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COHERENT RADAR MEASUREMENT OF OCEAN CURRENTS FROM GEOSTATIONARY ORBIT*

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INTRODUCTION: Delta K Spectra for Ocean Waves

A coherent HF radar system developed by Barrick [1] has successfully measured ocean surface currents near shore. This innovative system, called CODAR, can map the current vector for coastal areas as large as $10^4 km^2$. CODAR's range is limited owing to the strong attenuation suffered by HF ground waves.

An alternate technique was proposed by Schuler [2], in which the cross-product power spectrum of two (different frequency) microwave signals is processed. The resulting power spectrum exhibits a resonant peak like that seen in Fig. 1. The frequency of the resonant peak corresponds close by to the Doppler shift of an ocean gravity wave traveling toward the radar at the phase velocity, v_p. The slight difference between the frequency of the measured resonant "ΔK" peak and the Doppler frequency shift caused by the motion of the gravity wave is attributed to be the current velocity in the pointing direction of the radar.

The Microwave Remote Sensing Laboratory (MIRSL) at the University of Massachusetts has considered the feasibility of using this technique to measure ocean surface currents from geostationary satellite platforms [3–5]. We discuss problems that must be overcome if a satellite current measurement system is to be realized. We describe MIRSL research activities that address some of these problem areas. We conclude the paper by presenting current measurements that were made using a specially-designed C-Band, step-frequency delta K radar. These measurements suggest that progress is being achieved in detecting ocean surface current motion for a wide variety of ocean surface conditions.

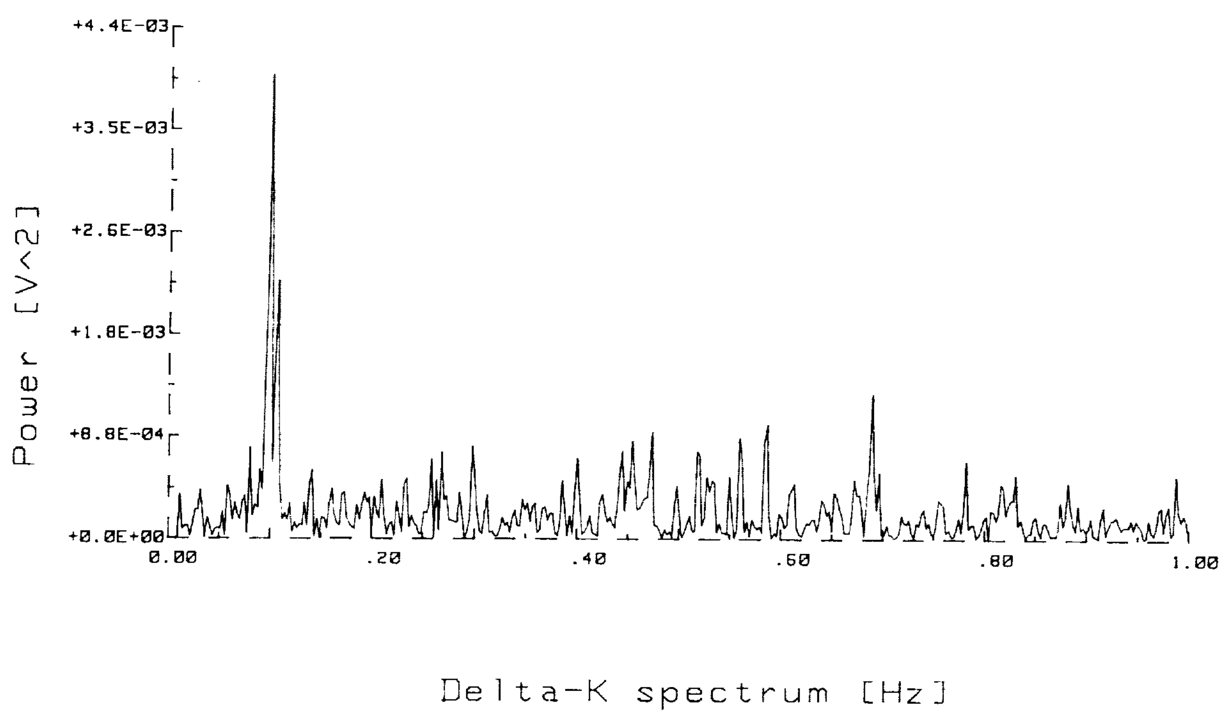

Figure 1

The CODAR system cannot be installed on a satellite because (1) the HF radar signals cannot penetrate the ionosphere and (2) antennas must be too large if reasonable spatial resolution of the ocean surface currents is expected. Consequently, the use of dual-frequency, "ΔK" radars must be considered for this application. Such radars promise the advantages that they might operate from satellite platforms using realistic antennas. In addition, extremely large ocean areas might be mapped by radars mounted on geostationary platforms [3].

Figures 2a and b show the ocean surface area that might be viewed by two radars mounted on geostationary orbits separated in longitude by an angle β. In Fig. 2a, the minor circle, A, corresponds to the loci of points on the ocean surface for which the incident signals from radar #1 are close to grazing. The minor circle, B, corresponds to the locii of points for which the radar signals are almost normally incident on the surface. Only the ocean surface area lying between these circles can scatter ΔK radar signals that can be used to measure the surface current. Fig. 2b shows the area of the North Atlantic Ocean that can be simultaneously viewed by two radars mounted 15° apart in longitude. For this case, the maximum incidence angle is 70° and the minimum incidence angle is 20°.

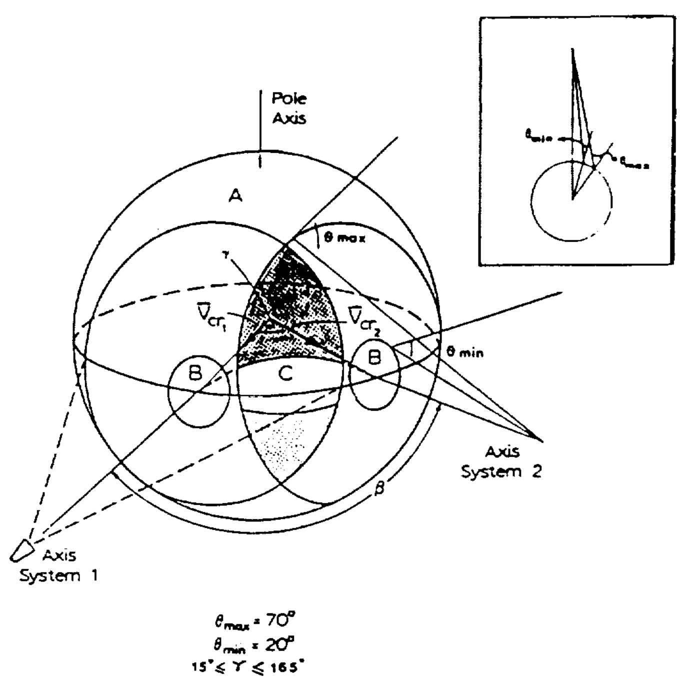

Figure 2a

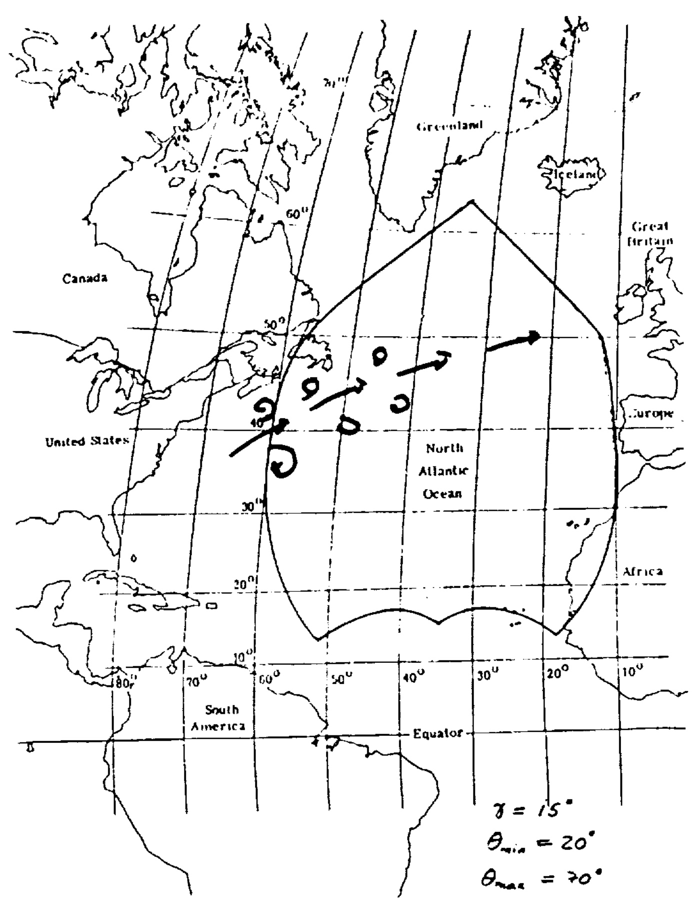

Figure 2b

SIGNAL-TO-NOISE RATIO OF MULTIFREQUENCY OCEAN CURRENT SENSING RADAR

We conducted a system feasibility study to determine the transmission power requirements of a ΔF radar operating from a geostationary platform. Fig. 3 shows how the signal-to-noise ratio of the received signal increases with transmitted power level when:

(1) The radar operates at X Band ($\lambda = 3cm$),
(2) The receiver temperature is 300°K,
(3) The Normalized Radar Cross Section σ° is -25 dB (near-grazing value)
(4) The transmitted pulse repetition rate is 400 Hz
(5) The transmitted pulse duration is 6 μs and,
(6) The antenna gain is 41.4 dB.

The feasibility study assumes two additional conditions that are not as straight-forward as those listed above.

The first condition assumes that the radar system can resolve pixels as small as 4km by 4km from geostationary altitudes. Resolving 4km dimensions in range is easily accomplished by transmitting pulses having 6μsec are shorter durations. Resolving 4km dimensions in azimuth would require the use of fairly sophisticated antenna systems that utilize direction finding techniques [5].

The second condition assumes that the ΔK peak of the cross-product spectra is always present and clearly distinguishable from spectal background noise peaks as shown in Fig. 1. The calculated S/N performance in Fig. 3 assumes that the peak power of the resonant ΔK peak is 10 dB greater than that of any other spurious peak in the cross-product spectrum. The validity of this last assumption has not yet been established because of the limited amount of experimental data that has been gathered with ΔK radars.

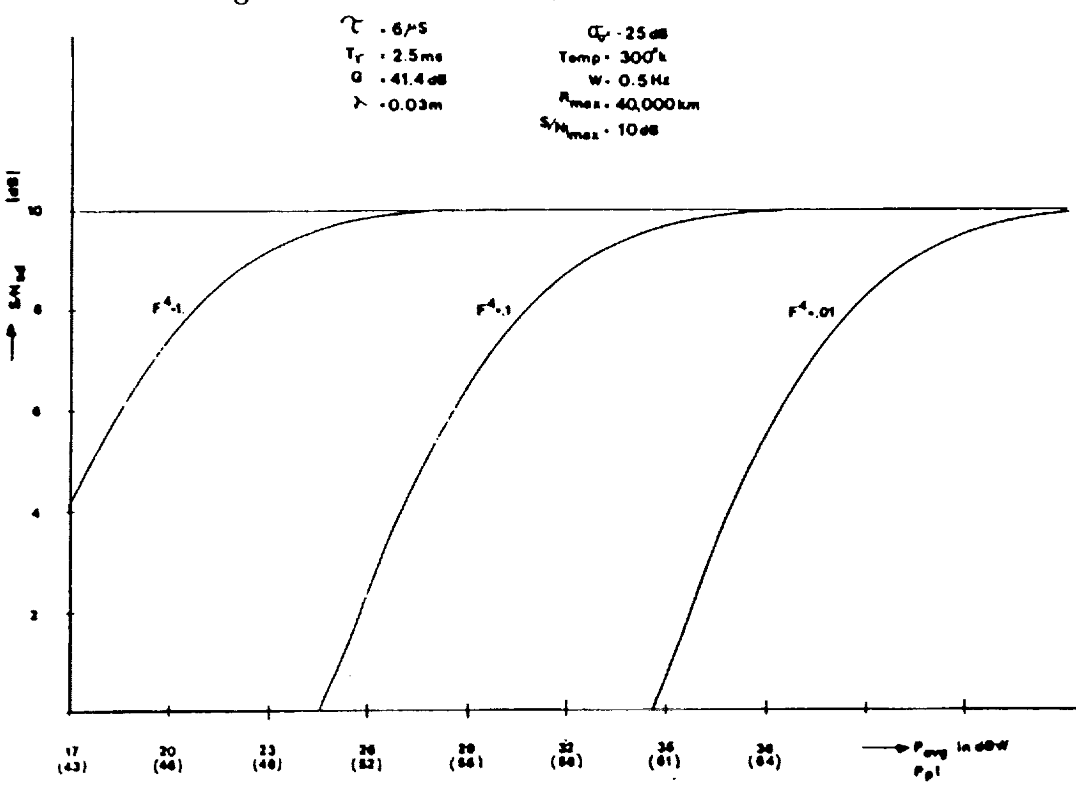

Figure 3

ENHANCEMENT OF CROSS-PRODUCT SPECTRUM MEASUREMENTS USING THE UMASS SFDK RADAR SYSTEM

During the past few years, MIRSL has considered techniques to enhance the resolution of the ΔK peak and minimize the background noise peaks seen in Fig. 1. To test these techniques we designed and built the SFDK radar system shown in Fig. 4a. This coherent C–Band radar system transmits microwave pulse pairs, where the frequencies of the two pulses are separated by a constant HF difference frequency. The radar can operate as a conventional dual–frequency, ΔK radar or the frequencies of the pulse pairs can be varied as shown in Fig. 4b. In the latter case, the HF frequency difference is maintained constant. Table 1 below specifies the characteristic of this system.

Table 1
System Specifications of UMass SFDK Radar

• transmitted power	30 dBm
• 16 carrier frequencies (16 simultaneous spectra)	5.95 to 6.28 GHz
• Δf frequency	2 to 40 MHz
• transmission pulse width	100 ns to 100 μs
• pulse repetition rate	1 μs to 100 μs
• antenna	1.5 m parabolic dish; 2.5^o beamwidth
• three IF stages	160 MHz, 5.8 MHz, 200 Hz

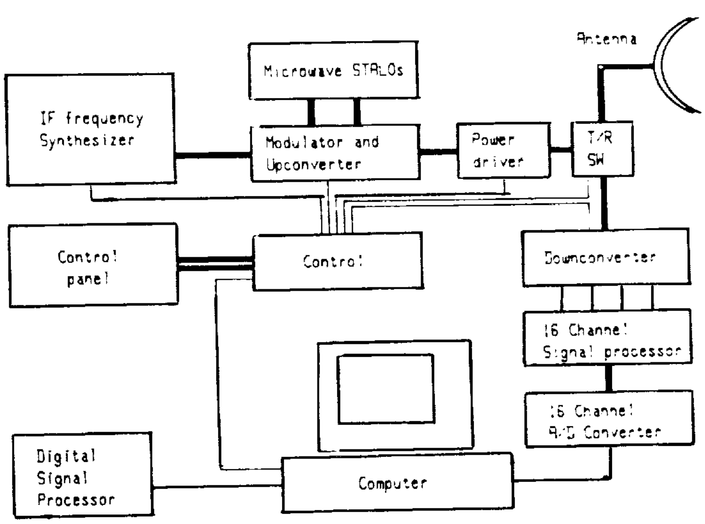

Figure 4a

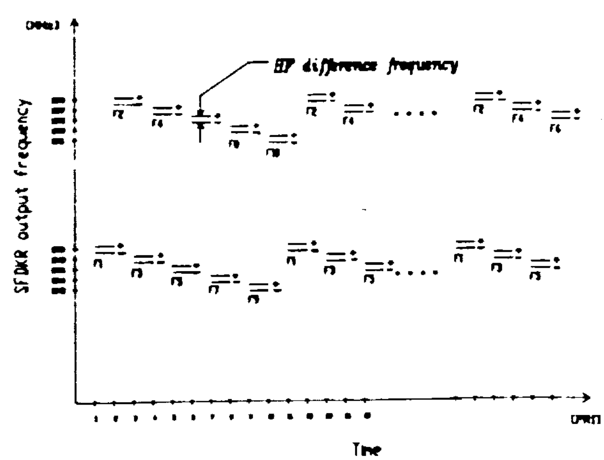

Figure 4b

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ΔK SPECTRA OBTAINED USING SINGLE FREQUENCY PAIRS

In Fig. 5 we show ΔK spectra obtained by the UMass SFDK radar during a field experiment at North Truro, Massachusetts (Cape Cod). Each of the ten spectra shown were obtained during the same 80 second interval by using only pulse pairs having the same frequencies. For example, spectrum A was formed from returns indicated by frequencies, f_1^+ and f_1^- in Fig. 4a, spectrum B from frequencies f_2^+ and f_2^-, etc. Averaging the ten spectra result in the spectrum shown in Fig. 6. Note that reduction in the background spectrum results from this averaging.

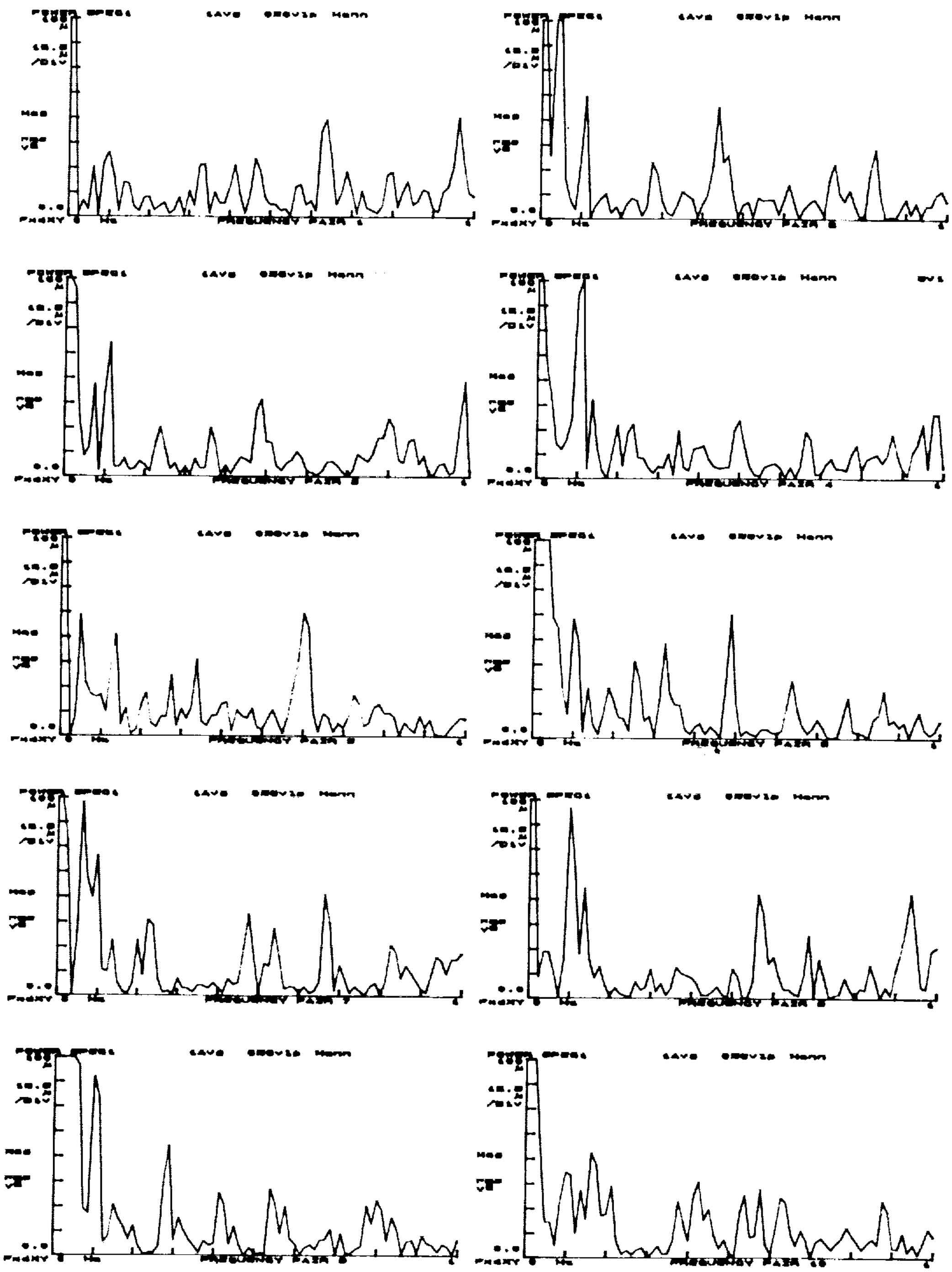

Figure 5

ΔK SPECTRUM OBTAINED BY AVERAGING SPECTRA OF FIG. 5

The UMass SFDK radar uses frequency agility to obtain a number of independent ΔK spectra during the same time interval when previous instruments obtained a single spectrum. We see enhancement of the ΔK peak relative to the background power of the ΔK spectrum in Fig. 6 because the resonant peak of each spectrum is caused by the same gravity waves that are responsible for the resonance in the other spectra. However, the backscatter that contributes to the background spectrum of the various spectra appear to be uncorrelated, indicating that independent samples are being achieved with each change in the carrier frequency.

To our knowledge, the ΔK spectra measured by the UMass SFDK radar are the first ones that demonstrate the ability to measure ocean currents with a C–Band system. This radar has been operating primarily at a test site at North Truro, Massachusetts during the past year. This shore site was chosen because it overlooks the open ocean from a height of approximately 150 feet above sea level.

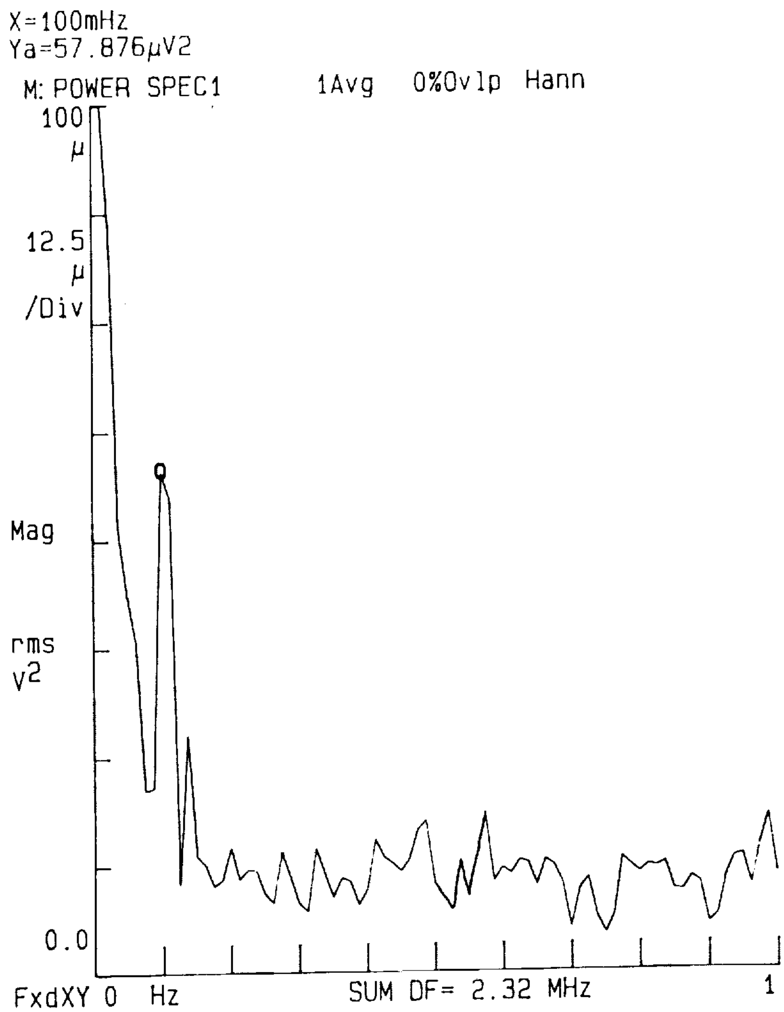

Figure 6

ΔK RESONANT PEAK AMPLITUDE AND DOPPLER FREQUENCY MEASURED BY UMASS SFDK RADAR AS FUNCTION OF TIME

We have automated the SFDK radar so that it can be operated for extended periods of time. We are able to monitor both the magnitude and the Doppler frequency shift of the resonance peak. Fig. 7 shows how the peak amplitude and frequency varied during an eleven hour period on December 23, 1986. Laboratory tests of the SFDK's frequency stability indicate that the frequency variations seen in Fig. 7 are caused by ocean surface effects and are not due to instrument frequency drifts. Thus the diurnal variation in the Doppler frequency shift of the ΔK line appears to be caused by tidal variations.

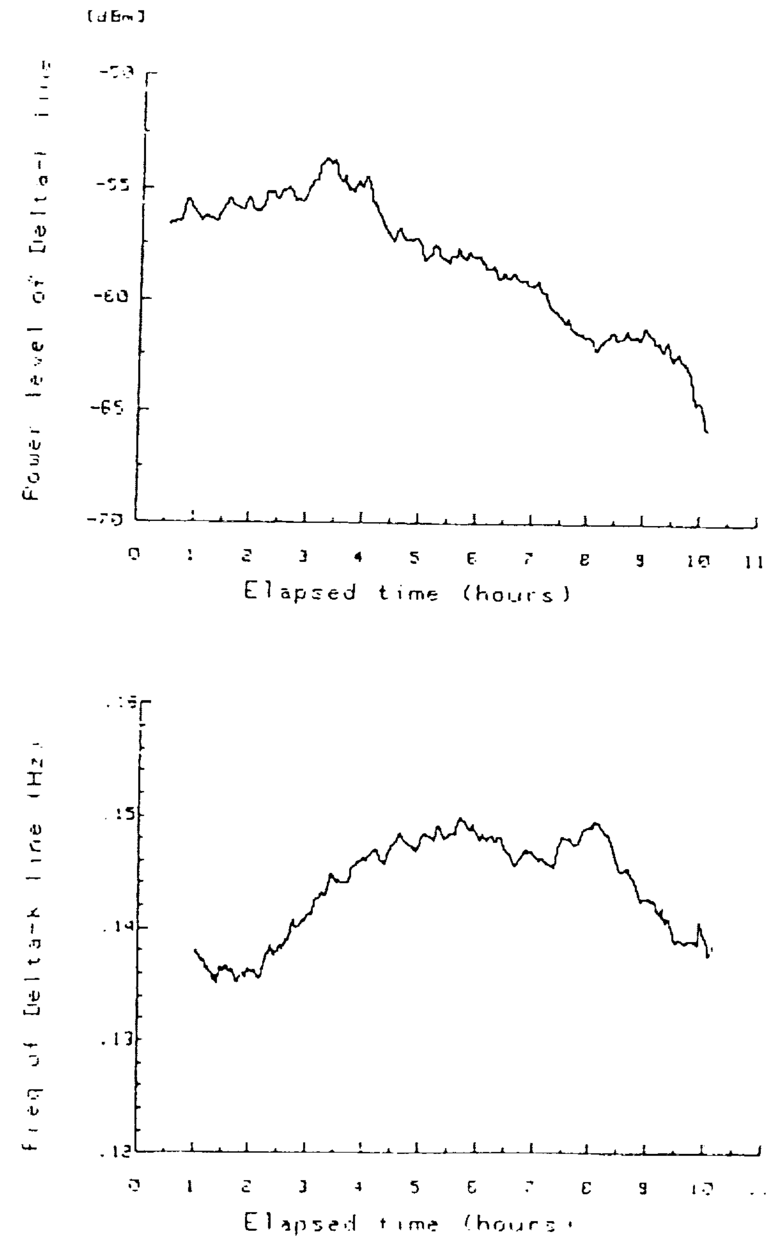

Figure 7

DOPPLER MEASUREMENTS OF OCEAN SURFACE CURRENT

MIRSL extended its field tests at the North Truro site to determine the reliability of measuring the Doppler frequency of the ΔK peak for a wide variety of ocean surface conditions. In addition, we wish to better understand the environmental conditions that affect the ocean surface current, which causes changes in the Doppler frequency of the ΔK peak.

MIRSL used the SFDK radar to monitor the ocean surface for approximately 720 hours during December 1986, March, August and October, 1987. During these field tests, the ocean surface varied between very calm (Beaufort index 1) to very rough (Beaufort index 5). The surface wind speed during these measurements varied between 0 and 30 mph. We observe that the variation of ΔK Doppler frequency shown in Fig. 8 has a diurnal component that may be ascribed to tidal currents. We have observed this periodicity in most of the SFDK data obtained from the North Truro tests.

The SFDK radar system has been able to clearly distinguish a resonant ΔK peak in more than 75% of the North Truro measurements. The ΔK peak tends to vanish whenever the surface winds fall below 4 mph and the capillary waves disappear from the ocean surface.

We believe that the reliability of the ΔK peak would increase beyond 75% if we could decrease the angle that the radar signal impinges on the ocean surface. Presently, this angle is more than 85° because the radar platform is only 150 ft. above the ocean surface. Thus, the incidence angle is substantially (15°) greater than the 70° worst–case incidence angle assumed in the system study of part II.

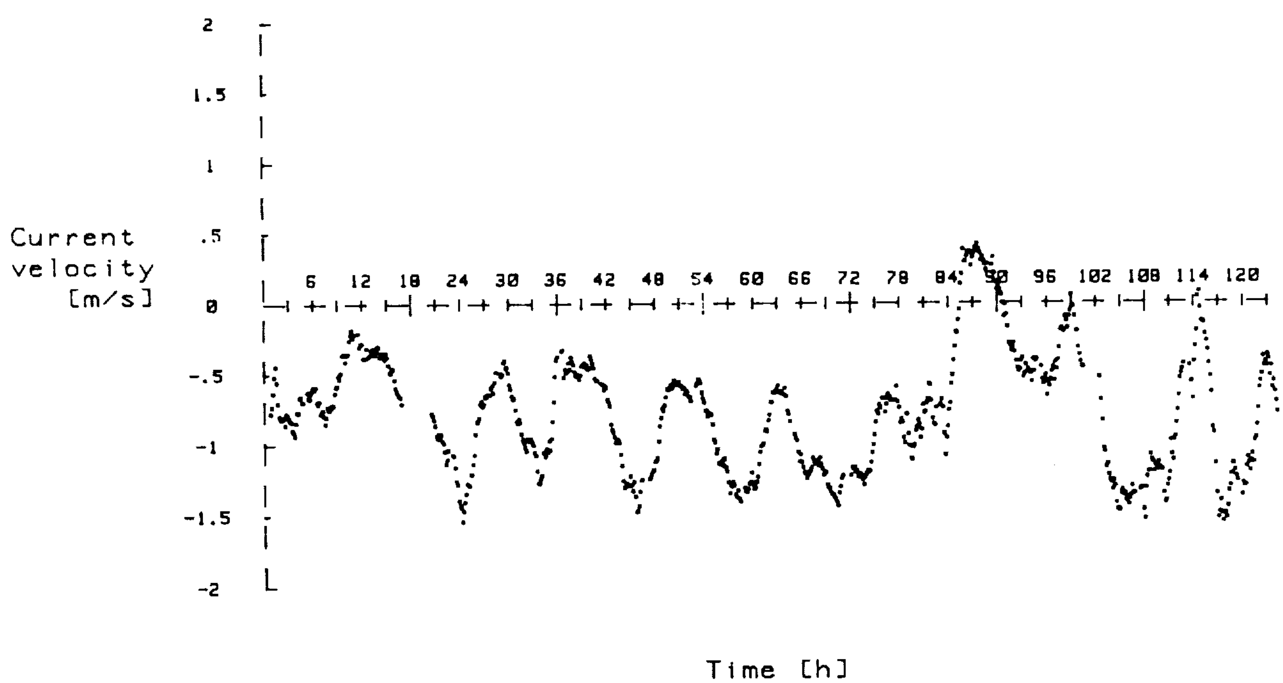

Figure 8

EFFECTS OF SURFACE WINDS ON MEASURED ΔK DOPPLER FREQUENCIES

The Doppler frequency in Figure 8 appears to vary with the tides during the first two days but we note that the ΔK frequency varies somewhat randomly on the third day. This random variation of the ΔK frequency occurred during a period when the wind speed and direction changed rapidly. Consequently, we conclude that the surface currents in the SFDK antenna footprint are strongly influenced by surface winds.

A clearer picture of the effect that surface winds have on the ΔK Doppler frequency measured by the SFDK radar is seen in Fig. 9. The surface wind was approximately 15 mph from the North East direction for the first seven hours, changed direction to come from the East for three hours, and changed back to its original orientation during the last two hours. In Fig. 9, we see that the ocean current measured by the SFDK radar varies somewhat diurnally during the twelve hour measurements, with the exception of the time following the change in wind direction (after the ninth hour). The observed dependence of the ocean surface current measured by the SFDK on the surface wind is not surprising, given that surface currents in the deep ocean are driven almost entirely by surface winds.

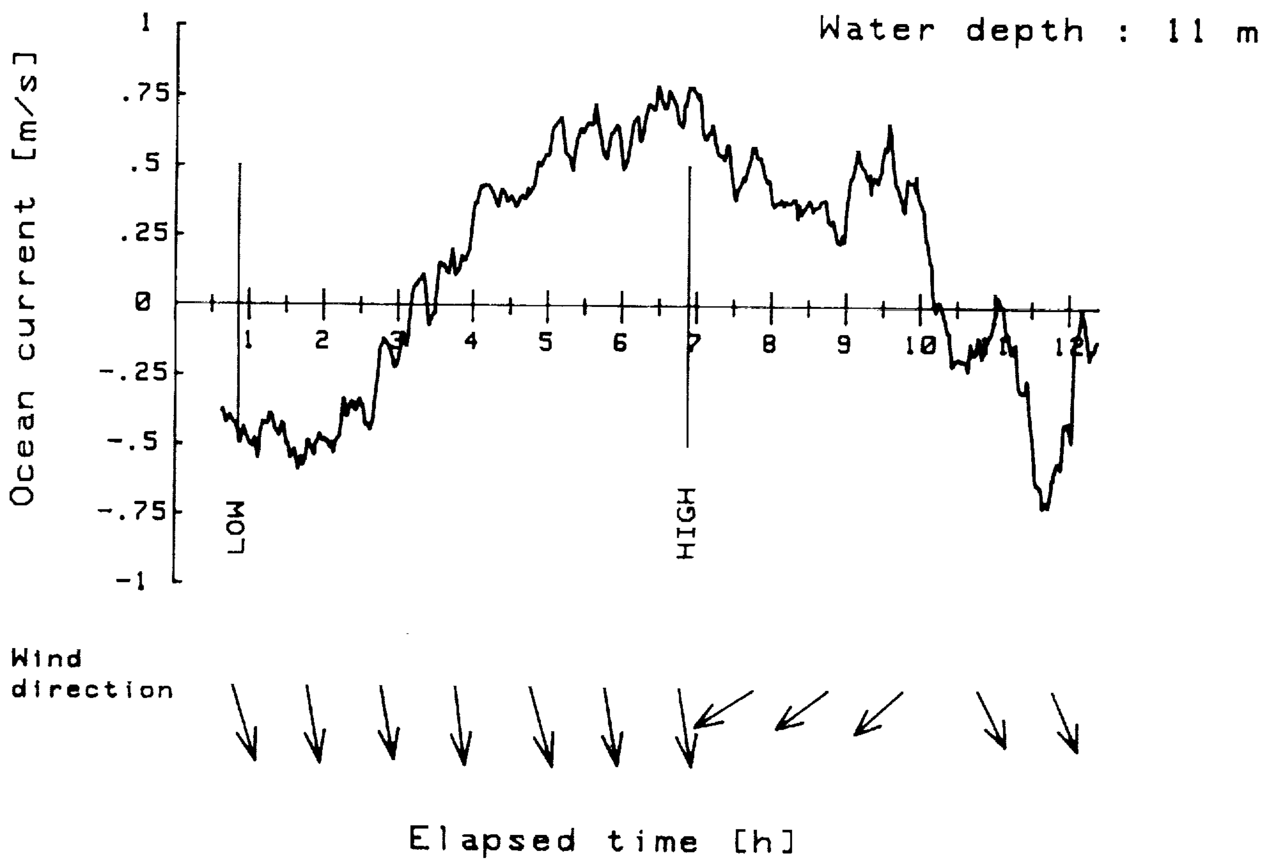

Figure 9

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