DEVELOPMENT OF A FOLDED COMPACT RANGE AND ITS APPLICATION IN PERFORMING COHERENT CHANGE DETECTION AND INTERFEROMETRIC ISAR MEASUREMENTS

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Abstract

A folded compact range configuration has been developed at the Sandia National Laboratories' compact range antenna and radar-cross-section measurement facility as a means of performing indoor, environmentally-controlled, far-field simulations of synthetic aperture radar (SAR) measurements of distributed target samples (i.e., gravel, sand, etc.). In particular, the folded compact range configuration has been used to perform both highly sensitive coherent change detection (CCD) measurements and interferometric inverse-synthetic-aperture-radar (IFSAR) measurements, which, in addition to the two-dimensional spatial resolution afforded by typical ISAR processing, provides resolution of the relative height of targets with accuracies on the order of a wavelength. This paper describes the development of the folded compact range, as well as the coherent change detection and interferometric measurements that have been made with the system. The measurements have been very successful, and have demonstrated not only the viability of the folded compact range concept in simulating SAR CCD and interferometric SAR (IFSAR) measurements, but also its usefulness as a tool in the research and development of SAR CCD and IFSAR image generation and measurement methodologies.

Keywords: Compact Range, RCS Measurements, Coherent Change Detection, Interferometry

1. INTRODUCTION

Sandia National Laboratories (SNL) is a forerunner in the development of high resolution synthetic aperture radars, and currently deploys SAR sensors which generate real-time images having sub-meter resolutions on a variety of airborne platforms. The folded compact range configuration has been developed at SNL in support of this mission, and is operated in such a manner as to simulate either a repeat pass coherent change detection (CCD) or an interferometric measurement system.

The objective in forming CCD images is to assess how a particular target area has decorrelated with the passing of time. Therefore, the formation of a CCD image requires that a pair of two-dimensional, complex images of a particular target be obtained using identical (or nearly so) imaging geometries for each of the complex, temporally separated measurements. Similarly, interferometric images for a repeat-pass SAR measurement system are also formed from a pair of two-dimensional complex images, but in this case the imaging geometries for the two measurements must be spatially separated, while the temporal separation between the measurements is minimized. In both cases, the final CCD or IFSAR image is formed by correlating the two complex, two-dimensional images in some fashion.

In the SNL folded compact range, complex images of the distributed target samples are created by performing wideband stepped-frequency measurements while rotating the target over an appropriate angular sector. The measured raw data is then calibrated, following which conventional signal processing is used to form focused, two-dimensional inverse synthetic aperture radar (ISAR) images of the backscattered return from the distributed target. This results in data which is equivalent to that which can be acquired with a circular spotlight-mode SAR [1]. The major advantage of using a compact range facility to perform CCD or interferometric measurements is the ability to control to a much larger extent the physical phenomena which influence decorrelation of a pair of complex SAR images, thus allowing various decorrelation sources to be isolated and independently investigated.

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2. FOLDED COMPACT RANGE CONFIGURATION

The SNL compact range antenna and RCS measurement facility is fundamentally configured as a prime-focus fed, single parabolic reflector system. This system can be operated in an inverse synthetic aperture radar (ISAR) mode, in which objects are simultaneously rotated and irradiated with a uniform plane wave over a relatively wide bandwidth of frequencies, following which signal processing is used to form two-dimensional radar images of the illuminated target. Due to the fact that data identical to that acquired with a circular spotlight SAR can be obtained by equivalent ISAR processing [1], it was conjectured that this system could also be used to perform indoor, environmentally-controlled, far-field simulations of SAR CCD and interferometric measurements. The intent of this section is to discuss how this was accomplished.

The compact range quiet zone is nominally centered approximately 13 feet above floor level. This location is rather inconvenient for mounting distributed targets (soil, gravel, etc.) for the purposes of making backscatter measurements; however, by placing a secondary planar reflector into the quiet zone of the compact range to redirect the collimated EM field from the parabolic reflector onto a sample holder placed at ground level, a "folded" compact range can be created that simulates a uniform plane wave over a region of space at ground level that is large enough to allow reasonably-sized samples (~6 feet in extent) to be measured.

The first order of business in creating the folded compact range, then, was to obtain a "flat plate" large enough to provide for a sample area at ground level roughly equivalent to the nominal quiet zone size of the compact range. This necessitated a planar reflector having dimensions substantially larger than the size of the specified compact range quiet zone (2 m x 2 m) in order to insure that the collimated field from the parabolic reflector was adequately intercepted and redirected toward the sample area. Furthermore, this planar reflector was required to satisfy stringent requirements for surface tolerance and accuracy. Surface quality criteria for compact range collimating reflectors in general are: surface deviation ≤ 0.007λ, surface gaps < λ/20 [2].

Applying these same criteria to the desired secondary planar reflector at 12 GHz would require a flat, conductive surface with a tolerance of less than 0.007" and with gaps no larger than 0.05". It was quickly realized that it would be prohibitively expensive to have such a large flat surface manufactured to such a high degree of accuracy that would also withstand the rigors of being handled and moved about.

In seeking for alternative solutions to this problem, it was discovered that the SNL Solar Thermal Test Facility (STTF) was nearing the completion of a series of tests on a multi-faceted stretched-membrane dish concentrator. Each facet of the dish concentrator is comprised of two 0.003 inch thick stainless steel membranes stretched over each side of a metal ring. The membranes are tensioned to 20,000 pounds per square inch and have a nominally flat, planar surface. The front membrane is laminated with a silverized polymer film to form an optically-reflective surface [3]. The facets are thus nearly ideal for use as the secondary planar reflector, and upon completion of solar testing, the STTF was willing to let one of the facets be used in the compact range.

An economical and readily-available distributed target sample holder was embodied as a cattle trough having an 8 foot diameter and 24 inch depth that could be purchased through a local hardware store. In order to attenuate undesired extraneous backscatter from the trough which could perturb the scattered signal from the test target, the trough was lined with microwave absorbing materials on all inner and outer surfaces.

In order to insure that the sample holder was properly illuminated by the incident electromagnetic field from the secondary reflector, it was of course necessary to geometrically align the planar solar facet with the existing features of the compact range. The planar reflector was initially oriented at an angle of 18° relative to vertical, resulting in a simulated look angle of 36° for the electromagnetic field incident upon the sample holder, and a distance from the center of the solar facet to the center of the sample holder of approximately 16.7 feet. Microwave absorbing material was applied to the edges of the solar facet in an attempt to create a simulated serrated edge, in hopes that diffracted energy from the edges of the facet could be attenuated and/or diverted away from the sample area.

Prior to placing the sample holder in the compact range, a "field probe" was placed at the position in the compact
range at which the sample holder would be located to measure the amplitude and phase of the electromagnetic field scattered from the solar facet at the location of the sample holder so that the field irradiating the sample could be accurately characterized. The field was measured at 8, 10, and 12 GHz for both vertical and horizontal polarizations. Plots of the measured amplitude and phase of the vertically-polarized incident field at 12 GHz are shown in Figure 2. These plots are representative of the data recorded at the other frequencies and polarizations.

The plots show the field scattered from the solar facet at the desired location of the sample holder to be a reasonable approximation of a uniform plane wave. Despite the fact that the edges of the facet were treated with absorbing material, the amplitude and phase ripple evident in the plots is believed to principally be due to diffracted energy from the edges of the solar facet entering the sample area.

From analysis of the measured field-probe data it can be determined that over a 6 foot region in the sample area (±36 inches about the sample area center) the incident electromagnetic field has the following properties: phase ripple = ±30°; amplitude ripple = ±3 dB; amplitude taper = 0 dB.

While these values are significantly degraded from the field properties specified for the quiet zone of the compact range, thus precluding use of this range configuration for highly accurate absolute radar-cross-section measurements, it is nevertheless quite adequate for use in measuring or detecting changes in backscattering levels. Photographs of the final range configuration are shown in Figure 3.

3.0 CCD IMAGE FORMATION

As previously mentioned, the formation of a coherent change detection (CCD) image first requires that a pair of two-dimensional, complex images be generated, following which the images are compared or correlated in some fashion to form the final CCD image. Fundamentally, decorrelation which occurs between a pair of two-dimensional radar cross section images is a consequence of any differences that may exist in the amplitude and phase values between the images. Thus, a CCD image displays not only decorrelation resulting from changes to the target, but from all other sources as well. In the case of an airborne SAR platform, decorrelation could occur as a result of several factors in addition to physical changes in the target area during the period of time between observations, including noise (thermally generated or otherwise), uncompensated motion of the SAR platform, variations in the viewing geometry due to alteration of the spatial location of the SAR platform between observations, image registration errors, calibration errors, etc. [4].

The primary advantage of using a compact range facility to perform CCD measurements is thus the ability to control superfluous sources of decorrelation, including holding the spatial location of the target relative to the radar sensor constant between target measurements, such that by far the most significant source of decorrelation appearing in the processed CCD images is due to the purposeful disturbing of the target sample, which allows the contributors to temporal decorrelation to be independently studied.

Decorrelation detection of two complex images is accomplished using the maximum likelihood estimate of correlation algorithm [4], given by

$$\gamma = \frac{\sum_{i} \sum_{j} g_{ij}^* h_{ij}}{\sqrt{\sum_{i} \sum_{j} |g_{ij}|^2 \cdot \sum_{i} \sum_{j} |h_{ij}|^2}}$$  (1)

where

- $g_{ij}$ = the first registered complex image for the $i^{th}$ range index and the $j^{th}$ azimuth index;
- $h_{ij}$ = the second registered complex image for the $i^{th}$ range index and the $j^{th}$ azimuth index.

The summations are over the number of "looks" or pixel samples used in range and azimuth for the estimation. A more detailed explanation of this algorithm is given in [5] and [6], but essentially it is designed to perform an optimal estimation of the magnitude of the normalized correlation of two images, and is very similar to the coefficient of correlation as given in standard texts on communication theory [7].

An image produced using the maximum likelihood estimate of correlation method is given in Figure 4, and
indicates the high level of sensitivity of the measurement system to very small disturbances in the target, as well as the power of performing coherent measurements.

4. INTERFEROMETRIC MEASUREMENT METHODOLOGY

Synthetic aperture radars have long been used to form two-dimensional images of terrain, etc., in which the down-range and cross-range resolutions of images are respectively dictated by the bandwidth of the radar and the length of the synthesized antenna aperture. A more recent innovation has led to the ability to resolve the third dimension, or height, of these digitally-created images, and is typically referred to as "interferometric synthetic aperture radar" (commonly referred to as either INSAR or IFSAR in the literature [4],[8],[9]). IFSAR techniques for the purpose of obtaining high resolution digital elevation maps have been investigated and successfully demonstrated by several researchers [4],[8],[9],[10],[11]. The basic operating principle of an IFSAR is that a radar interferometer may be formed by spatially separating two antennas. Backscattered signals are coherently measured at both antennas, and because of the slight difference in imaging geometry, a small phase difference will exist in the images created by the signals that are received and processed. The magnitude of the phase difference is dependent upon the height of the object or terrain being imaged. Due to the fact that the phase difference is measured relative to the wavelength of the received waveform, the height measurements can be accurate on the order of the radar wavelength.

A primary determinant in accurately assessing the phase difference in an interferometric image is the correlation properties of the backscattered return. Lack of correlation between the backscattered returns for two different observations leads to an increase in the standard deviation of measured phase difference values, ultimately resulting in uncertainty in the height measurements. Thus, the utility of using a compact range to quantify the deleterious effects of such decorrelation becomes readily evident.

The spatial diversity necessary to create an interferometric image in the compact range can be obtained by offsetting the elevation axis of the sample holder between measurements of the target. This can be understood from the Figure 1.

![Figure 1. Diagram of Compact Range Interferometric Measurement Setup.](image-url)

For the purposes of this study, a flat phase front normal to the direction of propagation is assumed. The phase difference between the scattered return from point scatterers located at \( r_1 \) and \( r_2 \) is given by

\[
\phi = \frac{4\pi}{\lambda} (r_1 - r_2).
\]

(2)

From the diagram it can be seen that

\[
r_f = r_1 + b = r_0 + \rho \cos(\psi + \delta)
\]

(3)

\[
r_f = r_0 + a = r_0 + \rho \cos(\psi + \delta + \alpha)
\]

(4)

where is the tilt of the elevation axis of the turntable between "passes." Therefore,

\[
\Delta r_f = r_1 - r_2
\]

(5)

Assuming that is small, \( \Delta r_f \) can be approximated as

\[
\Delta r_f \approx \rho \alpha \sin(\psi + \delta).
\]

(6)

From the figure, it can also be seen that the cross-boresight distance (c) to the target is given by

\[
c = \rho \sin(\psi + \delta)
\]

(7)

and

\[
c = r_1 \sin \theta,
\]

(8)

such that

\[
r_1 \sin \theta \approx \frac{\Delta r_f}{\alpha}.
\]

(9)

Similarly, the distance to the target along the boresight direction is found to be
5. REFERENCES


Figure 2. Measured Relative Magnitude And Phase Of Vertically-Polarized Electromagnetic Field Incident upon the Sample Area at 12 GHz. Orientation of the Field Probe is Parallel to the Surface of the Solar Facet ("Cross-Range Cut").

Figure 3. Photographs of Compact Range Configuration Used to Perform CCD Measurements.

Figure 4. CCD Image of Footsteps in Gravel.

Figure 5. Interferometric Image of Sand Berm.
Figure 6. Interferometric Image of Sand Berm.