3D Radar Imaging Using Interferometric ISAR
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ABSTRACT

Three-dimensional radar imaging is becoming increasingly important in modern warfare systems, leading to an increased need for deeper understanding of the 3D scattering behavior of targets as simple as a cylinder, to as complex as a main battle tank or air defense unit. Fully polarimetric, three dimensional radar signature data have been collected using 1/16th scale models of tactical targets in several indoor compact radar ranges, corresponding to data from S-band to W-band. ISAR image pairs, collected at slightly different elevations, were interferometrically processed into 3D imagery. The data collection, analysis, and 3D visualization methods are presented. Additionally, the results of mathematical 3D correlation are described. A detailed analysis of both measured and predicted 3D radar data on the UMass Lowell nominal rocket simulator target will be presented.

Keywords: Sub-millimeter, Radar, Imagery, Modeling, 3D, Terahertz, Interferometric.

1. INTRODUCTION

The continuing evolution of radar systems has increased the need for high quality radar cross-section (RCS) data. This data is commonly used in algorithms for target recognition and for validation of computational radar scattering prediction codes. The data of interest to these programs include synthetic aperture radar (SAR) and high-range-resolution (HRR) target profiles. The U. S. Army National Ground Intelligence Center (NGIC) Expert Radar Signature Solutions (ERADS) program including the Submillimeter-Wave Technology Laboratory (STL) at UMass Lowell have developed a variety of compact ranges to measure the radar return of scale models of targets of interest. Target signature data is collected by measuring the scaled targets (typically 1/16th or 1/35th scale) at proportionally scaled frequencies. The ERADS compact ranges currently model frequencies from UHF up to W-Band and with a new compact range that is also capable of far-field bistatic measurements.

With the continuing advances in 3D imaging systems such as monopulse radars, 3D radar scattering data has become more important. STL has developed new methods for collecting 3D radar scattering data. These methods rely on the precise motion control and positioning that is achievable when using an indoor compact radar range. The new methods, which are similar to monopulse radar, rely on measuring the phase change of ISAR images under a controlled induced motion. Using the precise measurements from high resolution position encoders, the height of each pixel in an ISAR image can be calculated accurately. Once the target has been scanned using this interferometric method, the resulting 3D information is then overlaid onto a CAD model of the target. The data can be displayed in a 3D viewer which allows the user to orient the CAD/Data overlay in real time in order to study the scattering from the target in 3D. Since the data collection requires only that the target be measured at two slightly different elevation angles and its ISAR images compared for phase changes, it does not require the time consuming effort of producing a 2D aperture in azimuth and elevation, which would require significantly more data. The ERADS program has applied this technique on a wide variety of targets and has achieved a high degree of success. The specifics of the method will be described in the following sections along with examples of 3D data overlays onto the CAD models of the targets. Additionally, STL has developed a number of programs to allow the 3D data to be cross correlated with other 3D data sets. These 3D data sets can include similarly collected radar data, CAD models, IFISAR predictions from programs such as Xpatch, and scattering center files produced by Xpatch.

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2. INTERFEROMETRIC ISAR THEORY

STL has described the general mathematics for 3D IFISAR previously. Therefore, only a brief description will be given here. Figure 1 shows a simplified diagram of a phase monopulse system and illustrates the method by which phase changes from a scattering center are related to its cross range position. In this diagram antennas A and B are separated from one another by a distance L and have parallel and overlapping fields of view. A target located at a range R from the center of the antennas will have a difference in phase between the two channels whose sign is dependent on the scatterer being located above or below the null axis, where there is zero phase difference. If the range to the target is much greater than the separation between the antennas, the phase difference registered between antenna A and B is given to a good approximation by Equation 1. Therefore, the change in phase of the target varies proportionally with the target’s crossrange position \( r_y \).

\[
\Delta \phi \approx 2\pi \frac{L}{\lambda} \sin(\psi) = 2\pi \frac{L}{\lambda} \frac{r_y}{r}
\]

This technique has been adapted for use in a compact radar range by again utilizing the phase information of the target. Figure 2 shows the basic geometry for an isolated scatterer. This isolated target has a phase in the direction of the radar given by Equation 2 with respect to an arbitrary point of rotation. Equations 1 and 2 represent single pass phases of the radar beam. For round-trip paths the equations must be multiplied by a factor of two. In this discussion we will limit ourselves to describing the single pass results. However, the equations can be modified by the relevant multiplicative factors to account for any combination of transmitter/receiver system. Additionally, STL has successfully used this method with a prototype bistatic compact range, where the calculations that are given above must be further modified. Taking a derivative, Equation 3 shows that the variation of phase for an individual scatterer is directly proportional to the crossrange distance out from the point of rotation.
\[ \phi = 2\pi \frac{R \sin(\theta)}{\lambda} \]  

\[ \frac{\partial \phi}{\partial \theta} = 2\pi \frac{R \cos(\theta)}{\lambda} = \frac{2\pi}{\lambda} r_y \]  

Therefore, if a careful measurement is made of the phase change of the target under differential changes in angle \( \theta \), the crossrange position can be calculated in a similar way to that of phase monopulse. Requiring that the phase change between the two methods be identical constrains \( \Delta \theta \) from Equations 1 and 3 such that

\[ \Delta \theta = \frac{L}{r} \]  

Since \( R \gg L \) this can be interpreted as constraining \( \Delta \theta \) to match the angular perspective of the two antenna in Figure 1 at range \( R \). The same result also holds when both radar systems (Figure 1 and Figure 2) involve a double pass phase change. It has been noted previously that if there are multiple unresolved scatterers involved in this calculation, there may be a false representation of the calculated coordinate. Since the technique will be applied to ISAR images this will mitigate the ambiguity, and the results will improve with higher resolution data sets.

In order to ensure the highest accuracy, the change in elevation angle between the two ISAR data sets should be matched so that the height of the target will produce a phase change of \( +/- \pi/2 \). This requirement prevents the height coordinates from wrapping on themselves. The elevation difference is therefore dependent upon the height of the target and the wavelength of the radar. Typically, an elevation angle difference of 0.05 degrees is required for a ground target such as an MBT and using an X-Band radar system. In order to produce the most accurate 3D scattering coordinates it is therefore necessary to use high accuracy position encoders which provide a continual readout and are recorded at all azimuth angles. Using the encoded information and Equation 3 provides 3D scattering coordinates accurate enough to identify individual scattering centers when the data is merged with the 3D CAD model of the target.

3. 3D IFISAR EXAMPLES AND CAD MODEL OVERLAY

Figure 3 shows an example of the reconstruction of 3D coordinates from two ISAR images taken at slightly different elevation angles. In this figure, the ISAR images of a truck were compared at 90 degree azimuth angle and 15 degree elevation. The phases of each pixel in the images are compared. Equation 3 is used to calculate the height associated
with the pixel. In this manner, a 3D coordinate map of the scattering from the target is formed. Note the 3D image shown in Figure 3 once the calculation is performed. The CAD model of the target viewed from the same perspective is displayed below the 3D image. The data is then merged with the CAD model so that it can be examined in detail. The scattering centers can be identified and the nature of the scattering can be studied by manipulating the view of the Data/CAD model fusion. The calculation and overlay is performed through all 360 degrees of azimuth with each ISAR image spaced 1 degree apart. Using this method it is possible to study the target’s scattering in 3D from any view angle.

![Figure 3. Demonstration for translating phase changes in ISAR images into height coordinates and fusion with CAD model.](image)

Figure 4 and Figure 5 show another example of 3D data. In Figure 4, X-Band data is displayed for a D-30 artillery piece. The data were taken with the D-30 gun mounted on simulated ground terrain. Note the ground terrain forming a planar surface in 3D and also the fact that the D-30 gun casts a distinct shadow on the surrounding ground. Figure 5 shows a CAD model of the D-30 gun at the same view angle. The 3D data can be correctly registered with the CAD model by using the 3D cross correlation methods described in the next section. Once the registration point is found, the data is overlaid onto the CAD model. The result of the overlay is shown in Figure 6.

![Figure 4. X-Band data displayed for a D-30 artillery piece.](image)

![Figure 5. CAD model of the D-30 gun.](image)

![Figure 6. Result of overlay.](image)
Figure 4. X-Band 3D IFISAR imagery of a D-30 gun on ground terrain.

Figure 5. CAD model of D-30 Gun.
ERADS has created an interactive three-dimensional visualization utility specifically for overlaying the collected 3D IFISAR data in false color onto a 3D CAD model of the target. The utility uses OpenGL to perform typical 3D functions such as walk-through, pan/zoom, and clip-plane cross sectioning. A simple ray tracer was created to follow a given beam path from CAD model facet to facet, and a laser-pointer beam-finder functionality was created to determine sources of target multi-bounce in the 3D data. Figure 6 shows an image exported from the 3D visualization utility. The 3D data and the CAD model are rendered in full-scale coordinates. Registration of the data to the CAD model can be performed either manually or through the use of automatic cross correlation calculations in order to find the common origin of both coordinate systems.

With the 3D IFISAR data and 3D CAD model accurately registered, the data was overlaid in false color, and the analyst is able to navigate the 3D data in real time, flying in and around the CAD and data. Particularly interesting is the ability to navigate into cavities and chambers of targets to see the scattering features where the radar beam had penetrated a dielectric, or entered a small opening and bounced around.

Figure 7 shows the more complex scattering that is observed in a T-72 MBT. The X-Band data shown in this figure are taken at 90 degrees azimuth and 15 degrees elevation. Note that the main gun barrel shows a very good overlay with the flash seen in the data. The Data/CAD model overlay allows the operator to articulate pieces of the target so an exact match is found. The articulated CAD model can then be exported and used in a predictive computer code such as Xpatch in order to provide the most accurate prediction of the target for comparison. STL has performed 3D correlation studies on such measured and predicted data sets with a high degree of success.
Figure 8 shows the overlay results for the STL rocket simulator target. The rocket simulator is designed to provide a number of simple scattering mechanisms. These mechanisms include seams, rounded surfaces, cylinders, and sharp edges. Note that the 3D overlay of the data onto the CAD model shows a good correlation with the surface features on the rocket simulator. The edge diffraction from the tail fin is seen in the rear of the target along with the spherical scattering centers on the edges of the fins. The flash from the nose of the rocket simulator is also seen. The X-Band data in this image were taken at 30 degree roll and -70 degree azimuth. The rocket simulator provides a convenient test object for comparing with predictive computer codes such as Xpatch.
4. 3D CORRELATION

The IFISAR data described heretofore allows for the analysis and comparison of data sets in 3D. The 3D data can be cross correlated with other 3D data sets including similarly collected radar data, CAD models, IFISAR predictions from programs such as Xpatch, and scattering center files produced by Xpatch. The discrete cross correlation mathematics has been described previously. Therefore, only a short description will be given here. Consider the three-dimensional functions $f(j,k,l)$ and $g(j,k,l)$. Each of these functions represents a 3D array corresponding to a discrete volume the size of which is defined by the maximum indices $J$, $K$, and $L$. Equation 5 shows the discrete cross correlation function.

$$C(m,n,p) = \frac{\left[ \sum_{j=0}^{J} \sum_{k=0}^{K} \sum_{l=0}^{L} [f^*(j,k,l) - \bar{f}] [g(m+j,n+k,p+l) - \bar{g}] \right]}{\left[ \sum_{j=0}^{J} \sum_{k=0}^{K} \sum_{l=0}^{L} [f^*(j,k,l) - \bar{f}]^2 \right]^{1/2} \left[ \sum_{j=0}^{J} \sum_{k=0}^{K} \sum_{l=0}^{L} [g(m+j,n+k,p+l) - \bar{g}]^2 \right]^{1/2}}$$

Where the normalized correlation function $C(m,n,p)$ is a three dimensional array whose maximum value denotes both the percentage of correlation between the two data sets and the position of best correlation. This position value will prove very useful for finding the best overlap region when comparing 3D data sets and provides a convenient mathematical technique for registering targets in 3D.

Figure 9 shows an overlay of data onto the CAD model of the rocket simulator. The overlay shows a dual image with IFISAR predictions generated from two Xpatch generated ISAR images on the left side and measured data from a
compact range on the right side. Figure 10 shows the same 3D data with the CAD model removed so that the data sets can be visually compared more easily. The 3D data that is shown in Figure 9 and Figure 10 have been correlated using Equation 5. Figure 11 shows the result of the 3D correlation between the two data sets as a function of azimuth angle. The rocket simulator was cross correlated between the measured data and the Xpatch predictions at 30 degree roll and across 360 degrees of azimuth spaced every 1 degree in azimuth. The average 3D correlation between the measured and predicted data for this simple object is on the order of 85 percent with the majority of the results well above the 80 percent level. STL has used this method of analysis to compare Xpatch predictions with measure data for the D-30 gun and the T-72 MBT.

Figure 9. Comparison of Xpatch (left) and measured (right) 3D data for the ERADS rocket simulator with CAD overlay.

Figure 10. Comparison of Xpatch (left) and measured (right) 3D data for the ERADS rocket simulator without CAD overlay.
Figure 11. 3D cross correlation results between the measured and Xpatch predicted data on the ERADS rocket simulator.

5. SUMMARY

Fully polarimetric, three dimensional X-Band radar signature data have been collected using 1/16th scale tactical targets measured in indoor compact radar ranges. ISAR image pairs, collected at slightly different elevations, were interferometrically processed into 3D imagery. The data collection and analysis methods have been presented. 3D visualization methods which allow the measured data to be overlaid onto a CAD model of the target have been described. Data for targets such as the D-30 gun and the T-72 tank have been demonstrated using this technique. Additionally, the results of mathematical 3D correlation are described. The ERADS rocket simulator object has been cross correlated in 3D with predictions using the Xpatch computer code.

REFERENCES

