

Acquisition and Analysis of X-Band Moving Target Signature Data using a 160 GHz Compact Range

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ABSTRACT

Acquisition of full-polarimetric millimeter-wave, or microwave, moving target signature sets sufficient for developing ATR algorithms have proven to be costly and difficult to achieve operationally. Thorough investigations involving moving targets are often hindered by the lack of rigorously consistent signature data for a sufficient number of targets across requisite viewing angles, articulations and environmental conditions. Under the support of DARPA's TRUMPETS (through Mission Research Corporation) and AMSTE programs in conjunction with the US Army National Ground Intelligence Center (NGIC), X-band far-field turntable signature data has been acquired on 1/16th scaled models of the Bradley and BTR-70 vehicles specifically constructed for moving target investigations using ERADS' 160 GHz fully polarimetric compact range. The tracks/wheels of the scale models were translated incrementally as the radar's transmit frequency was stepped across a 10.5 GHz bandwidth. By acquiring a full frequency sweep at each track/wheel position with appropriate translation resolution, HRR RCS profiles of doppler-shifted body/track components were generated. HRR profiles of the equivalent stationary vehicle were also generated for analysis using the vehicle's HRR profiles for any given track position.

These full-polarimetric HRR RCS profiles were acquired at an azimuth resolution and sweep-to-sweep phase stability sufficient for generating doppler shifted and standard ISAR imagery of either/both the moving and stationary vehicle. As a low-cost technology, this signature survey enabled researchers on the TRUMPETS and AMSTE programs to perform correlation studies between moving and stationary target HRR RCS profiles as well as ISAR imagery for a complete spin of the vehicle at a single elevation angle.^[1-4] Data sampling was of sufficient density to enable researchers to simulate complex (non-linear) vehicle movement such as driving around a curve. Certainly more complex scenarios could be investigated with the existing signature data like acceleration/deceleration effects. A summary of the moving target signature data acquired is presented, along with a description and examples of the signature analysis techniques exploited. This signature data is available from NGIC on request for Government Agencies and Government Contractors with an established need-to-know.

Key words: X-Band, Polarimetric, Radar, ISAR, Imagery, Moving, Target, Doppler, Signature.

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Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE OCT 2001		2. REPORT TYPE		3. DATES COVERED 00-00-2001 to 00-00-2001	
4. TITLE AND SUBTITLE Acquisition and Analysis of X-Band Moving Target Signature Data using a 160 GHz Compact Range				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 11	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

1.0 THE SIGNATURE ACQUISITION TECHNIQUE

The high resolution X-band moving target signature data was acquired on 1/16th scale models of the M2A3 Bradley and BTR-70 depicted in Figure 1 using a 160 GHz fully polarimetric compact range radar⁵. For the M2A3 Bradley, the tracks of the scale model were translated incrementally as the vehicle was translated forward and the radar's transmit frequency stepped across its bandwidth. As a wheeled vehicle, the scaled BTR-70's chassis was incrementally translated/rolled forward to simulate the moving target environment during the acquisition sequence. By acquiring a full frequency sweep at each track/target position with appropriate translation resolution, HRR RCS profiles of doppler-shifted body/track components were generated. HRR profiles of the equivalent stationary vehicle were also generated for analysis using the vehicle's HRR profiles for any given body/track position.

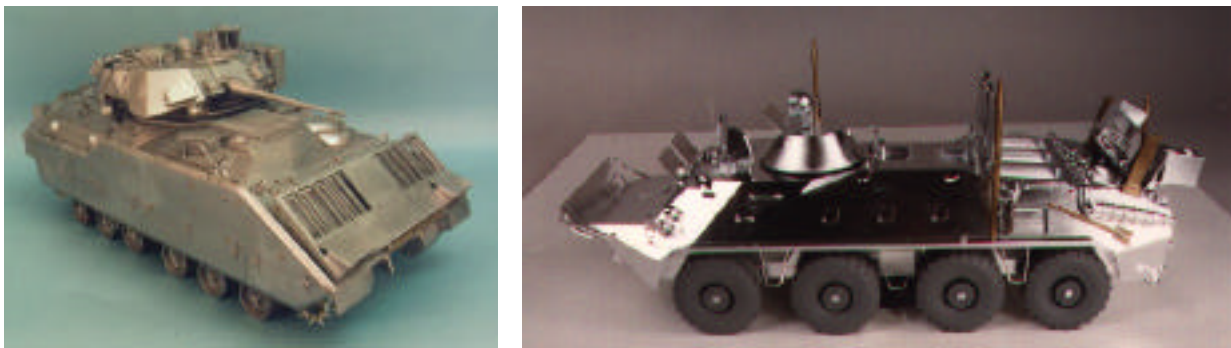


Figure 1. The 1/16th scale models of the Bradley Fighting Vehicle and BTR-70.

These full-polarimetric HRR RCS profiles were acquired at an azimuth resolution sufficient for generating ISAR of either, or both, the moving and stationary vehicle. With a signature acquisition rate of 0.2 sec/ full polarimetric sweep (i.e. ^a 1 hour/look angle), the solid-state radar's sweep-to-sweep phase stability was sufficient for generating doppler shifted ISAR imagery. The signature survey enabled correlation and RCS variability studies between moving and stationary target HRR RCS profiles as well as ISAR imagery for a complete spin of the vehicle at each elevation measured.

2.0 SCALING REQUIREMENTS OF A TARGET'S MOTION PARAMETERS

The acquisition of X-band moving target signature data at 160 GHz was achieved by simply scaling the vehicle's ground relative movement between sequential frequency sweeps of the radar. For this measurement exercise, a pulse repetition frequency (PRF) of 2000 Hz was used which indicates that a vehicle travelling 40 mph has moved 0.9 cm or ^a 1/3 between sequential frequency sweeps. Knowing that the vehicle's motion cannot exceed 1/4 between frequency sweeps to allow coherent processing of the doppler velocity means that a maximum scaled velocity of 33.5 mph will be sufficiently sampled during the signature acquisition sequence. Establishing the radar's signature measurement characteristics in this manner, one is able to calculate the change in phase which occurs for a scattered signal from a moving vehicle.

Table 1. Phase shift of the moving vehicle between frequency sweeps of the radar.

Velocity(mph)	Distance(cm)	Phase Shift	Scaled Dis.(mm)
40	0.9	107°	0.56
30	0.67	81°	0.42
20	0.45	54°	0.28
10	0.22	27°	0.14

Tabulated is the center frequency phase shift one might observe for a moving vehicle using this radar. Since in-scene objects have different relative velocities, i.e. the top and bottom of the tank tracks in reference to the tank frame, each will appear to separate in the doppler shifted images and HRR profiles. To scale a 10 mph moving target signature appropriately, a spatial increment for the track/vehicle translation of $Dx = 0.14\text{mm}$ was implemented simulating an incremental time difference of $Dt = 1/2000\text{th sec.}$ between frequency sweeps. The doppler of the moving vehicle was established by the down-range target velocity, v , ie. $v = Dx/Dt$ and frequency sweep rate. By acquiring 256 target/track positions, use of 128 consecutive steps enabled a 10 mph simulation while a 128 double-step FFT enabled 20 mph doppler. Although the phase shift for the duration of the frequency sweep could have been scaled, unless this value is greater than $\pi/8$ its impact is considered minimal to the moving target signature characteristics. Listed below are the parameters for the scaled signature acquisition sequence.

Table 2. 160 GHz CR measurement parameters for acquiring moving target signatures

model scale factor:	1/16th
center frequency:	160 GHz
bandwidth:	10.5 GHz
# of Frequency steps:	64
azimuth resolution:	0.061°
track step resolution:	0.14 mm
#steps/track extent:	256
ground plane	Arizona soil (moderate roughness, reflectivity $\approx 10\%$) ⁶

3.0 CONSTRUCTION OF THE APC SCALE MODELS



Figure 2. With applique armour on the Bradley, modular construction was necessary to not only provide feature articulation but also allow access to the vehicle's drive train.

Two 1/16th scale models of the Bradley were constructed to allow scaled signature investigations on all three versions of the M2 Infantry Fighting Vehicle (IFS) and all three versions of the M3 Cavalry Fighting Vehicle (CFV). Fabrication of the two base structures were required to simulate the six versions designated as M2, M2A1, M2A2, M3, M3A1 and M3A2. Since the M2A2/M3A2 Bradleys have an additional layer of applique armour, one base structure supports those two versions and has been motorized for moving target signature studies. The second base structure supports the remaining four versions and interchangeable features provide the configurational differences as depicted in figure 2.

To raise the fidelity of the model, all composite structures of the Bradley are scaled using artificial dielectric materials. The most challenging of these structures is the single-pin type tracks with rubber pads. Since the Bradley's tracks are motorized for doppler studies, it was necessary to mold the simulated rubber composite pads around a light weight aluminum link and connect the links using stainless steel pins. As shown in figure 3, beyond feature articulation the modular design of these models allows one to access the target's mechanization through fully functional scale-model bolts.

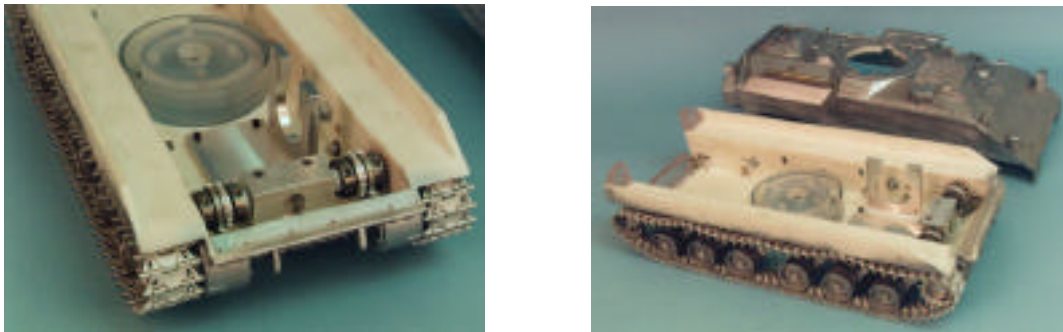


Figure 3. Depicted is the drive train and motor mount of the 1/16th scale model.

The 1/16th scale Bradley's movement is achieved using six dual rubber-tired road wheels on each side of the vehicle with fixed-height drive sprocket and idler wheel at the vehicle's front and rear, respectively. Simulated hydraulic shock absorbers have been fit to the first, second, third and sixth road wheel stations with the height of the second, third, fourth and fifth road wheels vertically free to lie on the moving track. Precision bearings on every road wheel allow rotation through realistic track interaction. There are two track-return rollers that support the inside of the track only, and one double roller.

Shown in Figure 3 is the drive train and motor mount, where timing chains will be used between the drive motor and gear box. The ^a 3.4 cm diameter front end sprocket will be driven by a DC stepper motor set at 50,800 steps/revolution using a timing chain and sprockets with a 2:3 gear ratio. With this configuration a spatial step resolution of ^a p $(3.4 \text{ cm} \times 2/3)/50,800$ or ^a $1.4 \mu\text{m}$ (22 μm full scale) is achieved for the track translation.

4.0 THE MOVING TARGET SCENE AND CLUTTER ENVIRONMENT

The moving target scaled signature investigations of the Bradley and BTR-70 were measured in a clutter environment. A 1/16th scale 1-meter diameter ground plane simulating ^a 3,000 sq.ft. of rough terrain was designed and fabricated for use in ERADS' 160 GHz compact radar range. The dielectric properties of soil as a function of moisture were

obtained from the literature^{6,7,8} and a castable polyurethane was loaded with powdered silicon to adjust the dielectric constant of the urethane from a value of $2.72+i0.04$ to $3.80+i0.20$. As a result the front surface reflectance of the composite plastic at 160 GHz modeled the front surface reflectivity, ^a 10%, of Arizona soil at 10 GHz.

The 1/16th scale models were supported above the rough dielectric ground plane and articulated in the drive direction with a low-RCS motorized-center post hidden between the vehicle's rolling wheels. See Figure 4. With the wheel treads/tracks contacting the ground (stationary), the chassis was moved toward (or away) from the radar with the top of the wheel treads/tracks moving at twice the vehicle's velocity. Target/ground multi-bounce was captured to simulate full-scale signature measurements and the clutter environment realistically separated from the target signature as the velocity increased.

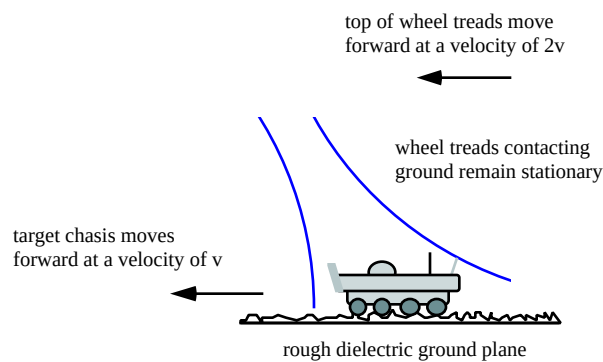


Figure 4. Depicted is in-scene modelling of moving target signatures for clutter separation studies.

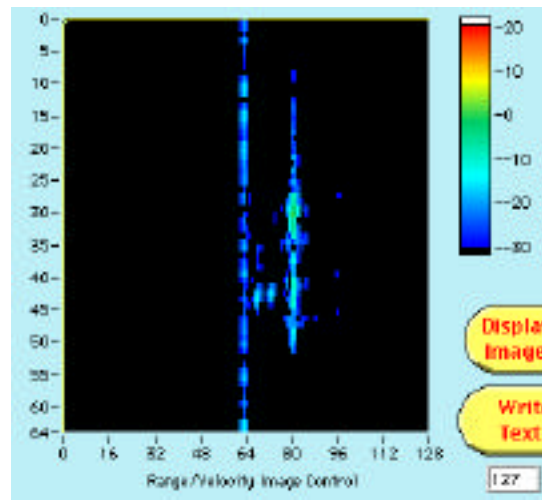
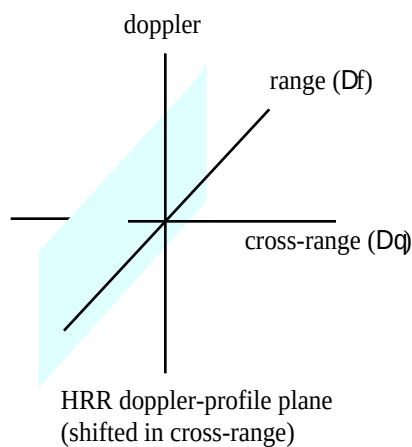


Figure 5. The dimensionality of the moving target signature processed as HRR doppler imagery.

The tracks were driven an extent of ^a 38 l and sampled at 256 increments (i.e. Δx ^a 0.15l) for generating the doppler shifted HRR RCS signature profiles at two velocities. Table 3 indicates the dimensionality of this signature data by the order in which it was acquired and processed.

Table 3. The moving target signature space as ordered in the acquisition sequence.

<i>Order</i>	<i>Dimension</i>	<i>set by</i>	<i>System Parameter</i>
1	down-range resolution	“ “	frequency bandwidth (radar)
2	doppler range resolution	“ “	spatial bandwidth (tank tracks)
3	cross range resolution	“ “	angular bandwidth (turntable)

By acquiring a full frequency sweep at each track position with appropriate translation resolution, HRR RCS profiles of doppler-shifted body/track components were generated and displayed as 2-D imagery in Figure 5. As depicted on the right of Figure 5 in the range-doppler display, bin 64 contains the zero doppler range profile. Bin 80 is the range profile of the BTR-70's moving hull. At twice the velocity, i.e. the range profile in bin 96, scattering has been captured off the top of BTR-70's four tires. The same signature data may also be used to generate HRR profiles of the stationary vehicle at any given track/wheel and body position. This combination enables one to perform correlation studies between a moving and stationary target establishing a target-based RCS variability envelope with no measurement differences.

In the same manner, the full-polarimetric HRR RCS profiles were acquired at an azimuth resolution sufficient for generating ISAR of either/both the moving and stationary vehicle. Since the signature acquisition rate was 0.2 sec/ full polarimetric sweep (i.e. ^a 1 hour/look angle, 64 azimuths by 256 track positions), the use of in-scene calibration objects will insure that the sweep-to-sweep phase stability is sufficient for generating doppler shifted ISAR imagery. As depicted in Figure 6 and demonstrated with measurements acquired of the 1/16th scale BTR-70 in Figures 7 and 8, doppler separated ISAR imagery can be generated using the moving target signature data enabling correlation studies between moving and stationary target ISAR imagery.

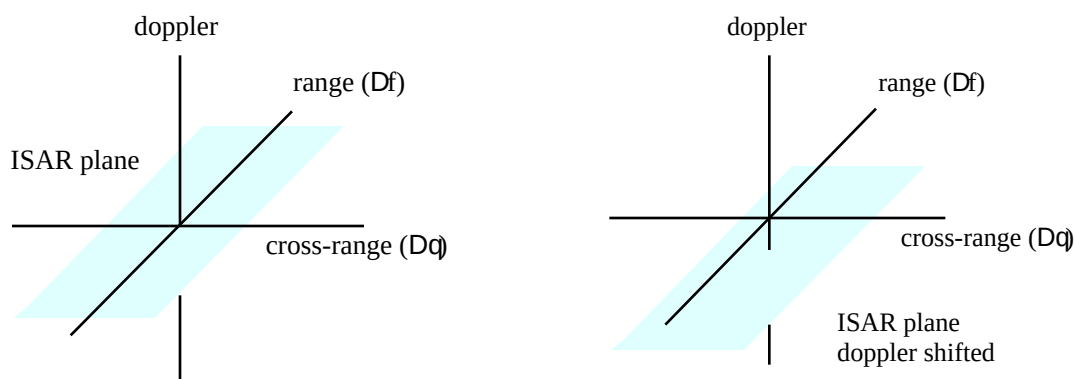


Figure 6. The dimensionality of the moving target signature processed as doppler separated ISAR.

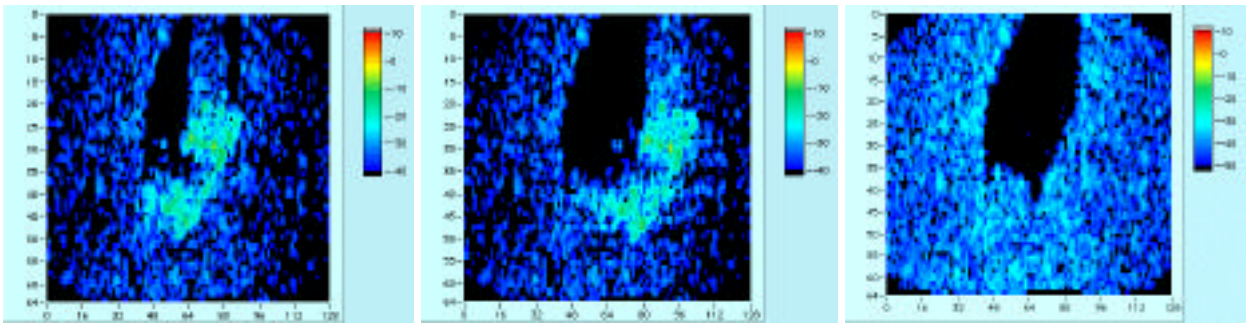


Figure 7. The stationary (left) and moving(center) target ISAR for a 22° azimuth, 17° elevation BTR-70 depicted along side the ISAR (right) generated from the zero-doppler component dominated by the ground terrain.

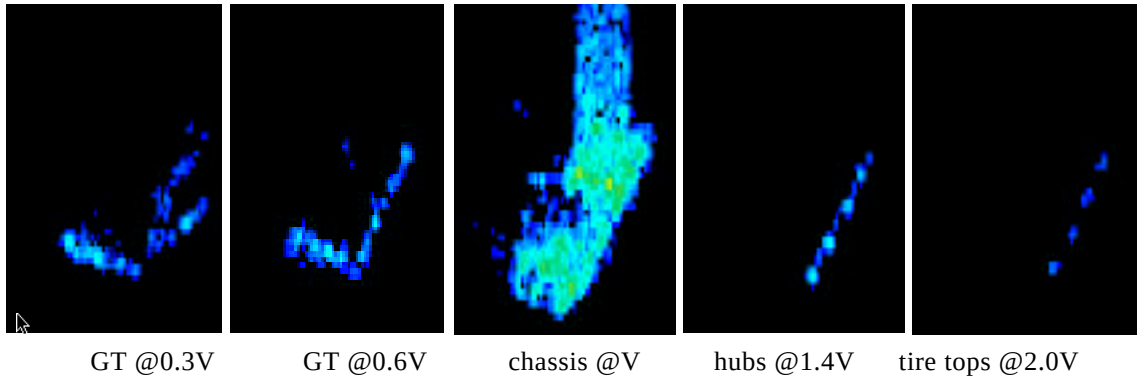
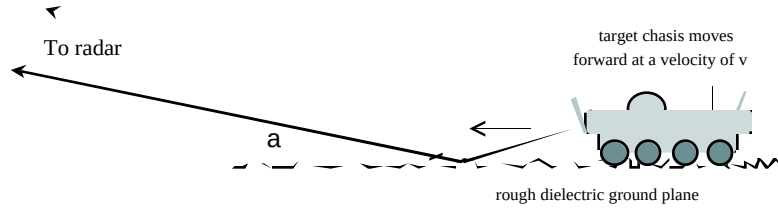


Figure 8. The 22° azimuth, 17° elevation moving target signature data of the BTR-70 displayed as doppler separated ISAR.

Typical of the imagery acquired using full-scale radars, the left and center images displayed in Figure 7 represent stationary and moving (10 mph) target ISAR of the BTR-70 measured in NGIC's physical scale modelling compact range laboratory environment. Because acquisition of the moving target signature data is achieved by simply stepping the vehicle's ground relative movement between sequential frequency sweeps of the radar, velocity-induced doppler exists within the data base as a third dimension. Shown in Figure 8 are a few of the BTR-70's doppler separated ISARs displayed in layers of increasing velocity from left to right. At a Doppler velocity bin capturing the scattered signal from the target's chassis and hull, observed in the center ISAR image is scattering beyond the vehicle's range extent generated from a pair of louvered compartments in the back of the BTR-70. Scattered signal was observed from the top of the BTR-70's four hubs, and tires, at Doppler velocities of 1.4, and 2, times the chassis velocity, respectively. Less intuitive is the behavior of peak scattering as a function of doppler that is generated by ground/target interactions (GT). While a variety of low-level scattering was observed in all doppler bins between zero and that of the chassis, peak scattering which outlined the vehicle was observed at 3 tenths and 6 tenths the chassis doppler ($\pm 1/10$) for the respective vehicle look as shown in Figure 8.

5.0 DERIVATION OF THE MOVING TARGET/GROUND DOPPLER COMPONENTS



Whether characterizing moving or stationary target signature data, there are three principle paths by which the specular scattered signal is returned to the radar. The first is the direct path (radar-target-radar) and equivalent to a free space measurement at the desired elevation. The second involves two bounces from the groundplane (radar-GP-target-GP-radar). It's equivalent to viewing the target from under the ground-plane (GP), the negative of the elevation angle. The third involves one bounce with the ground-plane (radar-target-GP-radar and simultaneously the reciprocal of this). This is equivalent to a bistatic measurement where the transmitter is above the GP and the receiver is below the GP (and the reverse for the reciprocal path).

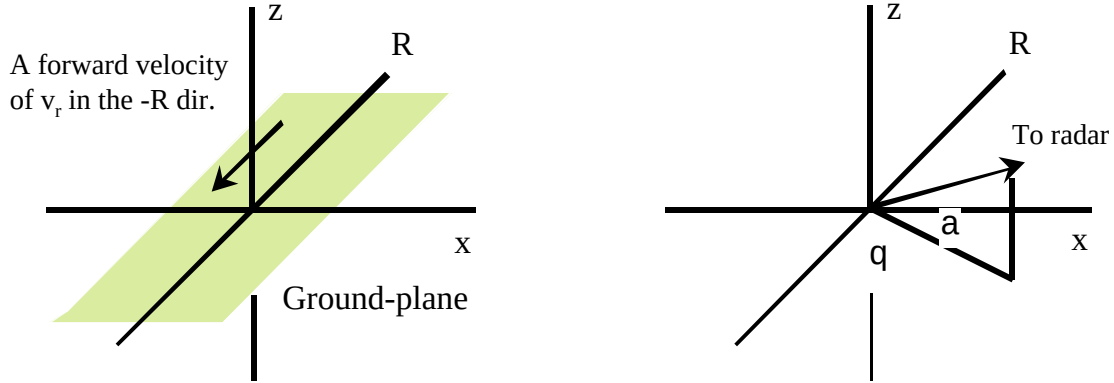


Figure 9. The 0° azimuth, 0° elevation target frame (left) and the rotation pointing to the radar.

Originally described by Paddison et al.⁹, STL researcher M.J. Coulombe experimentally verified this approach in 1994 by synthesizing a ship's RCS through three independent scale-model measurements rather than constructing a sea-state ground-plane. For the formation of ISAR, these three contributions add coherently and the ground bounce characteristics must be accounted for to gain an understanding of its contribution to the target's signature. Predicting the doppler shift of direct path scattering from the target is achieved by establishing a target frame coordinate system as depicted in figure 9 and then performing an azimuth/elevation rotational transformation to the radar's reference frame. The vehicle's velocity vector in the target frame can be defined as: $V = [0, -v_r, 0]$ for the coordinate representation: $C = [x, R, z]$ where R is the range direction of the target at 0° azimuth, 0° elevation. Depicted on the right of figure 9, rotation of the target in azimuth, q , and elevation, a , is performed using the following matrices;

$$M_q = \begin{bmatrix} \cos q & \sin q & 0 \\ -\sin q & \cos q & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad M_a = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos a & \sin a \\ 0 & -\sin a & \cos a \end{bmatrix}$$

where $V' = M_q M_a V$ is the vehicle's velocity vector transformed to the radar's frame of reference. Using this notation,

the doppler velocity for the three principle paths in target/ground-plane signature data are $2 M_q M_a V$, $2 M_q M_{-a} V$ and $[M_q M_a V + M_q M_{-a} V]$. Expanded as vector notation in the radar's frame of reference, the three doppler velocities are:

$$D_t' = | -2 v_r \cos a \sin q, -2 v_r \cos a \cos q, 2 v_r \sin a | \quad \text{direct path}$$

$$D_d' = | -2 v_r \cos a \sin q, -2 v_r \cos a \cos q, -2 v_r \sin a | \quad \text{double ground bounce}$$

$$\text{and } D_s' = | -2 v_r \cos a \sin q, -2 v_r \cos a \cos q, 0 | \quad \text{single ground bounce.}$$

Since the only component contributing to the motion induced doppler measured by the radar is in the range direction (i.e. $-2 v_r \cos a \cos q$), both single and double specular multibounce off the ground exhibits the same doppler shift as the direct path.

More difficult to characterize, diffuse scattering from the ground plane interrogates the target over a wide range of incident angles. As in the case of figure 8, peak ISAR images at velocities of 0.3 and 0.6 that of the chassis are traceable to the front hull's flat plate structure tilted at an angle, $b \approx 50^\circ$, to the vertical as shown in figure 10. While functionally the target's direct path scattering remains unchanged, the doppler velocity of the two principle paths for target/terrain interactions are driven not only by the look angle of the radar but also the vertical tilt, b , and horizontal twist, f , of the specular target structure's normal with respect to the direction of motion. :

$$[M_q M_{-b} + M_{-(q+2f)} M_{-b}]V \quad \text{double ground bounce}$$

$$\text{and } [M_q M_a + M_{-(q+2f)} M_{-(a+2b)}]V. \quad \text{single ground bounce.}$$

Retaining only the doppler components in the range direction of the radar's reference frame, the doppler velocities for diffuse terrain scattering reflected by the moving target are:

$$d_t' = -2 v_r \cos a \cos q \quad \text{direct path}$$

$$d_d' = -v_r \{ \cos b \cos q + \cos b \cos (q+2f) \} \quad \text{double ground bounce}$$

$$\text{and } d_s' = -v_r \{ \cos q \cos a + \cos (a+2b) \cos (q+2f) \} \quad \text{single ground bounce.}$$

Using the above equations and retaining only the doppler components in the range direction of the radar's reference frame, the doppler ratios for diffuse terrain scattering with respect to the direct path scattering are:

$$d_d'/d_t' = \{ \cos b \cos q + \cos b \cos (q+2f) \} / (2 \cos a \cos q) \quad \text{double GB/T}$$

$$\text{and } d_s'/d_t' = \{ \cos q \cos a + \cos (a+2b) \cos (q+2f) \} / (2 \cos a \cos q) \quad \text{single GB/T}$$

under the constraint equation, $b > a$ for ground-target scattering involving a double ground bounce and $b > -a$ for ground-target scattering involving a single ground bounce. For the BTR-70's front lower hull, a vertical tilt of $b \approx 50^\circ$ and horizontal twist of $f \approx 0^\circ$, the doppler ratios for scattering which involves the single and double bounce ground return is 0.26 and 0.67, respectively, just as observed at an azimuth of 22° , elevation of 17° , in the ISAR displayed in Figure 8.

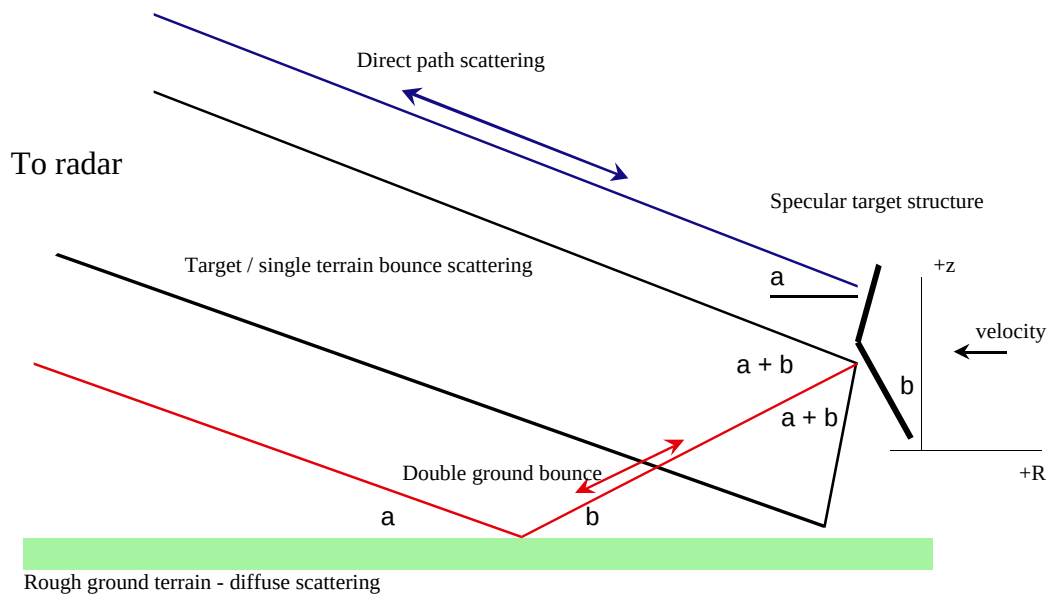


Figure 10. The geometry of terrain (diffuse) scattering back-reflected by a moving target structure.

6.0 THE MOVING TARGET SIGNATURE DATA

HRR moving target signature data was acquired for a complete spin of the Bradley and BTR-70 at four elevations, 13°, 15°, 17° and 19°. This signature data, deliverable on five CDs for each elevation as (^a 20 MB) files of 5902 consecutive look angles, is stored as either NGIC Labview™-based ASCII or binary text formatted files of fully calibrated signature data with background subtraction and in-scene stationary scatterers eliminated.

Labview-based software has been generated for in-house calibration, processing and analysis of the moving target X-Band signature data described in this report. The program is designed to execute signature file I/O and a TRCS, HRR and/or ISAR analysis, as well as the type of file storage and data processing techniques; such as background subtraction, polarimetric calibration, doppler processing, image/profile sizing, thresholding and/or averaging.

The full polarimetric (4 LP transmit/receive channels) complex in-phase/quadrature (I,Q) signature information for a single frequency, track position, azimuth and elevation angle requires 16 bytes of storage space. Initially the frequency bandwidth is swept across 1024 steps to enable software range gating and is post processed to an unambiguous range of ^a 47 ft (which leaves the analyst with 64 frequency steps). Doppler processing is achieved by the acquisition of each HRR profile at 256 track positions with a spatial resolution no greater than 1/4. The generation of ISAR imagery is possible by the acquisition of these doppler swept HRR profiles across 64 azimuth angles with a resolution of 0.061°. For a 360° spin of the vehicle this entails acquiring 25 GBytes of information as follows:

$$5902 \text{ azimuth} \times 256 \text{ doppler} \times 1024 \text{ frequencies} \times 4 \text{ t/r polarizations} \times 2 \text{ I,Q} \times 2 \text{ bytes}$$

Post processing of the raw signature information brings the unambiguous range to ^a 1.55 GBytes of deliverable data for each elevation spin of the moving target.

7.0 SUMMARY

X-band full-polarimetric HRR RCS in-scene moving target signature data was acquired on the Bradley and BTR-70 at an azimuth resolution sufficient for generating ISAR of either/both the moving and stationary vehicle. As a low-cost technology, this signature survey enabled researchers on the TRUMPETS and AMSTE programs to perform correlation and RCS variability studies between moving and stationary target HRR RCS profiles as well as ISAR imagery for a complete spin of the vehicle. Presented are examples of signature analysis techniques exploiting the doppler dimension to characterize ground-target scattering contributions. This signature data is available from NGIC on request for Government Agencies and Government Contractors with an established need-to-know.

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