

SANDIA REPORT

SAND2014-1376

Unlimited Release

Printed February 2014

Supersedes SAND2001-3705
dated December 2001

Apodized RFI Filtering of Synthetic Aperture Radar Images

Armin W. Doerry

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>



SAND2014-1376
Unlimited Release
Printed February 2014

Supersedes SAND2001-3705
dated December 2001

Apodized RFI Filtering of Synthetic Aperture Radar Images

Armin Doerry
ISR Mission Engineering

Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185-0591

Abstract

Fine resolution Synthetic Aperture Radar (SAR) systems necessarily require wide bandwidths that often overlap spectrum utilized by other wireless services. These other emitters pose a source of Radio Frequency Interference (RFI) to the SAR echo signals that degrades SAR image quality. Filtering, or excising, the offending spectral contaminants will mitigate the interference, but at a cost of often degrading the SAR image in other ways, notably by raising offensive sidelobe levels. This report proposes borrowing an idea from nonlinear sidelobe apodization techniques to suppress interference without the attendant increase in sidelobe levels. The simple post-processing technique is termed Apodized RFI Filtering (ARF).

Acknowledgements

This edition of this report is the result of an unfunded Research and Development effort.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Contents

Foreword	6
Classification	6
1 Introduction & Background.....	7
2 Details of Apodized RFI Filtering (ARF).....	9
3 Example Imagery.....	13
4 Summary and Conclusions	21
References	23
Distribution	24

Foreword

This report details the results of an academic study. It does not presently exemplify any modes, methodologies, or techniques employed by any operational system known to the author.

This report supersedes an earlier report[†] that had limits to its distribution. The technique described herein, as well as the examples, have since then been disclosed and issued a patent,[‡] rendering the previous release restrictions no longer necessary.

Classification

The specific mathematics and algorithms presented herein do not bear any release restrictions or distribution limitations.

This distribution limitations of this report are in accordance with the classification guidance detailed in the memorandum “Classification Guidance Recommendations for Sandia Radar Testbed Research and Development”, DRAFT memorandum from Brett Remund (Deputy Director, RF Remote Sensing Systems, Electronic Systems Center) to Randy Bell (US Department of Energy, NA-22), February 23, 2004. Sandia has adopted this guidance where otherwise none has been given.

This report formalizes preexisting informal notes and other documentation on the subject matter herein.

[†] Armin Doerry, “Apodized RFI Filtering of Synthetic Aperture Radar Images,” Sandia Report SAND2001-3705, Specified Dissemination - Official Use Only, Printed December 2001.

[‡] Armin W. Doerry, “Method for removing RFI from SAR images”, US Patent 6,608,586, August 19, 2003.

1 Introduction & Background

Synthetic Aperture Radar (SAR) systems achieve fine range resolution by employing wideband signals. Ever-finer resolutions required of SARs require ever-wider bandwidths. Currently, available spectrum that is useful to SAR is used by a myriad of services including communication and remote sensing. These other emitters pose a source of Radio-Frequency Interference (RFI) to SAR, and energy from them degrade the SAR image, by increasing noise levels and obscuring detail within the SAR image. An example is illustrated in Figure 1, where an L/S-band SAR image of a circle of military vehicles is corrupted by interference from wireless digital service emitters. This image displays a resolution of 9 inches from data collected at a center frequency of 2.16 GHz.



Figure 1. SAR image corrupted by interference.

Heretofore, interference was mitigated by a variety of cancellation techniques and filtering techniques. These techniques generally fall into one of two categories. The first category attempts to filter the interference in some manner from the raw data prior to image formation.^{1, 2, 3} A variation of this technique exploits any pulse-to-pulse coherence of interfering sources to compress the interference in ‘Doppler’ before excision.^{4, 5} This technique works reasonably well for interfering Broadcast Television stations in the UHF band, and was exploited in Sandia’s UHF SAR project in the mid-1990’s.⁶ Other emitters, such as wireless digital services at microwave frequencies do not appear to correlate very well over multiple pulses, and hence do not compress in Doppler. The second category attempts to model the interference and nullify, or cancel the interference in the raw data.^{7, 8, 9} None of the techniques surveyed in the literature attempt to perform any significant processing in the ‘image domain’ itself.

However, in excising the offending spectrum by whatever means, so too is radar echo energy excised that is both desirable and valuable. Thereby, while removing interference effects, the SAR image is degraded in a different manner, by increasing offensive sidelobes typically and primarily in the range dimension.

The technique disclosed herein is able to excise interference without increasing sidelobe levels, thereby rendering an improved SAR image.

2 Details of Apodized RFI Filtering (ARF)

The technique disclosed herein renders an improved SAR image by processing the available data in a non-linear manner that excises interference without increasing sidelobe levels. It does so by forming two distinct images, the first that includes the interference, and the second with interference excised but which exhibits consequentially higher sidelobe levels. The crucial step is to compare the images on a pixel by pixel basis and keep the minimum pixel magnitude value in a final combined image.

Any particular one of a variety of techniques for interference removal can be used in forming the second image. As such, this technique is an extension of most other mitigation algorithms. That is, the basic technique described herein makes other techniques work better. The embodiment of this idea for the following examples presumes that interference removal for the second image is accomplished by zeroing the appropriate raw SAR phase history data, or equivalent. The raw phase-history data is a result of stretch-processing, where a Linear-FM chirp waveform was transmitted and removed prior to digitization. Figure 2 illustrates the basic algorithm steps in a block diagram form, beginning with raw SAR phase-history data. Figure 3 illustrates the algorithm steps beginning with a complex SAR image corrupted by interference. Beginning with the complex data, pseudo-phase-history data is first obtained by Inverse-Fourier Transforming the complex image, whereupon spectral excision is performed and the second image is formed. The examples in this report are processed in this manner, that is, beginning with complex images exhibiting RFI.

An important note is that in comparing the first image to the second, the second image must be properly scaled to account for the signal energy lost during excision of its spectrum.

An extension of this technique might include comparing against a third image (or even more images) using an alternate RFI mitigation scheme, or a different filtering strategy, such that the final result is the best combination of all processing techniques.

We also note that the concept of selecting minimum pixel values from multiple images processed with different window functions is the fundamental idea behind sidelobe apodization techniques, including Spatially Variant Apodization (SVA).^{10, 11}

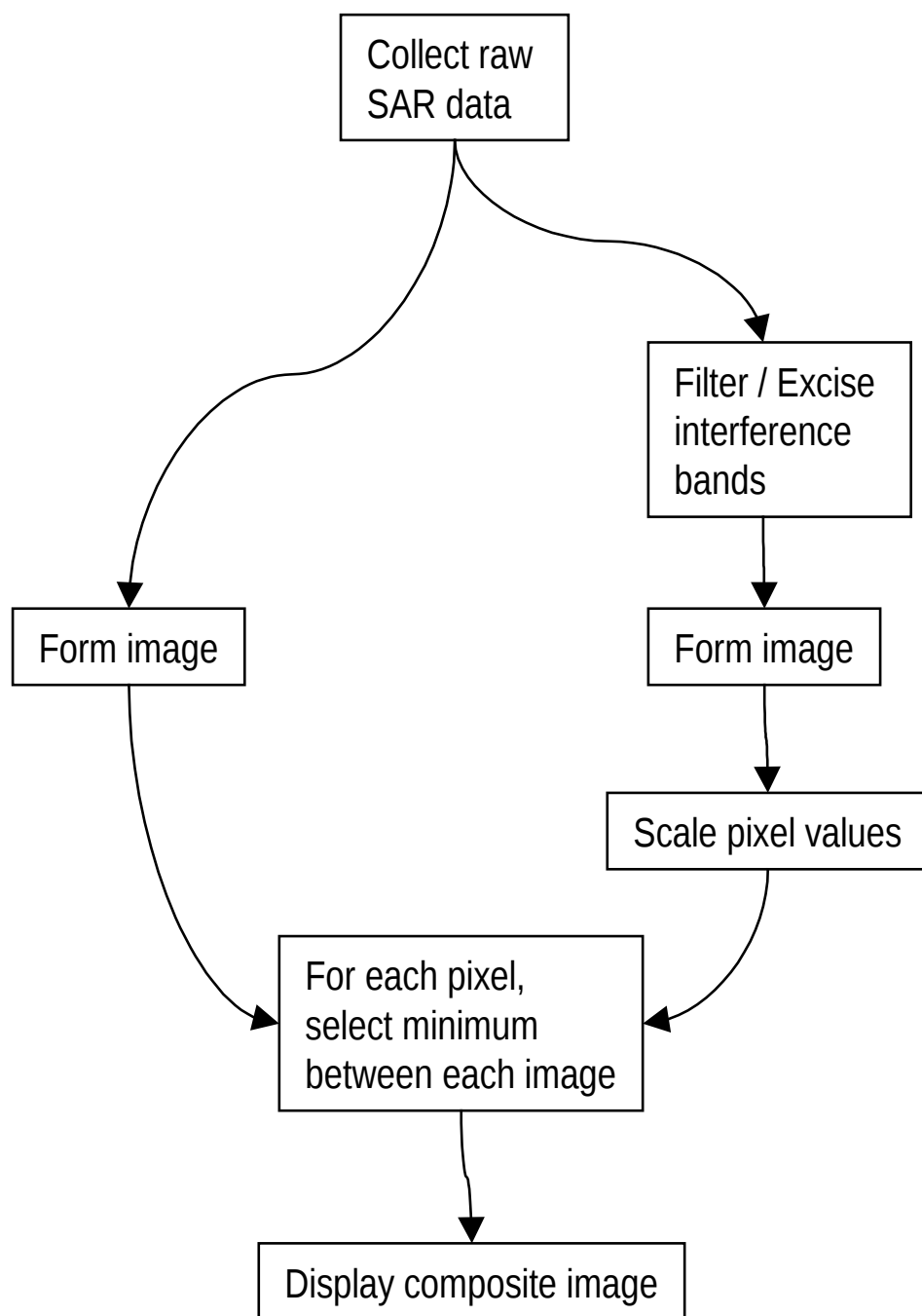


Figure 2. ARF beginning with SAR phase history data.

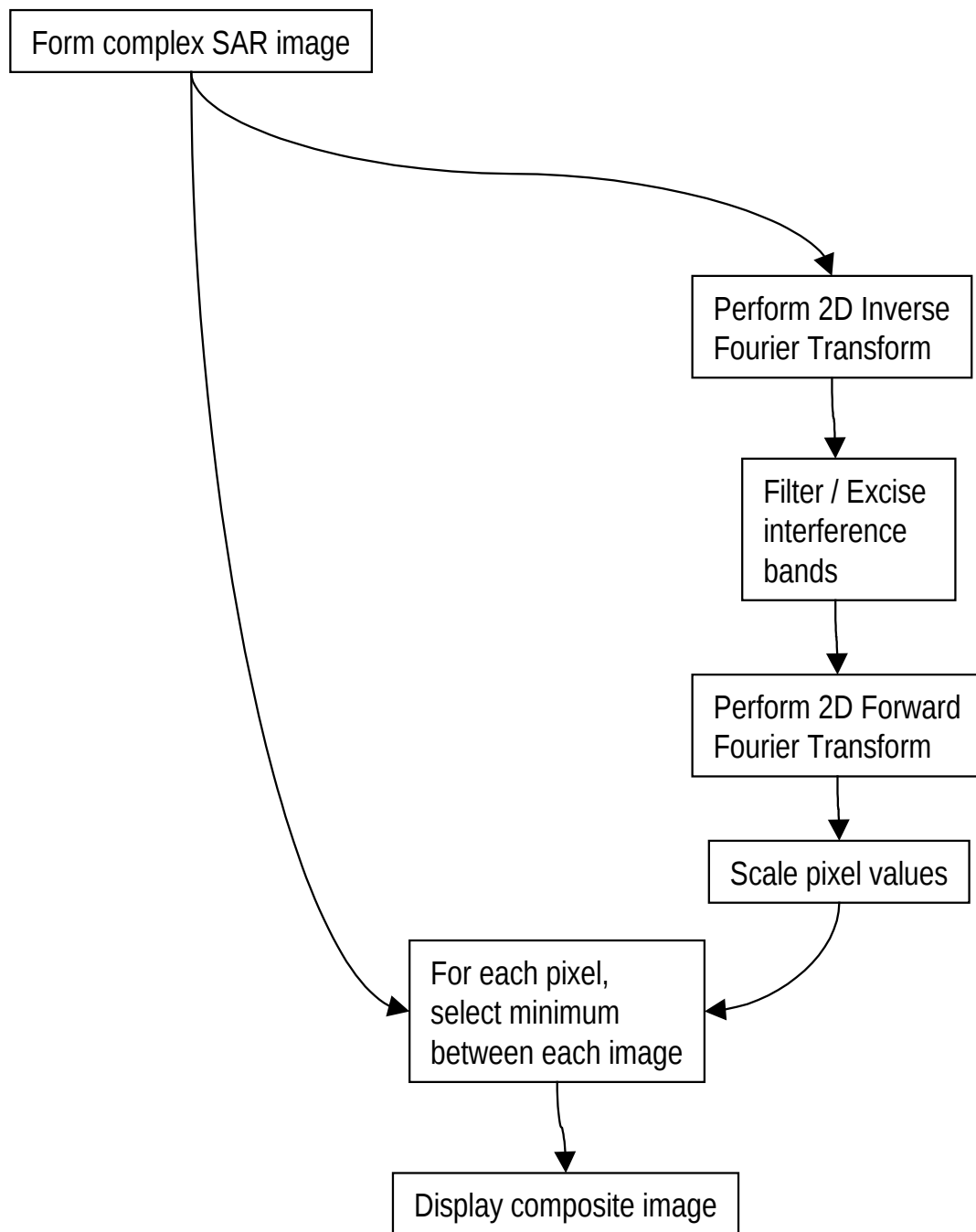


Figure 3. ARF beginning with complex SAR image.

“If you don't interfere with me, I'll always do something really good.”
-- John Malkovich

3 Example Imagery

What follows are some examples of the application of the ARF technique to complex images exhibiting RFI degradation.

Figure 4 is an enlarged view of the targets in Figure 1.

Figure 5 is the Inverse FFT (and hence the pseudo-phase-history data) of the complex image of Figure 1, clearly showing bands of interference due to wireless digital services in proximity to the scene.

Figure 6 is the image re-formed from the modified pseudo-phase-history data displayed in Figure 7, where the interference bands have been excised. Note the degraded sidelobe response of the center trihedral (corner-reflector) in the image.

Figure 8 is a pixel-by-pixel minimum of the magnitudes of the pixels in Figure 4 and Figure 6. Clearly the sidelobes have been reduced. Figure 9 is the entire image after ARF processing.

Figure 10, Figure 11, and Figure 12 illustrate the range dimension amplitude response that includes the center trihedral response. In each pair, the top is a full line from the image, and the bottom is an enlarged view near the trihedral response. Note that Figure 11 has a lower noise floor but worse target sidelobes compared to Figure 10, but Figure 12 contains the best features of both.

Figure 13 and Figure 14 show additional images of a section of the Albuquerque Rio Grande Zoo both before and after ARF processing. These images also display a resolution of 9 inches from data collected at a center frequency of 2.16 GHz.

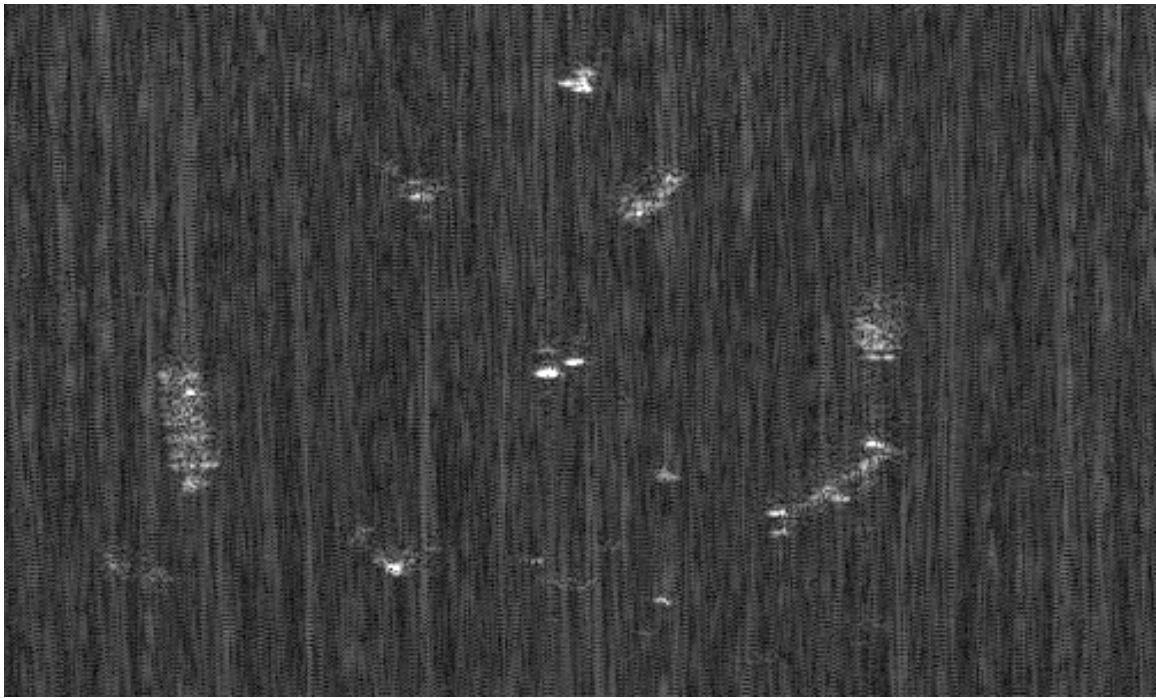


Figure 4. Close-up of targets from Figure 1.

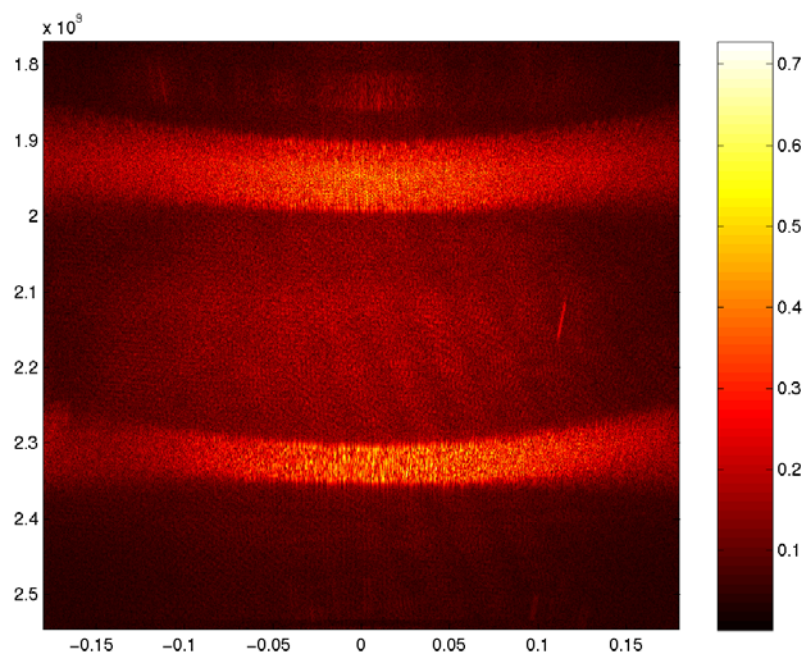


Figure 5. Pseudo-phase-history data for Figure 1.

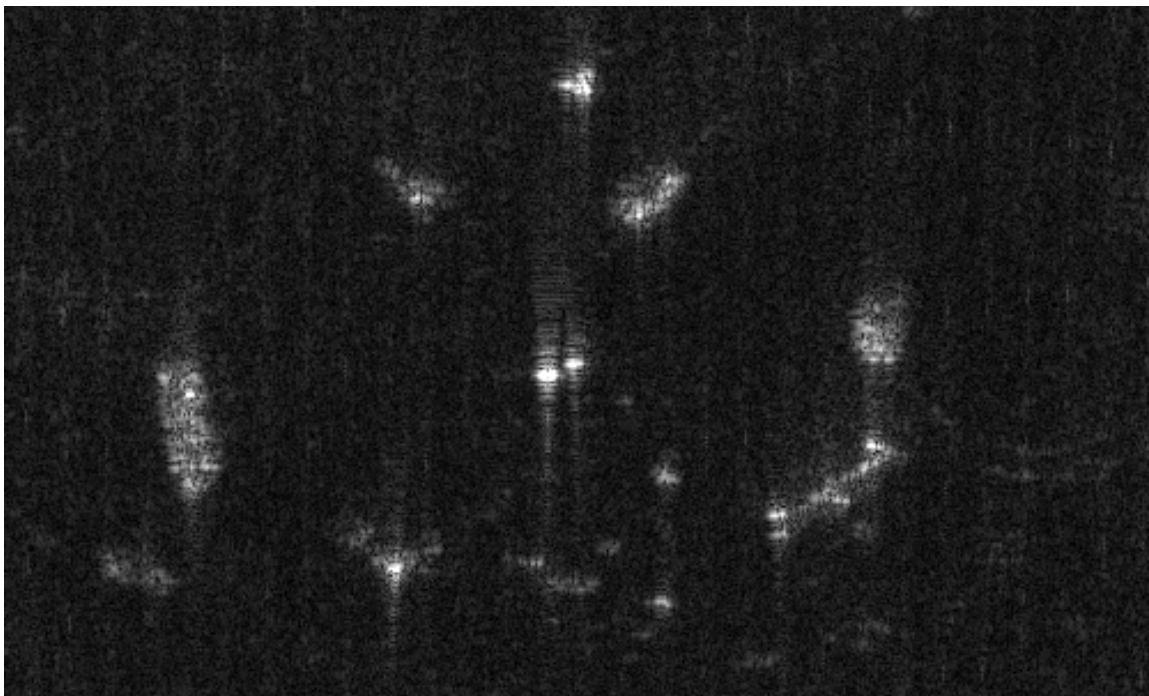


Figure 6. Image of targets after interference excision.

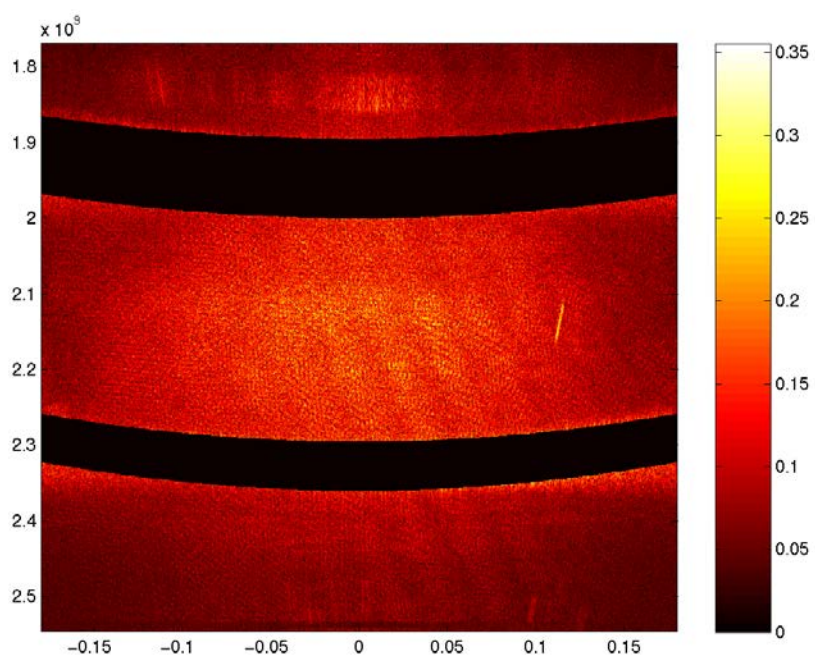


Figure 7. Pseudo-phase-history data after interference excision.

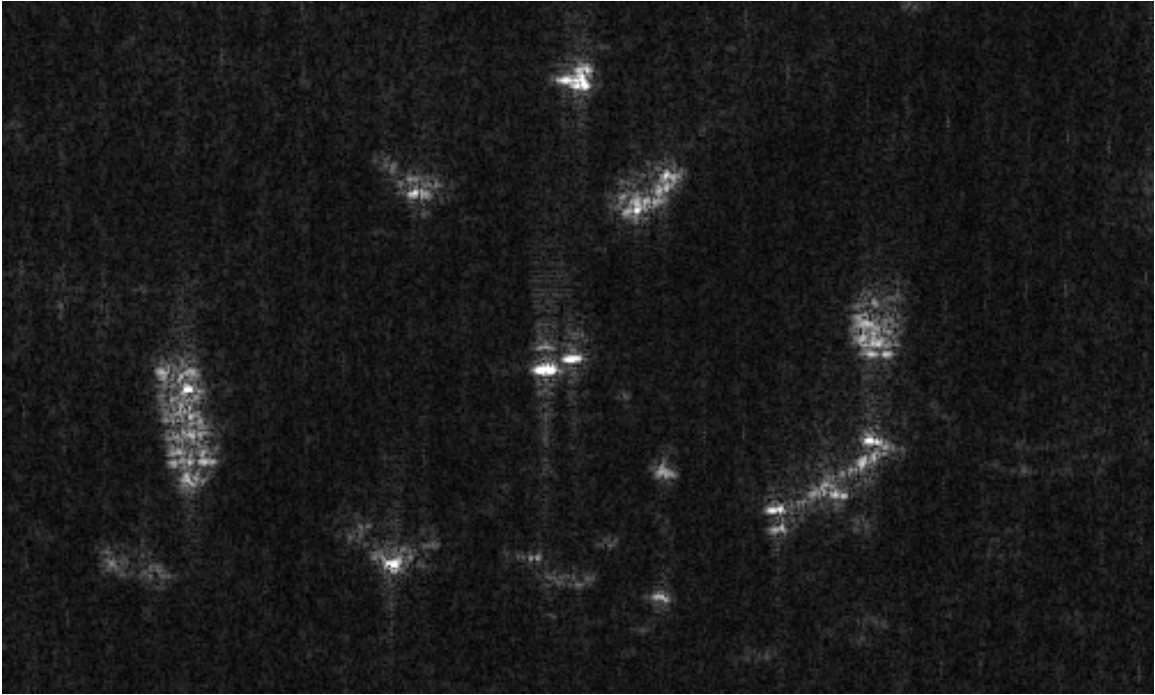


Figure 8. Image after ARF processing.

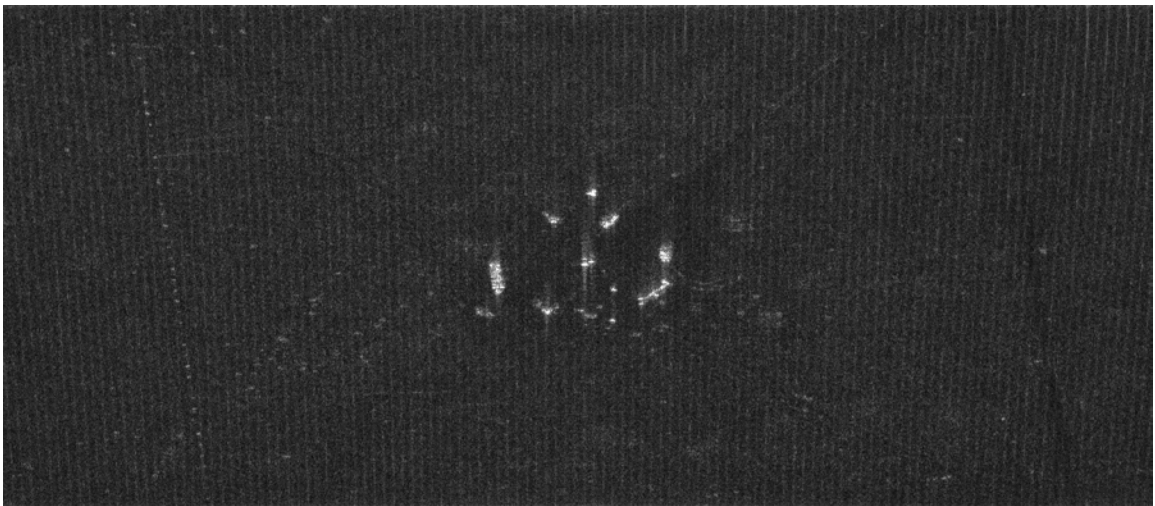


Figure 9. Entire image after ARF processing.

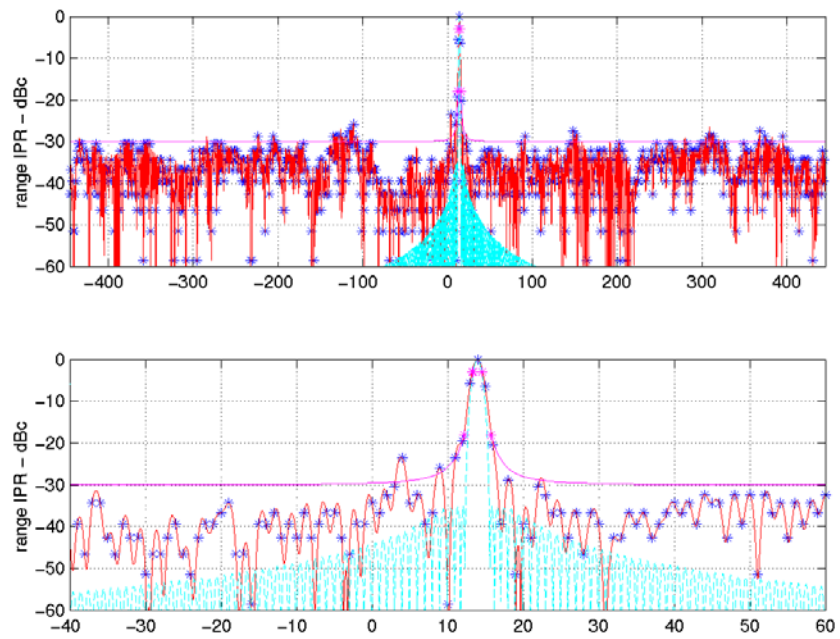


Figure 10. Range slice of original RFI contaminated image.

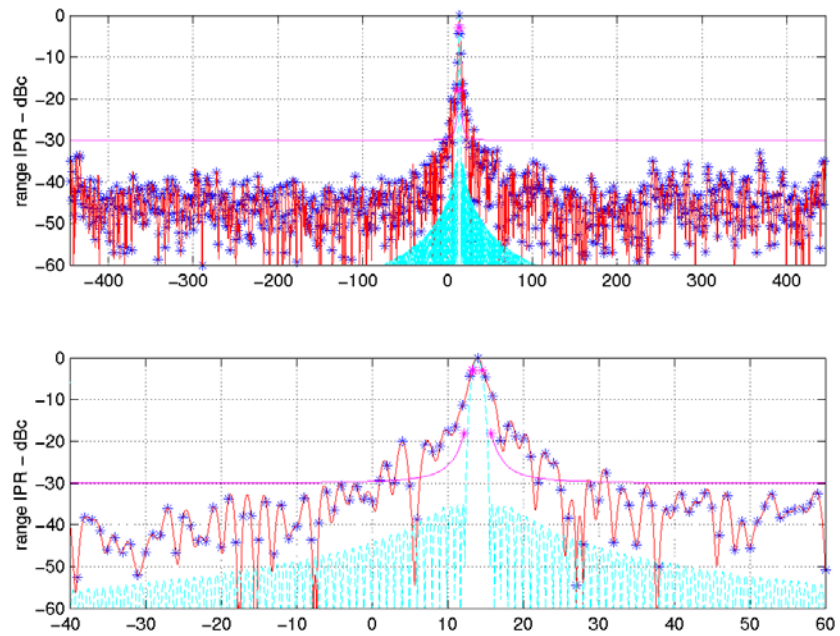


Figure 11. Range slice of RFI excised image.



Figure 12. Range slice of ARF processed image.

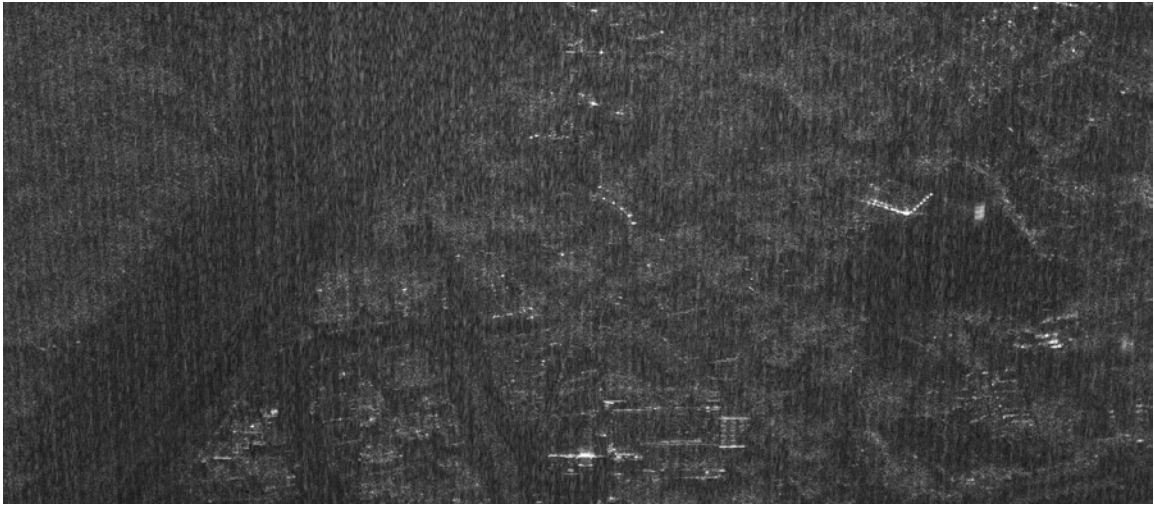


Figure 13. Image corrupted by interference.

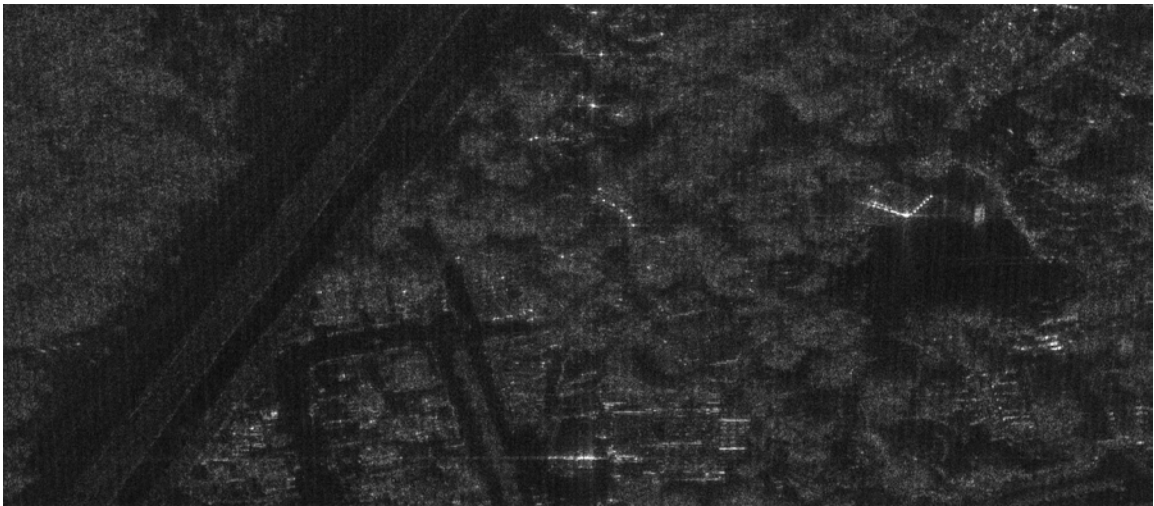


Figure 14. Image after ARF processing.

“Nature is often hidden, sometimes overcome, seldom extinguished.”
-- Francis Bacon

4 Summary & Conclusions

We reiterate the following points.

- Images may be compared to each other that have been formed both with, and without interference excised or filtered. A final image is assembled on a pixel-by-pixel basis that is the minimum of either of the original two.
- The technique disclosed herein is a post-processing step that is able to use the results of other interference removal or filtering techniques and combine them with an unimproved image into a further-improved resulting image.
- This technique allows excising interference without increasing sidelobe levels. This addresses a shortfall of other existing RFI mitigation techniques.

*“Don't mess with a wizard when he's wizarding!”
— Jim Butcher*

References

- ¹ R.T. Lord, M.R. Inggs, "Efficient RFI suppression in SAR using LMS adaptive filter integrated with range/Doppler algorithm," *Electronics Letters*, 15 April 1999, vol. 35, no. 8, pp. 629-30.
- ² Hans Hellsten, "Ultra wide band coherent radar system optimising the radio interference discrimination capability," US Patent 6,072,420, June 6, 2000.
- ³ Ron S. Goodman, Ronald A. Schneider, "Method for improving SAR system sensitivity in the presence of RF interference," US Patent 5,850,202, December 15, 1998.
- ⁴ B. H. Ferrell, "Interference suppression in UHF synthetic-aperture radar," *Proceedings of the SPIE - The International Society for Optical Engineering, Algorithms for Synthetic Aperture Radar Imagery II*, vol. 2487, pp. 96-106, 19-21 April 1995.
- ⁵ John A. Garnaat, Bruce H. Ferrell, William C. Woody, "Separating coherent radio-frequency interference from synthetic aperture data," US Patent 5,546,085, August 13, 1996.
- ⁶ D. F. Dubbert, B. C. Brock, A. W. Doerry, T. J. Flynn, R. B. Hurley, M. L. Pedroncelli, "A VHF/UHF SAR for Imaging Buried Targets (U)," 41st Annual Tri-Service Radar Symposium, Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, 27-29 June 1995.
- ⁷ A. Golden Jr., S. A. Werness, M. Stuff, S. DeGraaf, R. Sullivan, "Radio frequency interference removal in a VHF/UHF deramp SAR," *Proceedings of the SPIE - The International Society for Optical Engineering, Algorithms for Synthetic Aperture Radar Imagery II*, vol. 2487, pp. 84-95, 19-21 April 1995.
- ⁸ T. Miller, L. Potter, J. McCorkle, "RFI suppression for ultra wideband radar," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 33, no. 4, pp. 1142-56, Oct. 1997.
- ⁹ Jen King Jao, "Fourier-transform-based adaptive radio interference mitigation," US Patent 6,166,678, December 26, 2000.
- ¹⁰ H. C. Stankwitz, R. J. Dallaire, J. R. Fienup, "Nonlinear Apodization for Sidelobe Control in SAR Imagery," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 31, No. 1, pp. 267-279, Jan. 1995,.
- ¹¹ Rodney J. Dallaire, Herbert C. Stankwitz, "Spatially Variant Apodization," US Patent 5,349,359, September 20, 1994.

Distribution

Unlimited Release

1	MS 0519	J. A. Ruffner	5349	
1	MS 0519	A. W. Doerry	5349	
1	MS 0519	L. Klein	5349	
1	MS 0532	J. J. Hudgens	5240	
1	MS 0899	Technical Library	9536	(electronic copy)

