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# PRACTICAL SEAKEEPING USING DIRECTIONAL WAVE SPECTRA

During the past decade, ship drivers, owners, and designers have realized that knowledge of the prevailing wave environment can be put to good use in improving ship-seakeeping performance. The wave height is important, but ignorance of the wave length and wave direction(s) can have equally adverse effects on ship performance. This article identifies some sensitivities of ships to the wave spectrum and provides resolution requirements for engineering applications.

## INTRODUCTION

For decades, ocean-going Navy ship hulls had been designed merely to optimize calm-water performance. That is, ship hull forms had been developed to ensure maximum speed in calm water. Nearly 20 years ago, an attempt was made to consider ship performance in waves, i.e., seakeeping. Such early attempts resulted in less than optimum ships. Using the best advice available at the time, the Navy designed several classes of ships to maintain speed in a seaway defined by a Pierson-Moskowitz Sea State 5 spectrum. Thus, the ships were constrained to perform well in about a 3-meter unidirectional seaway with a fixed modal period. The result was that the ships were well tuned for a wave spectrum that may never occur in nature. Actually, lower sea states could (and did) cause much more excessive motions of the ships from other combinations of wave height, period, and direction.

About 10 years ago, the Navy decided to try again. By then, naval architects worldwide had adopted the Bretschneider two-parameter spectrum combined with a cosine-squared angular dependence to reflect directional spreading of the seas about a given, fixed primary direction. These spectra were initialized with wave heights and periods derived from visual observations from ships of opportunity. Thus, probabilities of occurrence were developed for the spectra by the joint occurrence statistics of the wave heights and periods. While this methodology was a vast improvement, it had the following faults:

1. Reliable global height and period statistics were unavailable.
2. Visual estimates of wave conditions were/are biased by the capability of the observers, ship size, shipping lanes, etc.
3. Swell-corrupted wind-generated seas were ignored.

In 1975, the Navy seized an opportunity to address these deficiencies. The Spectral Ocean Wave Model (SOWM), based on the theories of Pierson and his colleagues,[1] had been made operational at the Fleet Numerical Weather Center by Lazanoff and Stevenson.[2] The SOWM provided twice-daily forecasts of directional wave spectra throughout the Northern Hemisphere. Concurrently, Fleet commanders were calling for improved seakeeping performance. Too often, U.S. ships were just not able to keep up with NATO allies and Soviet counterparts. Figure 1 illustrates a ship pitching-and-slamming problem that clearly limits forward speed. The turning point came from the many research programs initiated as a result of a workshop held at the Naval Academy in 1975.[3] Some of the programs are identified in Ref. 3. Of prime interest here is the program proposed by the Environment Group, chaired by Cummins of the David W. Taylor Naval Ship R&D Center. The group, which consisted of naval architects, oceanographers, meteorol-

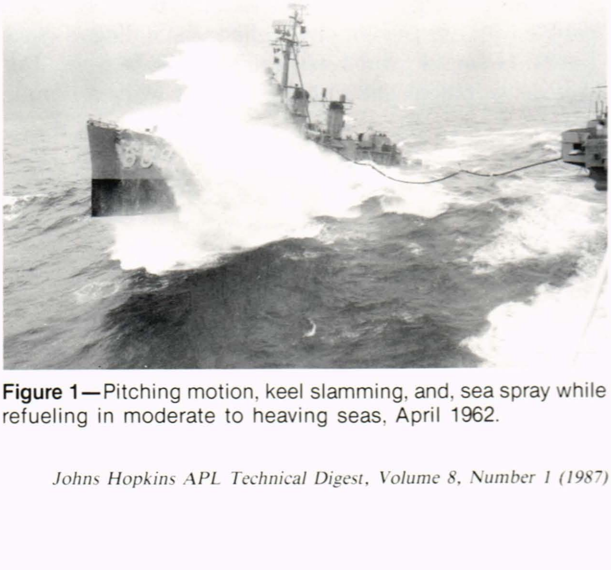

**Figure 1**—Pitching motion, keel slamming, and, sea spray while refueling in moderate to heaving seas, April 1962.

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ogists, and modelers, postulated the concepts that have become, in many cases, the state of the art. For instance, a massive wave-hindcasting effort resulted that has been reported in numerous papers, articles, and atlases (e.g., Ref. 4).

At present, the Navy has addressed, to some extent, all of the deficiencies. In ship design, the Bretschneider cosine-squared spectra are still routinely used, but they are initialized by hindcasted significant heights and modal periods. For specific investigations where multidirectional seas are critical, either Cummins' stratified sample of hindcast directional or other SOWM spectra are used. The SOWM has been replaced by a global version (GSOWM) implemented by Clancy, Kaitala, and Zambresky[5] in 1985. However, the Navy is still deriving great benefit from the SOWM hindcasts, and the GSOWM forecasts are now being used operationally with other sensors and models to analyze ship seakeeping behavior during ship deployments.

## DIRECTIONAL SPECTRA REQUIREMENTS

But more still needs to be accomplished. N. Bales[6] and Walden and Grundman[7] have clearly demonstrated that ship hull forms can be optimized to the seaway. In fact, acceptable operability in northern latitudes can probably be extended upward by several sea states by desensitizing the natural resonances of the ship hull to the estimated prevailing wave conditions. The engineering community has developed a highly sophisticated ship-motion program that requires a directional wave spectrum as the forcing function. Given the wave spectrum, most motions in moderate to heavy sea states are predicted to within ±10 percent accuracy when compared to towing-tank simulations.

The response amplitude operators (defined as the square of the ship-transfer function) are different for every ship and depend on its size, shape, appendages, hull form, and ballast condition. They also vary for every combination of speed and course relative to the prevailing seaway. In Fig. 2, it is obvious that the frigate (about 122 meters long) has substantially more response in pitch (the vertical angular motion about the center of gravity, as seen in Fig. 1) and at higher frequencies than does the aircraft carrier (about 274 meters long). Clearly, the wave spectrum (plotted on the lower portion of Fig. 2) that most closely aligns with the response function peak causes the greatest pitch motion. The wave spectra in the figure are Bretschneider unidirectional spectra for a fixed height but for varying modal periods.

A deficiency in ship motion prediction remains in the modeling of wave directionality. The cosine-squared law is still applied to spectra such as those in Fig. 2, occasionally using SOWM/GSOWM spectra, as mentioned previously. Figure 3 illustrates what is presently used versus what is really needed in order to achieve adequate information about swell-corrupted wind-generated seas. The importance of directionality is clearly illustrated in Fig. 4, where there is about a factor of two between predicted ship-rolling (side-to-side) angles for unidirectional (long-crested) and cosine-squared (short-crested) beam seas (seas traveling 90 degrees to the major ship axis).

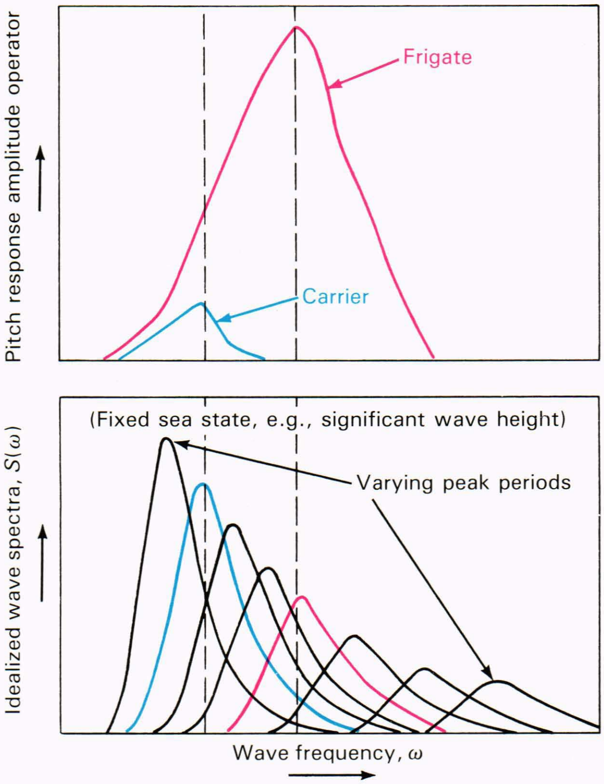
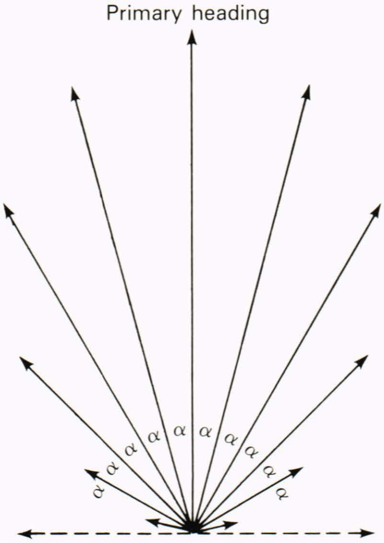


**Figure 2**—Prediction of ship response, e.g., rms pitch = $[\int \text{RAO}(\omega)\ S(\omega)\ d\omega]^{1/2}$.

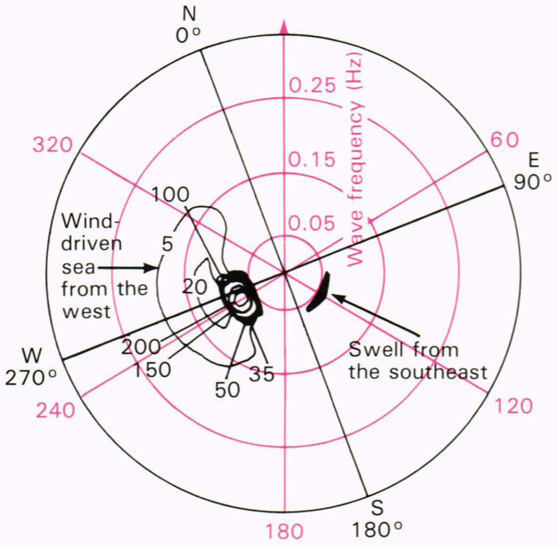
Another side of the problem lies in the operational application of directional wave spectra. Future tactical-decision aids require a good in-situ directional wave spectrum. The Navy's Tactical Environmental Support System (TESS) will require a reliable spectrum in order to predict ship responses. Required spectral resolutions are given in Table 1. These resolutions are based on the known variability of the ship's transfer functions, as illustrated for pitch in Fig. 2. Figure 5 shows some generic sensitivities to modal wave period as ship length and hull form are changed.

Several approaches could help achieve the data requirements of Table 1. It is not clear that ships at sea can depend on a single land-based forecasting system nor does a single spaceborne system seem to be emerging that could accomplish the requirements. The optimum is to have available data from a variety of sensors and models so that the tactician can select data to appropriate levels of complexity and resolution. Such a strategy might include the following elements:

1. Deploy a disposable wave buoy that, by telemetry, provides acceleration data to be rapidly processed (on board) into wave-height spectra. The current cost is about $4,000 per buoy, including antenna and receiver. Processing requirements are minimal. Total cost could probably be decreased to about $500.



Symmetric cosine$^2$
(applied to two-parameter
spectra of Fig. 2)



Swell-corrupted, wind-driven sea (SOWM)

**Figure 3**—Generic comparison of cosine-squared directional model against a more representative hindcast directional spectrum, showing a swell-corrupted wind-generated sea.

**Table 1**—Required directional wave-parameter resolutions for ship-response prediction.

| *Parameter* | *Resolution* |
|---|---|
| Significant wave height | ±0.3 meter for Sea States 4–7 (1.25–9 meters) |
| Modal wave period | ±1 second for waves from 3–24 seconds |
| Directional spreading | ±7.5 degrees for primary and secondary systems (or 15-degree increments about the compass) |

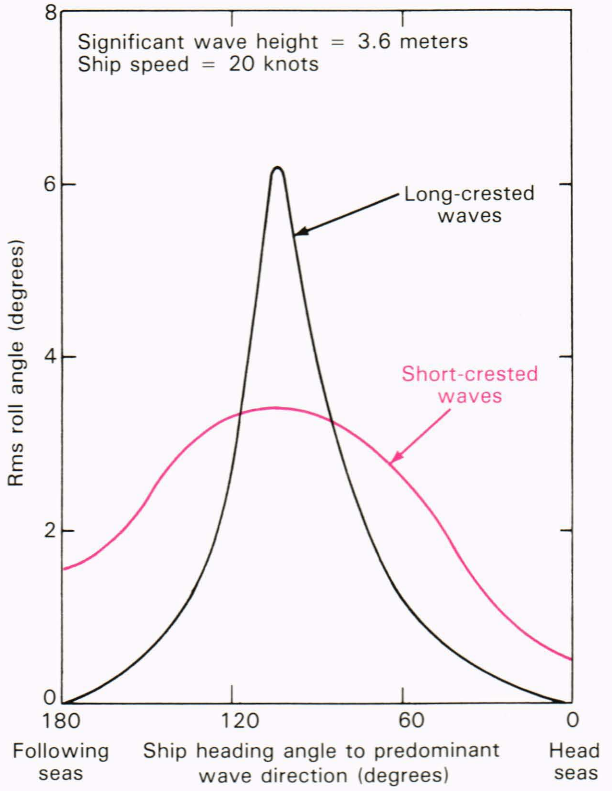


**Figure 4**—Comparison of predicted rolling (side-to-side) motion using Bretschneider long-crested and short-crested sea models.

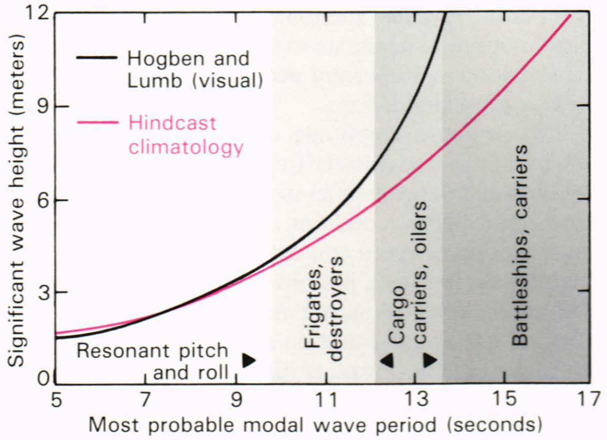


**Figure 5**—Significant wave height versus the most probable modal wave period showing ship pitch and roll resonant period ranges.

2. Use the disposable wave buoy together with the shipboard navigation radar (e.g., the SPS-64) to get direction information as well. Trizna and his colleagues at the Naval Research Laboratory are currently exploring this technique.
3. Deploy an Endeco/Datawell or other portable directional wave buoy. Costs range from $15,000 to $80,000 and are related to buoy size and the required spectral resolution.
4. Use space or aircraft remotely sensed data. Geo-

sat altimeter wave-height data appear to be the only hopeful sign for the United States in the near term, with the delays in the Shuttle Imaging Radar Program and the recent (December 1986) apparent demise of the Navy Remote Ocean Sensing System. It is clear that the United States now lags both Japan and Europe in a national space–oceanography program, particularly one to support military environmental-monitoring requirements. Routine deployment of aircraft sensors has not yet been established as a requirement. But from the Navy battle group viewpoint, aircraft sensors may offer a viable alternate to some spaceborne systems, particularly for timely local weather forecasting.

5. Use properly validated GSOWM and other land-based forecasts of directional wave spectra. In a statistical sense, we have found the SOWM/GSOWM data to be quite reliable, and, on some occasions, individual forecasts could be used to provide meaningful guidance to the ship driver. Figure 6 is a speed polar-graph for a ship that encountered high waves in the Northeast Pacific. Here, the concentric circles represent ship speed in increments of 5 knots. The radial lines represent ship-to-wave relative headings. The ⊗ represents the operating condition of 17 knots in port bow seas, a condition in which severe damage was incurred by the 8.2-meter waves. The wave forecasts agreed well with the ship observations. The red area represents conditions posing a 95 percent probability of damage, while the yellow area represents conditions posing more than a 5 percent probability of damage. If this wave forecast and speed polar-graph had been available to the captain, he would have quickly seen that a slight (30-degree) change of course to port would have drastically reduced the potential of damage to the ship. It is planned to incorporate these types of tactical decision aids into the Tactical Environmental Support System.

The usefulness of Fig. 6 is obvious, but the forcing function or directional seaway must be well defined to predict ship motion. Figure 7 illustrates a North Pacific case where buoy and GSOWM data are compared and

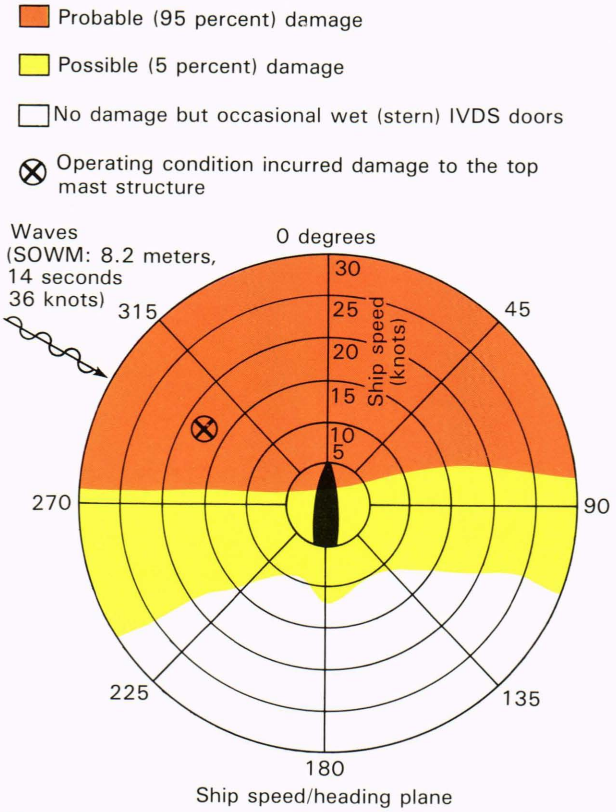


**Figure 6**—Speed polar-graph of a ship operating in the northeastern Pacific on March 8, 1974, where a heading change of about 30 degrees would have reduced the probability of damage by 90 percent; speed changes would have far less impact, if any.

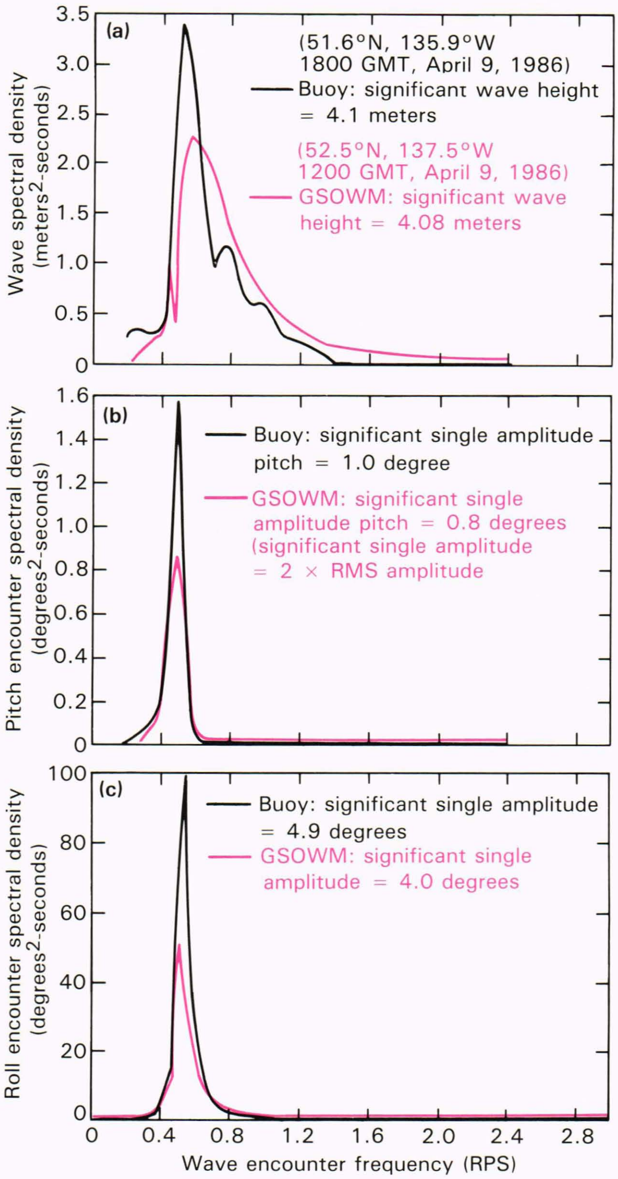


**Figure 7**—Comparison of GSOWM and buoy measurements and motion predictions for an aircraft carrier. The agreement between spectra permits a good forecast of ship motion.

the resulting pitch and roll motion is computed for an aircraft carrier. The Delft Disposable Wave Buoy, a standard for developing wave-height spectra, was deployed along a ship's route. The GSOWM forecasts were taken for the closest temporal and spatial GSOWM gridpoint. The point spectra (Fig. 7a) agree well with the forecasts, and the resulting predicted pitch and roll responses (Figs. 7b and 7c) are also comparable to the predictions.

Figure 8 provides a comparison during the same ship transit when the measured and forecast spectra differ. The GSOWM spectrum contains substantially more energy than that derived from the buoy vertical-acceleration measurement, resulting in a substantial difference between the two predicted ship responses. These differences could be even larger for a frigate, which has more response in the modal wave-frequency region of the wave spectrum. Analytically derived ship-response transfer functions were used to develop both Figs. 7 and 8.

Wave forecasts can also be useful even when they are at variance with measurements of the local area. For example, GSOWM wave heights can be scaled by Geosat altimeter wave heights. During recent ship trials in the Northwest Pacific, the forecast wave period and directions agreed well with those observed by experienced personnel and with those derived from ship-motion measurements. However, the forecast wave energy of the GSOWM directional spectra appeared to be too high. Figure 9 provides a comparison of these data during December 16–18, 1986. The darkened circles represent the Geosat versus GSOWM significant wave heights. The colored lines approximate the error associated with the altimeter heights as derived by Monaldo.[8] In general, the GSOWM data for the period indicate a 30 percent higher significant wave height than what was measured. If the two points with a distance greater than 100 nautical miles between the grid point and the overflight point are excluded, the GSOWM data indicate a 22 percent greater height. The conclusion here is that in some cases the GSOWM spectra can be scaled by simple height data to develop a directional wave spectra. Other comparisons of forecast and Geosat data have recently been reported by Pickett.[9]

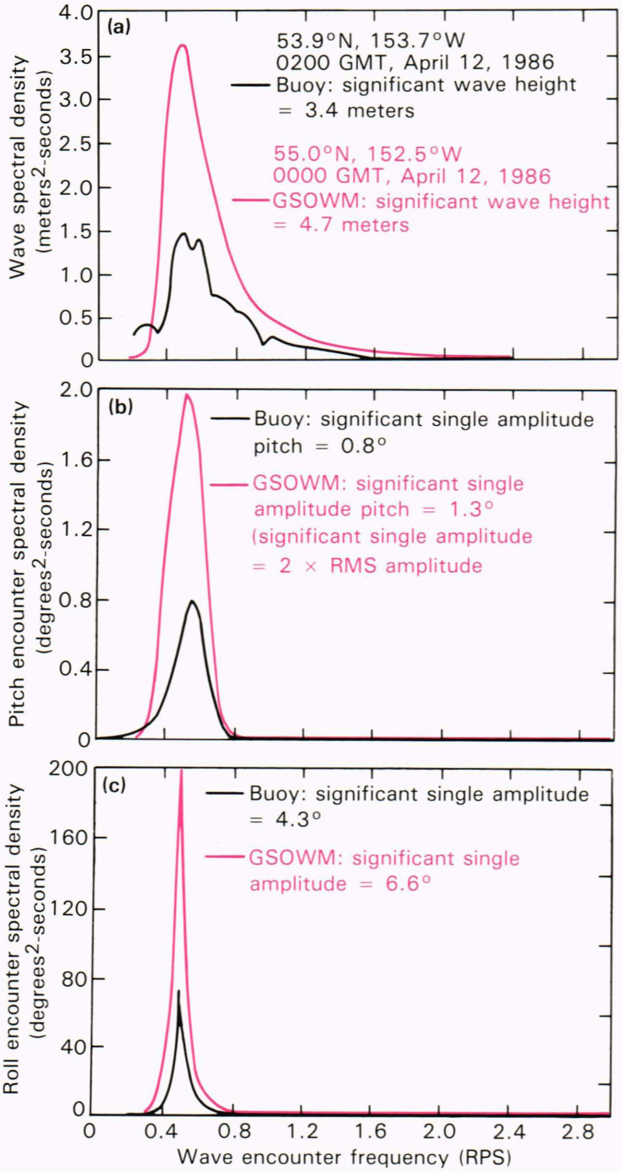


**Figure 8**—Comparison of GSOWM, buoy measurements, and motion predictions. The disagreement between spectra provides a poor forecast of ship motion.

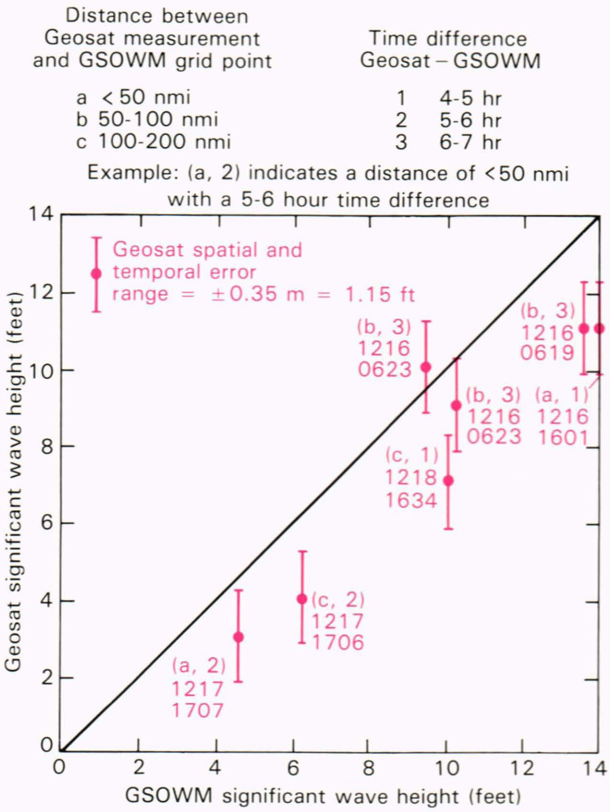


**Figure 9**—Comparison of Geosat and GSOWM significant wave heights in the northwestern Pacific for December 16-18, 1986. The comparison generally shows that the GSOWM forecasts are somewhat high. 1217 1707 = date and time of Geosat; December 16-18, 1986.

## CONCLUSIONS

This article has established some of the practical applications for which accurate directional wave spectra are required. The spectral resolutions required for practical ship applications have been identified, though it is expected that they will be achieved only in incremental steps. From the engineering viewpoint, climatological data are generally sufficient. They can be developed by hindcasting techniques or by global wave measurements, although the latter can probably be achieved only by means of spaceborne sensors. Spaceborne altimeters such as those on Seasat and Geosat appear to provide adequate estimates of wave heights. These height estimates can be used to "tune" land-based global models or sea-based regional models and measurements. It is not yet clear that space sensors such as the synthetic aperture radar will provide the full directional wave-energy spectra. The article by Beal in this issue describes some of the limitations of synthetic aperture radar at the shorter wavelengths of interest. Further measurements and intercomparisons in realistic sea states should help resolve this question.

Naval engineers must take advantage of every technological edge in order to gain even the slightest improvement in seakeeping. A better knowledge of the prevailing wave environment will improve operability. Additionally, real-time measurement of global wave conditions could vastly improve forecasting products available to the Fleet. But to counterbalance the vulnerability of satellites, it is essential that both in-situ and shipborne sensor development be accelerated. With the recent cancellation of the Navy Remote Ocean Sensing System program, these alternative approaches take on added importance.

With regard to national responsibilities, joint agency programs are required in the areas of sensor development, data assimilation into models, and model validation. A critical problem here is in identifying areas of responsibility. Such national programs should be reflective of NASA's fundamental science interests, the Navy's interest in improving Fleet readiness and operability, and NOAA's interest in supporting commercial fishing, offshore industry, and the civilian population in general. Such programs can be established only through careful interagency negotiation and cooperation.

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