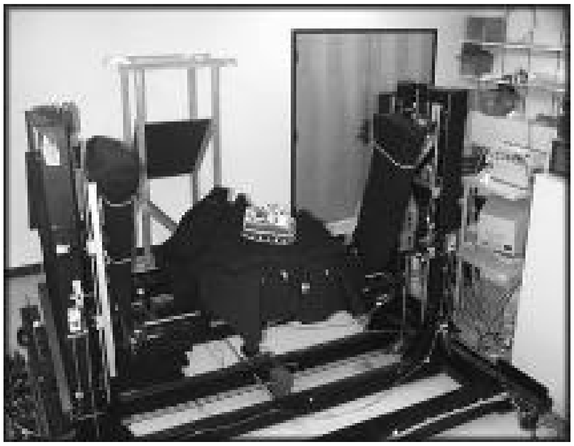

Figure 3. 3DI System 5-Axis Translation Stage (with Target and Calibration Objects).

The range resolution of the system is determined by the bandwidth of the frequency chirp and is approximately 34 cm. The cross-range resolution is determined by the beam width at the target and the allowable amount of beam overlap and is approximately 4 cm.

4. 3DI System Data Analysis

A primary goal of the 3DI system data analysis routines is to obtain the three components of the 3-dimensional weighted centers, C_i, for each region as per equation (1). Here "S" is the sum of the intensity values of all the voxels in a region, determined using equation (2), where "m" is the number of voxels included within the region of interest (a voxel is a three dimensional pixel element), "I_j" is the intensity of the jth voxel, and "γ_{ij}" is the ith component of the jth voxel location [6].

$$C_i = \frac{\sum_{j=1}^{m} \gamma_{ij} I_j}{S} \qquad (1)$$

$$S = \sum_{j=1}^{m} I_j \qquad (2)$$

Other significant goals for the data analysis routines are to obtain the RCS (in dBsm), and the polarimetric properties of the various scattering centers found on the given target. This goal is accomplished through the use of a number of separate computer programs which allow the user to; calibrate the data (using the results of amplitude calibration runs and the calibration procedure from [5]), "chop" out a 3-dimensional region within which exists the target, and then use a set of image processing algorithms to obtain the 3-D weighted center locations and RCS of the centers [6]. Each of the existing data analysis programs were appropriately modified, and new routines added, to allow the processing of fully polarimetric data, with phase measurements taken relative to VV.

The image processing techniques of thresholding and region growing are employed to determine the boundaries of a given scattering center. Starting at a given RCS threshold value, "seed" voxels are obtained from which scattering regions will be determined. The threshold is lowered and, using such restrictions as pixel connectivity and allowable amplitude variation, the routines determine if voxels near a given "seed" voxel belong to a given scatterer. This process is continued until the threshold level has dropped to the pre-determined noise floor level. The RCS values and weighted centers are then determined for each scattering center.

In order to form a full PSM a preliminary routine was implemented wherein regions corresponding to the different polarimetric components are associated with each other based upon location. For instance the HV, VH, and HH regions found closest to a VV region (within a specified 3-dimensional search window) are assumed to be associated with each other and form a unique PSM. The final weighted centers, RCS sizes, and relative phase for each scattering center and for each transmit-receive state are determined upon completion of the data analysis.

5. Measurements of Simple Objects

A data run was performed using calibration objects possessing different PSMs. The general PSM format is shown in equation (3) where, for example, σ_{VH} (θ^o) represents the RCS in dBsm (phase angle in degrees relative to VV) for the V-transmit H-receive state [1].

$$\begin{bmatrix} \sigma_{HH} & \theta_{HH} & \sigma_{VH} & \theta_{VH} \\ \sigma_{HV} & \theta_{HV} & \sigma_{VV} & \theta_{VV} \end{bmatrix} \qquad (3)$$

A photograph of the setup is shown in Figure 4. The black material seen in this figure is used as an anechoic. The 2 large dihedrals, sphere, mirror, and a small circular flat plate under the sphere, are used in the system calibration routines [5]. The 5 smaller objects in the background are the objects used for the actual data run.

For the sphere and flat plate the PSM values in the co-pol states (VV and HH) are predicted to be equal in both RCS and phase angle. For the dihedral the co-pol states should have equal RCS values as should the cross-pol states respectively (for a given orientation of the dihedral seam with respect to the incident E-field vector). A phase difference of ±180° should be apparent between the two dihedral co-pol state PSM elements, whereas the cross-pol states should possess identical relative phase values.

The PSM results of the data run after processing are presented in Figure 5. Phase values for each transmit-receive state were made relative to the VV-state at the RCS weighted center of each object. In the processing of this data a scaled RCS threshold of -20 dBsm was selected for each transmit-receive channel. The results are displayed in Figure 5. It can be seen that the experimental results closely match the well known theoretical predictions. The dihedrals illustrate the predicted cross-pol reciprocity along with the approximately ±180° phase difference between the VV and HH states.

Figure 4. Calibration Objects Mounted on Target Stage.

Object	PSM
Flat Plate	$\begin{bmatrix} 22.07 \quad +1.88^\circ & 0 \\ 0 & 22.02 \quad 0^\circ \end{bmatrix}$
Dihedral-A	$\begin{bmatrix} -0.02 \quad -173.17^\circ & -6.52 \quad -174.28^\circ \\ -7.12 \quad -172.48^\circ & -0.36 \quad 0^\circ \end{bmatrix}$
Dihedral-B	$\begin{bmatrix} -0.36 \quad -178.74^\circ & -3.01 \quad -174.54^\circ \\ -2.34 \quad -174.72^\circ & -0.66 \quad 0^\circ \end{bmatrix}$
Sphere-A	$\begin{bmatrix} -9.00 \quad +5.39^\circ & 0 \\ 0 & -9.31 \quad 0^\circ \end{bmatrix}$
Sphere-B	$\begin{bmatrix} -13.29 \quad +14.98^\circ & 0 \\ 0 & -14.12 \quad 0^\circ \end{bmatrix}$

Figure 5. Measured Polarization Scattering Matrices for Simple Objects (RCS in dBsm, Phase in Degrees).

6. Measurements of a Complex Target

Having shown that the 3DI system yields excellent results for simple calibration objects, data for a tank (a highly complex target) was acquired. An overlay of the VV RCS scattering centers on a photograph of the tank is shown in Figure 6 (a gray-scale copy of an original color image). The RCS threshold was taken as -20 dBsm in order to reduce the number of resolved centers to approximately one hundred.

Figure 6. Tank at 221° Aspect, 30° Depression, Az-El View.

Figure 7. Selected Regions on Tank Chosen for Inspection.

The PSMs for five regions with labeled weighted center locations are shown in Figure 7 and PSMs presented in Figure 8. Regions 0 and 2 (12 and 24) exhibit PSMs similar to dihedrals with seams parallel (rotated) with respect to either the V or H transmit radiation. Region 24 clearly illustrates a direct reflection characteristic of a flat-plate.

Upon processing this data PSMs were found possessing regions of only partial overlap in space. These complex centers were especially prevalent in the tank treads. Scattering between the wheels and the tread, or unresolved scattering centers, may account for the spatial separation and odd phase relationships found between such associated regions.

7. Conclusion

In this paper the design and operation of a 3D-imaging radar range has been presented. This spot scanning system is currently used to obtain the PSMs (RCS and relative phase) for resolved scattering regions on scale model targets. Data has been collected and reported from a group of simple calibration objects as well as tank, which provided an example of a typical complex scatterer.

Region	**PSM**
0	$\begin{bmatrix} 6.67 \quad -176.88^\circ & 0 \\ 0 & 6.01 \quad 0^\circ \end{bmatrix}$
2	$\begin{bmatrix} 2.19 \quad +179.98^\circ & 0 \\ 0 & 3.95 \quad 0^\circ \end{bmatrix}$
12	$\begin{bmatrix} -8.68 \quad -171.87^\circ & -7.94 \quad +4.39^\circ \\ -7.89 \quad -2.31^\circ & -6.05 \quad 0^\circ \end{bmatrix}$
21	$\begin{bmatrix} -9.44 \quad +163.67^\circ & -6.97 \quad 176.3^\circ \\ -6.58 \quad 174.71^\circ & -9.08 \quad 0^\circ \end{bmatrix}$
24	$\begin{bmatrix} -10.98 \quad +7.77^\circ & 0 \\ 0 & -9.94 \quad 0^\circ \end{bmatrix}$

Figure 8. Measured PSMs for Five Regions on Tank. (RCS in dBsm, Relative Phase in Degrees).

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