Directional Characteristics of Sea-Wave Scattering Observed at Low-Grazing Angles

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***Abstract*— The mathematical and statistical description of waves on the sea surface has evolved over more than two centuries starting with Laplace (1776), Gerstner (1802), Airy (1845), Stokes (1847), Kelvin (1887), and Helmholtz (1888). Most of the major developments in this century are summarized by Apel [1] who has derived an improved model for the ocean surface wave vector spectrum of equilibrium sea states. Part of the motivation for this paper is Apel's observation that "... in spite of the incorporation of an anisotropic angular distribution of wave energy, the observed azimuthal variation of radar scatter is not captured ..." The data set analysis summarized in this paper show that wave group processes are responsible for directionally organized sea surface radar back scattering patterns, which are long lived and consequently extend over large areas. This includes crosswind traveling wave systems. A property of wave group process structure is the steepening of waves as they pass through the center of the group. The mid-group sharpening of the waves, which can include crest spilling or breaking, significantly increases the radar scattering cross section observable with low-grazing-angle radars, usually most noticeable with horizontal (HH) polarization. Therefore, low grazing angle (LGA) radar provides a vastly improved means of seeing wavegroup phenomena over conventional oceanographic methods.**

***Index Terms*— Sea surface electromagnetic scattering, wave groups.**

I. Introduction

SEA surface radar backscatter data collected at low grazing angles (LGA's) can provide spatially resolved intensity and doppler information on directional wave patterns and processes. Radars with range resolution on the order of 1 or 2 m and azimuth beamwidths on the order of 1° have a significant radial directional selectivity for most of the range of surface gravity wave lengths of interest, i.e., a few meters to a few tens of meters [2]. Analysis of coherent dual-polarized radar data collected in the fixed antenna mode at LGA's has already provided significant information on the nature of the enhanced non-Bragg horizontal (HH) backscatter in this regime [3]–[5]. Data collected from seaside locations by a radar operated in a fixed antenna mode or with a high-rate limited field-of-view scan [6] are able to provide essential statistical measures of point, linear, and area correlation and covariance functions of the sea surface backscatter that have previously been beyond the capability of instrumentation to adequately collect and record. Such measurements also provide an important link between wave tank measurements and open-water results.

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II. Experiment Description

This paper presents a summary of directional wave spectra observed in images collected by hillside-located radars operating in a fixed antenna mode viewing ocean lochs, sounds, and coastal waters in experiments from 1989 to 1994 [7]–[10]. The referenced documents and supporting archives contain considerable ground truth data including meteorological, water column, water depth, pycnocline, current meter, and some nondirectional wave staff data. Averaged and pulse-by-pulse radar returns are also archived for most data sets as is co-boresighted video for some data sets. The specific data applicable to the subject of this paper are the radar beam pointing direction and wind direction and speed at 10-m height. The wind data points are 1 min averages. Almost all the data was collected at a grazing angle near 6° with a range resolution of about 2 m. The azimuth beamwidth was approximately 1°. The data range swath varied between a few hundred to a few thousand meters with the beam footprint center around 2 km from the radar. Information on a typical site and radar configuration is provided in [7].

III. Data Analysis

The first two figures show examples of range time-intensity (RTI) images collected under moderate wind conditions. The upwind viewing conditions of Fig. 1 result in an RTI image that is dominated by linear features which indicate a constant-velocity scattering process approaching along the radar line of sight. This is typical of data sets collected under upwind conditions by LGA X-band ($\lambda = 3$ cm) radar operating with HH polarization. Crosswind viewing conditions in Fig. 2 result in linear features with both approaching and receding slopes. Closer examination of the linear features reveals that they are not continuous, but periodic high-intensity spikes that were analyzed and recognized by Tulin [11] as resulting from the passage of waves through the peak of their wave group envelope where the associated peaks of radar scattering mark the progress of the wave group in the radar intensity map. The slope of the linear features in RTI images is the wave group velocity, from which the wave length and phase speed can be derived. Also to be noted is the lifetime of these features, many lasting hundreds of seconds and longer. Once established, the wave group processes are observed to be little affected by wind gusting or even temporary changes in wind direction.

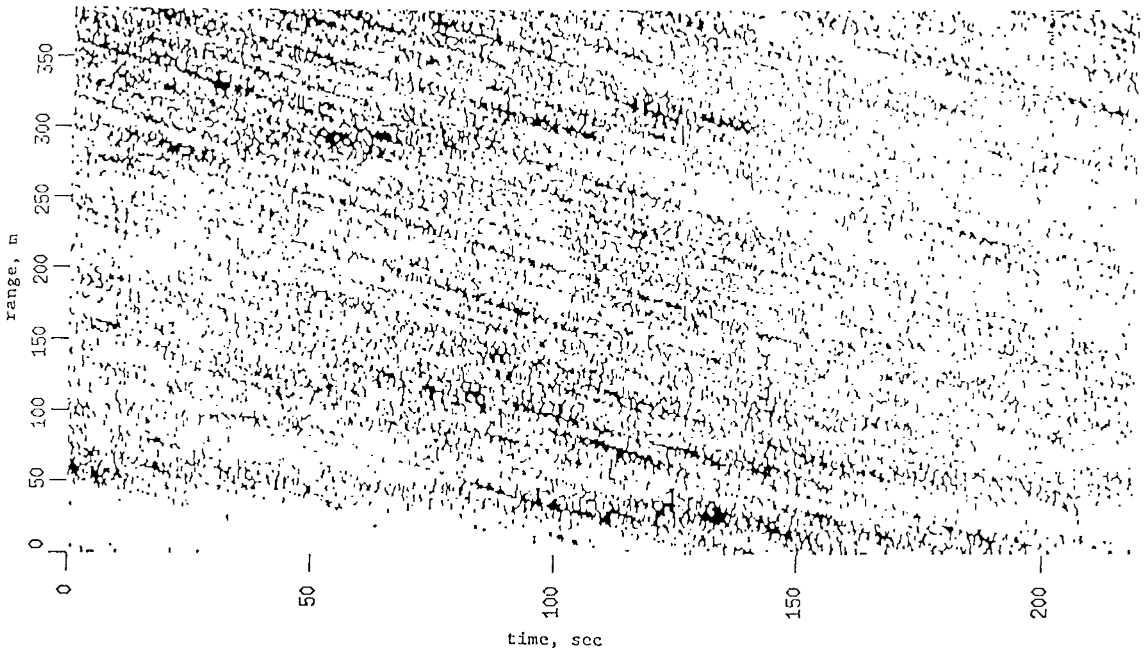

Fig. 1. HH backscatter for LL90 run 16, 16 : 23 : 15 to 16 : 27 : 01 GMT, 64 pulse averaging (0.128 s).

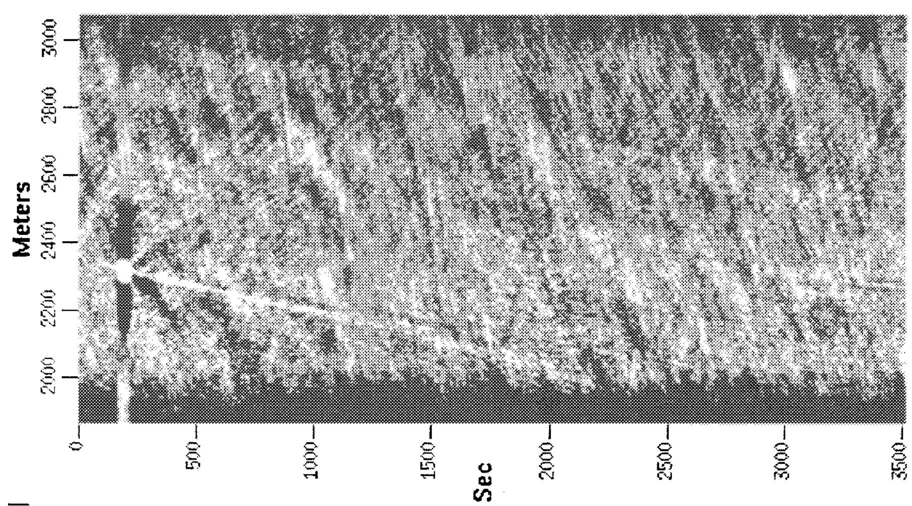

Fig. 2. HH backscatter for LL94 Sept. 15, run 3, 16 : 25 : 24 GMT start time, range sample interval: 4.5 m/pixel. Time sample interval: 6.5 s/pixel.

The slope of the linear features in Fig. 1 (nominally 0.9 m/s) gives the wave group velocity c_g. For deep water gravity waves, the phase velocity c_p is twice the group velocity yielding 1.8 m/s for the phase speed of the underlying wave system. For deep water

$$c_p = (gk)^{1/2} \quad k = \frac{2\pi}{\lambda}$$

where λ is the water surface wave length giving $\lambda \cong 2.1$ m. The period of the underlying wave system is about 1.2 s. The period of waves peaking at the group center is twice the period of the underlying wave. The time interval between many of the bursts can be seen to lie between 2–2.5 s corroborating the wave group nature of the process. The separation of the wave group lines can be seen to be three or four wavelengths in most areas. The average steepness of the underlying wave system can be estimated based on the wavegroup length, but a number of factors must be properly taken into account requiring a discussion, which is outside the scope of this paper.

RTI plots have been produced from data collected at experiments conducted from 1989 to 1994 under low to moderate wind conditions for a variety of wind directions relative to the radar line of sight. For about 100 images, the group velocity value was derived from the range/time slope for each visible pattern of wave group lines. For near upwind or downwind viewing, usually only a single approaching or receding wave group line pattern was observed. For a number of crosswind cases, both an approaching and a receding wavegroup line pattern were evident.

The observed wavegroup velocities have been plotted in Figs. 3 and 4 for two ranges of wind speeds, low wind speed covering 2–6 m/s in Fig. 3, and intermediate wind speeds covering the range 6–10 m/s in Fig. 4.

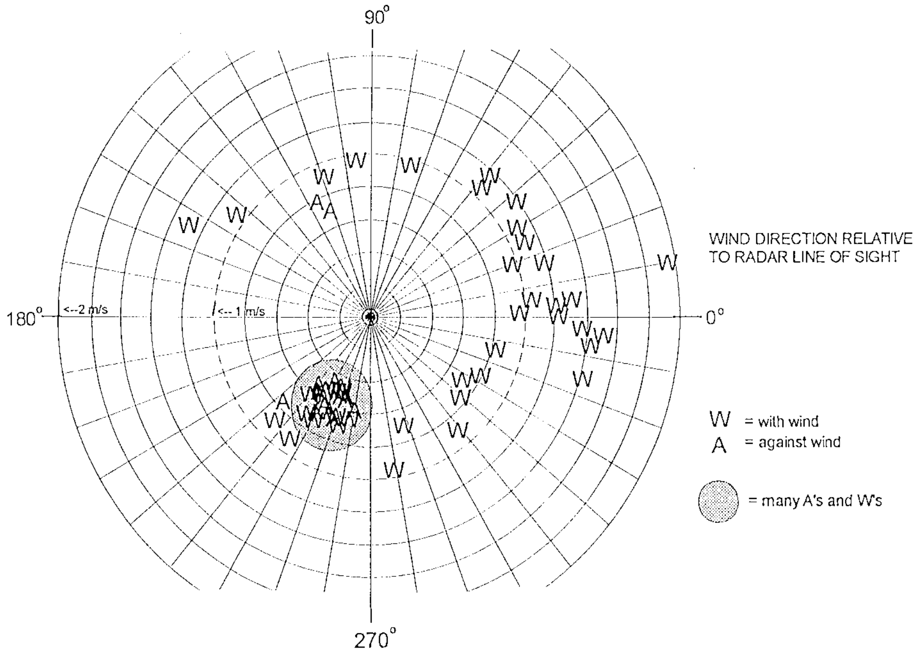

Fig. 3. Wave group velocities observed for low wind velocities 2–6 m/s.

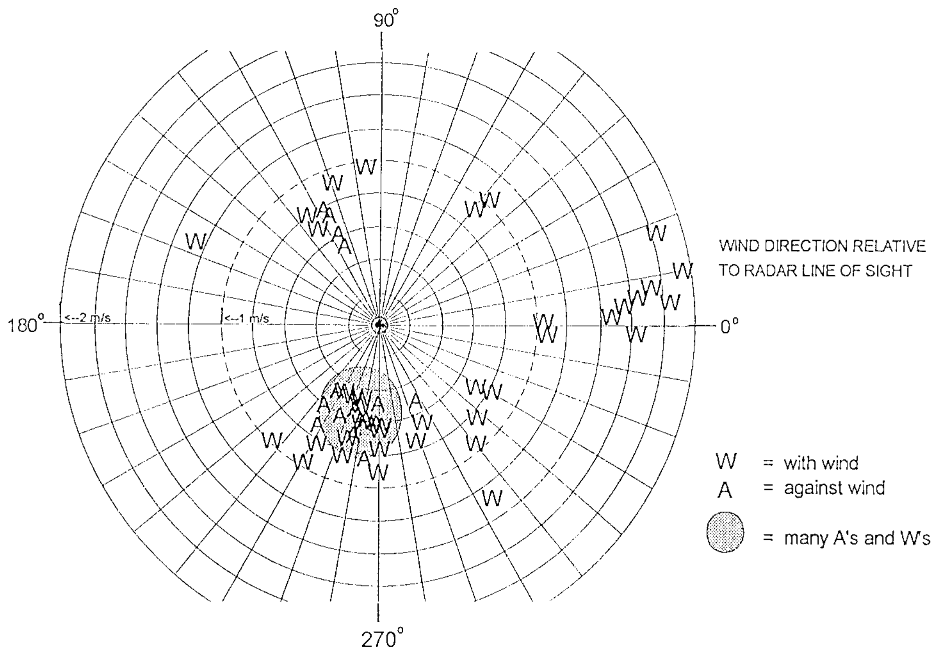

Fig. 4. Wave group velocities observed for moderate wind velocities 6–10 m/s.

The highest group velocities in Fig. 3 are where the radar line of sight is near upwind and downwind, i.e., 0° and 180°. In some downwind images the wavegroup lines are more visible for vertical (VV) than HH, but both polarizations see the same wave group. Other data sets show that S-band (10 cm) [10] and Ku-band (2 cm) radars operating with the same grazing angle see the same wavegroups. The limit on up and downwind wave speeds is the result of limited fetch along the radar line of sight, nominally 1–2 km in most directions. Lower group velocities are observed for near crosswind viewing conditions. There are also cases where both an approaching and a receding wavegroup were observed simultaneously, Fig. 2 being an example. Simultaneous approaching and receding wavegroups are more common than appears in these plots. This inability to see both approaching and receding wave groups is largely the result of the signal processing and image preparation used, i.e., time-averaged total intensity of HH or VV backscatter presented in a black and white map format, resulting in a limited effective dynamic range. More fine-grained spectral processing usually reveals the presence of the lower level, usually upwind wave group. The presence of bi-directional wave spectra has been recognized by early researchers for narrow wave spectra [12] and more recently [13] for extended ranges of surface wavelengths as displayed in dispersion plots. Wave group processes have been observed and analyzed [14], [15] in upwind radar data. However, the degree to which the wave spectra were organized in wave group processes in crosswind directions as well has not been observed or reported previously.

The wave group velocity distribution (shown in Fig. 4) for wind speeds from 6–10 m/s is similar to Fig. 3. The group velocities near upwind and downwind viewing directions are higher than for crosswind and, for some crosswind cases, both approaching and receding wavegroups were evident.

Of particular note in Fig. 4 are the wavegroups observed with velocities less than 0.5 m/s. The multiwavelength separation of the wave group lines allows identification of processes involving sea surface wavelengths, which are not directly resolvable by the radar (a 1 m/s wave has a surface wavelength of about 0.6 m).

IV. Summary and Conclusions

Data collected by high resolution radars at LGA shows a significant degree of organization in the sea surface directional wave scattering not previously recognized. Emphasized in this paper are the observations of crosswind traveling wave groups. For low and medium wind conditions (2–10 m/s), wave group processes are evident for upwind, downwind, and most crosswind viewing conditions. The wavegroup systems can have long lifetimes—hundreds of seconds or more. The data shows numerous cases of simultaneous counter-traveling wavegroups. Recent published results show that wave group processes, and the extended time and spatial correlation of radar clutter backscatter (including sea spikes) do not depend on the presence of local wind as shown in wave tank experiments [17]. This is consistent with radar observations of sea spikes at low sea states and low wind conditions [18].

The existence of multiple simultaneous wave group systems moving in different azimuthal directions creates a significant level of time and spatial organization in the directional surface wave spectra and the resulting radar backscatter, especially at LGA. This has significant implications for shipboard radar system design. The effective suppression of sea clutter without unnecessary loss of detection of stealthy low-flying or surface targets depends on exploiting the knowledge of the directional distribution and equations of motion governing these organized clutter processes.

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