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INTERFEROMETRIC SYNTHETIC APERTURE RADAR IMAGERY OF THE GULF STREAM

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1. INTRODUCTION

The advent of interferometric synthetic aperture radar (INSAR) imagery brought to the ocean remote sensing field techniques used in radio astronomy. Whilst details of the interferometry differ between the two fields, the basic idea is the same: Use the phase information arising from positional differences of the radar receivers and/or transmitters to probe remote structures. The success of airborne INSAR methods (Goldstein *et al.*, 1987) provided ample incentive to investigate numerous other applications, *e.g.* topographic mapping (Zebker *et al.*, 1986), surface ocean currents (Goldstein *et al.*, 1989) and internal waves (Thompson *et al.*, 1993). In this paper, we apply for the first time INSAR methods to the Gulf Stream boundary. A primary advantage of the INSAR technique when applied to ocean surfaces is the ability to observe the motion of surface scatterers.

The interferometric image is formed from two complex synthetic aperture radar (SAR) images. These two images are of the same area but separated in time. Typically the time between these images is very short — approximately 50 msec for the L-band AIRSAR. During this short period the radar scatterers on the ocean surface do not have time to significantly decorrelate. Hence the two SAR images will have the same amplitude, since both obtain the radar backscatter from essentially the same object. Although the ocean surface structure does not significantly decorrelate in 50 msec., surface features do have time to move. It is precisely the translation of scattering features across the ocean surface which gives rise to phase differences between the two SAR images. This phase difference is directly proportional to the range velocity of surface scatterers. The constant of proportionality is dependent upon the interferometric mode of operation. In our case, the total phase difference between the two SAR images is

$$\Delta\phi = \frac{2\pi\ell}{v_{air}\lambda} u_{range} \quad ,$$

where ℓ is the spacing between the radar receivers, λ is the radar wavelength, v_{air} is the aircraft velocity and u_{range} is the component of the scatterer's velocity in the range direction. The motion of the scatterers may arise from ocean currents, internal wave motions, winds or most generally all of the above. Identifying these different components of u_{range}, without recourse to additional information, is a formidable task.

One immediately sees several possible limitations to the INSAR technique. The time between images must be short enough that the ocean surface does not decorrelate, otherwise the phase difference contains no new information. Also the time between images must be long enough so that the surface features have time to move and thus provide a phase difference. We implicitly require that the SAR images have been corrected for the aircraft sidewards drift and yaw, both of which will produce (unwanted) phase differences. Therefore as a practical matter the phase difference arising from the surface motion should be greater than the errors in compensating for aircraft motion — the signal-to-noise ratio should be large. Perhaps more irksome than the above is the problem of large surface velocities, when the phase difference is greater than 2π. The interferometric image determines the phase differences modulo 2π, therefore many velocities map onto the same phase difference. Typically, range velocities of scatterers of approximately 0.0 m/sec., 2.7 m/sec., 5.4 m/sec., *etc.* all yield a zero phase difference in the interferometric image. One possible means of lifting this phase ambiguity is to use multi-frequency and/or multi-baseline interferometry. These methods have been discussed by Carande, 1992 and Carande *et al.*, 1991. Therefore the interpretation of INSAR images may require other information, additional assumptions and/or modeling.

2. GULF STREAM IMAGES

The particular interferometric images which we have analyzed are from the 1990 AIRSAR flight of July 20^{th}, previously identified as G-Stream NI 120-1 (Kobrick, 1990; Valenzuela *et al.*, 1991). The complex interferometric image is the product of one complex SAR image with the complex conjugate of the other. Therefore the amplitude of the INSAR image is the product of the individual SAR image amplitudes. The phase of the INSAR image is the phase difference (modulo 2π) between the two SAR images. The amplitude and phase of the INSAR image are shown in Figure 1. The amplitude image shows no detailed structure and provides only hints of large features. In contrast the phase image clearly depicts the Gulf Stream boundary. The Gulf Stream boundary is the one large feature that may be seen in the amplitude image. In addition, the phase image clearly shows the Research Vessel Cape Henlopen, her wake and other smaller surface structures. We have interpreted the dark–light banding as internal wave motion. The orientation of these images is independently verified by the ship's wake and log — she was southbound at 10 knots when the INSAR image was taken.

This comparison of INSAR phase and amplitude images may downplay too much the value of complex SAR imagery. Milman *et al.*, 1990 have developed and applied ambiguity function techniques to complex SAR images to obtain information about surface velocities. However, the amplitude of SAR images conveys no relevant information about velocities (other than velocity bunching effects) and, as seen in Figure 1, little information about small-scale surface features.

The complementary nature of SAR and INSAR images produces a powerful oceanographic remote sensing tool. INSAR is sensitive to surface velocities whereas SAR amplitudes depend strongly on the surface shape. Presumably these two features (shape and velocity) are, in at least some cases, correlated. Therefore employing the additional information which interferometry provides will assist the interpretation of the region surveyed.

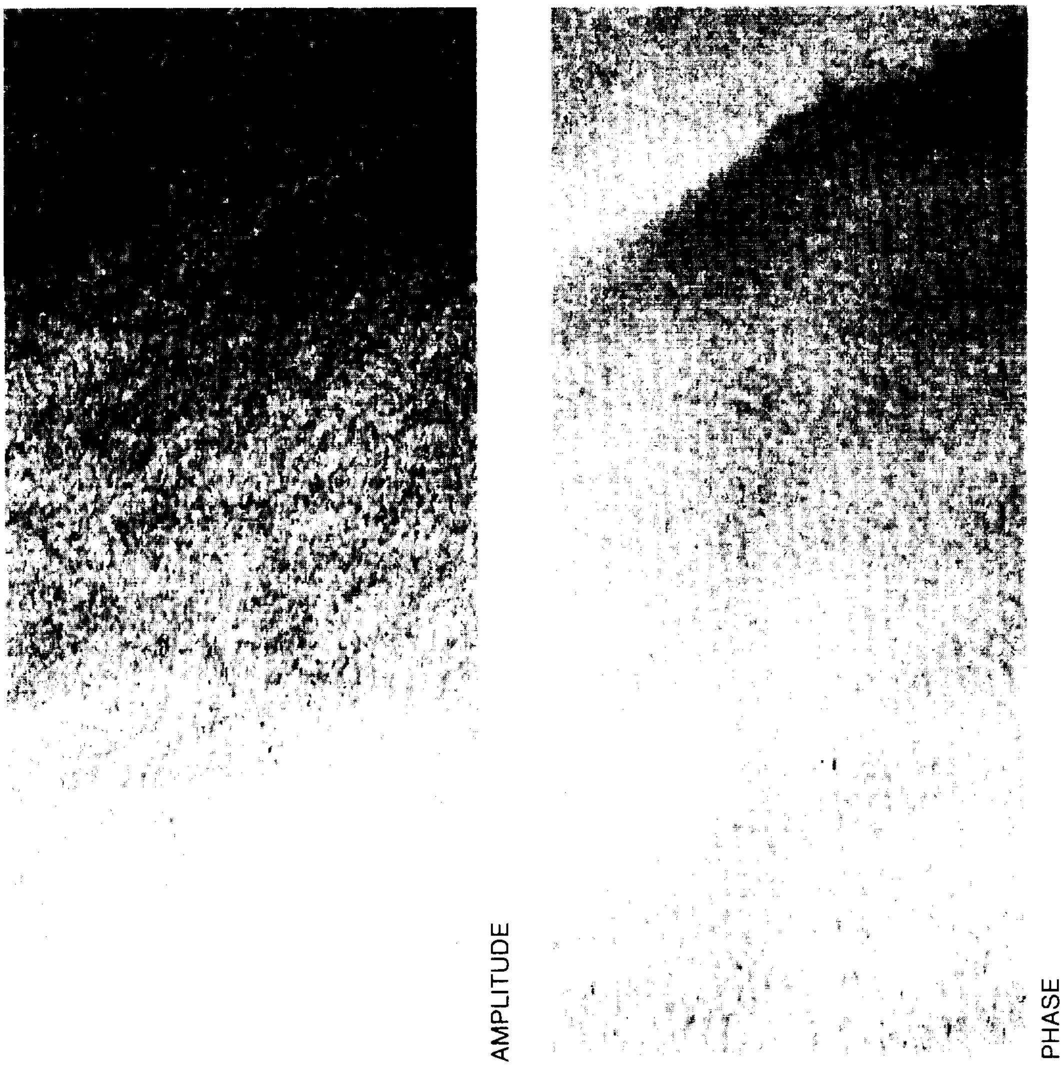

Figure 1: The INSAR amplitude (left) and phase (right) images for run G-Stream NI 120-1 taken July 20, 1990 are displayed. The area of each image is approximately 5 km in azimuth and 10 km in range. See text for additional discussion.

3. GROUND TRUTH INFORMATION AND MODELING

Ground truth information is available in the form of buoy measurements of the wave spectrum and direction. Two buoys were deployed both before and after the INSAR image of Figure 1 was taken. We have Fourier analyzed the phase image to determine the spectrum of the wave-like structures seen throughout the image. The frequency and direction are directly compared to the buoy data. The Henlopen's wake also may aid in our interpretation of surface features. Thus the available ground truth in conjunction with the INSAR image provides useful constraints for modeling Gulf Stream boundary features.

We are currently modeling both INSAR and SAR radar return from ocean surfaces. This is an ongoing project and results will be reported at a future date.

4. CONCLUSIONS

Our initial investigation has yielded several interesting characteristics of INSAR imagery: The wave spectrum is clearly seen in the phase image but not in the amplitude. The boundary of the Gulf Stream is a strong linear feature — barely resolved in the amplitude image — which dominates the phase image. Similarly, the Henlopen's wake is easily seen in the phase image. Of course, the ship is clearly resolved in both the amplitude and phase images.

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