The Effect of Ionospheric Scintillation on Phase Gradient Autofocus Processing of Synthetic Aperture Radar

Dennis L. Knepp[1] and *Keith M. Groves*[2]
[1] NorthWest Research Associates, 301 Webster St., Monterey CA 93940, dennis.knepp@nwra.com
[2] Air Force Research Laboratory, Hanscom AFB, Boston, MA 01731, Keith.Groves@hanscom.af.mil

Abstract

Depending on the transmission frequency and signal bandwidth, space based synthetic aperture radar (SAR) may be impacted by disturbances caused by small-scale structured ionization. This paper considers the effects of scintillation (variations in amplitude and phase) on a narrow band SAR that utilizes the phase-gradient autofocus (PGA) method that attempts to compensate for the effects of phase errors across the synthetic aperture.

We develop a simulation of SAR/PGA processing that is applied to several simple "scenes" consisting of scatterers that are combinations of straight lines and circles. The multiple phase screen (MPS) technique is used to model the effects of amplitude and phase scintillation for a SAR operating in the equatorial region. Here we assume that the Fresnel zone in the ionosphere is on the same order or larger than the maximum separation of lines-of-sight from any point on the aperture to all points on the scene to be imaged (this is referred to as the small target assumption).

It is well known that the degradation in SAR imaging performance is a function of the ratio of the synthetic aperture length to the decorrelation distance of the ionospheric propagation channel. In general if the decorrelation distance is small relative to the required SAR aperture length, scintillation will degrade SAR imaging performance. We use Monte-Carlo simulations involving many MPS calculations with similar statistics to quantify this relationship and to investigate the effect of realistic combined amplitude and phase scintillation on autofocus compensation.

Examples are presented of the performance of spotlight-mode SAR/PGA for values of the decorrelation distance and scintillation index that represent natural ionospheric scintillation at UHF. Quantitative results are given for SAR performance in terms of the rms spread of the SAR image of a hypothetical isolated point target in the scene.

1 Introduction

A space based synthetic aperture radar (SAR) achieves high resolution images of objects on the earth's surface by moving a single relatively small antenna over a large linear distance, creating a large synthetic aperture with resulting improved angular resolution. A number of experimental and operational spacecraft have been flown over the last 20 years operating at frequencies from L-band (1.25 GHz) through X-band. Lower frequencies (300 MHz) are presently being considered since these signals are able to penetrate vegetation canopies, glaciers, sea-ice and soil. The effects of small-scale ionization irregularities are important for SAR frequencies from VHF through L-band. Reference [1] discusses these topics and describes the use of measurement of TEC variation to characterize small-scale ionization and predict the defocusing of a SAR with a linear aperture of 5 km. A recent paper describes a phase screen approach similar to that applied here to model the effects of scintillation on SAR [2].

Narrow-band scintillation is well described by multiple phase screen propagation techniques wherein a phase changing screen represents the basic interaction between the ionosphere and the propagating EM wave. As the wave propagates diffraction causes interference between points on the wavefront and converts phase scintillation into amplitude scintillation. Under these conditions, we show that the PGA technique can improve SAR imaging performance.

PGA was developed to account for unknown (generally small) deviations in the position of the individual points or locations comprising the synthetic aperture [3]. Each location across the aperture may be displaced by an independent spatial deviation that causes phase deviations in the received signal. In PGA, there are many range measurements recorded at a single cross-range location. Therefore all measurements at a single aperture location experience the same phase deviation. This geometry applies to spotlight-mode SAR where the aperture is focused on a single patch on the ground represented by range and cross-range as seen from the SAR.

978-1-4244-6051-9/11/$26.00

If the satellite is in an equatorial orbit and the target is small, then the phase variations caused by field-aligned irregularites should resemble the phase variations that are well-compensated by PGA. However, the amplitude variations are not considered by PGA and their presence may be problematic. The ability of PGA to compensate for scintillation also depends on the exact implementation of the PGA algorithm and on the details of the observed scene. In this work we consider a simple artificial scene consisting of straight lines and circles comprised of omnidirectional point scatters of user-chosen RCS. We apply the PGA algorithm to investigate the performance of SAR/PGA. Results are presented for the compensated images and for the spread of a hypothetical point target in the scene before and after application of PGA.

2 SAR geometry and simulation

Fig. 1 shows the central region of the original scene. The original scene consists of a grid of 300 cross-range points over a distance of 10 km with 240 points in range over a distance of 10 km. The range and cross-range point spacing is not equal. The larger of the two circles has a radius of 800 m. The smaller circle has a radius of 400 m. The lines have relative RCS of 1 and 3 dB. The larger circle has relative RCS of 16 dB and the smaller circle has relative RCS of 18 dB. The peak signal-to-noise ratio is large here so that noise plays little roll in the results.

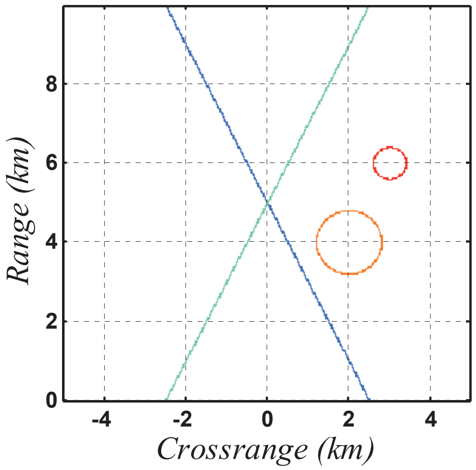

Figure 1. Original scene. See Fig. 4 for the color scale for all figures.

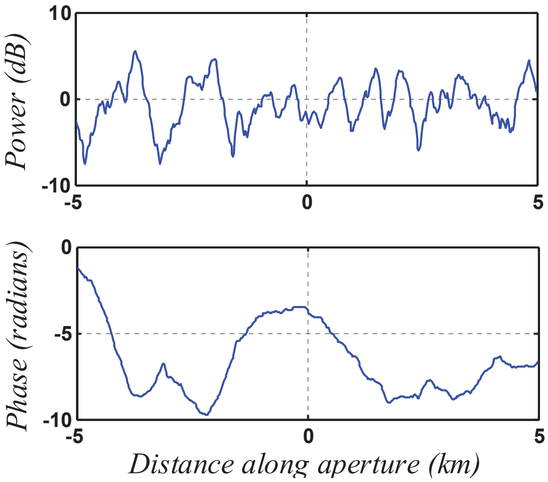

Figure 2. Amplitude and phase along the aperture.

Figs. 2-4 show examples from a single MPS realization where $S_4 = 0.5$ of SAR/PGA performance. Fig. 2 shows the amplitude and phase along the aperture of the contribution of the signal due solely to ionospheric scintillation. The SAR consists of an aperture of 512 phase-centers over a total length of 10 km. The slant range to the SAR is 500 km and the transmission frequency is 400 MHz. PGA automatically identifies point targets in the image, isolates them, and averages over range to estimate the actual phase error across the aperture [3]. This estimate is subtracted from the measured phase in an iterative process to remove the error. Figs. 3 and 4 show portions of the reconstructed SAR images prior to the application of PGA (Fig. 3) and after the second iteration (Fig. 4). In Fig. 3 the scintillation severely distorts the image. In Fig. 4 the compensated image is significantly improved with respect to the uncompensated image in Fig. 3.

Many MPS realizations of the ionospheric transfer function can be generated separately and used as a Monte-Carlo data base to evaluate PGA performance. We also measure the signal decorrelation distance for each realization and find the average. Then we spatially resample the realization as desired to simulate various values of the ratio of the signal decorrelation distance to the SAR length. For the example above, the ratio of the signal decorrelation distance to the SAR length is 0.05. All the MPS realizations in this work are generated using a single phase screen of length 100 km (2^{17} points), a q^{-3} power spectrum for the phase, an outer scale of 5 km and an inner scale of 10 m [4]. The

100 realizations therefore resemble actual signals received after ionospheric propagation.

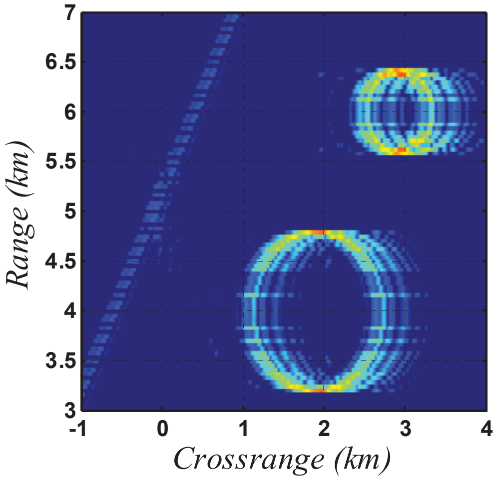

Figure 3. Incompensated image.

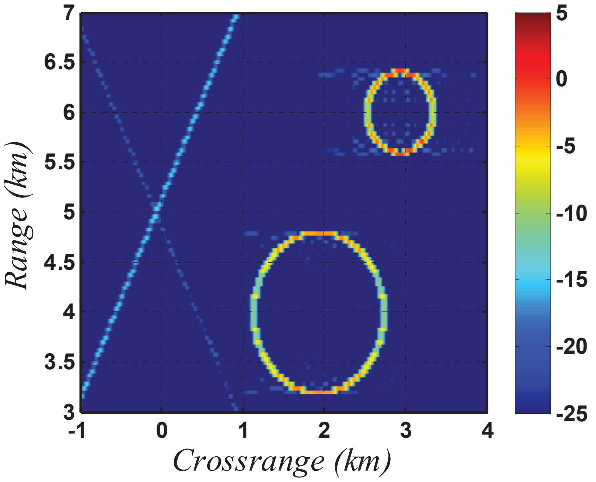

Figure 4. Compensated image after iteration 2.

3 Results

One method to quantify the degradation in the SAR image is to consider a hypothetical point target in the SAR scene. The image of this point target is found using identical processing algorithms as used in the SAR processing. With perfect processing, the image would be a point target (i.e., a delta function) as a function of distance along the reconstructed scene. In fact, the reconstructed image is limited by the finite window, the use of any smoothing filters, the finite number of samples, and any interpolation used to obtain the image. One can measure the rms spread with respect to distance of this undisturbed image. Then calculate the rms spread of a hypothetical point target for the case where amplitude and phase fluctuations exist and are uncompensated, and for the case that the PGA compensation algorithm is applied. The ratio of the disturbed to the undisturbed spread (normalized spread) is a quantitative measure of imaging performance.

Fig. 5 shows the normalized rms spread as a function of the ratio of signal decorrelation distance to the SAR length for the case that S_4 is 0.5. Three curves are shown. “Iteration 0” (red) refers to the normalized spread for the case of no application of PGA. That is, the red curve shows the effect of ionospheric scintillation that spreads the image. “Iteration 1” gives the normalized spread after the first PGA iteration and “Iteration 2” gives the spread after the second PGA iteration. Each point on these averaged curves is obtained by applying SAR/PGA processing to 100 MPS calculations, all with the same statistical description of the ionosphere. For the cases shown with $S_4 = 0.5$, the rms spread is large when the signal decorrelation distance is much smaller than the synthetic aperture length and PGA reduces the spread and improves the image. At the other extreme, when the decorrelation distance is large, there is no degradation in the spread in the uncompensated SAR image (red curve). Our application of PGA in this case actually causes a small increase in the rms spread and consequently a decrease in imaging performance.

Figs. 6 and 7 show the normalized rms spread as a function of S_4 for values of the ratio of the signal decorrelation distance to the aperture length of 0.1 and 0.2, respectively. In Fig. 6, imaging is severely degraded for all values of S_4. For a length ratio of 0.2, the image degradation (as measured by the rms spread) is fairly constant for the entire range of scattering severity.

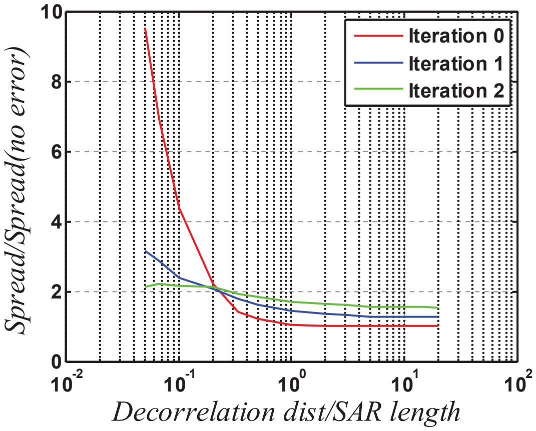

Figure 5. RMS spread for $S_4 = 0.5$.

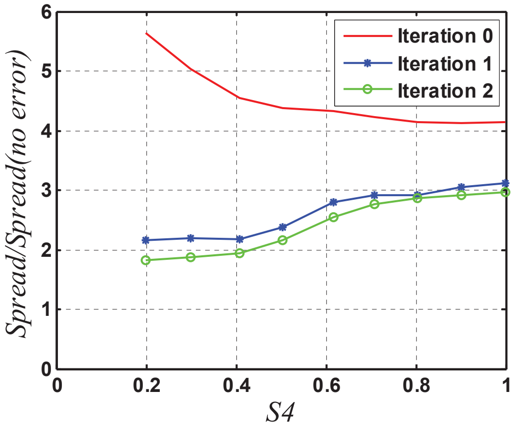

Figure 6. RMS spread for a length ratio of 0.1.

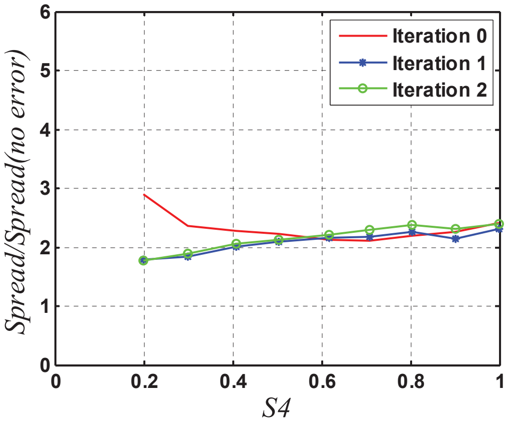

Figure 7. RMS spread for a length ratio of 0.2.

4 Conclusion

This work considers the performance during scintillation of the PGA algorithm used in SAR processing. It appears that application of PGA can improve SAR imaging performance over the entire range of values of scintillation index, especially for the case that the decorrelation distance is small with respect to the aperture length.

5 References

1. M. van de Kamp, P. S. Cannon, and M. Terkildsen, "Effect of the ionosphere on defocusing of space-based radars," *Radio Science,* Vol. 44, RS1003, doi:10.1029/2007RS003808, 2009.

2. C. S. Carrano, K. M. Groves, and R. G. Caton, "A phase screen simulator for predicting the impact of small-scale ionospheric structure on SAR image formation and interferometry," IGARSS, 2010.

3. C. V. Jakowatz, D. E. Wahl, P. H. Eichel, D. C. Ghiglia, and P. A. Thompson, *Spotlight-mode synthetic aperture radar: a signal processing approach*, Springer, New York, 1996.

4. D. L. Knepp and L. J. Nickisch, "Multiple phase screen calculation of wide bandwidth propagation," *Radio Science,* Vol. 44, RS0A09, 11 pp., 2009, doi:10.1029/2008RS004054.