A 1.56THz compact radar range for W-band imagery of scale-model tactical targets

Thomas M. Goyette[*] [a], Jason C. Dickinson [a], Jerry Waldman [a], William E. Nixon [b]

[a]Submillimeter-Wave Technology Laboratory, University of Massachusetts Lowell, 175 Cabot St., Lowell, MA 01854

[b]U.S. Army National Ground Intelligence Center, 220 Seventh Street, N.E., Charlottesville, VA 22902

ABSTRACT

A new very high-frequency compact radar range has been developed to measure scale models of tactical targets. This compact range has demonstrated very good signal-to-noise and is useful in measuring low observable targets. In addition to normal ISAR imaging of targets (range vs. horizontal cross-range), the system can also produce two-dimensional images in azimuth and elevation (vertical cross-range vs. horizontal cross-range). The 1.56THz transceiver uses two high-stability optically pumped far-infrared lasers, microwave/laser side-band generation for frequency sweep, and a pair of Schottky diode receivers for coherent integration. Measurements made on 1/16th scale models of tactical targets, simulating W-band frequencies, allows the formation of images of very high cross-range resolution (3.5cm full scale) while still integrating over a reasonably small angular extent (2.5degrees). The results from several targets that have been recently measured will be presented.

Keywords: Sub-millimeter, Radar, Imagery, Modeling.

1. INTRODUCTION

The need for high-resolution radar data of tactical targets is growing rapidly. Such data is currently being used to develop databases for automatic target recognition (ATR) and to test current predictive electromagnetic codes. The data needed for these programs include high range resolution (HRR) and synthetic aperture images (SAR). Compact ranges, which measure scaled models of targets, have proven very useful in their ability to collect a large volume of radar signature data in a short amount of time. Since these ranges obtain the desired data by using models scaled proportionally to their wavelength, they are often much more practical than measuring full-scale targets. The Submillimeter-Wave Technology Laboratory (STL) at UMass Lowell has developed several compact ranges, which specialize in using scaled frequencies to measure high-fidelity models. [1]

Radar measurements made on target models using scaled frequencies have continued to grow in interest since the technique was first demonstrated in the submillimeter-wave region in the late 1970s.[2] These early systems were based on optically-pumped submillimeter lasers and bolometric detectors. STL has improved and refined these laser-based systems by the addition of Schottky diode sideband generators and heterodyne receivers to provide a wide-band capability and coherent detection at THz frequencies. The STL THz compact range is currently being modified to provide fully polarimetric radar cross section (RCS) information. At frequencies up to about 0.75THz, laser systems have been replaced by stepped frequency solid state transceivers, which use frequency multiplication of synthesized microwave signals.

Since target signature data requires precise measurement of phase and amplitude information, the 1.56THz compact range has been assembled in a very stable, air-conditioned laboratory. Measurements taken on a calibration object placed 500" from the transmitter show that the phase stability of the compact range is typically 4° of phase drift/hour. This is more than stable enough for the collection of data that is to be used for the formation of target images.

[*] Correspondence: Email: Thomas_Goyette@uml.edu; Telephone: (978) 458-3807; Fax: (978) 452-3333.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **A 1.56THz compact radar range for W-band imagery of scale-model tactical targets**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Massachusetts Lowell,Submillimeter-Wave Technology Laboratory,175 Cabot Street,Lowell,MA,01854**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

2. THE 1.56THZ COMPACT RANGE

Since the modeling of W-band radar systems at 16th scale requires the generation of frequencies at approximately 1.56THz, it has proven convenient to use lasers as the source for electromagnetic radiation. Figure 1 shows the diagram of the 1.56THz compact range. The source consists of two 150 Watt, ultra-stable, grating-tunable CO_2 lasers, which are used as the optical pumps for the two far-infrared lasers. The CO_2 lasers are set to produce 9μm (9P22 CO_2 laser line) and 10μm (10R10 CO_2 laser line) wavelengths respectively. The output of these lasers are then used to pump the laser transitions in the molecular gases difluoromethane (CH_2F_2) and methanol (CH_3OH) at 1.5626THz and 1.5645THz respectively.

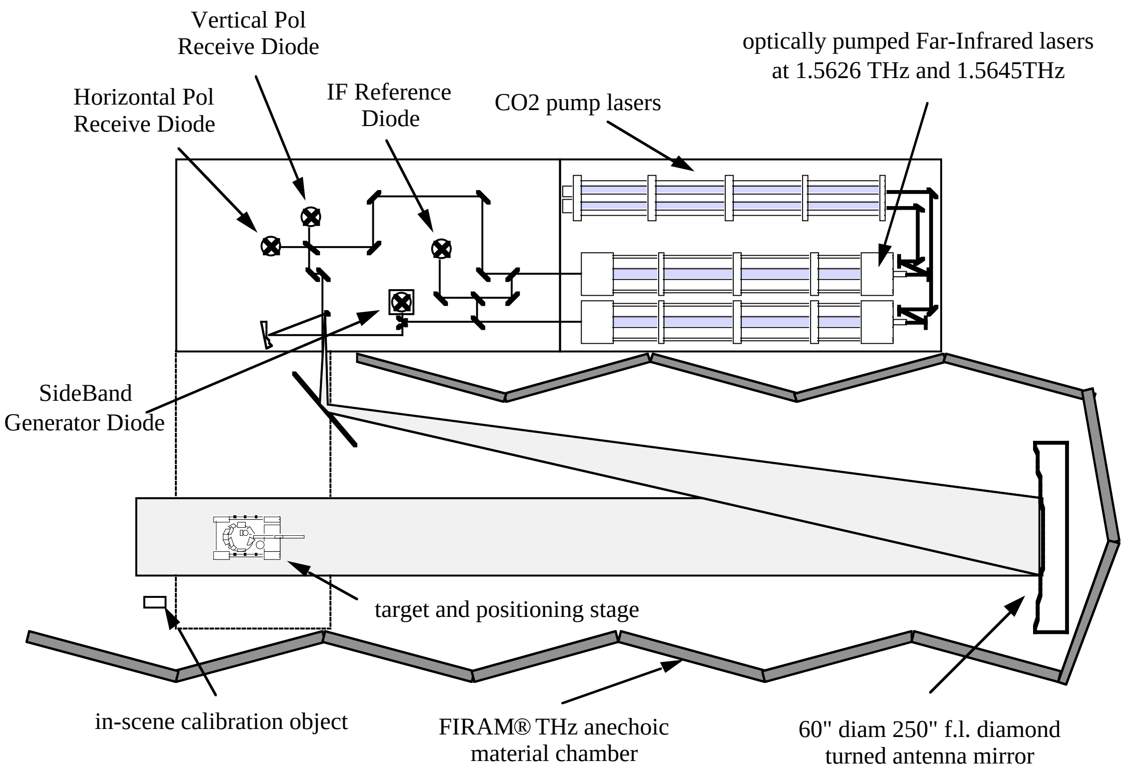

Figure 1. Diagram of the 1.56THz compact range.

The far-infrared lasers produce gaussian modes with 10mm full width at half maximum (FWHM) and typically 100mW of power. One laser is used as the transmitter while the other serves as the receiver local oscillator. The transmitter beam is propagated to the target range and is collimated by a 60" diameter, 250" focal length mirror before illuminating the target. Radiation that is back reflected from the target is collected and mixed with the local oscillator using corner-cube-mounted Schottky diodes as heterodyne receivers. The receiver can simultaneously detect both vertical and horizontal polarization returns from the target by use of a wire grid, which reflects horizontal polarization into the H-Pol diode, or transmits vertical polarization into the V-pol diode. Currently, either vertical or horizontal polarization may be transmitted. The system is being upgraded to provide for automated switching from one to the other to provide fully polarimetric data.

The transceiver has a two way FWHM beam size of 18" corresponding to a beam size of 24' on the full-scale target. This is sufficient to provide complete illumination of typical scale models. The models are mounted on a low cross section pylon. The pylon is set in the middle of a range whose walls are covered with an anechoic material (FIRAM®) specifically designed for THz frequencies. This is done to minimize the amount of radiation scattered back into the receiver by objects other than the target.

The far-infrared lasers produce very stable narrow-band frequencies with short-term drift ≤ 50KHz ($\Delta\nu/\nu \approx 10^{-8}$). The output of the transmitter laser can be used directly to make very high sensitivity measurements of the radar cross-section

(RCS) of the target. This mode of operation offers the best possible signal-to-noise since it makes use of the full power of the transmit laser. Although care has been taken to minimize unwanted signal in the system, background radiation scattered from the edges of the optical components, back wall of the range, and target supports can still be seen. However, introducing a controlled motion of the target and performing a Fourier analysis can isolate the background signal. This technique has produced images with noise floors as low as -65dBsm per image resolution element.

In addition to the use of the narrow-band laser output for the transmitter, a technique has been developed[3] whereby a tunable frequency is generated by mixing the transmitter laser (1.5645THz) with the output of a microwave sweeper (10-18GHz) on a Schottky diode. This technique produces two sideband frequencies that can be swept and are separated from the original laser by the frequency of the microwave source. The receiver electronics are designed to only detect the lower sideband frequency by a frequency-shifted, asymmetric down-conversion. When a linear sweep of the frequency is performed the range to the target can be calculated with a range resolution of 10" at full scale. Using Fourier analysis the target can be sub-resolved in range. This technique also allows the target to be easily separated from other background signals. Since the sideband generation is limited by the efficiency of the Schottky diode mixer, the total amount of transmit power is reduced to approximately 5μw. This is sufficient power to form ISAR images with typical noise floors of -30dBsm per image resolution element.

3. Imaging

Before discussing the formation of target images it is useful to briefly review the basic mathematics of ISAR imaging. Figure 2 shows a simplified setup where an isolated scatterer is rotated about a central point. Down range is defined in the direction of propagation of the radar beam and cross-range is defined as the distance from the axis of rotation. For convenience, only a rotation in the aspect direction will be considered. However, the description may also be applied to motion in the elevation direction. Since the radar source is coherent, the object will have a well-defined amplitude and phase. If the target is rotated, the phase of the object will change proportionally to the cross-range distance from the center of rotation as it undergoes a change in range. Equation (1) gives the change in phase corresponding to rotations through small angles.

$$\Delta\phi = \frac{2\pi\theta_t x}{\lambda} \qquad (1)$$

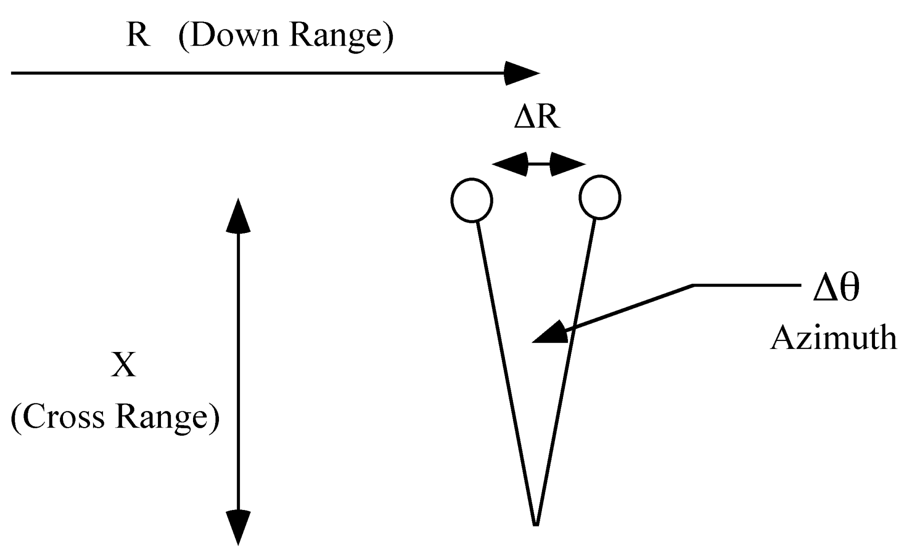

Figure 2. Simple diagram of target rotation and the resulting change in range.

Where θ_t is the total angle that the target is rotated through and x is the cross-range. Therefore, if the phase of the target is measured over a finite angular extent, the cross-range coordinate of the scatterer can be calculated by performing a simple

Fourier transform. In a similar manner, the downrange distance to the target can be calculated by varying the frequency of the radar and carefully measuring the change in phase of the scatterers. The cross-range resolution is easily calculated[4] as

$$\Delta X = \frac{\lambda}{4Sin(\theta_t/2)} \approx \frac{\lambda}{2\theta_t} \quad . \tag{2}$$

Range-gated data is taken by the use of the sideband generator to produce a frequency sweep. The frequency data is then Fourier transformed to obtain the range information. Range gated data is taken at evenly spaced angular increments (typically 0.005˚) to form the ISAR (downrange vs. cross-range) image.

We have recently developed a technique whereby two-dimensional images of the target are formed in azimuth cross-range and elevation cross-range (Az/El). This is done by applying the above formalism to motion of the target in both azimuth and elevation angle. Single frequency, coherent RCS data is collected over a solid angle in aspect and elevation. The data is then Fourier transformed to produce cross-range images in both the azimuth and elevation directions. An advantage of this technique is that the image that is formed shows the target in the same perspective as it was illuminated. In this respect, the Az/El image is similar to a photograph of the target since the images show the target from the front, which makes identification of individual scattering centers much easier. In contrast, the range-gated ISAR images form the image by translating frequency information into range information and then integrating over aspect angle. Since the range information comes from a direction that is parallel to the propagation of the radar, this leads to top down images being formed for a target that is illuminated from the front. Since there is no elevation information it leads to ambiguity in identification of individual scatterers.

4. Results

4.1. ISAR Images of the BMP-2 ground vehicle.

To demonstrate the ISAR capability of the compact range, data were collected on the BMP-2 ground vehicle. Figure 3 and Figure 4 show sample ISAR images for Vertical-transmit/Vertical-receive (VV) at elevation angles of 45˚ and 55˚ respectively and at 30˚ and 60˚ aspect. Full 360˚ azimuth data sets were taken at these elevation angles. These images were generated by sweeping the frequency of the transmitter using the Schottky diode sideband generator. Precisely machined flat plate reflectors were used to calibrate the amplitude and phase response of the system. Before each data run a calibration object of known size was placed in the target location to generate an amplitude and phase correction at each frequency in the sweep. This array was then used in the analysis to compensate for reproducible amplitude and phase variations across the sweep. The empty range was also measured to generate a correction array that can be used to subtract the constant signal from sources other than the target. While this correction is useful, it was not generally needed since the

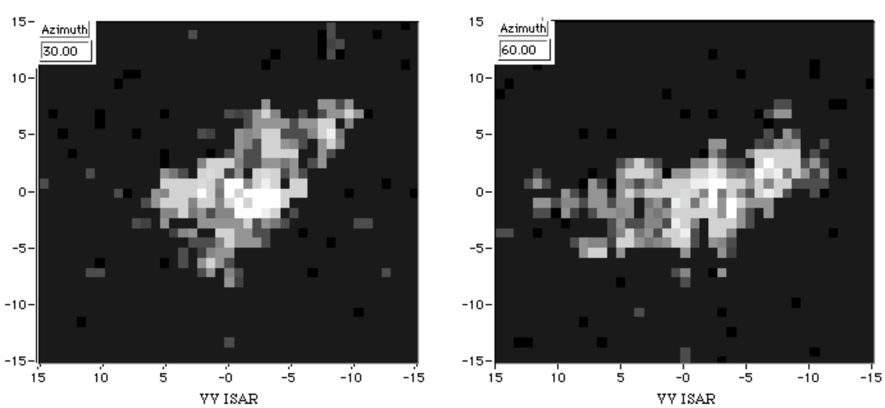

Figure 3. ISAR images of the scale model of the BMP-2 taken at 45˚ elevation, resolution is 10" x 10" at full scale.

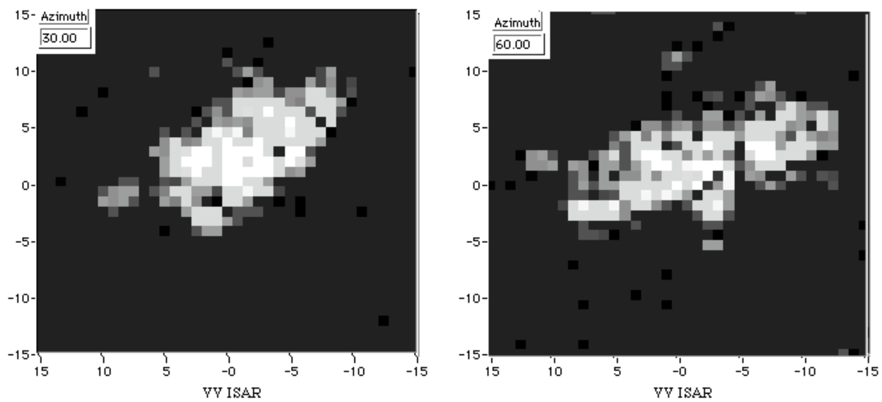

Figure 4. ISAR images of the scale model of the BMP-2 taken at 55˚ elevation, resolution is 10" x 10" at full scale.

target range is well separated from any background signal. Nevertheless, the stability of the compact range was such that the background did not change significantly during a 12-hour period (approximately the time for a 360˚ data run).

4.2. Comparison with high quality turntable BMP-2 RCS and ISAR measurements.

Since there has been full scale W-band data taken on several tactical targets it is useful to make a comparison with the 1/16 scale data taken in the STL compact range. There are high quality turntable measurements made on the BMP-2 ground vehicle using an outdoor full scale range. Measurements were made at STL to compare with this data. Figure 5 shows the results for the RCS measurements for VV at 40˚ elevation. It can be seen that the STL data and the turntable data are in general agreement. Specific differences exist due to differences in illumination of the target and differences between the configuration of the model and the actual vehicle. The model that was used in the STL range was of the generic BMP-2 and no attempt was made to match the exact configuration of the turntable target. The STL range illuminates the target with a far-field phase front while the turntable data is taken in the near-field. Considering these differences it is expected that the average RCS of the two data sets will be in agreement. It can be seen that the STL and turntable data are well overlapped and are generally within 2 dB of one another.

Figure 6 shows the ISAR images of the STL and turntable data at 55˚ elevation and 30˚ aspect. These images show the general agreement between the two data sets. The two images show the targets have the same shape with specific differences in amplitude that are due to the difference in target configuration. Data were taken at several elevation angles on the BMP-2 with complete 360˚ spins in azimuth. The images in Figure 4 were formed over a 0.64˚ Fourier transform window. The pixel sizes down-range and cross-range are approximately 10" at full scale.

4.3. Azimuth/Elevation Imaging.

Single frequency RCS data was taken over a 5˚ by 5˚ solid angle as described above to generate very high-resolution images in azimuth cross-range and elevation cross-range. Figure 7 shows one image of a model of the T80 main battle tank taken with horizontal-transmit/ horizontal-receive (HH) at 15˚ elevation and 120˚ azimuth. The figure also shows a photograph of the model at the same azimuth and elevation view angle. It is evident that the Az/El image shows very good detail of the scattering on the target with very small features being seen. Using equation (2) the pixel resolution of the image is calculated to be ≈ 0.7" on the full-scale target.

Measurements have been made in 5˚ solid angles in 360˚ of azimuth on the T80 model to provide complete HH data set at the 15˚ elevation angle. The data can be processed to form images at evenly spaced increments (typically 5˚) suitable for displaying in digital movie format. Additionally, since pictures can be taken of the model by use of an automated digital camera the Az/El image can be automatically overlaid with the digital photo. This technique has been found useful for the identification of individual scattering centers. For example, many of the smaller features such as the wheels, sections of the tread, and smaller sections of the top machine gun are easily identified.

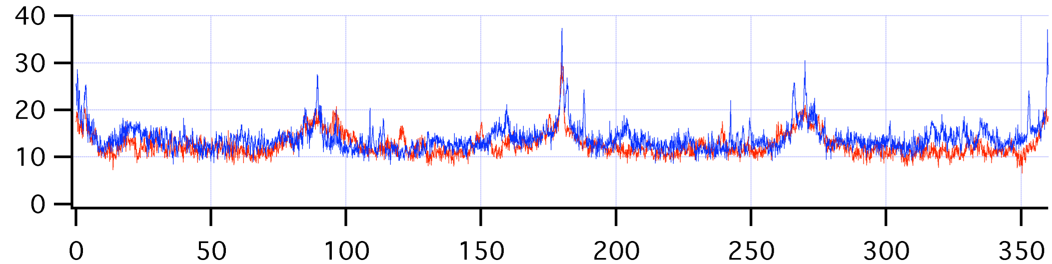

Figure 5. Comparison of STL (blue) 40˚ elevation RCS data with turntable data (red) in VV polarization on the BMP-2 vehicle. Data is medianized over 0.1˚.

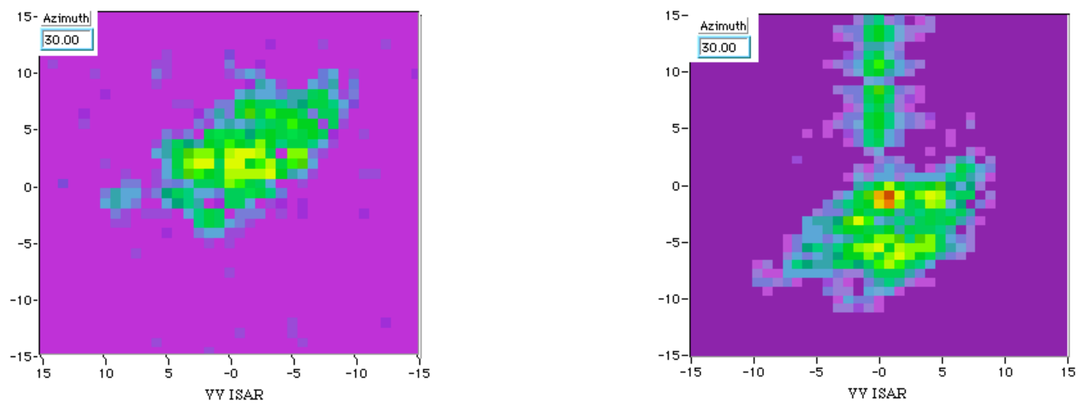

Figure 6. Comparison of STL (left) ISAR image with turntable (right) ISAR image of the BMP-2 target in VV polarization at 55˚ elevation and 30˚ aspect , resolution is 10" x 10" at full scale.

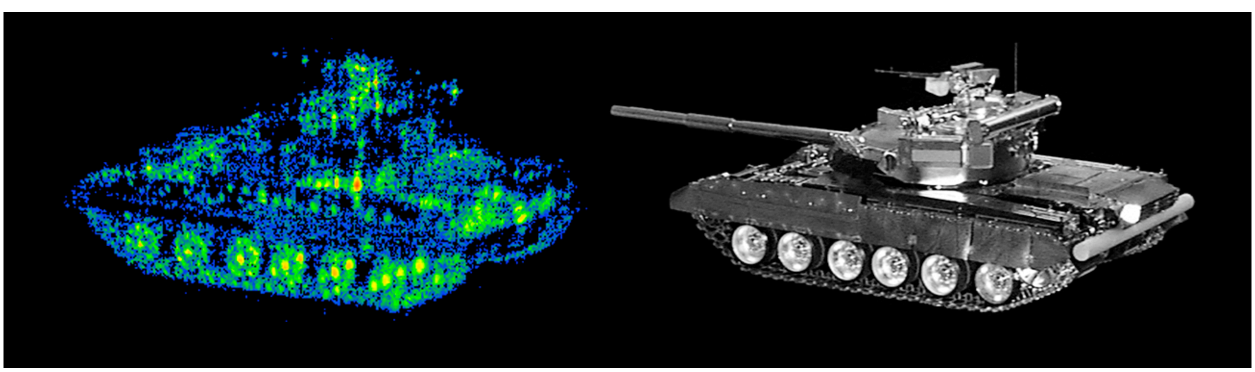

Figure 7. Az/El image (left) of model (right) of T80 tank taken in HH polarization ,W-Band at 15˚ elevation and 120˚ aspect

4.4. Sample Az/El Images of various targets.

Figure 8. F-16 48th scale model (left) and Az/El image (right) at 15° elevation and 260° aspect, 35 GHz (Ka-band) HH polarization, 2" full scale resolution.

Examples of Az/El data collected at STL using various in-house scale model targets are shown in Figures 8-10. Figure 8 shows a 48th scale model (left) and Az/El image (right) of the F-16 at 15° elevation and 260° aspect modeling 35 GHz (Ka-band) HH polarization with 2" full-scale resolution. The vertical stabilizer fin and engine exhaust hardware of the F-16 are clearly visible on the left of the image. Note that the center of the image shows little radar return, mostly due to the smooth surfaces along the top of the fuselage. The external fuel tank can be seen just forward of the front of the wing. To the right, the image shows the cockpit, visible due to the radar return difference in the materials. Note that the resolution of Ka-band is fine enough to pick out the pitot tube in the nose of the jet.

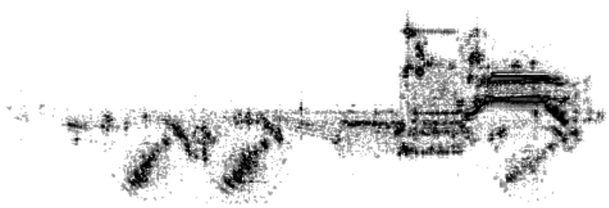

Figure 9. Az/El image of M-813 Truck at 15° elevation and 275° aspect, 95 GHz (W-band) HH polarization, 0.675" full-scale resolution.

Figure 9 shows the Az/El image of the M-813 Truck at 15° elevation and 275° aspect, 95 GHz (W-band) HH polarization, 0.675" full-scale resolution. This truck typically hosts the Roland Air Defense Unit (ADU). Data was collected with the ADU removed from the model. The image of the bare 5-ton truck shows the distinct truck cab profile, including the side window and wheel wells. Note that the metallic wheel hubs are brightly lit (darker) as compared to the tires of the truck due to proper radar materials modeling of the rubber tires. Upon closer inspection, the fuel tank can be seen just behind the outline of the truck door. Towards the rear of the truck, the rear wheel mudguards are also visible above the rear wheels.

Figure 10. Mig29 48th scale model (left) and Az/El image (right) at negative 15° elevation, 235° aspect, 35 GHz (Ka-band) HH polarization, 2" full-scale resolution.

Figure 10 shows the photo of the 48th scale model (left) and Az/El image (right) of the Mig29 at negative 15° elevation, 235° aspect, 35 GHz (Ka-band) HH polarization, and 2" full-scale resolution. Here, the Mig29 was measured with the underside exposed, to simulate a ground based radar measurement. The two rear vertical stabilizers can be seen clearly, and the twin engine ducts along the underside show little radar return along their rounded edges as the energy is reflected away from the receiver (visible as two white lines on the underside). Upon very close inspection, the two vertical stabilizer rudders show their outlines, indicative of the small gap between the stabilizer and the rudder itself.

5. Summary

A new high frequency compact radar range operating at 1.56 THz has been developed. The compact range has demonstrated very good stability and signal to noise. The system has been used to collect data suitable for the generation of ISAR images in range and cross-range using a frequency agile source. RCS and ISAR image comparisons between a full scale BMP-2 measured at 95 GHz and a 1/16th scale model show good agreement. Additionally, a new two-dimensional image technique has been presented which forms very high-resolution images in azimuth cross-range and elevation cross-range. This technique has proven useful in identifying individual scattering centers on models of tactical targets.

ACKNOWLEDGMENTS

The authors wish to thank William T. Kersey for his help. This work was supported by the U. S. Army National Ground Intelligence Center's (NGIC) Expert Radar Signature Solutions (ERADS) Project.

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