INSAR Imagery of Surface Currents, Wave Fields, and Fronts

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***Abstract*—We demonstrate the ability of interferometric radar imagery to determine both relative and absolute surface velocities in the open ocean. Absolute phase calibration is accomplished by noting the azimuthal displacement of range-travelling targets—demonstrating for the first time that under favorable circumstances phase calibration can be achieved in open-ocean in the absence of ground truth. The high resolution of radar imagery permits observation of sharp velocity discontinuities, e.g. the Gulf Stream boundary and the wave field. The recent SIR-C/X-SAR shuttle missions dramatically emphasize the experimental and observational aspects of space-based radar. The combination of absolute velocities, high spatial resolution, and wide-area coverage suggest that interferometric radar imagery can provide a unique and powerful aid both for studies of global circulation patterns and detailed analysis of slope/shelf water interactions with ocean currents. In particular, we employ this measurement of the surface currents and wave field near a velocity front to help refine and bound results of our modeling of calculated radar images of the front. The results of this paper are compared with available ground truth.**

I. Introduction

INTERFEROMETRIC synthetic aperture radar (INSAR) has lead to a resurgence of interest in space-based and airborne remote radar sensing. The information obtained from INSAR studies is often of high quality, detailed and oft times unique.

Along-track INSAR [1], [2] is an enhancement of standard synthetic aperture radar (SAR) technique that can provide a detailed description of the motion of the radar scatterers. Ocean surface velocities are composed of a superposition of the wave field (orbital velocities), currents, etc., which directly influence the phase of the interferometric complex signal, but only indirectly affect the amplitude through the microwave modulation. Here we demonstrate how interferometric imagery can be used to quantitatively measure velocity gradients (fronts and wave fields) in the open ocean and under *some conditions* absolute (not merely relative) velocities can be determined. We also find that the signal-to-noise ratio is greater for the interferometric phase signal than for the amplitude signal of standard synthetic aperture radar (SAR). In addition, applying wave-current interaction models to the problem of simulating radar imagery, we are able to employ interferometric phase information in a self-consistent manner to test the quality of the modeling.

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II. The Model

An interferometric image is formed by combining two complex SAR images, received by two antennas separated along-track by a distance, ℓ. These two images are of the same area but displaced temporally relative to one another. Typically the time interval is very short—approximately 50 ms for the L-band ($\lambda = 24$ cm) JPL airborne SAR. When the individual SAR images are separated by a time short compared with the scene decorrelation time, one obtains the average slant-range velocity of the radar scatterers [1], [2]. The translation of scattering features produces phase differences between the two SAR images. The phase difference, $\Delta\phi$, is directly proportional to the slant-range velocity of surface scatterers [1]

$$\Delta\phi = \frac{2\pi\ell}{v\lambda}u_s, \tag{1}$$

where λ is the radar wavelength, v the platform speed and u_s the slant-range velocity of the scatterers. The interferogram is the product of the first complex SAR image with the complex conjugate of the second. Therefore its amplitude is the product of the individual SAR amplitudes, and its phase is the difference (modulo 2π) between the two SAR phases. A complicating aspect of ocean imagery is that the motion of the surface scatterers has many components which arise from different sources: intrinsic scatterer velocities, ocean currents, orbital wave motion and wind-driven features. Therefore the interpretation of the resultant current is not always straightforward [3].

The above sources of surface motion obscure the underlying currents. Separately identifying each of these surface velocity components requires the simultaneous determination of all sources of surface motion. Ground-truth can provide guidance, however, it is not always available and thus techniques which do not rely upon ground-truth should be investigated. One such method is to incorporate modeled INSAR imagery to iteratively improve the evaluation of surface velocity components [4]. We therefore need a means of comparing modeled and experimental imagery which displays directly the effects of surface velocities. Additionally, one would like to be able to iteratively refine the model either to reduce the amount of experimental information required for the model or to allow the model to better describe the INSAR measurements of the ocean surface. In this paper we show that an INSAR phase

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image can be calibrated in the absence of ground truth and then determine the accuracy of the calibration by explicitly employing available ground truth. Initial results of image modeling are also presented.

III. Setting the Scene

For definiteness, we analyze a specific INSAR image taken by the JPL AIRSAR on July 20, 1990, during the Gulf Stream experiment [5], [6]. The image is centered at 72° W longitude and 36.7°N latitude—approximately 220 miles east of Virginia Beach, Virginia. This region was extensively studied that day owing to the proximity of the north edge of the Gulf Stream [6]. This image has been studied previously [7] to ascertain absolute surface velocities, wave fields and velocity gradients near a front. The calibration of this image is important and is described below. Particular attention is paid to comparisons between the calibrated image and the available ground truth [8] to assess the adequacy of the phase calibration.

In the processing of the INSAR images the absolute phase difference between the two individual SAR images is lost. Therefore an independent means of calibrating the phase image is crucial. Typically, land is incorporated somewhere in the image to provide an absolute reference. In the open ocean this is not possible. Thus we must rely upon other means of calibration. SAR images are focused assuming stationary targets. A range-travelling target will be displaced in the azimuthal direction by an amount, Δ_{az}, proportional to its slant-range velocity.

$$\Delta_{\mathrm{az}} = \frac{u_s r_s}{v} = \frac{r_s \lambda}{2\pi \ell}\Delta\phi, \tag{2}$$

where r_s is the slant range to the target. This relationship is employed to derive $\Delta\phi$ from Δ_{az} by assuming that the true position of the displaced target is given by either its wake or the "hole" left behind in the image by the target.

The amplitude and phase of this INSAR image are shown in Figs. 1 and 2. Some relevant JPL AIRSAR parameters for this image are provided in Table I. The amplitude image contains only a weak signal for the edge of the Gulf Stream and no waves. The dark band running diagonally across the upper right portion of the image is the Gulf Stream edge as determined by in situ temperature measurements [7], [8]. Although denoted as the "temperature front", this is also the site of velocity shear and convergence [7], [8]. In contrast, the phase image clearly depicts the Gulf Stream boundary (the sharp linear dark-to-light change) and the wave field (the periodic light-dark striations throughout the image). The abrupt change of phase at the front implies a similar velocity change. In both images the research vessel Cape Henlopen, which was used to obtain the in situ measurements during the experiment, and her wake are visible.

We utilize the displacement of the Cape Henlopen from her wake to compute both her velocity and the actual phase difference of the Henlopen in the phase image, via (1) and (2). Comparison with the observed interferometric phase yields the desired calibration. The calibrated image (modulo 2π) yields the absolute slant-range velocity of the radar scatterers, (1). The 2π ambiguity in the phase can only be lifted by

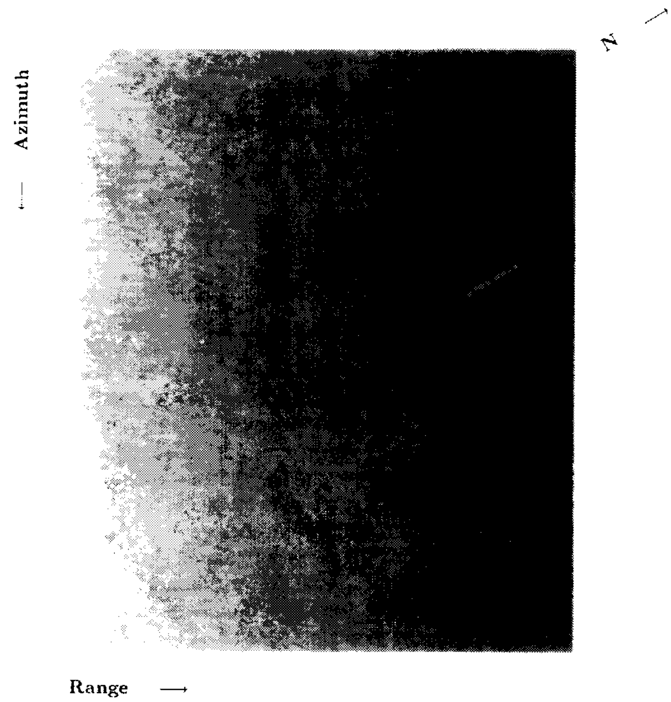

Fig. 1. The amplitude image of the complex INSAR measurement is shown. The north edge of the Gulf Stream is the diagonal dark band crossing the upper right corner. The image is approximately 10 km in the ground-range and 12 km in the azimuthal direction. The general trend from light to dark as the range increases arises from the angle dependence of the strength of the back scattered signal. The amplitude image has an arbitrary scale. The outlined area is the cut across the front that is analyzed in Fig. 3.

incorporating additional information about the scene. For this image, slant-range velocities of 0.0 m/s, 2.7 m/s, 5.4 m/s, etc., all produce a zero phase difference (modulo 2π). Therefore these velocities are indistinguishable. However, ocean scenes rarely have velocities greater than 2.7 m/s, and generally the velocity varies slowly and continuously across the image. Applying this information removes the phase ambiguity. So far, the calibration of the INSAR phase image and removal of the 2π phase ambiguity has not required specific ground truth. The only information used was either obtained directly from the phase image or concerns the characteristics of the radar system and its platform.

We have implicitly made the (in this case, reasonable) assumption that the phase correction is uniform across the image. The aircraft altitude and attitude are used in SAR processing. A small altitude offset in the original SAR processing would result in a predictable, overall drift of the INSAR phase in the range direction. This seems to have occurred in other applications of INSAR imagery to ocean scenes [9]. Time-dependent altitude and attitude errors are more varied and thus more difficult to assess *a priori*. We will return to this below. We find little, if any, drift of the average phase with range and therefore conclude that *for this image* the altitude offset is insignificant. Random phase drifts may still arise from the processing or noise. One means of estimating the random and time-varying phase drifts *a posteriori* is to determine the uniformity of the wave field. Two-dimensional Fourier analysis of the wave spectrum shows that the frequency and direction of the wave field is constant across the INSAR phase image.

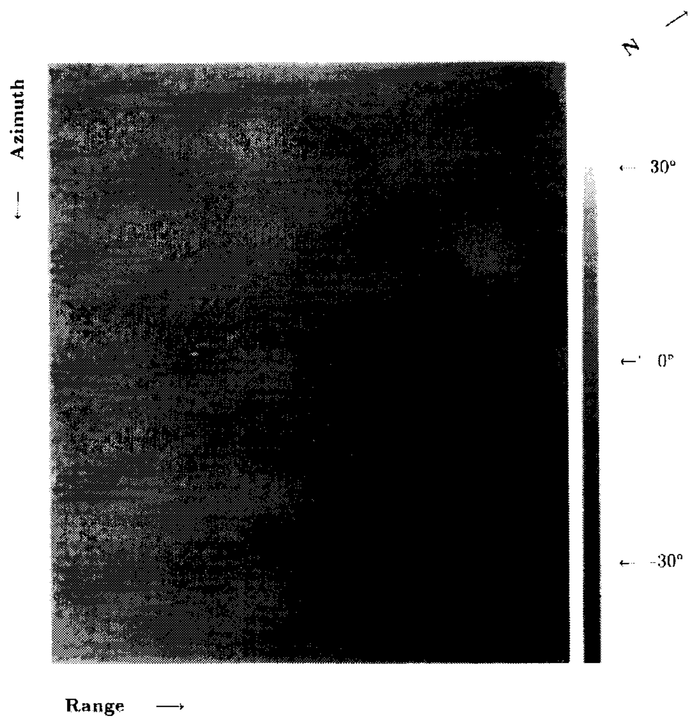

Fig. 2. The phase image from the same complex INSAR measurement shown in Fig. 1. The sharp current gradient at the temperature front stands out strongly as the sharp linear dark-to-light change. The wave field (periodic dark-light striations), the Henlopen and her wake are also apparent. The Henlopen is located approximately mid-azimuth at one-quarter range. From the angle of the wake with respect to the ground-range direction, ($\sim 14°$), the azimuthal displacement of the Henlopen and the mean surface current in the wake region, we infer both the speed and direction of the Henlopen. The boxed region is the same cut across the front as shown in Fig. 1.

TABLE I
THE PARAMETERS OF THE JPL/DC-8 INTERFEROMETRIC RADAR AND THE SLANT-RANGE AND AZIMUTHAL OFFSET OF THE HENLOPEN USED TO CALIBRATE THE INSAR PHASE IMAGE. THE AZIMUTHAL OFFSET AND SLANT-RANGE, WHICH ARE NEEDED TO CALIBRATE THE PHASE IMAGE, ARE OBTAINED DIRECTLY FROM THE IMAGERY AND THE INTERFEROMETRIC RADAR PARAMETERS WITHOUT REFERENCE TO GROUND TRUTH

Antenna Separation ℓ [m]	Radar Wavelength λ [cm]	Slant Range r_s [m]	Azimuthal Offset Δ_{az} [m]
19.3	24	10,409	124

Platform Speed v [m/sec]	Platform Altitude [m]	Platform Heading [° T]
216.5	8,350	120

Thus, both qualitatively and quantitatively the wave field is uniform across the image. For this image one infers that phase drifts are negligible and therefore that the uniform calibration is adequate.

A more detailed interpretation of the individual components of the scatterer velocity and the determination of the accuracy of this method *must incorporate ground truth.* In order to assess the accuracy of the calibrated INSAR phase, we check for consistency among independent ground truth data and information obtained from the imagery.

The wake is swept downstream by the current. A simple vector diagram relates the speeds and directions of the Henlopen and the surface current to the imaged wake. Using the current direction (78° T) from ground truth [8] in conjunction with the slant-range velocities of the Henlopen and surface current and the wake angle from the calibrated image, we

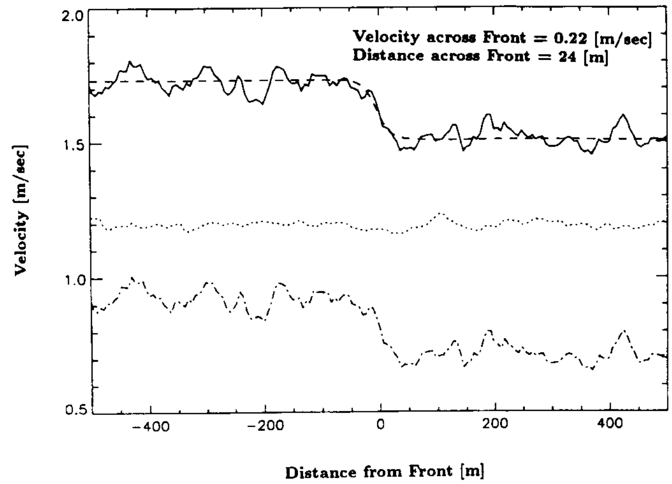

Fig. 3. A representative cut across the front is displayed. The region of interest is outlined in Figs. 1 and 2. The solid line shows the calibrated ground-range velocity of the surface scatterers. The dotted line depicts the amplitude image along the cut. (The amplitude plot has an arbitrary scale.) The dashed line is a least-squares fit of the function, $\alpha + \beta \tanh(d/\delta)$, to the velocity. From this fit we obtain 24 m for the width of the front and magnitude of the velocity jump at the front is 0.22 m/s. The signal strength ($\sim$5 dB) is estimated by considering the velocity jump as signal and the root-mean-square variation of the velocities about the fitted tanh function as noise. Removing the periodic wave motion would further enhance the signal-to-noise ratio of the velocity jump to $\sim$8 dB. A typically SAR amplitude signal strength at a velocity front is 1–3 dB, here the amplitude signal is $\sim$1.2 dB. The dot-dash line shows the surface current speed in the ground-range direction after compensating for wind drift and the intrinsic phase velocity of the Bragg scatterers.

infer both the heading and speed of the Henlopen, as well as the surface current speed. We employ knowledge of the radar parameters and platform geometry to convert amongst slant-range, ground-range, true heading, etc.

Ocean surface features tend to drift downwind. Therefore to ascertain the underlying current, wind drift must be removed. The wind drift is taken to be 4% of the wind velocity, $\sim$9 m/s from 220° T, and is assumed to be constant over the image. The wind drift velocity is $\sim$0.36 m/s in the ground-range direction. If either the wind drift correction or the phase image calibration were significantly in error then the inferred surface current, ship heading or ship speed would not match with ground truth. The magnitude of the surface current is within 10% of the ground truth determination after correcting for wind drift and the intrinsic phase velocity of the Bragg scatterers.

The ship rides upon the ocean swell and any radial motion of the ship arising from swell will be translated into an INSAR phase. If ocean swell produced significant radial motion during the SAR integration time then the wake, which also rides upon the swell, would appear jagged in the image. In this image the wake is straight and the effects of swell insignificant. Therefore, the velocity of the Henlopen determined from the imagery should be her "true" velocity. The calibrated image and the ship's log (loran-based navigation) agree: the Henlopen is headed due south at 10 knots.

Quantitative comparison of the SAR and INSAR images has been made by taking cuts across the front. An example is shown in Fig. 3; the region of interest is outlined in both images. The dashed line in Fig. 3 is a χ^2 fit of the functional form

$$\alpha + \beta \tanh(d/\delta) \tag{3}$$

to the surface velocity, d is the distance from the front and α, β and δ are fitting parameters. The relative surface velocity across the front, 0.22 m/s, is within 5% of the ground truth determination [8] and is tightly constrained by the χ^2 fit with a 68% confidence limit of approximately ± 0.01 m/s. The relative velocity is independent of our phase calibration, wind drift or Bragg phase velocity corrections and therefore reflects the quality of the original SAR (INSAR) imagery. The width of the front, ~24 m, is not so well determined having a 68% confidence limit of about ± 11 m. The absolute surface velocities on either side of the front (0.93 m/s and 0.71 m/s, respectively) do depend explicitly upon the phase calibration and the wind drift and Bragg phase velocity corrections, ~0.36 m/s and ~0.44 m/s, respectively. The absolute velocities on either side of the front are within 10% of ground truth measurements. This relatively small increase in error (5% → 10%) when determining absolute rather than relative velocity suggests that the wind drift correction and, more importantly, the phase calibration, have not introduced large uncertainties in the ground-range velocity extracted from the INSAR phase image. Even these potential differences, as well as the deviations from ground truth, may be within the limits of the errors of the ground-truth measurements, since the in situ measurements correspond to ~9 m deep subsurface currents.

The calibration and initial investigation has yielded several interesting characteristics of INSAR imagery: 1) The Gulf Stream boundary is easily inferred from the INSAR phase image. 2) Absolute calibration of the phase, and therefore velocity, can be performed in the open ocean. Any range-travelling target of opportunity suffices. 3) Both the width, 24 m, and the velocity difference, 0.22 m/s, across the front at the north edge of the Gulf Stream are quantitatively measured and agree well with available ground truth. 4) The obvious increase in signal-to-noise ratio of the INSAR image allows quantitative determination of features not contained in the amplitude image.

IV. Ocean Surface Current Modeling

The calibrated surface velocity field shown in Fig. 3 was further corrected to remove the phase velocity of the Bragg scatterers and wind-drift. A cut of the resulting surface currents and INSAR (SAR) amplitude signal near the front is shown in Fig. 4. The previous analytic fit to the mean surface current, (3), is also depicted. Unfortunately, only one component of the velocity is available from the imagery, therefore our initial calculations employ a one-dimensional model of surface currents.

For the modeling of radar scattering from an ocean surface we employ the ERIM Ocean Model (EOM) [10]. This model incorporates the effects of wind and surface currents on the hydrodynamical modeling of the ocean wave spectrum. From these generated wave spectra, the composite-scattering model is employed to calculate the radar signal. Wave breaking is not explicitly included in the radar return. This effect is addressed elsewhere [11]. The interferometric phase obtains from the instantaneous velocity field of the surface realization. For clarity and ease of presentation, results from specific calculations are compared directly to both the INSAR-derived surface current and the INSAR amplitude signal.

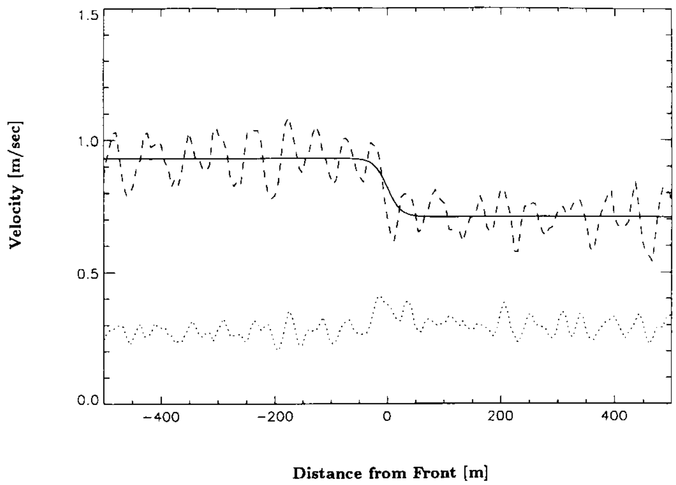

Fig. 4. The solid line shows the surface velocity used as input to the EOM. The dashed line is a realization of the total surface velocity provided by EOM. The difference between these two curves is the orbital wave motion associated with the modeled wave spectrum. The dominate wavelength of the orbital motion is ~60 meters. The dotted line shows the SAR amplitude image across the front. The modulation of this image arises from the orbital motion.

V. Analysis

The analysis starts from the actual INSAR imagery from which the surface velocity field is constructed. This velocity field comprises both the wave spectrum, specifically a snapshot of the spectrum, and the underlying ocean current. (As mentioned earlier, this is actually only the ground-range component of the actual ocean surface velocity and the following refers only to the one-dimensional modeling of this component.) We consider primarily the example of an ocean current exemplified by the tanh functional fit. This is employed as the input current to the EOM program which models the ocean surface and subsequently provides a model INSAR image. From the modeled image "new" velocity fields are calculated and separated into orbital wave motions and surface currents. Juxtaposing the new and old surface velocities allows direct comparison.

The scene is set by assuming the front to be oriented East-West with the high-velocity side to the South and the wind to be 8 m/s from the Southwest. This geometry remains fixed throughout these calculations. This wind and geometry are in accordance with ground-truth.

Fig. 4 displays the resulting surface velocity calculated by the EOM, as well as the input surface current. The orbital motion superimposed upon the surface current is apparent. Compared with Fig. 3, the orbital motion depicted in Fig. 4 implies that the EOM provides a simpler, more regular orbital wave distribution than that seen in the actual INSAR image. However, the modeled amplitude signal at the front, approximately 1.3 dB, compares favorably with the 1.2 dB signal in the INSAR amplitude image. From this we conclude that the amplitude signal at the front is favorably modeled, however, the orbital motions are both larger in amplitude and simpler in structure than actual imagery suggests.

That the amplitude signals both from imagery and from calculation are similar implies that the composite-model accurately reproduces the radar backscattering relative to background. However, the amplitude of the calculated orbital motions is larger and this thus produces a more strongly modulated INSAR amplitude image. These conclusions, based upon the relatively weak amplitude signal, are also clearly supported in the phase image. This suggests several possible solutions: 1) the wave spectra used in these calculations are too simple to reproduce observed INSAR image, 2) the one-dimensional calculation is inadequate, or 3) the extraction of the surface velocities from the imagery excessively smoothed the wave field.

VI. Wave Field

The Bjerkaas-Riedel wave spectra [12] employed in this study may be too restrictive. Hydrodynamic modulation of 1 m or shorter waves by longer waves (ocean swell) is not incorporated into the EOM. The effects of this nonlinear wave-wave interaction may be approximated by modifying the surface velocities employed as input to the EOM. Imposing the surface velocities from the observed wave field on the EOM spectrum will test the model sensitivity to nonlinear wave-wave interactions. In general, imposing this wave field shifts the strength of the EOM spectrum displayed in Fig. 4 away from 60 meter waves to both longer and shorter wavelengths. Another comparison is to consider simply a mean current of 0.819 m/s with neither a velocity front nor a wave field. In this case, the wave spectrum peaks near 50 meters and is relatively smooth. Both the presence of the front and the wave field affect the resultant wave spectrum. Therefore, imposition of an appropriately chosen "wave field" might permit more detailed modeling. However, for this image the lack of a two-dimensional velocity determination undermines this approach.

VII. Two-Dimensional Models

A second possibility is that the one-dimensional model is inherently too restrictive and therefore has no chance of accurately describing the physical scene. The simplistic nature of the one-dimension model may, in fact, also cause an excessive smoothing of the wave field. In the INSAR imagery the velocity front and the wave field are not aligned, thus the filtering done to obtain a sharp velocity front could have smoothed the wave field. A straightforward remedy is to employ the full two-dimensional image for the radial velocity and use the full geometry of the scene. This requires a two-dimensional ocean surface, with the full two-dimensional velocity field [8]. This leads precisely to the inverse problem of trying to adjust the unknown parameters, here, the shear velocities near the front, so as to best reproduce the original radar imagery. This inverse-problem approach should also lead to a clearer, more accurate separation of the processes that give rise to the ocean surface velocities.

Multiple INSAR images of the same target area would be extremely beneficial and would avoid the need to adjust unknown parameters, e.g. shear velocities near the front. To be useful, the INSAR images need to be temporally separated by less than the coherence time of the target features, e.g. Gulf Stream current, velocity fronts. This requirement is generally easy to meet. If the images are from the same look direction then one observes the time development of the velocity features. If the INSAR images are from two different directions, then a determination of the complete velocity field, rather than just one component, is possible. In either case, new information would be obtained from INSAR imagery which could not be determined in such detail or with such precision by either ship-based measurements or other remote sensing techniques.

VIII. Conclusion

We have provided a demonstration of the capabilities of INSAR measurements in the open ocean. Several general features of INSAR phase imagery are the ability: 1) to resolve sharp velocity fronts and gradients, 2) to employ range-travelling targets of opportunity for absolute calibration of the INSAR phase, and therefore the range velocity, and, 3) to provide a quantitative determination of features not seen in the amplitude image owing to the increased signal-to-noise ratio of the INSAR phase image.

We do not imply that every INSAR image can be calibrated employing the methods used here. We show merely that the phase image contains much information, some of which may be used to provide absolute phase calibration of specific images.

Because INSAR resolution is independent of range separation, these techniques allow quantitative measurements of open-ocean currents from space. This is especially important in light of the NASA's SIR-C/X-SAR shuttle experiments which include INSAR capabilities. Two of the primary ocean targets for SIR-C/X-SAR were the South Pacific Ocean and Gulf Stream "supersites." Extensive ground/sea truth has been provided for SAR/INSAR data at the Gulf Stream supersite. Therefore calibrated SAR/INSAR data will be available to quantitatively address scientific questions concerning current-wave interaction processes, flow boundaries, ocean waves and large-scale circulation.

We have also presented one-dimensional models of a Gulf Stream velocity front. The comparison of the currents extracted from the original INSAR image and those from the models shows that average features are well reproduced but that the detailed structures differ. In all calculations, the strength of the amplitude signal is similar to that from the actual INSAR image. However, the peaks of the modeled wave spectra shift when fronts or wave fields are incorporated. Also, the variance of the orbital motion about the applied surface currents is much greater than seen in the INSAR imagery.

Some problems might be most easily resolved by employing a two-dimensional model. In this way, ambiguities concerning our use of a restrictive geometry and simplified wave field could potentially be removed. The initial modeling has shown that the INSAR phase image, and to some extent the amplitude image as well, responds to changes in the underlying surface currents and orbital velocities peculiar to wave fields. Thus, with the assistance of model calculations, a self-consistent procedure for determining surface currents employing INSAR imagery may be achievable. Obtaining the self-consistent currents provides direct tests of ocean-surface modeling and the applicability of INSAR imagery to distinguish amongst the various sources of surface scatterer motion.

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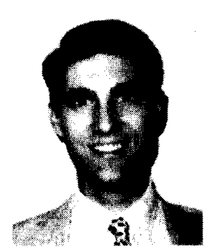
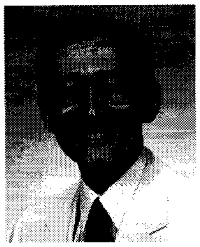
He joined the staff at the Jet Propulsion Laboratory in 1958, where his research includes telecommunications systems, radio ranging of spacecraft, and radar observations and mapping of the planets, their moons, and occasional asteroids and comets. His current work is in radar interferometric measurements of Earth's topography and displacements, glacier motion, and ocean currents and ocean wave spectra.



Robert W. Jansen was born in Mankato, MN, on October 4, 1959. He received the B.S. degree in mathematics and physics from Mankato State University, Mankato, MN, in 1981. In 1987 he received the Ph.D. degree in theoretical solid state physics from Arizona State University, Tempe.

From 1987 to 1989, he worked as a Postdoctoral Associate in the condensed matter and radiation science division of the Naval Research Laboratory. He worked from 1989 to 1991 at Dynamics Technology where he became interested in remote sensing. Since January 1991 he has been employed in the Remote Sensing Division of the Naval Research Laboratory at Washington, DC. His research efforts have encompassed a broad range of topics. In the area of solid state physics he has made numerous contributions to the understanding of the electronic structure and energies of defects in semiconductors. Since 1990 he has been involved in research relating to remote sensing of the ocean surface. His primary focus has been the effects of wave-current interaction on surface wind waves and real- and synthetic-aperture radar imaging of the ocean surface. He is also involved in other aspects of ocean research, including signal processing, system modeling and simulation, bathymetry prediction from radar signatures, radiowave propagation, and electromagnetic scattering.



Jong-Sen Lee (S'66–M'69–SM'91) received the B.S. degree in electrical engineering from the National Cheng-Kung University, Taiwan, in 1963, and the A.M. and Ph.D. degrees from Harvard University, Cambridge, MA, in 1965 and 1969, respectively.

Since then he has been with the U.S. Naval Research Laboratory (NRL), Washington, DC, where presently he is the head of the Image Science Section, Remote Sensing Division. He is also the principal investigator of the remote sensing program on frequency and polarization diversities. He developed several speckle filtering algorithms for SAR images, which have been implemented in many GIS software packages. His research covers a wide spectrum of areas. He worked on control theory, operations research, radiative transfer, image processing, and SAR processing, image segmentation, speckle analysis, and filtering. His current research interests are in the area of polarimetric SAR image segmentation, statistical analysis, scattering signature modeling, and SAR interferometry.

Gaspar R. Valenzuela (S'54–M'56–SM'66) was born on January 6, 1933, in Coelemu, Chile. He obtained the B.S. and M.S. degrees from the University of Florida, Gainesville, in 1954 and 1955, respectively, and Ph.D. degree from the Johns Hopkins University, Baltimore, MD, in 1965, all in electrical engineering.

From 1955 to 1957 he was an Associate Engineer at Westinghouse Electric Corp., Baltimore, MD, performing R&D and design of microwave and antenna systems. From 1957 to 1968 he was an Associate/Senior Staff at the Applied Physics Laboratory, Laurel, MD, and Research Associate at the Carlyle Barton (formerly the Radiation) Laboratory, Baltimore, MD, both at the Johns Hopkins University, where he performed research in wave-field theory and its applications, including millimeter waves, quasi-optical techniques, and scattering for statistical rough surfaces (in particular, the ocean). From 1968 to 1993 (when he retired from the Civil Service of the U.S.), he was Electronic Engineer/Project Leader/Section Head at the Naval Research Laboratory, Washington, DC, performing and leading research in radio oceanography, nonlinear wave dynamics, and space oceanography. During this time, he also organized remote sensing experiments involving airplanes, ships, and NASA's Shuttle to investigate current-wave interaction processes at Nantucket Shoals, MA and the Gulf Stream off the East Coast of the U.S. His latest involvement was in NASA's/Navy SIR-C/S-SAR programs at the Gulf Stream Supersite in 1994. After his retirement from the Federal Government, he was a Senior Scientist with Allied Signal Corp., Camp Springs, MD, for about one year. Presently, he is a Consultant in Remote Sensing, Columbia, MD. He has written about 60 journal publications, more than a dozen formal reports, and has presented about 80 oral presentations at national and international symposia and workshops, many by invitation.

Dr. Valenzuela is a member of Commissions B and F of the International Union for Radio Science (URSI) and has been a U.S. delegate to five General Assemblies. He is a member of the American Geophysical Union (AGU), and is a Registered Professional Engineer in the State of Maryland. He has been listed in *American Men and Women of Science* since 1973.