

Volumetric interferometry for sparse 3D synthetic aperture radar with bistatic geometries

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Synthetic Aperture Radar (SAR) renderings in 3D provide additional target information when compared to 2D by separating out features overlaid in height. However, the required 2D SAR aperture, when Nyquist sampled, necessitates large scanning times that would be impractical for most realistic collections. This research has developed a novel volumetric approach to sparse aperture 3D SAR imaging, which is applicable to bistatic SAR near-field geometries, a generalization of far-field cases. This approach is first demonstrated in simulation and then applied to a measured scene containing a model vehicle target, producing sub-Nyquist sampled 3D SAR renderings.

Introduction: Conventional finely sampled volumetric images can be impractical to produce from realistic synthetic aperture radar (SAR) collections, as achieving suitable resolution and coverage in the vertical direction requires a finely sampled 2D SAR aperture, necessitating many radar platform horizontal flight passes with varying heights over the scene [1, 2]. Producing volumetric renderings with few passes would typically be insufficient to satisfy the Nyquist sampling criterion in the vertical direction, leading to image wrap-around aliasing artefacts [3].

Several methods have been developed for forming 3D renderings from sparsely sampled SAR datasets, allowing for fewer collection passes over a scene, including SAR interferometry, the SAR Point Cloud Generation System, and 3D SAR compressive sensing [4–6].

Here, a novel interferometry-based approach for sparsely sampled aperture 3D SAR imaging has been developed, that can be used for bistatic and SAR near-field geometries, which are generalizations of both monostatic and SAR far-field geometries. The SAR near-field is defined as the regime where the range $d < 2L_{cr}^2/\lambda_c$ for centre wavelength λ_c and for a scene with cross range extent L_{cr} . No phase unwrapping or intensive signal reconstruction methods are required for the developed approach, as is the case for interferometry and compressive sensing, respectively. Conventional SAR interferometry is also unable to fully separate scatterers overlaid in height, which is problematic for imaging complex targets [7]. The measured data used to demonstrate the algorithm was collected at the Cranfield University Ground-Based SAR (GBSAR) laboratory [8, 9].

Outline of approach: Sparse 3D point cloud renderings have previously been formed from simulated far-field interferometric SAR data using monostatic collection linear trajectories [10]. The approach presented in [5, 10] utilizes the change in layover of scatterers when processing the interferogram phase factor of the returned signals, assuming a constant radar trajectory height for each of the separate passes. However, the assumptions made, for example that the grazing angle is constant across the scene, are not generally valid for SAR near-field geometries. Bistatic geometries, where the transceivers have a non-negligible separation, add further complexities [11, 12].

The new approach described here exploits volumetric processing of interferograms to account for the effects of layover in the processing of the data in a natural way. Volumetric interferograms are formed from volumetric SAR images generated with the Backprojection Algorithm (BPA) [13, 14], which accounts for complications associated with bistatic and SAR near-field geometry imaging [15].

Linear horizontal radar platform passes are employed to form the individual volumetric SAR images, and these linear passes should be distributed in height in an irregular manner to avoid strong aliasing artefacts in the final 3D scene rendering. Although the initial individual volumetric images have no vertical resolution, when they are combined,

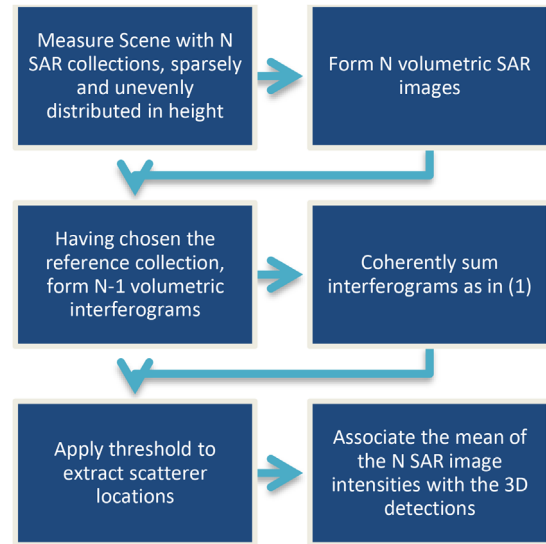


Fig. 1 Flow chart illustrating key principles of new approach.

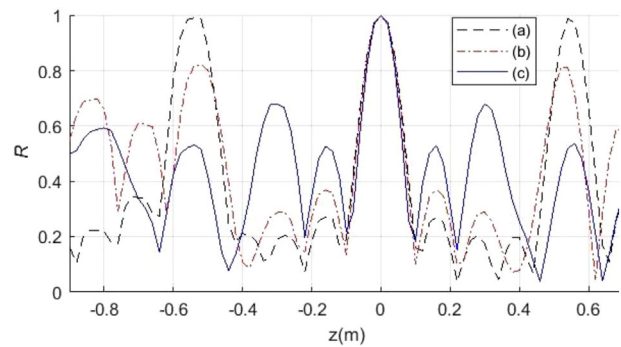


Fig. 2 Summed phase factor, R , along a vertical iso-range through the target location ($z = 0$ m), with trajectory $\hat{\sigma} = 0$ (a), $\hat{\sigma} = 0.17$ (b) and $\hat{\sigma} = 0.52$ (c).

3D information is obtained due to the variation of collection grazing angle across the set.

As outlined in Figure 1, N sparsely and non-evenly distributed in height horizontal linear SAR apertures are collected and formed into volumetric SAR images. Having chosen one of these to be the common reference image, $N - 1$ volumetric interferograms are then formed.

The phase factors of the interferograms are coherently summed for each voxel, $\mathbf{x}$, giving the volumetric summed phase factor response at the voxel,

$$R(\mathbf{x}) = \frac{1}{N} \left| 1 + \sum_{n=1}^{N-1} e^{i\varphi_n(\mathbf{x})} \right| \quad (1)$$

where $\varphi_n(\mathbf{x})$ is the phase at voxel $\mathbf{x}$ of the n th interferogram. Point scatterer detections are determined by applying a threshold to $R(\mathbf{x})$. Scatterer detections surpassing the threshold form part of an output 3D point cloud rendering. To each of these detections, it is useful to associate the corresponding mean sparse-volumetric SAR image intensity value at the voxel.

Simulations: Bistatic near-field SAR simulations were conducted with sparse 2D apertures, consisting of five linear horizontal transmitter SAR apertures distributed in height with a stationary receiver positioned to the side. Three height distributions, labelled a to c, were implemented, with a fixed overall vertical extent of 1.4 m. The standard deviation of normalized transmitter pass height spacing (pass height spacing divided by its mean) ($\hat{\sigma}$) provides a measure of unevenness of the height sampling. The frequency range measured was 6 to 10 GHz and the distance to the target from the transmitter aperture was 5.0 m.

Figure 2 shows R along a vertical iso-range line through a point scatterer situated at 0 m in height, for the three SAR geometries (a–c), as follows:



Fig. 3 The measured scene, consisting of the quarter-scale model tank on gravel.

- an even distribution of passes is employed with height spacings of 35 cm, so that $\hat{\sigma} = 0$. This results in large scatterer height ambiguities 52 cm from the true scatterer position, with $R = 1$, so that unique scatterer localization is not possible,
- two of the inner passes are offset by 5 cm so that $\hat{\sigma} = 0.17$ resulting in a reduction in ambiguity sidelobe height to just over $R = 0.8$, and thus an accurate height estimation of the scatterer position can be made with appropriate threshold in R ,
- the transmitter pass heights are further randomized so that $\hat{\sigma} = 0.52$, and sidelobes have been further suppressed to under $R = 0.7$.

The examples show that with unevenly spaced trajectories, the application of a suitable threshold to R can allow the detection of point scatterers at their correct locations. For scenarios of low SNR, lower sidelobes are required for correct target estimation, so that a more uneven distribution of pass spacings is required for greater sidelobe reduction. However, if trajectory distributions with $\hat{\sigma}$ greater than about 0.6 are employed, sidelobes begin to increase again. This behaviour can be attributed to trajectory clustering.

Measured data validation: The measured scene consisted of a quarter scale tank model situated on gravel, as shown in Figure 3. A finely sampled vertical 2D SAR transmitter aperture was measured, for monostatic and bistatic geometries, where in the bistatic geometry the receiver was fixed and offset to the side. The SAR transmit apertures had vertical and horizontal extents of 1.4 and 3.5 m. A frequency range of 6.62 to 10 GHz was measured in the VV linear polarization channel.

Starting from the fully sampled measured dataset, the SAR aperture was repeatedly randomly downsampled in the vertical axis, keeping the overall extent constant, to find the minimum acceptable vertical sampling (maximum sparsity) which formed an acceptable 3D scene rendering with the algorithm developed.

At the frequencies measured, and for the volume of interest (VoI) around the model tank set to 1.8 m in height, aperture height spacings of approximately 5.3 and 7.8 cm are required for monostatic and bistatic geometries, respectively. These are considered to be Nyquist sampled, ensuring that the features of the wider scene do not wrap around, producing aliased artefacts in the vertical direction.

A histogram-based thresholding approach was used, taking the difference between the maximum value of R and its modal value across the scene, and then selecting voxels in the upper 25% of this range. Similar approaches are taken in other image processing applications [16].

The BPA volumetric SAR image results for the full 2D aperture data provide a useful comparison for assessing the quality of the point-cloud image results. The figure shows normalized cross-correlation results between full-Nyquist BPA images (bistatic and monostatic) and the corresponding downsampled aperture point cloud results.

The values shown were generated by first forming initial sparse uneven 2D SAR monostatic and bistatic apertures which provided good quality renderings, with the mean height spacing corresponding Nyquist sampling for the VoI. It is noted that due to the uneven sampling, parts of these apertures were actually sub-Nyquist sampled, but were found to provide the best starting point for the further downsampling investi-

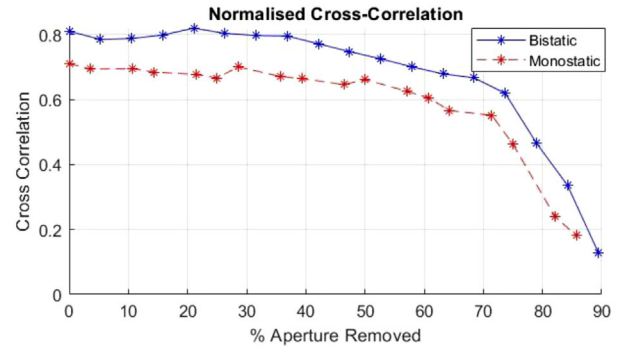


Fig. 4 Normalized cross-correlation of sparse point cloud renderings with the corresponding full aperture BPA volumetric SAR geometry images. BPA, Backprojection Algorithm; SAR, synthetic aperture radar.

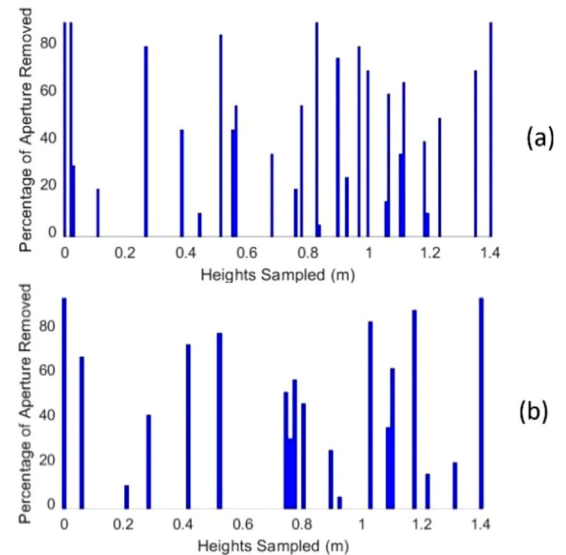


Fig. 5 Downsampled transmitter height apertures, monostatic (a) and bistatic (b). Blue lines indicate individual SAR heights, fully sampled in azimuth, remaining after each successive downsampling. White spaces consist of fully removed SAR passes. SAR, synthetic aperture radar.

gation. The successively downsampled SAR transmitter horizontal pass heights are shown in Figure 5.

Hence employing the cross-correlation, combined with inspection of the point clouds, a lower limit for aperture sampling for useful point cloud results was determined.

Figure 4 initially shows a high normalized cross-correlation with the full-Nyquist BPA rendering, for both monostatic and bistatic geometries, with a low rate of decline in correlation until 70% sub-initial sampling (SIS) as the sampling density decreases (by 'percentage SIS' it is meant the percentage of aperture removed from the initial uneven sampling). Only minor erroneous detections are present in the SIS ranges from 58% to 74% and from 39% to 71% for the monostatic and bistatic renderings respectively. Example point cloud renderings without errors are presented in Figure 6 with SIS values of 50% and 37% for monostatic and bistatic; the tank structure is discernible with cannon and main body as distinct features. The gravel below the tank is also visible. Here, the monostatic and bistatic apertures have 14 and 12 passes respectively, with mean height spacings of 10.9 and 12.8 cm, respectively.

The clustering of points detected for the bistatic rendering is visibly larger than the monostatic rendering due to the coarser underlying SAR resolution of this antenna geometry as derived from the overall SAR aperture extents. There are no aliasing artefacts present in either of the renderings, which was not the case for the corresponding conventionally formed BPA sub-Nyquist SAR aperture volumetric images.

Erroneous detections increase dramatically after the 74% and 71% sub-Nyquist limits for the monostatic and bistatic cases respectively. After this limit, the tank structure is not discernible from erroneous

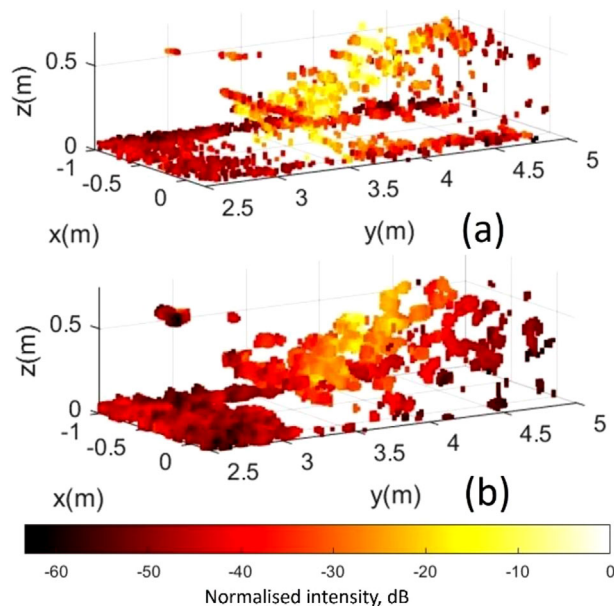


Fig. 6 Model tank measurement sparse aperture point cloud renderings, 50% and 37% SAR aperture removed for monostatic (a) and bistatic (b) SAR geometries. SAR, synthetic aperture radar.

background detections. This limit corresponds to the sharp decrease in correlation with the BPA rendering (Figure 4). The mean spacing between passes at this limit was 47.0 and 23.6 cm for the bistatic and monostatic geometries, respectively, which for evenly sampled heights would have given vertical unambiguous cross-ranges smaller than the height of the tank structure when using the BPA algorithm on evenly sampled data.

Conclusions: The developed 3D point cloud imaging approach produces accurate height estimates of scatterers using bistatic SAR near-field geometries, which is a generalization of the monostatic far-field case. Simulations were validated with complex model target laboratory measurements, forming sub-Nyquist SAR aperture point cloud renderings. Good quality results were obtained for SIS up to 50% and 37% for the monostatic and bistatic cases, respectively. The nature of the SAR near-field geometries tested shows the versatility of the approach.

The determined downsampling limits indicate the minimum sampling needed to obtain useful 3D target information with no aliasing artefacts. The approach is applicable to non-linear sparse aperture SAR collections employing formation flying between pairs of transceivers, including UAV's and satellite constellations as examples.

Future research will focus on improvements in algorithm efficiency, demonstrating the new approach on multistatic geometries with non-linear trajectories, and on incorporating polarimetric information.

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