

Study for Material Identification via Synthetic Aperture Radar

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It is possible that SAIC will decide to submit a disclosure to the U.S. Patent office for the application of the advanced data processing techniques for the challenging problem of measuring delayed material responses amongst background clutter.

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

Recent advances in the understanding of the interactions of radio-frequency waveforms with different materials have yielded the potential of performing remote identification of different materials within synthetic aperture radar (SAR) imagery. The immediate reflections from typical targets and foliage are not unique with regard to differing material compositions – it is only the much weaker precursor signals that contain the required discrimination information. In effect, the immediate returned radar energy from neighboring foliage is likely to obscure precursor signatures that provide for the identification of specific materials, unless sophisticated signal processing algorithms are developed and applied in order to extract this fragile information. SAIC has developed a multi-delay-resolution processing technique that offers to separate the delayed radar echoes resulting from different material reflectors for the purpose of performing remote characterization of material objects. This technique separates "immediate reflection" echoes in an image from echoes that are the result of delayed material echoes and then maps each set of reflections to a metrically correct image space. SAIC's technique addresses the challenging problem of separating the relatively weak radar returns due to the delayed material echoes from those of the background clutter environment.

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1. Objectives

Recent advances in the understanding of the interactions of radio-frequency (RF) waveforms with different materials have yielded the potential of performing remote identification of different materials within synthetic aperture radar (SAR) imagery. There are a number of technology challenges that must be overcome in order to enable this critically important capability. In particular, the precursor signatures of various materials-of-interest must be sufficiently separable within an appropriate feature space in order to permit correct material identification with a high probability. Another technology requirement is that these precursor signatures must be relatively stable with regard to the narrow span of aspect angles typical of SAR data collections. In addition, advanced signal processing techniques must be utilized in order to prevent these relatively weak precursor signals from being overwhelmed by the side-lobes of primary radar returns from neighboring objects and clutter. Furthermore, multipath interactions can also interfere with the desired precursor signals-of-interest. This high-risk, high-payoff technology capability requires techniques for obtaining accurate estimates of the radar precursor signatures corresponding to different materials in the midst of many of the real-world operating conditions listed above.

The primary objective of this proposed effort is to make the extremely challenging technology of remote identification of materials via SAR imaging robust enough to overcome environmental and system engineering challenges associated with operational requirements. This objective requires the development of an overall system design and advanced signal and image processing algorithms in order to obtain reasonable estimates of the material precursor signatures in the midst of a myriad of interfering effects, as discussed above. These signatures would be input into a classification algorithm in order to provide a map of the material compositions contained within each image pixel, in a fashion similar to that of hyper-spectral imaging for material identification.

The focus of the SAIC Advanced Research and Engineering Solutions (ARES) approach has been to perform a detailed quantitative analysis of the various perturbing and interfering effects that distort and obscure the radar precursor signatures of interest. The immediate reflections from typical targets and foliage are not unique with regard to differing material compositions – it is only the much weaker precursor signals that contain the required discrimination information. That is, in order to use a classification algorithm for determining material composition of the cells within a SAR image, it is first necessary to obtain accurate estimates of the distinguishing precursor profiles in the midst of much stronger interfering effects. A potential serious problem in the proposed challenging technology arises due to the extremely weak strength of the desired precursor signals relative to that standard clutter within typical SAR scenes. In effect, the immediate returned radar energy from neighboring foliage is likely to obscure precursor signatures that provide for the identification of specific materials, unless sophisticated signal processing algorithms are developed and applied in order to extract this fragile information.

2. Activities

SAIC-ARES has participated in a number of technical interchange meetings with AFRL-Brooks, as outlined in Section 5. The purpose of these meetings has been to validate the current body of research in materials identification via radar. SAIC-ARES has studied the extensive literature on delayed echo responses for radar. There are a number of techniques that have been developed for the case in which a radar waveform impinges upon a relatively large slab of the material that is to be interrogated. Thus, this particular geometry assumes that there is effectively no background clutter from which the delayed echoes due to the particular material properties must be separated. This situation is not typically viable for realistic measurement conditions. Almost all radar measurements occur in a spatial location wherein there is down-range clutter that competes with the delayed material echoes of the targets of interest. Therefore, one of the primary areas of focus under this work effort has been to develop techniques for extracting the fragile delayed echo information amidst a background of competing clutter.

3. New Findings

Under this effort, SAIC-ARES has developed a multi-delay-resolution processing technique that offers to separate the delayed radar echoes resulting from different material reflectors for the purpose of performing remote characterization of material objects. This technique addresses the challenging problem of separating the relatively weak radar returns due to the delayed material echoes from those of the background clutter environment. A summary of the theoretical foundations of delayed-echo SAR is presented in the remainder of this subsection.

The primary challenge of this technology is to develop techniques for mitigating the effects of down-range clutter due in estimating delayed target echoes, due to the particular material properties of the target. Recent analysis at SAIC has resulted in an innovative technique for forming SAR images that separates the effects of various delayed target echoes. This algorithm is based upon the analysis of the cross-range drift in conventional SAR imagery of the delayed echo scattering events with respect to changes in the relative aspect angle. This technique separates "immediate reflection" echoes in an image from echoes that are the result of delayed material echoes and then maps each set of reflections to a metrically correct image space. Conventional SAR image formation algorithms place the delayed echoes at incorrect (i.e., ghost) locations due to fundamental assumptions implicit in conventional array processing.

Two desired results are achieved by use of this algorithm. First, the intensities of the ghost returns are reduced in the primary image space, thereby improving the relationship between the image pattern and the physical distribution of the scatterers. Second, the algorithm process creates a higher dimensional image space that enhances the intensities of the delayed echoes and thereby provides additional characteristic information about the scene being imaged. Additionally, these auxiliary "delay" image planes offer the potential of providing detailed information about the material properties of the targets being imaged, thereby improving target detection and identification capabilities. Thus,

SAIC's processing technique offers a potential break-through in the extraction of material signatures in SAR imagery.

The conventional theory of SAR image formation presupposes an overly simplistic assumption that is rarely mentioned. Specifically, the physical mechanism of a given scattering event is assumed to involve only a single, instantaneous (i.e., non-delayed) reflection of the mediating waveform with a portion of the extended object-of-interest. That is, conventional SAR theory does not account for the effects of delayed responses in the reflected waveform energy. These facts motivate the need for a more generalized SAR image theory. The proposed effort incorporates the effects of such delayed scattering events via the SAIC-ARES processing approach.

Conventional SAR image formation assumes that all scattering events which affect the measured phase history data are due to non-delayed reflection effects. That is, the theory of conventional SAR does not account for the delayed components of radar signature, which are indicative of the particular material properties. However, the physical reality of radar scattering dictates that the material relaxation time can be significantly larger than the temporal resolution cell size. Thus, there can be significant interference between the immediate reflection at one spatial position and the delayed material reflection component at a "closer-range" spatial position.

The original contribution of this approach is that it presents an image formation algorithm that separates the effects of the delayed material response echoes from that of non-delayed echoes by projecting the delayed echoes into a series of auxiliary delay image planes. Therefore, this approach yields an improved estimate of the scattering centers via the immediate reflection image reconstruction. Perhaps more importantly, SAIC's processing also produces a number of auxiliary image planes containing the material delayed scattering events, thereby enhancing the performance of target detection and identification via radar material signatures.

SAIC's processing algorithm is based upon an analysis of the cross-range drift of the delayed-echo responses with respect to the mean aspect angle at which the phase history data are measured in conventional SAR magnitude imagery. In particular, the ideal response in SAR magnitude imagery of each immediate response scattering event does not drift with regard to aspect angle. In contrast, the SAR magnitude response of each delayed echo event does drift in the cross-range direction with respect to aspect angle, and the amount of drift is directly proportional to the value of the material delay. The ideal responses of these delayed echo cross-range drifts can be used within a deconvolution framework in order to estimate the material delayed echo reflectivity based upon the separate co-registered magnitude SAR images formed at different aspect angles.

It can be shown that the conventional SAR image response of a particular delayed echo contribution characterized by an effective scattering event position at (x_0, y_0) and round-trip delay path $2\gamma_0$ merely rotates on a circle with radius γ_0 about (x_0, y_0) . For small values of the aspect angle ω such that second and higher order terms in ω can be ignored, only the variation in the cross-range coordinate is significant, i.e.,

$$x(\omega) \cong x_0 + \gamma_0, \quad (1)$$

$$y(\omega) \cong y_0 + \gamma_0 \omega. \quad (2)$$

This resulting cross-range drift $\gamma_0 \omega$, which is directly proportional to the total material delay y_0 through first order in the aspect angle ω , is the basis for SAIC's processing.

Given the drift of the delayed echo ghost responses with respect to aspect angle, it is necessary to develop a method for estimating the various contributions to the delayed echo reflectivity. In particular, the effects of immediate reflection scattering must be separated from that due to delayed echoes. The overall processing is initiated based upon some number N of SAR magnitude images formed at N uniformly incremented mean aspect angles. Of course, the individual sets of phase history data for each of these initial SAR images can overlap in order for the processing to be practical.

The processing begins by separating the N initial SAR images into $N/2$ pairs of adjacent images. Then, within each pair of images, it is necessary to estimate the contributions of two different functions. The first such function $p(y)$ corresponds to immediate echo scattering events that exhibit little or no cross-range drift in progressing from the first image of the pair to the second. The other essential function $q(y)$ for this image pair contains the contributions due to delayed echo scattering events characterized by a particular delay γ , such that there is a cross-range drift in progressing from the first image to the second. The dependence of the along-range coordinate x is suppressed in these two functions and the remainder of the analysis, since Equations (1) and (2) show that only the cross-range coordinate y of a delayed echo scattering event exhibits a significant variation with respect to the mean aspect angle ω . Thus, the two adjacent SAR magnitude images can be delineated by $b_1(y)$ and $b_2(y)$.

The mathematical relation describing the dependence of the two adjacent SAR magnitude images upon the immediate echo and delayed echo functions can be expressed in the form

$$b_1(y) = p(y) + q(y + 1/2), \quad (3)$$

$$b_2(y) = p(y) + q(y - 1/2). \quad (4)$$

The offsets of $-1/2$ and $1/2$ in the arguments of q in Equations (3) and (4) correspond to a shift to the right of one unit of length (e.g., one pixel) in the b_2 SAR magnitude image with respect to that of b_1 . Half-integral shifts are used in Eqs. (3) and (4) in order to make the drift effects symmetric relative to that of the non-drift effects. For values of the cross-range spatial frequency η that are not equal to an integer, this system yields the following estimates for the Fourier transforms of the desired functions $p(y)$ and $q(y)$ [5,6]:

$$\hat{P}(\eta) = H_0(\eta) - \cos(\pi\eta)\hat{Q}(\eta), \quad (5)$$

$$\hat{Q}(\eta) = -\frac{jH_1(\eta)}{\sin(\pi\eta)}, \quad (6)$$

in terms of the Fourier-transformed average and difference images defined by

$$H_0(\eta) \equiv [B_2(\eta) + B_1(\eta)]/2, \quad (7)$$

$$H_1(\eta) \equiv [B_2(\eta) - B_1(\eta)]/2. \quad (8)$$

The inversion given in Equations (5) and (6) is not well-defined for η equal to zero or unity, but the solution exists for the open set between these two values, i.e., $0 < |\eta| < 1$. However this problem becomes ill-conditioned for some non-zero span of low frequencies in the neighborhood of $\eta = 0$ for the realistic case of noisy estimates of the different images $b_1(y)$ and $b_2(y)$ resulting from noisy phase history measurements. A practical means for ameliorating these inversion issues is to apply an appropriate weighting to $H_1(\eta)$ in Eq. (8) prior to applying the inverse Fourier transform to obtain the desired function $q(y)$. Empirical analysis has revealed that the application of a Hanning window over the span of $0 < |\eta| < 1$ seems to give a reasonably good estimate of both the immediate echo and delayed echo scattering effects, especially for the realistic case in which the delayed echo results from spatially localized interactions between scattering centers. Results can be further improved by preconditioning the input images $b_1(y)$ and $b_2(y)$ at each stage in the pyramid synthesis to ensure that only effects consistent with the immediate echo $p(y)$ and delayed echo $q(y)$ effects remain.

The estimation of separate pairs of the immediate echo $p(y)$ and delayed echo $q(y)$ functions as described above are applied to each of the $N/2$ pairs of adjacent images. The variation in the values of these functions with respect to aspect angle can occur since the response of each scatterer is not necessarily uniform with respect to changes in the relative aspect angle. The $q(y)$ functions contain the highest resolvable material delay, i.e., those satisfying $|\omega_1 - \omega_2| \gamma_{max} = 1$, with ω_1 and ω_2 the mean aspect angles corresponding to the two images corresponding to a pair of interest. However, the $p(y)$ functions contain not only the effects of immediate reflection scattering events, but also those with lower values of material delay $\gamma < \gamma_{max}$. Thus, it is possible to further this analysis in a multi-delay-resolution approach by considering the $N/2$ distinct $p(y)$ functions as the input images into the process. If we delineate these images via p_1 , with the subscript 1 delineating the first level in the multi-delay-resolution approach, then the application of the inversion process yields $N/4$ pairs of delayed echo $q_2(y)$ and immediate echo $p_2(y)$ functions of the second level. The functions $q_2(y)$ contain the delayed echo effects corresponding to the delay at one-half of the maximum unambiguous value, i.e., $\gamma < \gamma_{max}/2$. This processing is repeated at each level until the final pair of $p_{M-1}(y)$ images, with $M = \log_2(N)$, are inverted to obtain the delayed echo $q_M(y)$ and immediate echo $p_M(y)$ functions of the final level. The immediate echo $p_M(y)$ image suppresses the effects of delayed material echo scattering, and the remaining set of $q_1(y)$ functions contain the effects of delayed material echoes at different levels of delay resolution and at different relative aspect angles ω . Figure 1 shows the processing diagram for the multi-delay resolution architecture.

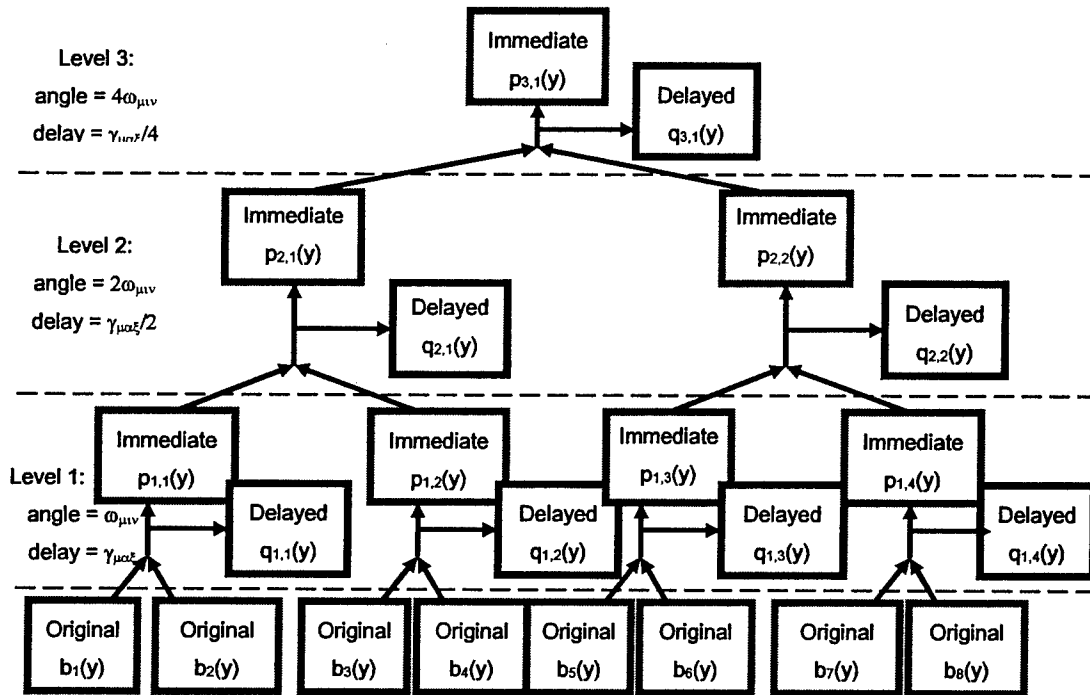


Figure 1: This figure shows a processing diagram for the multi-delay resolution architecture that estimates the various immediate echo $p(y)$ and delayed echo $q(y)$ scattering contributions corresponding to different values of the delay γ and aspect angle offset ω .

SAIC's processing approach is initially validated using simulated point-scattering data. The "truth" plot of Figure 2a shows an example containing five actual scattering centers, and the projected locations of the corresponding delayed material responses for the case in which the radar waveforms impinge from the bottom of the figures. The true values of the scattering centers and their corresponding delayed material responses were used to simulate the phase history measurements for a signal-to-noise ratio (SNR) of 60 dB. A total of 16 distinct co-registered SAR images were formed at different aspect angles ω using overlapping sets of phase history data. Figure 2b shows one of the original images, which is the result of conventional SAR image formation applied to the simulated phase history measurements containing both the immediate reflection and delayed reflection scattering effects. Although the point locations of the various actual scattering centers of Figure 2a are well-reproduced, Figure 2b contains additional spurious scattering centers that arise from the delayed echo contributions to the simulated phase history data. Thus, conventional SAR processing yields a single image wherein the effects of immediate reflection events and delayed reflection events are displayed together. That is, there is no obvious means for separating immediate from delayed reflection events for the case in which there is much clutter in the scene.

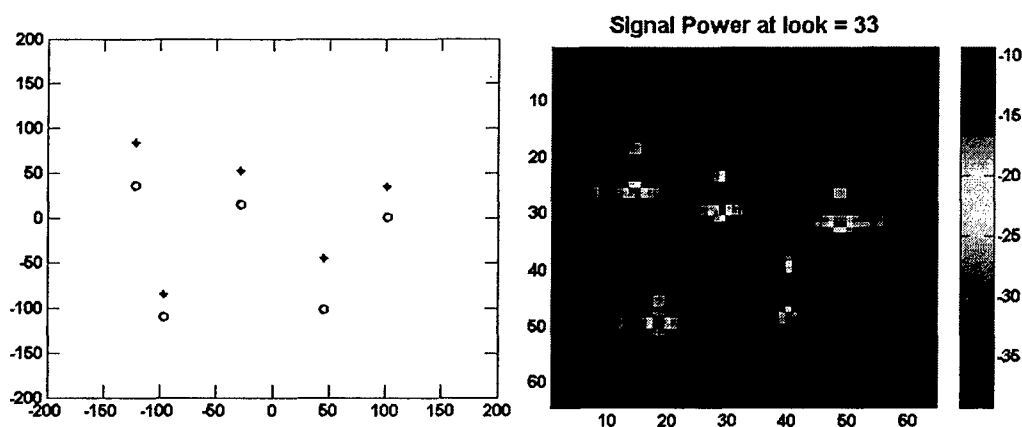


Figure 2: a) The locations of the five actual scattering centers are shown by the small blue circles, and the projected locations of their corresponding delayed material responses are shown by the red asterisks for the case in which the radar waveforms impinge from the bottom of the figure; b) Resulting conventional SAR image, wherein the simulated phase history data includes the effects of simulated delayed echoes from each of the scattering centers denoted by blue circles.

Figure 3 summarizes all of the images corresponding to the last three levels of the multi-delay-resolution processing tree in the manner of Figure 1. Figures 4 and 5 give the immediate reflection and delayed reflection images, respectively, at level five in Figure 3. Clearly, the delayed reflection image of Figure 5 correlates well with the projected locations of the delayed echoes in the true plot of Figure 2a. Also, the immediate reflection image of Figure 4 correlates well with the true scattering center locations in Figure 2a, although there is some non-ideal leakage of the delayed scattering energy into the non-delayed image at the final level.

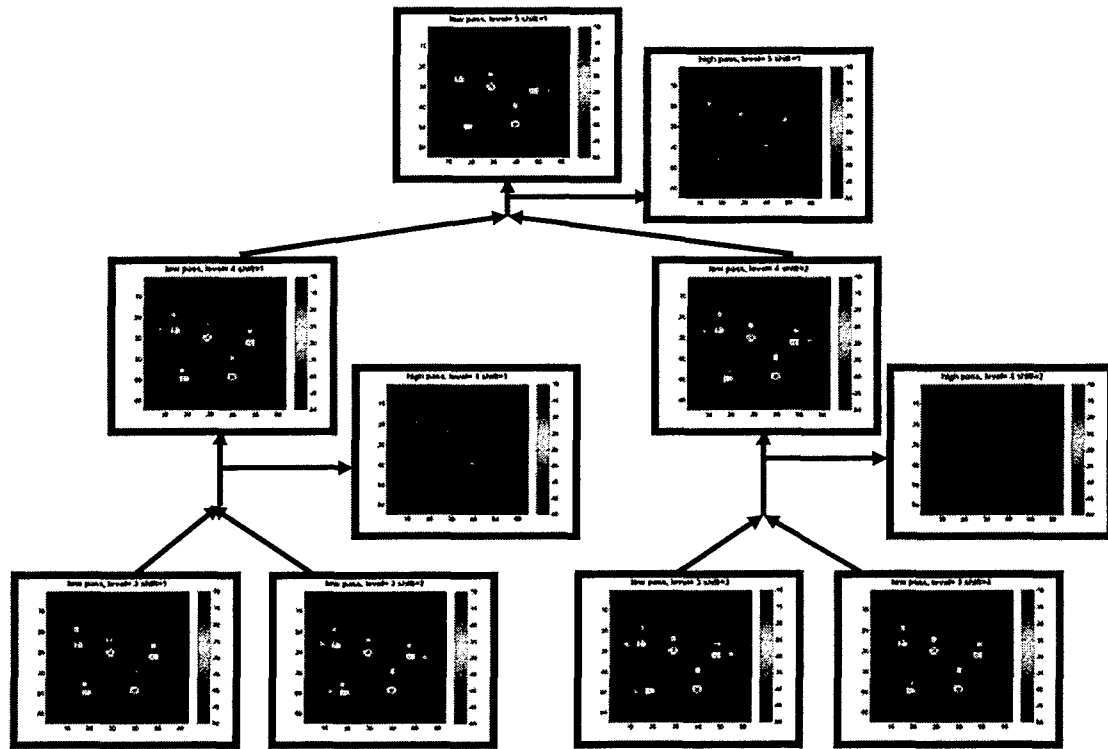


Figure 3: This figure shows the last three levels of the multi-delay-resolution tree of Figure 1 corresponding to the example using idealized point scattering data presented in Figure 2.

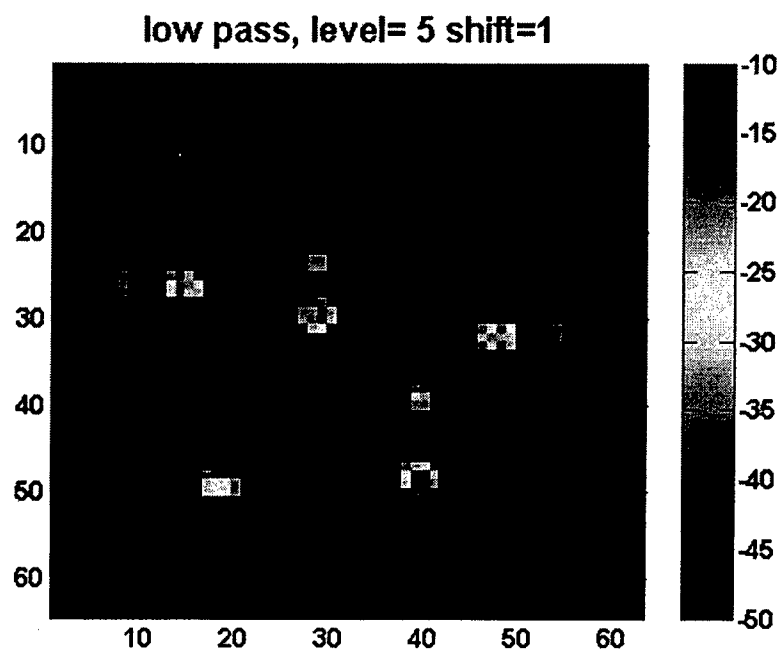


Figure 4: The result of final immediate reflection image at the fifth level contains primarily the effects of the immediate echo scattering centers while suppressing the material delayed echo ghost effects.

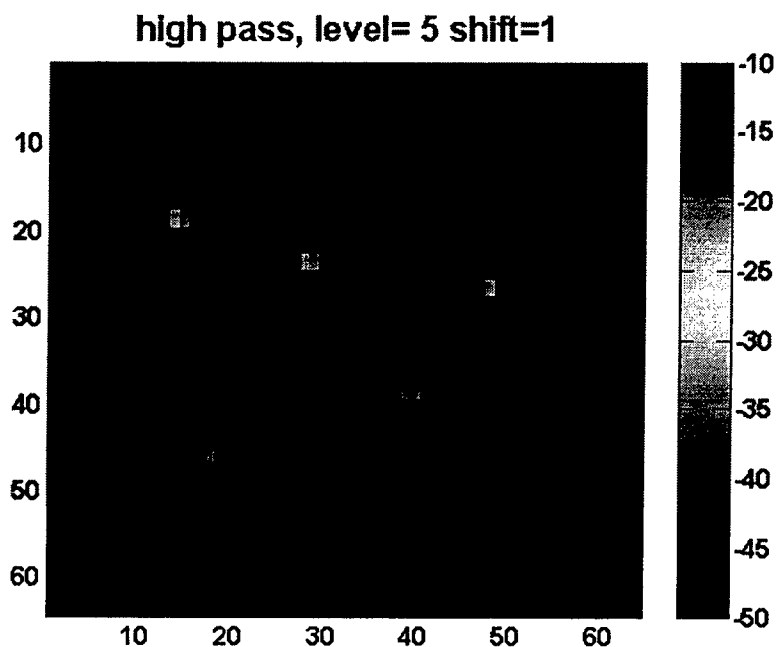


Figure 5: The result of final delayed echo image at the fifth level contains primarily the material delayed echo ghosts while suppressing the effects of the immediate reflection scattering centers.

3. Personnel Supported

The following are experience summaries for the personnel who have worked on this project:

J. Scott Goldstein (Ph.D., Electrical Engineering, University of Southern California) is a Vice President at SAIC and has more than 19 years of experience in the fields of radar, sonar, communications, navigation, and imaging sensors. He has performed fundamental research and development in the technical areas that support C3I and ISR functions. He has also directly influenced the development of new programs within DARPA, the national intelligence community, and the individual military services. In his current position, he manages the Signals and Signatures Operation consisting of three divisions and over 100 engineers and scientists. In addition, he provides technical leadership in a number of programs developing advanced sensor systems. He is a member of the SAIC Executive Science and Technology Council. He was recently elected to the 2003 National Academy of Engineering Frontiers of Engineering Program as one of the Nation's 100 outstanding young engineers from industry, academia, and government. He also received the 2002 IEEE Fred Nathanson Radar Engineer of the Year Award.

David A. Garren (Ph.D., Physics, College of William and Mary, Williamsburg, Virginia, 1991) is the Chief Scientist of the Advanced Research and Engineering Solutions (ARES) Division at SAIC. He has been performing program management and signal analysis activities as principle investigator for several programs in the defense and intelligence communities. He is the author of more than thirty-five scientific and technical publications. In addition, he is the inventor of a patent pertaining to multipath SAR techniques which has been issued by the U.S. Patent Office recently. He has served on the Technology Development Team for the National Security Space Architecture (NSSA) Space-Based Radar Congressionally Directed Action Team. He was also recently elevated to Senior Member of the IEEE.

Randy Chapman (M.S., Space Operations, Air Force Institute of Technology; M.S., Systems Management, Troy State University; M.S., National Security Strategy, National War College; B.S., Physics, U.S. Air Force Academy) is a retired USAF Colonel with a rich background in tactical fighter operations, space operations, space control, space reconnaissance, and intelligence. He has more than twenty-nine years of experience leading and directing complex, technology-intensive organizations in a variety of mission, functional, and geographical domains. He currently supports a variety of classified programs within SAIC in the areas of program management, concepts of operations development, and strategic program development, and advises the technical staff on the operational application of advanced technologies.

Jerry Brown (Ph.D., Physics, Illinois Institute of Technology, 1985) is a Technical Director for the ARES Division at SAIC. His work involves the creation of programs with unanticipated, exquisite capabilities through research in physics, mathematics, and advanced signal processing. He proposes potential solutions to new and existing customers for their investigation, testing, and the ultimate creation of new programs and program offices.

4. Publications

There have been no publications under this work effort to date.

5. Interactions / Transitions

SAIC-ARES personnel have participated in a number of meetings with relevant government personnel. The primary purpose of these meetings has been to discuss various aspects of materials identification techniques. The dates of these meetings are delineated below.

- 1) Program Kick-off Meeting; Chantilly, Virginia; August 15, 2003. Attendees: David Garren, Randy Chapman.
- 2) Workshop on Synthetic Aperture Radar; Huntsville, Alabama; October 22-23, 2003. Attendee: David Garren.
- 3) Technical Interchange Meeting; San Antonio, Texas; January 28, 2004. Attendees: David Garren, Scott Goldstein, Jerry Brown.
- 4) Technical Interchange Meeting; San Antonio, Texas; February 17, 2004. Attendees: David Garren, Scott Goldstein, Jerry Brown, Randy Chapman.
- 5) Technical Interchange Meeting; San Antonio, Texas; March 12, 2004. Attendees: David Garren, Jerry Brown, Randy Chapman.

6. Discoveries, Inventions, or Patent Disclosures

Dr. David Garren developed a new application of an existing technique for separating the delayed echo responses due to material properties. This technique is based upon an existing invention for separating the effects of multipath scattering in SAR image formation [Ref. 1]. In effect, the delayed radar echoes due to delayed material responses have a similar signature to that of multipath radar echoes. Thus, the previously developed techniques offer to provide signatures for materials identification using radar amidst a background of competing clutter. In order to make the technique truly viable, it will be necessary to develop additional modifications for distinguishing between the ghost scattering effects due to delayed material responses vice that due to multipath scattering. It is likely that SAIC will decide to submit a disclosure to the U.S. Patent office for the application of these multi-delay-resolution imaging techniques for the challenging problem of measuring delayed material responses amongst background clutter.

[1] D. A. Garren, "Process for Mapping Multiple-Bounce Ghosting Artifacts from Radar Imaging Data," U.S. Patent No. 6,646,593; filed: January 31, 2002; awarded: November 11, 2003.

7. Honors / Awards

Dr. J. Scott Goldstein was elected to the National Academy of Engineering Frontiers of Engineering Program in 2003 as one of the Nation's 100 outstanding young engineers from industry, academia and government.

Dr. J. Scott Goldstein was elected Fellow of the Washington Academy of Sciences in 2003 and received the Washington Academy of Science's 2004 Award for Scientific Achievement in Engineering.

What's New

Date: 2004-07-30

SAIC's Scott Goldstein Wins Prestigious Washington Academy of Sciences Award

Dr. Scott Goldstein has joined such celebrated scientists as Nobel Physics Prize winner Bill Phillips and primatologist Jane Goodall in receiving an award from the Washington Academy of Sciences. Scott was presented with the prestigious Engineering Sciences Award in a ceremony on May 11, recognizing his work on adaptive detection of low-powered signals in complicated noise fields.

Scott said that he was honored to receive the award, one of several categories of prizes given annually. "It really reflects on the people in my operation and SAIC's Technology Research and Integration Business Unit," said Scott. "I've never before had the pleasure of working with as many brilliant people in an environment that so fosters innovation."

The Washington Academy of Sciences was formed in 1898 to conduct, endow, and assist scientific investigations. Among its founders were Alexander Graham Bell and Samuel Langley, secretary of the Smithsonian Institution.

This award is only the latest in a string of honors Scott has been accorded. He was recently elected a Fellow of the Washington Academy of Sciences and is also the youngest Fellow of the Institute of Electrical and Electronics Engineers. Last year, he was invited as one of the top 100 U.S. engineers to join the National Academy of Engineering's Frontiers of Engineering Program with a nomination from Dr. Beyster.

