A Study of Target Variability and Exact Signature Reproduction Requirements for Ka-Band Radar Data

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ABSTRACT

A variety of ATR algorithms have promised improved performance, not yet realized operationally. Typically, good results have been reported on data sets of limited size that have been tested in a laboratory environment, only to see the performance degrade when stressed with real-world target and environmental variability. To investigate exact signature reproduction requirements along with target and environment variability issues for stressing new ATR metrics, the U.S. Army's National Ground Intelligence Center (NGIC) and Targets Management Office (TMO) originated, sponsored, and directed a signature project plan to acquire multiple target full-polarimetric Ka-band radar signature data at Eglin AFB, as well as its submillimeter-wave compact radar range equivalent using high-fidelity exact 1/16th scale replicas fabricated by the ERADS program. To effectively understand signature reproduction requirements through the variability of multiple target RCS characteristics, TMO and NGIC sponsored researchers at U Mass Lowell's Submillimeter-Wave Technology Laboratory (STL) and Simulation Technologies (SimTech) to analyze the intra-class and inter-class variability of the full-scale Ka-band turntable signature data. NGIC, TMO, STL and SimTech researchers then traveled to the location of the vehicles measured at Eglin AFB and conducted extensive documentation and mensuration on these vehicles. Using this information, ERADS built high fidelity, articulatable exact replicas for measurement in the NGIC's compact radar ranges. Signal processing software established by STL researchers in an NGIC directed signature study was used to execute an HRR and ISAR cross-correlation study of the field and scale-model signature data.[1] The signature-to-signature variability quantified 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.

Keywords: HRR, Ka-band, polarimetric, signature, ISAR, imagery, ATR

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1.0 INTRODUCTION

While some evaluative performance studies of high-value structures and conceptual radar systems may be effectively executed with limited field radar data to minimize signature acquisition costs, pose-independent studies of ATR algorithms are best served by signature libraries fashioned to encompass the complexity of the collection scenario.[2] A variety of ATR algorithms have promised improved performance, not yet realized operationally. The good results reported on data sets of limited size that have been tested in a laboratory environment, typically see the performance degrade when stressed with real-world target and environmental variability. Near-field outdoor radar ranges do not typically measure the target in varied operational poses and therefore a template library is most likely to report a match when the configuration of the vehicle in the field matches or resembles that in the library. Furthermore, near-field ranges do not measure the varied operational environment or capture the multi-bounce interaction between the target and ground. Finally, radar signature measurements are typically designed to meet the requirements of comparison modules currently in the ATR but do not always anticipate future emerging metrics.

To investigate exact signature reproduction requirements along with target and environment variability issues for stressing new ATR metrics, the U.S. Army's National Ground Intelligence Center (NGIC) and Targets Management Office (TMO) originated, sponsored, and directed a main battle tank (MBT) signature project plan to acquire multiple target full-polarimetric Ka-band radar signature data at Eglin AFB,[3] as well as its submillimeter-wave compact radar range equivalent using high-fidelity exact 1/16th scale replicas fabricated by the ERADS program. To effectively understand signature reproduction requirements through the variability of multiple target RCS characteristics, TMO and NGIC sponsored researchers at U Mass Lowell's Submillimeter-Wave Technology Laboratory (STL) and Simulation Technologies (SimTech) to analyze the intra-class and inter-class variability of the full-scale turntable data. NGIC, TMO, STL and SimTech researchers then traveled to the location of the vehicles measured at Eglin AFB and conducted extensive documentation and mensuration on these vehicles. Using this information, the Expert Radar Signature Solutions (ERADS) program built high-fidelity, articulatable exact replicas for measurement in their compact radar ranges located at the U.S. Army NGIC in Charlottesville, VA.

Figure 1. One of the two 1/16th scale replicas of the T-72/M1 along side its full-scale equivalent (#940) at Eglin AFB.

The Ka-band scaled signature data for this investigation was acquired in a free-space configuration simulating Eglin's turntable measurements. The ERADS team measured these targets in several poses of increasing complexity of articulation by fixing the target in the pose measured at Eglin AFB and then articulating the scaled vehicle, with changes such as fuel drum presence or turret rotation. Using signal processing software established in an NGIC/STL-based signature study, researchers executed an ISAR cross-correlation study involving six inch resolution field and scale-model signature data. Enabling future ATR performance studies as a function of ground terrain clutter, ERADS is fabricating a variety of ground planes and measuring these scaled vehicles on simulated terrain as well.

2.0 THE SIGNATURE MEASUREMENTS AND TARGET DESCRIPTIONS

As described in the facility based documents referenced, the Ka-band full-scale signature data was collected at the Eglin Air Force Base Seeker Test and Evaluation Facility (STEF) at Range C-52A,[3] while ERADS scale-model data was collected in NGIC's 520 GHz 1/16th scale compact radar range measurement facility.[4] Using a rail mobile low RCS turntable, Eglin's MBT signatures were acquired at elevations from 5° through 60° at a constant range of 330 feet with 40' FWHM beam diameter maintained during the acquisition sequence. Replicating only the 5° and 15° elevation data originally reported[3], NGIC's far-field compact radar range optics was reconfigured in a manner to acquire near-field turntable signatures in similitude with Eglin's Ka-band STEF data. The critical system characteristics common to both facilities are listed in Table 1.

Table 1. The Common Operational Parameters of NGIC's and Eglin's Ka-band Polarimetric Radar

Parameter	Characteristic
RF Agile Bandwidth	1.024 GHz
Frequency Step Size	8 Mhz at 128 steps
Polarization	full PSM linear

Shown (left) in Figures 1 and 2 are the 1/16th scale replicas of the T-72/M1 and T-72/BK specifically designed and fabricated to "fingerprint" the full-scale vehicles (right), bumpers #940 and #747, respectively. Investigating the exact signature reproduction requirements for each of these targets entailed extensive on-site inspection and documentation of the full-scale vehicle by a six member science and engineering team over a three day period. Armed with preliminary mechanical drawings and extensive photography of the vehicles, the team measured the dimensionality of all external hardware on the vehicle's hull to a precision of ±2mm. Samples of the composite materials were also collected for dielectric characterization at Ka-band frequencies, completing the informational requirements necessary to fabricate the articulatable exact replicas for signature exploitation using ERADS compact radar ranges.

Signature measurements were performed by NGIC on three exact replicas of the T-72/M1 (940R1 & 940R2) and T–72/BK (747R1) as well as three additional MBT models that were fabricated as a "generic" class representation of the M1, T-72M1 and T-80UD. Detailed in Table 2, twenty-four turntable signature sets were measured to explore the intra-class and inter-class RCS target variability issues. Beyond target identification, characteristics recorded in table 2 are target elevation, turntable configuration, fuel drum presence, turret orientation and archival file name. Also identified is the subset of signatures used in the MBT cross-correlation study presented in this document.

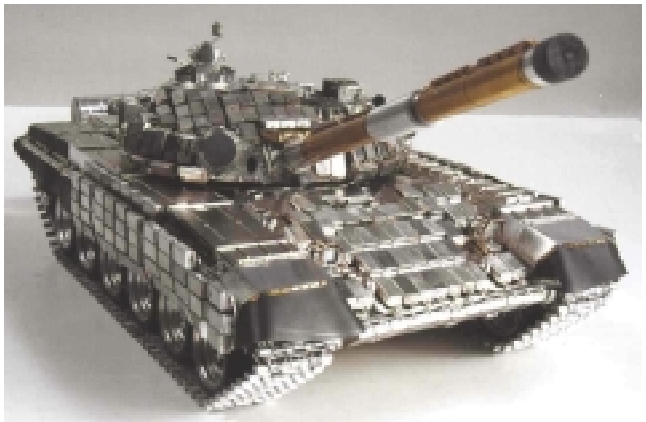

Figure 2. The 1/16th scale replica of the T-72/BK along side its full-scale equivalent (#747) at Eglin AFB.

Table 2. The sequence of MBT Ka-band scaled-signature data acquired using ERADS' 520 GHz Compact Range Facility.

Target	Replica	Elev.	Turntable	Drums	Turret	Corr.	File Name
T-72BK	#747	5	free space	on	9	yes	00L050KBAA.CID
	#747	5	free space	on	9		00L050KBBA.CID
	#747	5	low RCS	on	9		01A050KBBA.CID
	#747	5	free space	on	9	yes	01A050KBAA.CID
	#747	4	free space	on	9		01A040KBAA.CID
	#747	5	free space	on	0		01B050KBAA.CID
	#747	5	free space	on	36		01B050KBBA.CID
	#747	5	free space	off	9		01B050KBEA.CID
	#747	15	free space	on	9		01B150KBCA.CID
	#747	15	free space	off	9		01B150KBDA.CID
T-72M1#1	#940	5	free space	none	9	yes	01B050KBAA.CKD
	#940	15	free space	none	9		01B150KBBA.CKD
	#940	5	free space	none	9	yes	01C050KBAA.CKD
	#940	5	free space	none	9		01B050KBCA.CKD
T-72M1#2	#940	5	free space	none	0		01B050KBCA.CLD
	#940	5	free space	none	36		01B050KBDA.CLD
	#940	5	free space	none	9	yes	01B050KBAA.CLD
	#940	5	free space	none	9	yes	01B050KBBA.CLD
M1	generic	5	free space	none	9	yes	01B050KBAA.BKD
	generic	15	free space	none	9		01B150KBBA.BKD
T-80UD	generic	5	free space	none	9	yes	01B050KBBA.AZD
	generic	15	free space	none	9		01B150KBAA.AZD
T-72M1	generic	5	free space	on	9	yes	00H050KBAA.ALD
	generic	5	free space	on	9		00H050KBBA.ALD

3.0 ANALYSIS OF THE SIGNATURE MEASUREMENTS

The comparative methodology executed by STL researchers to quantify the signature-to-signature RCS variability of the twenty-four signatures of the six 1/16th scale main battle tanks (MBTs) was originally developed for evaluating (and establishing similitude between) MMW field data and scaled submillimeter-wave compact range turntable measurements[6]. Initially, the arithmetic mean and median of the azimuth averaged RCS turntable data were calculated for each signature measured using ERADS' compact range (CR) radar as shown in Tables 3. Achieving average mean and median values on any single MBT with a maximum difference of 0.7 dB is considered indicative of the CR radar's measurement variation. The maximum difference between the mean and median values of 5.5 dB for the twenty-four signatures is considered indicative of the measured MBT configurations where the M-1 has the highest RCS (180. dBsm) and the T-72/M1 has the lowest RCS (13.6 dBsm).

Table 3. The Ka-band RCS(dBsm) Statistics for the fourteen scaled MBT signature sets used in the cross-correlation study.

Vehicle	Size	bumper #	VV Mean	VV Median	HH Mean	HH Median	File Name
T-72M1	full-scale	940	14.7	13.1	14.8	12.8	tgt6715.sub
T-72M1	full-scale	940	15.1	13.6	15.2	13.3	tgt6724.sub
T-72BK	full-scale	747	15.5	14.3	15.7	14.3	tgt6717.sub
M-60	full-scale		16.7	15.6	16.3	15.1	tgt6722.sub
M-1	full-scale		18.0	16.1	18.1	15.9	tgt6723.sub
T-72BK	1/16th	747R1	13.8	12.2	13.8	12.2	01A050KBAA.CID
T-72BK	1/16th	747R1	14.5	12.6	14.5	12.9	00L050KBAA.CID
T-72M1	1/16th	940R1	13.6	11.5	13.3	11.8	01B050KBAA.CKD
T-72M1	1/16th	940R1	13.6	11.6	13.3	11.7	01C050KBAA.CKD
T-72M1	1/16th	940R2	13.9	11.5	13.8	11.5	01B050KBAA.CLD
T-72M1	1/16th	940R2	13.7	11.5	13.6	11.3	01B050KBBA.CLD
T-72M1	1/16th	generic	12.5	10.6	12.8	10.8	00H050KBAA.ALD
M-1	1/16th	generic	16.7	14.1	16.8	14.4	01B050KBAA.BKD
T-80UD	1/16th	generic	17.1	15.6	17.0	15.9	01B050KBBA.AZD

To evaluate the impact of these differences on the signature-to-signature RCS variability of high-resolution field and scale-model imagery, an averaged percent difference (APD) algorithm, developed and detailed by STL researchers in prior signature investigations[5] was executed. The APD algorithm was implemented on the high resolution ISAR imagery at 1° aspect increments for the entire spin of the target (360 images) and angular adjustments were performed to minimize the APD, thus eliminating azimuth misalignment between signature sets. The range and cross-range of the second target $r2 = r1 \pm \delta r$ and $cr2 = cr1 \pm \delta cr$ were defined as variables relative to the first target for performing the positional adjustments in the ISAR minimizing the imagery's APD and eliminating error contributions due to image alignment. Since the signatures were determined to be well calibrated, no adjustment in the RCS gain was made.

Using the spatial average of the percent difference between the 360 VV amplitude images (in units of dBsm) of paired signature sets, an APD was calculated for thirty-six combinations of scaled signatures, ten combinations of field signatures and forty-five combinations of scale-to-field signatures to typify the RCS variability encountered in the data. See Tables 4, 5 and 6. As the probability density function (PDF) of this cross-correlation data, figures 3, 4 and 5 depict the typical statistical spread (≈ ±1% fwhm) in agreement between the paired field and scale-model VV ISAR imagery of the MBTs that has been documented in Tables 4, 5 and 6.

There was satisfaction in the observation that the cross-correlation values between any two measurements of a single scaled vehicle are consistently the lowest tabulated values. In fact the value for two measurements performed consecutively on the $1/16^{th}$ scale replica of the T-72/M1 (bumper #940) exhibited the highest correlation, 2.5% (lowest value in Table 4). The cross-correlation between the four measurements performed on the two individual replicas of the T-72/M1(#940) exhibited a value of 8.3% which is consistent with observations on identical configurations in a prior study of 4 inch resolution Ka-band imagery collected at Aberdeen Proving Ground on eleven T-72 tanks[1]. The higher correlation, 10.4% and above, between individual measurements of different MBTs indicates that there are statistically measurable differences in the signature content between targets using Ka-band ISAR imagery.

Table 4. The VV ISAR APD Cross-Correlation of the MBT Ka-band scaled-signature data acquired at NGIC.

	T-72Bk#747	**T-72Bk#747**	**replica 1 T-72M1#940**	**replica 1 T-72M1#940**	**replica 2 T-72M1#940**	**replica 2 T-72M1#940**	**T-72M1**	**M1**
T-72Bk#747	6.9							
T-72M1#940	12.1	11.9						
T-72M1#940	11.9	11.9	6.0					
T-72M1#940	12.4	12.4	8.3	8.3				
T-72M1#940	12.5	12.4	8.3	8.3	2.5			
T-72M1 generic	12.6	12.6	10.4	10.4	10.5	10.6		
M-1 generic	15.8	16.0	16.5	16.4	16.3	16.5	16.5	
T-80UD generic	12.5	12.6	12.7	12.7	12.8	12.9	12.6	15.7

By graphing the PDF of typical examples spanning the six model cross-correlation combination, Figure 3 further illustrates the measurable differences between the scaled Ka-band signatures. Since all these MBTs possess spatially similar ISAR imagery, only agreement of the uniquely resolved RCS amplitude characteristics and their relative location for each target structure drive separability in the correlation values. As the two left most peaks in Figure 3, statistical separability from the cross-correlation of different MBTs exists for multiple measurements of a single vehicle as well as measurements of exact replicas. As the central peak of Figure 3, the APD cross-correlation values (≈10.5%) between a scaled generic class representation of the T-72/M1 and the two exact replicas encroach on the cross-correlation values (12.5% and above) between different MBTs. This feature could challenge an ATR metric if the generic signatures were chosen as the template with an objective of separating the T-72/M1 from a T-80UD. Most significant are the differences in imagery between a T–72/M1 and the Abrams M1 making them easily separable using generic class-only templates.

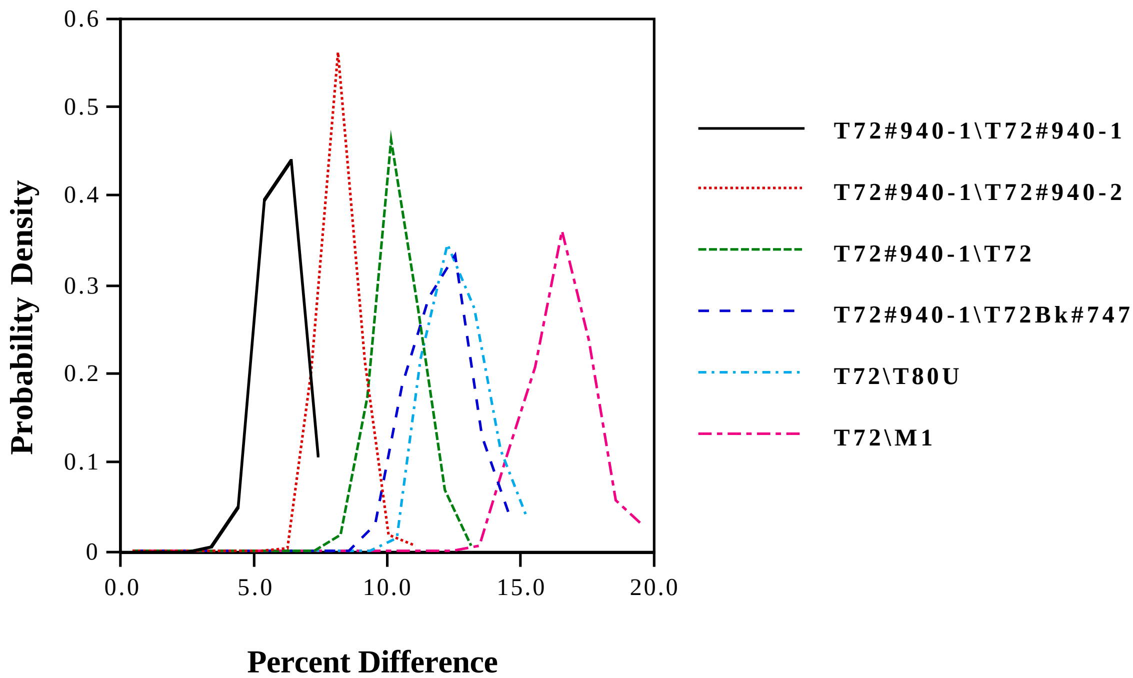

Figure 3. The probability density displayed as a function of the APD correlation for MBT Ka-band scaled-signature ISAR.

For the full-scale turntable signature data acquired at Eglin AFB, the cross-correlation value between two measurements of a single vehicle (T-72/M1, bumper #940) was also satisfactorly the lowest tabulated value (7.2%) in Table 5. Unlike the scaled-signature equivalent data, however, cross-correlation differences between imagery of measurements performed on the other three MBTs extend over only 2.2%. Figure 4 illustrates the manner in which the cross-correlated imagery between different MBTs encroaches on the cross-correlated images of similar and even identical structures. Since all these MBTs possess spatially similar ISAR imagery, the uniquely resolved RCS amplitude characteristics and their relative location which was preserved in the signature content for each target structure was insufficient to drive separability in the correlation values using only an APD metric on the high-resolution VV imagery.

Table 5. The VV ISAR APD Cross-Correlation of the MBT Ka-band signature data acquired at Eglin AFB.

	T-72M1	**T-72M1**	**T-72Bk**	**M-60**
T-72M1	7.2			
T-72Bk	9.4	9.2		
M-60	10.5	10.0	9.7	
M-1	11.4	11.0	10.5	9.8

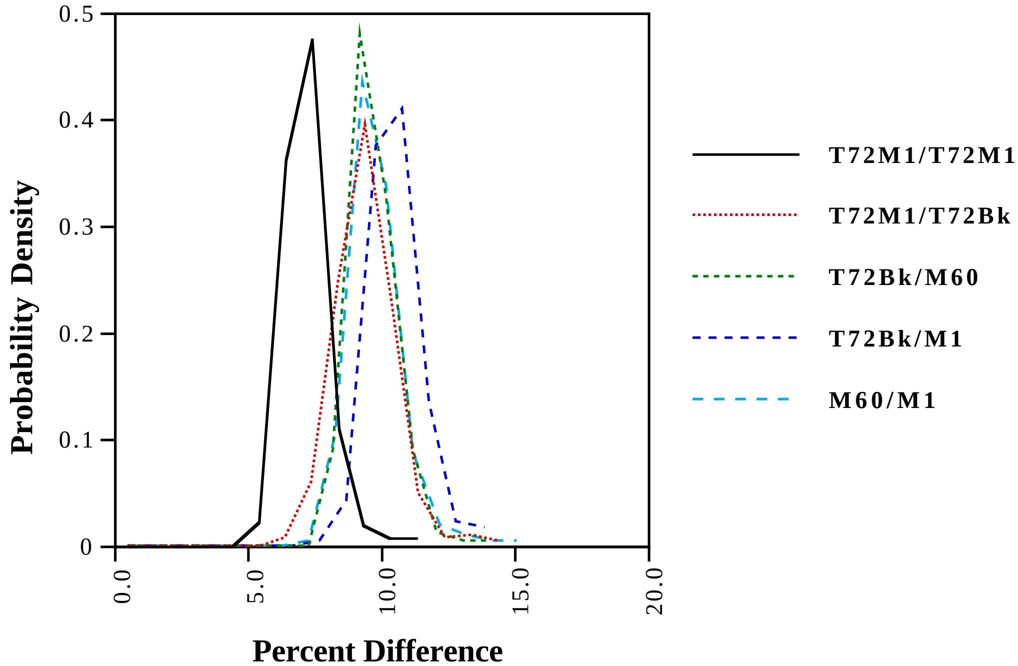

Figure 4. The probability density displayed as a function of the APD correlation for Eglin's MBT Ka-band signature ISAR.

Table 6. The VV ISAR APD Cross-Correlation of Scale-Model and Field MBT signature data.

	Full-scale Vehicles				
ERADS Model	**T-72 (#940)**	**T-72 (#940)**	**T-72Bk (#747)**	**M-60**	**M-1**
T-72Bk *747R1	10.4	10.6	10.6	12.4	13.1
T-72Bk *747R1	10.5	10.6	10.6	12.5	13.2
T-72M1*940R1	10.1	10.4	12.6	13.5	13.8
T-72M1*940R1	10.3	10.4	12.6	13.5	13.8
T-72M1*940R2	10.2	10.3	12.8	13.5	13.8
T-72M1*940R2	10.3	10.3	12.8	13.7	13.8
T-72M1 "generic"	10.7	11.0	12.8	13.7	13.9
M1 "generic"	13.2	12.6	12.5	11.9	10.3
T-80UD "generic"	10.7	10.6	11.8	11.9	12.5

Detailed in Table 6, the correlation between the Ka-band VV ISAR imagery of Eglin's turntable measurements and ERADS' scale-model data was evaluated to investigate cross-platform compatibility issues. Movement from left to right across the columns represents a change in the full-scale vehicle measured while a transition from row-to-row up or down Table 6 represents a change in the equivalent scale-model. There was satisfaction in the observation that the cross-correlation values between any measurement of a single vehicle and its scaled equivalent was always lower than the tabulated values of the cross-correlation between that vehicle, or scaled equivalent, against dissimilar scaled structures, or full-scale vehicle. Since all the signature sets possessed spatially similar ISAR imagery, this agreement speaks well of the uniquely resolved RCS amplitude characteristics and their relative location preserved between the signature content of ERADS' replicas with respect to each vehicle modeled. The only violation of this rule seems to be the confusion between imagery of the scaled T-72/BK (#747R1) and the T-72/M1 (#940). Since these vehicles all have the same hull and only the turret differs any ATR metric may be challenged to separate these structures. It is of interest, however, that the cross-correlation results for the reciprocal arrangement of the T-72/M1 (#940R1 and #940R2) with respect to the T-72/BK (#747) is separable.

Illustrated in Figure 5 is the typical separability achieved using the APD cross-correlation of field and scale-model imagery. Good agreement was found in the separation between the cross-correlation of similar structures against that of different structures even though the signature sets compared were from entirely different measurement sources.

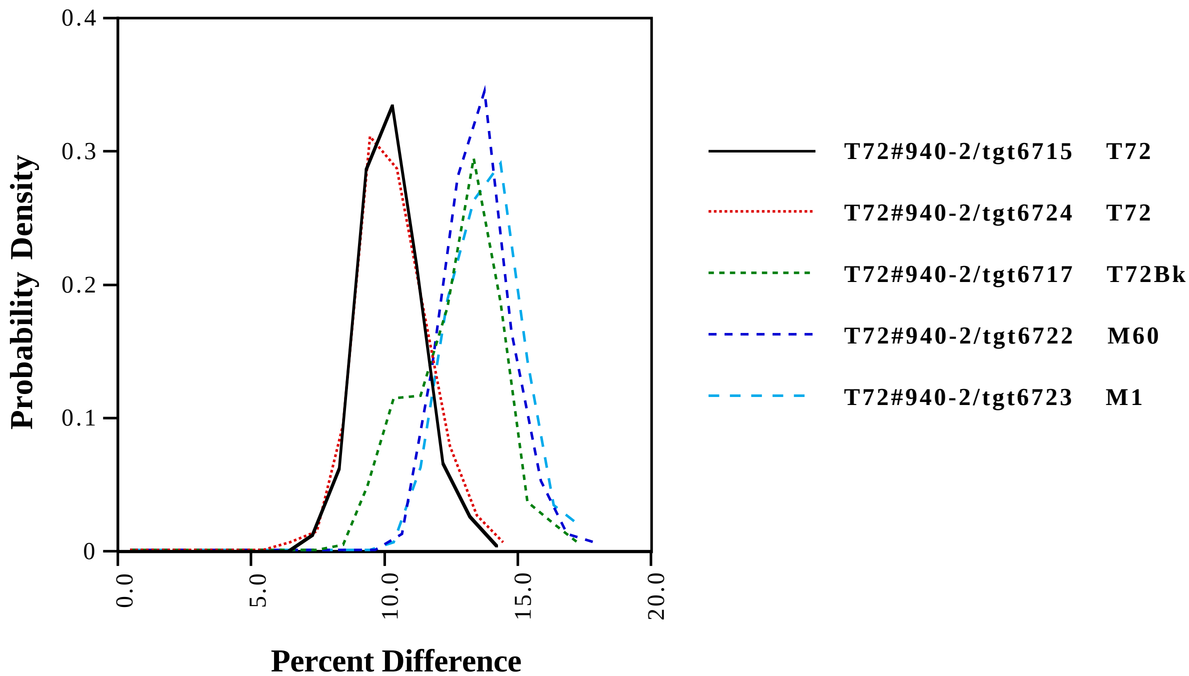

Figure 5. Displayed is the APD cross-correlation of field and scaled MBT Ka-band signature ISAR.

4.0 CONCLUSIONS

The cross-correlation of field and scale-model signatures between five main battle tanks (MBTs) has been explored through the use of 5° elevation six inch resolution ISAR imagery. Confidence in the metrics and signature data exploited was quantified through ISAR cross-correlation values between the multiple measurements of the MBTs. While target separability seems easily achievable between these five MBTs using 6” resolution ISAR, the difficulty of exploiting signatures from different measurement platforms has been made evident. Even though all these MBTs possess spatially similar ISAR imagery, the uniquely resolved RCS amplitude characteristics and their relative location for each target structure seemed sufficient to drive separability in the cross-platform correlation values.

With these results, the signature reproduction requirements of target variability issues have been investigated using the multiple target full-polarimetric Ka-band radar signature data acquired at Eglin AFB[3] in conjunction with ERADS’ submillimeter-wave compact radar range equivalent. Enabling future ATR performance studies as a function of ground terrain clutter, ERADS is fabricating a variety of ground planes and measuring these scaled vehicles on simulated terrain as well. This signature data is available from NGIC/TMO on request for Government Agencies and Government Contractors with an established need-to-know.

5.0 REFERENCES

1. W.E. Nixon, W. T. Kersey, L. C. Perkins and R.H. Giles, "A Variability Study of Ka-Band HRR Polarimetric Signatures on Eleven T-72 Tanks", SPIE Proceedings of the 12th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Controls, Vol. 3370, April 1998.
2. L.M. Novak, S.D. Haversen, G.J. Owirka, and M. Hiett, “Effects of Polarization and Resolution on the Performance of a SAR ATR System”, MIT Lincoln Laboratory Journal, Vol. 8, No. 1, pp. 49-67, Spring/Summer 1995.
3. R. Finley, M.S. McFarlin, B.G. Woodruff, R.H. Giles, and W.E. Nixon, “Main Battle Tank (MBT) Requirements Analysis”, Targets Management Office Final Report, March 2000
4. M.J. Coulombe, T. Horgan, J. Waldman, G. Scatkowski, and W. Nixon, “A 520 GHz Polarimetric Compact Range for Scale Model RCS Measurements”, Antenna Measurements and Techniques Association (AMTA) Proceedings, Monterey, October 1999.
5. R. H. Giles, W. T. Kersey, M. S. McFarlin, B. G. Woodruff, R. Finley, W. E. Nixon, "A Multiple Resolution Study of Ka-Band HRR Polarmetric Signature Data”, SPIE Proceedings of the 14th International Symposium on Aerospace/Defense Sensing, Simulation and Controls, Vol. 4050, pp 408-417, April 28, 2000
6. R.H. Giles, M.J. Coulombe, T.M. Horgan, W.E. Nixon, W.F. Reinhold, J. Shostak and T. LaVella: “Establishment of a Submillimeter Compact Range Meeting Longbow Radar Requirements”, Proceedings of the 38th Tri-Service Radar Symposium, West Point, NY, June 1992.