Technical Report RSC-12

WAVELENGTH DEPENDENCE OF BACKSCATTER FROM ROUGH SURFACE

by

John W. Rouse, Jr.

September 1970

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TEXAS A&M UNIVERSITY
REMOTE SENSING CENTER
COLLEGE STATION, TEXAS

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ABSTRACT - *The wavelength dependence of backscatter from a smooth undulating, randomly rough surface was examined experimentally using acoustic waves in water. The acoustic backscatter cross section for a statistically rough surface was measured over a broad, continuous range of wavelengths. The experiment resulted in discovering a transition region in which the wavelength dependence changed abruptly from* λ^0 *to* $^{+3}$ *due to a null in the surface height spectrum. The wavelength dependence corresponded almost exactly to the measured surface height spectrum through the transition region in the manner predicted by the composite surface model formulated by Wright. The same transition effect is shown to exist in two independent radar sea clutter experiments in the wavelength region where the surface spectrum has a partial null caused by the transition between gravity waves and capillary waves in calm seas. The results presented demonstrate that a wavelength "size-filtering" or "spectrum-filtering" process, about which several authors have speculated, does exist.*

INTRODUCTION

The relationship between the wavelength dependence and the incidence angle dependence of radar backscatter is a basic problem in the understanding of rough surface scattering. Based on measurements compiled by Katz [1] it has been concluded that (1) natural surfaces exhibit a distinct variation of radar cross section with changes in incident electromagnetic wavelength, (2) for most surfaces the cross section decreases with increasing radar wavelength, (3) if the cross section variation is expressed as λ^{α}, the values of α generally lie between -6 to +2, and (4) the value of α varies with depression angle. It has been suggested [2], [3], that the variations of the coefficient, α, as a function of wavelength are due to a "size-filtering" effect which restricts the range of surface parameters which influence the radar return for any particular incident wavelength. The recent development by Wright [4], in which the energy scattered by the surface is determined by perturbation techniques, provides a means of describing several important aspects of the wavelength dependence and the "size-filtering" effect. This conclusion is the principal result of the work presented in this paper.

The wavelength dependence of backscatter from a smoothly undulating, randomly rough surface was examined experimentally using acoustic waves in water. The acoustic backscatter from statistically rough surfaces was measured over a broad, continuous range of wavelengths. The experiment resulted in discovering a transition region similar to that predicted by Spetner and Katz [5], although their particular models do not adequately describe the observed phenomena. The effect, which has also been found to exist in airborne radar backscatter measurements of sea clutter, can be described using the model developed by Wright.

WRIGHT'S MODEL

The interaction of electromagnetic waves with slightly rough surfaces has been formulated by Wright [6] and Bass *et al.* [7]. Their approach parallels the work of Rice [8], Peake [9], and Valenzuela [10]. These developments are applicable to scatter from a slightly rough surface, i.e., one whose height variations are small compared with the incident wavelength and whose slopes are small compared with unity. The energy scattered by the surface is determined by perturbation techniques and is found to be directly proportional to the two-dimensional energy density spectrum of the surface hieght variations.

In general the small height assumption of the slightly rough surface restricts the use of this approach for predicting scatter from natural terrain. However, by employing a composite surface concept, Wright [4] has partially resolved this difficulty. In his model for sea clutter, the sea surface is viewed as one consisting of large swells on which are superimposed small wave structures. The effect of the underlying swell is to produce tilting of the slightly rough scattering surface. The tilting has the effect of altering the apparent direction of the incident energy. The model has been studied experimentally by Guinard and Daley [11], and good agreement with airborne backscatter measurements from the sea was reported.

The basic model consists of a surface whose height variations on a plane may be described by

$$= f(x,y) = \sum_{m,n} P(m,n)e^{-ia(mx+ny)} \qquad (1)$$

where m and n are integers ranging from $-\infty$ to $+\infty$, a is the wavenumber of a surface of periodicity L, and P(m,n) are independent random, normal Fourier coefficients of zero mean. The coefficients are related to the energy density spectrum W, by

$$\langle P(m,n)P^*(m,n)\rangle = W(am,an)\frac{a^2}{4} \tag{2}$$

Under the slightly rough surface conditions the first order solution of the energy scattered from the surface in terms of the normalized radar cross section is

$$[\sigma^0]_{HH} = 4\pi\beta^4 \sin^4\theta\, \alpha_{HH} W(K_x, K_y)$$

$$[\sigma^0]_{VV} = 4\pi\beta^4 \sin^4\theta\, \alpha_{VV} W(K_x, K_y) \tag{3}$$

for direct polarization, where β is the wavenumber of the incident energy, θ is the depression angle, and K_x, K_y are the wavenumbers in the x and y directions on the infinite surface. The α terms are

$$\alpha_{HH} = \left| \frac{(\varepsilon - 1)}{[\sin\theta + (\varepsilon - \cos^2\theta)^{1/2}]^2} \right|^2$$

$$\alpha_{VV} = \left| \frac{(\varepsilon - 1)[\varepsilon(\cos^2\theta + 1) - \cos^2\theta]}{[\varepsilon\sin\theta + (\varepsilon - \cos^2\theta \; ^{1/2}]^2} \right|^2 \tag{4}$$

where ε is the complex dielectric constant.

The wavelength dependence of the normalized radar cross section is dominated in (3) by $\beta^4 W(K_x, K_y)$. As an example of the influence of the energy density spectrum, the portion for ocean wave spectra in the equilibrium range has been found by Phillips [12] to be of the form

$$W(K) = BK^{-4} \tag{5}$$

where

$$K = (K_x{}^2 + K_y{}^2)^{1/2}$$

and the constant B is averaged over the entire spectrum. Combining (3) and (5) with the Bragg backscatter resonance condition, i.e.,

$$K_x = 2\beta\cos\theta$$

$$K_y = 0 \qquad (6)$$

the normalized radar cross section is shown to be independent of wavelength for the mid-angles for which Wright's model applies. If instead of Phillip's spectrum, those of Kinsman [13] or Neumann [14] are employed, the wavelength dependence of (3) is $\lambda^{-1/4}$ and $\lambda^{+1/2}$, respectively.

Because of the nature of the Wright model, it is possible to explain certain observed wavelength dependence characteristics by noting that the natural surface spectra are not necessarily uniform throughout the entire range of microwave wavelengths, hence the wavelength dependence of σ^0 is not necessarily uniform. This statement seems intuitively obvious, yet no previous theories have adequately incorporated this fact. The attempts using the Kirchhoff method [15], [16] have been only marginally successful and are completely unsatisfactory for explaining the transition effect reported in this paper [17].

MEASUREMENTS

A direct attempt to explain the wavelength dependence of backscatter has been made by Spetner and Katz [5] using two different scattering models. The significance of their work in terms of the present discussion is that they envisioned transition regions in which the wavelength dependence of the normalized radar cross section varied depending upon the relationship between the incident wavelength and the density and size of scatters viewed. For example, the predicted wavelength dependence of their random scatter model is shown in Figure 1 where λ_1 and λ_0 define transitions caused by changes in the effective density of scatterers. Katz [1] subsequently compiled data showing the wavelength dependence observed by several investigators viewing several different terrain types, but the results failed to clearly establish the existance of transition regions. With the possible exception of data recorded by Wiltse, *et al.* [18], no known verification of the existence of a transition region has been reported prior to this paper.

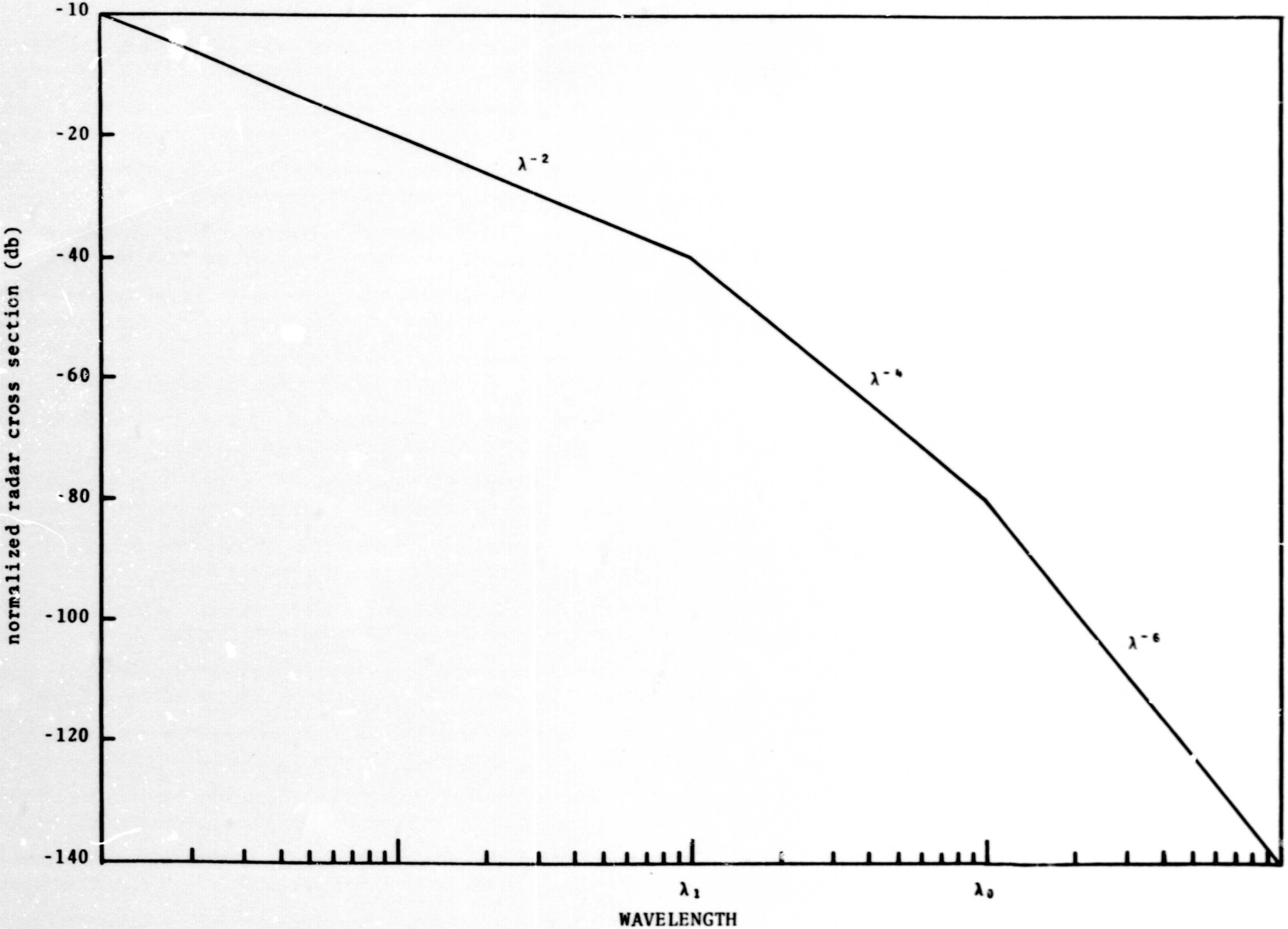

Figure 1 Wavelength dependence of normalized radar cross section - random scatterer model (after Spetner and Katz)

Wright [4], using data by MacDonald [19] and Wiltse, *et al.* [18], showed that a mean-squared height spectrum $W(K) = BK^{-4}$ resulted in a reasonably good fit to the data for high windspeed conditions. A point not noted by Wright is that the measurements at low windspeeds did not conform to a K^{-4} spectrum. In Figure 2, the MacDonald and Wiltse, *et al.* data as shown similiar to Wright's presentation with the addition of a straight-line curve fit to the MacDonald data for the larger values of K. This fit suggests a spectrum proportional to K^{-7}. In this region the normalized radar cross section has a wavelength dependence of λ^{+3}, rather than being wavelength independent. Wright and Keller [20] have subsequently observed in a series of wave tank measurements, that in the transition region between capillary and gravity waves the water wave spectrum has a partial null, especially for low windspeed conditions. The null was observed to disappear at higher windspeeds, presumably because under such conditions there are sufficient capillary waves which feed energy back into the transition region. It is not unreasonable to assume that the transition region shown in Figure 2 is due to such a spectrum null.

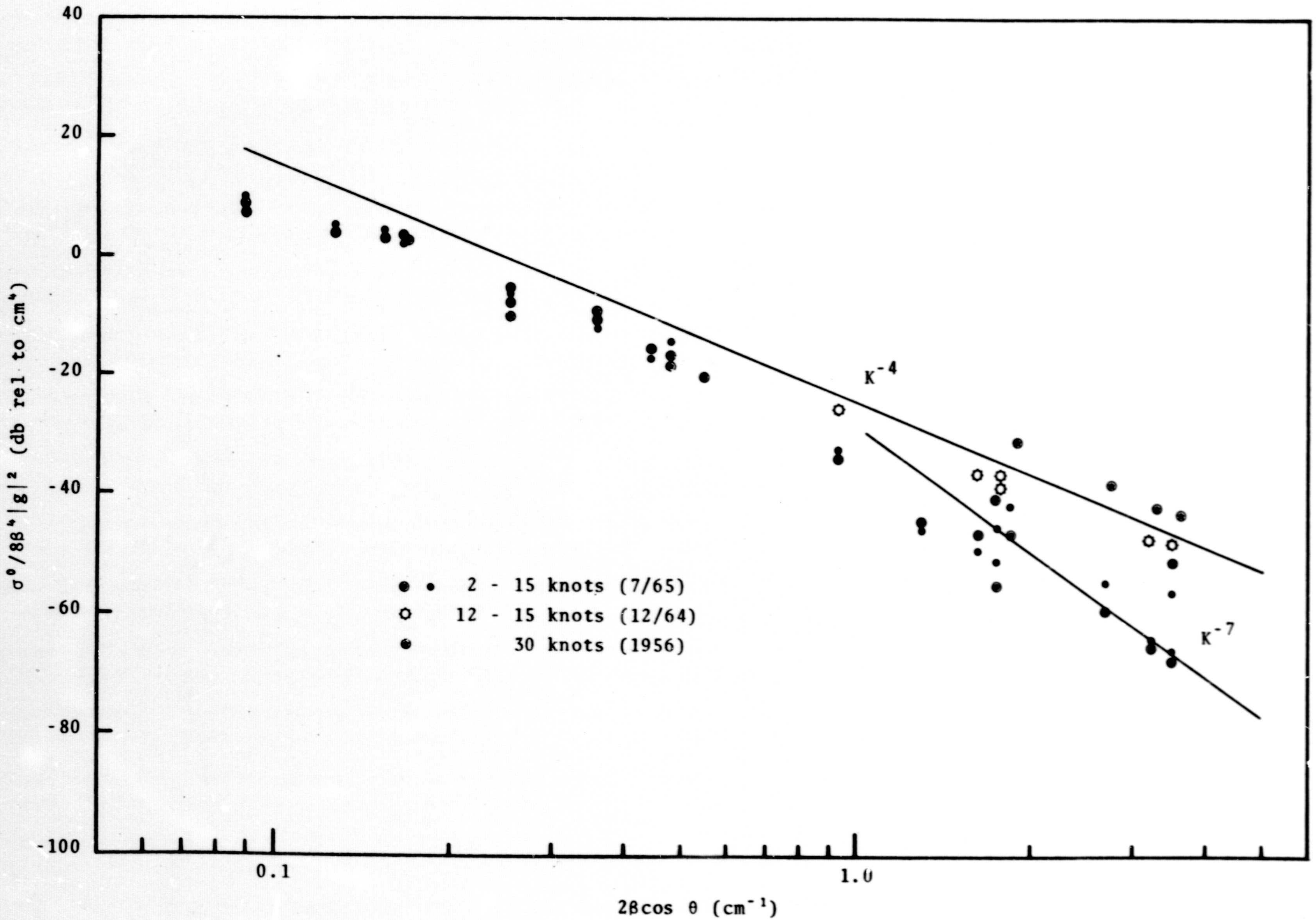

Figure 2 Vertical polarization sea clutter cross section measurements by MacDonald and Wiltse, et al. (after Wright)

In a recent set of airborne radar measurements conducted by the Naval Research Laboratory [11] especially to verify Wright's model, a transition region similar to that seen in the MacDonald data was also observed. These data are shown in Figure 3. The majority of the measurements were recorded during high windspeed conditions and conform reasonably well to a K^{-4} spectrum; however, the low windspeed measurements again conform more nearly to a K^{-7} spectrum for the larger values of K.

EXPERIMENT

The measurements reported here were originally initiated as an attempt to verify the wavelength dependence of the normalized radar cross section as predicted by the Kirchhoff method. The transition region subsequently discovered was not anticipated, and, until the recent papers of Wright [4] and Guinard and Daley [11] were examined relative to the experimental results, no explanation was found and no independently obtained supporting data were believed to exist.

The experiment performed is an extension of work reported by Parkins [21] who made omnidirectional,

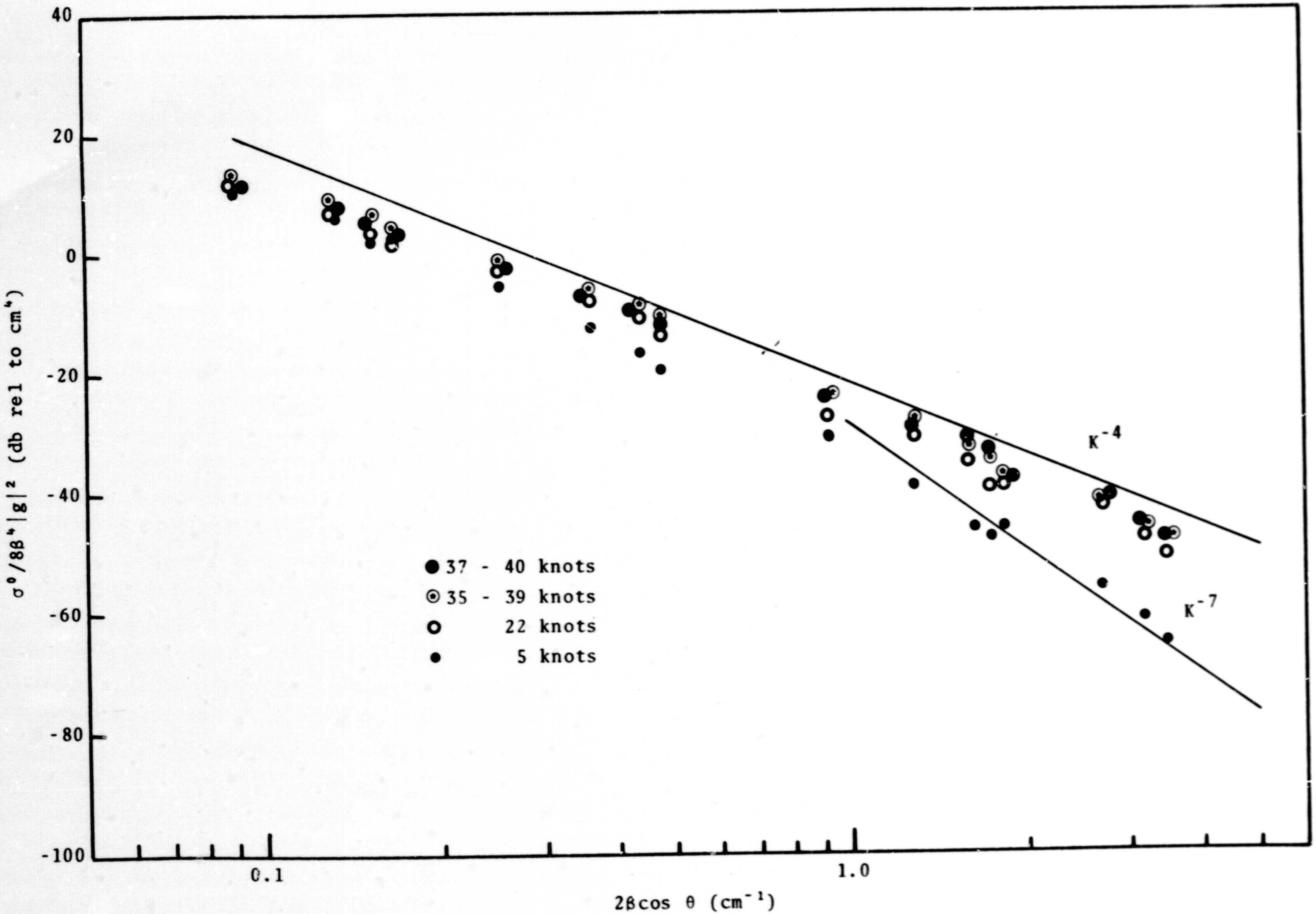

Figure 3 Vertical polarization sea clutter cross section measurements by Naval Research Laboratory (after Guinard and Daley)

single-frequency acoustic scatter measurements using a plane homogeneous surface. The surface roughness was described by a stationary process having a Gaussian distribution of surface heights. The surface employed for the present measurements was made of depolymerized rubber having the same shape as that used by Parkins, and the measurements generally supported his conclusions. However, it was found that the single wavelength selected by Parkins (1.5 mm wavelength in water) was just slightly greater than the wavelength at which a transition occurs (approximately 1.2 mm). In the region of shorter wavelength signals, the angular dependence measured at the transition wavelength tends to remain unchanged as the wavelength decreases and the overall backscatter power decreases rapidly.

The rough surface target was placed on a rotating table near the bottom of a large water tank. It was illuminated by an acoustic wave transmitted by a 6° beam piezoelectric piston transducer. The receiving transducer was located directly beside the transmitting transducer and was almost identical.

The transmitted signal was supplied by a specially designed wide-wavelength range system (15 mm to 0.5 mm in water) which provided 0.3 millisecond wide samples of the frequency spectrum at a 50 Hz rate. The full signal spectrum was swept once every five seconds. The backscattered signal was recorded on a multi-channel pulse height analyzer which was modified to display the spectrum of the return signal. The average received backscatter power was recorded with the target rotating at 3 rpm, which allowed four complete frequency sweeps per revolution. The sample rate was sufficiently low to insure independent data points. A data run consisted of averaging for 300 seconds, i.e., 60 sweeps.

The statistics of the rough surface target were estimated from a series of sampled height measurements taken at 0.5 mm spacings along profiles of the target. The sample autocorrelation coefficients were approximately Gaussian with a correlation distance of about 14 mm. The surface spectrum calculated from the autocorrelation coefficients is shown in Figure 4. Also shown are points from frequency spectra of wind-generated waves reported by Phillips [12] for a fully-developed sea. It can be seen that both spectra can be approximated by a K^{-4} variation. However the experimental surface spectrum has a partial null which causes an abrupt spectrum decline at a K^{-7} or

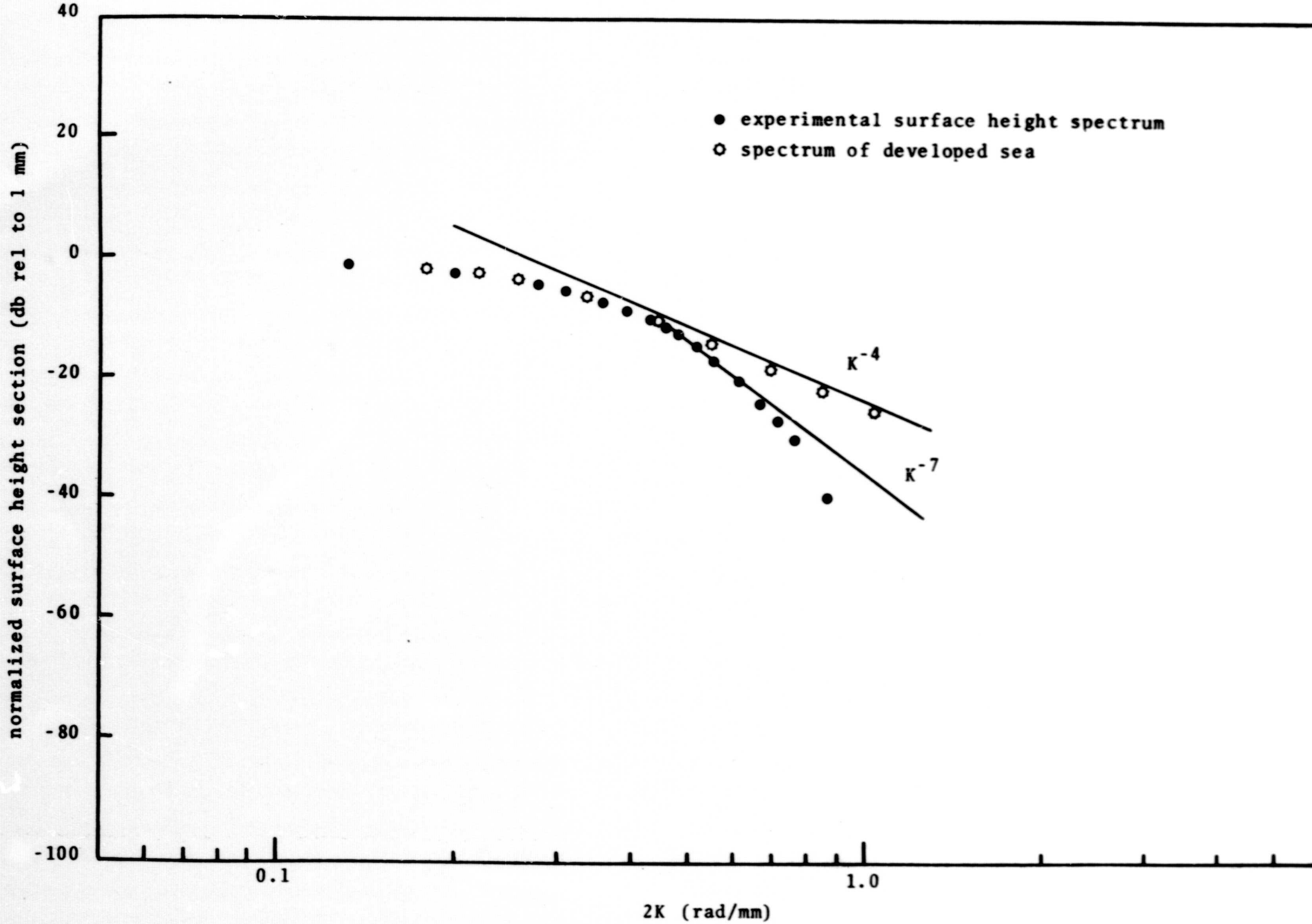

Figure 4 Measured experimental surface height spectrum compared to spectrum of fully developed sea

greater rate. The wave spectra for a fully-developed sea does not exhibit this transition. However, the work by Wright and Keller [20] verifies that the transition effect does exist for spectra of calm seas.

RESULTS

Measurements of the backscatter coefficient were recorded over the continuous wavelength range from 15 mm (0.1 MHz) to 0.5 mm (3.0 MHz). The transition region lies within the 3.0 mm and 0.75 mm range. The data obtained in this band were consistently within equipment tolerances. The measurements at the extremes of the range were not as consistent due to limitations on the piezoelectric transducer performance characteristics.

The scattering cross section measurements, shown in Figure 5, exhibit two behavioral regions as a function of the wavelength of the incident energy; above and below about 1.2 mm. The measurements for wavelengths longer than 1.2 mm conform to a $K^{-\gamma}$ variations, where γ is in the range 4.0 to 4.5, depending upon the depression angle. This corresponds to a wavelength dependence of λ^{0} to $\lambda^{.5}$ For shorter wavelengths, the data conform to $K^{-\beta}$, where β

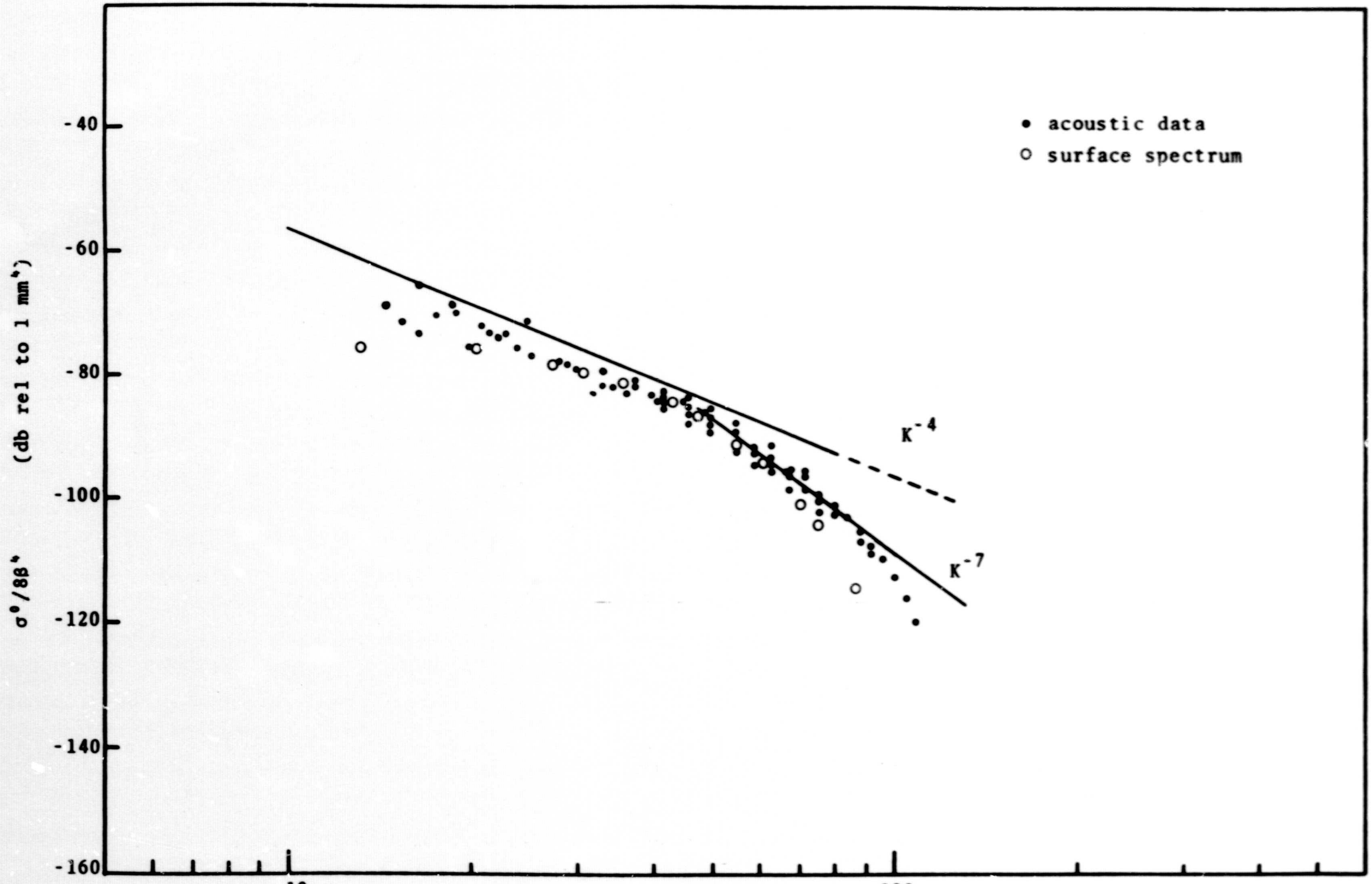

Figure 5 Acoustic backscatter cross section measurements at 60° depression angle compared to the surface height spectrum

is in the range 6.7 to 7.5, depending upon depression angle. This corresponds to a wavelength dependence of $\lambda^{2.7}$ to $\lambda^{3.5}$. The angular dependence is also influenced by the transition effect. The anticipated "flattering" of the curve with decreased wavelength occurs as the wavelength decreases toward 1.2 mm; however, below 1.2 mm the curve remains generally unchanged and experiences an overall decrease in magnitude.

Figure 5 also shows amplitude normalized points of the surface height spectrum (Figure 4). It can readily be seen that the acoustic measurements almost precisely define the transition region of the surface spectrum. The differences in the two plots in the region above about 0.8 is attributed to errors in the surface spectrum measurements, not the acoustic measurements. The course sampling interval of 0.5 mm did not provide sufficiently accurate definition of the short wavelength components in the spectrum.

The basic surface used for the measurements was designed to test the Kirchhoff method, and care was taken to achieve a valid "tangent plane" approximation, that is, short wavelength components of the surface spectrum were deliberately avoided. In an attempt to reduce the transition effect due to the null in the surface spectrum, small sand particles were coated onto the surface to introduce small structure overriding the larger undulations. These particles contribute substantial short wavelength components to the surface spectrum. The subsequent measurements showed that the transition region had been eliminated in both the wavelength dependent and angular dependent behavior of the scattering coefficient. The wavelength dependence of the scattering coefficient of the sanded surface was approximately $\lambda^{-1.0}$ over the entire wavelength range recorded, which is in agreement with measurements reported by several investigators for natural terrain surfaces [1].

DISCUSSION

The validity of using acoustic, i.e., scalar, measurements to simulate electromagnetic wave behavior has been examined extensively [21]. It has been concluded that linearly polarized electromagnetic waves can be simulated reasonably well, and considerable experimentation has been performed employing this analogy [22].

As seen in Figure 5, the acoustic measurements predict a surface spectrum proportional to $K^{-\gamma}$, where γ is in the range 4.0 to 4.5, in the region of wavelengths longer than the transition wavelength. The measured surface spectrum shown in Figure 4 generally agreed with this prediction. The transition effect in the acoustic measurements indicated a surface spectrum decline proportional to about K^{-7}, and the rate of decline is increasing as λ decreases (Figure 5). The surface spectrum measurements show a variation of about K^{-7} beyond the transition region, and the null deepens in the shorter surface wavelength region at approximately the same rate suggested by the acoustic measurements. The addition of short wavelength components to the surface spectrum in the form of small sand particles eliminated the transition region in the acoustic measurements. A surface spectrum measurement was not possible for the sand covered surface, and the extent of influence of the sand on the surface spectrum is not known.

CONCLUSION

Using three independent sets of measurements, namely those of Wright [5], Guinard and Daley [11], and the acoustic data reported here, a transition region in the wavelength dependence of the radar cross section has been shown to exist. The transition effect corresponds to nulls in the surface energy density spectrum. These data have shown that the overall wavelength behavior of the radar cross section corresponds to the surface spectrum as predicted by Wright.

A basic contention emphasized by this work is that surface spectrum components on the order of the incident wavelength dominate the behavior of the radar backscatter. That is, a "size-filtering", or "spectrum-filtering", process does indeed exist. Consequently the validity of several theories used to estimate surface statistics, including the popular Kirchhoff method, is restricted by the nature of the surface spectrum.

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