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SCATTEROMETER MEASUREMENTS OF WIND, WAVES, AND OCEAN FRONTS DURING NORCSEX

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ABSTRACT

During March 1988, active microwave radar coefficient measurements were made from a ocean going research platform during a wind-wave-current field experiment on the Norwegian Continental Shelf (NORCSEX). Radar backscatter data were collected at 1.5, 5.25, and 9.38 GHz for incidence angles 20° to 80° and with both like and cross polarizations. One of the primary objectives of this study was to investigate the ability of SAR to image ocean surface features caused by current fronts and eddies in the moderate circulation regime off the Norwegian coast. In addition to supporting the SAR imaging aspects of the study, data were acquired for use in the study of the backscatter response of a wind driven sea. Detailed sea truth and meteorological characterizations acquired spatially and temporally coincident with the scattering measurements, and SAR imagery allows the examination of the influence of wind speed, wind direction, and sea state on radar cross section.

1. INTRODUCTION

In preparation for the 1990 launch of the first European Space Agency (ESA) Earth Resource Satellite (ERS-1) which will include a C-band synthetic aperture radar (SAR), a two week wind-wave-current oceanographic field investigation was conducted during March 1988 along the Norwegian Continental Shelf known as the Haltenbanken. A primary objective of this Norwegian Continental Shelf Experiment (NORCSEX) was to investigate the capability of SAR to image ocean surface features associated with current fronts and eddies in the moderate current regime off the Norwegian coast. Secondary objectives of the study were to assess the potential of a C-band SAR to measure ocean surface wind and waves.

In support of the SAR imaging aspects of the study, data were acquired to study the microwave backscatter response of a wind driven sea. A three-frequency four-channel scatterometer operated from the research vessel HAKON MOSBY collected microwave data at frequencies centered at 1.5, 5.25, and 9.38 GHz (L-, C-, and X-band, respectively), with incidence angles from 20° to 80°, and at like and cross linear polarizations. The scatterometer collects microwave data in a real-aperture mode, and thus is not dependent on platform motion (i.e., Doppler effects) as in the case of the SAR.

In this paper the L-, C-, and X-band scatterometer data collected during NORCSEX is first described. Data collected over a meteorological and oceanographic front that was imaged coincidentally with the C-band SAR is then presented. Exponents relating the scattering coefficients (σ_0) to wind speed are then calculated for the L-, C-, and X-band coincidentally collected radar data.

2. DATA SETS

The location of the March '88 NORCSEX investigation is shown in Figure 1. The remote sensing, meteorological and oceanographic data collected during NORCSEX is summarized in Table 1. The remote sensing data included the ship scatterometer, the C- and X-band SAR, the NOAA satellite Advance Very High Resolution Radiometer (AVHRR) imagery, the GEOSAT satellite altimeter, and DMSP satellite Special Scanning Microwave Imager (SSM/I).

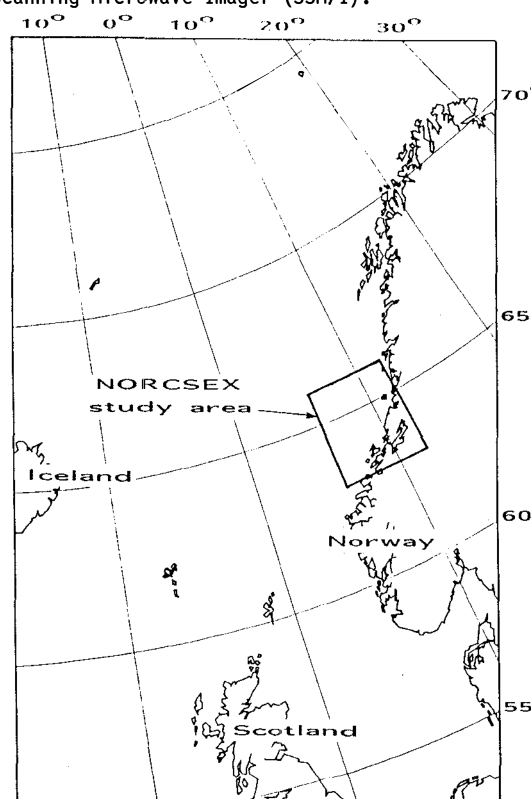

Figure 1. Location of the Norwegian Continental Shelf Experiment Study Area

Table 1. OVERVIEW HALTENBANKEN EXPERIMENT 1988

PLATFORM	INSTRUMENT (PARAMETERS OBTAINED)	OCEAN CURRENT	TEMPERATURE SALINITY DENSITY	SURFACE WAVES		INTERNAL WAVES	FRONTS EDDIES	NEAR SURFACE WIND	AIR-SEA STABILITY
				WIND	SWELL				
HÅKON MOSBY	SHIP RADAR							X	
	WEATHER STATION							X	X
	ADCP	X					X		
	SEASOAR		X				X		
	SCATTEROMETER	X (R)						X	
KRONSORT	CODAR	X							
ELDJARN	WEATHER STATION	X						X	X
IMR#2									
MOORINGS	CURRENT	X						X	
	THERMISTOR		X			X		X	
	WAVES			X	X			X	
	METEOROLOGY							X	X
NOAA 9,10	AVHRR		X				X		
GEOSAT	ALTIMETER	X		X	X		X (R)	X	
DMSP	SSM/I							X (L)	
SFT	SLAR					X	X (R)		
AIRCRAFT	SAR	X (R)		WAVE LENGTH		X	X	X (R)	

R: Research Evaluation. L: Limitation due to land effect.

The meteorological measurements and data assimilation were conducted during the entire NORCSEX field investigation period. Time series of surface layer meteorological data from ship mounted sensors and profilers of temperature, humidity and vector wind from rawinsondes were obtained. Surface layer wind fluxes (i.e, dragg coefficients) were obtained from ship mounted hot-film and the use of miniature cups.

The oceanographic sea truth was obtained by the use of a ship mounted thermistor (sea surface temperature), a towed undulating SeaSoar (salinity and temperature from the surface to 250 m), and the ship mounted 150 KHz Acoustic Doppler Current Profiler (ADCP). The ADCP provides a measure of absolute current every 5 m from the surface to near the ocean bottom.

3. SCATTEROMETER OBSERVATIONS

During this investigation the L-, C-, and X-band radar scatterometer was mounted on the starboard side of the wheelhouse of the R/V HAKON MOSBY (Figure 2). Detailed scatterometer system specifications have been included in Table 2. It was positioned as far forward on the ship as possible and pointed slightly forward of where the ship generated bow waves are produced. Thus, the effects of the bow generated waves were minimized. Bow waves which interacted with the ambient ocean wave field did however, break near the ship creating minimum observation angles of incidence which were sea state dependent. Calm conditions allowed observations at incident angles as small as 20 degrees, where as, in the extreme wave cases minimum angles were between 40 and 50 degrees. Ship roll and pitch motions were recorded as part of the data stream and when they were great enough to cause the backscatter returns to fall outside of the radar intermediate frequency processing filter, these data were noted and not included in the averaging process. To date, 2 and 10 minute averages have been processed. As the ship transited through the oceanographic features and wind fields, four channels of backscatter data and a visual time-encoded video record were acquired.

Radar observations at L-VV, C-HH, X-VV and X-VH or L-HH, C-VV, X-VV and X-VH were made as the ship transited through ocean fronts and internal waves. The first letter refers to the radar frequency used while the VV, HH, and VH denotes the transmit and receive polarizations. For example, VH indicates a cross polarization measurements where vertical polarization was transmitted and horizontal received. The range of meteorological and oceanographic conditions that occurred during the period of scatterometer observations 5 to 18 March are summarized in Table 3.

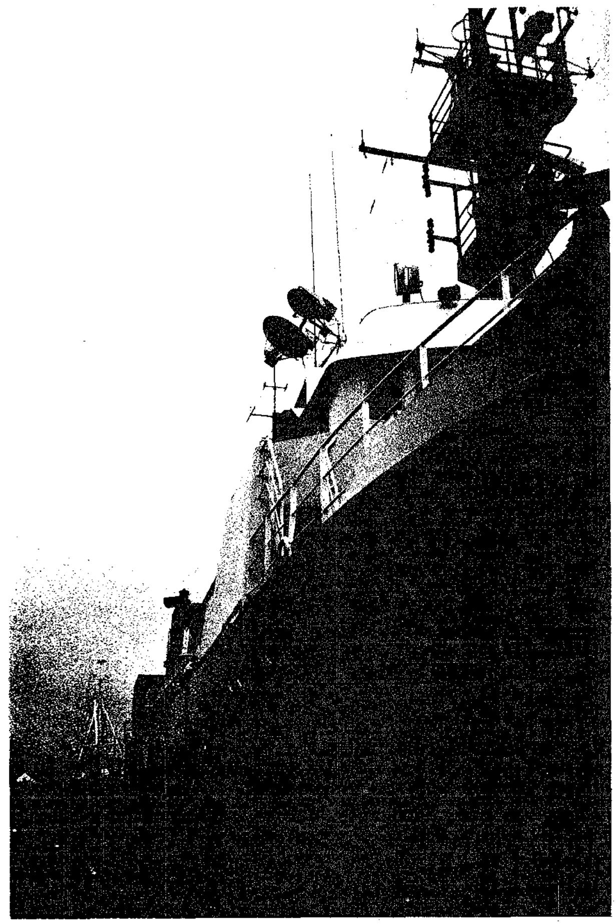

Figure 2. Three - Frequency, Four - Channel Scatterometer Operated at 1.5, 5.25, and 9.38 GHz, at Angle From 20° to 80°, and Like and Cross Linear Polarization

Table 2. SCATTEROMETER SYSTEM PARAMETERS

Parameter	L-Band	C-Band	X-Band
Frequency (GHz)	1.50	5.25	9.38
Wavelength (cm)	20.0	5.7	3.2
Polarization		- VV, VH, HV, HH -	
Incidence Angle		20° to 80°	
Height (m)		10	
Spot Size (m) at 40°	2.1	0.7	0.7
Bandwidth (MHz)	350	525	575
Independent Samples* Per Meter at 40°	12	6	8
Precision* (dB) at 40°	±1.1	±3.0	±2.6
Absolute Accuracy	±1.0	±1.0	±1.0
Ship Speed (m/s)		4	
Look Direction		Starboard	

* Assumes the Surface is Stationary

Table 3. Range of Meteorologic and Oceanographic Conditions During Scatterometer Observation Period 5 to 18 March

Wind Speed (15 m)	0 to 25 m/s with gusts to 30 m/s
Tempature Air (15 m)	-5°C to +6° C
Tempature Sea (Surface)	2° C to 7° C
Waveheight (H 1/3)	1 to 10 m with 2 - 4 m typical
Swell Wavelength	150 to 300 m

An example of an ocean front observed on 13 March is shown in the photograph provided in Figure 3. The temperature gradient for this front was +2°C and was created at the boundary between warm Atlantic Ocean water (T~7°C) and the colder Norwegian coastal water (T~5°C). The photograph illustrates the importance of sea surface temperature on the small scale surface roughness. Backscatter angular and polarization response measurements were made on each side of this ocean frontal feature. Quad-polarization measurements (VV, VH, HV, AND HH) were made at L- and C-band and dual-polarization measurements (VV and VH) at X-band. Seven leg star patterns were made to address wave and wind aspect angle dependencies.

Figure 3. Example of an Ocean Front which was Transited on 13 March. The Temperature Gradient was 2 °C. The Front was Created at the Boundary of Warm Atlantic Water (7 °C) and Colder Coastal Water (5 °C).

An interesting data collection took place on 17 March in which fluctuations in wind speed of 2 to 13 m/s were experienced during a ten hour period as the ship transited an oceanographic/meteorological front. Sea temperatures ranged from 5° to 8°C while the air temperature was 3°C. The air-sea temperature difference ($T = T_{air} - T_{sea}$) ranged from -2°C to -5°C producing unstable conditions since $T < -2°$ C. A gravity wave swell traveling in the same direction as the wind with 2-4 m significant wave height was present during the scatterometer observation. The wind and wave direction with respect to the radar was approximately 90° (i.e., upwind/downwind look direction). In Figure 4a, the L-, C-, and X-band radar scattering coefficients measured during this ten hour period are shown as a function of time. The wind speed and direction measured coincidentally with the scatterometer at a height of 15 m is shown in Figure 4b. These figures visually shows the correlation between wind speed and radar scattering cross section. Features that are instructive include the general increase in cross section as wind speed increases, the hysteresis associated with wave decay after a reduction in wind speed, and the change in the scattering coefficients of 10-13 dB for an increase in wind speed of 3 m/s to 13 m/s.

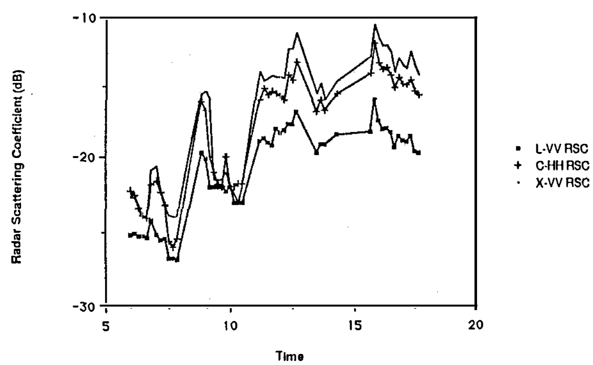

Figure 4a. Radar Scattering Coefficient at L-, C-, and X-band Measured While Crossing an Ocean-Meteorological Front on 17 March

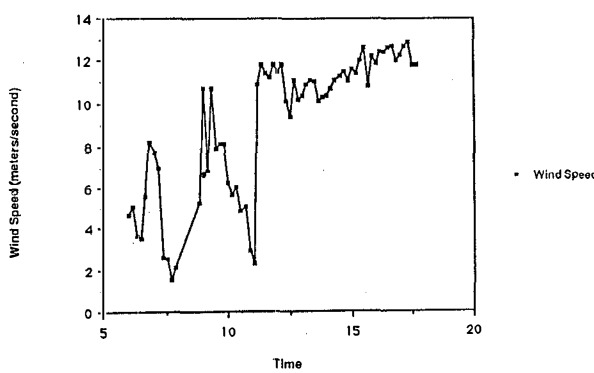

Figure 4b. Wind Speed Measured From Ship While Crossing an Ocean-Meterorological Front on 17 March.

It is also interesting to report that a response identical to that of the C-band scatterometer was observed by the SAR 5.6 GHz data. During this period a rapid transition from a spatially large region of weak returns where winds were calm (<3m/s) to strong radar returns where the winds greatly increased (>10 m/s) produced a 10 dB difference in backscatter intensity for these two regions [reported by Shuchman et al, 1989, these proceedings]. The ship transited across this front about 30 minutes after the SAR and noted this change in wind speed immediately prior to crossing the ocean front at 11 GMT. The wind friction velocity (U^*) can be related to dragg coefficient (C_d) and true wind speed (U) by the following expression

$$U^* = C_d^{1/2} U \qquad (1)$$

In this case U* changed from 0.1 to 0.5 m/s across this front illustrating the important difference in sea surface roughness.

The radar scattering coefficient $\sigma°$ has historically been related to wind speed through a transfer function of the form

$$\sigma°(U) = CU^{\gamma} \qquad (2)$$

where U is related to the surface wind vector, C the scaling coefficient, and γ the wind vector exponent. In addition to the local wind vector, the radar scattering coefficient can be additionally influenced by a array of other environmental parameters which include wave slope, sea surface temperature, air-sea temperature difference, and surfactants [Donelan and Pierson, 1987; Plant, 1986]. In Figure 5, the radar scattering coefficients at L-, C-, and X-bands are shown as a function of equivalent 10 m (height above the ocean surface) winds. Forty ten-minute intervals were used in producing these plots. All three frequencies produce approximately the same scaling coefficient, but yield different wind vector exponents and correlation coefficients (i.e., they range from 0.6 to 0.8). Exponents increased with increasing frequency and ranged from 1.30 to 1.76.

Keller et al [1989] reported data collected from a tower situated in the North Sea for C-VV and an incident angle of 45° which showed a response very similar to the NORCSEX observations. The radar cross-sections ranged in value from about -24 to -15 dB for a change in wind speed of 2 to 10 m/s. For this same change in wind speed, our scattering coefficients ranged from about -26 to -17 dB. Recall the NORCSEX C-band measurements utilized HH polarization. This change in polarization from vertical to horizontal is sufficient to account for the observed difference. The agreement in absolute level is reasonable and each set of measurements produced a 9 dB change in cross-section for this wind speed difference. The computed wind vector exponent for the results reported by Keller was 1.50. In our case, the exponent is 1.64.

4. SUMMARY

A wide range in meteorological and oceanographic conditions with respect to winds, waves, temperatures occurred during NORCSEX. Several distinct moderate to high winds (greater than 10 m/s) events were encountered as well as low wind conditions (2-4 m/s). Preliminary analysis indicates excellent correlation between variation of observed wind conditions and drag coefficients and variations of shipboard and aircraft remote sensing data. Future efforts will be directed at examining the relationships between wind stress, sea surface temperature, stability, sea and swell on remote wind vector determination.

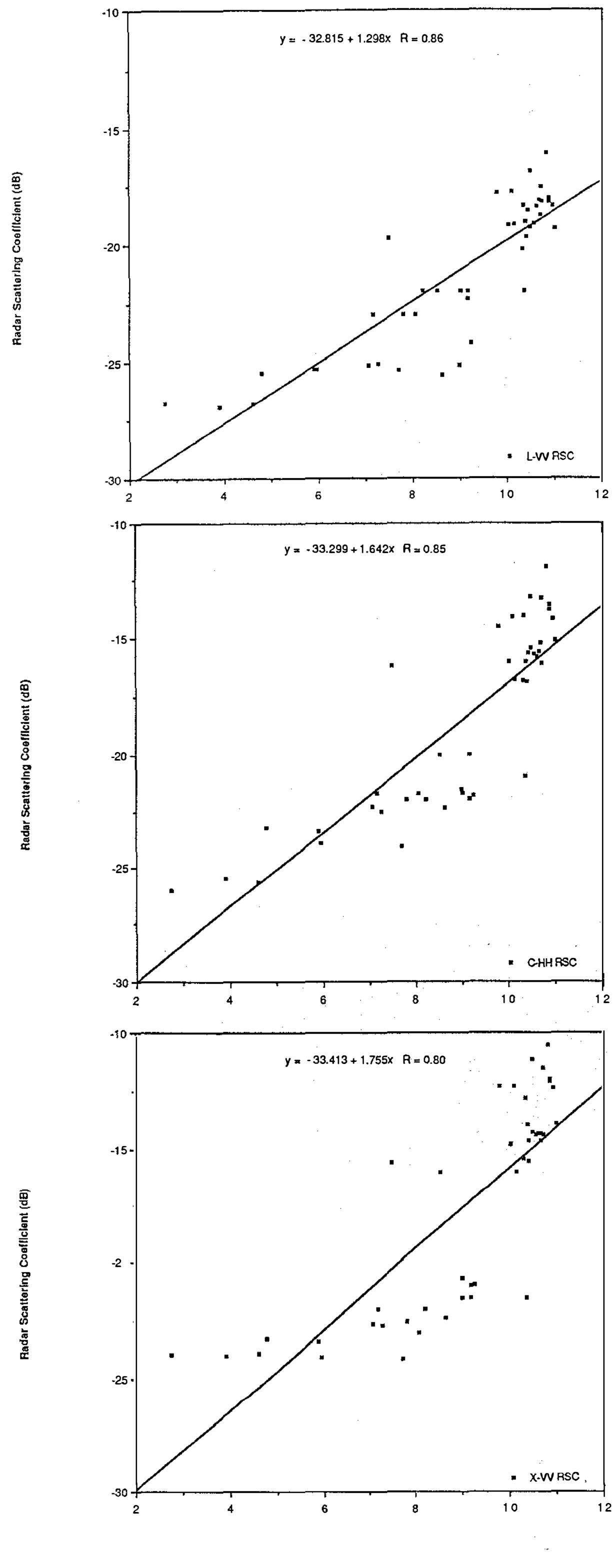

Figure 5

Radar Scattering Coefficients Measured on 17 March at L-VV, C-HH, and X-VV are Shown as a Function of Equivalent 10-m Winds.

ACKNOWLEDGEMENTS

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