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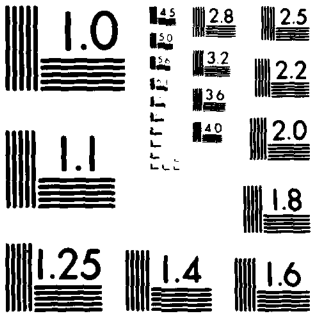

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NORDA Technical Note 104

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Naval Ocean Research
and Development Activity
NSTL Station, MS 39529

Describing Ocean Phenomena Using Coherent Radars

Proceedings of a NORDA Workshop held at NSTL Station, Mississippi, 13-15 November 1979

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Washington, D.C.

MAY 1981

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II. INVITED TALKS - SUMMARIES

III. PLENARY SESSION

A. Working Group Reports

I. INTRODUCTION

The Naval Ocean Research and Development Activity (NORDA) inaugurated a series of oceanographic workshops during the fall of 1979 covering various topics in ocean science and technology. These workshops were sponsored by the Chief of Naval Research. On 13-15 November 1979, a workshop entitled "Describing Ocean Phenomena Using Coherent Radars" was held at NORDA, which is located at the National Space Technology Laboratories near Bay St. Louis, Mississippi. Leading workers in both hydrodynamics and electromagnetic scattering came together to discuss the status of relevant scattering theories, the kinds and reliability of data obtained with different sensor systems, and the hydrodynamic information extractable from these data.

Unlike the many conferences and symposia available for the formal presentation of contributed papers, this workshop concentrated on maximizing group discussion and interaction. Its format consisted of one day of invited talks and two days of participation in working groups. Overviews of the various areas relevant to the workshop topic were presented in the invited talks, and ample time was allowed for lively discussion. The time in the working groups was spent assessing "where we are," "where we should be going," and "how do we get from here to there."

To assure that the working groups addressed the most relevant issues, the participants were canvassed ahead of time for suggested topics and specific questions to be addressed. Based on these inputs, the Workshop was broken into four Working Groups, each covering a specific area within the Workshop's general theme. Topics and questions were listed for each working group and distributed to participants well before the workshop convened. These topics and questions were utilized only to provoke discussion and serve as initial guidance, and were not employed to set limits on the working groups' deliberations. It should be noted that the list is too long for every question to be adequately addressed during the time allotted. It was therefore up to the concentrated wisdom of the participants to select topics which could be usefully addressed. Participants were free to choose which working group to join. Although some specific time had been set aside for interactions between working groups, much informal interaction occurred among individuals throughout the Workshop.

Judging by the participants' comments, the Workshop was a success. In the following material the invited talks and the plenary session are summarized along with the presentation of the reports of the working groups. During the interval between the conclusion of the workshop and the publication of these proceedings, many papers that were in preparation or had been submitted to journals subsequently appeared in print. For completeness, these later references have been cited. A sample of the give-and-take interplay that occurred throughout the workshop may be found in the Open Discussion at the end of this report.

WORKING GROUPS - SUGGESTED TOPICS & QUESTIONS

1. SEA SURFACE HYDRODYNAMICS (Chairman: DR. F. W. Dobson)

   - Which oceanographic research problems can be uniquely addressed with coherent radar? (e.g., can radar returns improve our understanding of nonlinear wave-wave interactions?)
   - Are the parameters of wave prediction models proper radar observables?
   - What are the present capabilities and future needs in establishing sea truth for coherent radar measurements of the sea surface?
   - What is the character of the sea surface in the neighborhood of a breaking wave? (of interest in radar image interpretation)
   - Dynamics of capillary wave fields (e.g., role of capillary waves in wave dispersion and absorption of momentum).
   - Is there a known transfer function for relating wind stress to surface roughness.
   - Remote probing of the mixed layer (e.g., Langmuir circulation, inertial motion, internal waves, etc.).

2. SCATTERING THEORY AND PHENOMENOLOGY (Chairman: DR. A. F. Fung)

   - Can present scattering theories adequately explain the returns from a high-resolution coherent radar? Or, are there important phenomena not included in present formulations (time-varying small-scale scattering elements; scattering from breaking waves, foam and spray, effects of shadowing and diffraction at low grazing angles)?
   - What ambiguities exist in the inference of surface dynamics from the scattered signal? (e.g., strain-rate effects due to internal waves as compared with those due to orbital motion in mild swell.)
   - Is σ^0 a significant parameter in describing returns from a high-resolution coherent radar?
   - Can formal inverse-scattering methodology be successfully applied to coherent radar data?

3. SYNTHETIC APERTURE RADAR (SAR) (Chairman: Dr. R. O. Harger)

   - How does scatterer motion affect SAR imagery, and what are the implications in imaging wave patterns, currents, and other surface features?

- What "spectrum" may be deduced - if any?

- What are the present performance limitations, and how can information encoding and extraction be optimized?

- What is the status of digital SAR processing, and how far off is real-time imagery?

- How much sea truth has been available for use in interpreting SAR images? Should the acquisition of this information be more strongly emphasized?

- What is a good strategy for approaching an adequate physical understanding of SAR images?

4. REAL APERTURE RADAR (SINGLE FREQUENCY, MULTIPLE FREQUENCY, AND HF)
(Co-chairmen: Dr. W. J. Plant and Dr. D. E. Barrick)

- What are the capabilities and limitations of simpler microwave radar configuration in obtaining information about the sea surface?

- How effectively can multi-frequency coherent oceanographic radars operate from moving platforms?

- How accurately does HF radar determine sea state? The directional spectrum?

- What are the present and projected capabilities of HF radar in mapping such features as the Gulf Stream and mesoscale eddies?

- What is the nature of, and how does one remove, ionospheric contamination of oceanographic information obtained by a sky-wave HF radar?

- What cost-effectiveness trade-offs exist among the various tested coherent oceanogrpahic radar systems (single-frequency, two-frequency, HF, SAR)?

AGENDA

Tuesday, 13 November 1979

All day - Invited Talks and Discussion

K. Hasselmann
Models of the Sea Surface and their Application for Understanding the Sea Surface Using Coherent Radars

G. Valenzuela
Electromagnetic Scattering from Stochastically Varying Rough Surfaces

R. K. Raney
SAR Sensors, Systems, and the Processing of Dynamic Phenomena

D. Barrick
Ocean Surface Features Using HF Doppler Radar

W. Plant
Single and Multiple Frequency Radars

R. C. Beal
Seasat SAR Overview

Wednesday, 14 November 1979

Morning First Meeting of Working Groups
Establish Group Identity

a. Agree on major topics to be addressed
b. Describe "where we are"
c. Decide "where we want to go"

Afternoon Second Meeting of Working Groups

a. Identify information needed from experts in other working groups
b. Select representatives to obtain the required information from the other Working Groups

Third Meeting of Working Groups

a. Working Group Interactions - Representatives attend other Working Groups and discuss information requirements

Thursday 15 November 1979

Morning Fourth Meeting of Working Groups

- a. Determine "How we get from 'Here' to 'There'"

Afternoon Plenary Session

- a. Individual Working Group Summaries
- b. Wrap Up

MODELS OF THE SEA SURFACE AND THEIR APPLICATION FOR UNDERSTANDING THE SEA SURFACE USING COHERENT RADARS

K. HASSELMANN - Max-Planck-Institut fur Meteorologie

Editor's Summary

This talk was divided into two parts. The first part presented a generally optimistic view of our present understanding of ocean wave spectra and how this understanding can be expected to grow in the next few years. The radiation transport equation provided a convenient theoretical framework on which to hang the various elements which produce and structure the spectrum. While there are still many unknowns - in the atmospheric input, in the dissipative processes, and in the nonlinear wave-wave interactions - we know pretty well which experiments are required to answer most of the questions. Even in the difficult area of modulation transfer functions (which describe the modulation of short waves by long waves), it is expected that useful models will be at hand in a few years.

The second part treated topics in mapping the moving sea surface into a SAR image, and how best to utilize the data collected by a SAR. After deriving the received signal phases associated with various motions of the scattering facets (assumed to be Bragg scattering patches which are small compared to the length of the long waves), it was noted that each setting of the quadratic coefficient in the matching filter will focus on a different class of target facets according to their acceleration in range and/or velocity in cross-range (azimuth). This process raises an essential ambiguity in the inferences to be drawn from the filter correction required to bring a SAR image of the sea into focus. Under most SAR operating configurations, normally occurring orbital accelerations require about the same focusing correction as would the phase velocity of a normally occurring cross-range wave. Thus the need to provide such a correction could mislead the SAR operator into believing he is seeing a "wave velocity," when actually he is looking at an accelerated Bragg patch bobbing up and down on the surface as the wave goes by. Finally, it was argued that if the goal is simply to extract the wave spectrum, there are probably simpler and cheaper ways to use the SAR data. An example of such a method has since been published (see K. Hasselmann, "A Simple Algorithm for the Direct Extraction of the Two-Dimensional Surface Image Spectrum for the Return Signal of a Synthetic Aperture Radar," Int. J. Remote Sensing, Vol. 1, No. 3, p. 219-240, 1980).

ELECTROMAGNETIC SCATTERING FROM STOCHASTICALLY VARYING ROUGH SURFACES

G. R. Valenzuela - Naval Research Laboratory

Author's Summary

Advances in remote sensing of the ocean surface from satellites, aircraft, and coastal zones offer new opportunities and challenges in basic research to both oceanographers and engineers. To take advantage of these powerful experimental techniques one must understand not only the physical processes involved in the interaction of EM radiation and ocean waves, but also the analytical techniques of EM theory used to extract physical information from the sensed data.

In this presentation classical methods in EM scattering (e.g., geometrical and physical optics, perturbation, iteration and integral equations) and their application to the ocean surface are reviewed (for details see Valenzuela, 1978a and 1978b). In dealing with EM scattering from the "weakly" nonlinear ocean surface, the boundary-value problem cannot be solved exactly, since only the first few moments of the surface displacement distribution are known. As a first approximation the ocean surface is taken to be a homogeneous, stationary, Gaussian process. For the ocean, the high frequency scattering methods (geometrical and physical optics) and perturbation (Rayleigh-Rice), or a combination of them, have provided tractable analytical results (i.e., the specular-point, the slightly rough Bragg scattering and the two-scale surface models). At present these models are widely accepted and used in remote sensing applications of oceanic parameters at HF and microwave frequencies. However, unsolved problems remain in scattering at near-grazing incidence where shadowing, diffraction, refraction, focusing, and intermittency become important (Wetzel, 1978).

Applications of these models may be found in altimetry, scatterometry, HF and microwave probing, delta-K radar and SAR/SLAR imagery of the ocean. A new formulation to interpret SAR imagery of ocean waves, based on two-scale Bragg scattering, has been developed (Valenzuela, 1980).

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Valenzuela, G.R., "Theories for the interaction of electromagnetic and oceanic waves - A review," Bound.-Layer Meteorol., 13, 61-85, 1978a.

Valenzuela, G.R., "Scattering of electromagnetic waves from the ocean," Surveillance of Environmental Pollution and Resources by Electromagnetic Waves (T. Lund, ed.), 199-226, D. Reidel Pub. Co., Dordrecht, Holland, 1978b.

Valenzuela, G.R., "An asymptotic formulation for SAR images of the dynamical ocean surfaces," Radio Sci., 15, 105-114, 1980.

Wetzel, L.B., "On the origin of long-period features in low-angle sea backscatter," Radio Sci., 13, 313-320, 1978.

SAR SENSORS, SYSTEMS, AND THE PROCESSING OF DYNAMIC PHENOMENA

R. K. Raney - Canada Centre for Remote Sensing

Editor's Summary:

In a brief review of SAR processing, it was emphasized that the choice of the processor involves certain assumptions about the coherence properties of the scene being viewed, and the failure of the scene to satisfy these assumptions leads to difficulties in the reliable interpretation of the resulting image. The ocean contains moving scatterers whose returns remain coherent only over finite lifetimes. But even when fully coherent returns are processed through a conventional coherent SAR processor, scatterer motion will lead to failures in the accuracy of mapping scene-to-image, as well as a degradation of system resolution. These failures can be illustrated by the simple scene of a highway system populated by cars moving in various directions. The images of the cars are blurred and displaced according to the speed and direction of their motion. The return from the ocean is only partially coherent, in the sense that the reflectivity experiences random fading with lifetimes (or coherence times) that are generally shorter than the integration time of the SAR processor. It was shown that a partially coherent SAR processor, whose quadratic filter contains a coherence weighting function matched to the scene, will improve the imaging of such returns. The details of this discussion have since been published (see R.K. Raney, "SAR Response to Partially Coherent Phenomena," IEEE Trans. Antennas Propagat., AP-28, 777-787, 1980; see also, "SAR Processing of Partially Coherent Phenomena," Int. J. Remote Sensing, Vol. 1, No. 1, pp 29-51, 1980.)

OCEAN SURFACE FEATURES USING HF DOPPLER RADAR

D. Barrick - NOAA/Wave Propagation Laboratory

Editor's Summary:

A movie entitled "CODAR - Coastal Ocean Dynamic Application Radar" introduced this talk. The movie described the basic approach used in CODAR, provided examples of its application in mapping the currents in Cook Islet, Alaska, and in the Straits of Juan de Fuca, and discussed tests of its accuracy and the improvements that have been made. Technical details of recent current measurements followed.

Next, HF skywave radar was received. Skywave radar involves an ionospheric reflection and is therefore able to look out to relatively long distances (3000 km). The key to using this type of system is to learn how to deal with the ionosphere and the signal perturbations and distortions created by its fluctuations. Strategies to deal with this problem have been worked on during the last several years. One technique, for example, is to determine automatically the width of the first-order Bragg line and assign a quality factor to it. The value is then used to help determine which samples to use, based on how many you have and their relative quality factors. The hierarchy of parameters that are measurable from skywave radars include: surface wind direction, surface currents, the dominant periods of waves and swell, RMS wave height (or significant wave height), wave direction, non-directional spectrum, and, possibly, the wave height directional spectrum (but much more work is required before it is clear that this parameter is obtainable). Several examples of measurements were shown.

The final topic discussed was that of getting the wave height directional spectrum from second order Doppler scatter. Second-order interactions fill the spectrum around the first-order Bragg lines with components determined by both hydrodynamic and electromagnetic nonlinearities in the boundary conditions at the ocean surface. The theory is straightforward, but the problem of inverting the HF signal spectrum to recover the ocean wave spectrum presents formidable analytical difficulties. The inversion problem simplifies if one operates at the high frequencies where the first-order Bragg lines are saturated (no wind speed dependence), and the sea is swell-like. Comparisons of skywave radar data with buoy records and ships reports were shown. Finally the progress in going to compact antenna systems was presented.

SINGLE AND MULTIPLE FREQUENCY RADARS

W. J. Plant - Naval Research Laboratory

Author's Summary:

This talk concentrated on the information which may be extracted from the outputs of single and dual frequency microwave radars viewing the ocean surface at angles away from nadir. If a surface area small in both dimensions compared to dominant ocean wavelengths is illuminated with a single-frequency radar, a two-scale radar wave probe is produced. This system is two-scale in the sense that power spectra of long ocean waves may be derived from the FM part of its output, while information on smaller-scale structure (modulation transfer functions, modulated surface wind stress) may be derived from the AM part. If the azimuthal dimension of the footprint of such a system is made large compared to oceanic wavelengths, directionality is obtained from the two-scale wave probe. That is, the system responds only to ocean waves traveling in a nearly radial direction.

Similar directionality is obtained with dual-frequency systems which illuminate surface areas large in both dimensions. Such a system backscatter is due to a "pseudo-Bragg" resonance between the envelope of the transmitted signal and long, radially traveling ocean waves. In addition, the spectrum of the returned signal contains a smeared background which acts to limit the signal-to-noise ratios that can be obtained. A variety of comparisons of dual-frequency data with theoretical expectations shows sufficient agreement to lead us to believe that dual-frequency systems are well understood. Such systems have the potential of measuring directional ocean wave spectra, currents, and modulation transfer functions of meter-length surface waves. Details of much of this talk have since been published (see W. J. Plant and D. L. Schuler, "Remote Sensing of the Sea Surface using One- and Two-Frequency Microwave Techniques," Radio Sci. 15. 605-615, 1980).

SEASAT SAR OVERVIEW

R. C. Beal - Applied Physics Laboratory/John Hopkins University

Editor's Summary:

This talk started with a discussion of the quantity and geographical and temporal coverage of SEASAT SAR data. After examples of typical passes were shown, the discussion concentrated on an area around Cape Hatterais on September 28, 1978, when "surface truth" was available from the NOAA SLAR aircraft working in the same area.

A comparison was made between optically processed SAR data using an algorithm which works over land and the same data processed with a matched filter that takes into account the velocity of the spacecraft and of the earth's rotation (i.e., net effective velocity). The matched-filter processing was shown to provide better wave train resolution.

Additional SEASAT SAR images and processed data were shown in which an 11 second wave train was identified. This wave train was seen to undergo wavelength shortening as it progressed into shallower and shallower water. It could also be seen to disappear in areas of low wind (no scatterers present), reappear in areas where the winds increased (as determined by SEASAT Scatterometry), disappear in the area of maximum Gulf Stream Current and reappear on the other side.

Additional points discussed: after the winds increased, the 11 second system was all that was seen because the wind had not been up long enough to create a new system that would show up within the resolution limit of the SAR; the Fourier Transform (Spectrum) brings out a lot more information than the eye can see in an image; airplane-derived data showing areas of high air-sea temperature differences corresponded to areas of high roughness in the SAR imagery; and in some cases an expression of bathymetry could be obtained from the SAR (e.g., Cape Cod).

PLENARY SESSION

REPORT OF THE WORKING GROUP ON SEA SURFACE HYDRODYNAMICS

F. Dobson, Chairman

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Experiment 8: Measurement of gravity-capillary and breaking waves (H.-T. Liu)

Experiment 9: Joint studies of the remotely sensed sea surface wave height and general oceanographic "signatures" of sea surface features (P. La Violette)

10. Further ideas on wave height measurements:

   i Laboratory measurements, by "conventional" and radar techniques, of the high-frequency dispersion relation of growing gravity-capillary waves (W. Keller)

   ii Radar studies of wave climate and prediction (D. Ross, W. J. Pierson, Grafton Hui)

   iii The straining of short waves by long ones (K. Hasselmann, W. Keller)

b. Wind Velocity

Comment 1: SASS (T.P. Barnett)

Comment 2: The accuracy of ground-"truth" wind measurements (F. Dobson)

Comment 3: Wind speed and direction measurements (W. J. Pierson)

Comment 4: The wind stress - wind speed relationship (F. Dobson)

Comment 5: Surface truth for surface wind stress (P. Smith)

Comment 6: Ground truth and models of the Planetary Boundary Layer (F. Dobson)

c. Current

Experiment 1: The measurement of mean current profiles near the sea surface (F. Dobson, T. P. Barnett)

Experiment 2: Measurements of the current fields associated with Langmuir circulations, in the laboratory and at sea (M. Y. Su)

Experiment 3: Study of current shears associated with fronts (P. La Violette)

Comment 1: Study of geostrophic currents with radar altimeters (L. S. Fedor)

d. Temperature

E. Bibliography

LIST OF PARTICIPANTS

NAME	Field of Interest	Affiliation
T. P. Barnett	Climate dynamics	Scripps Institution of Oceanography
F. W. Dobson	Wave generation	Bedford Institute of Oceanography
L. S. Fedor	Satellite altimeter	NOAA/Wave Propagation Laboratory
W. H. Hui	Gravity wave dynamics	Department of Applied Mathematics, University of Waterloo
W. C. Keller	Coherent microwave sea	Naval Research Laboratory
D. Kwoh	Microwave backscattering	TRW Systems, Inc.
P. E. LaViolette	Air-sea-interaction Deep-sea oceanography	Naval Ocean Research and Development Activity (NORDA)
H. T. Liu	Wind waves, internal waves	Flow Research Company
P. C. Liu	Surface wave measurements	NOAA/Great Lakes Environmental Research Laboratory (GLERL)
T. Mottl	Remote sensing	The Analytic Sciences Corporation (TASC)
W. J. Pierson	Wave forecasting/ SEASAT	Institute for Marine and Atmospheric Sciences, City College of N. Y. (IMAS)
D. Ross	Waves	NOAA/Atlantic Oceanographic and Meteorological Laboratories (AOML)
L. Rouse	Coastal circulation/Air-sea-interaction	Louisiana State University Coastal Studies

LIST OF PARTICIPANTS (continued)

Name	Field of Interest	Affiliation
P. Smith	Radiometry	NORDA
M. Y. Su	Wave dynamics/Langmuir circulation	NORDA
F. Wu	Air-sea interaction/ Coastal wave characteristics	Tetra Tech, Inc.
R. L. Zalkan	Physical Oceanography	NORDA

A. List of presubmitted questions

1. Which oceanographic research problems can be uniquely addressed with coherent radar? (e.g., can radar returns improve our understanding of nonlinear wave-wave interactions?)

2. Are the parameters of wave prediction models proper radar observables?

3. What are the present capabilities and future needs in establishing sea truth for coherent radar measurements of the sea surface?

4. What is the character of the sea surface in the neighborhood of a breaking wave? (of interest in radar image interpretation)

5. What are the dynamics of capillary wave fields (e.g., role of capillary waves in wave dispersion and absorption of momentum)?

6. Is there a known transfer function for relating wind stress to surface roughness?

7. How may properties of the mixed layer be probed remotely (e.g., Langmuir circulation, inertial motion, internal waves, etc.)?

B. Summary of activities

a. Introduction

As can be inferred from the list of participants, the Working Group (WG) was made up of individuals with interests covering a wide variety of fields. The group found common grounds for discussion only with great difficulty and often required rather forceful leadership to prevent general anarchy. On the first day it took most of the morning to reach agreement on what the best course to follow should be.

It was decided not simply to answer the preselected list of questions; the answers would hopefully come out in the course of the "structured" discussions. An initial attempt was made by the chairman to organize the meeting around discussion of important oceanographic and meteorological problems, assigning priorities and means for their solution. This attempt failed. Instead, the group opted for a listing of the oceanographic and meteorological observables, followed by general discussions on measurement difficulties, particular experiments that needed to be done and attempts at assigning priorities. It was further decided to take careful notice of the reports from three other meetings: The Hamburg Remote Sensing Symposium of 1974 (Hasselmann, 1978); the second SEASAT GOASEX Workshop (Barrick, Wilkerson et al., 1979); and the August Scripps/JPL Workshop on Oceanography from Space (JPL, 1980). The WG expressed eagerness to see some of the early MARSEN results (but nothing from MARSEN is expected until, at earliest, the beginning of 1980).

b. The current situation

The use of coherent radars as an oceanographic tool has progressed a long way since the recommendations of the Hamburg Symposium were penned: SEASAT has come and gone, and many collaborative efforts are in progress now in all the special areas mentioned at the Symposium. Significant new techniques (that is, new in the sense that they have appeared since the Hamburg Symposium) have not materialized; rather, the old ones have been refined and broadened in their range of applicability. An example would be Barrick's "Codar," which has now been polished into an operational tool but which, at the time of the Hamburg Symposium, was only in the testing stage.

It seemed to the Group that in general the coherent radars discussed at the present workshop were now "to first order" calibrated against ground truth measurements to within the limits of existing comparison techniques. Many of the radars are now believed by their proponents to be capable of achieving greater accuracies than can be attempted with surface truth techniques. Examples are many: wave power spectra measured by conventional techniques in the open ocean only give ±25% answers for the energy in a given spectral band and ±10% at best for the variance, while SEASAT altimeter results (see Barrick, Wilkerson et al., 1979) are considered to be more accurate. The problem is outlined by W. J. Pierson and D. Ross in the commentary that follows.

1. Inherent Difficulties in Comparing Conventional Oceanographic and Meteorolgical Data with Remotely Sensed Data (W.J. Pierson)

Measurements of winds, waves and currents by conventional means are being more and more frequently compared with measurements of winds, waves and currents by remote sensing techniques. When compared in this way the two measurements differ. Usually the "accuracy" with which each measurement was made is not well known, and there are difficulties in extrapolating and interpolating the measurements in space and time so that they can be compared.

It is usually a misnomer to refer to the difference between a conventional measurement and a remotely sensed measurement as an "error." Such differences are often found to be the sum of "small" errors in the conventional measurements, "small" errors in the remote measurement, and an actual difference in the quantities measured at two slightly different locations at two slightly different times that is the result of turbulent fluctuations (or random fluctuations for waves) at scales comparable to these time and space differences. These turbulent fluctuations are inhomogeneous and anisotropic, occurring in an inhomogeneously stratified fluid at scales bordering on the mesoscale, for which conventional Kolmogorov scaling and Taylor's hypothesis are of doubtful validity. A considerable effort will be required to define optimum current and wind sampling times and optimum wave recording times in terms of statistics and turbulence theories before comparisons between remotely sensed data and conventional data can be improved.

2. Difficulties in Ground Truthing Radar Observables: comparisons of remote and in situ measurements of ocean surface geophysical variables (D. Ross)

The Group considered the state of the art in "ground truth," and how it might be improved. The intercomparison of satellite and/or airborne measurements of surface winds, waves, and temperatures is complicated by (1) the degree of stationarity and homogeneity of the environment, (2) the calibration of the "ground truth" instrumentation, and (3) the degree of understanding of the physics involved in the transfer function required to extract the geophysical variables from the remotely sensed variables. Wind speed references are most often drawn from operational meteorological buoys, weather and research ships, research aircraft, and merchant ships. Each class of measurement platform has its attributes and drawbacks. Research aircraft, for example, can obtain detailed spatial measurements in severe hurricanes and winter storms. A boundary layer model, however, must be imposed to estimate the surface wind characteristics. Operational buoys are subject to calibration errors and the comparison of the measured variable to the remote measurement must be made with a relatively poor knowledge of spatial and temporal variations. The result is accuracies on the order of 10% in both instruments. This is not to say that such accuracies preclude use of the information; climatological (e.g., long-term) variations in many situations are much greater than ±10% of the mean (the trade wind system, for instance, has typical climatological standard deviations of 30-50%).

With respect to wave measurements, the same difficulties with stationarity and homogeneity apply with the additional complication of lack of directional information. At the present time, only research buoys give reliable measurements of the wave directional properties in deep water. Unfortunately, the buoys are limited to moderate conditions and do not have the same directional resolution as the airborne or satellite-borne instruments. Again, the result is, at best, a 10% measurement (Stewart, 1980). It appears that aircraft or satellite-borne radar systems can measure surface wind speed and wave height to an accuracy of 10%; wave direction properties observed by SAR appear to be accurate to 10% in the restricted case of swell traveling predominantly in the range direction (Barrick, Wilkerson et al., 1979). It therefore appears to this Group that:

(1) The existing accuracies are suitable for a variety of purposes and should be exploited by the oceanographic community, and

(2) The goal of future development programs should be to reduce the bases in the measurements by careful experiments designed to improve the physics of the algorithms and the accuracy of the ground truth data used to calibrate the instruments.

Summary

In the Workshop itself it was clear that there is excellent theoretical talent investigating the problem of what a radar return from the rough sea surface means. There also appears to be more than adequate engineering talent available to build the necessary instrumentation. There existed, in spite of this, a general lack of understanding by the sea surface hydrodynamicists of the radar experts' point of view, and vice versa. What struck the Working Group most strongly was the lack of any imaginative scientific programs associated with remote sensing projects. Most particularly, it was apparent that there were a number of projects which could be undertaken now with the current state of the art that would be potentially of first-order importance to oceanography and meteorology. Such projects are mentioned below and are discussed in detail as individual experiments under "Radar Observables". There is evidence (JPL, 1980) that the satellite remote sensing community is awakening to the knowledge that the data it collects must be archived in a form both easily accessible to and easily interpreted by the scientific community. The Workshop participants welcomed the proposals on data management set forth in the JPL-SIO Report (JPL, 1980: Sections 3.6, 4.4), which call for a structured series of data banks and planned data bank management, and strongly urged their implementation by the remote sensing community in general.

C. The importance of collaborative experiments

The Working Group felt that in spite of the ground truth problem enormous fields of study have been opened up by the use of coherent radars; fields which are now only beginning to be entered by the investigators. In the upper few tens of meters of the ocean, wave-induced currents dominate the motions observed by conventional devices such as current meters (see McCullough, 1980, for example). Devices such as those used by the Standford/Scripps Group (C. Teague, R. H. Stewart) and the NOAA Wave Propagation Lab Group (D. Barrick, B. Lipa), which effectively average out wave-induced effects over a large area by asking what mean current is advecting the wave along, offer unprecedented opportunities for studying the rather complex but extremely important transfer processes which occur in the upper few tens of meters of the ocean. Such features as internal wave packets, mesoscale circulation patterns ("rings') and fronts (discontinuities in current velocity, sea surface temperature, air-sea temperature difference, salinity, etc.) are commonly made visible to radars by changes of the small-scale wave field in their vicinity.

Joint experiments which use conventional oceanographic techniques to delineate the subsurface structure of the features, conventional or newly-developed wave and current measurement techniques to provide information on perturbations of the wave field, and various radars to provide the large-scale structure of the surface features are required. Such experiments would provide badly needed information on the relation between surface manifestations and underwater processes, the development in time and space of the features themselves and of the mixing processes involved, and on the interactions of surface waves with various types of flow. Typical specific questions being asked by the oceanographers are (see Kraus, 1977): (1) what happens to the momentum lost by a growing wave field, once it gets into the water by means of wave dissipation? (2) How fast does this momentum propagate downward? (3) What proportion of the strong mixing of the water column that occurs during storms is forced directly by the wave field? (4) What is the "transfer function," in time and space, between fluctuations in the depth of the mixed layer and the overlying wind field? (5) What time and space scales are dynamically and thermodynamically important in the upper layers of the ocean? For temperature? For salinity? For velocity? What are the directional and spatial characteristics of wave and current fields, and the variation in mean water level, in the near-shore regions (and the surf zone)? Questions of equal importance are being asked by the radar experts of the oceanographers and hydrodynamicists: (1) Why does SAR have so much more trouble imaging sea waves than swell? (2) How phase-coherent are the scatterers in SAR? (3) What are the detailed slope statistics of the high-frequency waves which scatter the radar (the answer is crucial for the radar altimeter)? (4) Can better estimates of the wave directional spectrum and of the wind stress field over the ocean be made available for more accurate testing of the radars (How "representative" are Eulerian point measurements)? (5) Is the microwave brightness a significant parameter? Can it be reliably related to u_*? To U_{10}? (6) What are the statistics of foam and spray distributions over the ocean, as a function of wind speed? As a function of air-sea temperature diffference?

Obviously these questions cannot be answered by the oceanographers or by the radar people in isolation. Joint experiments, designed to answer crucial questions, are what is required. Because such experiments are inherently expensive and time-consuming, and have a large likelihood of failure due to the lack of suitable oceanographic or meteorological conditions at the time they are mounted; they must be designed to be as independent of the weather as possible and be carefully focused to look at one phenomenon at a time. This design requires extensive preplanning and study, by conventional means, of the phenomena concerned; it means careful choices of sites and times; it means, in other words, studies which are as complete and self-contained as is feasible, with a maximum utilization of the particular tools needed for the particular experiment. Some such experiments are about to begin, for instance, in the coastal waters of Oregon and California - a collaboration of Barrick's group with people from Scripps and OSU. But numerous other such experiments are possible.

The ground truthing exercises of today must be inverted to provide the data banks for tomorrow's experiments, e.g., on western boundary current dynamics and deep ocean tide studies. The radar altimeters from SEASAT and from GEOS-3 have provided a wealth of information on wave fields over the entire globe, and therefore should provide wave climate information in hitherto inaccessible areas, while the SEASAT altimeter simultaneously provided physical oceanographers with a great deal of useful information on relative dynamic sea surface topography. The oceanographic experiments often require a precision, for instance, in the case of relative dynamic topography studies, which presently lies at the limit of the capabilities of the radar. Many difficulties remain to be overcome, but the payoffs, in better understanding of the interactions between the air and the sea on scales of motion, are enormous in terms of what we have learned so far.

D. Radar Observables

This section contains a listing of what the Working Group believes are the important radar observables and of experiments designed to provide information on these observables. Many of the experiments are described by the Working Group participants who suggested them; such descriptions are prefaced with their author's names in parentheses.

a. Wave height (or full wave spectrum $E(\vec{k}, ;x,t)$

Radars in general measure a wave number $(\vec{k})$, not a frequency (ω) spectrum. Ground truthing schemes must take the difference carefully into account. In fact we should be aiming, with conventional techniques, at obtaining $E(\vec{k},\omega)$ so the radar techniques, which typically give $E(k_n)$, where k_n is some Bragg- and vector wave number selected by the radar wavelength and propagation direction, can be used in conjunction with conventional techniques to obtain accurate estimates of the wave dispersion relation and the scatter about the relation (as discussed by Hasselman in his invited talk). We should also be considering the possibility, using radar, of redoing the JONSWAP experiment by determining $E(K,t)$ and following the dominant wave at its group velocity, thus providing an independent (2-D instead of 1-D) verification of the JONSWAP source function (See Pierson, 1977, and recent work by Kuo et al. (1979).

The frequency spectrum of ocean waves covers the range from 0.05 to 50 Hz, or three orders of magnitude. The wave number spectrum covers 5 orders of magnitude. Conventional deep sea spectral measurements are perhaps good to 0.3 Hz. Lab systems can go to 50 Hz. For a large range of wind speed, little is known about the wave spectrum in nature for frequencies between 0.3 and 10 Hz or for wavenumbers corresponding to wave lengths from 10 cm to 10 m (i.e., the wavelength range sensed by radars). There are some data that show that capillary waves (centimeter scales), and waves of meter lengths are strongly wind speed dependent. More and better field data are needed to resolve these gaping voids in our ability to describe and understand the sea surface.

Experiment 1: The azimuthal dependence of the ability of SAR to image waves (D. Ross)

The ability of SAR to image waves is compromised by vertical motions which are most severe for azimuth traveling waves. Because of this azimuthal dependancy, the mean direction and the directional properties of the spectrum may be compromised. Studies of this distortion phenomenon are best accomplished in combination with a real aperture system which is not subject to motion problems. Accordingly it is strongly recommended that joint experiments be carried out whereby real and synthetic aperture radars are flown together on an 8-sided pattern centered around a pitch-roll buoy where the surface wave conditions vary from a dominant sea to a dominant swell.

Experiment 2: SAR imaging of wind-driven seas (F. Dobson, D. Ross, Paul Liu)

An experiment was conducted in Lake Michigan during October 1977 in which an aircraft with SAR flew over an instrument tower 2 km offshore from Muskegon, Michigan. A directional wave frequency spectra obtained from three Zwarts wave gauges on the tower was compared with a wave number directional spectrum obtained from FFTs of X-band SAR measurements over the tower. The waves were considered to be wind driven. The resulting SAR directional spectrum was in qualitative agreement with the directional wave frequency spectrum obtained with the wave gauge array. These results appear to be the only clear-cut example of SAR images obtained from wind waves. The study is presently being carried out jointly at GLERL (P. Liu and David Schwab) and ERIM (Environmental Research Institute of Michigan) (Robert Schuchman).

At the moment, most SAR images, at least from SEASAT, are of swell, not wind-driven-seas, reflecting the SEASAT SAR resolution, which is about 25 m. The point is, that from the point of view of mixed-layer energetics and the energy and momentum balance within a given wave field, swell does very little. It propagates through large regions of the ocean without losing or receiving any significant energy or momentum (Snodgrass et al., 1966). But wind seas are much more difficult to image than swell (as discussed in Hasselmann's invited talk). Therefore, a strong interaction is needed between SAR experts and experts on ocean surface waves, so that suitable algorithms can be developed to image wind-driven waves reliably (see also the report from the Working Group on SAR).

Experiment 3: The acceleration field of breaking waves (F. Dobson)

A careful experimental/theoretical study should be done on the acceleration field of nonlinear and breaking waves. The basic field work has been done (see e.g., Garner, 1969), and a group at Cambridge under Longuet-Higgins has been studying the problem from a theoretical and laboratory model point of view for a number of years (Longuet-Higgins, 1978). As K. Hasselmann pointed out in his lecture to this Workshop, the acceleration field is a crucial quantity in interpretation of SAR imagery. Since the radar "sees" acceleration, it is fair to ask if a simpler version of a SAR could be used to provide the information needed for an accurate mapping of acceleration fields in the open sea, thus providing tests of some of the theory and aiding in the interpretation of SAR images. That having been done, can one produce on-board wave spectra with a SAR, as suggested by Hasselmann? See the SAR Working Group report.

Experiment 4: Multiple SAR, SLAR and MTI (Moving Target Indicator) radar wave imaging experiment (W. J. Pierson)

Both the SAR and the MTI radar depend on different Doppler effects in order to image a scene. If these two radars were operated on the same aircraft with a SLAR so that each imaged exactly the same sequence of range lines in similarly scaled images, many of the questions about the effects of focusing and orbital versus phase speed effects could be resolved. Other features would become apparent as the heading of the aircraft and the range of wind sea and swell conditions were varied. A list of predictions could be given as to how the images would change as a function of wave conditions and aircraft heading.

For waves with apparent crests parallel to the line of flight, and moving towards the aircraft, for one example, the bright patches in the image should be shifted forward (i.e., to the left with the flight line horizontal) and the dark patches rearward for the SAR relative to the SLAR. Similarly for a MTI radar, the stronger images would come from those portions of the sea surface where the orbital velocity was directly toward or away from the radar transmitter. They would not be displaced, however, relative to the SLAR image. Such an experiment may not, of course, be feasible in view of the different "modus operandi" of the three types of radar, but approaches to the problem should be made.

Experiment 5: Improving wave height and wave spectral estimates in comparison with remotely sensed values (W. J. Pierson)

Typical wave measurements by buoys, usually based on acceleration measurements, are for a 20 minute long record, with the data sampled at once per second. Then there are about 1200 data values, and for convenience many groups have shortened the sample of 1024 values so as to use a Fast Fourier Transform. If 50 spectral bands are resolved, each band will have about 20 degrees of freedom (d of f). With 25 bands, there are 40 degrees for freedom. Crudely the 90% confidence intervals for such bands are 1.67 and 0.59 for 20 d of f and 1.43 and 0.69 for 40 d of f. The significant wave height estimate depends on the spectral estimates, but typically this height is only known to 10-15% for a 20 minute (or 17 min 4 second) measurement. Two hundred to four hundred degrees of freedom would result in intervals of 1.18 and 0.85 and of 1.12 and 0.89, respectively, for the spectral estimates and a significant wave height accurate to perhaps 3 to 5%. For a stationary random process, a record ten times longer might be feasible, but in the real world the wave spectrum probably changes by a significant amount in 3h 20 min.

Alternatively, for the deep sea where wave refraction is not important, ten wave records taken two or three kilometers apart would measure independent time histories for essentially the same large scale wave pattern and the ten spectra could be combined so as to increase the degrees of freedom of the spectral estimates.

Only by extending conventional measurements over considerably longer periods of time or larger spatial domains can we provide independent verifcations of remotely sensed wave measurements.

Experiment 6: Sea surface dynamic height measurements (S. A. Fedor)

Studies of the effects of sea state on the measurement of the mean sea surface level by the radar altimeter have not reached a satisfactory conclusion. Two sources of tracking bias have been identified. They are labeled "waveform" and "electromagnetic" for discussion purposes. Both of them come about because of the skewness in the wave height and slope distributions. Typically a radar altimeter is designed to track the median of the returned pulse, as for SEASAT. Skewness will distort the returned waveform from the expected shape, resulting in a tracking error. If the capillary waves are not uniformly distributed along the longer gravity waves the resultant coupling of the height and slope distributions affects the electromagnetic estimate of the mean sea surface level because of skewness. Theoretical estimates of the "electromagnetic" bias have been made by Jackson (1979): these estimates indicate that the electromagnetic bias is twice as large as the waveform bias. Waveform biases on the order of 15 cm in a 10 m sea have been observed by the SEASAT altimeter. In order to achieve a 10 cm tracking by the altimeter it is necessary to know the statistical distribution of the capillary waves on the longer gravity waves since they are the source of the specular returns observed by the radar. This in turn calls for a field experiment planned in such a way that a large variety of wave conditions are encountered.

Experiment 7: The study of Langmuir circulations (M. Y. Su)

Although considerable experimental evidence exists pointing to the presence of Langmuir circulations in the open ocean, it is not at the moment possible to distinguish among the various theories (Craik and Leibovich, 1976; Garrett, 1976; Faller and Caponi, 1978). The particular experimental evidence needed is (1) the temporal and spatial history of wave groups on the sea surface and their "coherence" time and spatial scales in steady state wind conditions, and (2) a study of the correlation between local rms wave height and drift current. The first is needed since one of the basic hypotheses of the Craik-Liebovich (1976) theory is that wave groups do retain a regular pattern on the sea surface over temporal and spatial scales of the right order to generate and maintain the Langmuir circulations. The second is needed to account for Langmuir circulations by the feedback theory of Garrett (1976). Another measurement, important for all the theories, would be the variation in surface drift velocity across the circulations (which typically have a 100 m repetition distance). The experiments should be done at a variety of dimensionless fetches and/or wave ages.

Experiment 8: Measurement of gravity-capillary and breaking waves (H.-T. Liu)

The dynamics and statistical properties of gravity-capillary and breaking waves have received much attention recently because the waves themselves provide strong scattered signals for coherent radars. Theories have been developed to describe the spectral characteristics of pure capillary waves but not for breaking waves.

There have been few field or laboratory measurements available of wave energy spectra in the capillary wave regime because of the inherent difficulty in measuring capillary waves with wave staffs or capacitance probes (Sturm and Sorrel, 1973). Attempts were made by Mitsuyasu and Honda (1974) to design a differentiation circuit which amplifies the high frequency components of the wind waves to compensate for the meniscus effect. Their results qualitatively support the spectral form proposed by Pierson and Stacy (1973, fig. 3), that is, that the high-frequency wave energy spectrum should depend on the wind speed (see also Pierson, 1976 and recent work at APL/Johns Hopkins by Bjerkaas and Riedel, 1979).

Laser slope gauges have been developed by Huang et al. (1974) and Chang et al. (1978). Using the slope gauge, Long and Huang (1976) have demonstrated that the wave slope spectrum has the form proposed by Phillips (1966) for $8 < f < 30$ Hz. The dependence of the energy density on wind speed or u_* has also been observed. For a given wind speed, however, the wave energy density is independent of fetch for $2.6 < x < 6.7$ m. A laser displacement gauge has been developed by Liu and Lin (1979). This gauge has been used in the laboratory to measure gravity-capillary and breaking waves (mechanically generated waves with wind). For the case of breaking waves, the water velocity components in the vertical and longitudinal directions were measured separately by a laser doppler velocimeter (LDV). Some recent findings are summarized below. For detailed information refer to Liu and Lin (1979) and Lin et al. (1978), and also to Donelan (1978).

1. The wave spectrum in the capillary regime follows a $f^{-7/3}$ power law, as predicted by Phillips, and is independent of fetch (from 3 to 5 m) for a given wind speed. It increases with wind speed at a fixed fetch. The $f^{-7/3}$ slope, however, appears to hold for all wind speeds studied.

2. When wave breaking takes place, the spectral gaps between harmonics are filled in. The energy density at high frequency increases, indicating that small-scale waves are generated during the breaking process.

3. From the LDV measurements the rms value of the local vertical acceleration, which is much higher than that of the local longitudinal acceleration, is as high as 1.6 g under breaking waves, suggesting very high dissipation rates.

4. Velocity spectra of both vertical and longitudinal components shows extensive $f^{-5/3}$ regimes at high frequencies. There is an energy excess in the spectrum of the vertical component but an energy deficit in the spectrum of the longitudinal component ($2<f<4$Hz), suggesting large energy transfer from the vertical to the horizontal motions under breaking waves.

Although it is clear from the above that considerable progress has been made in laboratory study of fine-scale waves on the water surface, there has been little corresponding work in the field situation. It is fervently hoped that the MARSEN experiment wil provide a wealth of useful information on the remote sensing aspect of these fine-scale waves. Stewart (1980) reviews "conventional" field studies of short waves. No one has resolved questions central to an understanding of the radar sensing of the sea surface. These questions include: how are the short waves coupled to the longer ones? How important is wave breaking to the dynamics of the wave field? Of the mixed layer beneath it? To the radar return?

It is planned to adapt the Liu-Lin laser displacement gauge for use in the field, with the hope of addressing some of these questions.

Experiment 9: Joint studies of the remotely sensed sea surface wave height, and general oceanographic "signatures" of sea surface features (P. La Violette)

A carefully planned joint experiment is needed in which radars are used in conjunction with "conventional" oceanographic and wave sensing techniques to investigate the dynamic relationships between a well-defined oceanographic feature (a permanent "front," for example) and its surface manifestations (wave modulation, strong gradients of velocity, temperature and salinity). Generalizations from such an experiment would be extremely valuable for future mapping of the global effects of such oceanographic features.

Groups at NORDA (La Violette), Scripps (Bernstein, Davis, etc.) and Woods Hole/MIT (Richardson, Mollo-Crhistensen), are active in this field at the moment. None, however, are directly measuring the wave field in the vicinity of the features nor are they measuring surface currents. Since waves and surface currents provide the coupling between surface features and deep-water phenomena, it will pay to investigate the coupling in considerable detail.

10. Further ideas on wave height measurement

A listing of further ideas put forward by members of the Working Group is provided below. The names of the people who put forward the suggestions are included in parentheses. For the most part the experiments suggested have not been fully thought through (their proposer did not see fit to expand on them during the last hours of the life of the Working Group); nevertheless the interested reader would profit by contacting the people named for background details.

i) Laboratory measurements, by "conventional" and radar techniques, of the high-frequency dispersion relation of growing gravity-capillary waves (W. Keller)

The results from the IMST Marseilles group (see e.g., Ramamonjiarisoa et al., 1978) indicate, in a wind-water tunnel, large departures from the theoretical high-frequency dispersion relation. The NRL group (see e.g., Plant and Wright, 1977) find no such discrepancies, and suggest that the result comes from the IMST group using two probes at fixed spacing to measure the dispersion relation over a large range of wavenumbers.

ii) Radar studies of wave climate and prediction (D. Ross, W. Pierson, Grafton Hui)

A study should be carried out on all radar altimeter data now available to update the wave climatology of the world's oceans. A search should be instituted for a "fully developed wave spectrum". Does it exist? Proof must be supplied. Further studies are needed of the wave fields existing under hurricanes. A study with radar and conventional techniques is needed of the transient response of wave (both sea and swell) fields in nonhomogeneous/unstationary wind fields and water depth configurations. A study should be done on the down-fetch development of the wave directional spectrum, using radar techniques, fixed wave arrays, and pitch/roll buoys.

iii) The straining of short waves by long ones (K. Hasselmann/W. Keller)

The predictions of Longuet-Higgins (1969) do not agree with the so-called "modulation transfer functions" measured by Keller and Wright (1975). Although this controversy is at present the subject of active research (the NRL group, for instance, and Shemdin of JPL both made measurements during MARSEN), its outcome is of crucial significance to the interpretation of radar (particularly SAR) images. What are needed are experiments in open-sea conditions designed to relate the modulations observed by the radars with those observed with conventional or unconventional (laser slope and height gauge) techniques. Because the short wave energy variation with long wave height is required, higher-order spectral techniques, or perhaps conditional sampling techniques, are indicated.

A serious difficulty with the measurements in progress now is the fact that the modulations are being observed in the presence of waves backscattered from the supporting towers. Although the backscattered waves themselves are naturally separated from the incoming waves by their doppler shift in the radar measurements, the possibility exists that the nonlinear transfers of backscattered with incoming short waves will significantly modify the modulation process being studied.

b) Wind velocity $\vec{U}(\vec{x},z,t;\omega)$ $z < 0$

Winds are only indirectly sensed by radars; the radars really sense the effects which the wind has on the sea surface (waves, spray, foam). So in a real sense many of the experiments suggested under "waves" have a bearing on the measurement of wind; in fact the ultimate goal of many of those experiments is the specification of the wind speed at sea. To be able to do so often, with global or near-global coverage, and within known error bounds would be of enormous advantage to the weather forecasters, the wave forecasters, and meteorologists and oceanographers interested in the dynamics of atmospheres and oceans and in particular the coupling between them. The problem is, that there lies a tortuous and ill-defined path between remotely sensed information (such as microwave brightness, for instance) and a determination of U. Some of the problems are outlined by Pierson and Ross in their discussion of the current situation ("Inherent difficulties" and "Comparisons," section B.6.1 and 2); others are brought forward below. Since no specific joint radar/conventional experiments not already mentioned in "Wave Height" were proposed, the material has been arranged as a series of comments.

Comment 1. SASS (T. P. Barnett)

An item of extreme promise and potential importance to oceanographers is the SASS (SEASAT A Scatterometer System). If it really were possible to measure wind stress on the surface, then we would have the first-order driving force for ocean circulations. This observed forcing function could then be used to drive large-scale ocean models accurately. Comparison with observations would surely improve the model, for any errors would then be due to model deficiencies...not errors in the forcing function.

A crucial element here is to make sure that the SASS is measuring wind stress or something related to wind. Thus a large-scale program is needed to measure both the capillary wave spectrum and the gravity wave spectrum simultaneously with SASS observations. This measurement program should be carried out over an extended period of time (say, one year as opposed to a one-month shot) so as to encounter a wide range of wind, wave, current and stability conditions. We might also find it possible to gain some remote measure of atmospheric stability from such a "benchline" study.

It is perhaps worth noting that such a proposal must await the launching of the next SASS-carrying satellite, and it is not clear when that will be.

Comment 2. The accuracy of ground-"truth" wind measurements (F. Dobson)

The measurement of wind speed at sea is itself in need of considerable refinement. When one looks at the output from, for instance, SASS (SEASAT A Scatterometer System) as displayed, for instance, in Barrick, Wilkerson et al. (1979), one finds that the differences in speed and direction, both means and standard deviations, between the SASS and the ground truth measurements were of the same size (5-10% in speed, 20-30° in direction) as those expected to apply to the winds from the ships and buoys which supplied the ground truth and from typical natural variability!

Wind speed measurements at sea come from three sources: Beaufort force estimates (if they can be considered measurements; they will be here), "standard" ship's anemometer observations (including weatherships), and meteorological buoys. The question of how to improve accuracies is a very difficult one since, for measurements at least, there are very few carefully executed (and therefore bias-free) comparisons. One such comparison was that done by Augstein et al.(1974) during GATE, where the anemometer winds from R/V METEOR (height 25 m) were compared with those from the University Hamburg, Meteorologisches Institute profile buoy, by extrapolating the ship's winds downwards using the (log) profile measured by the buoy and a KEYPS profile. It was found that METEOR's uncorrected 25 m winds gave better agreement (± about 2%) with the 10 m winds from the buoy (which had one of its anemometers at 10 m) than did the corrected 10 m winds (±10%).

The reason for the bias is thought to be flow distortion: the ship's anemometer underestimated the true wind speed because the bulk of the ship beneath it modified the air flow at the anemometer. If this is so, and it is difficult to see how the measurements, or even their extension to ships of similar configurations, can be refuted, then all ship reports may be biased, possibly in the same direction, at the 5-10% level. And that sort of accuracy (at least in the sense of bias) is now becoming important not only to the ground truth for SASS, but also to oceanographers and meteorologists alike (WMO 172, 1977).

It is clear that there are significant obstacles to be overcome before the biases in ship reports can be corrected to better than 10% accuracy. We now understand the reason for the biases, but not how to correct for them. Some potentially useful intercomparisons between ships winds and buoys were made during JASIN; it is hoped that these and other such measurements can be used to determine the feasibility of making (perhaps eventually routinely making) corrections for distortion biases.

Comment 3: Wind speed and direction measurements (W. J. Pierson)

The variation of wind with height and the concept of an "average" wind has to be reviewed. Preliminary investigations indicate that 10 minute averages of wind speed and direction depart substantially from 3 hourly averages. The conventional 2 minute average from a ship can be shown to have large error bias compared to a 20 minute average. For synoptic scale meteorology perhaps much longer time averages of an hour or more may be the most useful for ship reports. If, on the other hand, it is the response of the oceanic mixed layer to meteorological "events" which is being studied, even longer averages may be required.

Editors' Note: The information from the JASIN workshop was provided by Professor Pierson during the interval between the end of our workshop and the publishing of these proceedings. The relevance of the material to this general area of discussion warranted its inclusion.

A JASIN workshop was carried out from 17 to 25 March 1980 as sponsored by NASA and administered by the Jet Propulsion Laboratory. The Joint Air-Sea Interaction Program is an international oceanographic and meteorological program sponsored by the Royal Society, whose data-taking phase took place in the North Atlantic between July and September 1978.

The purpose of the workshop was to compare the SEASAT SASS winds with the winds measured by the array of closely spaced ships and data buoys. The JASIN experiment from the point of view of the SEASAT program had numerous advantages over the preceding GOASEX experiments and comprised a "withheld data set". Moreover, the numerous anemometers in the JASIN array were all "cross calibrated" one against the other to remove instrument biases, especially for those on ships. Finally the array of instruments were close enough together to permit valid interpolations and extrapolations of the wind field based on better averages of the wind than were available previously.

When tested against a previously developed model relating wind speed and direction to backscatter measurements, the SASS winds averaged -0.04 m/s too low for V polarization H polarization paired SASS cells, + 0.50 m/s too high for V polarization pairs and -0.44 m/s too low for H polarization pairs. The root mean square difference in the same order was ±1.41 m/s, ±1.35 m/s and ±1.64 m/s. The winds in the JASIN data set went from 0 to 16 m/s. The corresponding direction biases and root mean square differences were 0.87 degrees, 3.38 degrees and 1.18 degrees for bias and 17.1 degrees, 15.9 degrees and 17.9 degrees for root mean square differences.

The data also showed that the model relating wind speed to backscatter could be improved especially at low and high incidence angles. A further fine tuning resulted in biases of -0.05 m/s, -0.03 m/s and +0.10 m/s; root mean square differences of 1.22, 1.22 and 1.41 m/s; direction biases of 0.96 degrees, 3.07 degrees and 0.75 degrees; and root mean square direction differences of 16.1 degrees, 16.1 degrees, and 17.9 degrees. All of these results reflect a substantial improvement over the GOASEX results, and the remaining differences can be interpreted in the light of the preceding discussion. The question of the wind stress - wind speed backscatter relationship is still a valid one, however, and requires further study.

Comment 4: The wind stress - wind speed relationship (F. Dobson)

A major problem, and a continuing one, is the relation between the friction velocity, defined by

$$U_*^2 = \tau/\rho \simeq C_D U_s^2$$

where τ is the wind stress or rate of transfer of horizontally directed momentum per unit areas, ρ is air density, C_D is a (supposedly) dimensionless "Drag Coefficient", and U_s is the wind speed at some standard height (usually 10 or 19.5 m). Since u_* is related directly to the wind stress, assumed constant with height in the friction layer close to the sea surface, it thus characterizes the air flow near the sea (and perhaps the mean drift in the water too), and is the proper parameter to which radar observables should be related. But u_* itself has not proven at all easy to measure. Air-sea interaction specialists have been attempting for some time to determine C_D; a summary by Garratt (1977) indicates the present state of agreement on the "variation of C_D with wind speed". And it does vary with wind speed, even though it is supposed to be dimensionless. One way out of the dilemma is to assume that the variation of C_D with wind speed is the result of a variation with u_* of the "roughness length" z_0 (z_0 is the constant one gets from integrating the general wind profile relation

$$\partial U(z)/\partial z = u_* \phi(z/L)/\kappa$$

where $\kappa = 0.4$ is von Karman's constant and $\phi(z/L)$ is a function of atmospheric stability which equals 1 in neutrally stable air). Charnock (1955) proposed, on dimensional grounds,

$$z_o = \alpha u_*^2/g$$

which produces realistic variations of C_D with wind speed for $U > 5$ m/s; as pointed out by Cardone (1969) it is necessary to model the low wind speed dependence of C_D, where the air flow appears to be aerodynamically smooth, with

$$z_o = \beta\nu/u_*$$

where ν is the dynamic viscosity of the air (see, for instance, Dittmer, 1977). Thus with a relation of the form

$$z_o = \alpha u^2{}_*/g + \beta\nu/u_*$$

the variation of C_D with wind speed can be modelled for wind speeds from 0-30 m/sec. The problem appears when applying the model to the "commonly" available measured ground-truth quantity: wind speed. It is not possible to put error bars (one standard deviation) any closer together than ± about 50% on the u_*-U relation. The scatter of individual measurements about the "mean" relation is so large that to date it has been necessary to relate the radar observables to U, not to u_*. At the moment, relating to U is the best thing to do. Only by averaging over many observations of U^2 will the user gain accurate estimates of the wind stress via the drag coefficient relation. Recent work by Large (1979) may improve the situation considerably.

Comment 5: Surface truth for surface wind stress (Peter Smith)

There is a need to develop inexpensive instrumentation for measurement of the wind stress from a ship. Balloons/kites can provide profile measurements at selected heights from deployed ships as a time series. Moored buoys should be developed with the capability to measure correlations of u'w' possibly employing on-board processing to handle high data rates. Buoys can also measure wind profiles in the lower 10 meters. Buoys should be capable of easy deployment in order to allow their use at different locations as part of different measurements.

Is the wave field fine structure (capillary/small gravity) correlated with surface wind stress in a determinable way under varying conditions of swell? Cox and Munk (1954) suggest that this is possible. Can the glint method be pushed to yield more information about the spatial distribution of capillaries? A joint radar/glint measurement may be illuminating.

Comment 6: Ground truth and models of the Planetary Boundary Layer. (F. Dobson)

The friction layer, and the PBL above it, takes some time to react to a change in conditions (a sudden change in wind velocity, for example, associated with a frontal passage, or a change in sea surface roughness where the wind passes over an oceanic front). The vertical wind profile readjusts to a sudden change in wind stress at a rate proportional to the size of the change relative to the former stress, the total momentum in the layer up to the measurement height, and the rate of change of momentum of the layer (i.e., the wind stress itself). Thus the wind speed observed by an aircraft flying at a height of 100 m, for instance, may not strictly speaking be extrapolated downwards to get the wind speed at the sea surface (or to estimate the wind stress) unless meteorological and oceanographic conditions are stationary and homogeneous over distances and times long compared with the reaction distances and times of the boundary layer. These parameters can be estimated by assuming a neutral log profile, integrating vertically to obtain total momentum, and then comparing the results with the wind stress. Typical numbers are approximately 30 km for distance and 60 min for time following a 25% step change in wind speed to a mean speed of 10 m/sec, for measurements at a height of 100 m. For greater heights and lower wind speeds, the reaction distances and times increase rapidly. Therefore, two questions arise: Are wind speeds measured at large heights (which is the typical way of obtaining ground truth winds from aircraft) representative of winds at the surface in nonhomogeneous or nonstationary conditions? And if they are not, how may we make estimates of the "true" surface winds? None of the existing PBL models attempt to account for spatial or temporal variability of the wind stress. Can PBL models be designed which do?

c) Current $\vec{U}(\vec{x}, z, t; \omega)$ $z < 0$

It is the field of current measurements that radars have the greatest unfulfilled potential. No other techniques (see, for example, McCullough, 1980) has proven capable of making reliable and accurate field measurements of mean currents, and their gradients in space and time, near the sea surface where wave orbital velocities exceed the mean currents by about two orders of magnitude. To see this, assume the wind stress is continuous across the interface, so

$$\tau_{air} = \rho_{air} \, u^{2}_{*\,air} \simeq \tau_{water} = \rho_{water} u^{2}_{*\,water}$$

Also, $u_{orbital} \simeq (ka)c$,

where a is the wave amplitude and k and c are the wave number and phase velocity. Therefore

$$u_{*\omega} / u_{orb} \simeq (\rho_a/\rho_\omega)^{1/2} u_{*a}/(kac)$$

For typical ocean wave conditions $u_{*a} \simeq U_{10}/30$, $(ka) \simeq 0.1$, and $U_{10} \simeq c$, so

$$u_{*\omega}/u_{orb} \simeq 0.01$$

No one has yet succeeded in relating mean velocity to $u_{*\omega}$ in the top layers of the ocean.

Experiment 1: The measurement of mean current profiles near the sea surface (F. Dobson, T. P. Barnett)

Because the size of the mean currents are so small, very accurate measurements must be made, which very effectively average out the wave orbital motions. Such measurements are possible with radars, which use the waves themselves to sense the currents. A knowledge of the structure of the mean and turbulent flow to depths of 50-100 m would permit estimation of the heat and momentum fluxes within the water column, and (eventually) of the heat and momentum budgets of the upper mixed layer of the ocean (see, e.g., Royal Society, 1977). Such measurements, taken over a wide area, could have profound significance to oceanography. For instance, we could gain information on the flux of momentum from the surface (wave field?) down into the mixed layer. We could also look at the formation of the seasonal mixed layer in certain regions of the world thereby perhaps gaining better parameterizations for entrainment processes. It goes without saying that the vertical profiles could be used to test the theory of Ekman (cf. Saunders, (1980).

The same type of studies could be done on the horizontal field of momentum fluxes in the near-surface ocean. The ability of the coherent radar to measure not only U as a function of depth but also to measure the horizontal derivatives of U is the crucial element here.

From comments at this Workshop by D. Barrick and personal communications with C. Teague of Stanford, it is clear that at this moment radars are getting close to the capability of making the necessary measurements (their resolution is now about + 10 cm/sec). What appears to be missing is the development of techniques for improving their current-measuring accuracy by about one order of magnitude, and some means of calibrating them to that accuracy. But therein lies the difficulty. No other field instruments are available to calibrate the radars to ± 1 cm/sec. The only hope is that absolute calibrations using scatterers other than waves, or lab calibrations, will be sufficient. There is an obvious need for a stable platform in the open ocean; oceanographic ships tend to be small and not stable enough. One suggestion brought forward was to mount the radars on a larger, stable ship such as an aircraft carrier!

Experiment 2: Measurements of the current fields associated with Langmuir circulations, in the laboratory and at sea (M. Y. Su)

See Experiment 7 under "Wave Height"; the experiment described here would most conveniently be carried out as part of the wave work. Of the mixing processes so far identified as having the potential for influencing the response of the oceanic mixed layer to forcing by the wind, "Langmuir circulation" is one of the most studied but least understood. The formation of the water near the surface into so-called "wind rows" aligned parallel with the wind has been observed many times in the open ocean, with spacings of tens to hundreds of meters. But the currents associated with these rows are of the order of the mean drift currents, and are therefore weak compared with the wave orbital motions.

A rash of new theories has appeared over the last five years (see the references in Experiment 7) which attempt to explain the circulations dynamically. What is needed now are some accurate field current measurements to test the theories and suggest further theoretical development. The end result of such tests would be a better understanding of mixing in the upper ocean; such circulations are capable of distributing throughout the mixed layer much of the momentum and energy transferred from the wave field and from the wind field to the drift current profile, which is localized near the sea surface. At the moment, no radar exists which can make the required measurements: in the open sea the currents have typical horizontal spacings of 10-500 m, and are probably only 1-20 cm/sec in strength; they are not steady over periods of time greater than 10-30 minutes or over distances greater than 100 m - 1 km. The only places where the circulations are better defined is on lakes, where spacings are smaller (1-10 m) but where individual wind rows can remain coherent over many hundreds of meters. Perhaps initial tests of the radars could be carried out in small scale over lakes or channels, with the ultimate aim of "taking the experiment to sea".

Experiment 3. Study of current shears associated with fronts (P. La Violette)

It is well-known (e.g., Hughes and Stewart, 1961) that a velocity shear on the sea surface (or sufficiently close to the surface that it is "felt" by the waves concerned) interacts with the surface gravity wave field (and, of course, vice versa: see Saunders 1980), transferring energy to the dominant waves, steepening them, and generating as a side effect an enhancement of the high-frequency wave spectrum. This effect is easily observable with radars, and if the wave-shear interactions are understood and the undisturbed wave field known, it may be possible to estimate the strength of the shear and hence describe some dynamic (and acoustic) properties of the fronts with which they are so often associated. If "conventional" oceanographic measurements are made in the vicinity of the front (CTD casts, Batfish tows), a full study may reveal techniques of categorizing such fronts in terms of their surface signatures, and thus of surveying large areas with radar and making estimates of the mesoscale current field dynamics, mixing rates, and acoustic properties associated with the fronts, particularly in active regions, such as the confluence regions of the Gulf Stream and Kuroshio with cold waters from the north, estuaries of large rivers such as the Amazon, and regions of strong upwelling.

Comment 1: Study of geostrophic currents with radar altimeters (L. S. Fedor)

This comment is really part of experiment 6 under Wave Height. It is clear that oceanographers are highly interested in obtaining the sea surface topography over large regions of the ocean to an accuracy of ± a few cm. As is pointed out in Experiment 6, that capability does not exist, and so considerable effort remains to be expended in improving as much as possible the present resolution of ± 10 cm. Even so, large, relative changes in sea surface height can be mapped now, and so there is ample opportunity for oceanographers to study tides on continental shelves (i.e. in areas where heretofore no gauges have been available) to study shears associated with strong currents such as the western boundary currents and their eddies, and possibly very large scale geostrophy. Cooperative experiments are also required between altimeter experts and experts in geodesy, both to better understand the geoid and to minimize the error bands of the radar.

d) Temperature $T_S(\vec{x},z,t)$, $Ta-Ts\ (\vec{x},z,t)$

Temperature is not well-measured by radars. Certainly, the scattering from the sea surface is related to temperature, both to the sea surface temperature and to the air-sea temperature difference. But because radars, unlike infrared sensors, are not sensitive to clouds (although they are to rainfall), they can provide information about surface temperature over a much wider range of intervening meteorological conditions. Such information is enormously valuable to meteorologists and oceanographers engaged in the study of large-scale, long-period ocean - atmospheric coupling. The two quantities of real interest are the heat storage in the ocean mixed layer

(cf. Kraus, 1977) and the air-sea heat flux

$$H = \quad C_p \ \overline{T_a'w'} \simeq \rho C_p C_T (T_s - T_a) \ U_{10}$$

where ρ is air density, Cp is the specific heat of air at constant pressure, T_a' is fluctuating surface temperature, w' is fluctuating vertical wind speed, the subscripts a and s refer to air and sea, U_{10} is the mean wind speed at 10 meters height, and C_T is an experimentally determined "Stanton Number" $\simeq 0.8 \times 10^{-3}$. Knowledge of the air-sea heat flux provides an estimate of the rate of transfer of heat from air to sea which can be integrated over time (and, eventually, depth) to provide one of the terms in the heat budget of the upper oceanic mixed layer. The complete budget could allow estimation of oceanic heat storage, a necessary variable for large-scale ocean-atmosphere coupled models. The problem is that estimates of H must be provided with error estimates and no one has yet provided guidance as to what the required accuracy really is. If one assumes ±20% as a "reasonable" figure, then $T_s - T_a$, which is typically of magnitude 0.5° C or less, must be measurable to about ±0.1°C, and this is about one order of magnitude better than presently quoted accuracies of microwave sensors in the best conditions. Also, the sea-air temperature difference affects the wind stress and (apparently) the sea roughness and hence the radar return; thus temperature effects are not easily separable from wind stress effects. A multi-probe approach (as for SMRR) is recommended, in which the various dependencies are sorted out by solving a matrix of algorithms.

In spite of the above difficulties existing systems could be used to measure the large-scale meridional transport of heat in key regions of the ocean, e.g., the equatorial region. This could shed light on a number of questions such as the exchange of properties between equatorial current systems, the importance of oceanwide meridional heat flux as opposed to oceanic heat flux that is confined to the strong western boundary currents, etc.

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REPORT OF THE WORKING GROUP ON SCATTERING THEORY AND PHENOMENOLOGY

A. K. Fung, Chairman

Our group study began with a discussion of the questions raised by various members of this workshop. The first question addressed was the relevance of as a significant parameter for SAR. It was noted that the gray level of each point on the SAR image came from a fading signal whose mean was σ^o while the location of each point in azimuth was determined by its Doppler history which, in general, was contaminated by ocean wave motion, orbital velocity, etc. Presentations and discussions on the first day of the workshop indicated that it is possible to generate wave-like patterns in SAR images or to lose the intensity pattern due to contaminations in the Doppler history. Hence, for SAR images phase information is at least as important as the intensity, if not more so. In addition, due to the better resolution capability of the SAR, the return signal experiences more fading. Hence, it would be of interest to study in addition to σ^o the fading statistics of the return signal, in particular, signal correlation. This will provide the coherence time of the scene, a quantity relevant to the imaging capability of SAR. The signficance of σ_0 in the design of the SAR is the same as for the design of other radar systems. In radar image simulation work σ^o is a basic reference parameter.

In the course of our discussion we noted that the strain-rate effects due to internal waves were small compared with those due to orbital motion even in mild swell. Hence, one should not rely on strain-rate effects to identify internal waves.

The question of recovering the directional wave spectrum from HF measurements was discussed during a presentation on the first day of this workshop. A member of this working group pointed out that Labianca (1980) has studied a comparable problem using coherently detected acoustic signals from 10 to 500 Hz, whose wavelengths correspond approximately to the HF region in the electromagnetic case. It would be beneficial to examine the inversion methods used there for possible application to the recovery of the directional sea spectrum using HF data.

In discussing the adequacy of the existing scattering theories for sea scatter applications, we felt that the two-scale scatter model for polarized scattering was satisfactory except for small grazing angles, confused sea conditions, and possibly at millimeter wavelengths. The existing theory of depolarized or cross-polarized scattering is restricted to a second-order perturbation approach with or without tilting effect. Such a theory does not explain cross-polarized scattering for incidence angles in the regions less than 30° and near grazing incidence. While this theory is expected to apply in the mid-range of incidence angles, extensive comparisons between theory and measurements have not been reported. It is well known that the two-scale theory does not account for breaking waves, foam and spray. Measurements to date have indicated that breaking waves are associated with strong radar returns and spray can have significant influence at near grazing incidence. While the effect of foam has not been found to be significant in radar observations, some radiometric measurements have indicated that it contributed to a significant rise in the brightness temperature. Further modeling studies and measurements are needed to understand these effects. In considering scattering at small grazing angles, additional mechanisms such as wedge diffraction and shadowing are also expected to be important. In this connection some modeling studies have already been reported by Wetzel (1977, 1978) and by Kalmykov and Pustovoytenko (1976). Further studies are currently in progress at NRL and NWC.

In summary, the following theoretical problems are recommended for further study at microwave frequencies:

(1) Modeling of the scattering characteristics of breaking waves, foam and spray.

(2) Investigation of various possible scatter mechanisms (wedge diffraction, Mie scattering, etc.) and conditions (refraction by evaporative layer, intermittency, etc.) that affect near grazing scattering.

(3) Development of a theoretical model for spatial and temporal correlations of the sea surface scattered signal.

(4) Investigation of the fading statistics of the sea scattered signal.

(5) Development of a cross-polarized scatter theory for the two-scale sea model which includes multiple scattering effects.

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REPORT OF THE WORKING GROUP ON SYNTHETIC APERTURE RADAR

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In a number of space and other remote sensing programs in the United States and Western Europe, synthetic aperture radar ("SAR") systems viewing the sea play an integral, even central, role: though actual and proposed budgets sum to hundreds of millions of dollars, there has not existed a sufficiently adequate system model on which to base experiment and system design, to predict system performance and utility, and to interpret data already gathered. A satisfactory system model should incorporate the salient functions of the sensing system, the scattering of electromagnetic ("EM") fields from a time and space varying, random surface, the hydrodynamic restraints appropriate to the air-sea interface, and desirable - if not optimal - data processing: as each of these subjects are complex indeed, the derivation of adequate models is a substantial task. Since the last review [1], [2] of this type, some models have appeared incorporating some of these requirements and hopefully increasingly comprehensive and useful models will appear in the near future to influence, and be influenced by, ongoing programs.

Any successful model will need to include basic knowledge from each of a number of fields. The Panel agreed on the following general guidelines:

1° - The SAR system is generally extremely sensitive to the temporal variation of scatterers (e.g., Bragg resonant waves, specular points or other) - both in their position and other scattering characteristics; the scatterers are preferably described ab initio by sample functions - not by averaged characteristics such as scattering cross-section density (σ^o).

2° - Generally the "two-scale" model of EM scattering from the sea surface has been proven adequate to microwave frequencies at least a significant share of the time. In particular, the presence of well-developed Bragg resonant waves is significant for backscattering at the expected intermediate incidence angles.

3° - The Bragg resonant waves producing the scattering, with their own spatial and temporal characteristics, are free waves traveling at their own phase speed plus advection by the orbital Lagrangian motion of dominant waves and currents if present.

The models reported to date [8], [9], [10], and [11] generally do not incorporate all of these requisite features.

The Panel also took note of the following:

4° - Microwave Doppler measurements in wavetanks and in the ocean made by NRL [12], [13] are in basic agreement with a linear relaxation hydrodynamic model developed for the straining of short gravity waves by longer ocean waves.

5° - As a consequence of (2°), the Bragg resonant waves and the dominant waves of the ocean interact nonlinearly in the EM scattering models.

6° - New developments on the SAR image for the nonstationary ocean surface have been reported [8], [9] & [10]. The effect of partial coherence in the scene has also been included.

7° - Some features of SAR images are predictable, including the "scaling and skewing" inherent in the side-looking scan method and the "azimuth bunching" due to the radial components of the orbital velocities. Generally SEASAT SAR image interpretation is at a preliminary stage.

8° - Appropriate to small amplitude waves, linear models have been proposed which, e.g., connect image wavenumber spectral density with that of the atmospheric pressure field at mean sea level at a reference time.

9° - In "focusing" experiments of SAR images of the ocean surface the phase speed of the dominant waves seems to be involved [14]. Since, this cannot be possible through coherent processes (e.g., phase) (3°) it must be due to a different mechanism.

SAR MODELS FOR SEA IMAGING

The Panel noted that while image formation may not be desired or necessary for some system purposes, most of the essential difficulties in modelling arise in considering the nature of a SAR image of the sea. Indeed, a successful model for the SAR image will surely inform the modeling problem for other coherent radar systems.

SAR image: time-invariant scene [3]. A linear model that has been fundamentally useful in SAR systems gives the (complex) image I (the magnitude square of I is recorded on film) as the convolution

$$I(x,r) = q(x,r) * [e^{i2\underset{\sim}{k}_0\cdot \underset{\sim}{r}}\, g(x,r)], \qquad (1a)$$

under appropriate conditions; that is, a linear, space-invariant mapping of the SAR system "impulse response" q with exp $i2\underset{\sim}{k}_0\underset{\sim}{r}$ times the scene's "reflectivity density" g, the ratio of scattered to incident EM fields at azimuth and range position (x,r); the nominal wave-number is $k_0=2\pi/\lambda_0$ where λ_0 is the nominal RF (radiated) wavelength. If F is the transmitted pulse (compelex) modulation and A is the "azimuth" (complex) modulation then

$$q(x,r) = q_F(r)\cdot q_A(x) = [F(r)*F(-r)^*]\cdot[A(x)*A(-x)^*] \qquad (1b)$$

and q_F and q_A are the SAR system's impulse responses in the range and azimuth directions, respectively. As is evident, a linear, space-invariant processor of impulse $\{F(-r)^*A(-x)^*\}$ - the "matched filter" - was assumed. The presence of the factor (exp $i2\underset{\sim}{k}_0\underset{\sim}{r}$) implies that the reflectivity density's part centered on radial spatial frequency $2\underset{\sim}{k}_0\bullet\underset{\sim}{r}/r$, and of bandwidth determined by q, determines the image. Note that the recorded data prior to processing is the convolution.

$$S(x,r) = [F(-r)\ A\ (x)] * [e^{i2\underset{\sim}{k}_0\cdot\underset{\sim}{r}}\, g(x,r)] =$$
$$\int\!\!\int d\bar{x}\ d\bar{r}\ F(r-\bar{r})A(x-\bar{x})\ [e^{i2k_0\bar{r}}\ g(\bar{x},\bar{r})]. \qquad (1c)$$

SAR image: time-variant scene [10]. - If a scene, characterized by a time-variant reflectivity density g(x,rmt), were scanned by a side-looking system whose physical antenna beam was arbitrarily narrow in azimuth, a little thought reveals that - assuming also arbitrarily fine range resolution for simplicity - the recorded signal would be (since t=x/v)

$$S(x,r) = g(x,r,x/v) \qquad (2a)$$

where v is the radar sets relative velocity component along-track. Because of the relatively near-instantaneous nature of the scanning in the range direction, it is fairly clear intuitively that the SAR's recorded ("dispersed") data is

$$S(x,r) = \int\!\!\int d\bar{x}\ d\bar{r}\ F(r-\bar{r})A(x-\bar{x})\ [e^{i2\underset{\sim}{k}_0\cdot\bar{\underset{\sim}{r}}}\ g(\bar{x},\bar{r},x/v)] \qquad (2b)$$

and under appropriate conditions this can be shown: this transformation is not a convolution and hence the image will not be so expressible. Again assuming the same linear, space-invariant processor, "matched" to a stationary point scatterer,

$$I(x,r) = \int\!\!\int d\bar{x}\ d\bar{r}\ q_F\ (r-\bar{r}) \int dx'A(-x')A(x-x'-\bar{x})^*\ [e^{i2\underset{\sim}{k}_0\cdot\bar{\underset{\sim}{r}}}g(\bar{x},\bar{r},\frac{x-x'}{v})]. \qquad (3a)$$

When g is time-invariant or as $v \rightarrow \infty$, (1a) is recovered from (3a). If the tilde and caret dencte, resp., the Fourier transform over the spatial variables (x,r) and time t, one can write the equivalent wavenumber-frequency domain characterization.

$$I(x,r) = \frac{1}{8\pi^3}\iiint d\,k\,dw\, e^{i\vec{\rho}\cdot\vec{k}+i(x/v)\omega}\,\tilde{\Phi}(\vec{k},\tfrac{\omega}{v})\tilde{g}(k_x,k_r-2k_0,\omega), \tag{3b}$$

where $$\tilde{\Phi}(\vec{k},\tfrac{\omega}{v}) \equiv \tilde{q}_F\,(k_r)\,[\tilde{A}(k_x)\tilde{A}(k_x+\tfrac{\omega}{v})^*] \tag{3c}$$

and $$\rho \equiv \binom{x}{r}\ ,\ \left(k \equiv \begin{matrix}k_x\\ k_r\end{matrix}\right)$$

Eqs. (3) are rather involved; some simplification is achieved with little loss of interest here by assuming the far-field (physical) antenna pattern in azimuth is Gaussian-shaped and the azimuth modulation is linear FM: then

$$I(\vec{\rho}) = \frac{1}{8\pi^3}\iiint dk\,dw\,e^{i\vec{\rho}\cdot\vec{k}+i(x/v)\omega}\cdot\tilde{\Phi}(k_x,\tfrac{\omega}{v})\cdot\tilde{q}(\vec{k})\cdot\tilde{g}(k_x,k_r-2k_0,\omega) \tag{4a}$$

and
$$\tilde{\Phi}(k_x,\frac{\omega}{v}) \equiv \exp\ \{-\ \frac{1-iKX^2}{X^{-2}+K^2X^2}\cdot(2k_x+\frac{\omega}{2v})\cdot\frac{\omega}{v}\}\ , \tag{4b}$$

where $X=\lambda_0R_0/D_h$ is the antenna pattern's "azimuth footprint" dimension and $K = 4\pi/\lambda_0R_0$ the azimuth modulation's linear FM rate. (D_h is the physical antenna's azimuth aperture dimension.) The factor $\tilde{\Phi}\to 1$ as $X\searrow 0$, the SLAR "brute-force" limit of finite resolution; but $\tilde{\Phi}\not\to 1$ as $X\nearrow\infty$, the SAR fine resolution limit (roughly speaking). This factor appears to have been overlooked in some discussions of SAR images in the asymptotic limit $X\nearrow\infty$.

Reflectivity density: two-scale model [4],[5],[6],[7]. The appropriate reflectivity density must be found via the methods of EM scattering theory hydrodynamics and experiment. It is well known that the ocean surface may be represented as a two-scale rough surface for the purpose of microwave probings. The two-scale model has been very successful in the past years in predicting and interpreting ocean scatter received by microwave Doppler radars. As a matter of fact a number of ocean parameters have been inferred with the two-scale model using microwave Doppler radars (e.g., phase speed, waveheight directional spectrum, modulation transfer function, etc.) in wavelands, coastal piers and towers (12), (13).

Since the short Bragg resonant waves are modulated by the fluid motion of the dominant waves of the ocean one may express the "reflectivity density" of the ocean as (for intermediate angles of incidence)

$$g(x,r,t) = g_{\sigma}\xi_s(x,r,t,)e^{\pm i\chi_s(x,r,t)}[1+\varepsilon\,\xi_e(x,r,t)e^{\pm i(\chi_e+\varphi)}], \tag{5}$$

where ξs is the surface displacement of the Bragg resonant waves, ξe is the surface displacement of the dominant waves of the ocean and ε is the modulation index dependent on the slope and direction of the dominant waves. χs and χe are the phases of the short and dominant waves, respectively, and it is a constant phase angle. Of course, the Bragg resonant waves travel at their own phase speed and are advected by the orbital motion of the dominant waves (3°).

Distributed models with orbital motion [9]. A one-dimensional analysis accounting for orbital motion can be accomplished as follows. In place of (2a), the recorded data is written as

$$S(t) = \int A(\bar{x},t) \exp\{i\Phi(\bar{x},t) - i\frac{ko}{Ro}(vt-\bar{x})^2\}\, d\bar{x} \quad , \qquad (6a)$$

where

$$\Phi(\bar{x},t) = 2\int^t \underset{\sim}{ko} \cdot \underset{\sim}{U}(\bar{x},t)\, dt. \qquad (6b)$$

$\underset{\sim}{U}$ is the natural speed of the short Bragg resonant waves on the ocean and A $(\bar{x},t)$ is equivalent to the "reflectivity density" g(x,r) for a constant range. $A(\bar{x},t)$ includes, among other factors, a spatial variation corresponding to the dominant ocean waves and their harmonics, weighted by coefficients that account for nonlinear hydrodynamic interaction of the short Bragg resonant waves with the dominant waves. Again assuming the matched filter processing discussed above - but here matched only in phase - the SAR image (denoted by m(t) in [9]) which replaces (3a).

$$I(t) = \iint A(\bar{x},t^1)e^{i\Psi(\bar{x},t';x)}\, dt'd\bar{x} \quad , \qquad (6c)$$

where

$$\Psi(\bar{x},t^1;x) = \Phi(\bar{x},t') - \frac{ko}{Ro}\bar{x}^2 + \frac{2ko}{Ro}(\bar{x}-x)t' . \qquad (6d)$$

The integral (6c) is evaluated by the method of stationary phase asymptotically as x /α or when the phase fluctuations are much more rapid than the amplitude fluctuations; that is, by requiring that

$$\frac{\partial x}{\partial \bar{x}} = \frac{\partial x}{\partial t'} = 0 \qquad 7$$

which gives the relationship between t and x.

For time-invariant scenes the solution of (7) yields x-tv as used in earlier sections.

This model was applied to the case of grazing incidence and a sinusoidal dominant wave; the "azimuth bunching effect" (see below) was predicted, as was harmonic generation and the distortion of the "dominant wavenumbers". However, the model is not restricted to these conditions.

Point scatterer models with orbital motion. A relatively straightforward model that is based on orbital motion only is that of a "point" scatterer - or "small scattering patch" - with motion identical to a water parcel at the surface of a large, sinusoidal structure. Approximating such a motion of a quadratic variation - applicable if the SAR azimuth integration time T is sufficiently short- it is well-known that (1°) a spurious radial component of velocity (v_R) and acceleration will cause, resp., an azimuth position error and a defocusing and that (2°) a spurious along-track component of velocity (v_p) also causes a defocusing: in order that these effects be negligible one must have ([3], pp. 36-37).

and
$$\left(\frac{v_R}{v}\right)\left(\frac{2R_0}{D_h}\right) << 1 \tag{8a}$$

$$\left(\frac{v_P}{v}\right)\left(\frac{\Omega T}{2\pi}\right) << 1 \tag{8b}$$

It is readily estimated that these bounds are violated for typical SAR systems viewing the sea: ($2R_0/D_h$) and the azimuth "time-bandwidth product" ($\Omega T/2\pi$) are typically very large numbers.

Details of these effects in the azimuth dimension have been worked out [10] assuming the processor, a matched filter, has been adjusted for a best quadratic fit to the phase of this assumed violated scatterer. With a Gaussian-shaped azimuth (physical) antenna pattern and a linear FM azimuth modulation - and of course a time-invariant cross-section of the scatterer, the image can be explictily calculated and the position error and resolution degradation noted explicitly - in particular, the dependence of SAR parameters, geometry, and orbital motion parameters. It is concluded, e.g., that azimuth resolution degradation increases with λ_0 and, not surprisingly, ocean wave frequency and amplitude. The "azimuth bunching effect" is noted to be independent of λ_0, as expected, and increases with wave amplitude: for this analysis an effectively uncorrelated distribution of point scatterers is assumed.

Alternative, partially-coherent processing. The processing generally considered - in particular that one discussed above - is a linear, spatially (quasi) invariant filter "matched" to the returned waveform of a stationary point scatterer. It is reasonably observed that, if there is sufficient object motion to degrade the SAR image, then processing a shorter segment of the "histories" could be desirable - though at the cost of reduced resolution (for stationary scenes); of course several such processed segments - with an optical processor an infinitude of (overlapping) segments are in principle easily processed - can be (incoherently) combined. Such processing systems have been utilized. There is a large body of relevant theory and application on this type of problem and these "mixed integrator" processors are known to be optimal in certain problems of detection and estimation.

A general model of this kind has been examined [11] for its resolution and noise properties and a possible application to SAR imaging of the sea discussed. The model emphasizes the effects of the randomness of the scatterers; it does not incorporate "orbital effects". The one-dimensional model for the SAR recorded data is that of (2b) above with the specific choice (exp $i2k_0r$) $g(\bar{x}, x/v) = f(\bar{x})\,\alpha\left(\frac{x}{v} / \bar{x}\right)$ where f is regarded as the scene - e.g., a "large scale" variation - subject to a "random fade" α - due, e.g., to a random capillary structure; f and α are assumed independent, the first Gaussian and white, the second spatially white.

SAR IMAGERY OF THE SEA

It was not the purpose of the panel to examine imagery and model agreement in detail but note was taken of some work of groups interpreting SAR imagery of the sea, specifically that of SEASAT and the JASIN experiment. The "ground truth" is fairly extensive but has not yet been available to the interpreters. Figure 3 shows the area concerned and Figure 4 is a SAR image processed by JPL: structure is evident - not always true of SAR imagery. Figure 5 shows the wavenumber power spectrum of this image, the upper solid line the omnidirectional spectrum, the integral over all angles, while the lower curve is an integral over an angular interval ± 15° about various angles to the flight path. Examination of the curves for $O_0 = 55°$ and 85° may show experimental support for the prediction of peak wavenumber distortion by orbital motion. Figure 6 is a directional spectrum averaged for ocean wavelengths over (about) 100-250 m: it does not agree too well with wind direction, averaged over the most recent 4 hours; in part - but probably not entirely - this lack of agreement may be due to scaling and skewing predicted by some models.

Panel Recommendations

The Panel made a number of recommendations:

1° - A number of suggestions were made by individual panel members to broaden the applicability of existing models. In particular, to include realistic SAR systems parameters and ocean surface properties, such as integration time, bandwidth, antenna pattern and an ocean wave coherence function which is more complex than a simple Gaussian or exponential function. Coherence functions of ocean waves are of the band-pass type including both the rapid decorrelation of the short gravity waves and the persistent residual correlation of the dominant waves. Generally modeling progress is crucial.

2° - As more sophisticated models become available, existing and proposed SAR systems should be re-examined and existing data - especially that with thorough "ground truth" be reinterpreted where appropriate; especially mentioned was the SEASAT-JASIN experiment. This interaction of modeling and experiment is essential.

3° - A joint experiment simultaneously employing SAR, SLAR and scatterometer systems, with thorough "ground truth", could be very rewarding if carefully planned to assess wave motion effects in SAR images. An experiment of this kind might be feasible in the North Sea in the near future.

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REPORT OF THE WORKING GROUP ON REAL APERTURE RADAR

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I. INTRODUCTION

The Real Aperture Radar Working Group discussed the capabilities and uses of high frequency (HF) radar, and one- and two-frequency coherent microwave radars. In an invited presentation, Dr. Donald E. Barrick described the present state of the art of HF surface wave and skywave radar ocean wave measurement techniques. HF radar measurement techniques are summarized in Barrick (1977), Barrick and Lipa (1979 a), and Lipa et al. (1981); skywave radar measurements are summarized in Georges (1981) and Maresca and Carlson (1980 b). The present state of the art of one- and two-frequency X-band and L-band microwave radar systems was described by Dr. William J. Plant in an invited presentation. Single and dual-frequency microwave measurement techniques are summarized in Plant (1977), Schuler (1978), and Plant and Schuler (1980). This working group agreed that the present demonstrated capabilities of these radar systems offered both the basic and applied oceanographic communities several remote measurement tools that could be used now to describe the waves and currents in deep water, on the continental shelf, and near the shore.

Real aperture radar measurement techniques have several advantages over conventional in situ sensors. The radar techniques provide more continuous coverage in time and space, do not have to be deployed and operated in the ocean environment, and can be used to make several types of measurements such as wave direction which are not possible, not practical, or too expensive to attempt with more conventional systems.

Many basic theoretical and experimental investigations have been completed that demonstrate the accuracy of these HF and microwave radar measurement techniques. The results of these investigations can be found in the literature. Three general types of experiments have been conducted: experiments to verify the equipment design and operation; internal consistency measurements to verify theoretical prediction; comparative measurements with conventional sensors. Determination of the accuracy of the radar estimates of waves and currents by comparative measurements with conventional in situ sensors is difficult because of differences in the spatial and temporal measurement properties of the instruments. In some instances, investigation of the radar measurement accuracy is limited by the accuracy of the confirming in situ conventional sensor. For example, the accuracy of HF and two-frequency radar measurement of the surface current is limited by the accuracy of the surface drifter measurements of the current in the upper 50 to 100 cm of the ocean.

This working group primarily discussed the question of how to begin the transfer of these relatively new radar measurement techniques from a few groups and organizations responsible for their initial development to the various user communities in general. We decided that a brief summary of the types of measurements that have been developed and tested in the field and a brief description of the theory used to make each measurement would be a first step. Our intent is not to present mathematical details of the theory. Rather, we attempt to point out important aspects of the theory that would be useful in determining if a particular measurement has a particular application. For example, both HF and two-frequency microwave radar systems can be used to measure the surface current by inference from accurate radar measurements of the phase speed of decameter wavelength ocean waves. The difference between the measured and theoretical phase speed is a function of the current in upper meter of the water. For some applications, this type of measurement is adequate. For example, a detailed map of the surface can be used to describe small eddies in the surface flow or the effect of tidal currents at the surface. However, for some applications in which the surface flow is extremely complex, inferring the surface current from the phase speed may not be adequate.

II. HF RADAR WAVE AND CURRENT MEASUREMENTS

Barrick (1972 a, b) and Weber and Barrick (1977) have derived theoretical expressions that relate the radar cross section and the directional ocean wave spectrum; the theory accurately describes the predominant features observed in both experimentally measured surface wave and skywave radar measured sea echo Doppler spectra.

The sea echo Doppler spectrum consists of two sharp spectral lines produced by a simple Bragg scattering of the radio-waves from the ocean waves, and a weak (second-order) continuum of echoes produced by a double scattering from the ocean waves. An estimate of wind direction and surface current can be inferred from the sharp line echoes, and an estimate of the directional ocean wave spectrum can be obtained from the second-order continuum structure.

The wind direction estimates are inferred from the direction of ocean wind-waves (~10 m in length) producing the first-order Bragg scattered spectral lines. A model of the directional distribution of these waves is required to make this measurement. The ratio of the power in the two first-order echoes is used as input to the model. Radar-derived wind direction estimates have been compared to anemometer measurements made from research vessels and NOAA data buoys. Agreement is better than ±20°. Wind direction measurements by skywave radar have been used to map the surface circulation over large ocean weather systems (low and high pressure systems, and across atmospheric forms) and tropical storms and hurricanes (Long and Trizna, 1973; Maresca and Carlson, 1980 b; Barnum et al., 1977). Based on the surface circulation the location of these weather systems can be identified. For tropical storms and hurricanes agreement between the skywave radar positions and the National Hurricane Center smooth track positions is ±20 km (Maresca and Carlson, 1981). The inaccuracies in the wind-field maps arise from (a) failure of the wave directional models to accurately describe the directional distribution for different meteorological situations and (b) occasional problems in resolving the left-right direction ambiguity about the radar beam.

The speed and direction of the current near the ocean surface can be inferred from the measured phase speed of the same ocean wind-waves (~10 m in the length) used to measure wind direction. A single radar can be used to estimate the component of the current vector along the radar beam (Stewart and Joy, 1974). Two radars located at different sites are required to map the absolute current field (Barrick et al., 1977). In the presence of an ocean current, these ocean waves will be advected and their phase speed will increase or decrease depending on the wave direction, the radar steer direction, and the current direction. Theoretical expressions that relate the phase speed to the underlying current are required to infer the current in the upper 50 to 100 cm. Accuracy between the radar-derived current and surface drifters is generally within ±10 cm/s. These measurements have been primarily made using surface wave radars, although this measurement can be made using a skywave radar if a reference signal such as land or an offshore oil platform is also observed in the radar spectrum (Maresca and Carlson, 1980 a). This capability is being developed into a prototype capability at NOAA using novel, compact surface wave radar antenna systems.

The directional ocean wave spectrum and various descriptions of the spectrum, such as rms wave height, period, and direction, can be derived directly from the second-order radar echoes. Lipa and Barrick (1980) and Lipa et al., (1981) have derived and experimentally verified theoretical expressions for the directional wave spectrum for long period ocean gravity waves (greater than 8 s). Approximate expressions have also been developed by Barrick (1977 a,b), Lipa (1977, 1978), and Maresca and Georges (1980) to estimate the frequency spectrum of ocean wind-waves. Using several radar look directions, more accurate estimates of the directional spectrum over all wave frequencies are being developed. Unlike the wind direction and surface current estimates, these wave measurements are not derived in terms of empirical fits to hydrodynamic models. Instead, the theoretical expressions are derived directly in terms of the radio-wave scattering from the ocean waves.

The primary difference between skywave and surface radar measurements of the ocean wave spectrum is the mode and range of propagation. Skywave radar can make wave measurements up to 3000 km from the radar by reflection of the radio-waves off the ionosphere. The ionosphere will sometimes smear and degrade the quality of the radar measured sea echo spectrum. Recent work by a joint NOAA/SRI International team has led to the development of a real-time software data acquisition package that allows high quality sea backscatter to be collected and analyzed for rms waveheight (Georges, 1980 and George et al., 1981). Because of the large coverage area, skywave radar has found applications in tracking and monitoring tropical storms and hurricanes (Maresca and Carlson, 1980 b).

Several attempts have been made to develop empirical expressions to infer with speed from the sea echo Doppler spectrum for skywave radar wind mapping applications (Stewart and Barnum, 1975; Maresca and Barnum, 1977, 1981). In general, these empirical algorithms have been inconsistent with subsequent theoretical and experimental investigations. Wind speed estimates have been made during hurricanes using a wind-wave growth model normally used to estimate wind speed from the rms wave height and radial fetch (Maresca and Carlson, 1980 b). The accuracy of these estimates ultimately depends on the accuracy of the wave prediction model and the radar measurements.

Historically, HF radar antennas have been large. For the past five years NOAA has developed several new surface wave radar antennas to measure currents (Barrick et al., 1977) and waves (Barrick and Lipa, 1979 b) which are small, compact, and portable. Large antenna arrays are still required by skywave radar to make long-range measurements. The simple large linear array of whip antennas used at the WARF skywave radar is a prime example (Washburn et al., 1979).

III. ONE- AND TWO-FREQUENCY MICROWAVE RADAR WAVE AND CURRENT MEASUREMENTS

One- and two-frequency, coherent microwave radars can be used to measure currents and waves. When the angle between the incident field and the mean surface is larger than the rms ocean wave slope and less than 70°, microwave scattering is described by Bragg scattering. The microwave scatter from centimeter ocean waves is modulated, tilted, and advected by large scale ocean waves. Wright (1966, 1968) and Bass et al. (1968 a, b) have derived theoretical expressions which describe microwave radio wave scatter from ocean capillary and short gravity waves in terms of a two-scale model. One-frequency (Plant et al., 1978) and two-frequency (Plant, 1977; Alpers and Hasselmann, 1978; Schuler, 1978; Plant and Schuler, 1980) microwave radar experiments have been conducted to verify the theory. Features of the long ocean gravity waves can be estimated from the interaction of the large and small-scale waves through empirically derived modulation transfer functions (Wright et al., 1980).

Wave orbital velocities can be accurately measured using a one-frequency CW microwave radar provided that the illuminated ocean area is sufficiently small such that the surface velocities inducted by the long waves can be assumed constant over the scattering area. These wave orbital velocity measurements are not directional. Directional wave orbital velocity measurements can be made with a pulsed radar system when the illuminated ocean area has narrow radial resolution and coarse azimuthal resolution. Directional wave height power spectra are inferred from these wave orbital velocity measurements.

Theoretical expressions have been derived and experimentally verified to measure the energy density spectra of long ocean waves from a single-frequency radar (Plant and Schuler, 1980). The technique is best applicable when surface wave conditions consist of a well-defined dominant wave traveling in one direction. To first-order, the wave spectrum is computed from measurements of the wave orbital velocity because terms involving the modulation transfer function are small. The accuracy of this technique decreases for waves traveling in directions other than the dominant wave direction when a spectrum of waves exists. Knowledge of the modulation transfer function as a function of wind speed and angle between the wind and wave is required to evalute the theory for complex situations.

Accurate measurements of the phase speed of ocean wind-waves can be made with both one- and two-frequency radars. Plant and Wright (1980) describe measurements of short wind-waves (4 to 36 cm in wavelength) using a single-frequency microwave radar system. The phase speeds of these short gravity waves differ from those of irrotational gravity waves primarily because of advection by the wind drift and secondarily by inertial pressure and finite amplitude effects.

The phase speed of ocean gravity waves measured by a two-frequency radar is similar to that measured by an HF radar. Accurate estimates of the ocean surface current can be made using a two-frequency radar. The measured radar Doppler spectrum consists of a sharp line produced by long gravity waves superimposed on a broad background produced by shorter waves. The frequency of the sharp line is related to the frequency of the ocean wave whose wavelength is related to the difference between the two radar frequencies being used.

The two-frequency surface current measurement is analogous to the HF radar measurement except that the illuminated area is much smaller. The phase speed of ocean waves (~10m) is measured directly from the magnitude of the frequency separation between the two measured peaks in the Doppler spectrum (Schuler, 1978). The radial surface current is then inferred from the measured phase speed. The depth of the surface layer over which this current is measured depends on the separation between transmitted frequencies. Since this separation is easily varied, dual-frequency radars have the potential of accurately measuring current profiles. Initial efforts to extract the waveheight directional spectrum from a two-frequency measurement have been reported by Plant and Schuler (1980). This measurement requires an accurate knowledge of the modulation transfer function. In a nadir-looking mode, however, significant wave heights may be obtained from dual-frequency systems without knowledge of transfer functions (Weissman, 1973, Weissman and Johnson, 1977).

The one- and two-frequency microwave radars are generally small and compact and can be operated from the shore or from aircraft. The limited range (~500 m) of these radars can be increased by mounting the radar in an aircraft (Weissman and Johnson, 1977). The small footprint allows detailed spectral measurements of the wave and current fields to be made.

IV. SUMMARY

The capability for remote measurements of ocean surface waves and currents by HF radar, and one- and two-frequency microwave radar system have been demonstrated for many different types of measurements in the field. Sufficient work has been accomplished to encourage the oceanographic and radar engineering communities to work more closely in establishing a fruitful exchange of ideas and the design of better scientific experiments.

Our understanding of radio-wave scattering from ocean waves has dramatically increased over the last five to ten years. Because radio wavelengths at HF are comparable to the ocean wavelengths, perturbation analyses can be used to derive expressions that describe scattering of radio-waves from ocean waves. Measured modulations transfer functions are required, however, to quantify the one- and two-frequency microwave radar scattering. These transfer functions are empirically derived and are a complex function of frequency, amplitude, and direction of wind-waves, swell waves, and radar. Significant progress is being made in measuring these transfer functions (e.g., Wright et al., 1980).

HF radar is primarily a shore-based measurement system; the new smaller surface wave radar antenna designs being developed, however, should be capable of being mounted on offshore platforms or buoys. The typical footprint size is large (1 to 10 km^2 for surface wave radars and 300 to 1200 km^2 for skywave radars). Areal maps of the wave and current fields have and can be made using HF radar. The microwave radar systems can be operated from shore, offshore platforms, or from aircraft. The footprint size (typically 1000 m^2) depends on the type of measurement and radar system, although extremely narrow radial resolution is required for one-frequency wave spectral measurements.

The experimental evidence confirming the measurement of currents and waves by HF surface wave and skywave radar is becoming quite large. HF radar has been successfully used in several oceanographic applications to provide data in conjunction with other conventional sensors to study ocean phenomena and processes (Maresca et al., 1980 and Frisch et al., 1981). For surface wave radar, most of the effort is being expended to develop new small portable radar antenna systems that are properly designed, engineered, and validated. For skywave radar, the emphasis has been to determine the operational limits imposed by the ionosphere.

The effort expended in testing and evaluating one- and two-frequency microwave radars has been less than the effort expended for HF radars. For one-frequency microwave radars, measurement of the directional wave spectrum is the primary focus. For dual-frequency microwave radar, measurement of the surface current is the primary focus.

Closer work by the radar engineers and physicists, oceanographers, and the general user community is required to make these radar measurement tools part of the "conventional sensor" measurement techniques. Significant progress has been made, and interaction between the ocean user groups should help improve this technology in the future.

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PANEL DISCUSSION

(Reconstructed from notes taken by L. Wetzel.)

Dobson: The Hydrodynamics Panel is in basic disagreement with the assertion by the RAR panel that "they would make many measurements in many locations to gather data in order to establish the credibility of the HF current-measuring technique." What should be done is to make completely instrumented comparisons between hydrodynamic and electromagnetic measurement techniques at a single location.

Maresca: Many HF radar measurements have already been made in many locations - wherever other sensors have existed the agreement has been good.

La Violette: We have to agree finally to accept good remote sensing data where there are only bad or inconsistent measurements by classic oceanographic techniques.

Maresca: At one time we measured surface currents with HF radar and compared them with current meters below the surface. From the differences, we inferred that fresh water was moving out on the top, while salt water flowed in below. Often a combination of oceanographic and EM techniques are needed.

Pierson: When SEASAT released wind field data to users, one guy found a bias with respect to his ground truth observations, which was traced to a loose bolt in his equipment. So which is to be trusted?

Maresca: There are many such examples.

Barrick: There is a lesson in all of this. HF system development and experience are well along. It was a hard road to travel, but oceanographers are now coming to us. However, other techniques are not so well in hand, and we would be happy to join in joint experiments to help them establish credibility. We had to learn oceanography and meteorology in order to apply our techniques in these fields. It would be nice if oceanographers would learn enough about radar to help optimize those applications.

Pierson: Experience shows oceanographers to be insular and parochial.

Lake: Numerical modelers could help by pointing out areas of mutual interest.

Dobson: The Hydrodynamics Groups stressed the use of collaborative experiments to establish the validity of remote sensing techniques. The question is not "where are you?", but rather, "where are you going." You've established feasibility. Now the problem is in improving accuracy to a level of real interest to oceanographers.

[Brief flurry about what is meant by "improved accuracy and "real interest."]

Pierson: With a NOAA HF current meter, we could update our tables of tidal currents - which would be useful for understanding the effluents from nuclear plants, sewage disposal, etc.

Maresca: In response to "where are we going" - we of the RAR Group found the Hydrodynamics Group discussion of Langmuir circulation very enlightening. The discussion of the choice of sensor for measuring this circulation came down to a real attempt to evaluate measurement and experimental techniques, and for the first time produced a true interaction between the users and suppliers of remote sensing technology.

Pierson: In the Scattering Theory Group, what was the difficulty in SAR imaging resulting from an inadequacy in the number of scattering points?

Fung: In SAR, the imaging "footprint" or resolution cell is small. Consequently, the number of independent samples within the cell is also small. Thus, σ^o which is the average value from averaging a large number of samples, is in general not reflected at a given point on the SAR image. Instead, speckles resulting from fluctuating signals appear on the image. If enough points on the SAR image come from a statistical homogeneous area, then in principle σ^o can be recovered by averaging over these points. In scatterometry if the number of independent samples within the resolution cell is not enough, σ^o is obtained by averaging returns from additional cells.

Raney: In SAR the pixel brightness is related to σ^o, but it is a very noisy measure, with the ratio of rms deviation to mean value about unity. Doing incoherent processing with n independent looks drives this ratio down to 1/n. But this is less a problem of scattering than of processing.

Zalkan: What were some of the conclusions of the SAR working group?

Raney: (Referred to list of statements on board.) (1.) SAR is sensitive to the coherent phase $\Phi(t)$ of the signal; (2.) The orbital velocity enters as a coherent, time-dependent Φ; (3.) If a wave image has any meaning, the scattering "center" must move with the phase velocity, C, of the wave; (4.) Any scanning sensor sees σ^o(the point of brightest reflectivity) at velocity C. Once σ^o has moved to a new location the signal loses statistical dependence, so the SAR does not "track" coherently. It "sees" the scattering point, but doesn't coherently track it. For example, for a slightly modulated swell there is no correlation from one location to another - thus the SAR can't coherently focus. Only something like [a sharp, well-defined scattering facet or cusp that retains its form with time] would track coherently at the phase speed, C.

Brown: Can you see wind waves? What is the K-spectrum of short (about 30 cm) waves in the open ocean?

Dobson/ Pierson: This is poorly understood. It is crucial both to wind Pierson coupling and to SAR at L-band. One can't properly compare open ocean and wind tank measurements.

Su: We have a big tank, and can observe wind wave growth up to about 2 feet.

Dobson: What is the value of surface tension in your tank? This is absolutely crucial to your measurements. Your tank is probably dirty!

Su: Our tank is outside, but we assume the surface is clean.

[Some un-noted random discussion here.]

Fung: [Showed plots by Linwood Jones of NASA which displayed behavior of σ^0 versus wind speed for various incident angles: decreased with W for small angles (0 - 10°) and increased with W for larger angles (40°-50°).] The behavior of σ^0 with wind speed depends on the angle of incidence and frequency. This behavior was confirmed by JONSWAP measurements and is consistent with many experiments, including the NRL data. However, the NRL data showed a fixed bias between data taken in two separate experimental situations. By averaging these sets together, NRL data was erroneously interpreted to show a saturation effect.

Valenzuela: This bias was possibly due to differences in the fetch in the two experiments: longer fetch means longer waves, which means flatter seas and a smaller σ^0.

Pierson: The cross-section is proportional to alpha [scale factor on the ocean wave spectrum], and the idea that alpha decreases with increasing fetch is nonsense!

Valenzuela: JONSWAP measurements showed alpha decreasing with fetch. Another source of difference between experiments could be difference in air-sea temperature, presumably due to changes in friction velocity affecting the surface wind stress. NRL found cross-section changes of as much as 5 db attributable to temperature changes as a cold front moved through. Such effects were found in both the North Atlantic and the Gulf of Mexico.

Dobson: I'm delighted! This promises a way to measure changes in air-sea temperature by microwave radar.

Rouse: Maybe Pierson's comments relate to different scales of fetch.

Dobson: No. Each party (NRL and Pierson) talks in terms of dimensionless fetch.

Zalkan: We heard from Raney's talk that radar researchers need an estimate of correlation time from the oceanographers, and from today's discussion, the K-spectrum in the ocean as well. What else do the radar researchers need from the oceanographers?

Harger: We would like a physical chracterization of the fine-scale structure.

Dobson: That is poorly known - but is it really worthwhile to do it?

Harger: Once the model is pinned down we will need physical information to understand the character of the image. We would like spectral amplitudes and widths in the wavenumber bands corresponding to SAR wavelengths. We are assuming that large and small scale waves are independent. We can live with this assumption, but would like to know ultimately whether it is a true assumption.

Jain: Shemdin has given joint density functions for large and small scale features.

La Violette: We used infrared to study wave images - and also SAR and conventional radar. The latter shows excellent images of ocean fronts.

Zalkan: Have the oceanographers come up with things needed from the Radar and Scattering people?

Dobson: We have asked the HF people to get into the modeling of mixed layer dynamics. We want to find current shears just below the surface, which provides a principal unknown in determining energy transfer.

Maresca: The normal radar range of 15-30 MHz corresponds to depths of 50 - 100 cm. Standord has done some multiple-frequency measurements in an attempt to measure shear. Another radar system is the dual-frequency [delta-K] radar, which provides a larger range of effective wavelengths. Displacement of the sharp Bragg lines relative to one another has been observed and ascribed to turbulence. This displacement could perhaps be used to sense turbulence.

Dobson: We hope that radar techniques will be able to map the full K-spectrum, which would give us a more precise handle on the full wave-growth process, and hence, on the wave-dissipation process.

Maresca: We have a second-order theory that gives pretty good results in inverting the radar spectrum into an ocean wave spectrum. This has been done for low frequencies -- we have done swell. At higher frequencies (below 7-8 second periods) one runs into the equilibrium range, where it is doubtful that we can get accurate spectra by inversion. There is too much error. However, we can probably recover stuff at 7-8 seconds.

Dobson: Is there such a thing as a fully developed sea? And if so, can you prove it?

Pierson: I think so, but I can't prove it.

Raney: The SAR problem is hard when the integration time is much larger than the correlation time. We can reduce the problem by going to higher frequencies, e.g., C-band. Our X-band SAR in a Convair 580 has integration times of 0.05 to 0.1 sec. and shows good sea imagery.

Valenzuela: At X-band, the capillary waves are more wind dependent than the short gravity waves at lower frequencies, so the image is more variable.

Dobson:	We will write up the experiments suggested in the Hydrodynamic Working Group.
Pierson:	Getting back to why alpha appears to decrease with fetch - the early data was based on a shipboard wave recorder whose calibration killed the spectral range from 0.5 to 2 seconds. This was O.K. for wavelengths greater than about 50 feet (which was our interest), but no good for the higher frequencies in the equilibrium range where alpha is determined. It's not surprising that the NONSWAP wave-wire gave higher alphas. Any picture you look at of a developing sea demonstrates that the part of the spectrum determining alpha increases with wind speed and fetch.
Zalkan:	What form does the Workshop want its Proceedings to take? We can do anything from a NORDA Report, to publication of a Hardbound book.

The Working Group Chairmen unanimously opted for the NORDA Report, and after brief further discussion of publication format, the Workshop adjourned.

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The Naval Ocean Research and Development Activity inaugurated a series of oceanographic workshops during the fall of 1979 covering various topics in ocean science and technology. These workshops were sponsored by the Chief of Naval Research. On 13-15 November 1979, a workshop entitled "Describing Ocean Phenomena Using Coherent Radars" was held at NSTL Station, Miss. Leading workers in both hydrodynamics and electromagnetic scattering came together to discuss the status of relevant scattering theories, the kinds

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and reliability of data obtained with different sensor systems, and the hydrodynamics information extractable from these data.

In the material contained within this technical note, the invited talks and plenary session are summarized along with the presentation of the reports of the working groups. During the interval between the conclusion of the workshop and the publication of these proceedings, many papers that were in preparation or had been submitted to journals subsequently appeared in print. For completeness, these later references have been cited. A sample of the give-and-take interplay that occurred throughout the workshop may be found in the Open Discussion at the end of this report.

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