Scatterometer Resolution Enhancement

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Abstract– Scatterometers can be effective for large scale monitoring of the Earth's surface. However, their low resolution can limit the utility of the data. Thus, there is interest in resolution enhancement methods that can create high resolution imagery from scatterometer measurements. In this paper, a brief review of an iterative image reconstruction is presented, and the implications of this theory for enhanced resolution scatterometer imaging is presented. The result is that the multipass sample spacing is the single largest limiting factor in the reconstruction scheme, while the aperture function attenuation and noise level play secondary rolls in the limit of the enhanced resolution image reconstruction from scatterometer data.

INTRODUCTION

The frequent, global coverage of scatterometers can complement high resolution sensors such as synthetic aperture radars. The azimuth and incidence angle diversity of the measurements can be useful in determining the scattering mechanism, helping make scatterometers useful in global monitoring. However, the low resolution of the scatterometer can preclude its application in some studies of land and ice. The Scatterometer Image Reconstruction (SIR) algorithm was originally developed to generated enhanced resolution images from Seasat Scatterometer (SASS) data [7]. The algorithm has since been applied to European Remote Sensing (ERS-1/2) Active Microwave Instrument (AMI) scatterometer data [2, 1], NASA Scatterometer (NSCAT) data [5], and radiometer data [6].

In a previous paper, a method for image reconstruction from irregular samples was presented and algebraic reconstruction (ART) was demonstrated to be a complete reconstruction in the limit of infinite iterations [1]. In this paper, we present a discussion on the implications of this theory, and its application to the ERS-1/2 scatterometers, the NSCAT scatterometer, and the future QuikScat and SeaWinds scatterometers. We begin with a brief review of the results of a previous paper, and then outline the implications of the theory as applied to scatterometer image reconstruction with special emphasis on the effects the aperture function has on the resulting image reconstruction.

REVIEW

In [1], the work of K. Gröchenig [3] serves as a theoretical backdrop for this presentation of iterative reconstruction from irregular samples (see also [4]). The basic model for the measurements is

$$z = Hf + \text{noise} \tag{1}$$

where H is an operator that models the measurement system (aperture filtering and sample spacing), f is the true surface function (image), and z represents measurements made by the instrument. The sampling need not be uniform. For resolution enhancement, we are interested in the inverse problem:

$$\hat{f} = \hat{H}^{-1} z \tag{2}$$

where $\hat{f}$ is an estimate of f from the measurements z. $\hat{H}^{-1}$ represents the inverse of the operator H. Generally, H will not be exactly invertible. However, Gröchenig's analysis shows that under certain broad circumstances, the original surface is completely recoverable, at least in the noiseless case.

There are three essential assumptions for the application of Gröchenig's theory to image reconstruction:

- *Band Limited Original Function*: The original surface function f is assumed to be band limited. This has been extended to multi-band band limited surfaces [1].
- *Sample Spacing*: The sample spacing is sufficient for the frequency content of the original surface. For irregular samples, the algorithm Gröchenig presents requires sample spacing of approximately one third the size of the smallest wavelength in the original, compared to one half the smallest wavelength for the Nyquist criteria in the case of uniform sampling [3].
- *Algorithm Criteria*: The image reconstruction algorithm must meet certain criteria, i.e., being a bounded operator on the Banach space defining the band limiting.

If these criteria are met, then the original function can be completely reconstructed from the irregular samples by an iterative algorithm given by [3]

$$\phi_0 = Af$$
$$\phi_{n+1} = \phi_n - A\phi_n$$
$$f = \sum_{n=0}^{\infty} \phi_n$$

where A is a valid algorithm operator under Gröchenig's lemma. If the requirements are met, then the original function can be reconstructed from the samples in the noiseless case *regardless of any finite attenuation introduced by the aperture measurement system.*

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APPLICATION TO SCATTEROMETERS

Scatterometers inherently have low resolution, typically 25-50 km. Over the observation swath, measurements are collected on a 25 km grid. This makes them less than optimal in may applications. However, by modifying the sampling assumptions using multiple orbits, it is possible to get higher resolution from the scatterometer than the nominal resolution using a reconstruction algorithm based on Gröchenig's lemma.

Sampling

If multiple days of data are combined (e.g., 6 days are commonly used for ERS-1/2 and NSCAT in the polar regions), the samples do not coincide from one orbit pass to the next which results in an effectively denser sampling of the surface. Of course, we must assume the surface remains unchanged for the duration of the sampling period. The resulting sample spacing is approximately 13 km for ERS-1/2 and approximately 4 km for NSCAT in the polar regions. QuikScat and SeaWinds, which will have long narrow measurements similar in size to NSCAT, will achieve a sampling density of better than 2 km. A previous publication demonstrated that changes in the surface caused by motion resulted in an effective low pass filtering of the reconstructed image [2]. While this may have an affect on interpretation of the resulting imagery, this effect is ignored for the purposes of this paper and the surface is assumed constant over the sampling period.

Aperture Function

We note that the aperture function (the spatial response of the measurements) is not directly mentioned as part of Gröchenig's lemma. The only requirement is that it be a bounded function. A general aperture function may have nulls in its spectrum. Spatial frequencies in the original image corresponding to these nulls are thus removed from the measurement process and thus can not be recovered [1]. However, if we redefine the problem so that we do not attempt to recover the frequencies in the original image corresponding to the nulls the aperture function, the image as newly defined can be completely recovered, subject to the limitations of the sampling, independent of the details of aperture function (at least in the noiseless case): in the redefined problem, the aperture function does not destroy any frequency information needed to restore the "original" surface. Thus a complete recovery of the original, band limited function is possible and the "original" function can be recovered by iterative calculation based on the theory above since the amount of attenuation is irrelevant to the reconstruction. The only limiting factor in the noiseless case is the sample spacing.

The Hann window spatial filter employed in ERS-1/2 processing results in a circularly symmetric aperture function 50km in diameter [2]. The NSCAT scatterometer aperture function, for comparison, is effectively a rectangular step function which is generally thinner on one axis than the other (about 8-15 km on the thin side, 25-35 km on the long side) [8]. In both cases, the aperture functions introduce nulls in the frequency domain. The first side lobe for ERS-1/2 is substantially lower (< -30 dB) than the first NSCAT side lobe (-13 dB). For ERS-1/2, the aperture is designed to low pass filter the measurements to prevent aliasing for the 25 km uniform grid spacing used for a single pass. However, there are side lobes in the response containing information which can be recovered by a resolution enhancement algorithm. For NSCAT, the side lobe levels are generally higher and the higher frequency information is thus less attenuated.

In practice, the measurement noise and the fact that only a finite number of iterations can be used limits the effectiveness of the reconstruction. Thus, the low side lobes of the ERS-1/2 aperture function become a liability in such a scheme since a finite number of iterations may not be sufficient to recover the original signal. NSCAT, and scatterometers such as the Seasat scatterometer and the future QuikScat and SeaWinds scatterometers, do not suffer from this limitation as much as ERS-1/2. The sharp response functions and asymmetric nature of the measurement response for these instruments allows for better resolution enhancement. Consider the following: over several passes, the multiple beams result in various overlapping orientations of the measurement cells. The high side lobe levels along the short axis appear along different axes in the frequency domain. Even in the presence of noise, the result is improved potential for resolution enhancement since the side lobe levels of the filtered original are much higher than for ERS-1/2, requiring fewer iterations to bring them up to the desired level. This, combined with much closer sample spacing, results in significantly better resolution in enhanced resolution NSCAT imagery. Figure 1 presents a simple comparison of ERS-1 and NSCAT resolution enhancement over a tropical region.

A note about ERS-1/2: Currently, data is available only in an averaged, spatially filtered data set. Missing pulses and the pulse location jitter and uncertainty combine to reduce the effective resolution of the filtered measurements to below that predicted by the filter response function. If the raw pulse measurements were available in which the actual measurement locations and geometry were retained before spatial filtering, much better enhanced resolution imagery could be constructed from ERS-1/2 data.

SUMMARY

There are two primary limiting factors for enhanced resolution scatterometer imaging: the aperture function and the sampling. An aperture function favoring higher side lobe levels in the frequency domain is best suited for resolution enhancement using an iterative reconstruction algorithm such as SIR. The high side lobe levels help ameloriate the effects of noise in the reconstruction by requiring fewer iterations to reverse the effects of the attenuation. The sample spacing is the dominant limiting factor in reconstruction of this type. While noise and side lobe levels affect the achievable resolution enhancement, the enhancement can not be extended beyond the limits dictated

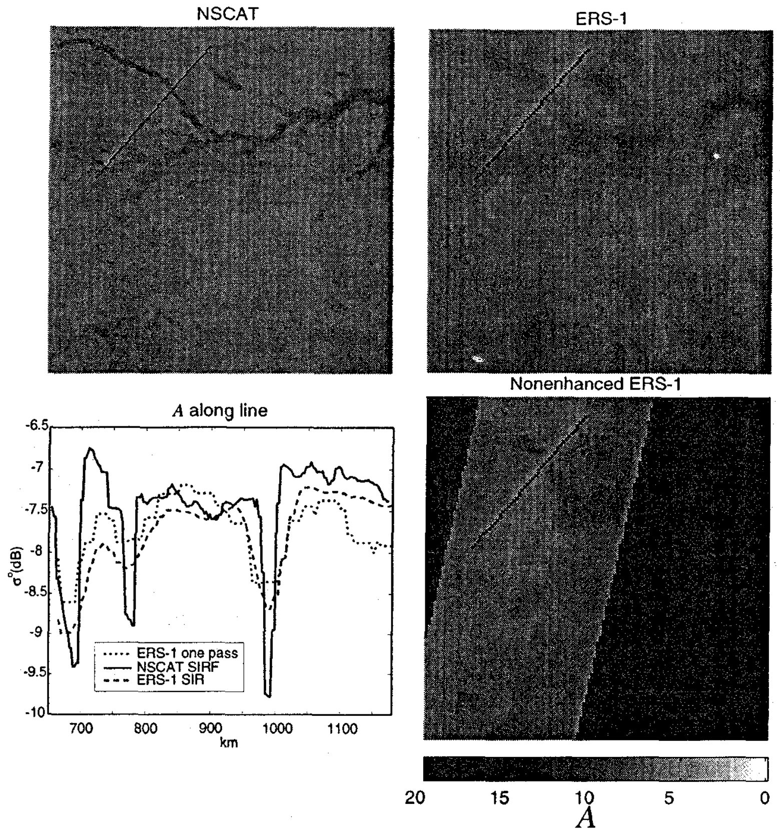

Figure 1: Comparison of ERS-1 and NSCAT resolution enhancement over the Amazon Basin using two weeks of data. Upper right: ERS-1 $\mathcal{A}$ image. Lower right: single pass ERS-1 σ^o image (no incidence angle correction applied). Upper Left: NSCAT $\mathcal{A}$ image. Lower left: plot of $\mathcal{A}$ values along lines in images.

by the sampling. Combining multiple passes provides a denser sampling than a single pass and can thus improve the resolution enhancement.

REFERENCES

[1] D.S. Early and D.G. Long, "Enhanced Resolution Imaging from Irregular Samples," *Proc. IGARSS'97*, pp. 1844–1846, 1997.

[2] D.S. Early and D.G. Long, "Error and Resolution Characteristics of the SIRF Resolution Enhancement Algorithm," *Proc. IGARSS'96*, pp. 124–126, 1996.

[3] K. Gröchenig, "Reconstruction Algorithms in Irregular Sampling," *Mathematics of Computation*, Vol. 59, No. 199, pp. 181–194, 1992.

[4] R.L. Lagendijk and J. Biemond, *Iterative Identification and Restoration of Images*, Kluwer Academic Publishers, Norwell, Mass., 1991.

[5] D.G. Long, "NSCAT Views Land and Ice," IGARSS'98.

[6] D.G. Long, and D.L. Daum, "Spatial Resolution Enhancement of SSM/I Data," *IEEE Trans. Geosci. Rem. Sens.*, Vol. 36, No. 2, pp. 407-417, Mar. 1998.

[7] D.G. Long, P. Hardin, and P. Whiting, "Resolution Enhancement of Spaceborne Scatterometer Data," *IEEE Trans. Geosci. Rem. Sens.*, Vol. 31, No. 3, pp. 700-715, May 1993.

[8] F.M. Naderi, M.H. Freilich, and D.G. Long, "Spaceborne Radar Measurement of Wind Velocity Over the Ocean – An Overview of the NSCAT Scatterometer System," *Proc. IEEE*, Vol. 79, No. 6, pp. 850-866, 1991.