

- N84 27282

MEASUREMENTS OF OCEAN WAVE SPECTRA AND MODULATION TRANSFER FUNCTION  
WITH THE AIRBORNE TWO FREQUENCY SCATTEROMETER

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ABSTRACT

The results of this research show that the directional spectrum and the microwave modulation transfer function of ocean waves can be measured with the airborne two frequency scatterometer-microwave resonance technique. The results here are favorable to the future application of this or similar techniques from airborne or spaceborne platforms. Similar to tower based observations, the aircraft measurements of the modulation transfer function show that it is strongly affected by both wind speed and sea state. Also detected were small differences in the magnitudes of the MTF between downwind and upwind radar look directions, and variations with ocean wavenumber. Unexpected results were obtained that indicate the MTF inferred from the two frequency radar is larger than that measured using single frequency, wave orbital velocity techniques such as tower based radars or "ROWS" measurements from low altitude aircraft. Possible reasons for this are discussed. The ability to measure the ocean directional spectrum with the two frequency scatterometer, with supporting MTF data, is demonstrated.

## 1. INTRODUCTION

This study is advancing the ability of active microwave radar to measure ocean wave spectra from high altitude aircraft. The experimental data analyzed here was acquired during the Atlantic Remote Sensing Land Ocean Experiment (ARSLOE) during November 1980. The NASA Langley two frequency scatterometer participated onboard the P-3 aircraft, and was able to receive supporting ocean data from the surface contour radar (operated by the NASA Wallops Flight Center), almost simultaneously. Directional spectra and non-directional spectra were available from the XERB buoy. The spectrum of the sea surface reflectivity can be measured directly from the backscattered signals at the two closely spaced microwave frequencies. The cross product of these signals displays a resonance whose intensity is analyzed using theoretical relationships and models that have been developed independently by three groups of researchers, (Alpers and Hasselmann, 1978; Plant and Schuler, 1980; and Johnson and Weissman, 1984). The validity of this equation was established in an earlier phase of this experimental data analysis.

The microwave radar frequency is  $K_u$ -band (14.6 GHz), and operates with two "simultaneous" (interrupted CW using time multiplexed long pulses) frequencies, that can be separated by a variable amount from 1 to 20 MHz. Data was collected during many high altitude flight lines between altitudes of 2800 to 7000 feet. Complete details of the



aircraft radar, its flight patterns, data collection and processing, and the supporting surface contour radar results can be found in the recent paper by Johnson and Weissman (1984).

The two frequency resonance technique samples one ocean wavelength with each  $\Delta f$ , which is then varied to allow a sweep (or tuning) through the ocean spectrum. At each  $\Delta f$ , the intensity of the cross spectrum between the backscattered microwave signals depends on the wave height or energy at that corresponding ocean wavenumber, and on the modulation transfer function, for that component. The MTF determines the strength of radar visibility for each ocean wave; it is produced by the local variations of roughness of the centimeter waves that contribute most to the microwave backscatter. One of the sources of these roughness variations is known to be the orbital velocity of the individual large gravity wave, as explained and demonstrated by Wright and his colleagues (Wright, 1978; Keller and Wright, 1975; Wright et. al., 1980). The results presented in this paper indicate that additional sources of modulation exist. Previous identification and discussions of this "non-wave induced modulation" have been given by Wright, et. al. (1980) and Plant, et. al. (1983).

Another feature of this experiment was the directional discrimination capability of the radar, as a result of its large illuminated surface area, relative to the dimensions of the long gravity waves. In effect, all MTF results presented in this study are directional because of this spatial filtering effect. The data taken on Nov. 13 observed the wave spectrum from 4 different directions. On this day, the surface spectrum was a combination of swell and a wind driven sea, differing in direction by  $45^\circ$ . The flight directions "A" and "B" in Fig. 1 show two of the directions in which the two frequency scatterometer made measurements. The directional spectra measured by the buoy in these flight directions is shown in Fig. 2. and the two frequency resonance results in Fig. 3 show a discrimination between these two different spectra. The analysis of this data shows differences in the magnitude of the directional MTF for these two directions.

## 2. EXPERIMENT DESCRIPTION AND DATA ANALYSIS

### 2.1 Aircraft Radar Operation

The data analyzed in this study was acquired from about 20 to 70 km offshore, near Duck, N.C. The flight operations and details of the illumination geometry are presented in the paper by Johnson and Weissman (1984). Of strong interest in this experiment was the behavior of the modulation transfer function as a function of illuminated area and the incidence angle of the radar wave. The illuminated area and the dimensions relative to the ocean wavelength were varied over a substantial range as the aircraft altitude varied from 2800 to 7000 ft, and as the incidence angle ranged from  $16^\circ$  to  $50^\circ$ . These conditions were met with the Nov. 12 data, which also included upwave and downwave flight directions. The smallest illuminated area was  $4.8 \text{ km}^2$  and the largest,  $46 \text{ km}^2$ . The shapes of these areas could be approximated by an ellipse, with an axial ratio of 2 or less. The four different flight directions employed on Nov. 13 were at a fixed altitude and incidence angle; 4500 feet and  $25^\circ$  from nadir. Support to the Nov. 12 radar data was given by the surface contour radar and the single frequency wave spectrometer referred to as the "ROWS" technique. The details of converting the backscattered two frequency signals into resonance intensity,  $X(k)$ , is discussed in the above reference. The results are shown in Fig. 3 and 4.

## 2.2 Buoy Data

The only surface measurement useful on Nov. 13 was that from the XERB buoy located 40 km offshore. This instrument is operated and supported by the NOAA Data Buoy Center. It is a pitch/roll/heave sensor, located where the water depth was 30 meters (Progress Report for NDBO Wave Measurement Systems, 1982). The products available for the estimation of wave spectra are five Fourier coefficients, evaluated at discrete frequencies spanning the practical range of interest. These Fourier coefficients are computed from the motions of the buoy as determined by the elevation and slope sensors. Usually these spectral values (cospectra and quadspectra) are telemetered to shore where they are converted to Fourier coefficients and then directional spectra. Unfortunately, one channel malfunctioned and destroyed the  $C_{33r}$  information that is used to compute the  $A_2$  coefficient. The other term,  $C_{22r}$ , was intact. In order to fill this gap in the needed wave information, a study was made of the fundamental spectral relations (Kinsman, 1965). This revealed an auxiliary method for recovering  $C_{33}$ , from the other measurements. This idea has been used here (with complete updated listings of the other quantities provided by Mr. K. Steele of the NDBO center) to generate directional spectra that appear to be valid (see Appendix ). The directional wave height spectrum is estimated for Flight line A & B on Nov. 13, as shown in Fig. 2. These results are then used to infer the modulation transfer function from the aircraft two-frequency data.

## 3. SYSTEM EQUATION AND MODULATION TRANSFER FUNCTION

The equation that relates the surface elevation spectrum to the two-frequency resonance response is:

$$X(k) = \frac{2\pi^2 |m(k)|^2 k^2 E(k,0)}{A} \quad (1)$$

where  $k$  = wavenumber of ocean wave that is in resonance with two-frequency EM wave  
 $X(k)$  = ratio of resonance intensity to background spectrum energy (modulation strength)  
 $E(k,0)$  = directional wave spectrum in "0" direction  
 $m(k)$  = modulation transfer function for ocean wave of wavenumber,  $k$ .

A critical assumption in this model is that the reflectivity variation sensed by the radar at each wavenumber is moderately coherent with that part of the height and slope spectrum. A more general relation, on which the above equation is based, is:

$$X(k) = \frac{2\pi^2 \bar{\Phi}_R(k,0)}{A} \quad (2)$$

where  $\bar{\Phi}_R(k,0)$  is the instantaneous two-dimensional reflectivity spectrum. The concept of modulation transfer function is then based on an input-output relation point of view, in which the surface slope spectrum,  $k^2 E(k,0)$  is the input and  $\bar{\Phi}_R(k,0)$  is the output. Then:

$$|m(k)|^2 = \frac{\bar{\Phi}_R(k,0)}{k^2 E(k,0)} \quad (3)$$

Detailed studies of this relation and the modulation function can be found in the recent paper by Plant, Keller and Cross (1983).

The key contribution of these ARSLOE results is to use Equation (1) to either:

- A. determine the MTF across a range of conditions of radar parameters (incidence angle, flight direction, altitude and wavenumber) and with different types of surface conditions, using  $X(k)$  obtained from the two-frequency resonances.
- B. determine the directional surface spectrum using estimates of the MTF from non-directional spectrum measurements and the values of  $X(k)$  mentioned above.

As discussed in the paper by Johnson and Weissman (1984), supporting measurements of the MTF, its spectral variation and its coherence properties, were made with a single frequency radar that receives and correlates the backscattered power and Doppler variations (related to the surface orbital velocity) to achieve an independent measurement of this quantity.

One important assumption in the use of Eq. (1) to (3) is that the aircraft velocity is much larger than the phase velocity of the ocean wave that is in resonance with each " $\Delta k$ ". Then the resonance observed from the aircraft is not sensitive to whether or not these periodic reflectivity patterns are coherent with the orbital velocity of the surface waves. Then the MTF measured with single frequency radars are not equivalent to those measured with the two frequency radar, but they are believed to be closely related to each other. This topic needs further study.

#### 4. MEASURED MTF RESULTS

The MTF results to be presented first are those derived from Eq. (1) for the various flight parameters of Nov. 12. A value of the MTF can be calculated at each  $\Delta k$  (or difference electromagnetic wavenumber) so that each flight line yields the functional dependence of the MTF vs. the matching ocean wavenumber, at a fixed altitude and angle, and direction relative to the wind. Twelve of these functions have been computed for the Nov. 12 data (and supported by the SCR derived wave spectra) and two from the "A" and "B" lines of Nov. 13 (based on buoy derived spectra). The functions obtained from the Nov. 12 data have been plotted individually for each upwave and downwave path in Fig. 5 to 7, those for the Nov. 13 data are in Fig. 8. An additional MTF was computed, based on the non-directional spectrum measured by the buoy on Nov. 13. This calculation is performed by integrating the resonance response ( $X(k, \theta)$  in Eq. 1) over  $360^\circ$  in  $\theta$ , at each value of  $k$ . The right half of Eq. 1 then contains the non-directional spectrum term.

Analysis of these results was done from several points of view. Almost all share the following characteristics: the magnitudes start high at the lowest wavenumbers, then decrease to a definite minimum about  $k=.06$  to  $.08$ , then usually rise by at least 25% or up to 100% above this minimum. This is often followed by a gradual change at the higher  $k$  values, either an increase or decrease. Another definitive and general result is that the magnitudes differed strongly on these two days, in accordance with the environmental conditions. On Nov. 12, the winds were high, about 12 m/s, with accompanying high waves. The MTF values averaged in the range from 8 to 16. In contrast, on Nov. 13 the values were usually between 20 and 40. The factor of two increase shows a good correlation with the inverse of the wind which, on this day was below 6 m/s when the flights were made. This is in good agreement with measure-

ments of the MTF conducted from towers (Plant. et. al. 1983; Weissman, 1983) where the magnitude was observed to depend inversely on the local wind, and on other environmental parameters.

Special attention was also given to other characteristics of the MTF, such as its dependence on incidence angle, upwind vs. downwind look directions, and any variations caused by changes of the flight path relative to the wind direction. Across the spectrum of wavenumbers from  $k = .05$  to  $.14$ , ratios of the MTF looking downwave vs. upwave have been computed to test for significant differences. These results are in Fig. 9 and 10. The data for incidence of  $16^\circ$  to  $25^\circ$  in Fig. 9 display no bias one way or the other. These ratios average to about unity, across the whole spectrum. The effect of incidence angle becomes important at values at  $40^\circ$  to  $50^\circ$ , where this ratio takes on a definite wavenumber dependence. The downwave to upwave ratio is usually greater than 1, and is often well above this value. The interesting property of all three data sets is that this function increases strongly with  $k$ , above  $k = .10$ , resulting in ratios of 1.5 to 2.7. The interpretation of these results should be done in a more general context, because previous studies of this ratio were conducted and discussed by Wright (1978), who found a strong wind influence on these characteristics in addition to variations of this ratio from unity.

The other important dependence of the MTF studied is that due to incidence angle. Flight operations on Nov. 12 encompassed a range from  $16^\circ$  to  $50^\circ$ , substantial enough to test conditions of interest for the remote sensing of ocean waves. Considering the large assortment of wavenumber values in the data set, a simplification was performed to work with the average of a subset of values of the MTF measured along each flight line. The data from each of the Figures from 5 to 7 was averaged, but only values of MTF whose wavenumbers are in the range  $.05 \leq k \leq .09$  were included in the average. These twelve average values are plotted in Fig. 11. The upwind/downwind condition creates a small "random" fluctuation, but they still show a definite trend, downward with increasing incidence angles. For the  $16^\circ$  case, the MTF ranges from 9.7 to 13.2, while at  $40^\circ$  its from 8.3 to 10.4, and the  $50^\circ$  value is 9.2. Numerically, this is not a large effect, but detecting its presence will be helpful in sorting out other dependencies in future applications.

## 5. CONCLUSIONS

Our major findings are the functional dependencies of the MTF on ocean surface wavenumber, flight direction and incidence angle. The large data set allows the quantitative description of these dependencies, as seen in Fig. 5 to 11. Small incidence angle dependence means that future remote sensing systems need not be limited in the choice of incidence angle of the radar beam. A difference in magnitude between the aircraft and tower results was also detected and found to be plausible, on physical grounds. In addition, the effects of environmental conditions have also been seen and analyzed: increases in wind speed and sea state cause strong decreases in the MTF. With this new knowledge, the two frequency scatterometer can now be considered a useful instrument for the measurement of ocean surface spectrum by aircraft. For the MTF, no theoretical explanation of these scattering effects based on electromagnetic scattering theory and air-flow over ocean waves (including all short capillary generation mechanisms) has yet been achieved.

Much progress has been made on accumulating tower based radar results and wave follower measurements under a variety of air-sea conditions (Plant, et. al., 1983; Hsiao and Shemdin, 1983), but more is necessary in order to explain the aircraft results. Such questions as: "what are the physical sources that generate the short capillary waves which are modulated by the long waves" and "why should the MTF observed from an aircraft be different from what is measured on an ocean platform", need to be

addressed.

It is recommended that two topics be focussed on to advance this technique:

- (1) Learning more about the mechanism for the modulation of ocean waves (their origin, linearity, and coherence with the orbital velocity) that is detected by remote sensing radars.
- (2) Combined (dual) sensor capabilities to improve the measurement accuracies of each separate instrument. Simultaneous two frequency scatterometry and conventional scatterometry would measure wave spectra plus wind speed. Since both quantities affect each sensor, the accuracy of each sensor could be improved.

## 6. APPENDIX

### Calculation of $A_2(f)$ , the Wave Spectrum Angular Coefficient by Substitution for the Missing Spectrum, $C_{33}(f)$

Our application of the XERB buoy data to compute the surface directional spectrum involves using the well known Fourier Series approximation (in the notation and format of the NOAA Data Buoy Office), with the smoothing coefficients developed by Longuet-Higgins:

$$S(f, \theta) = \frac{1}{2} A_0 + A_1 \left(\frac{2}{3}\right) \cos(\theta) + B_1 \left(\frac{2}{3}\right) \sin(\theta) + A_2 \left(\frac{1}{6}\right) \cos(2\theta) + B_2 \left(\frac{1}{6}\right) \sin(2\theta)$$

These coefficients are computed from the several spectral functions measured directly by the buoy. Among these are:  $C_{11}$ , the auto-spectrum of the surface elevation, with  $C_{22}$  and  $C_{33}$ , the auto-spectra of the two orthogonal components of slope. The difficulty encountered was for  $A_2(f)$  only, which depends on  $C_{22}(f) - C_{33}(f)$ . For the duration of the experiment,  $C_{33}(f)$  was not available because of a malfunction, and only  $C_{22}$  and  $C_{11}$  and the other terms were being returned to shore for data processing.

It was observed, in the course of this study, that a fundamental relation exists among  $C_{11}$ ,  $C_{22}$  and  $C_{33}$ . From Longuet-Higgins, et. al. (1963) it is easily proved that:

$$k^2 C_{11} = C_{22} + C_{33}$$

Therefore  $A_2(f)$  can be computed from:

$$C_{22} - C_{33} = 2 C_{22} - k^2 C_{11}$$

This substitution, and the available data listing for the other coefficients made it possible to derive valid estimates of the wave directional spectrum for Nov. 13, for application to the two frequency scatterometer analysis.

## 7. ACKNOWLEDGEMENTS

The results obtained in this study were made possible by the supporting ocean spectrum data from the Surface Contour Radar provided by Dr. Edward J. Walsh of the NASA Wallops Flight Center. His interest and cooperation in this study is greatly appreciated. We also appreciate the advice of Mr. Kenneth Steele of the NOAA Data Buoy Office, who provided us with the best available data set for Nov. 13. We thank Dr. William J. Plant of the Naval Research Laboratory for enlightening and stimulating discussions in the course of this study.

Support for this study, which was provided by the NASA Oceanic Processes Program, Dr. W. Stanley Wilson, Chief, through Grant NAGW-468, is gratefully acknowledged.

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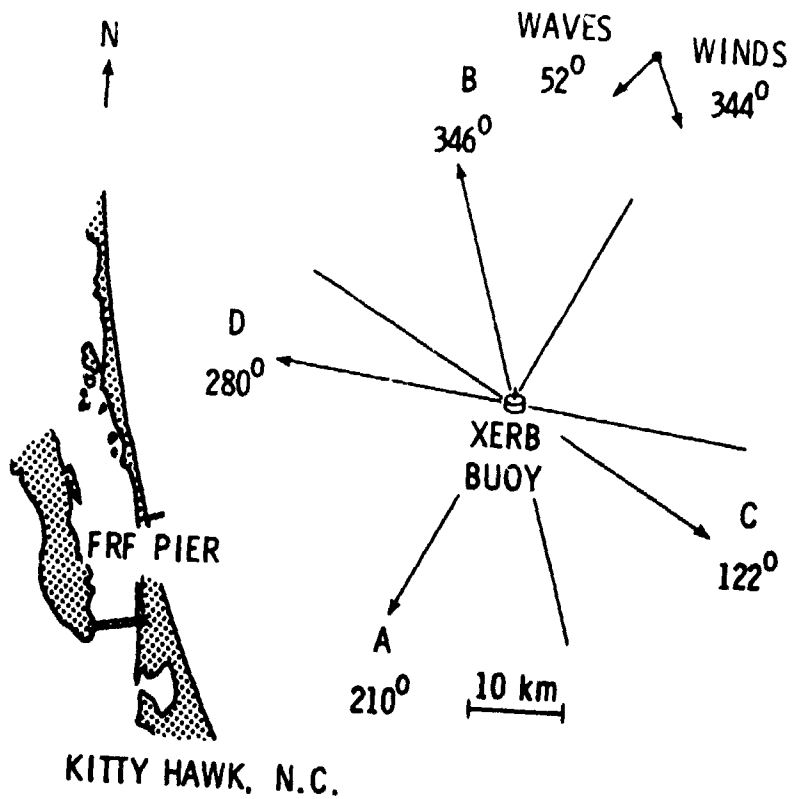
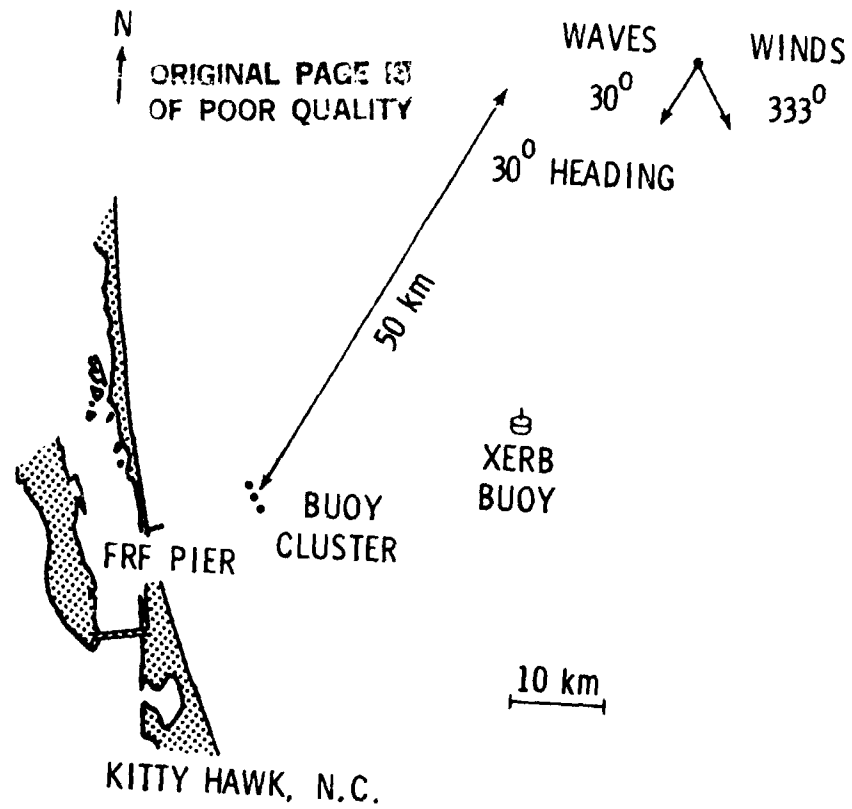


Fig. 1 ARSL0E Experiment Site, top: Nov. 12 flight paths;  
bottom: Nov. 13 flight paths



DIRECTIONAL WAVE SPECTRA FROM BUOY  
 DATA AND THE TWO FREQUENCY RADAR  
 RESONANCE - NOV. 13

SOLID CURVE - BUOY DATA  
 O - OPEN CIRCLES - AIRCRAFT RADAR

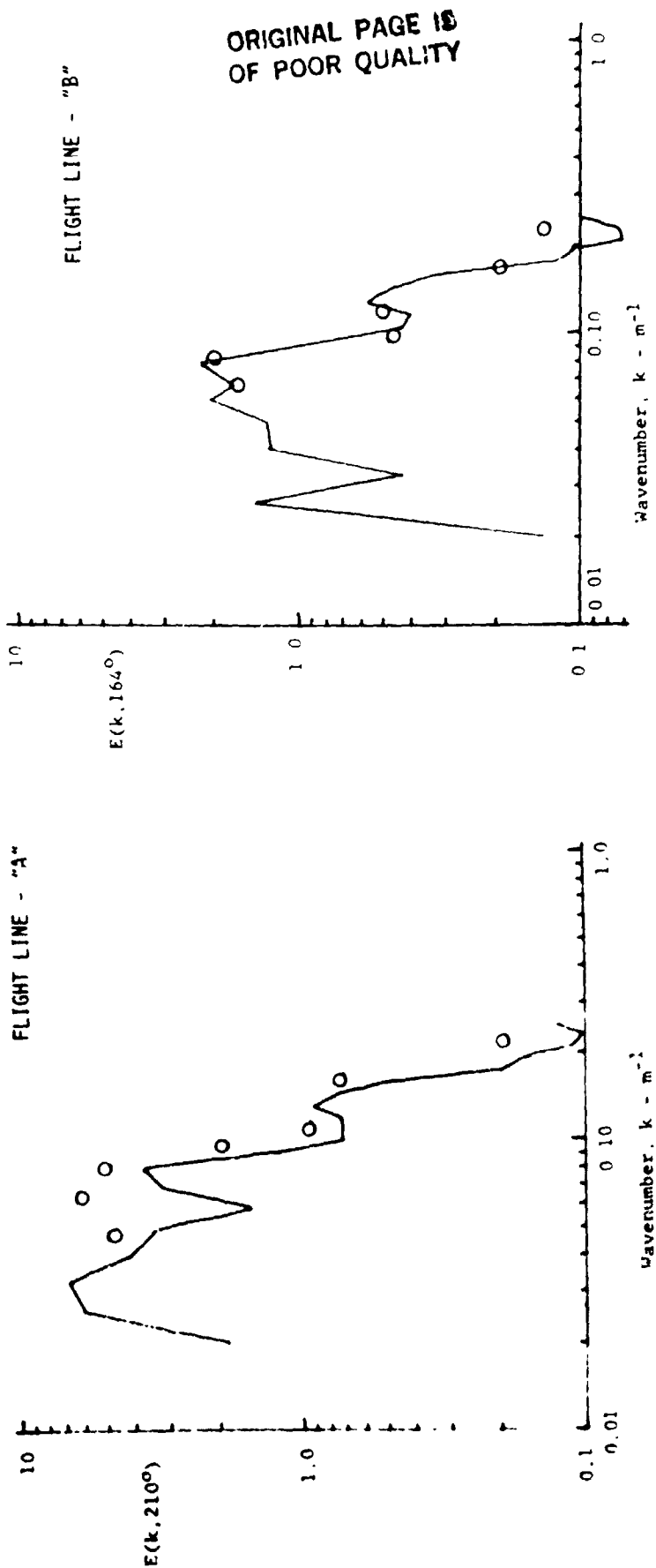


Fig. 2

ARSLOE, 11/13/80

 $\theta = 25^\circ$ 

H = 1370 m

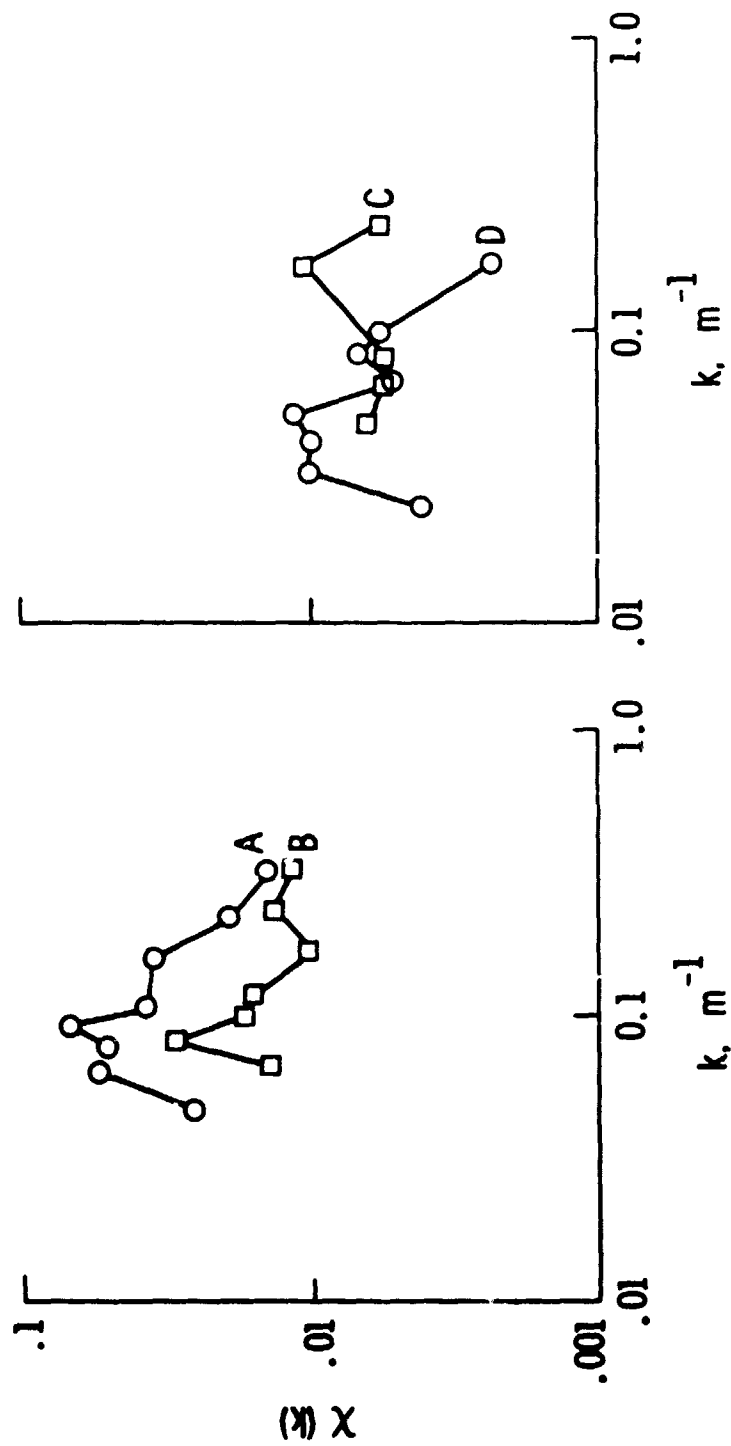


Fig. 3 Radar modulation spectra demonstrating the dependence upon radar viewing direction: lines A - radar aligned with dominant wave direction, B - radar aligned with wind direction, C & D - radar aligned with neither

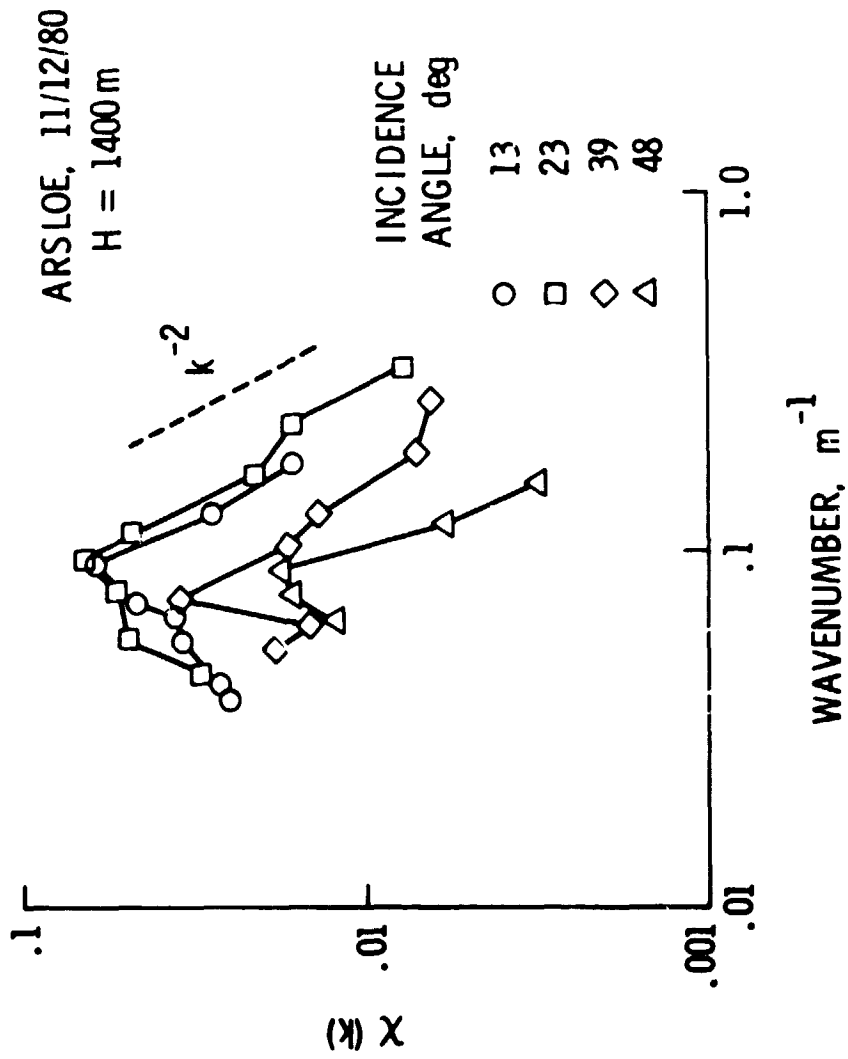


Fig. 4 Radar modulation spectra measured during ARSLOE at a variety of incidence angles

MODULATION TRANSFER FUNCTION VS.  
OCEAN WAVENUMBER

NOV. 12 DATA

SOLID CURVES - UPWAVE  
DOTTED CURVES - DOWNWAVE

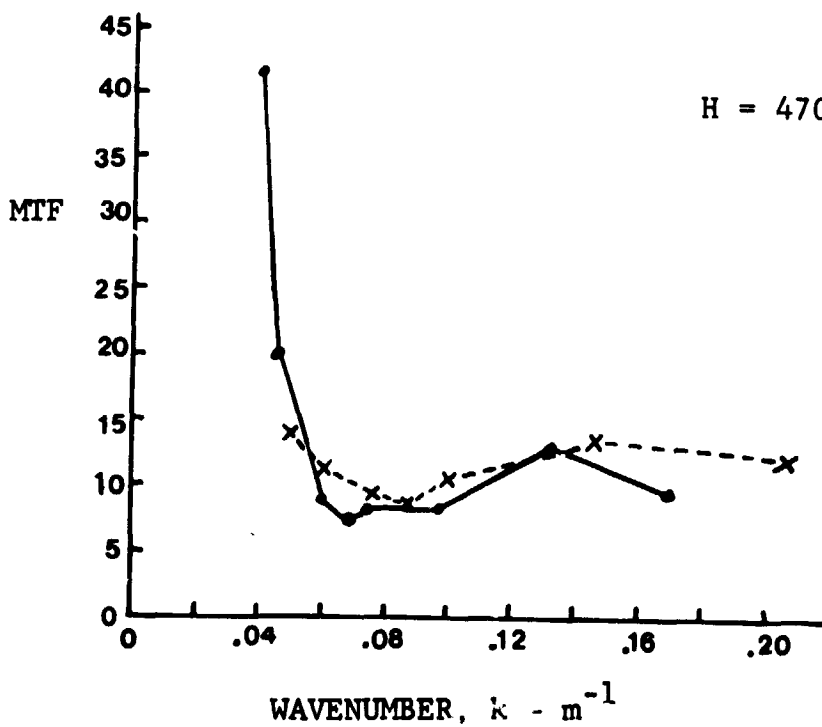
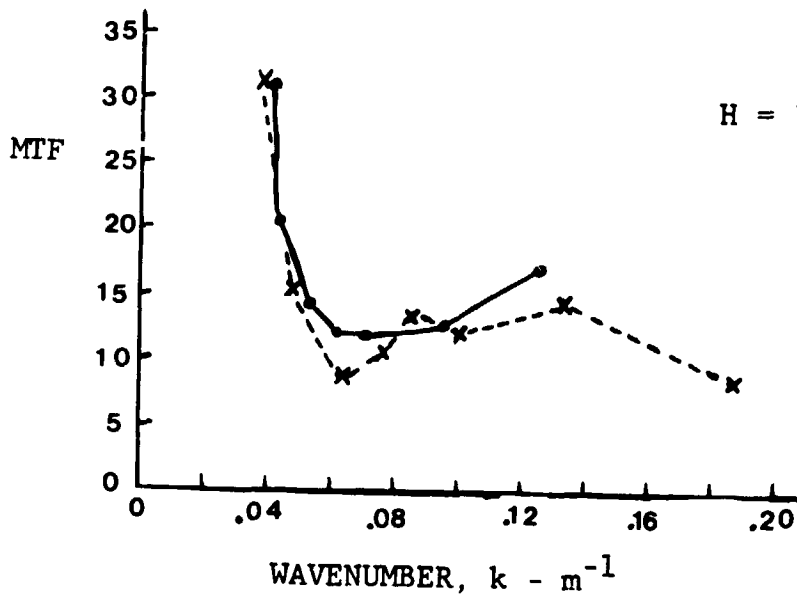


Fig. 5 Two Frequency Scatterometer inferred modulation transfer function versus ocean wavenumber

MODULATION TRANSFER FUNCTION VS.  
OCEAN WAVENUMBER

NOV. 12

SOLID CURVE - UPWAVE  
DOTTED CURVE - DOWNWAVE

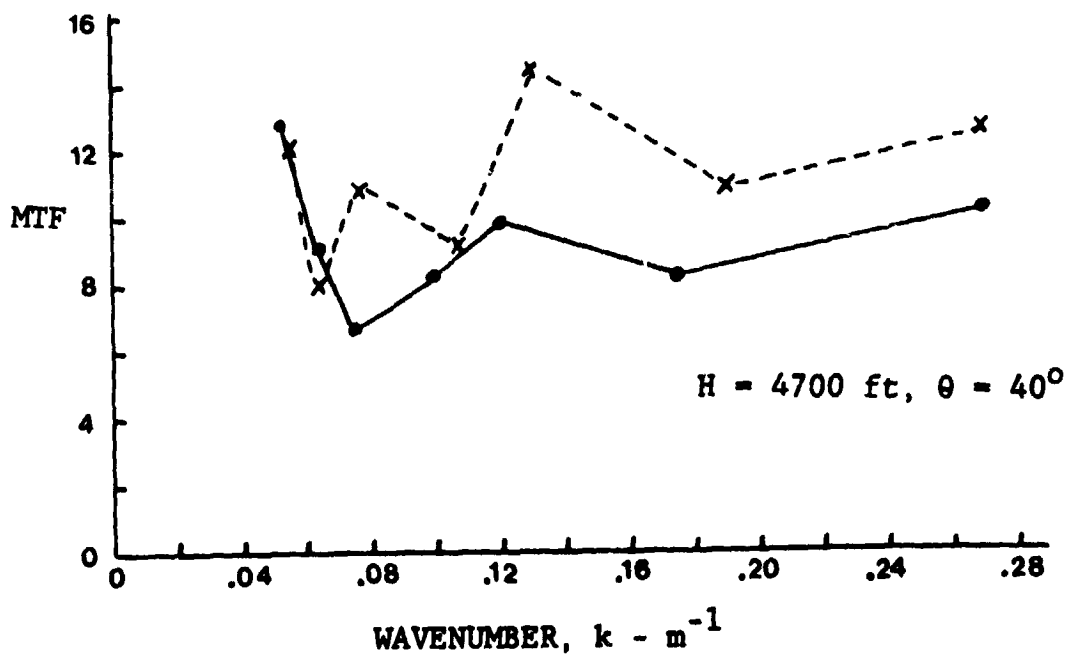
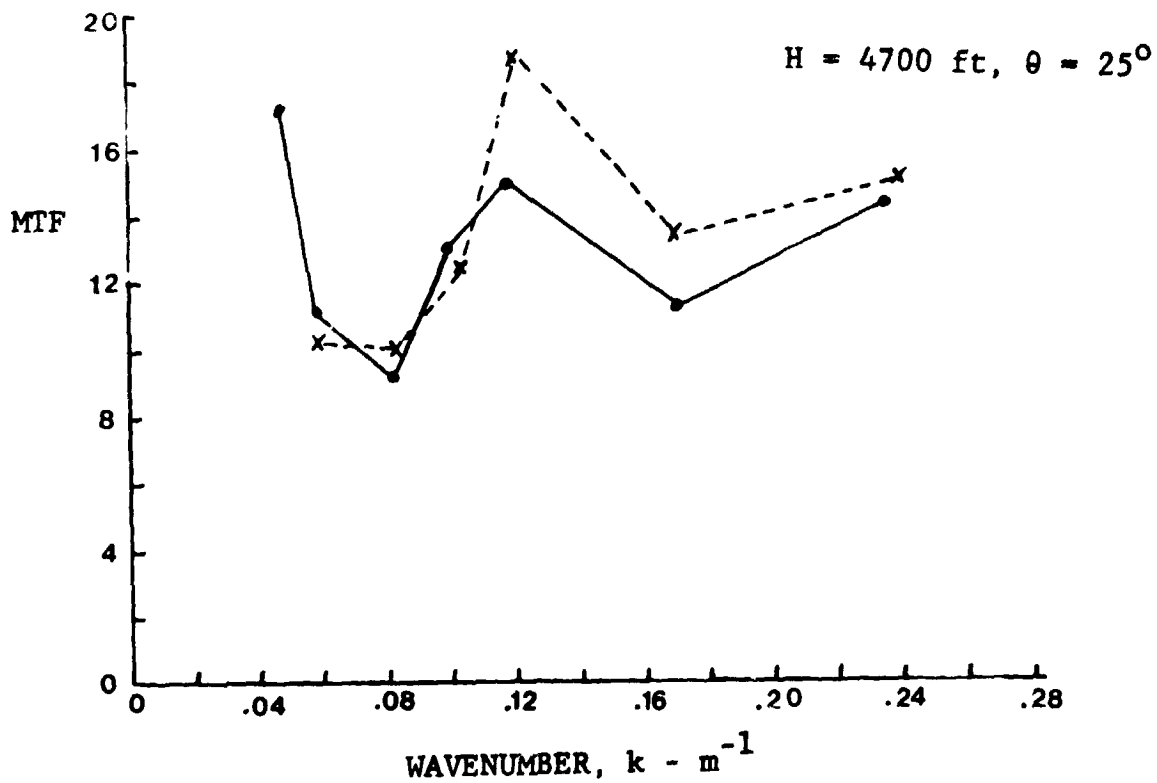


Fig. 6 Two Frequency Scatterometer inferred modulation transfer function versus ocean wavenumber

MODULATION TRANSFER FUNCTION VS.  
OCEAN WAVENUMBER

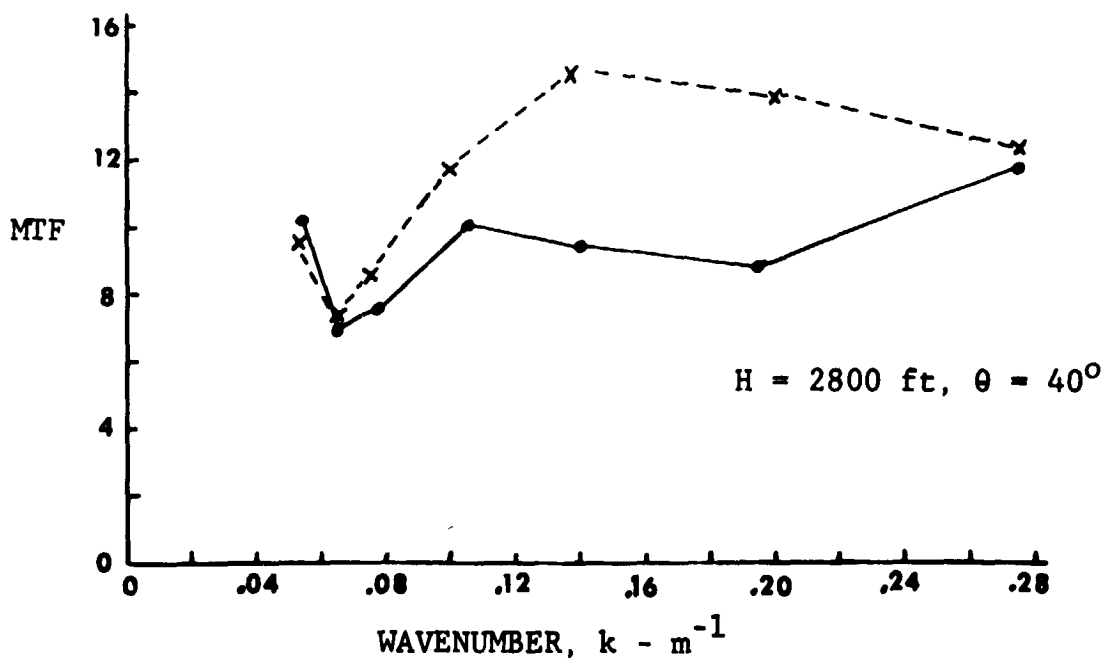
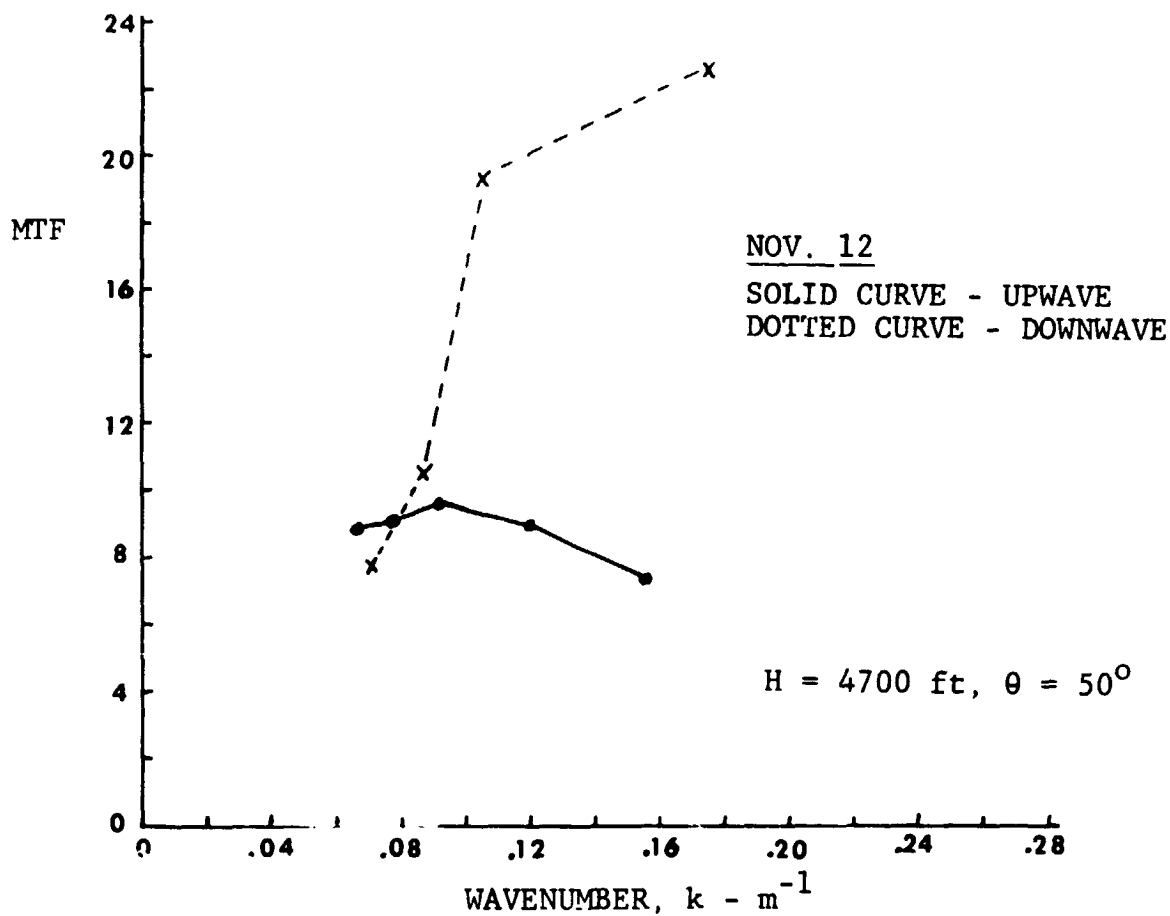


Fig. 7 Two Frequency Scatterometer inferred modulation transfer function versus ocean wavenumber

MODULATION TRANSFER FUNCTION VS.  
OCEAN WAVENUMBER

NOV. 13

H = 4500 ft

$\theta = 25^\circ$

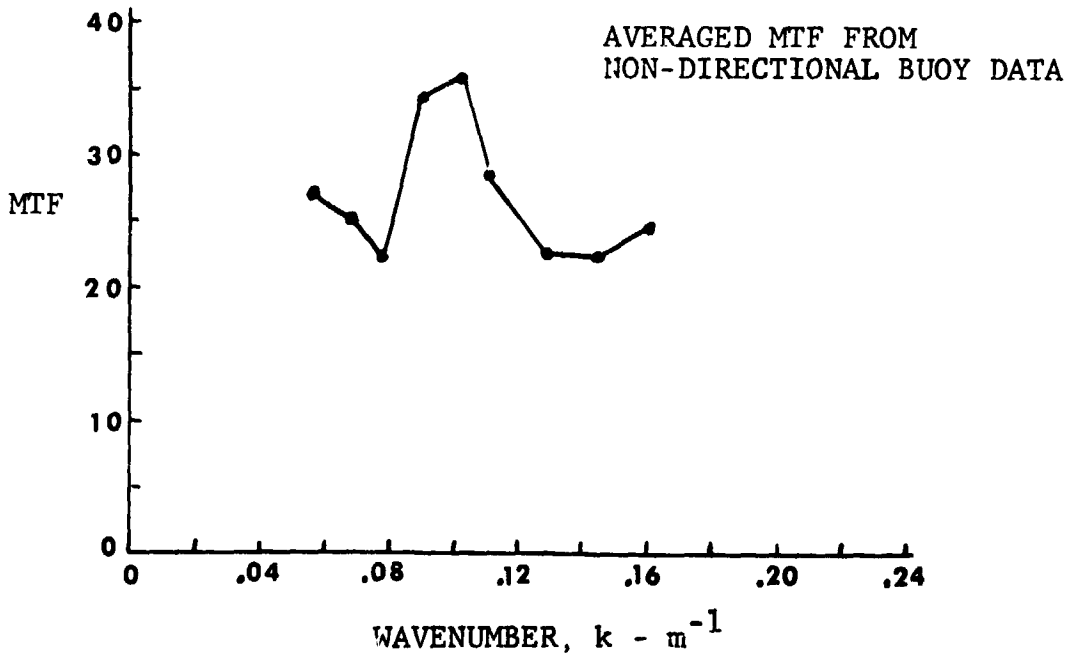
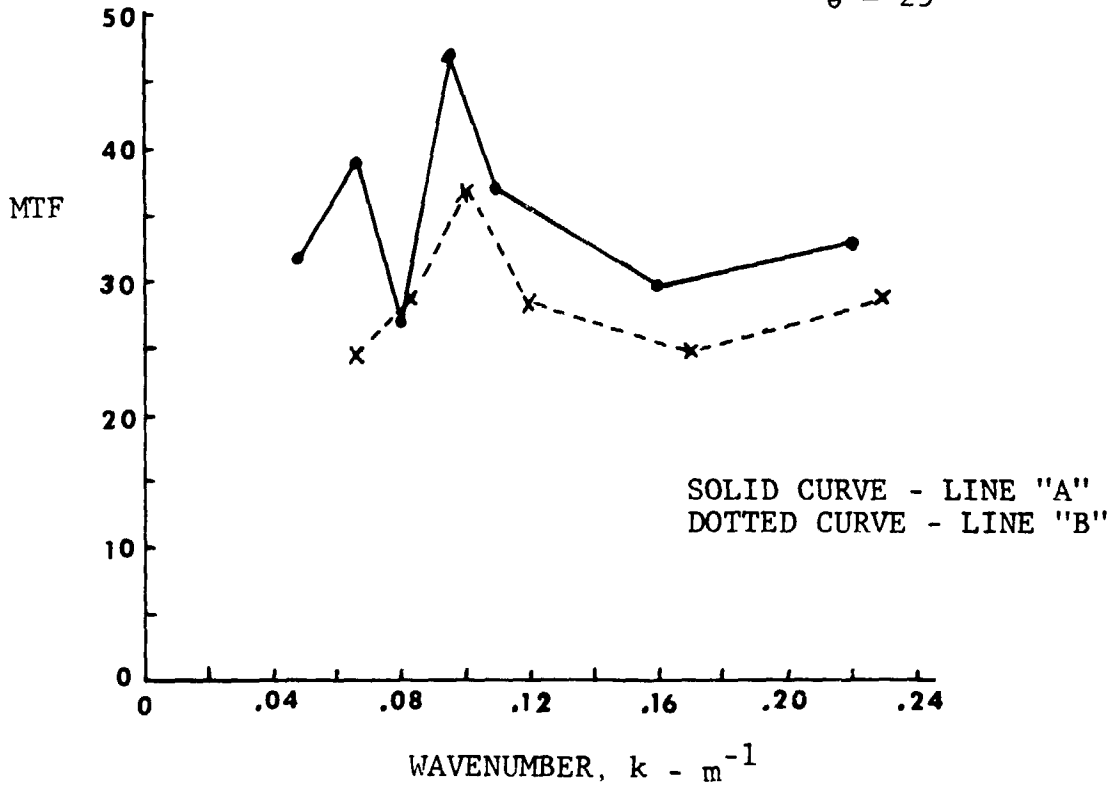


Fig. 8 Two Frequency Scatterometer inferred modulation transfer function versus ocean wavenumber, Nov. 13; top: values obtained from flight lines "A" & "B" using buoy directional data with radar data; bottom: results obtained by averaging radar and buoy measurements over  $360^\circ$ , using 4 flight directions.

# RATIO OF DOWNWAVE MTF TO UPWAVE MTF

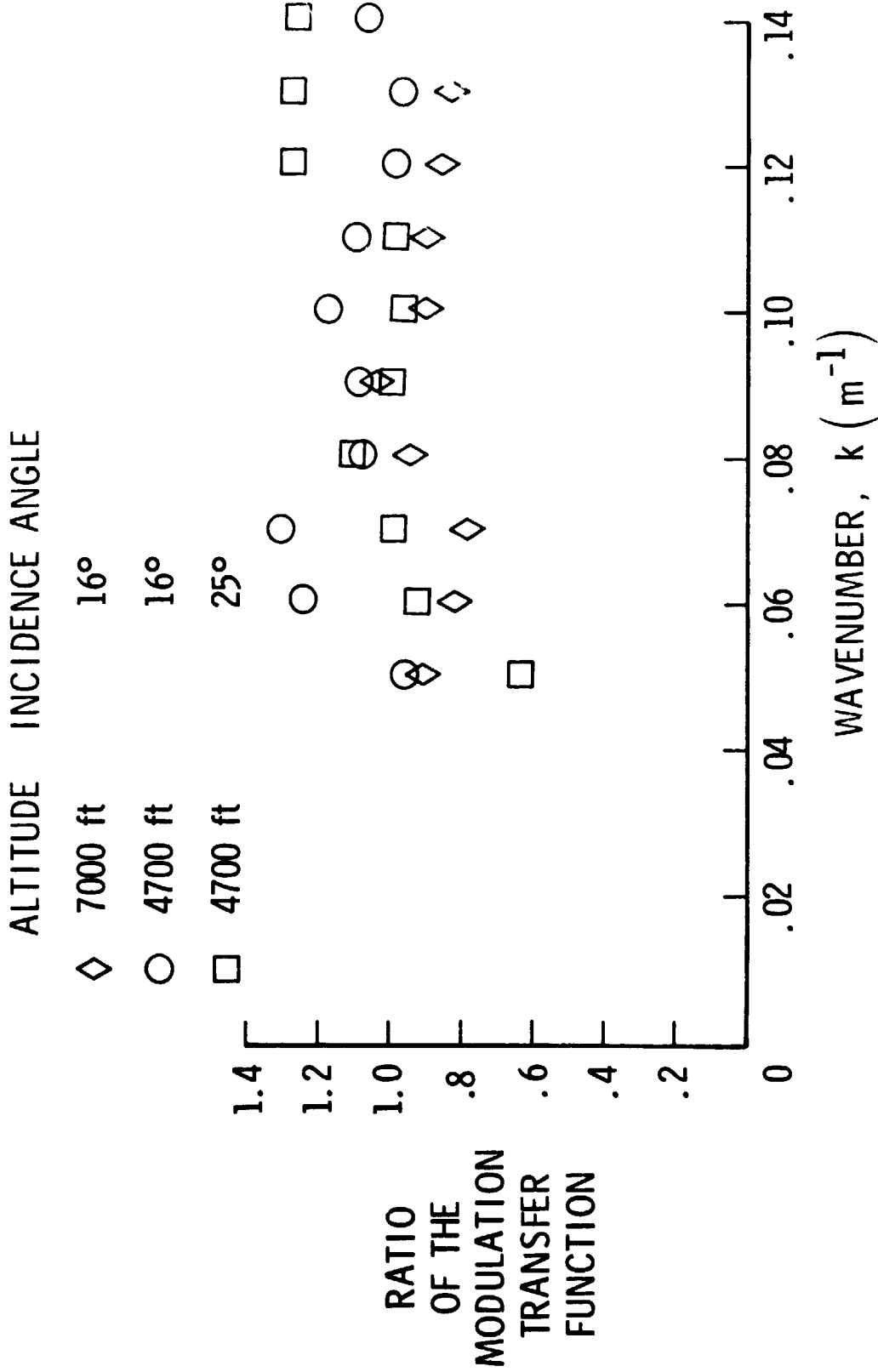
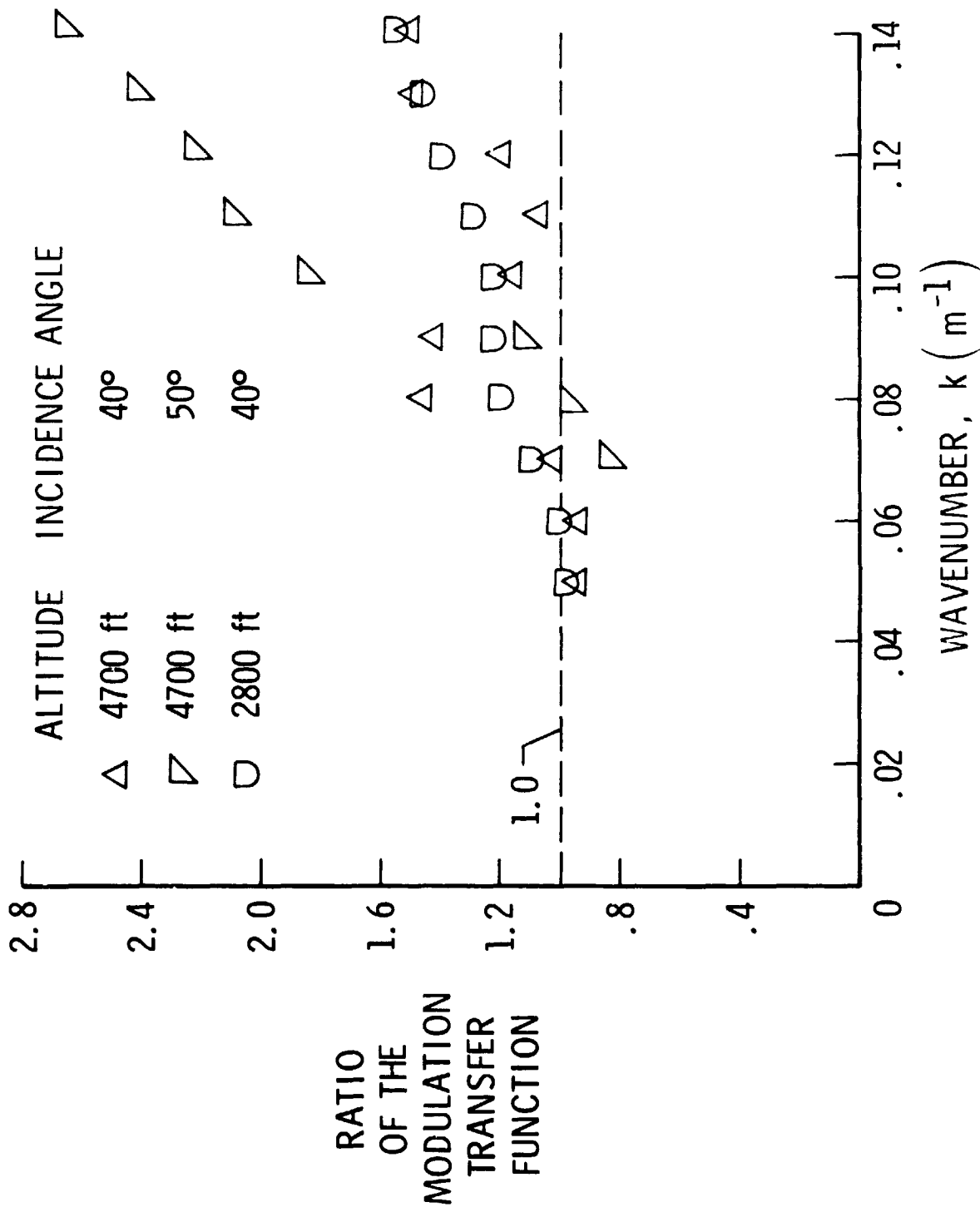


Fig. 9



# RATIO OF DOWNWAVE MTF TO UPWAVE MTF



**MTF AVERAGED OVER  $.05 \leq k \leq .09$**



Fig. 11