A scanning lidar system provides high-resolution two-dimensional measurements of the ocean wave displacement. The airborne operation further enhances the speed of data acquisition. These properties offer a capability for rapid characterization of the ocean wave environment. In addition to the active ranging, the scanning optics can obtain passive measurements of the surface emissivity. This yields a digital image of the surface brightness "on the fly." Processed into a binary image, the measurements can provide the statistical properties of the spatial distribution of breaking waves. Technical specifications of the system and examples of applications are presented.

1. Introduction

Laser ranging was introduced for airborne ocean wave measurement in the 70s [1, 2]. Using the high-resolution profiling (one-dimensional) mode, Schule, Simpson and DeLeonibus [1] obtained transect wavenumber spectrum in the wind direction to study the wave growth mechanism and the properties of wavenumber spectrum. Since then, many improvements have been incorporated in the design of newer generations of airborne lidars. The most significant advances include the two-dimensional scanning capability [3, 4] and the correction of the aircraft motion using the kinematic global positioning system (GPS) technique [5]. Although these improvements were mainly supported by the Greenland ice research, the technology is obviously also suitable for measuring the topography of ocean surface waves.

Most recently, a new capability is added to the system that uses the laser scanning optics in passive mode to collect the digital image of the ground or ocean surface. This latest addition is useful for the analysis of the spatial distribution of breaking patches on the ocean surface. In addition to the lidar system, video images or 70 mm photographs are routinely collected during each airborne measurement mission. The combination of active ranging, passive imaging and continuous video recording of the ocean surface represents a powerful tool for the study of ocean wave dynamics on the continental shelf. In Section 2, we provide a brief description of the measurement system. Section 3 presents a few applications of using the airborne scanning lidar data in ocean wave research. Section 4 summarizes the paper with concluding remarks.

2. Measurement System

The key instrument of the ocean wave measurement system described in this paper is the airborne topographic mapper (ATM). This is an airborne scanning lidar ranging system originally designed for monitoring the annual variation of the Greenland ice sheet. The hardware design has been described elsewhere [3, 4]. Here we only discuss briefly the scanning method and the technical specification of the vertical and horizontal resolutions.

The ATM measures the range between the aircraft and the surface of the ground or ocean. It uses a nutating scanning mirror to project the laser beam in a circular pattern on the surface with a 15° incident angle. Carried on a moving aircraft, the locus of the scanning pattern is approximately an oval shape with the major axis in the cross-track direction and the minor axis in the along-track direction. The repetition rate of the scanning cycles is 10 Hz. The laser return is sampled at 10 kHz. Each scanning cycle is therefore sampled at 1000 equal spacing. Because the laser is pulsed at 5 kHz, the 1000 samples are interlaced with 500 active ranging data and 500 passive digital measurements of the surface emissivity. The operational altitude of the aircraft is typically between 400 to 600 m. With an 1 mrad dispersion angle of the laser beam, the footprint of the laser spot on the ocean surface is between 0.4 to 0.6 m. The swath of the image is between 200 to 300 m. The spacing between neighboring active or passive image pixels is between 1.3 to 1.9 m. The vertical resolution of the ranging is dictated by the determination of the aircraft position. The theoretical resolution of the kinematic GPS system is 0.01 to 0.02 m. Dynamic calibration of the GPS measurements and the laser ranging of a calm water body shows that the rms error of the vertical resolution is better than 0.1 m [5].

3. Applications for wave research

3.1. Wavenumber spectrum

The most obvious utilization of these two-dimensional measurements of the ocean surface topography is the direct computation of the vector wavenumber spectrum. Fig. 1a shows a 20-s segment of the surface topography covering an area approximately 180 m × 1400 m. The data were collected on 9/24/97 starting at 09:35:11 AM. The rectangular grid size is 6 m in the along track (x) direction and 3 m in the cross track (y) direction. The wave pattern can be easily identified. The two-dimensional wavenumber spectrum can be calculated using a standard 2-D FFT procedure. (The results presented in this paper are processed using MATLAB.) Fig. 1b shows an example of the wavenumber spectrum computed from an image segment of 180 m × 200 m. Even with a small image of this size, the dominate wavelength and propagation
direction are clearly identified in both the spatial plot and the wavenumber spectrum. This is an equivalent of 3 s flight data and illustrates the capability of rapid characterization of the surface wave properties using an airborne scanning lidar.

Fig. 1. (a) A segment of the two-dimensional surface wave topography. The image area is approximately 180 m x 1400 m. The image is resampled from the scanning lidar data and reoriented in the rectangular coordinate system with respect to the flight track as the x-direction. (b) A two-dimensional wavenumber spectrum calculated from a subsegment (180 m x 200 m) of the data shown in (a). (c) The result of 3 x 3 bin averaging to smooth the wavenumber spectrum shown in (b). (d) The ensemble average of 7 spectra, each calculated from a non-overlapping segment of 180 m x 200 m wave field. (e) The 3 x 3 bin averaged spectrum of the ensemble averaged spectrum shown in (d).

One can apply ensemble averaging or bin averaging to increase the statistical confidence of the spectral estimate. Fig. 1c is a smoothed spectrum of the one displayed in Fig. 1b. The smoothing is over a 3x3 grid mask with a weighting function of 1/4 for the central cell, 1/8 for the four neighboring cells and 1/16 for the four corner cells. The degree of freedom of the new spectrum is 18 as compared to 2 for the raw spectrum. The result of ensemble average of 7 consecutive image segments (14 degree of freedom) is shown in Fig. 1d. The spectrum obtained by both ensemble average (of 7) and bin average (of 9) is shown in Fig. 1e, which results in a reasonably smooth spectrum. In either case, the spectral properties of the dominant waves are easily determined from the two-dimensional spatial measurement of the surface elevation. The significant wave height calculated from the ATM data is 1.44 m. The peak wavenumber of this wave field (Fig. 1a) is 0.11 rad m$^{-1}$. The propagation direction is approximately 40° with respect to the flight track, which was almost perpendicular to the coastline. These are consistent to the buoy measurements (at 900 m offshore) of the significant wave height (1.30 m), peak wave period (6 s), and the northeasterly wind direction that generated this wave system. More detailed comparison with in situ measurements is in progress.

3.2. Distributions of breaking patches

As discussed earlier, when the laser is on, the ATM produces active ranging of the distance between the aircraft and the ocean surface. When the laser is off, the ATM optics receives a reading of the surface brightness. This is an equivalent to digitizing the picture of the ocean surface "on the fly." One application of these digital surface images is the discrimination of breaking patches from the background water surface. Statistical analysis indicates that the intensity distribution is gaussian-like. The mean and the standard deviation of the passive intensity data are calculated. The threshold is then set at a level corresponding to several standard deviations above the mean. At this stage, the determination of the multiplication factor for the threshold is empirical. A limited number of tests suggest that the magnitude of the multiplication factor to be between 2 and 4. Fig. 2 shows two binary images of the ocean surface brightness with thresholds set at 2.5 and 3.5 standard deviations above the mean. The two solid lines on each plot indicate the swath boundaries of the measurements. This is the same region as that of Fig. 1a, but plotted in the longitude and latitude coordinates. The region is approximately 35 km offshore at 30 m water depth. The time of the data acquisition was 09:35:16 to 09:35:36, September 24, 1997. The wind speed measured by the nearshore station at the pier end is about 9 m s$^{-1}$. The breaking percentage (here defined as the percentage of the water surface that appears brighter than the threshold) can be calculated from the binary images. For the two thresholds used in Fig. 2, the fraction of breaking surface is found to be 0.0063 and 0.0020, respectively.

The quantitative observation of wave breaking events has been a difficult task. The data based on the measurements of whitecap coverage [e.g., 6-8] typically show an order of magnitude scatter. The formula proposed by Wu [8] for the whitecap coverage is

$$W = U$$

where $W$ is the whitecap coverage and $U$ is the reference wind speed at 10 m elevation. For the 9 m s$^{-1}$ wind speed, the calculated whitecap coverage is 0.0064, in good agreement with the present processing of the passive binary image with a threshold of 2.5 times the standard deviation. The technique is promising for the study of breaking statistics in the ocean. The empirical threshold can also be compared with the corresponding measurements from video recording for further validation. This verification remains to be done.
coverage over a large area in a reasonably short time, there is much less variation of the environmental conditions during each flight mission. The quasi-steady conditions simplify significantly the data analysis. In addition to the investigation of the source and sink functions, and the spatial distribution of braking events, the spatial measurements are also ideal for quantifying the shoaling wave transformation.

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References

Fig. 2. Binary images of the ocean surface brightness derived from the passive scanning measurements. The corresponding ocean surface topography is shown in Figure 5a. The threshold is (a) 2.5 standard deviations, and (b) 3.5 standard deviations.

The binary image of the breaking patches (Fig. 2) provides both the statistical average and the distribution pattern of breaking waves in a given area. The image can be further combined with the ocean surface topography (Fig. 1a) to yield quantitative information of the breaking distribution with respect to the wave profile. Such information offers a great potential to enhance our understanding of breaking waves in the ocean.

4. Summary and Conclusions
The airborne scanning lidar ranging offers a significant capability for a high-resolution mapping of the wave field in the ocean. The resulting two-dimensional images of the ocean surface topography are ideal for the investigation of the wavenumber structure of ocean waves. The concept of applying the airborne spatial wave measurements to derive the source and sink functions in the energy balance equation has been tested with success with scanning radar data [9-11]. The resolution of the lidar data is at least one order of magnitude better than the radar data, and has been used to calibrate the radar data in the past. High resolution lidar data will extend the wavenumber coverage and increase the measurement precision.

In addition to active ranging, the scanning optical system collects passive images of the surface emissivity and effectively generates instantaneous digitization of the surface brightness condition. The breaking patches which show up as bright spots against the dark background of the ambient ocean surface. These images can be used alone or be combined with the simultaneously measured surface topography to study the wave breaking processes.

Because airborne systems provides continuous spatial