MULTI-STATIC RADAR SIGNAL PROCESSING—IMPROVED INTERFERENCE REJECTION, TRACKING AND DISCRIMINATION

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1.0 Introduction

In a multi-static radar (MSR) the transmit/receive aperture is divided into a number of sub-apertures that can be placed in various locations relative to each other. These locations can be chosen to optimize the performance of the radar in terms of some specific task. Two multi-static approaches have been investigated:

- Closely spaced apertures – distributed aperture radar (DAR)
- Widely spaced apertures

Realizing the greater capability of MSR's requires unique waveform and signal processing approaches. A computer simulation has been developed that permits the analysis of MSR signal processing. This paper presents the results of a series of experiments to validate the results of that simulation.

1.1 DAR–Interference Rejection and Tracking

Multi-static radars, in a distributed aperture mode, can potentially provide significantly improved target tracking because of the large baseline between the various apertures. The resulting angular resolution can be orders of magnitude better than the resolution of a monolithic system (single large radar). This capability comes with a cost because of the resulting grating lobes (multi-statics with evenly spaced apertures) or high sidelobes (multi-statics with randomly spaced apertures).

The same angular resolution can provide improved electronic protection (EP) capability. For a single aperture radar, jammers located near to targets of interest cannot be nulled without impacting the antenna mainbeam and therefore the target returns. But the multi-static system, with its very long baseline, receive aperture gain on the target can be maintained while a deep null is placed in the direction of the jammer.

1.2 Imaging and Discrimination

Two dimensional images of moving targets can be obtained through inverse synthetic aperture radar (ISAR) processing. The range and cross-range dimensions of radars viewing the target from widely separated angles will achieve target-centered resolution in different dimensions. For example, two radars independently viewing an object in its plane of motion (linear, rotating) with ninety degrees of separation will provide complementary information: the range resolution of one radar will be the cross-range resolution of the other and vice versa. Coherent fusion processing of the data from these two radars can provide improved resolution. Fusion of the data from the bi-static path can further improve the resolution. Also, two or more radars viewing an object from different angles not in its plane of motion can provide three-dimension images. The overall 3-D resolution of the object will be a function of the range and cross-range resolution of the individual radars and their angle separation as viewed from the target location.

2.0 Multi-Static Interference Rejection

Interference can be rejected, if and only if, the target and interference are resolvable in the dimensions/domains in which the processing is being performed.

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 DEC 2008**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Multi-Static Radar Signal ProcessingImproved Interference Rejection, Tracking And Discrimination**	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) **US Air Force AFRL/RY**	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 ADM002187. Proceedings of the Army Science Conference (26th) Held in Orlando, Florida on 1-4 December 2008, The original document contains color images.

14. ABSTRACT

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**	**UU**	**10**	

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

Continuously radiating point sources (jamming) can be rejected in the spatial dimension if the target and EMI are separated in angle and cannot be rejected when that separation is sufficiently small. In general, spatially continuous interference (i.e., exo-atmospheric volume clutter) cannot be adequately suppressed by conventional non-adaptive means, i.e. by processing separately in either the spatial or Doppler domains. These techniques fail because they do not handle the space-time coupling inherent in the clutter signal return. Consequently leakage from one domain to the other limits the amount of suppression that can be achieved by operating in these domains separately.

For conventional single aperture radars the cross-range resolution may be so large that the target effectively falls within the main beam antenna spatial response. In this case, conventional space-time adaptive processing (STAP) will not be able to adequately reject the interference. However, assuming a distributed aperture radar with high range and cross range resolution, improvements in target-clutter separation is achievable along with improvements in interference suppression. Such architectures generally lead to space-time grating lobes that can degrade performance. Using simultaneous orthogonal waveforms, however, to form narrow spatial main beams, it is possible to develop space/time/waveform adaptive processing to suppress grating lobes, reject the clutter, and detect the target in jamming, clutter and joint jamming/clutter environments.

We have demonstrated the potential for orthogonal waveforms in distributed aperture radar architectures (DAR) in achieving improved resolution, interference suppression, and target detection and tracking performance while simultaneously controlling space-frequency grating lobes. System operation involves radiating orthogonal waveforms from multiple sub-apertures of the DAR and then receiving and processing these waveforms at each sub-aperture. The use of orthogonal waveforms provides an additional dimension (waveform) beyond the standard space-time dimensions typically used in conventional STAP for adaptive suppression of the interference background.

Adaptive processing using frequency diversity was simulated and demonstrated. The interference was first modeled as a single point EMI source. The signal theory was then generalized to handle the more difficult problem involving distributed volumetric clutter.

2.1 EMI Rejection – Simulation and Analysis

Several key considerations for systems employing advanced adaptive processing techniques using waveform diversity were considered. A distributed aperture system with N sub-apertures was assumed. Each sub-aperture is assumed to transmit a different (orthogonal) waveform. Each sub-aperture then receives target returns from each of the transmitted waveforms, resulting in a total of $N \times N$ returned samples for each radar range gate. In this situation, the classical space-time data cube is replaced by a data hypercube where the additional dimension is 'waveform'. In this effort, the orthogonal waveforms were chosen to be relatively narrowband signals offset in center frequency. For such a system, we note:

<u>Adaptive space-time-waveform processing:</u> Traditionally, adaptive processing has focused on the spatial and temporal dimensions leading to space-time adaptive processing. The spatial steering vector is related to the spatial look direction while the temporal steering vector is determined by the temporal look or Doppler frequency. In this case, the space dimension is augmented by the addition of the waveform domain. The space/waveform steering vector is determined uniquely by the look angle with a different spatial steering vector for each transmit frequency.

Sub-aperture waveform (frequency) separation: Distribution of the sub-apertures and separation of the transmit frequencies introduces two new degrees of freedom to the radar designer: namely the spacing between the antenna sub-apertures and spacing between frequencies. Generally sub-apertures and/or sub-bands are separated by multiple wavelengths. Consequently, equally spaced elements/sub-apertures with equally spaced frequencies can lead to grating lobes that can reduce the effectiveness of the adaptive process. Analysis has shown that appropriate distribution of the elements in the spatial and temporal (frequency) domains along with weighting can eliminate, or at least mitigate grating lobes in their respective dimensions and reduce the amount of adaptive processing required to suppress interference.

Targets/interference are not necessarily in the far field: By standard definition, the far field region is determined by three conditions: $R > \lambda$, $R > D$ and $R > D^2/\lambda$ where R is the radial distance, D is the total aperture baseline and λ is the wavelength of the frequency of operation. From a physical point of view, the far field is the region where the spatial steering vector is effectively independent of the radial distance. To illustrate, we assume the distance to the target, D = 200m and center frequency is 10GHz, i.e., the far field begins at approximately 1500km. The target and any competing interference are therefore not necessarily in the far field. This may impact the adaptive processing approach. As in bi-static STAP operation, a range dependent interference ridge results, and, if no additional processing is assumed, the size of the secondary data available to estimate the covariance matrix is reduced. This in turn may limit STAP performance. Another concept borrowed from bi-static radar applies a spatial un-warping to the data to remove the range dependency and allow a larger secondary data set size to be used.

Based on these considerations a high-fidelity multi-static radar simulation was developed and the performance of various geometries predicted.

2.2 Jammer Rejection - Experiment

A rooftop experiment was accomplished at the Air Force Research Laboratory/Rome Research Site to verify the multi-static radar simulation. Five sub-apertures were located in roughly linear orientation (Figure 1). The total separation was about 200 feet. A moving target and a jammer were located about 6000 feet away (Figure 2). The target was driven through the mainbeams of the five radars.

The suite of 5 transmitters collectively radiated 5 diverse frequencies that were recorded on each receiver channel. Activation of the jammers produced a 30dB jammer/noise ratio and completely masked out the target vehicle return. After multi-channel,

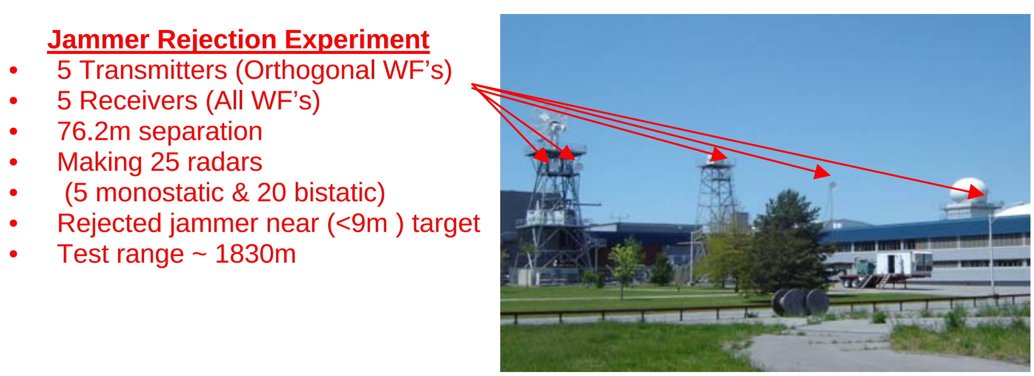


Figure 1: Distributed Aperture Radar (DAR)

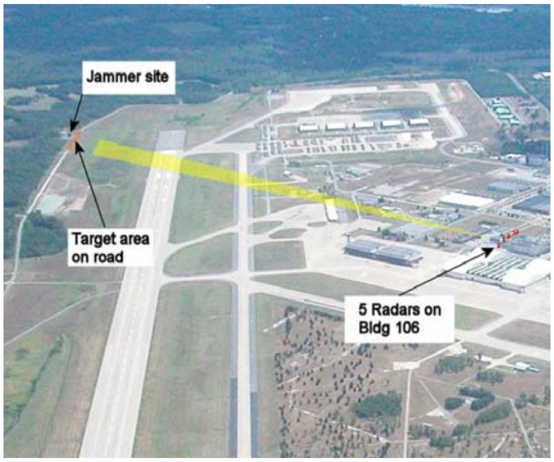
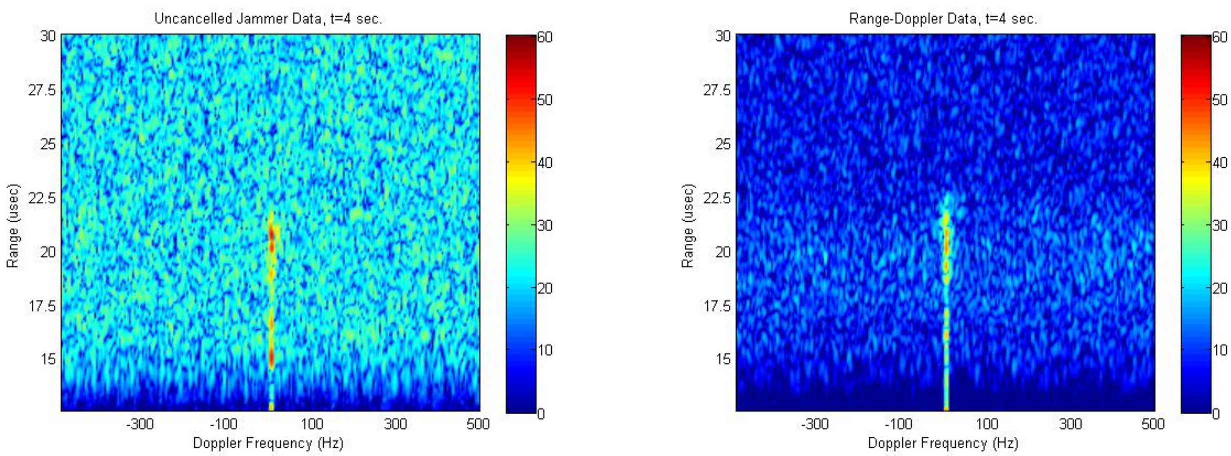


Figure 2: DAR Test Geometry

multi-waveform processing, jammer cancellation occurred along with target detection. Figure 3 presents a flick run of the jammer scene (left side) along side the cancelled jammer scene (right side). The frame rate is 2 seconds with each of the range Doppler frame plots recorded over a 256 millisecond interval at a 1kilohertz rate. Note the appearance and fading of the target as it moves through the lobe structure of the sub-aperture antenna. The target is quite visible when it is located at the 10 through 16 second positions.

t = 4 seconds



t = 6 seconds

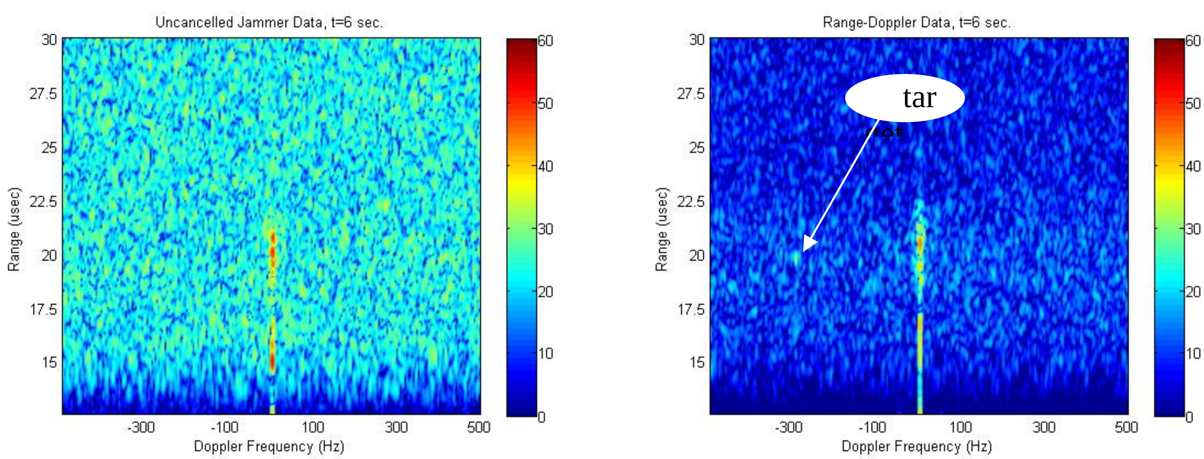
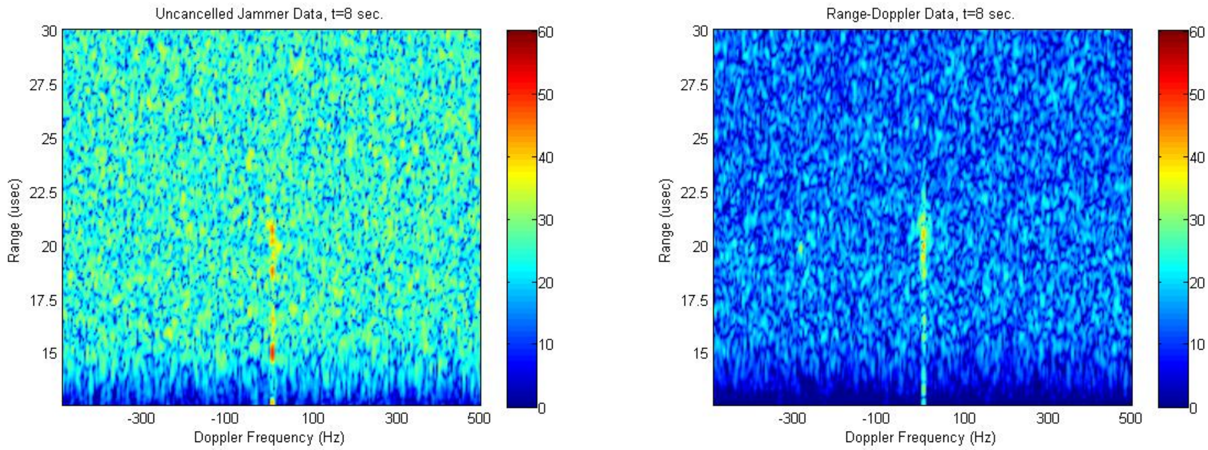
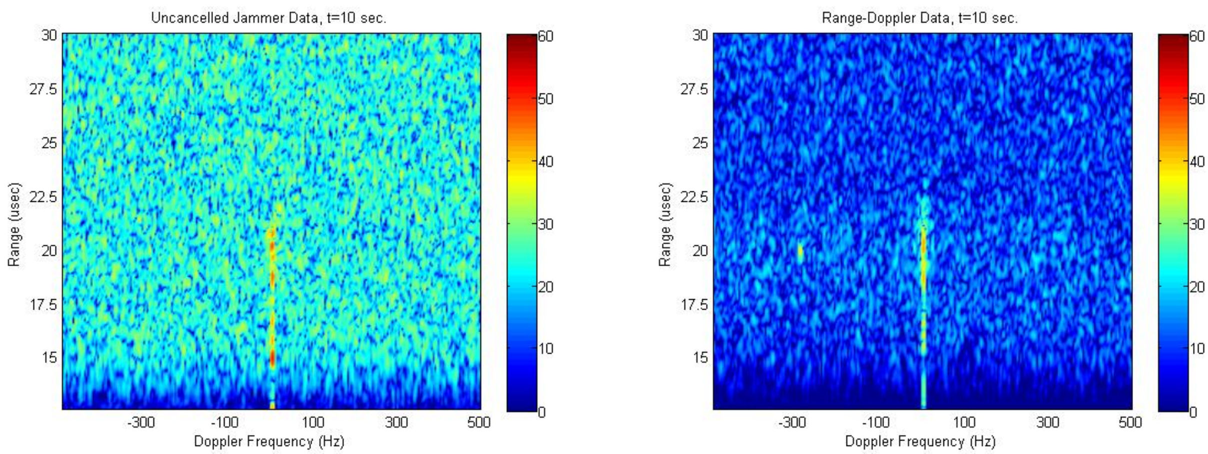


Figure 3. Flick Run of Jammer (left) and Cancelled Jammer Range/Doppler Scene (continued on next page.)

t =8 seconds



t =10 seconds



t = 12 seconds

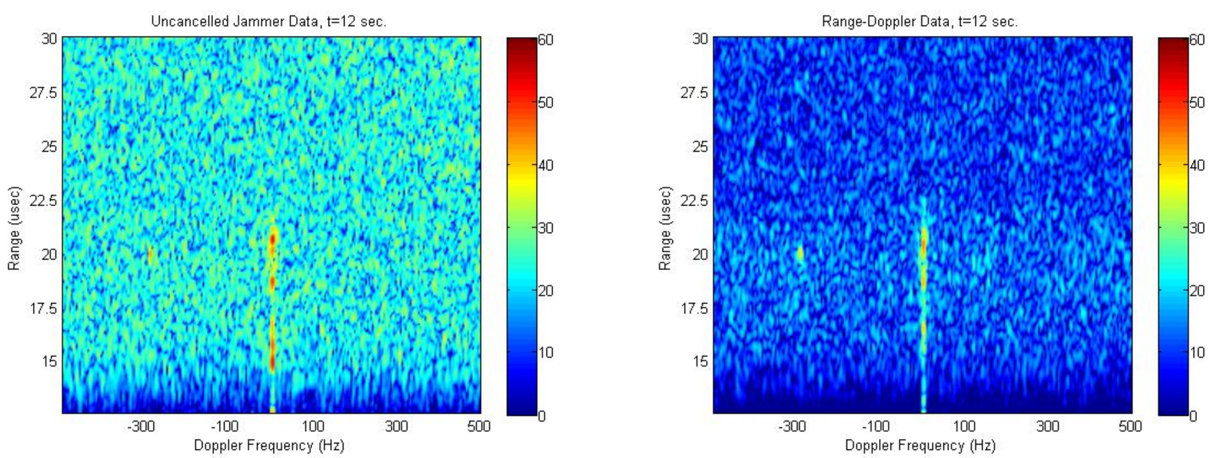
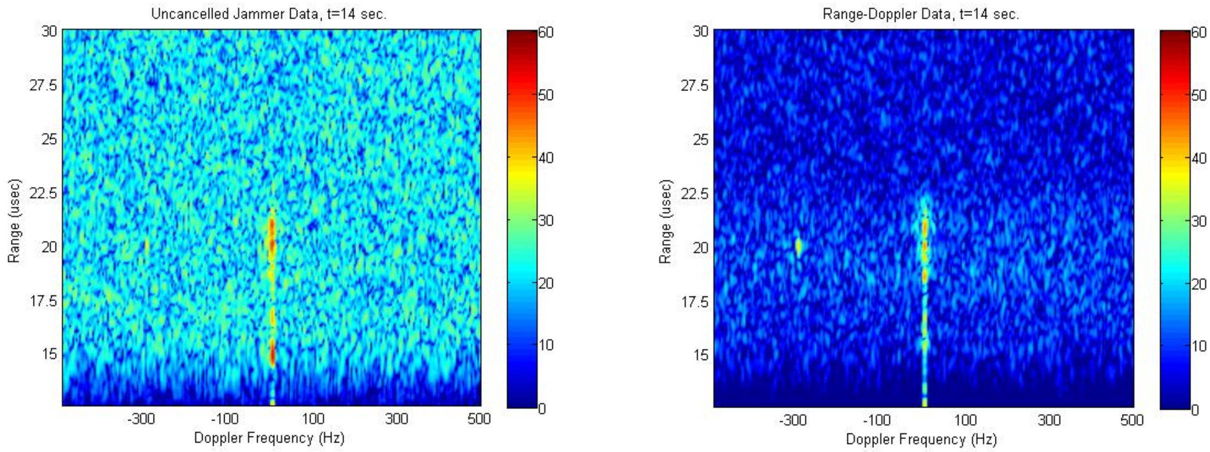
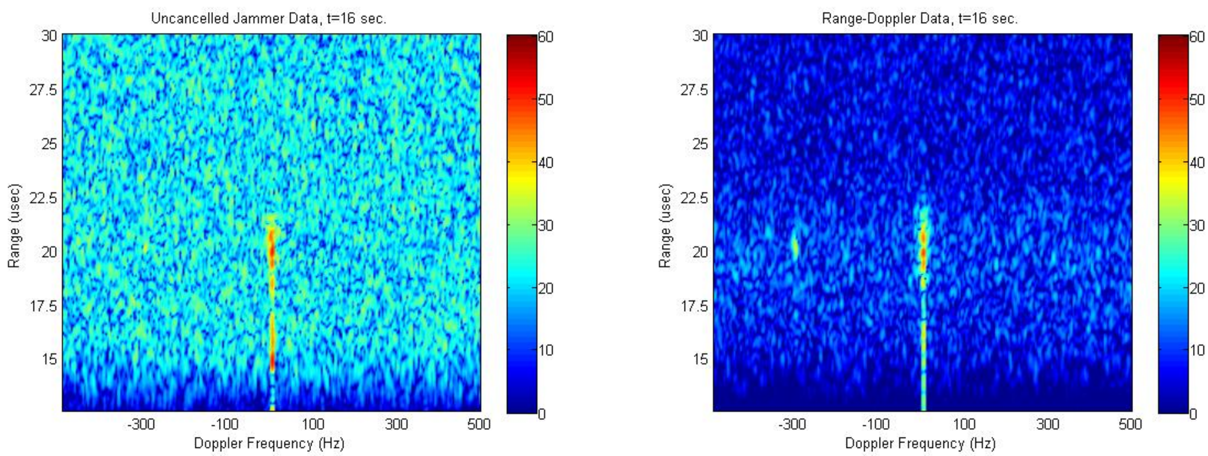


Figure 3. Flick Run of Jammer (left) and Cancelled Jammer Range/Doppler Scene (continued on next page.)

t = 14 seconds



t = 16 seconds



t = 18 seconds

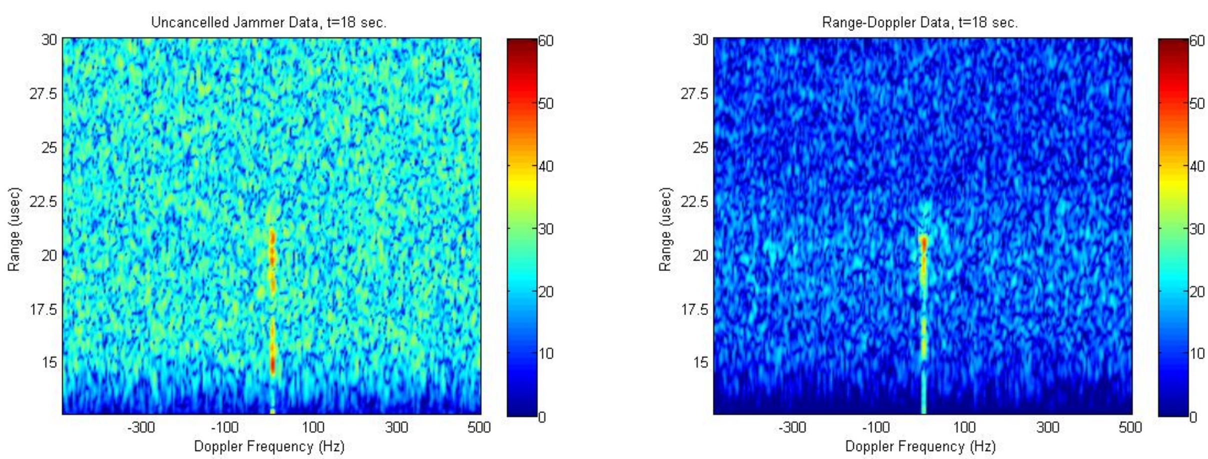


Figure 3. Flick Run of Jammer (left) and Cancelled Jammer Range/Doppler Scene

Data was collected and adaptively processed as the target vehicle traveled along a course that brought it past the jammer. Figure 4 shows the post processing SNR as the target traversed from -10 to +10 milliradians with respect to the jammer direction. Note that the SNR decreases significantly when the target and jammer are in the same direction. Had the sampling interval been smaller than 0.3 milliradians, the null may have been deeper.

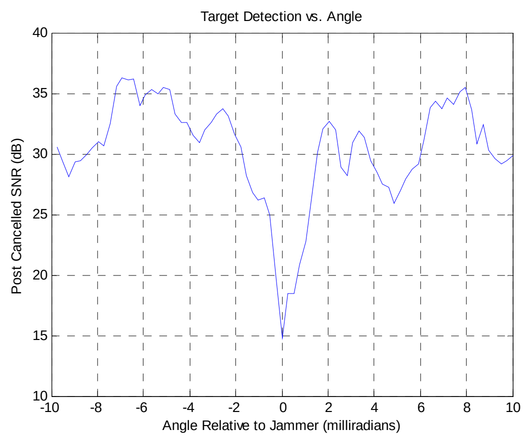


Figure 4: Post Cancellation SNR of Target Direction with respect to Jammer

2.3 Exo-Atmospheric Volume Clutter – Simulation

Our simulation was extended to model exo-atmospheric clutter in addition to jamming. The simulation generates an individual scatterer model that keeps track of particle position and velocity as a function of time. These scatterers are range gated and parsed out of the scatterer cloud. Ranges are then calculated for a set of spatially diverse sub-apertures each transmitting an orthogonal waveform relative to each other. Each sub-aperture however receives each transmitted waveform. Therefore assuming N_a sub-apertures there are $N_a^{\ 2}$ different mono-static and bi-static radar combinations (N_a mono-static radars and $N_a^{\ 2}–N_a$ bi-static radars). The range and frequency information are then used to calculate phase difference values for each of the $N_a^{\ 2}$ radars.

Figures 5 and 6 represent initial scatterer velocities that are normally distributed. The result of this scenario is a spherical cloud of dipole radiators.

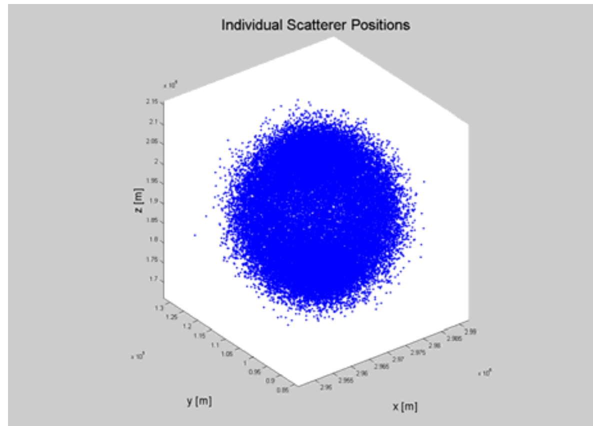


Figure 5: Individual Scatterer Positions Starting from Initial Velocities that Are Normally Distributed

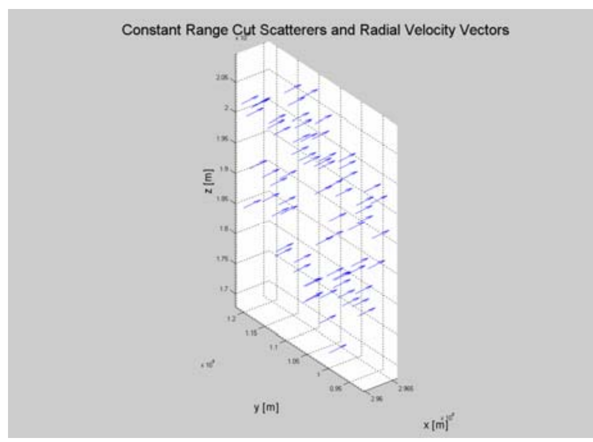


Figure 6: Quiver Plot of Range Gated Scatterers and their Velocities

The next plot, Figure 7, represents the range gated scatterers that were parsed out from a cloud of scatters that contains over 4 million individual scatterers (that is, those scatterers in the same range bin as the target of interest). There are approximately 25 hundred individuals in the parsed set. The parsed data is then used to calculate the phase differences between the scatterer returns at each aperture relative to each other aperture. The result is represented by a $N_a \times N_a$ matrix.

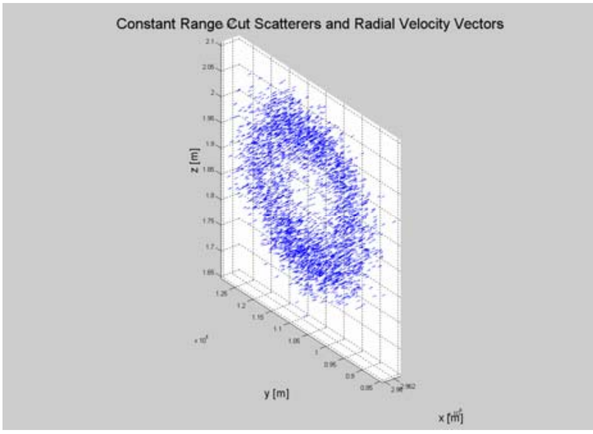


Figure 7: Range Gated Scatterers Parsed out of a Cloud of 4 Million Individual Scatterers.

3.0 Multi-Static Imaging

3.1 Analysis and Simulation

The resolution of a SAR or ISAR image is a function of how much of the Fourier space the measurements sample. The bandwidth of the ISAR measurement transforms to the radius in two-dimensional Fourier space. Bi-static measurements are more complex with the transform of the frequency being a function of that bandwidth and of the bi-static angle. Figure 8 shows the Fourier sampling for three sensors (two radars operating both mono-statically and bi-statically). The aqua and blue sectors are the Fourier sampling for

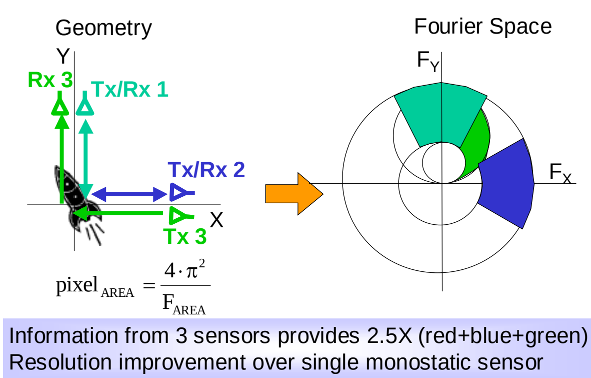


Figure 8: Multi-Static Imaging

the mono-static operation of these two radars. The green sector represents the bi-static sampling. For this geometry (ISAR images as the target flies through the field of view of two radars separated by 90^o, with 50% bandwidth) the combined multi-static image would have a resolution 2.5 times better than a single mono-static image.

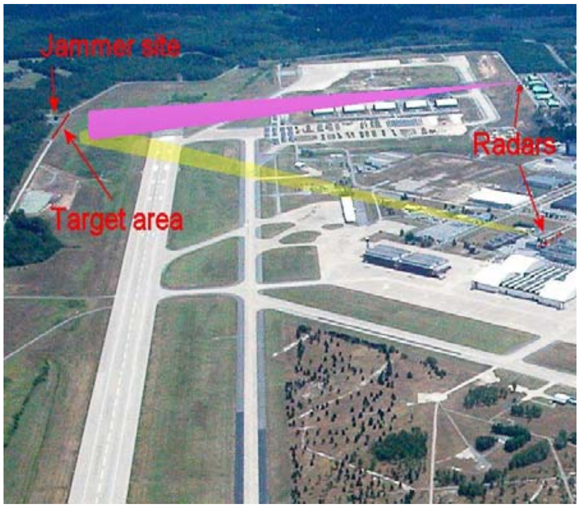
3.2 Rooftop Experiment

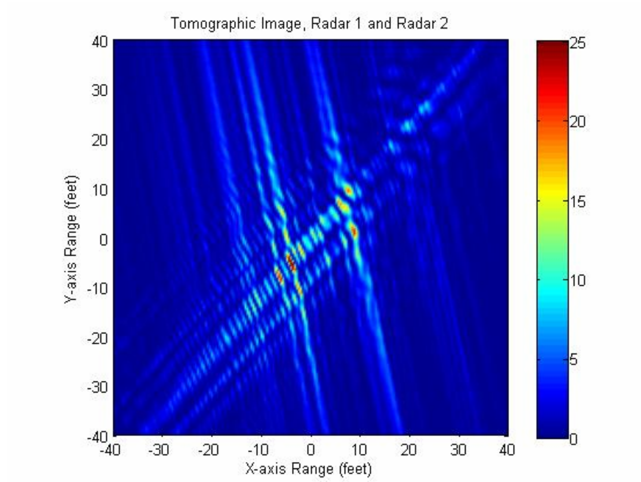
This experiment was also performed at the Air Force Research Laboratory, Rome Site, in Rome NY. The site layout is shown in Figure 9, with the radars shown on the right and the target area (Jammer site) shown on the left of the figure. The radar path shown in yellow indicates the target aspect from the first sub-aperture, and the path shown in violet indicates the target aspect from second sub-aperture.

Each radar was equipped with programmable waveform generators, frequency conversion equipment, timing and coherent local oscillators based on GPS receivers, as well as data recording servers with storage, processing, and display capability. A vehicle with two dominant scatterers was driven along the road in the target area. The objective of the experiment was to demonstrate an improvement in radar imaging capability by using data from both radars compared to mono-static data from a single radar. Imaging results are also presented in Figure 9.

3.3 Ongoing Space Object Imaging Experiment

An experiment is underway to further validate the multi-static imaging simulation (Figure 10). Two widely separated radars will track and image a space object (RadarSat or similar).





Coherent image for the test target consisted of two large scatterers on a vehicle that was driven through the radars field-of-view

Figure 9: Coherent Fusion Imaging Experiment

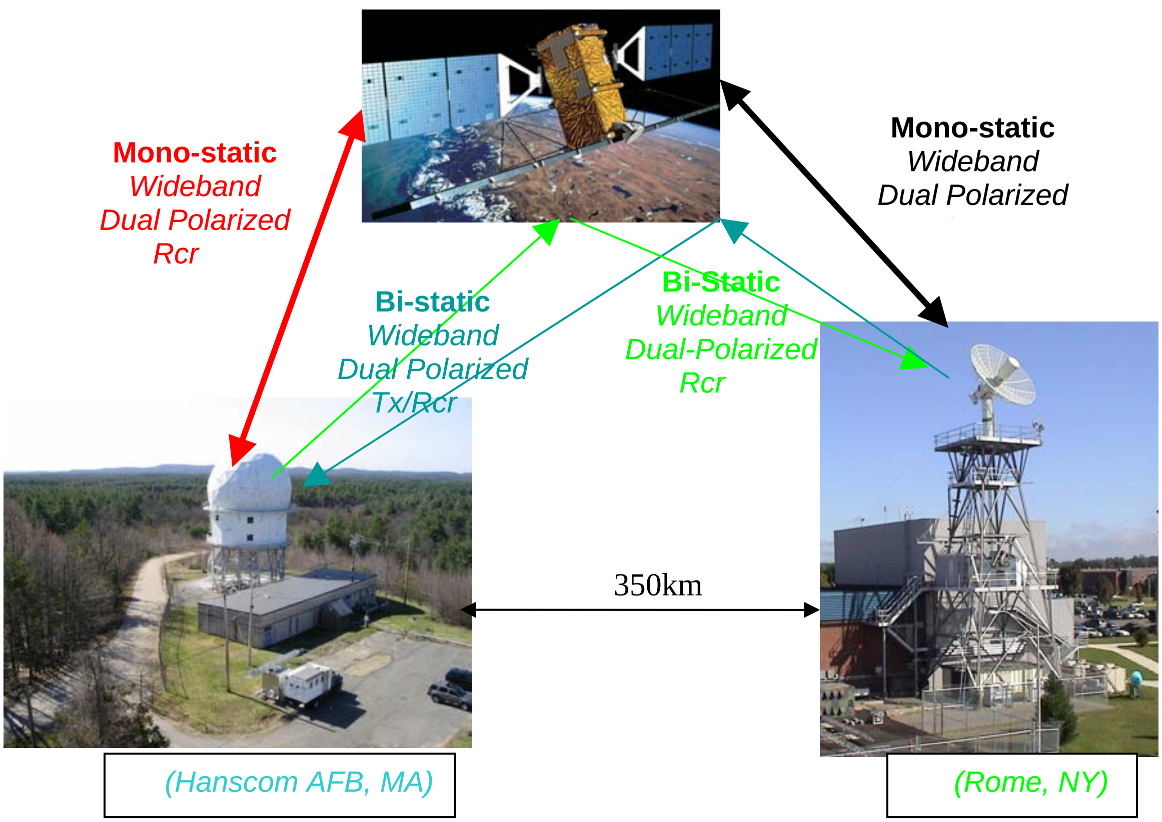


Figure 10: Planned Phase II: Fusion Experiment, Multi-Static Space Object Imaging

4.0 Summary

Compared to conventional radars, multi-static radars have the potential to provide significantly improved interference-rejection, tracking and discrimination performance in severe EMI and clutter environments.

They can potentially provide significantly improved target tracking accuracy because of the large baseline between the various apertures. The resulting angular resolution can be orders of magnitude better than the resolution of a monolithic system (single large radar). The same angular resolution can provide improved interference rejection. For example, a DAR system with apertures distributed over a couple of kilometers can detect a target at 2000 kilometers in the presence of an interfering source that is just 100 meters away.

Two dimensional images of moving targets can be obtained through inverse synthetic aperture radar processing. Coherent fusion processing of the data from multiple radars can provide improved resolution. Also, two or more radars viewing an object from different angles not in its plane of motion can provide three-dimension images.