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THE SINGLE ANTENNA INTERFEROMETER

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ABSTRACT

Air and space borne platforms using synthetic aperture radars (SAR) have made interferometric measurements by using either two physical antennas mounted on one airframe or two passes of one antenna over a scene. In this paper, a new interferometric technique using one pass of a single-antenna SAR system is proposed and demonstrated on data collected by the NASA-JPL AirSAR. Remotely sensed L-band microwave data are used to show the sensitivity of this technique to ocean surface features as well as a baseline for comparison with work by others using two-antenna systems.

1 DISCUSSION

The NASA/JPL airborne radar laboratory (also known as AirSAR), has a multifrequency (P, L, and C bands), multipolarization, synthetic aperture radar (SAR) capability [1]. Because there are L and C band antennas mounted both fore and aft on the DC-8 and a common coherent reference is used for receiving, SAR images can be formed at each antenna in parallel (one antenna transmits and both receive). Stripping the phase difference by beating the images from the two antennas produce SAR interferograms at both C and L bands. Two-antenna interferometric SAR for extracting topographic information (pixel-height) has been discussed in the open literature (see [2] and [3]). In addition, Li and Goldstein [4], have demonstrated with Seasat data that interferometry can be performed using two overlapping swaths obtained during separate orbits. The interferometric images produced with these geometries are often visually spectacular.

The proposed Single Antenna Interferometry (SAI), technique differs from earlier approaches because it collects the required data in one pass with one antenna. This requires either a pulse repetition frequency (PRF), greater than Nyquist (sometimes referred to as "super-Nyquist"), or special along-track filtering similar to presumming. The standard SAR data collection geometry is used for gathering the data required for the single antenna interferometer (see Figure 1). The size of the footprint is roughly $\lambda R/D$, where λ is the radar wavelength, R is the range

from antenna to the center of the scattering area, and D is the along-track dimension of the antenna. The forward motion of the aircraft is used to sequentially illuminate a swath on the ground. The PRF is selected such that the radar footprints from adjacent echoes overlap extensively. The Doppler frequency coding in the series of overlapping measurements is used to focus a synthetic antenna in the along-track direction [5].

Basically, the phase information for a single scattering element at broadside range R is encoded in the form

$$\Psi(t) = 2\pi \left\{ \frac{2R}{\lambda} + \frac{2v_r}{\lambda} t + \frac{v_c^2}{\lambda R} t^2 \right\} \quad (1)$$

where t is the time about broadside illumination and v_r and v_c are the range and cross-range components, respectively, of the relative velocity between antenna and scattering area. The along-track displacement from broadside is therefore given as $v_c t$ and the second term in the expression is recognized as the Doppler frequency shift $2v_r/\lambda$. The synthetic aperture resolution is obtained using a filter matched to this linear frequency modulation Ψ . The $4\pi R/\lambda$ term represents a constant phase offset corresponding to the center of beam range bin and can be ignored from a pulse compression viewpoint—i.e., it does not increase the bandwidth (resolution). Note that the footprint is of width $\lambda R/D$, implying an illumination time of

Figure 1. Data collection geometry for single antenna interferometric synthetic aperture radar.

$t = \pm(\lambda R)/(2v_c D)$ and a Doppler bandwidth of $2v_c/D$. A translation of the scattering element by a distance Δ results in a phase distribution $\Psi(t + \frac{\Delta}{v_c})$ equal to

$$2\pi \left\{ \frac{2(R + \frac{\Delta^2}{R})}{\lambda} + \frac{2(v_r + \frac{\Delta}{R}v_c)}{\lambda}t + \frac{v_c^2}{\lambda R}t^2 \right\} \quad (2)$$

This implies that translation by a distance Δ in the along-track direction cannot unambiguously be distinguished from a $\Delta v_c/R$ change in the radial component of the velocity.

Because the radar system and the SAR image synthesis use coherent processing, the SAR output can be generated as a complex-valued image (in-phase and quadrature). If the complex-valued SAR image is treated as a wavefront, then interferometry can be accomplished when a suitable reference wavefront can be provided for mixing. The reference wavefront is suitable if it is of the same scene as the original SAR image and within the coherence time (distance) of the system. For the multi-pass Seasat work [4], an arid ground-patch not expected to have changed dramatically during the time between passes was used. For radar ocean imaging applications, the scene decorrelation times are relatively fast and therefore not amenable to multi-pass techniques. Our approach is to generate two "synthetic passes" by exploiting an oversampling of the data in the along-track direction or inducing an oversampling by filtering. The alternative is to mount two antennas on one air frame. The two-antenna interferometric configuration on the NASA/JPL AirSAR has already demonstrated impressive imaging capabilities for ocean surface effects at L-band [6, 7]. A two antenna system has the fundamental advantage of collecting twice the data of a one antenna system. In addition, the simultaneous operation of the receivers allows measurement of phase center displacements due to propagation effects alone (no scene decorrelation). This is a fundamentally different quantity than is retrievable from a one antenna system. We are motivated both by the inherent simplicity of the single antenna system and by the possibility of applying the technique to existing SAR data sets.

The input to the single antenna interferometer (SAI) is two complex-valued wavefronts obtained by decimating the original radar echoes into two sets for separate processing (one set is from even-indexed echoes and the other set is from odd-indexed echoes). A standard SAR image is formed from each of these sets but now the intersample spacing has doubled and the pulse repetition frequency is half of the original system. However, un-aliased images can still be formed if the original PRF is at least twice the Nyquist rate. The two images are registered, one of the images is complex-conjugated, the images are beaten together on a pixel-by-pixel basis, and the phase is stripped from the resulting product. The data flow for the processing is outlined in Figure 2.

For SAI-SAR with the NASA/JPL data set, the registration operation corresponds to shifting one of the two images half a pixel. The current implementation uses a spatial domain filter for interpolation—the truncated (4-

Figure 2. Data flow for a single antenna interferometric synthetic aperture radar SAI-SAR processing algorithm.

point) sinc appears to work well. Alternatively, the along-track spatial shift could be implemented in the frequency domain as a phase weighting. As was mentioned earlier, translation (in this case by interpolation) is equivalent to changing the Doppler centroid used for processing—i.e., squinting the synthetic beam.

The along-track frequency interpretation results in an alternate processing algorithm. In fact, overlapping scenes can be generated using standard multi-look algorithms—this is particularly useful when the data has not been adequately over-sampled to permit decimation in the echo domain. The varying parameter is the time-delay between the scene and reference images. The optimum delay depends on the spatial and temporal decorrelation properties of the scene. It is apparent that multiple time-delays are possible by using multi-look algorithms or by patterned decimation of the echo sequence.

2 RESULTS

Figure 3 displays three images: on the left is the output of a standard SAR processor operating on full-prf data, in the center is an interferometer phase image generated using the SAI algorithm outlined in Figure 2 with a set of fringes running left-to-right through the center of the scene, and on the right is one of the two SAR images used in the SAI (this image is magnitude detected). The data was collected on August 27 at the Loch Linnhe 1989 experiment using the NASA/JPL L-band (24cm) system. The fringe

Standard SAR: LVV-27-12

Interferometer Phase

LVV-27-12

Interlaced SAR

Figure 3: Three images produced from one pass of the NASA/JPL AirSAR: standard full-prf SAR with intensity detected output, half-prf interferometer phase, and half-prf SAR with intensity detected output.

23.9 cm	- wavelength λ (L-band)
vertical	- transmit polarization
vertical	- receive polarization
290. Hz	- pulse repetition frequency (PRF)
219. m/s	- True Ground Speed
.756 m	- Azimuth sample spacing
12.0 km	- Near Slant Range
50.5 °	- Approximate Incidence Angle
8.0 °	- 3dB Azimuth Beamwidth
4.0 °	- Size of synthetic aperture

Table 1. Parameters of the NASA-JPL AirSAR used for the single antenna interferometer processing.

signature corresponds to the location of an ocean surface feature induced by an internal wave from a surface ship maneuvering in the lobe. The standard SAR output from full-prf input data has the highest resolution of the three images. Some of the important processing and physical parameters for these images are included in Table 1.

The phase difference output of the SAI has the same "confetti" texture associated with the corresponding phase difference images from the NASA/JPL two antenna system. In order to make the phase information more useful, JPL has been developing algorithms for combining the phase, magnitude, and polarization channels into one enhanced image. In addition, the two antenna phase difference can be interpreted as a velocity estimate [6, 7].

3 PRELIMINARY ANALYSIS

In order to discuss why it is possible to see a phase contour co-located with the ship wake, a quick review of the correlation between radar pulses is required. Suppose that ρ is the along-track dimension of the ground patch illuminated by a real aperture radar (RAR). For the antenna system shown in Figure 1: $\rho = AR/D$. After SAR processing using the maximum allowable synthetic aperture the resolution is $\rho = D/2$. Assume for the moment that the system were actually a RAR with the same resolution as the SAR ($D/2$), then for a scattering response of s , the received signal is given by

$$r_0 = \int_0^\rho s(x) dx. \quad (3)$$

When the antenna platform has moved a distance Δ , the received signal becomes

$$r_\Delta = \int_\Delta^{\rho+\Delta} s(x) dx. \quad (4)$$

For a scattering response with a Dirac-delta autocorrelation, the correlation of the received signal becomes

$$\begin{aligned} A_\rho(\Delta) &= E(r_0^* r_\Delta) \\ &= \int_0^\rho \int_\Delta^{\rho+\Delta} E(s^*(x_0) s(x_1)) dx_0 dx_1 \\ &= \begin{cases} \rho - |\Delta| & \text{if } 0 \leq |\Delta| \leq \rho \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad (5)$$

where $E()$ is the statistical expectation operator. In simple terms, two received signals must be uncorrelated if there is no overlap in their footprints. It is tempting to immediately conclude that the along-track echo spacing for a SAR system must be less than $D/2$ in order for the two SAR images in the interferometer to be mixed together and produce fringes. Recall that the $D/2$ is applicable only if the full synthetic aperture is used to process the imagery. Smaller synthetic apertures can be used in the processing which admit larger resolutions ρ and consequently better correlation and stronger fringes. Interpretations from optical interferometry are tempting: by reducing the bandwidth (in this case Doppler bandwidth), stronger fringes are possible. The SAI acts like a beam-splitter followed by superposition of the two beams after different propagation paths have been followed: smaller bandwidths increase the correlation time (length) of the radiation. In the extreme, the strongest correlation is between two adjacent echoes. Unfortunately this correlation is accompanied by the lowest resolution!

4 CONCLUSIONS

In this paper a single radar antenna with a high pulse repetition frequency and a single pass of the scene is used to form an interferometric image which, under initial investigation, appears to be sensitive to ocean surface features. Additional applications including velocity estimation and topographic mapping from air and space borne platforms are being considered. Using the SAI to iteratively correct for Doppler parameter errors is also being implemented.

The single antenna interferometer technique has demonstrated the existence of information in the phase difference signal of ocean scenes. The resulting imagery appears similar to phase maps from two antenna interferometers. Fundamentally, the two antenna system can collect more and different information than a single antenna system without having to increase the prf (decrease the swath width). Work is in progress to address the limitations of each system and to identify the physical conditions which generate strong phase difference signatures.

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