AIRBORNE MEASUREMENTS OF OCEANIC WIND VECTOR FIELDS OVER THE LABRADOR SEA USING PASSIVE POLARIMETRIC RADIOMETRY

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LONG TERM GOALS

The focus of this research is to develop algorithms and system concepts for the spaceborne imaging of ocean surface winds using passive microwave radiometers. The application of passive radiometry to ocean surface imaging, specifically using polarimetric microwave measurements of the third and fourth Stokes' parameters, has been identified as a potentially useful and low-cost means of obtaining the magnitude and direction of near-surface winds from space. The purpose of this work is to empirically characterize the polarimetric thermal emission signature from a wind-driven ocean surface using airborne measurements and to use the measured data to develop a theoretical emission model adequate for the prediction of satellite signatures at all wind speed ranges. An additional goal is to identify and develop the most practical and stable polarimetric radiometer hardware for airborne and spaceborne deployment.

OBJECTIVES

During the past grant period (October 1, 1996 through September 30, 1997) the immediate objectives of this work have been the completion and deployment of a new instrument, the Polarimetric Scanning Radiometer (PSR). The PSR consists of a gimbal-mounted set of tri-polarimatric (three Stokes' parameter) radiometers with operating frequencies near the important transmission windows of 10.7, 18.7, 37.0, and 89.0 GHz. The primary application of the PSR is the generation of a database of high-resolution polarimetric, conically-scanned images of the wind-driven ocean surface under a variety of sea, fetch, and atmospheric states. The unique scanning geometry offered by the PSR allows for radiometric observations around a full azimuthal scan of 360^o at a fixed cone angle. Questions to be answered using the PSR data include: (1) What are the relative impacts of foam, wave asymmetry, and resonant thermal emission on the wind signatures? (2) What are the frequency and wind-speed dependences of the observed azimuthal harmonic signatures? (3) What are the impacts on the azimuthal harmonic signatures caused by clouds? (4) What is the impact of fetch and stability on the azimuthal signatures? (5) Do the wind signatures observed from aircraft correlate with those observed from the SSM/I instrument? (6) What is the utility of a two-look (fore and aft) method for determining the wind vector at a given pixel?

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Strategies for performing the measurement of the third and fourth Stokes' parameter vary, although there are essentially three viable techniques: (1) adding analog correlation, (2) analog multiplication, and (3) digital correlation. The first two of these techniques have been previously documented; these techniques suffer from drawbacks related to difficulties in calibration. The third approach, digital correlation, has the fundamental advantage that the system can be fully calibrated using conventional hot-and-ambient blackbody targets. An additional objective of this work was thus to test a digital polarization correlator for use in measuring the third and fourth Stokes' parameters.

APPROACH

The development of the PSR was greatly facilitated through the use of state-of-art computer-aided design and manufacturing techniques. All mechanical components of the instrument were defined within a three-dimensional AutoCAD® computer-aided design (CAD) model, then fabricated using computer controlled numerical cutting (CNC) techniques. This philosophy of development allowed all members of the PSR engineering team to participate in the design process by trading CAD files over the internet, and provided a means of efficiently and accurately fabricating all components.

The PSR consists primarily of three components: a positioner, scanhead, and data acquisition system. The positioner consists of an independent azimuthal and elevation drive system using two 100 ft-lb geared stepper motors. Absolute position encoders provide position feedback information accurate to within 0.1^o, and slip rings are used to transfer power and data between the fixed and rotating sections. The positioner also accommodates hot and ambient blackbody targets that are periodically viewed to provide absolute calibration of the scanhead radiometers. A computer-based motor control system provides the proper drive signals to the stepper motors to accomplish a variety of complex scan motions, including fixed-angle conical, variable angle conical, cross-track, along-track, and fixed-position stare. All scan modes include calibration views at ~9 second intervals.

The scanhead consists of a 20" diameter and 20" long rotating drum containing the four tri-polarimetric radiometers, and includes the radiometer antennas, receivers, detector hardware, digital correlator hardware, a video camera, A/D converters and computer, and power conditioners. Each radiometer uses a linear orthogonal mode corrugated feedhorn with an integrated lens antenna and a dual-channel receiver. A common local oscillator (LO) is used to drive each of two mixers in each receiver, thus providing coherent downconversion of the orthomode signals. All radiometric detection is accomplished within the scanhead, allowing for a high degree of isolation from both power line and radio frequency interference. High-speed (1 GS/sec) digital correlators based on emitter-coupled logic (ECL) are used to detect either the first three Stokes' parameters or (alternately, by retuning an LO phase shifter) the first, second, and fourth parameters. The digital detection system is backed up by a conventional analog detection system for the first and second parameters. Data are communicated from the scanhead to an archival computer within the aircraft via a 10 Mb/sec ethernet link. The data acquisition system consists of two personal minicomputers located in the aircraft cabin. These computers are used to archive the scanhead data and to run the motor control software.

During the same grant period, equipment for installing the PSR on the NASA Wallops Flight Facility’s Orion P-3B aircraft (N426NA) was designed and fabricated. The equipment consists of an aerodynamic fairing covering the bomb bay of the P-3 and a support structure which fastens the PSR into the P-3 bomb bay. The fairing was jointly designed by Georgia Tech and Raytheon, Inc., and fabricated by the NASA/Ames Research Center's medium altitude missions branch. In addition to accommodating the PSR, the fairing was also designed to accommodate the University of Massachusetts' C-band radar scatterometer (C-Scat), thus allowing the first simultaneous high-resolution active and passive imaging of the ocean surface. The PSR support structure was designed and fabricated at Georgia Tech. Again, the CAD philosophy was used to coordinate the efforts of all engineering team members.

The PSR was installed in the NASA Wallops Flight Facility's (WFF) Orion P-3B aircraft (N426NA) in January 1997. The integration included several additional active and passive instruments provided by the University of Massachusetts Microwave Remote Sensing Laboratory (MiRSL), the NOAA Environmental Technology Laboratory (ETL), the NASA/WFF's Observational Science Branch (OSB), as well as GPS dropsondes provided by the National Center for Atmospheric Research (NCAR). The above complement of ocean winds imaging (OWI) instruments provided the first capability to observe ocean surface wind and wave fields using high-resolution active and passive sensors.

After two brief one-hour test flights, the PSR was operated in scanning mode during hex-cross flight patterns over ocean buoy sites. The hex cross was adopted to allow the OWI instruments to observe ocean wind fields over a broad area (typically 30-50 km in size) while simultaneously allowing overpasses of a centrally-located truth site at three different azimuth angles. Three local buoy flights were conducted during a transition period allowing substantial software improvements to the radiometer and motor control system.

In order to study the detection of particularly damaging winds, a wind speed range of 10-30 m/sec was deemed to be the most important in which to first operate the PSR. Such sustained winds were able to be readily observed within the Labrador Sea during winter. Accordingly, the aircraft was deployed to Goose Bay, Canada for flights over the RV *Knorr*, stationed in the Labrador Sea as part of the Fronts in Atlantic Storm Tracks Experiment (FASTEX). Four successful sorties over the Labrador Sea were conducted, providing observations over 10-25 m/sec surface winds. Flight patterns included local hex-cross patterns over the *Knorr* and long transects through weather fronts. Surface truth measurements of wind vector, stability, momentum flux, and sea state was obtained from instruments on the *Knorr* and supplemented by wind dropsondes released from the P-3.

Upon return, a multilevel data processing system was created to handle the special needs of the PSR data. The processing system incorporates data from the PSR radiometers, motion encoders, calibration load sensors, and aircraft inertial navigation system (INS) to create calibrated multiband polarimetric imagery of the ocean surface. In addition to processing the PSR data, the Labrador Sea working group consisting of scientists from the U-Mass MiRSL, NOAA/ETL, NASA/WFF OSB, NCAR, and GIT was formed to amalgamate the data observed during the Labrador Sea deployment.

In order to obtain data at particularly high wind speeds, the PSR was redeployed in August 1997 on the NASA P-3 as part of the Hurricane Ocean Winds Experiment (HOWEX). The objective of HOWEX is to fly the OWI complement of instruments into the rain bands of hurricanes to provide measurements over wind speeds exceeding 35 m/sec. Four modified hex-cross patterns were flown within the rain bands of hurricane Erika (category 3, maximum winds 110 kts, minimum central pressure 946 mb).

ACCOMPLISHMENTS

Approximately 60% of the design and fabrication of the PSR was performed during the previous grant period from March 1995 through September 1996. During the most recent grant period (October 1996 through September 1997) the remaining components of the PSR were completed, including the gimbal positioner, scanhead, and data acquisition system. The overall development period was relatively short given the complexities of designing and deploying a precision rotating instrument to operate within the slipstream of an aircraft. Nonetheless, all mechanical systems worked flawlessly from the first test flight, and with the exception of a software bug that was found and corrected during the first data flight, the instrument data acquisition system performed similarly. The fairing was similarly designed and fabricated in an unusually short period (six months) and fit the P-3 superbly without the need for molds or other significant on-site modifications. The fairing has proven versatile enough to be used in additional NASA aircraft experiments.

The Labrador Sea and HOWEX data from the PSR are unique in that they are: (i) the first high-resolution conically-scanned microwave imagery covering a full 360^{o} in azimuth, (ii) multiband, covering the major microwave transmission windows in octave increments, (iii) tri-polarimetric, and (iv) coincident with measurements from a variety of additional passive and active sensors, and (v) representative of medium to high wind conditions, particularly within hurricane rain bands. The PSR data processing system has been completed for data up through the level of calibrated brightness imagery without aircraft roll and pitch compensation. A preliminary intercomparison of surface wind data from several OWI instruments has also been performed by the OWI science team.

SCIENTIFIC/TECHNICAL RESULTS

Data from the Labrador Sea experiment [Piepmeier, J.R., and Gasiewski, A.J., "High-resolution Multiband Passive Polarimetric Observations of the Ocean Surface," *Proceedings of the 1997 International Geoscience and Remote Sensing Symposium*, presented in Singapore, August 3-8, 1997.] have shown X-band (10.7 GHz) azimuthal harmonics of amplitude 2-3 K in the vertical and 4-5 K in the horizontal polarizations that are correlated in phase with wind direction. Similar variations in the uncalibrated PSR data are also seen at 18.7 and 37.0 GHz, indicating the presence of a broadband ocean surface emission mechanism. This mechanism is postulated as being a combination of the effects of ocean wave asymmetry, ocean foam placement, and resonant thermal emission from gravity-capillary waves. The signatures are largely consistent with 19- and 37-GHz wind direction signatures observed using the SSM/I instrument [Wentz, F.J., "Measurement of Oceanic Wind Vector Using Satellite Microwave Radiometers", *IEEE Trans. Geosci. Remote Sensing*, vol. 30, no. 5, pp. 960-972, September 1992]. The direction of the wind signature is also consistent with that observed by other instruments on board the P-3, including the radars, nadir-viewing radiometers, and dropsondes.

While the preliminary study strongly supports previous observations of a passive oceanic wind direction signature, a more complete calibration procedure for both the principle orthogonal polarizations and the third Stokes' parameter is yet needed. Also, an accounting for the effects of atmospheric stability and fetch are needed to solidify the PSR-SSM/I comparison. Important surface data for the completion of this study are becoming available from instruments located on board the *Knorr*. Nonetheless, the study indicates that the nature of the polarized signature is relatively consistent when observed from either a satellite using a broad footprint or an aircraft at high resolution. The signature also appears to be consistent in amplitude over a wide range of wind speeds in the medium-to-high range and over at least a two octave range of microwave frequencies.

IMPACT FOR SCIENCE AND SYSTEMS APPLICATIONS

The PSR observations during the Labrador Sea experiment verified the application of a digital polarization correlator for performing measurements of the third Stokes' parameter. Using the digital correlator, approximately 80% of the sensitivity of an analog correlator can be achieved using three discretization levels, and the entire detection system can be calibrated using conventional unpolarized hot and ambient targets. Perhaps the most significant technical challenge in implementing a digital polarization correlator is the development of accurate samplers that are fast enough to accommodate the wide bandwidths used in passive radiometry (typically a few hundred MHz). While the PSR used fast, but albeit inefficient emitter coupled logic (ECL) for the above demonstration, a space-qualified version of the PSR digital correlator will require implementation using radiation hardened CMOS logic. Dual-channel coherent receivers interfaced to CMOS correlation circuitry operating at 500-700 MS/sec are currently feasible for space application in such tri- and full-polarimetric radiometers.

TRANSITIONS

During the upcoming grant year (October 1, 1997 through September 30, 1998) the PSR scanhead will be upgraded with microwave switches allowing calibration at shorter time scales than currently available. The installation of these switches will eliminate the effects of much of the short term gain and offset drift that could not be observed using the relatively long calibration intervals offered by the current calibration scheme. In addition, several other modifications will be made to improve the capabilities of the scanhead, including the installation of hardware for the detection of the fourth Stokes' parameter on at least the 10.7 and 18.7- GHz channels, and the possible installation of a 21-GHz water vapor channel. These upgrades will allow important new observations of surface emission in the presence of water vapor variations, of the fourth Stokes parameter, and with increased precision. Flights using the upgraded instrument are being considered for late 1998.

RELATED PROJECTS

CAMEX III - Under NASA sponsorship, the PSR will be flown on the NASA DC-8 in conjunction with the third Convection and Moisture Experiment (CAMEX III). The goal of this mission is to observe hurricane and severe storm evolution using a variety of instruments sensitive to precipitation, clouds, and associated parameters such as oceanic wind fields. The PSR will be used to provide geophysical data products comparable to those provided by the SSM/I, but at spatial and temporal resolutions of up to 100 times higher. CAMEX III is scheduled to be held from July-September, 1998.

Direct Data Assimilation - The PSR is currently being integrated into the NASA ER-2 aircraft for future high altitude flights over severe weather in an effort to demonstrate the direct assimilation of high-resolution passive microwave imagery into numerical weather prediction (NWP) models. The integration of passive microwave imagery directly into NWP models represents the most optimal use of the microwave data. The initialization and update of nested-subgrid NWP models with PSR data would directly benefit the prediction and tracking of severe storms and hurricanes near landfall.

Monte Carlo Surface Emission Modeling - The physical nature of the passive wind direction signature over open ocean is being modeled using a new asymmetric wave Monte Carlo surface model. The surface model incorporates the effects of gravity wave asymmetry and ocean foam into a Monte Carlo spectral surface model. In conjunction with a simple geometrical optics emission model, studies using the asymmetric wave surface model have shown that the observed azimuthal brightness harmonics are predominantly the result of wave asymmetry and ocean foam.

PUBLICATIONS

Kunkee, D.B., and Gasiewski, A.J., "Simulation of Passive Microwave Wind-Direction Signatures over the Ocean using an Asymmetric Wave Geometrical Optics odel," *Radio Science*, vol. 32, no. 1, pp. 59-78, January-February, 1997.

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Wang, J.R., P. Racette, and A.J. Gasiewski, "Airborne Millimeter-Wave Radiometric Observations of Clouds," *Proceedings of the 1997 International Geoscience and Remote Sensing Symposium*, presented in Singapore, August 3-8, 1997.