Suppression of Sidelobes and Noise in Airborne SAR Imagery Using the Recursive Sidelobe Minimization Technique

Lam Nguyen and Roberto Innocenti
U.S. Army Research Laboratory
2800 Powder Mill Rd
Adelphi, MD 20783
lnguyen@arl.army.mil

***Abstract*—The Army Research Laboratory (ARL) has recently developed the Recursive Side-lobe Minimization (RSM) technique (patent pending). The technique is integrated with a standard back-projection algorithm to form synthetic aperture radar (SAR) images with significant reduction in side-lobes and noise. We have achieved significant improvements in noise reduction by applying the RSM technique to our Ultra-wideband (UWB) Synchronous Impulse Reconstruction (SIRE) forward-looking radar. This paper presents the application of the RSM technique using data from a side-looking airborne SAR system from SRI International. We describe the RSM technique, the SAR data processing, compare the baseline and RSM SAR images, and quantify the image quality in term of signal-to-noise ratio (SNR) and the statistical distribution of the image pixels to show that significant improvement achieved using the RSM technique.**

I. INTRODUCTION

Ultra-wideband (UWB) synthetic aperture radar (SAR) systems have been used in many applications to detect concealed targets [1,2]. One of the challenges for using SAR system in this type of application is the detection of small radar cross section (RCS) targets in the presence of large man-made and natural clutter objects. Side-lobes from large RCS objects spread throughout SAR imagery and create a noise floor. Signatures of small RCS targets might be obscured or embedded in this multiplicative noise floor that is proportional to the RCS of surrounding clutter objects. In this paper, we present the Recursive Side-lobe Minimization (RSM) technique (patent pending) [3] designed to suppress the multiplicative noise floor in SAR imagery. Although the technique was originally developed and tested using data from the SIRE forward-looking radar, we show that is also applicable for other SAR data sets with different configurations, namely the SRI International airborne SAR radar. The paper first presents the RSM technique that is integrated with the back-projection image formation algorithm to form SAR imagery. The technique is then applied to the SRI International airborne SAR radar data. Significant suppression of the multiplicative noise floor was achieved in the application of the RSM technique to this data set.

II. THE RECURSIVE SIDELOBE MINIMIZATION TECHNIQUE

In this section, we present the Recursive Side-lobe Minimization (RSM) technique [3], which is designed to suppress side-lobes and noise from SAR imagery. In conventional signal processing techniques we usually try to avoid non-uniform and sparse data. From basic digital signal processing theory, it is well-known that if a gap is introduced in the time-domain (missing data points); the corresponding frequency spectrum would suffer from the large resulting side-lobes. This is also true for SAR processing, in which missing data (gaps in aperture) would generate sidelobes in imagery domain. One approach for improving SAR image in such situations is to estimate by interpolating the missing data samples in the aperture data domain [4].

However, we employed a different approach for the RSM since we already had a complete data set. To illustrate the approach, we generated a SAR simulation case. Fig. 1 shows a SAR image with two simulated point targets. The targets have severe side-lobes due to some sources (motion error, aperture aliasing) that we introduced in the SAR simulation. Fig. 2a shows a SAR image of the two point targets that is formed using a *randomly compressed aperture*, in which approximately 20% of the number of aperture positions are *randomly removed*. As expected, the compressed aperture SAR image has much larger side-lobes than that using of the complete aperture due to the gap introduced in the aperture. Next we formed another SAR image (Fig. 2b) using another randomly compressed aperture. Since the locations of the aperture samples to be removed are randomized, the gap (missing data) pattern would be different than the previous realization. We want to note the following two important factors: 1) Since the main responses from the targets are coherently integrated and normalized by the image formation process, the *locations and the peak values of* the targets in the resulting SAR images *are the same*, and 2) The *locations and amplitudes of peaks and valleys of the side-lobes change with each formation of the gaps in the compressed aperture*. The reason is that the only pixel locations in the SAR image that are coherently integrated are the target locations. Other pixel locations (with side-lobes) are incoherently integrated and thus the values and the locations change with each realization of compressive aperture. Thus applying the *minimizing* operator to every image pixel pair from the two resulting compressive SAR images would yield the minimum side-lobe level in the resulting image while the target amplitudes would remain the same. Fig. 2c shows the resulting SAR image after the minimum operator is applied to every pair of pixels of the two

978-1-4244-5813-4/10/$26.00 ©2010 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Suppression of Sidelobes and Noise in Airborne SAR Imagery Using the Recursive Sidelobe Minimization Technique**	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) **U.S. Army Research Laboratory,2800 Powder Mill Rd,Adelphi,MD,20783**	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

See also ADM002322. Presented at the 2010 IEEE International Radar Conference (9th) Held in Arlington, Virginia on 10-14 May 2010. Sponsored in part by the Navy.

14. ABSTRACT

The Army Research Laboratory (ARL) has recently developed the Recursive Side-lobe Minimization (RSM) technique (patent pending). The technique is integrated with a standard back-projection algorithm to form synthetic aperture radar (SAR) images with significant reduction in side-lobes and noise. We have achieved significant improvements in noise reduction by applying the RSM technique to our Ultrawideband (UWB) Synchronous Impulse Reconstruction (SIRE) forward-looking radar. This paper presents the application of the RSM technique using data from a side-looking airborne SAR system from SRI International. We describe the RSM technique, the SAR data processing, compare the baseline and RSM SAR images, and quantify the image quality in term of signal-to-noise ratio (SNR) and the statistical distribution of the image pixels to show that significant improvement achieved using the RSM technique.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**4**	

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

SAR images of Fig. 2a and 2b. The side-lobe level in Fig. 2c is lower than either input image while the amplitudes of the targets remain the same. Many realizations of compressive aperture are generated, each with a different gap pattern. Due to the randomness of the locations of the peaks and valleys of the side-lobes, the combined SAR image using all of these realizations has a very low side-lobe level. Figure 3 shows the results at various iterations. In the resulting image at iteration 50, the side-lobes are significantly suppressed while the responses of the two targets remained virtually unchanged. This is the main concept of the RSM technique.

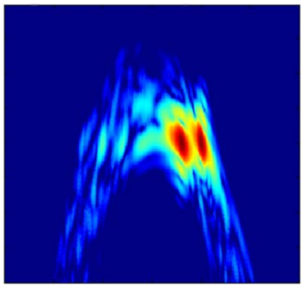
Figure 1. SAR image of two point targets with multiplicative noise.

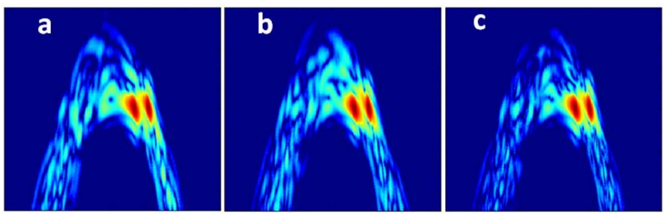

Figure 2. a) SAR image formed using a randomly compressed aperture, b) SAR image formed using another randomly compressed aperture, and c) Resulting SAR image after the minimum operator is applied to SAR images of a) and b).

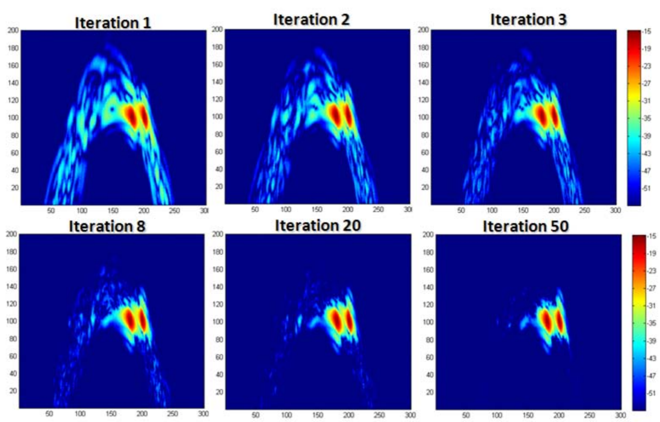

Figure 3. Results at various iterations.

A step-by-step description of the RMS algorithm follows:

- Radar data and its position information are acquired.
- The radar aperture is formed in preparation for image formation. The aperture consists of K elements. Each element in the radar aperture includes the radar receiving position information $(x_R(k), y_R(k), z_R(k))$, the radar transmitting information $(x_T(k), y_T(k), z_T(k))$, and the data record $s_k(t)$ that the radar measures at this location. For side-looking radar, the aperture is usually a linear path with data measured along the path. For the forward-looking radar, a 2-D radar aperture is generated [5]; formed by the physical antenna array and the forward motion of the radar. In general, the radar aperture may take a variety of shapes.
- The imaging grid is formed with $N=I.J$ pixels (I pixels in the down-range direction and J pixels in the cross-range direction). Each pixel P_i in the imaging grid is located at coordinate $(x_P(i), y_P(i), z_P(i))$, where $1 \le i \le N$.
- A random compressed aperture is generated using the radar aperture with K elements from step 2 by selecting only L elements ($L< K$) from the original aperture for the imaging process. The value for L is

$$L = p \cdot K \qquad 0 < p < 1 \qquad (1)$$

Accordingly, only a subset of the aperture positions is used for image formation. The remaining (K-L) aperture positions are simply discarded for this realization. The typical number that we use for our configuration is p = 0.8 (i.e., 80% of the aperture is employed and 20% of the aperture is discarded at each iteration). The value of p that can achieve best result should be examined and optimized for each configuration of geometry and radar data set. The selection of L aperture positions is completely random for each realization. If A_l represents a vector that contains the indices of aperture positions to be included in the image formation process for l^{th} realization, then:

$$A_l = \langle a_{l1}, a_{l2}, ..., a_{lL} \rangle \qquad (2)$$

where a_{lm} is a random number, $1 \le a_{lm} \le K$ and $a_{lm} \ne a_{lm}$ for $n \ne m$

- The image is formed using the compressed aperture generated from previous step. The compressed aperture derived from A_l with L elements is then used to form the l^{th} realization of the sub-image using the back-projection algorithm [Ref]. This results in the l^{th} realization of the compressed aperture SAR image.

$$I_l = \langle P_l(i) \rangle \qquad 1 \le i \le N \qquad (3)$$

- The envelope of the image generated in previous step is computed. The image generated in step 5 can also be written as:

$$I_l = \langle P_{lj}(i) \rangle \qquad 1 \le i \le I \qquad 1 \le j \le J \qquad (4)$$

where P_{lj} is the j^{th} down-range profile from the l^{th} realization sub-image.

The corresponding quadrature component of this image down-range profile is computed by applying the Hilbert transform filter to the in-phase component

$$PH_{lj} = Hilbert(P_{lj}) \qquad (5)$$

The envelope of the j^{th} down-range profile from the l^{th} realization of the image may be computed as:

$$PE_{lj} = \sqrt{(P_{lj})^2 + (PH_{lj})^2} \qquad (6)$$

The envelope of this image is simply

$$I_l = \langle PE_{lj}(i) \rangle \qquad 1 \le i \le I \qquad 1 \le j \le J \qquad (7)$$

- An intermediate resulting image is computed. The minimum operator is applied to two images: 1) the intermediate result from previous iteration $(l\text{-}1)^{th}$, and 2) the image formed from this iteration. For each image pixel, the values of the two images are compared and the minimum value is selected

$$\mathrm{Im}_l = \min\langle I_l, \mathrm{Im}_{l-1} \rangle \qquad 2 \le l \le M \qquad (8)$$

Where Im_l is the intermediate resulting image at l^{th} iteration. Note that equation (8) is defined for $2 \le l \le M$. For the first iteration ($l=1$), Im_0 is initialized with a very large values, so that the intermediate resulting image is $\mathrm{Im}_1 = \min\langle I_1, \mathrm{Im}_0 \rangle = I_1$

- The algorithm returns to step 4 to form another randomly compressed aperture and continue with the next iteration until the M^{th} iteration is finished.

III. APPLICATION OF THE RSM TECHNIQUE TO THE SIDE-LOOKING AIRBORNE SAR DATA

Although the RSM algorithm was originally developed for the *vehicle-mounted forward-looking* radar configuration, it is applicable for other imaging scenarios. In this section we will show that the RSM algorithm is also very effective to improve the SNR using data from the *side-looking airborne* SAR data from SRI International. The SRI radar is a linear frequency modulation (FM) based UWB radar that operates in the UHF band. Our objective is to process the SRI phase history data and form a baseline SAR , integrate the RSM technique into the baseline algorithm, and evaluate the performance improvement. The processing steps include the range compression and the backprojection image formation.

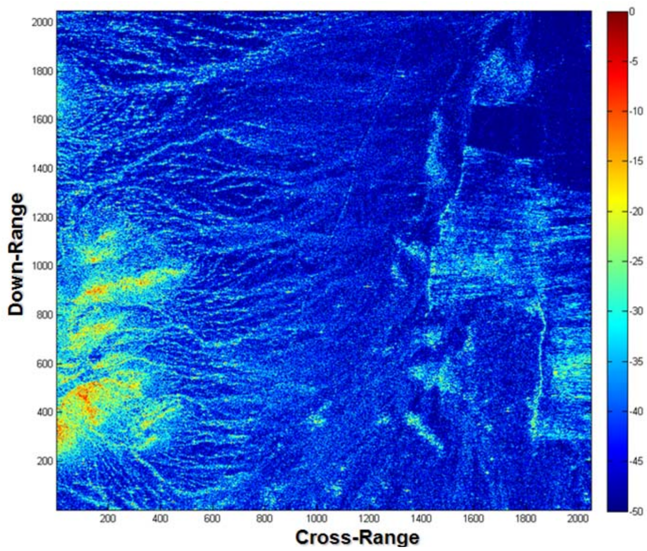

Figure 4. ARL baseline SAR image formed using data from the SRI airborne radar.

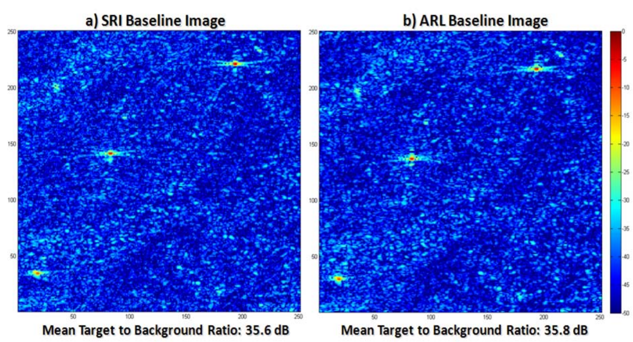

Figure 5. Baseline SAR image of calibration target area: a) SRI baseline image, and b) ARL baseline image.

The range compression phase consists of the following steps:

- Design a matched filter
- Apply a window function to the matched filter for side-lobe suppression.
- Apply a Hilbert Transform to the received signal to form an analytical signal.
- Down-shift the signal to baseband.
- Apply the proper matched filter to compress the signal.
- Up-shift the signal to the transmitted center frequency.
- Up-sample the signal in preparation to back-projection.

We employ the standard backprojection technique for SAR image formation. However, in order to keep the cross-range resolution consistent throughout a long aperture, we divide the image area in small sub-imaging grids. For each sub-imaging grid, we only use a segment of the aperture for image formation. Using this approach, we can achieve two important features: ensure that the cross-range resolution and the signal-to-noise (SNR) level almost constant across a long strip of SAR image.

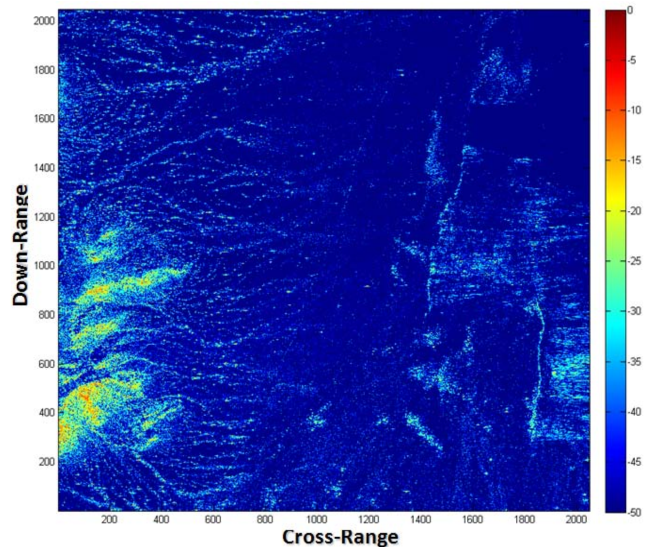

Figure 6. SAR image after the application of the RSM technique using data from the SRI airborne radar.

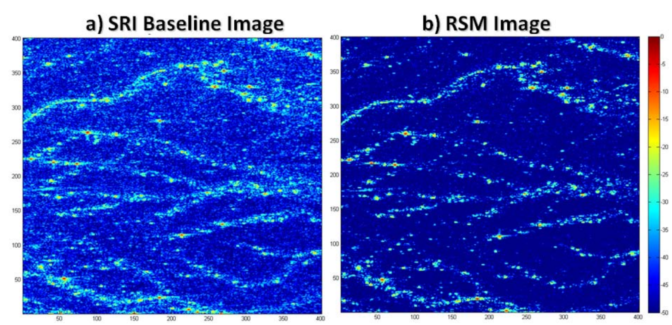

Figure 7. SAR image of a smaller area (400x400 m): a) Baseline image, and b) RSM SAR image.

Fig. 4 shows the ARL baseline SAR image that covers an area of approximately 2000x2000 m and is generated using the mosaic backprojetion algorithm described above. The ARL baseline image was formed using a narrow integration angle (9°) and calibrated to match with the resolution and amplitude of the SAR image provided by SRI. Although the 9° integration angle is not an optimal integration angle, it is important that we can reproduce the baseline performance that is comparable to that of the SRI image. From the baseline we can then measure the improvement achieved by the RSM technique. Fig. 5a and 5b show the SRI baseline and ARL baseline SAR images from a calibration target area. We define the image quality metric to be the ratio of the target amplitude and the mean of the background. The target-to-background ratio is 35.6 dB for the SRI baseline image and 35.8 dB for the ARL baseline image, which shows that the ARL formed baseline image is well matched to the SRI formed image.

Fig. 6 shows the resulting SAR image after the application of the RSM algorithm. Compare Fig. 4 and Fig. 6, it is obvious that the background level in the RSM image is significantly lower than that of the SRI baseline image. For better visual comparison, we display and compare images from several zoomed-in areas. Figure 7 shows the “before” and “after” SAR images of a smaller area (400x400 m). It is important to note that the amplitudes of the discrete objects in the RSM SAR image are similar to that from the original SRI baseline image while the background level and the amplitudes of the noise speckles are significantly reduced in the RSM SAR image. The enhanced SNR contrast achieved using the RSM algorithm is obvious and significant. Most of the image pixels in the RSM image are even lower than the floor (-50dB) of the display dynamic range. Similarly, the improvement is illustrated in Fig. 8 from another image area.

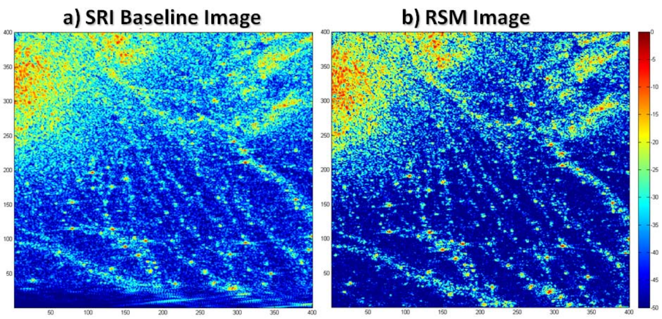

Figure 8. a) SAR image of another smaller area (400x400 m): a) Baseline image, and b) RSM SAR image.

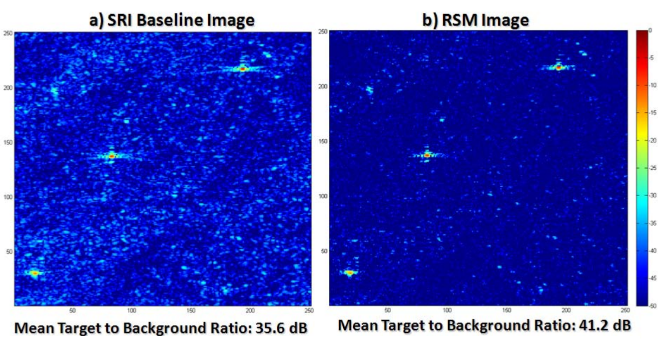

Figure 9. SAR image of calibration target area: a) SRI baseline image, and b) ARL RSM image. A 5.6 dB of improvement was achieved using the RSM algorithm.

To quantify the improvement, we compare the targets and background level from the calibration target area using the same metric that we described earlier in this section. Fig. 9a and 9b show the SRI baseline SAR image and the RSM SAR image of the calibration target area. The target-to-background ratios for the SRI baseline image and RSM image is 35.6 dB and 41.2 dB, respectively. In other words, a 5.6 dB of SNR improvement was achieved by the RSM algorithm.

Fig. 10 shows the improvement achieved by the RSM algorithm in more details. The x-y plots show the probability distributions of the image pixels versus their amplitudes. The blue curve represents the pixel distribution of the SRI baseline SAR image and the red curve represents the pixel distribution of the RSM SAR image. The pixels with high amplitudes represent the targets and the image pixels with lower amplitudes represent the background noise. The plots show that the RSM algorithm retains the amplitudes from the targets while significantly suppresses the background noise. The figure also shows that the RSM algorithm has moved the noise floor of the original image (about -50 dB) down by several dB.

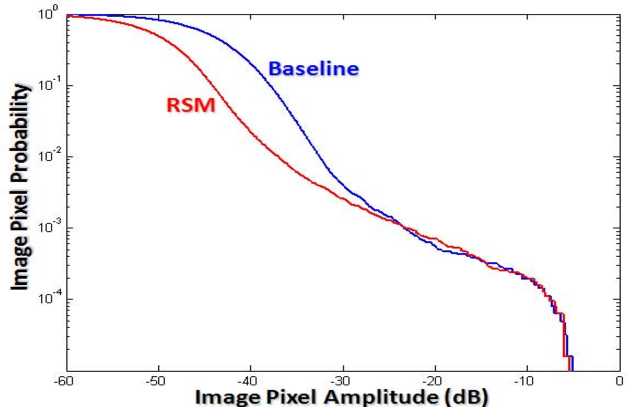

Figure 10. The exceedance distribution function of the image pixels versus their amplitudes. The plots show that the RSM algorithm retains the amplitudes from the targets while significantly suppresses the background noise.

IV. SUMMARY

ARL has developed the Recursive Sidelobe minimization (RSM) algorithm that is integrated with the standard backprojection image formation algorithm to form a SAR image with significant reduction in sidelobes and noise. The RSM algorithm has been shown to be very robust because of its simplicity (no training, no parameter tweaking). Although the RSM was initially developed for the forward-looking radar configuration, we have demonstrated its performance using a different data set (from SRI airborne radar) with a different configuration (side-looking). For this airborne side-looking configuration, the RSM improvement was 5.6 dB over the baseline algorithm. It suppresses many types of noise including the most challenging multiplicative noise that is originated from the target signal.

ACKNOWLEDGMENT

The authors would like to thank Mr. David Rutt, Mr. Dave Bender, Mr. Ronald Ueberschaer and Mr. David Krieger for providing the SRI radar data set, the radar data reader, and valuable information for the data set.

REFERENCES

[1] Lam Nguyen, David Wong, Marc Ressler, Francois Koenig, Brian Stanton, Gregory Smith, Jeffrey Sichina, Karl Kappra, "Obstacle Avoidance and Concealed Target Detection Using the Army Research Lab Ultra-Wideband Synchronous Impulse Reconstruction (UWB SIRE) Forward Imaging Radar,” Proc. SPIE 6553, 65530H (2007).

[2] Lam Nguyen, Marc Ressler, and Jeffrey Sichina, “Sensing through the wall imaging using the Army Research Lab ultra-wideband synchronous impulse reconstruction (UWB SIRE) radar,” *Proceedings of SPIE, Radar Sensor Technology XII*, Volume 6947, April 2008

[3] Lam Nguyen, Jeffrey Sichina, “Method and System for Forming an Image with enhanced contracts and/or reduced noise,” US Patent Office Application No. 12/331888, December 2008.

[4] Lam Nguyen, Jeffrey Sichina, “SAR Image Formation Using Phase-History Data from Non-Uniform Aperture,” *Proceedings of SPIE, Radar Sensor Technology XI, Vol. 6547*, May 2007.

[5] Lam Nguyen, “Signal and Image Processing Algorithms for the U.S Army Research Laboratory Ultra-wideband (UWB) Synchronous Impulse Reconstruction (SIRE) Radar,” ARL Technical Report, ARL-TR-4784, April 2009.