should be incorporated as complementary instruments, specifically in regard to ocean temperature measurements, salinity measurements, and inference of high windspeeds due to the presence of surface foam.

Parallel analytical and experimental efforts are recommended to establish the accuracy with which windspeed can be measured from the percent foam coverage.

PART C

LOCAL PHENOMENA

This section is devoted to the oceanic and coastal phenomena with dimensions ranging to 100 km. The two major categories discussed are waves (their generation and dynamics) and ocean-land related problems.

The dynamics of surface waves in both capillary and gravity ranges indicates that microwave technology provides a superior means of measuring simultaneously the spatial and temporal properties of ocean waves. The need for basic studies of physical phenomena in support of active microwave sensing is indicated. Active microwave scattering from surface waves is discussed in terms of wave dynamics. Ocean waves receive most of their energy from wind. The state of the art in wind measurements by conventional methods shows a gross inadequacy of present surface-sampling techniques for global weather and wave forecasting; microwave technology offers the potential to alleviate many of the problems. Global aspects of wind climatology are included in the discussion of large-scale phenomena in the section entitled "Global Wave Statistics." The subject of internal waves is relatively new and is less well understood in comparison with surface waves. Internal waves, even though they exist well below the microwave skin depth, are frequently detectable through surface manifestations such as convergence zone slicks, which have been visible in Earth Resources Technology Satellite (ERTS) imagery. Internal waves may also possibly be detected from surface temperature anomalies in the divergence zones. Thus, by monitoring surface properties with microwave sensors, a mathematical model for the prediction of internal waves might be developed.

The second category deals with the interaction between the ocean and its land boundaries in the coastal zone. The monitoring of shoreline changes is very important for coastal engineering and oil-drilling structures, beach erosion, coastal navigation, and recreation. The wave climate, the single most important parameter affecting coastal processes, could be monitored in great detail over large areas by satellite-borne active microwave sensors.

All these phenomena influence the ocean-surface structure in various ways, which are detectable by active microwave instruments. The signatures of signals obtained by such instruments and their relationships to oceanic and coastal processes provide an invaluable aid to understanding these processes.

WAVES

Human activities on the sea are very much influenced by waves, which damage structures and cargoes, change shorelines, and slow the progress of ships. A better understanding of waves and better wave predictions will benefit marine activities and yield concomitant economic benefits.

In the past, wave measurements have been difficult, and understanding of the generation, propagation, mutual interaction, and decay of waves on the ocean is based on several good oceanographic experiments. In the following paragraphs, the present understanding of wave spectra is outlined, and the ways in which microwave systems may facilitate wave measurement and how this might provide scientific and economic benefits are discussed.

Ocean waves may be defined as undulations of the surface with time scales in the range from 0.025 to 25 sec, corresponding to wavelengths in the range from 0.02 to 1000 m, respectively. These are subclassified as (1) gravity waves, with time scales in the range from 0.1 to 25 sec, length scales from 2 cm to 500 m, and heights to 30 m, or (2) capillary waves, with time scales in the range from 10^{-1} to 10^{-2} sec, length scales from 0.5 to 2.0 cm, and heights of less than 1.0 cm. Ocean waves are random, and a time record of the ocean-surface displacement in a storm region may contain wave periods in the entire range indicated earlier. Far from a storm center, waves become more organized as the longer waves propagate more rapidly out of the region. Long waves occurring away from storm centers are referred to as swells. Long waves approaching a coastline are influenced by the drag of the bottom and become shallow-water waves. Wave energy is eventually dissipated through breaking in an active near-shore area called the surf zone. Wave energy is also dissipated offshore through viscous effects and by breaking, which is evidenced by the presence of whitecaps. The processes of wave generation by wind; the transfer of energy between the various wave spectral components by wave-to-wave interaction; and the dissipation of energy by viscosity, breaking, and bottom effects are extremely complex and constitute a research area under intensive investigation by theoreticians and experimentalists.

The statistical properties of gravity waves vary slowly in time and space and can be described locally by a three-dimensional Fourier transform $F(k, \phi, \omega)$; that is, the sea surface can be considered as a superposition of waves of all wavelengths $L=(2\pi)/k$ and periods $T=(2\pi)/\omega$ traveling in all possible directions ϕ. Usually, the larger waves ($L>1$ m) are assumed to obey the dispersion relation applicable to infinitesimal amplitude gravity waves ($\omega^2=gk$). This reduces the dimension of the spectrum by one, and the resulting function is the directional spectrum $\psi(k, \phi)=\psi_1(\omega, \phi)$. The sea surface is now described as a superposition of plane waves with various wavelengths and directions. These wave components are generated by the wind, interact with other wave components, propagate away from their generating area, and eventually decay. Clearly, study of these processes requires a simple, routine method of measuring these individual components of the wave spectra. Such a method does not now exist.

Integration of the function $\psi(k, \phi)$ over all angles yields the one-dimensional spectrum $\psi(\omega)$. This is the more easily measured spectrum of sea-surface elevation measured at a point. Integration of $\psi(\omega)$ gives the variance of wave height at this point $<Z^2>$. This statistic is frequently reported in terms of the significant wave height $H_{1/3}$, which historically has been defined as the average of the highest one-third of waves present in a sea. More recently, it has been taken to be

$$H_{1/3}=4<Z^2>^{1/2} \qquad (3\text{–}13)$$

where $<>$ indicates ensemble average.

The statistics of the ocean surface, especially the statistics of wave-number distribution, are poorly known. In fact, $F(k, \phi, \omega)$ has never been measured. In discussing what is known about the various spectra, it is convenient to consider the simplest first.

From the wave-height variance, the rms wave height, $<Z^2>^{1/2}$, and significant wave height are easily estimated. Most data come from "eyeball" estimates of significant wave height reported by transient ships and, less commonly, from accelerometers on weather ships and buoys. Large amounts of data are available: atlases give wave climate over the world's oceans, wave height is routinely included in weather reports from ships, and wave height is routinely predicted by such groups as the Fleet Numerical Weather Central and the National Weather Service.

The one-dimensional spectrum is commonly measured with wave staffs or accelerometers mounted on buoys and ships. The general shape of the function and its relation to windspeed, duration, and fetch are reasonably well known for wavelengths greater than 1 m. Little is known of $\psi(\omega)$ in the region between 1 m and 1 cm because few measurements have been made. The equivalent function $\psi(k, \phi)$ is almost unknown for these wavelengths because the dispersion relation $\omega^2 = gk$ cannot be applied accurately to short waves. This has important consequences. Microwave signals are Bragg scattered by ocean wavelengths in this band, and lack of knowledge of the generating mechanisms of these waves hinders, to some extent, the application of active microwave systems that use sea scatter for inferring such factors as oceanic winds. Conversely, the Bragg scatter can be used to investigate this wavelength region of ψ.

The directional spectrum $\psi(k, \phi)$ is not well known. Measurements have been taken a few times in a few selected places, but the dependence on windspeed, duration, and fetch could be better described.

Capillary waves have been traditionally investigated by theoreticians and experimentalists with academic interests. More recently, and with the onset of microwave instruments as remote sensors, capillary waves have attracted more attention from a more practical point of view. The roughness of the sea is interpreted by the density and structure of capillary waves, which respond to windspeed. The detection of sea-surface roughness by active microwave instruments offers the potential of remote determination of windspeed.

Laboratory studies by Wright and Keller (ref. 3–36) indicate that Bragg scattering dominates radar return signals for angles greater than 20° from the vertical. The primary return is from capillary waves. The dynamics of capillary waves, therefore, assume central importance in understanding radar return at higher angles of incidence.

Capillary waves are sensitive to wind forcing, local currents, orbital velocities of long gravity waves, and changes in surface tension due to slicks induced by oil spills or biological activity. Laboratory experiments by Shemdin et al. (ref. 3–37) (fig. 3–23) indicate that a linear relationship exists between capillary wave slope energy ϕ_s and windspeed W for each frequency. A saturation level is achieved at a certain windspeed beyond which the slope energy remains constant. Higher frequencies achieve saturation at higher windspeeds. The same study (fig. 3–24) also indicates the influence of long waves on capillary waves at various windspeeds. These results provide an understanding of the scatter evidenced in relating windspeed to radar backscatter. Indeed, windspeed is only one of the variables that affect capillary waves, which in turn determine the magnitude of the backscatter.

Imaging radar has the capability of detecting long gravity waves and directions primarily because capillary waves vary in intensity along the profile of long waves. The variation is induced directly or indirectly by the orbital velocities of the long waves. The interaction between capillary waves and long gravity waves is nonlinear, and a com-

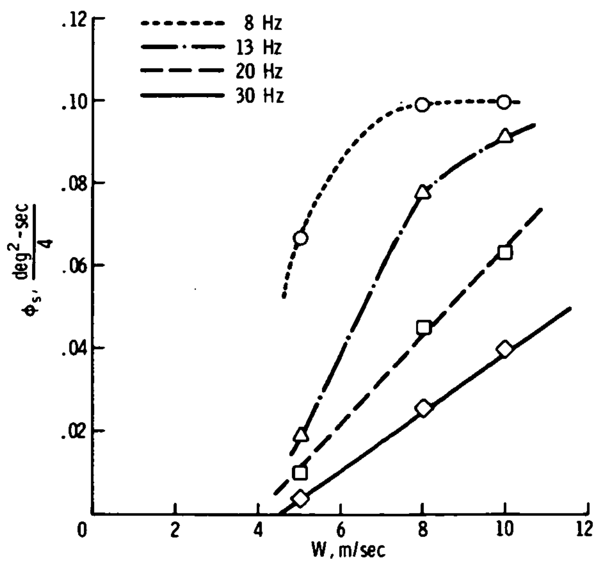

FIGURE 3–23.—Wind dependence of slope spectral values at different frequencies.

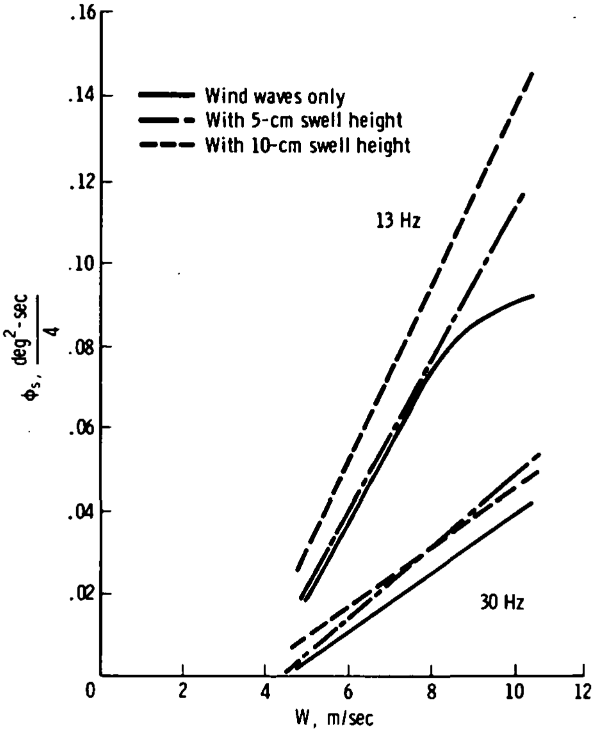

FIGURE 3–24.—Dependence of slope spectral values at 13 and 30 Hz on mechanically generated waves.

plete understanding of the process is under investigation. Presently, it is not evident how one may obtain heights of the long gravity waves from variations of the radar imager return from various phase positions along the profiles of the long waves. The remote determination of the directional wave spectra is of central importance to users involved in structural design and protection in coastal and offshore areas.

Microwave technology now provides a means of simultaneously measuring the spatial and temporal properties of ocean waves. This is far superior to the traditional methods of measuring the time history of water-surface elevation at a fixed position or the spatial distribution of waves from a photograph. The dynamics of wind-generated capillary waves as revealed by a Doppler radar mounted on a wave tank are far more complex than the traditional understanding based on hydrodynamics. The surface drift, for example, can increase wave dispersion by as much as 100 percent. The modulation of capillary waves by long gravity waves can be more easily investigated by active microwave instruments in a wide range of windspeeds.

For larger ocean waves, active microwave measurements are expected to produce routine estimates of significant wave height $H_{1/3}$ and of the directional wave spectrum $\psi(k, \phi)$. The dispersion of a high-resolution altimeter pulse gives $H_{1/3}$ directly. High-resolution real and synthetic aperture radars have shown images of waves. Suitable optical or digital processing is expected to yield the directional spectrum (or slope spectrum) of large ocean waves.

Satellite measurements of the directional spectrum of ocean waves are expected to have a number of important benefits to pure research, ocean engineering, and marine activities. First, development of the satellite instruments will lead to simple, reliable techniques for measurement of the spectrum. Given the development of such a technique, substantial benefits will accrue from the increased knowledge of ocean waves.

Wave forecasting models can benefit greatly by direct measurement of wind and waves with appropriate microwave sensors. Daily global coverage of areas of approximately 1000 km^2 will verify and update numerical models for forecasting wind and waves. Representative spot measurements over areas of approximately 5 km^2 will be more useful. Windspeed resolution of approximately ± 2 m/sec over a range up to 50 m/sec will be needed to cover storm areas. Measurement of wavelengths from perhaps 25 to 500 m and a resolution of 5 to 25 m will also be needed.

For pure research, measurements of the spectrum as a function of windspeed and fetch can be used to test theories of wave generation. To date, only a few measurements of wave growth have been published. Measurements near the edge of strong currents can test theories of wave trapping and refraction by current shears; the effect could be substantial but has never been measured.

Measurements made in conjunction with simultaneous oceanic internal wave fields can test theories for the generation of internal waves by surface waves; internal waves have often been measured. Internal waves affect the propagation of sound in the sea, but no generally accepted theory for their generation exists.

Routine measurements of wave size and direction will lead to reliable catalogs of wave climatology of benefit to marine engineering activities. A few examples can be listed as follows:

1. Offshore structures are designed to withstand the largest expected waves from a particular direction. Improved wave climatology will lead to more reliable, less costly, and safer designs.
2. The siting and design of breakwaters and harbors depends on the expected direction of arrival of large waves, and these data can be supplied by satellite.
3. Ships are often slowed and their cargoes damaged by large waves. If the oceanic wave field were known, ship routing predictions could be optimized for most economic operation. The wave field will be measured by satellite and its future development will be predicted from the improved models of wave generation that are themselves produced from satellite data.
4. The wave spectra are also important in more accurate forecasting of mixed layer dynamics, and hence the entire range of fluxes of heat, momentum, and energy between the ocean and the atmosphere.

As indicated, the dynamics of capillary waves have a central function in radar return from the ocean surface at angles greater than 10° from the vertical. Field measurements of capillary waves are extremely limited at the present time and must be developed. Recent laboratory measurements of capillary waves by Shemdin et al. (ref. 3–37) verify the existence of strong interactions between capillary waves and long gravity waves. Wright and Keller (ref. 3–38) more recently placed an X-band Doppler radar over the same laboratory facility and found that the return from the water surface is strongly modulated by the long gravity waves. Sufficient evidence already exists that suggests that radar return is governed not only by wind but also by all physical and dynamical factors that control the generation and decay of capillary waves.

The imaging radar detection of long gravity waves is another manifestation of the aforementioned observations. Although the wavelength and direction can presently be obtained from the imaging radar, wave height is not yet obtainable. Research into the dynamics of capillary wave modulation by long waves and the effect on surface backscatter may be useful in relating heights of long gravity waves to the modulation of the capillary wave backscatter over the wave profile. Photographic methods exist (ref. 3–39) by which directional wave-number spectra of long waves can be obtained. The aim must be to develop the methodology by which the imaging radar information can be treated as an all-weather "photograph" from which directional wave-number spectra can be extracted.

The full utilization of active microwave instruments for remote sensing will require a comprehensive program of basic studies of physical phenomena, evaluation of instruments, and comparisons with sea truth. The basic studies must include the response of instruments to wind and capillary waves in the presence of long gravity waves, currents, and surface agents. Field and laboratory programs will both help toward this end. Of paramount importance will be the availability of an adequately instrumented field station to monitor wind, capillary and gravity waves, currents, temperature, and surface tension. Airborne microwave instrument measurements can then be compared directly to the sea truth to delineate the various factors influencing the return.

The existing capability to predict ocean waves is primitive compared to what might be done subsequent to further development of satellite microwave instruments as remote sensors. The potential can only be realized in conjunction with numerical models, because the satellite coverage will not be frequent enough to monitor continuously the rapid changes normally encountered in storms. The periodic coverage will be best utilized to improve numerical models, which then become useful on an operational basis with continuous updating of new information.

WINDSPEED

From a historical standpoint, airborne remote sensing for oceanography began in January 1785 with the first balloon flight over the English Channel, from Dover, England, to the forest of Guines, France. However, the only remote-sensor system available at that time, and for a long time to come, was the human eye. The only observable phenomena probably seen on the sea surface by the observers were surface waves and whitecaps. At that time, the balloon flight itself was more important that any observations made. It is interesting to note that, once again, lighter-than-air craft are being considered as a platform for remote-sensing experiments.

In the early 19th century, technology had not yet advanced to the point at which instrumentation existed for the purpose of measuring windspeed and wave height. Probably the oldest and best known of the relationships between windspeed and wave height is the Beaufort wind scale (table 3–III) designed by Admiral Sir Francis Beaufort in 1805. The scale was based on the effects of various windspeeds on the amount of canvas that a full-rigged frigate of the period could carry. Table 3-III, a condensed modern version of the original Beaufort scale, describes the sea surface appearance as a function of windspeed.

With the development of the cup anemometer in the second half of the 19th century, (supposedly) accurate information on windspeed could be obtained. Although other, more accurate wind-measuring systems have been developed through the years, data from any windspeed sensor located on the sea surface should be considered with caution.

Ever since man has been able to estimate or measure windspeed and wave height, he has attempted to form some empirical rela-

TABLE 3–III.—*Condensed Version of Beaufort Wind Scale*

Beaufort number	Definition	Windspeed, m/sec	Description of effects on sea surface
0	Calm	Under 0.5	Sea mirror smooth.
1	Light air	0.5 to 1.5	Ripples present without foam crests.
2	Light breeze	2.1 to 3.1	Small wavelets; crests glassy but do not break.
3	Gentle breeze	3.6 to 5.1	Large wavelets; crests begin to break; occasional whitecap.
4	Moderate breeze	5.7 to 8.2	Small waves becoming longer; frequent whitecaps.
5	Fresh breeze	8.7 to 10.8	Moderate waves; many whitecaps.
6	Strong breeze	11.3 to 13.9	Large waves form; white foam crests more extensive; streaks develop.
7	Moderate gale	14.4 to 16.9	Sea builds up: streaks very noticeable in wind direction.
8	Fresh gale	17.5 to 20.6	Moderately high waves; well-defined streaks.
9	Strong gale	21.1 to 24.2	High waves; dense streaks.
10	Whole gale	24.7 to 28.3	Very high waves; sea surface appears white.
11	Storm	28.8 to 32.4	Exceptionally high waves; sea covered with large patches of foam.
12	Hurricane	32.9 or more	Air filled with spray and foam; sea completely white; driving spray.

tionship between the two. Probably the most famous of the studies was that of Sverdrup and Munk (ref. 3–40). For the first time, an attempt was made to relate windspeed to the significant wave height (the average of the one-third highest waves in a long sequence of waves at a given location) and predict the significant wave height at other locations from wind-velocity information. The significant wave-forecasting technique lends itself readily for computer application and, indeed, continues in operation on a daily basis by both the National Weather Service and the Navy's Fleet Numerical Weather Central. Unfortunately, the significant wave method is not able to fully describe what is occurring at the sea/air interface. For this purpose, the directional wave spectrum and momentum transfer rates are needed.

In the late 1940's, the English pioneered in experimenting with wave spectral processing, which led eventually to techniques for obtaining shipborne ocean-wave records with the Tucker meter. The wave spectral concept received added impetus from the superposition theory, which describes the sea surface as an infinite number of sinusoidal waves with different heights, periods, and phases all traveling in different directions. This theory is the basis for numerical prediction of ocean-wave spectra. Within 11 yr, many spectral forms were developed that purported to describe the limiting wave spectrum for a specific windspeed (i.e., a fully developed sea).

The fundamental requirement for producing accurate ocean-wave spectral forecasts is accurate wind velocity data over a dense data network. This data network is scarce at the present. In addition, the quality of available wind-velocity data is questionable. Numerous factors can adversely affect wind-velocity observations at sea as well as any unknown possible malfunction in the anemometer system itself. Some of these factors are the following:

1. Instrument sheltering: Mast-mounted anemometers could be sheltered by the mast and produce erroneous observations.

2. Anemometer height: Most anemometers aboard ships are not located at a standard height above the sea surface. Because windspeed does vary with elevation above the surface, windspeeds should be adjusted to a standard level.

3. Atmospheric stability: Atmospheric stability is important in determining how windspeed varies as a function of elevation above the sea surface. Stability is a function of sea-air temperature difference. Under neutral stability conditions, when the air and sea-surface temperatures are equal, windspeed varies logarithmically with elevation. This neutrally stratified air may range in thickness from a fraction of a meter to perhaps 1500 m in the extreme.

4. Ship motion: Ship motion will tend to truncate high- and low-windspeed estimates by changing the effective anemometer height; hence, the rougher the sea, the greater the effect. The wind-velocity vector must also now be corrected for the forward translation of the ship.

Windspeeds at sea are sometimes estimated by nonanemometer means such as the following:

1. Wind estimates from visual wave-height estimates: Observers would estimate the wave height and then correlate their observations with a windspeed/wave-height scale such as the Beaufort scale.

2. Whitecap density: The windspeed could be estimated from the percentage of whitecaps and foam present on the sea surface. Whitecap production begins with a 6- to 7-m/sec windspeed. At approximately 12 m/sec, the wind hurls the whitecaps downwind in the form of streaks.

3. Navigational estimates: Wind velocity could be estimated by vector addition from the position, heading, and drift of a ship.

Windspeed may also be inferred from the following other data:

1. Synoptic weather maps: Geostrophic and gradient winds may be estimated from surface weather maps where there are no ship observations.

2. Ocean-wave records: Windspeed may

be inferred from the variance of a wave spectrum obtained by spectrally analyzing an ocean-wave record.

From the previous discussion, one can see that the deficiency in oceanic wind data is due not only to technology but also to the paucity of ships at sea at any specific time. At no time are there more than six weather ships systematically obtaining ocean wave records on the world's oceans. Furthermore, there are no longer any weather ships flying the U.S. flag. The primary means for obtaining wave data at sea is by visual techniques. For the purposes of wave forecasting and describing what is occurring at the sea/air interface, visual wave observations are inadequate. A visual wave-height observation does not supply enough information. In addition, accurate visual wave-height observations are difficult to make in rough seas and at night.

The wave records obtained systematically at the six foreign weather ship locations have proved to be invaluable. Unfortunately, processing of these wave records for spectral content is delayed for as long as 30 days or more because each ship remains on station for several weeks and no processing facilities are aboard. Furthermore, not all the wave records are processed: those that are processed are not widely distributed and are mainly used for research. The processed wave records from the Tucker-type shipborne wave recorders yield only a one-dimensional spectrum. The most desirable method for ocean-wave prediction is the directional wave spectrum (i.e., the distribution of spectral wave energy with wavelength and direction). Although techniques exist for obtaining directional wave information, there remains no operational program (except in research experiments) for obtaining these data.

The orbiting of an active microwave sensor aboard a satellite has the potential for revolutionizing the methods by which global ocean wind and wave information are obtained and for improving the quality of presently obtained information. For both meteorologists and oceanographers, this could represent a great increase in the amount of global ocean wind and wave information to become available on a regular basis for both short- and long-range weather and wave prediction. The knowledge of Southern Hemisphere sea-surface conditions would improve tremendously, because little information is presently available from the Southern Hemisphere oceans by conventional means. Large-scale air/sea interactions between the Northern and Southern Hemispheres could be monitored and studied. Predictions of upper-air meteorological parameters would improve as a result of more reliable lower boundary (surface) input parameters. The total impact of an active microwave system orbiting the Earth cannot now be determined; however, the process of monitoring and forecasting the marine environment could be revolutionized by having such a system in orbit.

To provide the most meaningful information about global-scale ocean winds and waves, certain minimum specifications are required for parametric values (table 3–IV).

TABLE 3–IV.—*Sensor Specifications for Remote Sensing of Surface Winds and Waves*

(*a*) Deep Water (global)	
Surface winds:	
Velocity, m/sec	2 to 50 (±2 or 10 percent)
Direction, deg	0 to 360 (±20)
Field of view, km	20 by 20
Sample intervals, km	250
Waves:	
Length, m	50 to 500 (±25)
Direction, deg	0 to 360 (±10)
Height, m	0.5 to 30 (±0.5 or 10 percent)
Field of view, km	20 by 20
Sample intervals, km	250
(*b*) Shallow water (local)	
Surface winds:	
Velocity, m/sec	2 to 50 (±2 or 10 percent)
Direction, deg	0 to 360 (±5)
Field of view, km	3 by 3
Sample intervals, km	50
Waves:	
Length, m	50 to 500 (±25)
Direction, deg	0 to 360 (±5)
Height, m	0.5 to 30 (±0.5 or 10 percent)
Field of view, km	3 by 3
Sample intervals, km	50

Active microwave technology has not yet been proved capable of providing information over the entire windspeed range recommended. As a result, a complementary multifrequency passive microwave system should be part of the total sensor package aboard a given orbiting satellite. This system would allow more complete coverage of the required windspeed range, although greater complexity is necessitated by the inclusion of a passive system. The incident angle, polarization (preferably both horizontal and vertical), frequency, and atmospheric attenuation become important factors to be considered. Before operational deployment of such a combined system, a breadboard version should be tested aboard the Space Shuttle or as a scientific experiment aboard another satellite.

Information on global sea-surface conditions has many applications. Accurate sea-surface conditions are important to commercial fishing, both near shore and in the open ocean; naval operations; optimum-time ship routing; search-and-rescue operations; deep-sea and near-shore drilling operations; long-range weather prediction; hurricane detection, tracking, and prediction; near-shore recreational activities; and further scientific research. Within these major categories are numerous smaller categories. Essentially, a satellite system providing global wind and wave information on an operational basis will be immediately cost effective. Such a global ocean system has long been awaited by meteorologists and oceanographers.

INTERNAL WAVES

The existence of modes of internal oscillation in a stratified fluid has been known since the early part of the century, when such waves were postulated to explain the phenomena of "dead water" in Norwegian fiords. An internal wave is simply a trapped gravity wave propagating in a medium having vertical density variations, with the normal gravitational restoring force reduced by the buoyancy presented by the density changes. The dominant mode is a low-frequency, low-speed oscillation that exhibits very little surface amplitude but appreciable horizontal surface velocities.

Internal waves can be generated by a variety of mechanisms. Wind stress that excites a spectrum of surface gravity waves is one source; the surface waves scatter and form an interference pattern that is felt at depth, thereby generating an internal wave that propagates freely. Another mechanism is the scattering of tides by bottom roughness or depth discontinuities presented by the edges of continental shelves and island areas. A third mechanism is shear-flow instability caused by current systems such as the Gulf Stream.

The usual method for observing internal waves involves towing thermistor strings through the water to sense the associated temperature variations. Recently, Apel et al. (ref. 3–41) have shown that periodic surface slicks seen in ERTS–1 images serve to "tag" the underlying internal wave and thereby render them visible on a synoptic scale for the first time. Such slicks are probably due to the concentrations of oils arising from the convergence of wave-associated surface currents mentioned earlier. The oil damps the small capillary wave structure that is largely responsible for variations in the optical reflectivity of the surface. The periodic nature of the internal waves then leads to periodic surface slicks, which are a familiar sight at sea, especially on the Continental Shelf. In shallow water (200-m depth), these slicks usually appear in packets of a few kilometers in extent and consist of individual striations spaced at 500 to 1000 m. The slicks are generally oriented parallel to the local bottom topography.

Because changes in X-band radar reflectivity of the ocean surface result from essentially the same sources as do changes in optical reflectivity (i.e., capillary wave variations), one would expect internal wave-slick patterns to be visible to an imaging radar under conditions similar to those occurring for visible radiation.

Whether such waves have ever been observed on radar images is not known; nor is it readily apparent what frequencies, polarizations, or incident angles are needed. However, an estimate is obtainable from the variation in radar cross section with windspeed and incident angle. From unpublished curves of radar cross section available elsewhere in this study, one deduces that, for windspeeds below perhaps 5 m/sec, X-band frequencies at incident angles from 15° to 35° might be suitable. Resolutions of 10 m on the ocean surface should be more than adequate.

Further vague indications also exist that deepwater internal waves may leave very subtle signatures that might conceivably be visible with imaging radar. Observations of this sort would represent a significant advance in the understanding of an important oceanic phenomenon.

LAND/SEA INTERACTION

Land/sea interactions are most pronounced on the Continental Shelf and in the vicinity of islands. An estimated 90 percent of man's ocean activity occurs in water depths shallower than 30 m. In this region, the wave climate represents the single most important environmental factor affecting offshore planning and design. Tides and currents are equally important for navigation, fishing, and recreation. The Continental Shelf has a width scale of approximately 100 km and a mean maximum depth of less than 200 m. Around islands, ocean/land interaction can occur over a region 500 km along a given dimension.

Significant modification of the wave climate occurs in shallow water through shoaling, refraction, bottom friction, and breaking. In the presence of sharp discontinuities, wave diffraction is dominant in spreading the wave energy. Available procedures for wave forecasting are predominantly for deep water. The state of the art for extending deepwater forecasts to shallow water is in the embryonic stage. Isolated procedures exist for evaluating refraction and diffraction of simple waves. Attenuation of waves by bottom friction has been assessed with the aid of quadratic friction coefficients, which have been shown not to be completely satisfactory. Combined refraction and diffraction schemes have also been tried for single wave components. Directional spectra methods are being developed by the oil industry, but the results have not been published.

The use of remote-sensing methods can aid in providing significant information on the transformation of wave direction across a continental shelf. The return from a radar image can provide an all-weather photograph of waves over the entire region from deepwater to shore. Existing refraction and diffraction schemes can be verified. A low-altitude altimeter with a 3- by 3-km spot size can provide wave-height information along a path transecting the shore.

The catastrophic changes imposed on the shoreline by major storms in the coastal regions are obvious because the changes occur rapidly. Such monitoring of shoreline changes is particularly suited to observation by radar systems, which can assess shoreline damage and changes even before the storm has subsided enough to permit visual observation.

In addition to this use for storm damage assessment, aerospace radar systems are applicable to shoreline form analysis. During the last decade, there has been increasing scientific interest in alongshore variations in coastal processes and their relationship to rhythmic and crescentic beach morphology, shoreline erosion, and overwash processes. Efforts are underway to formulate the physical processes responsible for the alongshore variation; however, research is needed to characterize the beach features, their distribution in both time and space, and their relationship to erosion trends and overwash processes. Alongshore variations in coastal processes and shoreline form were not under investigation until the 1950's. Consequently, only recently have the effects of these dynamic features on the beach dune system been recognized. Aerial photographs of the coastline have assisted in this recognition. Radar imaging systems can extend the observation.

The study of shoreline form is far more than an academic exercise. Briefly, significant alongshore features of sandy coasts are cusp-like forms of that shoreline called shoreline sand waves, which migrate along the coast. The wavelength of the features range from approximately 100 m to 10 km. The larger sand waves are fundamental to the stability of the shoreline; therefore, the success or failure of the several types of costal engineering structures and facilities depends on an understanding and surveillance of these shoreline phenomena. The shoreline sand waves are part of a hierarchical pattern, the elements of which are often superimposed. These elements include (1) small cusps, or cusplets, only 1 m across; (2) beach cusps, which are up to tens of meters in length; (3) the shoreline sand waves, or giant beach cusps already mentioned; (4) secondary cusps spaced from 25 to 50 km; and (5) cusps spaced from approximately 100 to 200 km. Dolan has shown (ref. 3–42) that sand waves are important in focusing the destructive power of storm surges and storm erosion damage.

In addition, these sand waves migrate approximately 200 m/yr along the mid-Atlantic coast. Accelerated erosion (associated with the passage of a shoreline sand wave embayment) can severely damage a barrier dune (if one is present), cause the loss of valuable shore property, or destroy structures located too close to the shore. Passage of the sand wave point, or horn, leads to propagation of the beach. The point of focus of storm surge energy is gradually changed. Thus, the forecasting of storm effects must be modified in accordance with shoreline changes.

A significant advantage of radar imagery over visual photography is the acquisition of both shoreline shape and wave-energy spectrum information. Thus, the interactive system can be studied. The application of active microwave techniques to the coastal region is more extensive than the specific task of storm damage interaction and assessment.

Optimum use of remote-sensing instruments will require coverage over a 100-km-wide area with a 3- by 3-km spot size over 10-km intervals. Wavelength measurements are needed in the range from 25 to 500 m, with height measurements to 20 m. Wind measurements to 50 m/sec, with a resolution of ± 2.0 m/sec, are desirable to monitor storm propagation across the Shelf. In the vicinity of islands, somewhat larger coverage, spot size, and sampling interval would be useful.

Further improvement in remote-sensing capability can be achieved by the comparison of remotely sensed data with high-altitude photographs in good weather. The presence of directional wave gages will aid in interpreting results. Direct measurements can be used to test existing numerical schemes for wave transformation in shallow water and to develop new ones.

The derived benefits from improved shallow water wave climate data will be primarily in beach erosion prevention and minimization of hazards along the shoreline. The design and placement of offshore structures such as nuclear power plants, deepwater oil ports, and oil drilling rigs will also benefit.

INLAND AND ESTUARIAL WATERS

The objectives of a study done by D. E. Bowker of LaRC were to define the needs in the coastal zone related to the four LaRC-established national priority areas of pollution, fisheries, hazards, and geography/cartography. The approach to this study was to fund four independent contractors—The Virginia Institute of Marine Science (VIMS), Old Dominion University (ODU), TRW Systems Group (TRW), and Ocean Data Systems, Inc. (ODSI)—to study the problem. The results are summarized in appendix 3B.

PART D

LARGE-SCALE PHENOMENA

This section deals with oceanic phenomena with horizontal scales from approximately 100 km up to the widths of the oceans themselves. Their very size makes these phenomena difficult to monitor by surface-based methods, so that satellite-mounted active microwave techniques are especially valuable and may be the only way of gathering the information needed for scientific progress.

An important class of large-scale features consists of those concerned either directly or indirectly with the vertical topography of the ocean surface, estimated from the center of the Earth. This class includes the shape of the geoid, which is determined by the internal mass structure of Earth; the quasi-stationary anomalies due to spatial variations in sea density and steady current systems; and the time-dependent variations due to tidal and meteorological forces and to varying currents. These features are discussed in subsequent sections. All these features make use of the techniques of radar altimetry, although currents can also be studied by satellite tracking of floats.

Certain large-scale phenomena could, in principle, be usefully observed by satellite altimeters; however, it is unlikely that the necessary precision (approximately 1 cm) could be obtained in the near future. Steric variations in sea level, due to time-dependent changes in water density, notably at annual and semiannual periods, are known from shore-based tide gages to have amplitudes of less than 10 cm in most parts of the ocean. Tsunamis sometime reach meters of amplitude at a coastline, but in the open ocean where they would be most useful to measure, they merely consist of long waves of a few centimeters' amplitude and some tens of kilometers' wavelength. Prospects for detecting tsunamis by altimetry are discussed by Greenwood et al. (ref. 3–43).

MARINE GEODESY

Background

The primary function of geodesy is to determine the shape of the Earth by carefully measuring the geometric distance between points on its surface. For years, this approach seemed to be satisfactory because the surveyed areas were limited to portions of continental crusts and the measurements were not required to consider the micromovements of the solid Earth crust, which was considered as a perfectly rigid body. Problems related to the choice of a common reference datum for all those local determinations were approached through the use of a theoretical surface called the geoid, which is an equipotential of the Earth gravity field.

The geoid on land is not a physical surface; it is determined through a numerical process that involves the computation of an integral of gravity anomalies called the Stokes formula. The geoid on the oceans was long considered to be in coincidence with the physical surface of the sea (refs. 3–44 and 3–45).

During the last 10 yr, the problems of geometric geodesy have been extended to the open oceans mainly through the needs of accurate navigation and positioning. Marine geodesy has appeared as a separate scientific endeavor because most of the hypotheses of practical "land" geodesy were found to poorly match the physical properties of the ocean environment. At the same time, the accuracies of the available instruments for distance measurements were drastically improved so that movements of the crust of very small amplitude had to be considered.

Presently, serious difficulty is encountered in coping with the shape of the Earth per se, and marine geodesy must be concerned with four important surfaces (ref. 3–46): the physical surface of the Earth crust, the phys-