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During the past three years, we have successfully accomplished nearly all the project objectives listed in Section 2.0. We have developed and evaluated processing-algorithms for generating SAR images from a sparse array of radar satellites. An important result of this work is that it is possible, using a sparse satellite array, to generate a fine-resolution SAR image of arbitrarily large extent. In other words, the traditional limit on SAR swathwidth and/or spot size is not an issue for multiple satellite arrays, provided that a minimum number of satellites is available. Likewise, we have developed and evaluated Moving Target Indication (MTI) processors for sparse satellite arrays. We have shown that the large spatial extent of a radar satellite array can greatly improve the MTI performance of space-based radar systems, despite the sparse nature of the array. Moreover, we have shown that, for these sparse satellite systems, the SAR and MTI solutions are complementary in nature such that both SAR and MTI processing can be coupled (essentially, a SAR image is a mapping of moving targets with zero radial velocity). We conducted research into the optimal design of a transmit signal code. We have demonstrated an eigenvector solution that creates an optimal space-time transmit signal in the sense that it minimizes an upper bound of the sidelobe energy in a sensor ambiguity function. Finally, we created a high-fidelity sparse-array software simulator to evaluate the performance of these algorithms for specific sparse-array designs and scenarios. This simulator allowed us to create accurate complex space-time samples (i.e., A-to-D values) for realistic sensor designs and surface targets.

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FINAL REPORT FOR MULTI-DIMENSIONAL SIGNAL PROCESSING FOR SPARSE RADAR ARRAYS

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1.0 Introduction

The following report describes the work conducted on the research project "Multi-Dimensional Signal Processing for Sparse Radar Arrays" (AFOSR Grant # F49620-99-1-0172, P00001). This work was performed at the Radar Systems and Remote Sensing Laboratory (RSL) at the University of Kansas.

2.0 Objectives

The objectives of this research program remain those listed in the original proposal:

1. Develop and demonstrate SAR-processing algorithms that use the range, doppler, and angle-of-arrival information acquired using a multi-satellite radar defined by the TechSat 21 concept.
2. Develop and demonstrate GMTI-processing algorithms that use the range, doppler, and angle-of-arrival information acquired using a multi-satellite radar defined by the TechSat 21 concept.
3. Develop and demonstrate AMTI-processing algorithms that use the range, doppler, and angle-of-arrival information acquired using a multi-satellite radar defined by the TechSat 21 concept.
4. Develop a software radar simulator to test these algorithms on realistic target scenarios.
5. Evaluate the performance of these algorithms with regard to resolution, detection, minimum discernable velocity, search area rate, location accuracy, clutter rejection, and so forth.
6. Evaluate the processing performance as a function of system errors, including noise, clutter, transmitter/receiver errors, and errors in satellite position and orientation.

7. Investigate the methodologies for selecting the orthogonal transmit signals associated with the TechSat 21 concept. Evaluate the efficacy and improvement in sensor performance by using a spatially distributed transmitter.
8. Investigate methods for improving the computational efficiency of the processing algorithms, including computational methodologies and information theoretic methods of data preprocessing.
9. Quantify the performance of the processing algorithms in terms of computational cost. Assign a numeric measure to each algorithm.
10. Identify other potential benefits of the TechSat 21 concept, including surface height estimation, target tracking, change detection, and so forth.

3.0 Final Status of Effort

During the past three years, we have successfully accomplished nearly all the project objectives listed in Section 2.0. We have developed and evaluated processing-algorithms for generating SAR images from a sparse array of radar satellites. An important result of this work is that it is possible, using a sparse satellite array, to generate a fine-resolution SAR image of arbitrarily large extent. In other words, the traditional limit on SAR swathwidth and/or spot size is not an issue for multiple satellite arrays, provided that a minimum number of satellites is available.

Likewise, we have developed and evaluated Moving Target Indication (MTI) processors for sparse satellite arrays. We have shown that the large spatial extent of a radar satellite array can greatly improve the MTI performance of space-based radar systems, despite the sparse nature of the array. Moreover, we have shown that, for these sparse satellite systems, the SAR and MTI solutions are complementary in nature such that both SAR and MTI processing can be coupled (essentially, a SAR image is a mapping of moving targets with zero radial velocity).

We conducted research into the optimal design of a transmit signal code. This effort involved constructing transmit signals that minimize the sidelobe levels of the sensor ambiguity (i.e., point spread) function. Since the sensor collects information in both space and time, the transmit signal must be constructed such that sidelobes of the spatial array pattern are aligned with nulls in the time-frequency pattern, and vice-versa. We have demonstrated an eigenvector solution that creates an optimal space-time transmit signal in the sense that it minimizes an upper bound of the sidelobe energy in a sensor ambiguity function.

Finally, we created a high-fidelity sparse-array software simulator to evaluate the performance of these algorithms for specific sparse-array designs and scenarios. This simulator allowed us to create accurate complex space-time samples (i.e., A-to-D values) for realistic sensor designs and surface targets.

4.0 Accomplishments/ New Findings

The detailed results of our research are provided in three separate (attached) technical reports. RSL Technical Report 18221-3, "SAR and MTI Processing of Sparse Satellite Clusters," describes the work regarding SAR and MTI processing using sparse satellite arrays. RSL Technical Report 18221-2, "Design of Space-Time Transmit Codes for Optimizing Multistatic Radar Performance," describes our work in developing optimal space-time transmit codes. Finally, RSL Technical Report 18221-1, "A Software Simulator for Multi-Aperture Spaceborne Radar," details the development of the sparse array software simulator.

5.0 Personnel Supported

Over the course of this project, the following personnel have been supported by project funds:

1. James M. Stiles, Associate Professor of Electrical Engineering.
2. John Gauch, Professor of Computer Science.
3. Nathan Goodman, PhD. student (electrical engineering).
4. SihChung Lin, Master's student (electrical engineering).
5. Subash Gullapalli, Master's student (electrical engineering).
6. Anand Sundaram, Master's student (electrical engineering).

Upon graduation, Nathan Goodman accepted a tenure-track position at the University of Arizona, where he is currently working as an assistant professor.

6.0 Publications

The following is a list of publications that have thus far been produced from this project. Additional papers will likewise be written in the following year.

Referred Journal Articles

N. Goodman and J. M. Stiles, "Clutter rank estimation for 3-D, sparsely populated clusters of radar satellites," in preparation for submission to *IEEE Transactions on Aerospace and Electronic Systems*, 2002.

N. Goodman and J. M. Stiles, "Resolution and synthetic array characterization of sparse radar arrays," submitted to *IEEE Transactions on Aerospace and Electronic Systems,* Dec 2001.

N. Goodman, S. C. Lin, D. Rajakrishna, and J. M. Stiles, "Processing of multiple receiver, spaceborne arrays for wide-area SAR," *IEEE Transactions on Geoscience and Remote Sensing,* vol. 40, pp. 841-852, Apr 2002.

Published Conference Presentations

N. Goodman and J. M. Stiles, "The information content of multiple receive aperture SAR systems," in *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium,* July 2001.

J. M Stiles and N. Goodman, "Processing of multi-aperture SAR to produce fine-resolution images of arbitrarily large extent," in *Proceedings of the 2001 IEEE Radar Conference*, pp. 451-456, May 2001.

N. Goodman and J. M. Stiles, "A general signal processing algorithm for MTI with multiple receive apertures," in *Proceedings of the 2001 IEEE Radar Conference*, pp. 315-320, May 2001.

J. Stiles, N. Goodman, S. C. Lin, "Performance and processing of SAR satellite clusters," in *Proceedings of the International Geoscience and Remote Sensing Symposium*, pp. 883-855, July 2000.

N. Goodman, D. Rajakrishna and J. Stiles, "Wide swath, high resolution SAR using multiple receive apertures," in *Proceedings of the International Geoscience and Remote Sensing Symposium*, pp. 1767-1769, June 1999.

Technical Reports

Stiles, J. M., "Final report for multi-dimensional signal processing for sparse radar arrays," Radar Systems and Remote Sensing Laboratory Technical Report 18221-4, November 2002.

Goodman, N., "SAR and MTI Processing of Sparse Satellite Clusters," Radar Systems and Remote Sensing Laboratory Technical Report 18221-3, July 2002.

Lin, S. C., "Design of space-time transmit codes for optimizing multistatic radar performance," Radar Systems and Remote Sensing Laboratory Technical Report 18221-2, December 2000.

Sundaram, A., "A software simulator for multi-aperture spaceborne radar," Radar Systems and Remote Sensing Laboratory Technical Report 18221-1, Nov 2000.

7.0 Interactions/Transitions

The research resulting from this project was presented at various technical conferences around the world. The following is a list of these presentations.

"Synthetic Aperture characterization of radar satellite constellations," presented at the IEEE International Geoscience and Remote Sensing Symposium, Toronto, Canada, June 2002.

"The information content of multiple receive aperture SAR systems," presented at the IEEE International Geoscience and Remote Sensing Symposium, Sydney, Australia, July 2001.

"Processing of multi-aperture SAR to produce fine-resolution images of arbitrarily large extent," presented at the 2001 IEEE Radar Conference, Atlanta, GA, May 2001.

"A general signal processing algorithm for MTI with multiple receive apertures," presented at the 2001 IEEE Radar Conference, Atlanta, GA, May 2001.

"Wide-swath, high-resolution SAR using spatial array beamforming," presented at the URSI National Radio Science Meeting, Boulder, CO, Jan. 2001.

"A general signal processing algorithm for MTI with multiple receive apertures," presented at the International Geoscience and Remote Sensing Symposium, July 2001, Sydney, Australia.

"Performance and processing of SAR satellite clusters," presented at the International Geoscience and Remote Sensing Symposium, July 2000, Honolulu, Hawaii, USA.

"Wide swath, high resolution SAR using multiple receive apertures," presented at the International Geoscience and Remote Sensing Symposium, June 1999, Hamburg, Germany.

8.0 Inventions and Patent Disclosures

None.

9.0 Honors/Awards

Nathan Goodman—*Madison A. and Lila Self Graduate Fellowship*

Nathan Goodman and Jim Stiles—*2002 Interactive Session Prize Paper Award,* IEEE Geoscience and Remote Sensing Society, 2002. Received for the paper entitled "The information content of multiple receive aperture SAR systems," presented at the Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, Sydney, Australia, July 2001.