

Deconvolution method for resolution enhancement of Dual-Frequency Polarized Scatterometer (Postprint)

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Abstract

Dual-Frequency Polarized Scatterometer (DFPSCAT) is a new system utilizing Doppler beam sharpening (DBS) technology for azimuthal resolution enhancement. Considering the DBS technology is inapplicable for the middle areas of the swath, a theoretical framework of deconvolution signal processing is proposed to improve resolution. A deconvolution method of the nonlocally centralized sparse representation (NCSR) is adopted to verify its feasibility, and simulation results show that the deconvolution method have obviously better resolution enhancement and higher recovery accuracy than these of the classical scatterometer image reconstruction (SIR) method. ©2016 IEEE.

Full Text

Preamble

DECONVOLUTION METHOD FOR RESOLUTION ENHANCEMENT OF DUAL-FREQUENCY POLARIZED SCATTEROMETER

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ABSTRACT

The Dual-Frequency Polarized Scatterometer (DFPSCAT) is a new system that utilizes Doppler beam sharpening (DBS) technology for resolution enhancement. Since DBS technology is inapplicable for the middle areas of the swath, a theoretical framework based on deconvolution signal processing is proposed to improve

resolution. The nonlocally centralized sparse representation (NCSR) deconvolution method is adopted to verify its feasibility, and simulation results show that it achieves significantly better resolution enhancement and higher recovery accuracy than the classical scatterometer image reconstruction (SIR) method.

Index Terms—DFPSCAT, resolution enhancement, deconvolution method

1. INTRODUCTION

A scatterometer is a radar instrument that collects normalized radar backscatter () measurements of the Earth's surface. Originally designed for measuring near-surface wind vectors over the ocean, scatterometers are also valuable for land and ice applications due to their frequent global coverage. For these applications, improving spatial resolution is a critical challenge.

Pencil-beam scatterometers are real-aperture systems that employ range-gate discrimination to enhance slant-range resolution; however, their azimuth resolution is limited by the antenna beamwidth. This limitation has been partially overcome by the scatterometer image reconstruction (SIR) algorithm, which has been successfully applied to detect polar sea ice extent, track icebergs, and other applications [1]. Nevertheless, the resolution remains too coarse for many geophysical applications, such as snow water equivalent (SWE) estimation, which requires a spatial resolution of 1–5 km [2].

To achieve the desired spatial resolution, Doppler Beam Sharpening (DBS) technology combined with pulse compression is adopted for the Dual-Frequency Polarized Scatterometer (DFPSCAT) onboard the Water Cycle Observation Mission (WCOM). DFPSCAT is a pencil-beam scatterometer employing a 1.5 m dish antenna operating at 9.6 GHz and 17 GHz for SWE measurement and frozen/thaw detection. However, DBS is inapplicable for the middle areas of the swath, where azimuth resolution is limited by the antenna beamwidth to a few tens of kilometers. To address this low-resolution issue in the middle swath of DFPSCAT, this paper establishes a scatterometer measurement model based on a newly defined 2-D surface grid and proposes a resolution enhancement framework using deconvolution methods.

The nonlocally centralized sparse representation (NCSR) deconvolution algorithm is employed for resolution enhancement. Simulations are carried out to verify its feasibility, and the results demonstrate that the proposed framework achieves significantly better resolution improvement than the established SIR processing.

2.1. Measurement Model

[Figure 1: see original paper] shows the DFPSCAT measurement geometry. The antenna beam scans conically around the nadir axis at a predetermined rotation speed and constant incidence angle . The measured power P_r from a transmitted pulse equals the sum of the backscattered signal power P_s and

noise power P_n , which includes thermal noise from the receiver, radiometric noise, and speckle. The power reflected from the surface is given by the radar equation, which yields a weighted spatial average of σ_0 as

$$\hat{\sigma}_0 = C \int_A h(\nu) \sigma_0(\nu) d\nu$$

where C is the calibration factor and h represents the spatial response function (SRF) defined by

$$h(\nu) = \frac{G^2(\nu)}{R^4(\nu)} \bigg/ \int_A \frac{G^2(\nu)}{R^4(\nu)} d\nu$$

Generally, P_s is estimated by subtracting P_n , which is measured by the noise-only channel, from P_r . Additionally, calibration errors resulting from uncertainties in radar system parameters introduce discrepancies between $\hat{\sigma}_0$ and σ_0 . The scatterometer noise model is characterized by K_p , the normalized standard deviation of $\hat{\sigma}_0$, i.e., $K_p = \text{std}(\hat{\sigma}_0)/\sigma_0$. The total errors are modeled as additive noise n . Thus, we obtain the following scatterometer measurement model:

$$\hat{\sigma}_0 = \int_A h(\nu) \sigma_0(\nu) d\nu + n$$

2.2. Surface Grid Definition

To address this problem, we propose a new grid definition. The new grid consists of iso-range lines and iso-azimuth lines defined by the projection of the beam boresight onto the surface, as shown in [Figure 4: see original paper]. [Figure 5: see original paper] depicts the corresponding SRF h at the same locations as [Figure 3: see original paper], demonstrating that h remains almost constant for varying scan angles. In this case, the measured $\hat{\sigma}_0$ is equivalent to regularly sampled surface data convolved with a fixed h , expressed as

$$\hat{\sigma}_0 = h \otimes \sigma_0 + n$$

where \otimes denotes the convolution operator.

In the conventional measurement model, observations are spatially filtered surface measurements sampled over a two-dimensional (2-D) grid. Typically, the 2-D grid is defined as a uniform grid with the satellite's along-track and cross-track directions as coordinate axes [4]. [Figure 2: see original paper] depicts this typical grid definition, where r is the distance from the nadir point to the center of the SRF, and the azimuth angle φ denotes the instantaneous scan position of the antenna beam. [Figure 3: see original paper] illustrates three SRFs h at $\varphi = 77^\circ, 83^\circ, 90^\circ$, respectively. Note that h varies with each rotation location, so

the measurement is not equal to a convolution operation with a fixed h , making existing deconvolution methods inapplicable for this case.

3. DECONVOLUTION METHOD

Typically, the DFPCAT backscatter return from each pulse of each beam is partitioned into several “slices” using range gate processing, with each slice assumed to be statistically independent and having its own slice spatial response function. Based on the proposed 2-D grid, the slice spatial response function is fixed for all measurements. Therefore, the measured $\hat{\sigma}_0$ for each slice can be written as

$$\hat{\sigma}_0 = h_k \otimes \sigma_0 + n, \quad k = 1, 2, \dots, s$$

where k is the slice number and h_k represents the spatial response function for the k th slice. Using multiple overlapping slice measurements, the surface field is reconstructed through deconvolution.

Due to the ill-posed nature of the deconvolution problem, regularization-based techniques are employed to constrain the solution space. Since classical regularization models such as Tikhonov regularization produce over-smooth solutions, recent sparsity-based regularization methods from image restoration offer an optimal alternative. In this paper, the nonlocally centralized sparse representation (NCSR) model proposed by Dong et al. is adopted to solve the deconvolution problem [5]. Specifically, the high-resolution σ_0 is obtained through the following optimization framework:

$$\hat{\sigma}_0 = \arg \min_{\sigma_0} \left\{ \frac{1}{2} \left\| \sum_{k=1}^s h_k \otimes \sigma_0 - \hat{\sigma}_0 \right\|_2^2 + \sum_{i=1}^N \left(\|\alpha_i\|_1 + \frac{\beta}{2} \|\alpha_i - \mu_i\|_2^2 \right) \right\}$$

where α_i is the sparse coding vector for the i th patch, μ_i is the weighted average of the sparse codes of similar patches, and β is a regularization parameter.

Let $\sigma_{0i} = P_i \sigma_0$ denote a patch extracted at position i ($i = 1, 2, \dots, N$), where P_i is the patch extraction operator and N is the number of pixels in σ_0 . Given a dictionary D , each patch σ_{0i} can be sparsely encoded over D to produce a patch sparse coding vector α_i . Once the coding vectors for all patches are obtained, the complete σ_0 can be reconstructed by

$$\sigma_0 = \left(\sum_{i=1}^N P_i^T P_i \right)^{-1} \sum_{i=1}^N P_i^T D \alpha_i$$

More detailed explanations of NCSR can be found in [5].

4. PERFORMANCE ANALYSIS

To verify the feasibility of the NCSR deconvolution method for scatterometer resolution enhancement, simulations are carried out. In these simulations, the slice response function contours are approximately 1 km in the range direction and 16 km in the azimuth direction, with an azimuth sampling interval of 1 km. The normalized standard deviation K_p is assumed to be 0.5 dB.

First, a synthetic field is used for performance investigation. The field over the proposed 2-D grid consists of left squares measuring 1 km \times 1 km and spaced 2 km apart, a right square of 2 km width, and lines with widths of 1 km (narrow) and 2 km (broad). [Figure 6: see original paper] shows the simulation results for DFPSCAT resolution enhancement, including (a) the synthetic field, (b) the measurement, (c) SIR reconstruction, and (d) NCSR deconvolution. As expected, the SIR reconstruction is excessively smooth and significantly blurred. The proposed deconvolution algorithm achieves the most significant resolution enhancement, though it exhibits more noise amplification compared to the other methods.

To further investigate processing accuracy, a horizontal cut of values extracted from [Figure 6: see original paper] across the top row of spots is analyzed, as shown in [Figure 7: see original paper]. It is apparent that the proposed deconvolution method can reconstruct the true signal with the highest accuracy.

Second, real field reconstruction is implemented for further validation. The field is obtained from a SWE forward model based on DMRT-QCA [6] using SWE distribution data centered at 49°N, 115°W covering a 2° \times 2° area for February 29, 2004, acquired from the Snow Data Assimilation System [7]. The reconstruction results are displayed in [Figure 8: see original paper]. It is noted that the NCSR deconvolution method clearly discriminates edge areas and preserves more detailed information. Overall, the deconvolution method produces more obvious resolution enhancement and higher recovery accuracy compared with the classical SIR processing.

5. CONCLUSION

This paper introduces a deconvolution theoretical framework for scatterometer resolution enhancement, in which the slice measurement model is established based on a newly defined 2-D surface grid. The nonlocally centralized sparse representation (NCSR) deconvolution algorithm is utilized for the DFPSCAT middle swath to verify its feasibility. Simulation experiments demonstrate that the reconstruction produced by the deconvolution method achieves significantly better resolution enhancement and higher recovery accuracy compared with the classical SIR algorithm.

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