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RESEARCH TRIANGLE INSTITUTE

# GEODETIC SATELLITE ALTIMETER STUDY

## TECHNICAL REPORT

## A Review of Electromagnetic Scattering from the Ocean Surface

September 1969

Prepared Under

NASA CONTRACT NO. NASw 1909

For

Geodetic Satellite Program Office
J. D. Rosenberg, Manager
Office of Space Science and Applications
Washington, D. C.

# FOREWORD

This technical report summarizes the theory of scattering of electromagnetic waves by the surface of the sea. It examines the previous theoretical results from the standpoint of extracting information pertinent to the design of a microwave satellite altimeter.

The work was sponsored by the National Aeronautics and Space Administration under Contract No. NASw 1909, with the Research Triangle Institute. The report was principally authored by W. A. Flood with contributions from L. S. Miller and E. W. Page.

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# I. REPORT SUMMARY

The objective of this report is to concisely review the theory of scattering of electromagnetic waves by the sea surface as it is relevant to the design of a geodetic satellite altimeter. The specific problem considered is the dependence of backscattered radar energy on the characteristics of the sea surface. It is found that excellent agreement exists between the various theories for normal incidence geometry. For appreciable angles away from normal incidence, the problem greatly increases in complexity.

When the radius of curvature of the ocean surface is large compared to the illuminating wavelength and when the surface height statistics are normally distributed, the backscattered power is given by an integral containing the surface correlation function and the ratio of the rms (sea) wave height to the radar wavelength. If it is assumed that the surface correlation function is isotropic and that the ratio of the (ocean) wave height to radar wavelength is very large, the integral may be evaluated to show that the backscattered power at normal incidence is inversely proportional to the mean square slope of the sea surface.

A sample calculation is given to indicate the time scale of the correlation existing in the backscattered altimeter waveform. It is found that the return is independent over incremental nanosecond intervals up to a total of 150 nanoseconds for wave heights equal to or greater than one-half foot.

This report has served to highlight a number of engineering and oceanographic areas for which further information is needed. It was generally found that sea surface parameters of interest to traditional oceanography are not well suited to the needs of electromagnetic scattering analysis. For example, oceanographers are interested in spectral data with good resolution in the high energy range of the spectrum. Scattering phenomena, however, being slope dependent, involve a high frequency weighting of the spectral data, which tends to emphasize the poorly known region of the spectrum. Also, the effects of the surface anisotrophy on normal incidence scattering and the empirical relationships between radar cross-section and surface conditions should be investigated.

This is the first technical report to be issued under the present contract. The information gained from this effort is being applied to the development of a digital simulation of the altimeter waveforms. The following related problems are also under investigation: (1) the extraction of local mean sea level through radar observations; (2) the investigation of possible biases in the altitude measurement due to surface characteristics; (3) the transient effects on radar return due to "state-of-the-sea" characteristics. The results of the simulation work as well as these investigations will be the subject of subsequent reports.

## II. REVIEW OF ELECTROMAGNETIC SCATTERING FROM ROUGH SURFACES AS RELATED TO THE GEODETIC ALTIMETER

Satellite altimetry, as presently proposed for the GEOS satellites, results in a considerable simplification in the calculation of back-scattered power from the ocean surface. The altimeter techniques under consideration use a beamwidth sufficiently broad (2-3 degrees) that with reasonable satellite attitude control, initial radar energy received by the satellite will always be reflected from the sub-satellite point. The use of pulses in the range of 50-100 nanoseconds ensures that at satellite altitudes of 1000 km, the transient portion of the return will indeed be backscattered normally from the sea surface.

At satellite altitudes of 1000 km, the footprint of the initial 100 nanoseconds of the reflected pulse has a radius of 5.5 km which constitutes a half angle of 5 milliradians. Consequently, the angle of incidence is very nearly zero during this portion of the pulse, with a total variation of ± 5 milliradians. With the possible exception of a completely flat sea surface, this variation of incidence angle can be neglected and the analysis can be confined to the case of normal incidence. The specialization to normal incidence geometry simplifies analysis of the backscattered signal. This simplification is apparent when one surveys the effort that has gone into predicting angular dependence of scattered power over the range of angles from 0-90 degrees. Barrick [1] has demonstrated that the usual approximations made in evaluating the vector Kirchoff integrals generally lead to results which may be in error at angles of incidence greater than 20 degrees. There is, however, excellent unanimity for the theory near normal incidence; indeed, Barrick [1], Hagfors [2], and Fung and Moore [3] have shown that models employing geometrical and physical optics can lead to identical answers.

One limitation in almost all analyses for scattering at any angle, is that the surface roughness has been assumed to be isotropic; i.e., there is no preferred direction. It is further assumed that the minimum radius of curvature of the surface is "large" in comparison to the radar wavelength. This is the well-known tangent plane assumption that is necessary in the physical optics approach.

The physical optics approximation attempts to express the reflected fields, at a local point on the surface, in terms of a constant (reflection coefficient) times the incident field. This concept assumes that the reflected field near the surface is a plane wave. An equivalent assumption is that the ratio of the illumination wavelength to the radius of curvature of the surface is extremely small. So far, the integral equations have not been solved for bodies described by random height variables without this assumption. It is generally felt that the physical optics approximation is invalid for radii of curvature less than a wavelength [1]. This is a very real limitation to the theory when considering scattering from a sea surface in which capillary waves are dominant.

The tangent plane assumption is the link between geometrical and physical optics scattering theories. In the ocean scattering work of a decade ago, analyses were based on the concept of reflecting facets. Katzin [4] suggested that scattering was due to small reflecting facets overlaying the large scale wave structure. The more recent physical optics approaches have placed emphasis on the surface correlation function, with surface descriptions couched in terms of height, slope, and curvature variance. These analyses have shown that a significant portion of the scattered power is due to first-order scattering; i.e., from regions perpendicular to the incident field. Because of the intuitive appeal of the facet concept, the geometrical optics approach has been recently reexamined. Hagfors [5] has shown that the facet model is justified for a Gaussian shaped correlation function, but that in general it may apply to only smoothed or apparent slopes.

Using the tangent plane assumption, Barrick shows that for backscattering at angles near normal incidence, the scattered magnetic field $H_s$ is approximated by [1]

$$H_s = \frac{jke^{jkR_o}}{2\pi R_o} \hat{n}.\hat{z} \int_s \exp\{-jk\, \hat{n}.\vec{\alpha}\}\, K\, H_i\, dxdy, \qquad (1)$$

where $\hat{n}$ is a unit vector in the direction of propagation of the incident wave,

$\hat{z}$ is a unit normal to the mean surface,

$R_o$ is the distance between the radar and the center of the scattering surface,

$\vec{\alpha}$ is a vector from the coordinate center to a point on the scattering surface,

$K$ is the Fresnel reflection coefficient,

$H_i$ is the incident magnetic field intensity, and

$k = \frac{2\pi}{\lambda}$ where $\lambda$ is the free space wavelength of the radar.

This geometry is shown in figure 1.

At normal incidence, $\hat{n}$ has only a $\hat{z}$ component and the equation for the scattered electric field becomes

$$E_s = \frac{K E_i}{2\pi R_o} jke^{jkR_o} \int_s \exp\{-2jkz(x,y)\} \, dx \, dy \tag{2}$$

where x and y are position coordinates in the plane of mean sea level and z(x,y) is the surface displacement about mean sea level.

The mean square amplitude of the backscattered signal may be computed by multiplying equation (2) by its complex conjugate and hypothesizing ergodicity to equate a time average to a probabalistic average. Performing these operations yields

$$\overline{|E_s|^2} = \left[\frac{|K| E_i k}{2\pi R_o}\right]^2 \int_s \int_{s'} \overline{\exp\{-2jk\,[z(x,y) - z(x',y')]\}} \, ds \, ds'. \tag{3}$$

Kinsman [7] shows oceanographic data (see figure 2) which indicates that to a first order, z(x,y) is a normally distributed variable. The expectation operation in the integrand of equation (3) can be carried out using the fact that z is normally distributed with variance $z_o^2$ [6]:

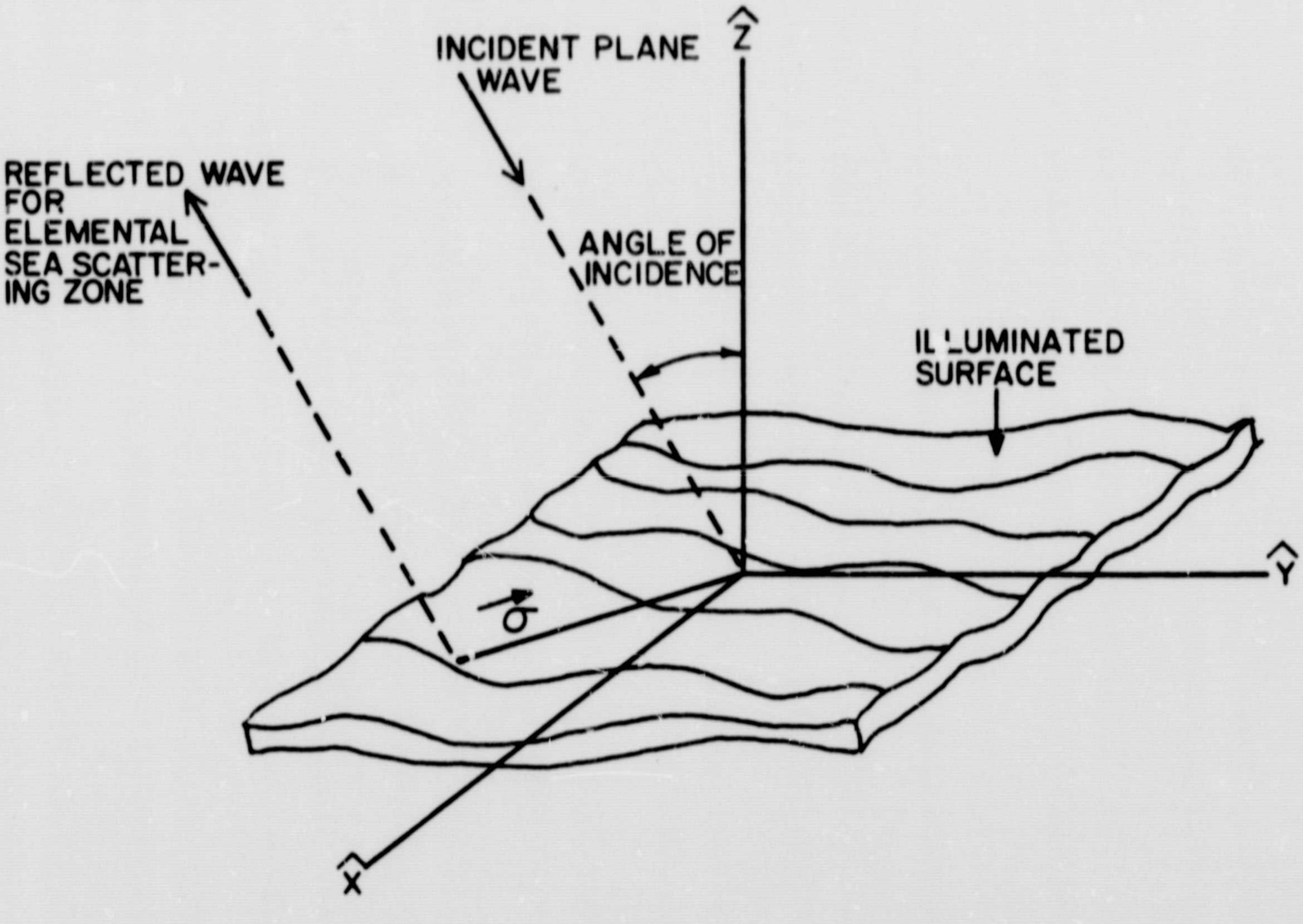


Figure 1. Scattering Geometry for a Plane Wave Incident Upon a Rough Surface.

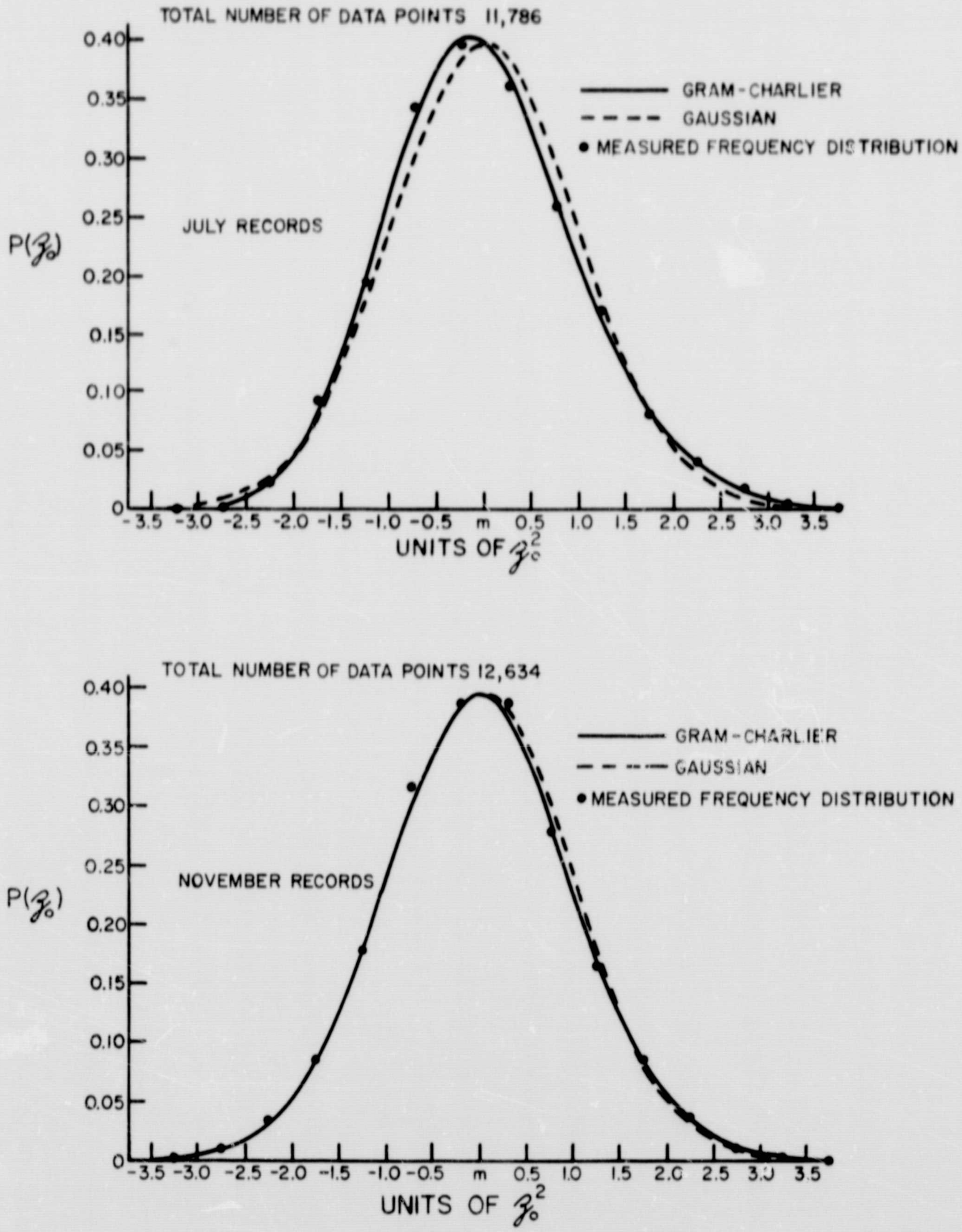


Figure 2. Distributions of Water Surface Displacement According to Kinsman.

$$\overline{\exp\{-2jk(z-z')\}} = \exp\{-4k^2 z_i^2 [1-\rho(\vec{r})]\}. \tag{4}$$

In equation (4), $\rho(\vec{r})$ is the normalized correlation function of the height fluctuations at two observation points separated by a vector distance $\vec{r}$ (it is also assumed that the surface statistics are homogeneous over areas considerably larger than the illuminated area). $\rho(\vec{r})$ may be anisotropic; that is, it may depend upon the direction as well as the magnitude of the distance separating the two observation points. The Fourier (spatial) transform of the normalized correlation function is the normalized height fluctuation spectrum.

Substituting equation (4) into equation (3), one obtains for the scattered power:

$$\overline{|E_s|^2} = \left[\frac{|K|\ E_i k}{2\pi R_o}\right]^2 \int_s \int_{s'} \exp\left\{-\frac{16\pi^2 z_o^2}{\lambda^2}[1-\rho(\vec{r})]\right\} dx\, dy\, dx'\, dy' \tag{5}$$

Since $\vec{r}$ is a relative distance vector,

$$x' = x + \Delta x$$
$$y' = y + \Delta y$$
$$\vec{r} = \Delta x\, \hat{x} + \Delta y\, \hat{y}$$

the above equation for $|E_s|^2$ may be expressed as

$$\overline{|E_s|^2}\ \left[\frac{|K|\ E_i k}{2\pi R_o}\right]^2 \int_s \int_{s\,rel} \exp\left\{-\frac{16\pi^2 z_o^2}{\lambda^2}[1-\rho(\vec{r})]\right\} d\Delta x\ d\Delta y\ dx\, dy. \tag{6}$$

Since, as will be shown, neither $\rho(\vec{r})$ nor its transform $S(\vec{k})$, the fluctuation spectrum, is accurately known, one must resort to further approximation. Consider the relative coordinate integral in equation (6). If $16\pi^2 z_o^2/\lambda^2$ is very large, the quantity $[1 - \rho(\vec{r})]$ must be extremely small if there is to be an appreciable contribution to the integral. In the absence of reliable detailed information about the wave height fluctuation spectrum, the following sections will specialize to the case where $16\pi^2 z_o^2/\lambda^2$ is very large compared to unity. Under these circumstances, $\rho(\vec{r})$ can differ from unity only by an infinitesimal amount if there is to be a substantial contribution to the relative coordinate integral. The limits of the relative coordinate integral may therefore be extended to include all space without incurring appreciable error. Thus, equation (6) becomes

$$\overline{|E_s|^2} = \left[\frac{|K|\ E_i k}{2\pi R_o}\right]^2 \int_s dx\, dy \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \exp\{-\frac{16\pi^2 z_o^2}{\lambda^2}[1 - \rho(\Delta x, \Delta y)]\} d\Delta x\, d\Delta y. \tag{7}$$

Assuming that the correlation function is isotropic and changing the relative integration into polar coordinates gives

$$\overline{|E_s|^2} = \left[\frac{|K|\ E_i k}{2\pi R_o}\right]^2 \text{Area} \int_0^{\infty}\int_0^{2\pi} \exp\{-\frac{16\pi^2 z_0^2}{\lambda^2}[1 - \rho(\vec{r})]\}\, r\,dr\,d\theta. \tag{8-a}$$

Integrating over $\theta$ yields

$$\overline{|E_s|^2} = \left[\frac{|K|\ E_i k}{2\pi R_o}\right]^2 \text{Area}\ 2\pi \int_0^{\infty} \exp\{-\frac{16\pi^2 z_0^2}{\lambda^2}[1 - \rho(r)]\}\, r\,dr. \tag{8-b}$$

Since the major contribution to the integral occurs for $\rho(\vec{r}) \sim 1$, $\rho(\vec{r})$ can be expanded in a two-term Taylor series to:

$$\rho(\vec{r}) = 1 - \frac{d^2}{dr^2}\rho(r)\Big|_{r=0} \frac{r^2}{2} = 1 - \frac{r^2}{\gamma^2} \tag{9}$$

Substituting equation (9) into equation (8), results in,

$$\overline{|E_s|^2} = \frac{|K|^2 E^2}{4\pi R_0^2} \left[\frac{4 z_o^2}{\gamma^2}\right]^{-1} \cdot \text{ Area.} \tag{10}$$

Barrick [1] has shown that for any correlation function that can be represented, for small values of the argument r, as

$$1 - \frac{r^2}{\gamma^2}$$

the backscattered power will always be a function of the mean square slope. In this context it should be noted that $\gamma$ is simply one-half of the second derivative of the correlation function evaluated at r=0; it is <u>not necessarily</u> the "correlation length". At sufficiently high frequencies such that the quantity $16\pi^2 z_o^2/\lambda^2$ is very large, the normal incidence backscattering cross section will always be inversely proportional to the mean square slope of the ocean surface. For a Gaussian shaped correlation function with a correlation length L, the mean square slope is equal to $4 z_o^2/L^2$ (the bracketed term in equation (10)).

At lower frequencies and longer wavelengths, the quantity $16\pi^2 z_o^2/\lambda^2$ may not be so large and the contribution to the integral of equation (6) will occur over a sufficiently wide range of r that $\rho(\vec{r})$ may not be adequately represented by a two-term expansion of r. Since the slope dependence comes from the quadratic term alone, the presence of other significant terms will cause the backscattered power to exhibit a dependence differing from the simple slope dependence at high frequencies. The frequency below which the backscattered power is not simply slope dependent need not be so low that the fundamental assumption of the radius of curvature being large in comparison to the radar wavelength is violated. The critical frequency is a function of rms wave height.

The results obtained thus far can be related to the geodetic altimeter program as follows: An operating wavelength of the satellite altimeter at X band (3 cm wavelength) is currently being considered. Kinsman [7] estimates that 80 percent of ocean waves have heights greater than 3 feet. It, therefore, seems reasonable to assume that $z_o$, the rms wave height, is greater than one-half foot for appreciable fraction of the time. At X-band the quantity $16\pi^2 z_o^2/\lambda^2$ has an approximate value of $4 \times 10^3$. Most of the contribution to the integral of equation (6) will occur over a range of r from zero to $r_1$ where $r_1$ is defined by

$$\exp\left[-\left(\frac{4\pi\ z_o}{\lambda}\right)^2 [1 - \rho(r_1)]\right] = e^{-4}.$$

Thus, $\rho(r_1)$ is found to have a value of 0.999. Over this range it appears reasonable to approximate $\rho(r)$ by equation (9) since the change in $\rho(r)$ is small from r=0 to $r_1$. On the other hand, if the operating wavelength were 75 cm (400 MHz) the term in equation (6)

$$\left(\frac{4\pi\ z_o}{\lambda}\right)^2 \simeq 6.4$$

with the result that the correlation function for the same range of r would decay to a much smaller value ($\rho(r_1) \simeq .375$).

Therefore, at 400 MHz one would not expect that $\rho(\vec{r})$ could be well represented by a simple quadratic. It is concluded that the backscattered power would not exhibit a simple slope dependence at 400 MHz if the wave heights were only one-half foot rms. At X-band, however, for the same wave heights, the backscattering cross section at normal incidence can be accurately related to inverse mean-square slope.

It is instructive at this point to examine equation (10) and the physical parameters which led to it. The derivation of equation (10) was founded on the following assumptions:

1. The radius of curvature of the ocean surface is large in comparison to the wavelength of the probing radar.

2. The departure of the ocean surface from mean sea level is a normally distributed random variable with zero mean and variance ${z_o}^2$.

3. The rms height of the waves is large in comparison to the radar wavelength.

4. The correlation function of the wave heights is a function only of the distance (magnitude) between two observing points.

It was not assumed that:

1. The shape of correlation function was Gaussian.

2. The parameter $\gamma$ was in fact the "correlation length".

It is worth noting that given the appropriate statistical description of the ocean surface, the assumption of the isotropic correlation function could be relaxed. For example, if the iso-correlation contours on the ocean surface were elliptical in nature, the backscattered power -- although still slope dependent -- would be a function of the degree of ellipticity of the iso-correlation contours. Kinsman [7] points out that the ocean surface is only approximately normally distributed. Given the true statistics for the departure of the ocean surface from mean sea level, the expectation in equation (3) could in principal be evaluated.

## III. USE OF OCEAN-SURFACE CORRELATION PROPERTIES IN SCATTERING THEORY

One-dimensional ocean wave spectra are given in the literature which have been obtained from measurements of wave height versus time at a single point. These measurements are first processed to yield an angular frequency spectrum which, through the application of the wave dispersion relation, is then interpreted as a one-dimensional spatial spectrum. This type of analysis is not without its difficulties because of the neglect of nonlinearities in the wave equation.

Two-dimensional spectra can be obtained directly from stereo photographs of the sea as demonstrated by Cote, Pierson, et al.[8]. For a variety of reasons, not the least of which is the sheer magnitude of the task, the spectra so derived does not represent the components whose spatial periodicity is less than 30 feet. Consequently the high wave number end of the ocean wave spectrum is not well known. It should be noted that the very high wave number end of the spectrum is far less important to the oceanographer than it is to the radar user. A few simplified calculations may illustrate this fact.

Consider a one-dimensional spatial spectrum S(k) and its Fourier transform R(r) given by

$$R(r) = z_o^2\, \rho(r) = \int_{-\infty}^{\infty} S(k) \exp\{ikr\}\, dk \tag{11}$$

If r = 0

$$R(0) = z_o^2 = \int_{-\infty}^{\infty} S(k)\, dk.$$

Also,

$$\frac{d^2\rho(r)}{dr^2} = \frac{1}{z_o^2} \int_{-\infty}^{\infty} k^2\, S(k)\, e^{ikr}\, dk, \tag{12-a}$$

$$\left.\frac{d^2\rho(r)}{dr^2}\right|_{r=0} = \frac{1}{z_o^{\,2}} \int k^2\, S(k)\, dk = \overline{\frac{dz}{dr}^{\,2}} \,. \tag{12-b}$$

In the analysis of backscattering from the sea, it was necessary to evaluate $d^2\rho/dr^2$ at $r=0$. It is clear from equation (12) that this is not equivalent to evaluating the area under the spectral distribution but rather the weighted area of $k^2$ times $S(k)$. The oceanographer may be interested in the mean square height of the waves (or equivalently the energy associated with the waves) and equation (11) indicates that this is the area under the spectral density curve. In the analysis of radar signals backscattered from the sea surface, the quantity of interest is $d^2\rho/dr^2|_{r=0}$ ; this is the area under the spectral density curve but weighted heavily in favor of the high k (short spatial periodicity) numbers. Equation (12) for the one-dimensional case, shows that the radar return is a function of $|dz/dr|^2$ the mean square slope. A few measurements of the mean square slope and the mean square height of ocean waves have been made. Munk [9] observed that when wave numbers corresponding to spatial wavelengths less than one foot were removed from the ocean spectrum by means of artificial slicks, the mean square height of the waves (proportional to the integral of $S(k)$) was essentially unaffected but that the measured mean square slope (proportional to the integral of $k^2S(k)$) was reduced by a factor of three. This means that although the scattered power at normal incidence is heavily influenced by sea slopes, it is rather insensitive to the mean square height of the waves, the latter being a reasonably common observed oceanographic variable.

Aircraft-borne radar scatterometer experiments have indicated that the backscattered radar power (slope dependent) is strongly proportional to winds at the surface. This experiment has been carried out in regions where the presence of slicks would not be expected. Presuming that slicks will not be a predominant feature of the ocean surface (this is akin to saying that deep water pollution by ocean vessel debris will be kept to a minimum), it would appear that an empirical relationship between radar backscatter and ocean surface winds has been or may be established.

Satellite measurements of radar cross section might be used to infer ocean surface winds which would be an extremely useful supplement to the present "sea state" forecast programs. At the same time, these sea state forecast programs, supplemented by satellite inferred wind data, may be able to estimate, with good accuracy, the rms wave height.

## IV. COHERENCE OF BACKSCATTERED SIGNAL

If the entire illuminated surface of the sea were to act as a flat coherent reflector, the returned power should be proprotional to the square of the area illuminated. However, the arguments leading up to equation (10) indicate that when the illuminated area exceeds a critical size, the return is proportional to the first power of the illuminated area. Just what are the dimensions over which the sea acts as a coherent reflector? The linear dimensions can never exceed (at high frequencies) the surface correlation length L, and in fact will be shown to be considerably smaller.

Consider for illustrative purposes, that the normalized correlation function of the sea surface is Gaussian

$$\rho(r) = \exp\left\{-\frac{r^2}{L^2}\right\} \simeq 1 - \frac{r^2}{L^2} \quad \text{for small r.} \tag{13}$$

At x-band, with an rms wave height of one-half foot, the previous analysis showed that the main contribution to the integral in equation (6) occurred for value of $r \leq r_1$ where $r_1$ was defined by

$$\left[\frac{4\pi z_o}{\lambda}\right]^2 [1 - \rho(r_1)] = 4$$

Therefore,

$$\rho(r_1) = .999 = 1 - \left(\frac{r}{L}\right)^2 \tag{14}$$

and

$$\frac{r}{L} \simeq 3 \times 10^{-2}.$$

This value of r, which is less than 3 percent of the correlation length, is a measure of the distance over which fields are correlated on the sea surface. Since the contribution to the integral in equation (6) is quite small outside of $r_1$, $r_1$ is considered to be a conservative estimate of the linear size of a coherent scattering element. Taking $r_1$ to be 3 percent of the surface correlation length, for L as large as 500 meters, $r_1$ is still only 15 meters.

The number of independent scattering areas can be estimated as follows: The radar footprint on the sea-surface expands radially with time. During each one nanosecond time increment that the radius of the footprint increases by 15 meters, the scattering from the incremental areas shall be considered to be independent (uncorrelated) of the previously uncovered area. The radius of the radar footprint as a function of time, t, after the leading edge of the pulse has reached the sea-surface is given by

$$r = [act]^{1/2} \quad \text{for } t \leq t_p \tag{15}$$

where r is the radius of the footprint
a is the satellite altitude
$t_p$ is the pulse length

For $t > t_p$ the radar footprint is doughnut-shaped and the radius of the leading edge is still given by equation (12). The radius of the trailing edge as a function of time, T, after the trailing edge of the pulse has reached the sea-surface is given by

$$r_t = [\ acT]^{1/2} \tag{16}$$

If a is taken to be 1000 kilometers, then for $t_p \sim 100$ nanoseconds, the increment of the radius uncovered between (t = 99 to 100 nanoseconds)

$$\Delta r_{100} = r_{100} - r_{99} \sim 25 \text{ meters}$$
$$\text{for } \Delta r_{100} > r_1 \tag{17}$$

In a similar fashion, $\Delta r_{150} = r_{150} - r_{149}$ is approximately 20 meters.

Therefore incremental signals at nanosecond intervals are incoherent for times as long as 150 nanoseconds after the leading edge of the pulse reaches the sea and the footprint radius is approximately 550 meters.

## V. DISCUSSION OF RESULTS

With x-band satellite altimetry, for waves with rms heights greater than one-half foot, and a Gaussian shaped correlation function,

1. the backscatter cross section at normal incidence will be inversely proportional to the mean square slope of the sea surface;
2. the incremental signals, sampled at nanosecond intervals for times up to 150 nanoseconds (after the leading edge of the pulse hits the sea), will be independent;
3. the incremental signal power will be proportional to the area uncovered during each incremental period;
4. the incremental areas uncovered at nanosecond intervals appear large enough to expect that the distribution of the amplitudes of the incremental signals will be Rayleigh-like.

In regard to the geodetic altimeter program, this study has led to the following conclusions: Backscattered power can be directly related to rms slope of the sea-surface. Experimental programs using radar scatterometers have indicated that empirical relationships can be used to relate the scattered power (slope dependent) to ocean surface winds. Considerably more information than is presently available regarding ocean spectrum would be needed to place these empirical relationships on a theoretical basis. Assuming that the empirical results can be used reliably to infer surface winds, the wind information might be used to infer rms wave height from wave height forecast programs. In addition, the wind information derivable from satellite altimetry can be used to improve wave height forecasting.

A consideration of the basic scattering mechanism suggests that the transient or time-of-arrival nature of the scattered signal (the so-called ramp region) will depend on height statistics. It appears that this transient region will be influenced by the surface height variable, and that an understanding of height effects will be required to develop an accurate technique for measuring mean sea level. Little prior work has been uncovered concerning this problem. This subject and the digital simulation will be the next investigative areas on the present programs.

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