Simultaneous Observations of Ocean Surface Winds and Waves by Geosat Radar Altimeter and Airborne Synthetic Aperture Radar During the 1988 Norwegian Continental Shelf Experiment

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Quasi-simultaneous measurements of the ocean surface by the Canada Centre for Remote Sensing (CCRS) Convair-580 (CV-580) synthetic aperture radar (SAR) were acquired on March 20, 1988, along an ascending pass of the Geosat radar altimeter as part of the prelaunch ERS-1 Norwegian Continental Shelf Experiment (NORCSEX '88). Over a region where the SAR look direction is parallel to the wind vector, a relationship between the ocean scattering cross sections measured by the Geosat altimeter and the SAR is obtained. In the regions where the wind direction is changing, an estimate of the wind direction is derived from the differences measured between the altimeter and the SAR scattering cross sections. Wavelength and wave directions derived from the SAR wave spectra are in good agreement with the sea truth data obtained with the wave directional buoys and with the altimeter-derived swell estimates. Significant wave height measured by the Geosat altimeter is compared with the buoy measurements and is used to assess the validity of the significant wave height deduced from the SAR.

1. INTRODUCTION

On March 20, 1988, as part of the Norwegian Continental Shelf Experiment (NORCSEX '88) prelaunch ERS-1 wind-wave-current investigation [NORCSEX '88 Group, 1989], the Canada Centre for Remote Sensing (CCRS) Convair-580 (CV-580) synthetic aperture radar (SAR) flew a data acquisition pattern over the Haltenbanken region of the Norwegian continental shelf. The purpose of this flight was to provide near-simultaneous supporting data for ocean surface measurements made during an ascending pass of the Geosat altimeter.

To our knowledge, this is the first time that coincident observations of the ocean surface from satellite radar altimeter and airborne SAR have been acquired quasi-simultaneously along a track several hundred kilometers long (Figure 1). Sea state parameters such as wind speed, significant wave height (SWH), and wavelength are inferred from the radar observations and are compared with corresponding parameters from surface observations. The measurements from one radar are used to improve and complement the capabilities of the other one. For instance, the ocean scatter cross sections from the altimeter are used to derive the wind direction from the SAR along part of the track. The altimeter significant wave height measurements are also used to assess the validity of the SAR significant wave height determination.

Figure 1 identifies the major features of the aircraft data set, the location of the four directional wave measurement buoys that monitored sea state and atmospheric conditions throughout the NORCSEX '88 experiment, and the location of two drilling platforms used to provide ancillary surface and meteorological data. The SAR swaths in this diagram are 22 km wide and span the incidence angle range from 0 ø (aircraft nadir) to 74 ø. VV polarization was used for image formation. The first line (1/1) was synchronized with the Geosat overflight time so that the aircraft and spacecraft data sets would be coincident in time and space in the vicinity of buoy 4. To provide data for modeling expected correlations between future satellite altimeters and spaceborne SARs, line 1/1 was positioned so that the center of the Geosat altimeter track corresponded to the SAR image at 30 ø incidence angle. The second line (2/2) retraced 1/1 from the seaward end to measure short-term, temporal variations of the sea surface roughness and to provide data needed to resolve the wave propagation direction ambiguity inherent in SAR measurements of waves. During line 2/2 the radar look direction (with respect to the sea surface) of line 1/1 was maintained. Flight lines 3/3 and 4/4 were flown to provide multiple aspect angle data in the vicinity of buoy 4 and to link the airborne measurements to the buoy 1 data set.

The simultaneous airborne SAR and Geosat altimeter data were acquired during a local storm that started on March 19 with strong winds blowing from the southwest along the coast. During the Geosat pass at 0800 UTC on March 20, an occluded front was located over the ocean, parallel to the Norwegian coast.
Fig. 1. Map of the March 20, 1988, experiment area showing the SAR swaths, surface measurement platforms, and major features of the SAR data set overlaid on the bathymetry contours of the test area. Large solid arrows identify the flight line numbers and the flight directions. (Line 2/2 ends at "A"). Small circled numbers 1 to 4 identify the wind front locations (dashed line) observed during flight lines 1/1 to 4/4. Numbered circles show the locations of wave scan buoys 1 to 4. The open square represents the drilling platform West Delta; the solid square is the drilling platform Polar Pioneer. B identifies regions of wave refraction; H identifies the "high wind speed" area. Small solid arrows indicate the wind direction observed from wind streaks in the SAR data, open-headed arrows show the calculated wind direction on the "low speed" side of the front, and dashed arrows show the wind direction calculated from combined SAR-Geosat data. The dashed line along the edge of the line 1/1 swath is the center of the Geosat track.
The SAR imagery obtained March 20 is characterized by well-defined wave fields throughout all passes and systematic slow variations in radar return with sudden discontinuities at the crossing of the frontal feature in the vicinity of buoy 4 (marked by 1, 2, 3, and 4 in Figure 1). This front is very sharply defined and is seen by the SAR at all incidence angles. This feature is not associated with any clear surface evidence of a current boundary in the ocean surface layers. Similar features observed during other NORCESEX flights were probed by the research vessel "Hidrun Mosby" and were found to be surface manifestations of rapid wind shifts [Johannessen et al., this issue].

The dominant swell field observed in the SAR imagery came from the southwest and was augmented by a wind sea especially to the east of buoy 4.

The complex meteorological and oceanographic conditions that were present during the SAR flight are described in section 2. The next section introduces the SAR system and the altimeter sea state measurements. The SAR and the altimeter ocean scattering cross section are analyzed in section 4 and, based upon the wind speed determination with the altimeter, wind vectors are derived from the SAR cross-section measurements over part of the flight when the wind direction was changing. The next section presents the wave analysis from the radar altimeter and the airborne SAR and is followed by a discussion and summary of the results.

2. THE METEOROLOGICAL AND OCEANOGRAPHIC CONDITIONS

The altimeter and SAR tracks crossed two directional wave measuring buoys (Wavescan) providing time series of wave height, wave propagation direction and wind speed at regular intervals of 3 hours (Figure 1). At these buoy positions, two current meter moorings were also deployed recording the subsurface current and temperature field from 25 m below the surface to within 25 m of the bottom.

Meteorological data (at 3-hour intervals) from all surface platforms in the measurement area except buoy 1 show the passage of a storm system through the area over a 9-hour period ending during the SAR data acquisition. Near the common intersection of the SAR passes, the drilling platform West Delta and buoy 4 report a large drop in wind speed over the reporting epoch ending at 0900 UTC. Wind directions reported by buoy 4 [Barstow and Bjerken, 1988] are anomalous in the context of the rest of the data set, probably owing to the application of the magnetic declination correction in the wrong sense. When the data are adjusted for this error, the surface data set is internally consistent.

During the evening of March 19, all four buoys measured maximum significant wave heights, which slowly decreased until approximately the time of the flight, during which conditions changed rapidly due to the passage of a storm. Prior to and during the flight, the main wave propagation direction measured by the buoys came from the southwest with periods varying between 11.8 and 12.8 s corresponding to wavelength between 220 and 250 m. These waves resulted from a storm which occurred on March 19 off the east coast of Scotland. The storm was characterized by strong winds blowing from the southwest along the Norwegian coast.

The reported air-sea temperature differences indicate that neutral stability conditions at the air-sea interface are satisfied over the experiment area. The water temperature at the drilling platform West Delta is 2° warmer than buoy 4 (30 km west-northwest), indicating the presence of a frontal structure.

The mean oceanographic conditions in the SAR-altimeter crossover region are schematically summarized in Figure 2. The bathymetry along the track shows considerable variations; on the broad continental shelf with a width of about 250 km the mean depth is 300 m. West of the shelf break, which runs northward, the bathymetry deepens rapidly into the Norwegian Sea with a mean depth of 3000 m. The presence on the shelf of a seamount rising to approximately 100 m below surface delimits the western boundary of a narrow, nearshore channel, 50 km wide, running northeastward parallel to the coast. The general ocean circulation is substantially steered by these significant bathymetric features [Haugan et al., this issue]. The relative cold and fresh Norwegian Coastal Current (NCC) forms a strong baroclinic jet in the channel with a maximum speed of 0.70 m/s directed northeastward. The main flow of the North Atlantic Norwegian Current (NANC) is steered northward along the outer shelf break at a mean speed of 0.25 m/s. Between these two currents, a weak barotropic eddy flows clockwise around the seamount. This predominant mesoscale circulation system can generate different wave-current and wave-bottom refraction patterns, which are observed at buoys 1 and 2 and are further discussed by Haugan et al. [this issue].

3. THE GEOSAT ALTIMETER AND THE CCRS CV-580 SAR

3.1. The Geosat Altimeter Measurements

The Geosat satellite was in a nearly circular orbit with an inclination of 108° at an altitude of 800 km. The satellite carried a short-pulse (3.125 x 10⁻⁹ s) nadir-viewing radar altimeter operating at 13.5 GHz. The geophysical measurements obtained from the radar altimeter were as follows: (1) the altitude of the altimeter above the ocean surface derived from the time delay between transmission and reception of the radar altimeter signal, (2) the significant wave height computed on board the satellite from the slope of the mean return waveform leading edge, and (3) the ocean surface wind speed deduced from the ocean back scatter coefficient determined from the automatic gain control (AGC) loop used to normalize the amplitude of the ocean return signal.

The Geosat radar altimeter system is described by MacArthur et al. [1987]. For the measurements of sea surface elevation and SWH, the effective footprint size on the sea surface varies from 2.4 to 11.6 km depending on the sea state.

The ocean backscatter coefficient is derived from the AGC, which drives the sum of 63 range gates of the return signal to a constant value. Sixty of the sample gates are separated by 3.125 ns with three gates halfway between gates 29, 30, 31, and
Fig. 2. Measured current directions and magnitudes at 25-m depth in the experiment area. Stations CMT1 to 3 reported current vector data throughout the experiment period. The current vectors show the conditions present on March 20, 1988. For reference, the swath imaged by the first flight line of the airborne SAR is shown as a double line. Some features of interest (circled numbers) are as follows:

1. The SAR images show a wave refraction event in the vicinity of the shelf break. A strong current is known to exist here.
2. A clockwise rotating eddy has been observed in the vicinity of the edge of the bank.
3. A weak flow has been observed around the peak of the Haltenbanken sea mount.
4. A strong and jetlike (spatially confined) current in the deep, nearshore channel. This feature has been observed by both the currentmeter at station CM2 and the SAR. In the SAR imagery the surface manifestation of the current jet is a localized region of wave refraction. The Geosat altimeter measures significant rms height anomalies.

32. The altitude tracker in the altimeter electronics package centers the mean sea level at gate 30.5. The footprint of the spherically expanding altimeter pulse projected on the mean sea level is determined by the area covered over the time interval from gate 30.5 to gate 60 (a total of 92.19 ns). This gate-limited footprint corresponds to a circle with a diameter of 9.5 km. The SWH and ocean cross-section measurements are acquired along the satellite track every second (over a distance of 6.7 km) and are used for sea state analysis.

3.2. The CCRS CV-580 SAR System During NORCSEX '88

The CCRS CV-580 C (5.30 GHz) and X band (9.25 GHz) SAR system was used as a data acquisition tool during the NORCSEX '88 flight program from March 11 to March 21, 1988. During this period, the C band SAR was nearing the end of its commissioning phase, but the X band was newly installed and provided its first extensive ocean imagery. The radar systems are described in detail by Livingstone et al. [1987, 1988].

Both C and X band radars employ selectable transmitter polarization and simultaneous phase coherent, dual-polarized receivers to allow the acquisition of simultaneous and cross-polarized images. Both antennas are carried on the same two-axis (azimuth/elevation) controlled drive, they view the same terrain and cannot be pointed independently. For the NORCSEX experiment, both radars were operated exclusively in a VV-polarized single channel mode for ocean measurements. The wide swath imaging mode (18-m range resolution, 61-km swath at 15-m range pixel separation) was
used for investigation of large-scale sea surface structure, and
the nadir mode (5.7-m range resolution, 16.4-km swath at 4-m
pixel separation) was used to measure ocean waves. The nadir
mode geometry allows imaging from incidence 0° to 74°, and
the real-time processed image is normally recorded in the slant
range plane to minimize field errors arising from errors in
aircraft attitude estimation.

4. ALTIMETER AND SAR OCEAN SCATTERING CROSS
SECTION AND WIND PARAMETER MEASUREMENTS

4.1. The Altimeter Measurements

The altimeter antenna measures specular returns from the
nadir sea surface. On board Geosat, the amplitude of the
ocean-return signal is normalized via the AGC loop. Properly
calibrated, the AGC setting measures the backscatter
coefficient at the ocean surface that is dependent on
wind speed at the ocean surface. The scattering cross section
of the ocean surface at the nadir can be modeled by specular
points assuming that the sea surface slopes are nearly Gaussian
and isotropic in their distribution [Barrick, 1974].

Several wind speed algorithms have been developed for
satellite altimeters. A comparison of these algorithms by
Dobson et al. [1987], shows that the algorithm first developed
with Geos-3 [Mognard and Lago, 1979; and Brown, 1979] and
later fine-tuned with the NOAA buoys for the Seasat altimeter
[Brown et al., 1981] yields the smallest rms discrepancy (1.7
m/s) and overall bias (0.5 m/s) for the 7-month comparison of
Geosat wind speed data to the National Data Buoy Center
network. This comparison used 5-s averages of Geosat data.
A study with Geosat of the algorithms performances over
various meteorological situations (cold, warm, and occluded
fronts, sharp isobaric gradients, anticyclones) showed that the
different algorithms measure qualitatively similar wind speed
gradients over the ocean but somewhat different quantitative
values [Mognard et al., 1987]. The Geosat data used in this
paper were processed with the Brown algorithm [Brown et al.,
1981] which yields validated wind speeds from 0 to 21 m/s.
The slightly modified Brown algorithm [Goldhirsh and
Dobson, 1985] has not been validated for wind speeds higher
than 14 m/s and is thus not used here.

The variations of the altimeter ocean cross-section along
with the derived wind speed are presented in Figures 3a and
3b. The altimeter senses the variations in specular reflection
along the track and thus responds to changes in wind speed
that are opposite to the SAR responses. For instance, the
position of the front is sharply defined by an increase in the
altimeter ocean cross section of 0.6 dB (Figure 3a) that
corresponds to a decrease in wind speed from 12 to 10.5 m/s
(Figure 3b).

The Geosat pass starts north of buoy 2 which has a sheltered
position near the Norwegian coast. On March 20, buoy 2
measured a wind speed of 8.5 m/s at 0500 UTC and 8.9 m/s at
0800 UTC, with a stable wind direction from the south-
southwest. A local fetch-limited sea is present at buoy 2,
where the wind speed measurements are in good agreement
with the Geosat wind speed of 9.3 m/s at the start of the
satellite pass, slightly west of buoy 2. In the area between
buoys 2 and 4, the altimeter wind speed first increases steadily
to 13 m/s to reach a plateau (between the latitudes 65.0°N and
65.3°N) where the Geosat wind speed oscillates between 12
and 13 m/s (Figure 3b). At the time of the Geosat overflight an atmospheric front was passing over buoy 4. The wind speed record from the buoy shows the wind decreasing from 20.5 m/s at 0600 UTC to 5.7 m/s at 0900 UTC; by 1200 UTC, the wind speed has again increased (to 10.7 m/s) and the wind direction has shifted to 150°.

4.2 SAR Measurements

4.2.1 Background. At incidence angles near nadir, the radar reflectivity of the sea surface is dominated by specular reflections. This is the Geosat altimeter measurement regime, and it also governs SAR returns from the sea surface at incidence angles less than 20°.

At larger incidence angles the radar returns are governed by Bragg scattering from surface structures whose slant range projected wave lengths are of the order of half the radar wavelength. Small-scale waves can, in turn, be related to the wind friction velocity $V^*$ at the sea surface and to the stability of the air sea interface. (Donelan and Pierson [1986] show that the wind speed gradient at the sea surface is a physically more satisfying parameter to use. It is not, however, accessible from the March 20, 1988, NORCSEX data set and would also need to be estimated from models.)

Following Panofski [1963], the friction velocity can be related to the measured wind speed $V$ at height $z$ above the surface by

$$V(z) = V^*\sqrt{0.04[\ln(z_0/z)]}$$

(1)

where $z_0$ is a roughness length and $\psi$ is the air-sea interface stability function.

Investigations by Keller et al. [1989] based on 1984 data from the research tower "Nordsee" show that when the air temperature difference $\Delta T = T_{air} - T_{sea}$ is less than $-2^\circ$C, the air-sea interface is unstable and both the C band $VV$-polarized scattering cross-section at 45° incidence and $V^*$ are high. $-2^\circ$C $< \Delta T < 2^\circ$C defines the neutral stability regime. For $\Delta T > 2^\circ$C the C band radar cross section and $V^*$ decrease with increasing $\Delta T$ with the rate of increase smallest at high wind speeds. For friction velocities less than 0.2 m/s, Keller et al. note a dependence of radar cross section on rms wave slope which vanishes at higher friction velocities. No relationship between radar cross section and water temperatures (predicted by Donelan and Pierson [1986]) was found.

The dependence of $V^*$ on surface currents was not investigated by Keller et al. The relationships between the wind stress vector $V^*$, the surface current vector $U$, and the surface current shear are expected to affect the capillary wave spectrum and thus the radar scattering cross-section of the ocean.

While nadir-looking radars provide non-directional measurements of sea surface roughness, SAR measurements are dependant on the vector relationships between the wind stress $V^*$ (and thus $V$) and the radar range $R$ to the measured element.

Setting aside the surface current effects on the generation and dissipation of capillary waves, the normalized scattering cross section of the sea surface will be some function of the wind velocity $V$, the radar wavelength $\lambda$, the incidence angle $\theta$, and the wind azimuth angle $\varphi$ (measured from the surface projection of $R$).

From airborne scatterometer measurements of the FROMESS experiment in 1984, and from Nordsee tower measurements, Attema et al. [1986] have derived a scattering cross section model for C band, $VV$-polarized radars. The model uses wind measurements at 10 m above the sea surface and is valid for a neutrally stable boundary layer, all azimuth angles, and incidence angles in the 20° to 50° range.

From Attema et al. [1986], the empirical normalized scattering cross section of the sea surface (in meters per square meter, not decibels) is

$$\sigma^0(\theta, \varphi) = C(\theta) V^*(\theta) \left[ \frac{1 + b_1(\theta, V)\cos\varphi + b_2(\theta, V)\cos2\varphi}{1 + b_1(\theta, V) + b_2(\theta, V)} \right]$$

(2)

The variables $V$, $\theta$, $\varphi$ have been defined previously and the coefficients $C$, $\gamma$, $b_1$, $b_2$ are listed in Table 1. The angle of $\varphi$ is equal to 0 when the radar beam is directed into the wind. The model $\sigma^0$ of equation (2) is ambiguous with respect to the sign of $\varphi$. When the wind speed is sufficiently high, wind streaks appearing in the SAR imagery can be used to resolve the $\varphi$ ambiguity. The ambiguity can also be resolved by imaging a region of the ocean at multiple aspect angles if the wind velocity is temporally stable over the measurement period.

In equation (2) the term $\sigma^0 = C(\theta) V^*(\theta)$ is the normally used power law expression for the radar cross section of the sea surface. Keller et al. [1989] note that there is no present theoretical justification for this functional form.

4.2.2 Experimental results. SAR image transects for the March 20, 1988, $VV$-polarized data were constructed by extracting radar returns corresponding to the 25° to 35° incidence angle range, averaging these in range (angle), and then averaging the results in 96-m blocks along the flight track.

The line 1/1 transect, shown in Figure 4, lies near the center line of the Geosat altimeter measurement profile. Since each point along the transect is computed from a large number (3800) of independent samples, SAR speckle effects can be ignored. The high (spatial) frequency components in Figure 4 vary in amplitude by up to 1.2 dB over time less than Geosat altimeter reporting interval and measure the local variations of $\sigma^0$ due to wind and wave features in the data. Similar transects were constructed for lines 2/2 and 4/4.

A typical plot of the SAR cross section as a function of incidence angle $\sigma^0(\theta)$, and the corresponding Geosat $\sigma^0$ estimate is shown in Figure 5 for a high-return portion of the SAR image where the wind vector was upwind (maximum return) compared with the SAR look direction. This curve spans both the specular and quasi-specular scattering regime ($\theta<10^\circ$) corresponding to the Geosat observations and the diffuse scattering regime ($20^\circ<\theta<70^\circ$). The scattering cross sections shown in Figure 5 are comparable to measurements by Daley discussed by Valenzuela [1978].
Table 1. ESA Wind Model Parameters From Attema et al. [1986]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi(\theta, \varphi, V)$</td>
<td>$C(\theta)\gamma(\theta)(1 + b_2(\theta, V)\cos\varphi + b_2(\theta, V)\cos2\varphi)/(1 + b_1(\theta, V) + b_2(\theta, V))$</td>
</tr>
<tr>
<td>$C(\theta)$</td>
<td>$10(1.877 - 0.1466\theta + 1.0610^{-3}\theta^2)$</td>
</tr>
<tr>
<td>$\gamma(\theta)$</td>
<td>$-0.09885 + 0.0506\theta - 4.0610^{-4}\theta^2$</td>
</tr>
<tr>
<td>$b_1(\theta, V)$</td>
<td>$2 - 4(\bar{u}_c + \bar{u}_d)/(\bar{u}_c\bar{u}_d + 2\bar{u}_d + \bar{u}_c)$</td>
</tr>
<tr>
<td>$b_2(\theta, V)$</td>
<td>$1 - 4\bar{u}_d/(\bar{u}_c\bar{u}_d + 2\bar{u}_d + \bar{u}_c)$</td>
</tr>
</tbody>
</table>

At 30° Incidence Angle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>$1.11410^{-3}$ (-29.53 dB)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1.0538</td>
</tr>
<tr>
<td>$b_1(V)$</td>
<td>$2 - 4(3.0627 + 0.0533V)/(6.4347 + 0.1193V + 1.310^{-4}V^2)$</td>
</tr>
<tr>
<td>$b_2(V)$</td>
<td>$1 - 4(1.156 + 2.5710^{-3}V)/(6.4347 + 0.1193V + 1.310^{-4}V^2)$</td>
</tr>
</tbody>
</table>

Here, $\bar{u}_c$ is the upwind/cross-wind ratio ($\bar{u}_c = 1.058 + 0.02835\theta - 2.10^{-6}\theta^2 + (-0.114 + 7.1410^{-3}\theta - 5.510^{-5}\theta^2) V$), $\bar{u}_d$ is the upwind/downwind ratio ($\bar{u}_d = 0.637 + 0.02507\theta - 2.9510^{-4}\theta^2 + (7.3710^{-3} - 9.410^{-4}\theta + 2.610^{-5}\theta^2) V$), $V$ is the 10-m wind in meters per second, $\theta$ is the incidence angle in degrees, and $\varphi$ is the azimuth angle in degrees.

Fig. 4. SAR measurements of the normalized radar scattering cross-section at 30° incidence angle, $\phi(30°)$, for flight line 1/1. Each data point in this graph is the average of 3800 SAR image pixels, and thus speckle noise is not significant here. The interval A-A defines the region of overlap of the SAR and Geosat data sets. In the common data region, the interval from 64.6°N to 65.3°N shows the effect of varying wind speed when the SAR beam looks directly into the wind. The sharp decrease near 65.3°N is an atmospheric front at which both the wind speed and direction change over less than 100 m. The fine structure immediately following the front can be interpreted either as wind speed and direction variations in the center of the low-pressure region bordered by the front or as evidence of a current shear known to be present in the area. From 65.5°N to 66.1°N wind speed and direction both change. Prior to the start of the interval A-A, the 1.5-dB step in $\phi$ near 64.5°N is associated with the SAR signature of the nearshore current jet referred to in Figure 2.
When Figure 4 is examined in the context of the corresponding SAR image, three distinct regions are evident over the pass segment common to both SAR image and the Geosat altimeter.

4.2.2.1. Region 1: Wind streaks in the SAR imagery for the first region (latitude 64.55°N to 65.35°N along the pass) show that the wind direction is constant with respect to the SAR look direction and is oriented parallel to the ground projection of radar range vector. From observations in line 4/4 the radar is looking unambiguously upwind.

The scattering cross section measured by the SAR and the altimeter are linearly related in the power domain by

\[ \sigma^0_{\text{Geosat}} = -218\sigma^0_{\text{SAR}}(30°) + 12.46 \]  

(3)

The data cluster in logarithmic form (dB) and equation (3) are shown in Figure 6.

The point scatter in Figure 6 illustrates the differences between the SAR and Geosat altimeter responses to small-scale variations in the surface roughness of the ocean. Contributing factors are differences between the scattering processes responsible for the Geosat altimeter (specular scattering) and SAR (diffuse scattering) measurements and differences between the sizes of the regions averaged to yield each measurement point (approximately 55 km² for Geosat and 0.2 km² for the SAR).

4.2.2.2. Region 2: The second region consists of a sharply defined atmospheric front (\( \sigma^0_{\text{SAR}}(30°) \) decreases 7 dB in less than 30 m; Figure 7), a region of reduced scattering cross section and a further decrease of 2 dB 5 km further down the
Norcsex
March 20
Pass 1

Fig. 7. SAR image section for line 1/1 showing the "discontinuity" in the ocean reflectivity across the atmospheric front.

The sudden change in radar cross section can be attributed to a sudden change in both wind speed and direction at the front.

From equation (2), the change in wind speed can be expressed in terms of radar cross-section change as

\[ \frac{V_2}{V_1} = \left[ 10^{(d_2-d_1)/10} \frac{(1+b_1(V_1)\cos \phi_1 + b_2(V_1)\cos 2\phi_1)(1+b_1(V_2) + b_2(V_2))}{(1+b_1(V_2)\cos \phi_2 + b_2(V_2)\cos 2\phi_2)(1+b_1(V_1) + b_2(V_1))} \right]^{1/\gamma} \]

where \( V_1 \) and \( \phi_1 \) correspond to \( d_1^0 \), \( V_2 \) and \( \phi_2 \) correspond to \( d_2^0 \), and \( d_1^0, d_2^0 \) are expressed in decibels. A similar approach is used in Johannessen et al. [1990].

An iterative solution to equation (4), taking into account the wind data from the drilling platform West Delta at 0900 UTC,
yields a change in the wind field from 12.5 m/s at 220° ± 5° on
the high wind side of the front to 5.5 ± 1 m/s at 340° ± 5° on
the low return side of the front.

The second radar cross-section decrease in region 2 can be
interpreted as a wind speed reduction with or without a change
in wind direction. For a wind direction of 350° the
corresponding wind speed is 2.4 ± 1 m/s. The data reported
by West Delta and buoy 4 at 0900 UTC show the wind speed
and direction to be variable in the low wind regime. This is
supported by SAR image features observed in line 3/3.

For the Geosat altimeter with its relatively large
measurement cell (approximately 9.5 km), the wind speed and
radar cross section discontinuity at the front approximates an
ideal step change. Combining the Geosat and SAR data for
this region, the half power step response distance of Geosat $\sigma^0$
measurement (plus algorithm) is 9.8 km along track.

4.2.2.3 Region 3: The third region (latitude 65.45°N to
66.15°N) contains an increase of the SAR cross section from
the low return (low wind) condition and an interval of
relatively stable return. Since the spatial gradient of the sea
surface roughness ($\sigma^0$) is sufficiently small over this region, the
Geosat cross section can be accepted as a wind speed measure,
while the SAR data provides a measurement of wind direction.

Using the region 1 $\sigma^0$ plateau as a reference, equation (4)
was resolved for wind angle in region 3 as is shown in Figure 8.
The ambiguity in equation (4) was resolved by the wind streak
orientation in the SAR imagery to create the dashed wind
direction indicators in Figure 1. The solid wind direction lines
are observed from wind streak data.

Wind information extracted from passes 2 to 4 confirmed
pass 1 results in the regions of overlap as well as providing
further information on the spatial distribution of wind speed
and direction (Figure 1).

The low wind-speed region is best observed by the SAR look
direction in pass 3, since the radar beam is orthogonal to the
wind vector in the high wind-speed region. In the low wind
regime, patches of radar return enhancement (and
suppression) with scale sizes ranging from 1 km to 5 km show
the wind to be variable in both speed and direction. The wind
front contrast for this pass is reduced to less than 0.5 dB by the
directional terms in equation (4) and frontal structure, in the
form of a line of 500 ± 100 m cells, is visible along the front
boundary. The wind direction on the high speed side of the
front (225° ± 5°) is visible in the radar imagery as wind streaks.
From equation (4) the best estimate for the mean wind speed
on the low wind side of the front boundary is 5.5 ± 1 m/s from
335° ± 5°; on the high wind side the wind velocity is 12.5 ± 1
m/s from 227° ± 5°.

In the pass 4 SAR data set the wind direction is
unambiguously defined in the imagery by the wind shadow of
the drilling platform Polar Pioneer. The wind speed and
direction derived from SAR data near the front, 12.5 ± 1 m/s
from 230° ± 5°, agree reasonably with the 0900 UTC
meteorology log from Polar Pioneer (at 0800 UTC 12.8 m/s
from 220° ± 5°). The 30° incidence angle transect for line 4/4,
Figure 9, shows a reduced wind velocity at Polar Pioneer
position, 10 ± 1 m/s, with an unchanged wind direction. At
the time of the pass 4 overflight, 1017 UTC, a second wind
front is close to the Polar Pioneer position as shown in Figure
1. The front south of Polar Pioneer is not as sharply defined as
the more northerly front and (from equation (4)) is associated
with a low return side wind of 4.5 ± 1 m/s from 180° as
observed by buoy 1 at 0900 UTC.

The decrease in SAR return south of the front lies outside of
the observed wind speed range of buoy 1 (2.3 m/s at 180° ± 5°
would be required) and may be, in part, due to the wind
interaction with a current system that is known to flow through
this area as shown in Figure 2.

4.2.2.4 Behavior of the northern wind front: Over the
course of the SAR data acquisition period the wind front near
65.2°N, 7.0°E was observed four times over an interval of 2.3
hours. During that period the front moved a total of 11.5 km
± 0.4 km at 132° with a mean speed of 5 km/h while
maintaining its approximate orientation as shown in Figure 1.
The motion in the SAR record is in agreement with the
observed eastward drift of the associated weather system
described in the 0900 UTC weather maps for March 20, 1988
(Figure 10).

5. ALTIMETER AND SAR WAVE MEASUREMENTS

5.1 The Geosat Significant Wave Height Measurements

The effect of waves in the altimeter's footprint is to stretch
the leading edge of the return radar pulse because of early
returns from wave crests and later returns from wave troughs.
The slope of the leading edge is inversely related to the wave
height and is reduced to SWH estimates on board the satellite.
The altimeter cross-track sea surface footprint varies from 2.4
to 11.6 km for SWH varying from 0 to 20 m. For 3-m SWH,
the typical altimeter footprint is 3 x 6.7 km² over 1 s. From the
7-month comparison between SWH measurements from the
Geosat altimeter and the NOAA buoy network, Dobson et al.
Fig. 9. SAR measurements of $\sigma^0$ at 30° incidence angle along a transect through the line 4/4 SAR image. This data shows the existence of two wind fronts. The northern front (near 65.2°N) is observed during all passes. The southern front (near 64.4°N) defines the southern limit of the storm system. The decrease in $\sigma^0$ south of 64.1°N is believed to be a result of surface current modulation of the wind stress.

[1987] found a mean difference of 40 cm, indicating a slight underestimation of the Geosat SWH compared to the buoys, and a rms discrepancy of 36 cm. Similar results were obtained from the statistical analysis performed during NORCSEX ’88 comparing the Geosat and buoy SWH measurements (O. M. Johannessen and T. A. Johansen, personal communication, 1990).

5.2. Comparison Of the Geosat and Buoy Significant Wave Height Measurements

The Geosat SWH variations and the buoy measurements along the satellite track are presented in Figure 11. The SWH variations show a steady increase from the start of the pass to almost the end of the continental shelf from 3 to 4.5 m.

Fig. 10. Weather map from 0900 UTC, March 20, 1988, clearly showing the occluded low-pressure region that generates the wind front observed by the SAR and the Geosat altimeter.
Beyond the continental shelf, the mean SWH remains stable at 4.5 m. An analysis of the buoy data on March 20 [Barstow and Bierken, 1988] shows that buoy 2 was measuring a local fetch-limited sea with westerly wave direction. Long waves were refracted by the Haltenbanken plateau toward buoy 2, which occupies a sheltered location behind the bank. At 0800 UTC, the SWH measured by buoy 2 was 2.1 m, which is low compared with the altimeter measurement of 3.2 m at the start of the Geosat pass (Figure 11). This 1-m difference between Geosat and buoy 2 might be due to the sheltered location of buoy 2 (at the same time, buoy 3 was measuring 4.7 m and buoy 1 3.6 m at 0900 UTC, in good agreement with Geosat). This sheltering effect might explain the almost constant overestimation of Geosat SWH in the vicinity of buoy 2 during NORCSEX '88 [Barstow and Bierken, 1988]. At 0900 UTC, a SWH of 5.3 m was measured at buoy 4, in good agreement with Geosat 4.8 m measurements. The crossing of the atmospheric front near buoy 4 is observed in the Geosat and SAR scattering cross-section variations (Figures 3 and 4). Across the front, the altimeter wind speed decreases from 12 m/s to 10.5 m/s (Figure 3b), which would correspond to a diminution of the fully developed wind wave from 3.6 m to 2.6 m. However, the sea has not had time to reach equilibrium because of the front motion. A decrease is not observed on the altimeter SWH which in this area oscillates between 4.6 m and 4.3 m. The crossing of the atmospheric front is not defined by a significant variation of the SWH measurement. This is an indication that the sea state is swell-dominated.

5.3. The Geosat Minimum Significant Swell Height

From the simultaneous measurements of SWH and wind speed ($V$) by the Geosat altimeter, a minimum significant swell height can often be inferred. This is the case when the SWH measured by the altimeter is greater than the fully developed wave height derived from $V$. The fully developed wave height is computed using the Pierson-Moskowicz expression of the spectrum [Pierson and Moskowicz, 1964]. When the fully developed wave height associated with $V$ is smaller than the altimeter-measured SWH, the difference between the energy in the altimeter SWH field and the fully developed wave field is due to the presence of swell, and a minimum significant swell height can be computed [Mognard, 1984]. The Pierson-Moskowicz spectrum used to derive the minimum significant swell height from the wind speed measurement assumes that the wind sea is fully developed. In the middle of a storm, when the conditions are not fully developed and the energy in the altimeter SWH measurement is lower than the energy in the fully developed sea (as derived from $V$), the altimeter-inferred minimum significant swell height cannot be estimated.

The Geosat minimum significant swell heights are presented in Figure 12 along with the 0800 UTC hindcast values from the Norwegian numerical wave model WINCH. At the start of the Geosat pass, near the Norwegian coast, the mean altimeter derived swell is 2.5 m, in good agreement with the hindcast values; north of the atmospheric front, the altimeter mean swell height reaches 3.5 m, slightly lower than the hindcast values from WINCH. South of the atmospheric front where the highest winds were measured, the swell height cannot be derived from the altimeter SWH and $U$ measurements.
During the SAR flight, the dominant swell and wind wave fields observed in the SAR imagery come from the southwest. The four buoys in the NORCSEX area are measuring, on March 20, a swell coming from the southwest that is still present and dominant during the SAR flight. This swell is coming from the region between Scotland and Norway and had been generated the preceding day by the same storm system. The only Geosat passes in the region on March 19 are a descending pass at 0200 UTC and an ascending pass at 0900 UTC that both crossed the NORCSEX area. These two Geosat passes do not probe the most intense part of the storm that is located southwest of the NORCSEX region. The high sea state measured by the Geosat altimeter on March 19 are obtained at 0900 UTC near the Norwegian coast at 64°N and 2°E with SWH of 6 m and $U$ of 18 m/s. If we assume that these measurements are representative of sea state conditions not too different from the highest sea state generated by the storm, a resulting swell period of 11 s can be inferred from the Geosat altimeter measurements using the Joint North Sea Wave Project (JONSWAP) form for the spectrum valid for varying between 11.8 and 12.8 s. The Geosat underestimation of the swell period (11 s) confirms that on March 19 the Geosat altimeter did not acquire data over the middle of the storm. On March 20 at 0900 UTC, buoy 4 measured a bimodal wave system with a residual southwesterly swell of 12.5-s period.

5.4. SAR Processing

SAR image formation was performed in real-time on board the aircraft. This processing used the on-board navigation system to maintain good spatial control of the image locations and to compensate for aircraft motion effects on the image focus. The on-board real-time processor performed a time domain correlation between seven defined subbeams and a stored azimuth reference function (computed for the radar imaging geometry and initial ground speed at the start of each flight line) then recombinen the time-shifted, detected single-beam images to form an output magnitude image. For the March 20, 1988, data, the real-time processed SAR imagery was recorded in a slant range format.

5.4.1. Estimation of wave spectra from SAR image. SAR spectra were extracted from the standard seven-look processed images collected in nadir mode as described in sections 1 and 3. Data segments consisting of 512 pixels in range by 1024 pixels in azimuth were selected at along-track intervals of 6.7 km, corresponding to the 1-s Geosat sample locations. The cross-track locations of these segments were chosen to be centered at an incidence angle of approximately 35°. These segments were first resampled onto a regular 4 x 4 m ocean surface grid to remove the distortion caused by recording the data in the slant plane. The resampled images were low-pass filtered, and the original images were divided by the corresponding filtered images to remove the low-frequency noise in the data, including that caused by the residual antenna pattern. Each of the 512 x 1024 image segments was then divided into two 512 x 512 subsets which were Fourier transformed, and the squared magnitudes of each pair of Fourier transforms were averaged together to form an estimate of the image spectrum for each data segment.

These image spectra were displayed in two different ways and were also used to estimate the SWH as described in section 5.4.2. Figure 13 is a map of the region showing the approximate location of the SAR spectra. Two-dimensional gray level displays of the image spectra are shown in Figure 14. The spectra were also reduced to one-dimensional wave number and wave directional spectra shown in Figures 15 and 16.

Plots of the wave number-intensity spectra provide information about wavelength and wave propagation direction (Figure 14); wave numbers in azimuth and range are indicated along the horizontal and vertical axis, respectively, while the circles identify wavelengths of 100, 200, and 400 m. The two-dimensional and one-dimensional SAR spectra (Figures 14 and 15) show only one consistent peak at a wavelength of approximately 250 m across the length of the pass. However, on the basis of the local winds estimated from Geosat to be of the order of 10-12 m/s at the time of the overpass, there was expected to be a second peak at a wavelength of about 100 m. Although there is some evidence of such a peak in a few of the two-dimensional spectra (Figure 14), this feature does not appear consistently in the SAR data as expected.

In addition to observing the general shape of the SAR spectra, we have also attempted to estimate the SWH from the SAR data.

5.4.2. Estimation of significant wave height from SAR data. There is a considerable amount of uncertainty with regard to the mechanisms by which ocean waves modulate the SAR image intensity, particularly for waves traveling at large angles with respect to the radar look direction. Nevertheless, there is a body of information about these mechanisms which can be exploited to yield at least a first-order estimate of the SWH for comparison with the Geosat estimates.

In the general case, the imaging of ocean waves by SAR is influenced by surface motion (velocity bunching and azimuth fall-off) effects, as well as by "real" radar cross-section modulation (tilt and hydrodynamic) mechanisms. In the data set considered here, however, since the peak of the spectrum is in the radar range direction, surface motion effects are expected to be minimal and have been neglected in this analysis. We assume therefore that the image spectrum $S_i(k)$ can be related to the wave height spectrum $S_w(k)$ by the equation

$$S_i(k) = |m|^2 k^2 S_w(k) + S_{sp}(k)$$

where $m$ is the ocean wave-radar modulation transfer function (mtf) and $S_{sp}(k)$ represents the contribution of coherent speckle effects to the image spectrum. The latter term was
estimated by computing the image spectrum over a region near
shore where no visible features were apparent in the image.
This term was then subtracted from the image spectra at the
other locations in the image, and the remainder was divided by
\[ |m|^2 k^2 \] to yield an estimate of the wave height spectrum,
which was then integrated over \( k \) to obtain the significant wave
height, i.e.,

\[
H_s = 4 \left[ \int |m|^{-2} k^2 \left[ S_{\theta}(k) - S_{\theta}(k) \right] dk \right]^{1/2}
\]

where the image spectrum is defined such that the integral
over \( k \) is equal to the image variance.

The value of the modulation transfer function used in this
analysis was calculated from theoretical expressions for the tilt
and hydrodynamic effects, i.e., \( m = m_t + m_h \). For a perfectly
conducting surface and a surface wave height spectrum of the
form \( S_{\theta}(k) = A k^p \) near the Bragg wave number, the tilt
modulation transfer function can be written as

\[
m_t = p \cot \theta - \frac{4 \sin \theta \cos \theta}{1 + \sin^2 \theta}
\]

where \( \theta \) is the incidence angle. The hydrodynamic modulation
transfer function, for the simplest case where relaxation effects
are neglected, is given by

\[
m_h = p + 1/2
\]

The total modulation transfer function is equal to

\[
|m| = \left[ |m_t|^2 + |m_h|^2 \right]^{1/2}
\]

which has the value 6.2 for \( p = 4 \) and \( \theta = 35^\circ \). The significant
wave height variations obtained from this analysis are plotted
versus latitude in Figure 17.

It can be seen from Figure 17 that for the whole region the
SAR and the Geosat SWH are in fair agreement. However,
Fig. 14. Two-dimensional SAR wave spectra obtained every 20 km along the Geosat pass for line 1/1 (see Figure 13 for locations). Horizontal axis is along-track wave number and vertical axis is cross-track wave number. Circles indicate wavelength of 100, 200, and 400 m. The dominant feature is a long wavelength between 200 and 300 m. Indications of the presence of shorter wavelength can be found on the SAR spectra D, E, and F, and also at the end of the pass in the open ocean on the spectra K and L.
the SAR appears to underestimate the wave height in regions where the wind speed is high (64.7°N to 65.3°N, and north of 65.5°N) and to overestimate the wave height where the wind speed is low (65.3° to 65.5°N). This discrepancy is due to the wind speed dependence of the ocean wave-radar modulation.
SAR vs. GEOSAT Significant Wave Height

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Fig. 17. Comparison of significant wave height along the Geosat pass as measured by the altimeter with that estimated from the SAR data.

Although this wind speed dependence of the radar mtf is a complicating factor in attempting to make quantitative use of SAR ocean wave data, it is quite conceivable that corrections can be made for this dependence based on wind speed estimates from the SAR data itself. These corrections are beyond the scope of this paper, however.

6. DISCUSSION AND SUMMARY OF RESULTS

Coincident observations were acquired on March 20, 1988, by the Geosat altimeter and the airborne SAR over a particularly complex oceanic situation where wind, swell, and current were interacting within an occluded low-pressure system that was located about 200 km off the coast of Norway.
In this low, the winds computed from SAR scattering cross-section measurements are light (2 to 5 m/s) and, as observed from SAR imagery, are varying randomly over distances of the order of 5 km. Because of the footprint size of the altimeter, this geographically very narrow region of low wind speed is not sensed by the altimeter. From the SAR ocean backscatter cross-section measurements acquired from line 1/1 (Figure 4), the approximate width of the low is 20 km.

Along the eastern edge of the low is a well-defined wind front which is observed by both the SAR and the altimeter. On the southeastern side of the front, the wind field is relatively uniform (Figure 1), with wind vector 12.5 ± 1 m/s from 227° ± 5°, in the zone parallel to the front. The northwestern (low wind speed) side of the front is delineated on the SAR images by 500-m-scale cellular disturbances along the front boundary and by wind vectors 5.5 ± 1 m/s from 345° ± 5°. Across this atmospheric front, the wind speed computed from the altimeter scattering cross-section decreases from 12 m/s to 10.5 m/s over a distance of approximately 23 km. Because of its footprint size (about 9.5 km in diameter) and of the time response of the AGC, the altimeter behaves as a spatial low-pass filter [Glazman and Pilorz, 1990]. The altimeter wind speed estimates are dominated by the step response of the instrument in a region of high spatial variability probed very accurately with the SAR.

Across the low-pressure center the winds turn through approximately 160° and increase in magnitude to produce SAR-Geosat measured wind vectors of 11.5 ± 0.5 m/s from 14° ± 5°.

In the region 130 km south of buoy 4, which is not sampled by Geosat, a second front is observed by the SAR with wind vectors of 10 ± 1 m/s from 220° ± 5° along its northern boundary and 4.4 ± 1 m/s from 180° ± 5° to the south. From meteorological measurements at buoy 1 this front defines the southern limit of the storm system.

The crossing of the atmospheric front near the location of buoy 4 does not produce significant changes in the wave field as observed by buoy 4, the Geosat altimeter, and the SAR. The crossing of the atmospheric front near the location of buoy 4 does not produce significant changes in the wave field as observed by buoy 4, the Geosat altimeter, and the SAR.

Along the Geosat track, the SWH measured by the altimeter increases steadily from 3 m near the Norwegian coast to 4.5 m near the end of the continental shelf. Over the Norwegian Sea, west of the continental shelf break, the altimeter SWH reaches a plateau at about 4.5 m. The Geosat SWH measurements are in good agreement with the buoy measurements (Figure 11).

When compared with the Geosat SWH measurements, the SWH values inferred from the SAR image spectrum are of the same order of magnitude (Figure 17): there is a fair qualitative agreement between both radars. The simple expression used for the SAR modulation transfer function (equation (9)) does not take into account a wind dependence or a sea state parameter. In the region of low wind speed, on the west side of the atmospheric front, the SAR SWH values exhibit an artificial, well-delimited increase that yields SWH values that are overestimated compared with the Geosat values. Outside the low-wind-speed region, the SAR SWH are underestimated compared with the Geosat measurements. Because of the variable wind conditions along the Geosat track, a constant SAR mtf cannot be expected to give accurate SWH values. The differences between the Geosat and the SAR SWH emphasize the importance of wind contribution on the SAR mtf.

Minimum significant swell heights varying from 2.5 m near the Norwegian coast to 3.5 m beyond the continental shelf break are derived from the altimeter measurements of SWH and wind speed. An approximate wavelength of 180 m is determined from the altimeter measurements of the highest sea state along the Geosat pass that sampled the northeast corner of the March 19 swell-generating storm. The Geosat-derived swell wavelength is underestimated compared with the buoys and the SAR because the satellite did not acquire data in the center of the storm.
The SAR-derived wavelengths vary between approximately 200 and 300 m along the Geosat pass. In the high-wind region east of the atmospheric front, the mean wavelength generally oscillates between 200 and 250 m. West of the front, the SAR-derived wavelengths increase to a mean value that oscillates between 250 and 300 m. Sporadic indications of energy at lower wavelength between 100 and 150 m are found in some of the SAR wave spectra (Figure 14). However, a consistent peak in energy between 100 and 150 m corresponding to a wind wave component in agreement with the measured altimeter wind speed is not obtained in the SAR wave spectra.

There are several possible explanations for this apparent discrepancy. However, we believe that the lack of a second wind wave peak in the SAR spectra may be due to the mechanism discussed by Donelan [1986] wherein the presence of a swell inhibits the growth of a higher-frequency wind wave and instead causes energy input from the wind to be deposited in the swell itself. The reason for this effect is not well understood but has been hypothesized by Donelan to be due to a "detuning" of the resonant nonlinear interactions which transfer energy to the long waves.

Swell directions determined from SAR wave spectra are mostly coming from the southwest (Figure 16). However, at the start of the pass, near the Norwegian coast, and at the end of the pass, beyond the continental shelf break, a larger scatter in the energy distribution from the SAR wave spectra indicates the possibility of interactions with the local current features.

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REFERENCES


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