FOCUSING TECHNIQUES FOR 3D SPOTLIGHT-MODE SAR: APERTURE EXPLOITATION AND OPTIMAL BEAMFORMING

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1. INTRODUCTION

The output of a SAR is typically a photographic-like image of a scene, or more specifically, a representation of the complex scene reflectivity as a function of range and cross range position. The projection of scattering objects in a three-dimensional scene onto the range direction is defined by the imaging geometry and occurs along arcs of constant range. Objects with height above the focus plane thus layover towards the radar and the height information is now encoded in this displacement and an associated phase term contributing to the computed SAR reflectivity. Recovery of the height information may be achieved through exploitation of this phase information by acquiring images with a cross-track baseline and applying interferometric SAR (InSAR) processing techniques. However InSAR using two data sets is unable to resolve the layover ambiguity wherein multiple targets at different heights lay over to the same resolution cell.

In order to recover the laid-over elevation information lost in the wavefront projection and provide resolving power in height an aperture along elevation may be formed by acquiring images with a diversity of incidence angles. This may be achieved with a single pass, multiple antenna SAR or via multiple passes with a single antenna system. The former suffers from considerable hardware complexity and significant physical limitations while the latter suffers from temporal decorrelation associated with scene changes that occur between passes. The acquired SAR data may be tomographically combined in a manner which is separate to, but developed partly out of, multi-baseline interferometry [1]. Considerable theoretical and experimental work demonstrating the concept is described in the literature [2], [3]. The quality of the tomographic reconstruction however, is limited by the number of images that can be acquired and hence the extent of the elevation aperture as well as the non-uniform sampling of the aperture that arises in repeat-pass acquisitions. Current research is examining the utility of beam-forming and spectral estimation approaches to address these problems [4]. In this paper the quality of various standard tomographic approaches for 3D reconstruction are examined through simulation by examining their point-spread function (PSF) response. The problem is also formulated in a beamforming framework and the utility of optimal beamforming algorithms is examined.

2. MULTIPLE-PASS IMAGES

The modelled data is acquired in a deramp spotlight SAR mode collected along a circular flight path without squint, and imagery is formed using the polar format algorithm [5]. The processed output $\hat{g}(x,y,z)$ is a spatial reflectivity map, and the acquired deramped data $G(k_x,k_y,k_z)$ is described as being in k-space (Fourier-space) and is indexed along spatial frequency. For a ground scene viewed at depression angle ψ by the collection platform, and a scatterer in the radar view at (x_0,y_0,z_0) (scene centre is the origin), the scatterer will appear in the output ground-plane image at $(x_0,y_0-z_0\tan\psi)$ (assuming plane waves and small fractional bandwidth) i.e. after two-dimensional processing, the off-focus-height scatterer will layover, and for a scatterer above the focus plane, this layover will be towards the platform (decreased ground range y).

Assuming a repeat-pass collection at different altitudes, the platform acquires data over N passes viewing a single scene at depression angles $\psi_n, n=1,2,...N$. Such a data collection G forms a wedge in k-space which is 3D, non-rectangular and non-uniformly sampled. Using Cartesian coordinates and inverting this data model, the scene reflectivity can be estimated as

$$\hat{g}(x,y,z) \quad = \quad \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G(k_x,k_y,k_z)e^{j(k_xx+k_yy+k_zz)}\,W\left(k_x,k_y,k_z\right)\mathrm{d}k_x\mathrm{d}k_y\mathrm{d}k_z, \tag{1}$$

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where the 3D aperture of support $W(k_x, k_y, k_z)$ allows for dependencies between the spatial-frequency dimensions k_x, k_y & k_z. The tomographic processing will be based around a DFT, but the aperture W requires careful treatment as it defines the nature of the PSF and hence the resolution and the height ambiguities.

Two conflicting considerations drive the processing choices. Whilst a larger Fourier aperture will support a smaller resolution along the corresponding spatial dimension, it is convenient to have a standard sinc PSF, which requires a rectangular aperture. One option is to resample the multiple-pass k-space data to a rectangular cubic grid inscribed in the data. The window function is now separable and rectangular in each dimension: $W(k_x, k_y, k_z) = \mathrm{rect}(k_x/\Delta k_x)\,\mathrm{rect}(k_y/\Delta k_y)\,\mathrm{rect}(k_z/\Delta k_z)$ leading to a sinc PSF in all three spatial dimensions. However, the method fails to use all of the available data, due to the irregular wedge shape. In addition, the multidimensional interpolation will be computationally intensive.

An alternative resampling of the aperture is motivated by the coherency requirement of interferometric processing. Here the processed k_y aperture of support is limited to the common overlapping aperture of support for all of the N acquisitions. Thus it is possible to resample the Fourier domain data associated with each pass onto a common rectangular grid in k_x and k_y. Note that increasing the collection interval $\Delta\psi = \psi_N - \psi_1$ increases the height resolution ($\rho_z = 2\pi/\Delta k_z \approx \lambda/2\Delta\psi$), but results in a decrease in the percentage overlap so that the trim in k_y is more severe resulting in a greater loss of range resolution. Crucially, this resample method gives rise to the dependence $k_z = k_z(k_y) = k_y \tan\psi_n$ from the geometry of the wedge, and we have simply $W(k_x, k_y, k_z) = \mathrm{rect}(k_x/\Delta k_x)\, W'(k_y, k_z)$. Applying the substition and properly accounting for the spatial-frequency offset k_0 leads to a tomographic process of resampling in range the pixels of the two-dimensional ground-plane images (to undo the layover term $z_0 \tan\psi_n$ for each pass and align the pixels) followed by coherent addition across passes (to synthesise the aperture in elevation) which is very similar to that outlined in [2]. Results show that the PSF in all dimensions is sinc-like and a tomographic image at some focus height z_0 will correct the layover of objects at that height.

The coherency feature mentioned above is not in fact a requirement of tomography. By transforming to cylindrical coordinates ($k_y = k_u \cos\psi$ & $k_y = k_u \sin\psi$), Jakowatz & Wahl describe a similar tomographic process that can be applied without limiting each pass to the overlap region in k-space. The full aperture of support in k_y is utilised avoiding any loss in resolution, and the aperture function is separable: $W(k_x, k_u, \psi) = \mathrm{rect}(k_x/\Delta k_x)\,\mathrm{rect}(k_u/\Delta k_u)\,\mathrm{rect}(\psi/\Delta\psi)$. The coherent addition across passes occurs along ψ (now an independent transform variable by virtue of the coordinate change), which suits the collected data. The trade-off is that the PSFs are not ideal sinc functions along the spatial Cartesian directions; result show, however, that the PSF is sinc-like, and achieves resolution in height. Furthermore, analysis of the effective aperture of support for the resulting images shows that as a function of k_y the number of contributing acquisitions differs leading to a reduction in range sidelobes. In a refinement of the method, the need for 'modified' SAR images in [2] (k-space data scaled by the Jacobian of the transformation k_u before Fourier inversion) is shown to be unneccessary for a narrowband radar collection. Unlike the other methods outlined here, this conveniently allows for SAR images from appropriate geometries formed using a conventional (unadjusted) two-dimensional processing chain to be tomographically combined.

Multiple-pass SAR tomography can be recast as an exercise in beamforming, allowing for the phase weights used in the coherent addition above to be replaced with optimal (and spatially adaptive) beamforming weights [4]. Whilst this improves the height resolution by an order of magnitude, results show that the nulling effect of adaptive MVDR weights on off-focus-height scatterers can obscure any genuine targets which are aligned in range or azimuth with the nulled interferences.

3. REFERENCES

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