# MWAVES – Software for Calculating the Directional Spectra and Statistical Properties of the Wave Field from MAVS-3 Triplet Measurements

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## Abstract

**Real-time knowledge of the directional spectrum and other statistical properties of the wave environment in coastal waters and harbors is critically important information for those involved in marine operations. Historical and real-time wave and tide statistics are also important for coastal engineering applications and for investigations of coastal processes. The spectral and statistical properties of the wave field can be calculated from accurate time-series of "triplet" measurements, either the three horizontal and vertical components of the velocity or the pressure and the two horizontal components of the velocity. MAVS-3, the 3rd generation of the Modular Acoustic Velocity Sensor, can make the necessary velocity vector and pressure measurements. Additionally, MAVS-3 can telemeter the measurements to shore in real-time and/or store them internally for later processing.**

**Accurately and reliably calculating the spectral and statistical properties of a complex stochastic process is, however, inherently a non-trivial task. This paper describes MWAVES, a software package that performs these calculations and presents the results to the operator in easily interpreted graphical and numeric forms. The kernel of routines that perform the calculation is fast and the graphical user interface through which the operator controls processing is full-featured and easy to use. A time history of the evolving statistical properties of the wave environment can be logged and plotted and all graphs can be stored in standard formats for later recall. MWAVES was developed for use with MAVS-3 data, but it has been successfully used with MAVS-2 measurements and can be applied to the triplet measurements of other instruments.**

## I. Background

Directing marine operations in harbors and coastal waters requires real-time knowledge of the directional wave spectrum and other temporal and statistical characteristics of the wave and current velocity field. Real-time and historical wave and tide statistics are also important for coastal engineering projects and for the investigation of coastal processes such as the erosion and deposition of sediments. The starting point for calculation of the spectral and statistical properties is an accurate velocity or velocity-pressure time-series.

Time-series velocity measurement using MAVS, the Modular Acoustic Velocity Sensor, is well established [Thwaites and Williams 1996, Williams and Tivey 2001, Rowsell and Skafel 2002, Williams 2002]. Williams and Terray have shown that the spectral and statistical properties of the wave field can be calculated from integrated MAVS time-series measurements of velocity and pressure [Williams and Terray 2000]. In that demonstration study, pressure and horizontal velocity "triplets" recorded by a rigidly mounted, near-bottom MAVS, were post-processed to determine directional and non-directional wave height spectra for Buzzards Bay, Massachusetts, during February of 2000.

While determination of the spectral and statistical characteristics of the wave field has been demonstrated, the calculation itself remains non-trivial, both numerically and for practical reasons. Consider, for example, that the wave-current velocity and pressure fields are complex stochastic processes that attenuate hyperbolically with depth as functions of wavelength, water depth, and height above bottom; measurements are typically made well below the surface and are not free of noise. Mapping the measurements to the surface will be numerically unstable in some formulations and must be band-limited without losing real information about the wave environment. Without suitable algorithms, setting those limits would require operator intervention during processing.

The need of marine operations personnel, coastal engineers, and oceanographers, however, is for reliable, automated calculation of the spectrum and statistics from the measured time-series. The ability to intervene manually is desirable, but a compulsory assessment at each processing step is not. Because marine operations personnel must make decisions in real-time, it is also important that the calculation is fast and that the results are presented in an easily interpreted form. Nobska has developed MWAVES directional wave spectra software to address these needs.

The operational features of MWAVES and the underlying algorithms on which the calculations of wave spectra and statistics are based are described in this paper. For clarity, the processing of a single burst of measurements will be used as a framework for the description.

## II. Loading Data Files and Sample Parameters
## The Load Control Frame

Processing is directed and controlled by the operator through the MWAVES Control Panel (Figure 1). The tools in the upper left frame of the Control Panel, the Load Control Frame, are used to select and Load a folder containing ASCII formatted MAVS-3 data files. The selected folder should also include the system configuration and deployment definition files, config.dat and deploy.dat. These binary system files are created by the instrument prior to deployment [see Morrison 2000-2002 for a description of MAVS-3 operation and terminology]. Load is run automatically on the default directory, C:\MAVS3, at startup. Load can be triggered manually by clicking the Load button.

During Load, in addition to detecting and displaying the data files, MWAVES reads config.dat and extracts the software version number and the content and arrangement of the numeric columns in the data files. MAVS-3 is a full-featured instrument that can make and log velocity and auxiliary measurements (date, time, conductivity, temperature, pressure, optical back-scatter, compass, tilt, etc.) in many possible combinations. Automatic recognition of the contents and format of the data files across all released versions of the MAVS-3 system control program relieves the operator of a significant burden.

MWAVES then reads deploy.dat to extract the sampling schedule. Again, this relieves the operator of a burden and ensures that accurate timing information is passed to the kernel of routines that perform the frequency domain and statistical calculations.

MAVS-3 instruments are commonly programmed to sample in regular bursts [Morrison 2000-2002]. For example, time, raw acoustic paths, Earth Cartesian velocity, temperature, and pressure might be sampled at 4 Hz with 5000 records in each burst (~20 minutes per burst) and a burst every two hours. Operators of both MAVS-3 and of MWAVES must be aware that MWAVES processes individual bursts of data to obtain spectral and statistical information. It is, therefore, of fundamental importance that the MAVS-3 operator collect data that are to be processed using MWAVES using a statistically meaningful sampling schedule. Measurements should be made fast enough to avoid aliasing the waves (1-2 Hz minimum). There should be enough samples in the burst and the burst duration should be long enough to allow for reasonable spectral resolution and confidence intervals (4096 records and 10 minutes minimum). Longer bursts also improve the resolution of lower frequency motions. Conversely, the burst duration should not be so long that the stochastic process being measured can no longer be considered stationary (30-60 minutes maximum). There is no one sampling schedule that is optimal in all situations; many environmental, technical, and practical constraints must be considered when choosing sampling parameters. A generally reasonable selection is 4 Hz sampling with a 20 minute burst each hour. Modification of this schedule, particularly the burst interval, to address actual or expected conditions or the requirements of a research or monitoring program, is suggested.

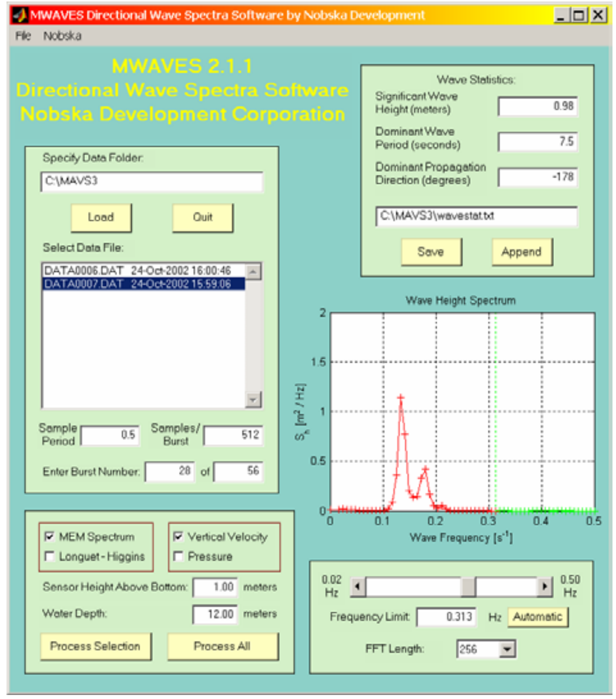


FIGURE 1 – The MWAVES Control Panel

MWAVES reviews the sampling schedule during Load. It will warn the operator if the parameters limit the reliability of the statistical analysis and continue processing at the discretion of the operator. In extreme cases, fewer than 256 records in the burst or sampling slower than 1 Hz, for example, MWAVES will simply reject the data and terminate processing.

Once Load is complete MWAVES will display a list of MAVS-3 ASCII data files from the selected folder. The operator is notified if the folder does not exist or no data files are found. In the latter case, if raw binary data files are found, the operator is prompted to run MAVSPack to unpack them. Files, each of which typically contains multiple bursts, are selected for processing with a mouse click. A double click will display the contents of the file using Notepad, the Windows text editor. MWAVES makes a temporary copy of the data file for Notepad to display; the data can be examined without risk of deletion or modification.

The sample period, the expected number of samples per burst, and the expected number of bursts per file are displayed near the bottom of the Load Control Frame once Load is complete. Operator actions during data acquisition may mean either of the latter quantities is incorrect. For example, the operator may have terminated the deployment in the middle of a burst and with only a few bursts in the last data file. MWAVES checks for such conditions when it loads a data file into active memory and begins processing a burst; the display is updated and any necessary steps to maintain processing integrity are taken.

Before leaving the Load Control Frame the operator selects one of the data files and enters a burst number. Alternatively, the Process All option will sequentially select and process each burst in each file in the list, displaying the results and logging a record. The time-series plots produced by this automatic loop are indexed and can be searched. A mouse click on a point with a high significant wave height, for example, will display the associated data file and burst number. This utility allows the operator to quickly identify bursts of interest. Process All is a good first step when beginning the analysis of a large data set.

## III. Burst and Process Selection<br>The Process Control Frame

Burst processing is triggered from the Process Control Frame, the lower left frame of the Control Panel. MWAVES can calculate directional wave spectra using either the maximum entropy method (MEM) of Lygre and Krogstad [Lygre and Krogstad 1986] or the approach of Longuet-Higgins [Longuet-Higgins, Cartwright, and Smith 1963]. The Longuet-Higgins directional spectrum is generated by calculating the first five Fourier coefficients of the angular distribution of energy in each frequency band directly from the measurements. In contrast, MEM estimates the Fourier coefficients by fitting the data to a model of the process that is complex Gaussian and stationary. MEM estimates exhibit greater angular and frequency resolution than either Longuet-Higgins or the maximum likelihood method (MLM) [Lygre and Krogstad 1986]. Arguably, Longuet-Higgins estimates retain more of the raw information contained in the measurements. Both approaches use autocorrelation sequences computed from the measurements at lags greater than or equal to one, so the resulting directional spectra are normalized; the integral over the angular range of each frequency bin is one. MWAVES subsequently weights the result with the wave height spectrum to produce directional wave spectra with units of $m^2$/Hz.

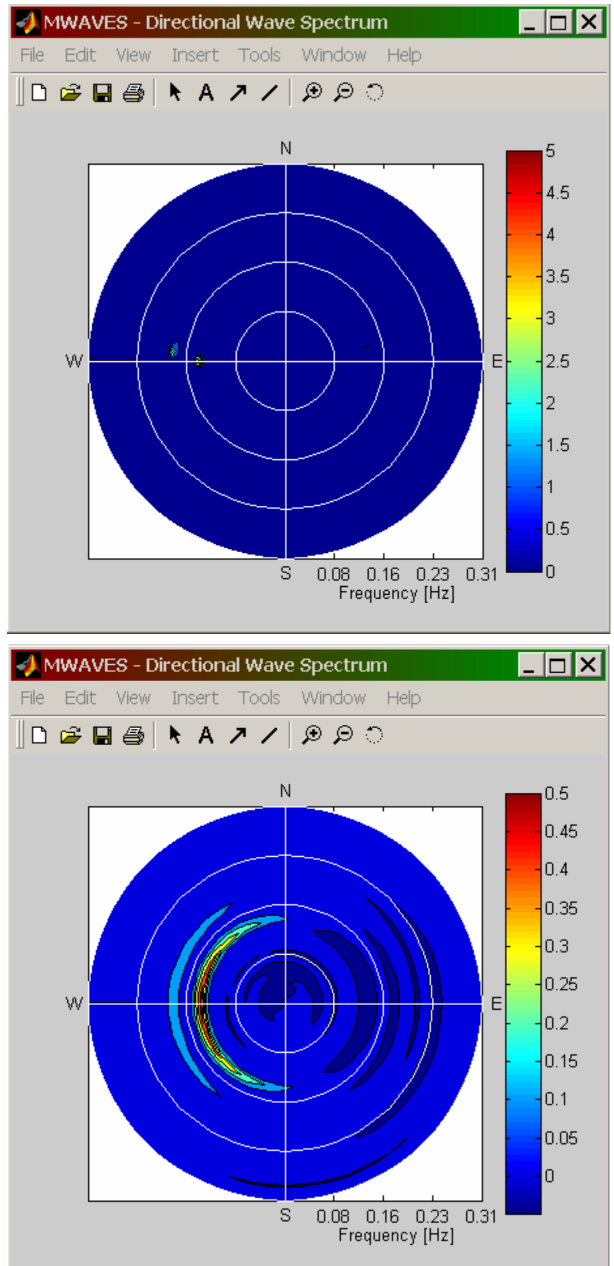


FIGURE 2 – Comparison of MEM and Longuet-Higgins Directional Wave Spectra. The plots were generated by MWAVES using a common burst of measurements. The burst was acquired near the western end of Lake Ontario beginning at 0400 on 15-Dec-2001. In this polar presentation, one of several MWAVES options, angle is the direction of wave propagation. Primary compass directions are marked. Wave frequency increases with radial distance from the center and relative intensity (wave energy ~ amplitude$^2$) is indicated by color. The spectra indicate that waves with periods of 5.5 seconds and 7.5 seconds (0.18 and 0.13 Hz) were propagating westward. Note the different distributions of wave energy calculated by the two approaches.

The most obvious characteristic of an MEM estimate of the directional wave spectrum is the extent to which wave energy is localized in both frequency and direction. In comparison, a Longuet-Higgins spectrum is “smeared” over a much broader range of frequency and direction. Examples are shown in Figure 2. From the Process Control Frame the operator may choose either approach or, as here, apply both to the data and compare the results.

With MWAVES, the calculation of directional wave spectra can be based on measurements of horizontal velocity and pressure [Williams and Terray 2000] or on measurements of the horizontal and vertical velocities. Recall that horizontal velocity and pressure attenuate with depth and wave number as $\cosh(k(z+H))$, where $k$ is the wave number, $z$ is the sensor depth, and $H$ is the water depth. Both quantities remain non-zero near the bottom.[1] The vertical velocity, however, attenuates as $\sinh(k(z+H))$, and becomes vanishingly small when the measurement is made close to the bottom. Even when not identically zero, the vertical velocity may be below the practical resolution limit of the sensor, ~1.0 mm/s for MAVS-3, when the horizontal velocity is still measurable.

In recognition of these physical characteristics of the velocity and pressure signals associated with surface gravity waves, MWAVES chooses pressure, by default, if it is available in the data. The operator retains the option of selecting velocity for the calculation. The system prevents manual selection of pressure if it is not available; vertical velocity is always available in MAVS-3 data. Importantly, when the calculation of the autocorrelation sequences does not use pressure, the magnitudes of the vertical and horizontal velocities are internally compared. The vertical velocity is preferred, but only if its standard deviation is at least half that of the horizontal velocity. Near the bottom, where the signal to noise ratio is worst, MWAVES automatically selects the clearest signal.[2] There are also practical concerns of numerical computation that suggest the same or similar preferences. The equations that describe the physics of the flow have been structured in the MWAVES kernel to be numerically robust and stable.

Measurements made at some depth are mapped to the surface during burst processing using linear wave theory. This operation is an essential part of the calculation of the non-directional wave height spectrum and the significant wave height. The calculation can only be made if the sensor and water depths are known. Sensor depth is available from the data if pressure has been recorded, but not otherwise. Water depth is never part of the data. When horizontal velocity and pressure are selected, the operator must enter the height of the sensor above the bottom. MWAVES will calculate the water depth as the sum of sensor height and mean pressure. When the horizontal and vertical velocities are selected the operator must enter both the sensor height and the water depth in the Process Control Frame.

MWAVES now has all the information necessary to select a burst from the data, determine the directional and non-directional wave spectra, and calculate the statistical properties of the wave field. The operator can click Process Selection (or Process All) at the bottom of the Process Control Frame. MWAVES will load the selected data file into active memory and extract the selected burst.

Before passing the burst to the kernel, a quality check detects and rejects bursts with an unacceptably high percentage of flagged measurements. Such flags typically indicate that the sensor was not in the water when the burst was recorded.

Finally, MWAVES assembles the velocity or the velocity-pressure triplet expected by the kernel. As previously noted, MAVS-3 is a full-featured instrument that can log and present velocity measurements in a variety of formats. MWAVES will use the Earth Cartesian velocity (East-North-Up) when it is available in the data stream. In the absence of Earth frame measurements, MWAVES will automatically construct them from instrument frame velocity or acoustic path measurements using compass and tilt measurements. Lacking compass and tilt, MWAVES will calculate the directional spectra in the instrument frame from velocity or path measurements and leave the rotation into the Earth frame to the operator.

Thus prepared, the burst is passed to the MWAVES kernel.

## IV. The MWAVES Kernel

The MWAVES kernel is based on the approach of Williams and Terray [Williams and Terray 2000]. However, it has been enhanced with a number of new capabilities and features. Importantly, the pipeline of kernel routines executes quickly and requires no intervention by the operator.

To begin, the triplet time-series is passed through an iterative, standard deviation filter. Data that fall outside

[1] The pressure variation is consistent with linear wave theory all the way to the bottom. In contrast, the horizontal velocity is consistent with linear wave theory only down to the top of the wave boundary layer and zero at the bottom. The thickness of the wave boundary layer is O(1 cm), however, so the distinction is not relevant for MAVS-3 sensors.

[2] The phase of the vertical velocity is retained to resolve the ambiguity in the direction of propagation.

a 3-sigma threshold at each iteration are replaced with linearly interpolated values. Power spectra and cross power spectra of the filtered triplets are calculated using Welch's averaged periodogram method. The FFT length is set by the operator and the sequences are zero padded as necessary. The sequences are weighted using a Hanning window and are not overlapped. The autocorrelation sequences for lags 1 and 2 are formed from the power spectra. The bandwidth at this stage is half the sampling frequency (Nyquist limit). This is subsequently hard limited to 0.5 Hz, a 2-second wave.

Depending on the Process Control Frame selection of the operator, the power spectrum of either the horizontal velocity or the pressure is mapped to the surface. The transfer function assumes linear wave theory and is structured for numerical stability and robustness. The result of the transfer is the non-directional wave height spectrum, $S_h$, which has units of $m^2/Hz$.[3]

Energy may be present in the high frequency bins of the power spectra due to aliasing or to noise or to actual motions of the water that may or may not be related to surface gravity waves. The exponential character of the transfer function will preferentially amplify this energy and the resulting wave height spectrum may not accurately represent physical reality. This is a common problem when the non-directional or directional spectra are calculated from measurements made well below the surface. Solution can be difficult and may require a subjective judgment to discriminate between real and false signals. MWAVES permits two approaches.

On the right side of the Control Panel (Figure 1) are a plot of the wave height spectrum and, at lower right, the Bandwidth Control Frame. After a burst has been processed, the plot displays the wave height spectrum up to the hard limit at 0.5 Hz. However, a limiting bandwidth, marked by the vertical dashed green line and the color change of the spectrum, excludes the potentially problematic high frequency bins from the calculation. After the wave height spectrum is calculated and the limiting bandwidth is applied, it is only information within the selected frequency bins that continues to propagate through the pipeline. For example, the significant wave height and the directional wave spectrum are calculated only for frequencies below the bandwidth limit.

That limit can be set by the operator using the tools in the Bandwidth Control Frame or by clicking on the plot of the wave height spectrum. Either action toggles the system to manual mode and fixes the bandwidth at that frequency. Manual bandwidth selection is one of the two approaches permitted by MWAVES. The default approach, however, is automatic mode, an algorithm that dynamically sets the bandwidth for each burst as it is processed. The operator can toggle between the automatic and manual modes by clicking on the Automatic/Manual button in the Bandwidth Control Frame. The dashed line marking the current bandwidth limit is green in automatic mode and red in manual mode.

The algorithm is relatively simple and has to date proven reliable when applied to field data. First, the power and wave height spectra are mildly smoothed with a 2nd order, zero phase shift, Butterworth low-pass filter. The cutoff frequency is 0.25 Hz. Then a finite number of peaks, exclusive of the endpoints, are located in the filtered power spectrum and the frequency of the first minima beyond the highest frequency peak is identified. It is important to detect and trap any of several possible pathologies related to spectral shapes during these steps. Finally, the associated minima in the wave height spectrum, which may occur at a lower frequency because of the transfer function, is located. Again, it is important to detect and trap any of several possible pathologies. The frequency of this minima in the wave height spectrum is the limiting bandwidth.

A noise floor is calculated as the mean value of the power spectrum for frequencies above the limiting bandwidth. Note that the power spectrum is calculated directly from the measurements, whether of velocity or pressure, and has not been amplified by transfer to the surface; this is a reasonable approximation of the actual noise floor. The noise floor is subtracted from the power spectrum and it is re-mapped to the surface. Any negative values that result from the subtraction of the noise floor are assigned a value of zero (after the calculation of the significant wave height). Finally, the frequency limit is applied to the corrected wave height spectrum, the power spectra, the cross power spectra, and the autocorrelation sequences.

The final stages in the pipeline are the calculations of the directional wave spectrum and the statistical properties of the wave field. The normalized directional wave spectrum is calculated using MEM or Longuet-Higgins and the result is weighted using the wave height spectrum (with noise floor removed and negative values assigned a value of zero) to produce the directional wave spectrum with units of $m^2/Hz$. The statistical properties of interest are the significant wave height, $H_{1/3}$, the dominant wave period, $T_P$, and the dominant direction of wave propagation, $\theta_P$. The significant wave height is defined by

$$H_{1/3} = 4\sqrt{\sum_f S_h \delta f}$$

where $f$ is the bandwidth and $\delta f$ is the bin width. The

[3] A ratio of 0.9945 m/dbar is assumed when converting from pressure to meters.

dominant period and direction are simply the period and direction of the highest peak in the spectrum. These three quantities are displayed on the Control Panel in the Wave Statistics Frame (upper right frame).

## V. Data Presentation and Storage

The statistical properties displayed in the Wave Statistics Frame can be saved in or appended to a text file using the tools at the bottom of the frame. The Process All option creates a complete time-series of these parameters for all of the bursts in the data files and stores it in the named text file. Process All presents this information in a searchable plot showing the evolution of the wave field over time. An example is shown in Figure 3. The significant wave height is shown for all bursts, however, the dominant wave period and propagation direction are shown only for bursts in which the calculated dominant wave period is less than 25 seconds.

Three plots are produced for each processed burst. One of these is the polar presentation of the directional wave spectrum shown in Figure 2. The directional spectrum is also presented on a rectilinear frequency-propagation direction grid (Figure 4). Wave energy is indicated by color. The third plot is the wave height spectrum, bandwidth limited and plotted as a function of the wave period. An example, which can be compared to the wave height plot on the Control Panel in Figure 1, is shown in Figure 5. The plots can be saved, collectively or individually, in any of several standard image formats or sent directly to a printer.

Calculations of the evolution of the wave field over time and selected directional and non-directional wave spectra will be useful to coastal engineers and those studying coastal processes. For marine operations, the polar presentation of the directional spectrum provides a complete and easily interpreted overview of the wave field. Coupled with the wave height spectrum and the significant wave height, the presentation allows a rapid assessment of the severity of the conditions. New features are still being developed, but MWAVES is ready now to become an asset to these communities.

## VI. Continuing Development

A number of enhancements and new features are currently planned for future releases. In response to feedback from potential users, an additional "front end" will be added so that MWAVES can process the triplet measurements of other velocity and velocity-pressure instruments.

Very importantly, the ability to accept and process a data stream in real-time will be added. In this mode,

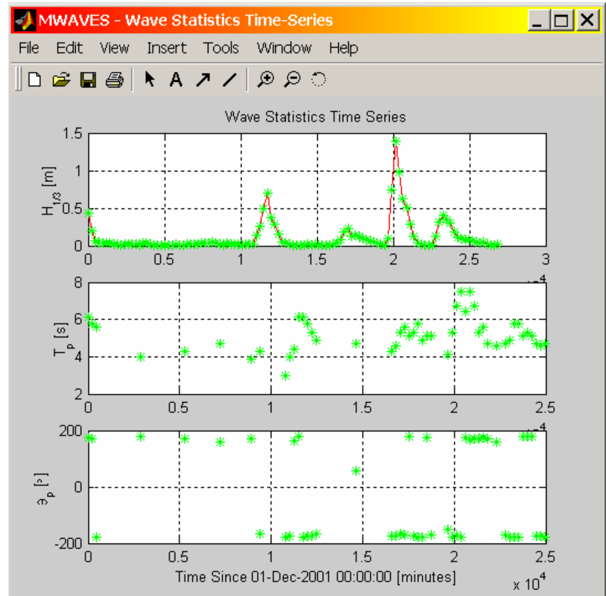


FIGURE 3 – Evolution of the wave field

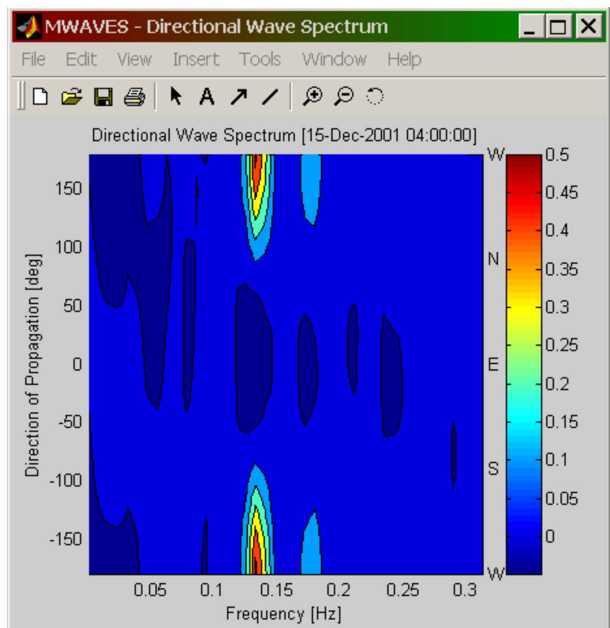


FIGURE 4 – Rectilinear presentation of the normalized directional wave spectrum. The spectrum was calculated using Longuet-Higgins and may be compared with the lower panel of Figure 2, which shows the same result in the polar format.

ASCII text records arriving at the serial port of a PC from a remote sensor will be accumulated in "bursts" of operator defined length. The burst length will define a sliding window so the spectra can be updated at intervals that are independent of the burst duration.

Other visible changes will include a contour plot showing the evolution of the wave height spectrum and the optional creation of a movie of the directional wave spectrum. Indications will be added to the directional wave spectra to show the magnitude and direction of the average current during each burst. Less visible will be a low frequency limit for the significant wave height. This will prevent low frequency flows unconnected to the motion of surface gravity waves from biasing that calculation.

For data sets that include both pressure and velocity, it will become possible to display both wave height spectra on a single plot. This is a convenient sanity check on the calculations and provides an indication of the relative noise floors of the two sensors. Plots of the wave height spectrum will also be marked with confidence intervals. Confidence intervals depend on the number of realizations into which a burst is divided and must be balanced against the need for some minimum level of spectral resolution. For many the preferred adjustment parameter is not the FFT length , but the number of degrees of freedom. A degrees of freedom/spectral resolution control will be added to a later release of MWAVES.

Finally, a long term goal is tracking the evolution of wave systems as they change in strength, spectral content, and direction over time [Gerling 1992].

### Acknowledgments

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My thanks also to Gene Terray of the Woods Hole Oceanographic Institution. Gene authored the kernel routines, a seminal contribution the importance of which cannot be overstated.

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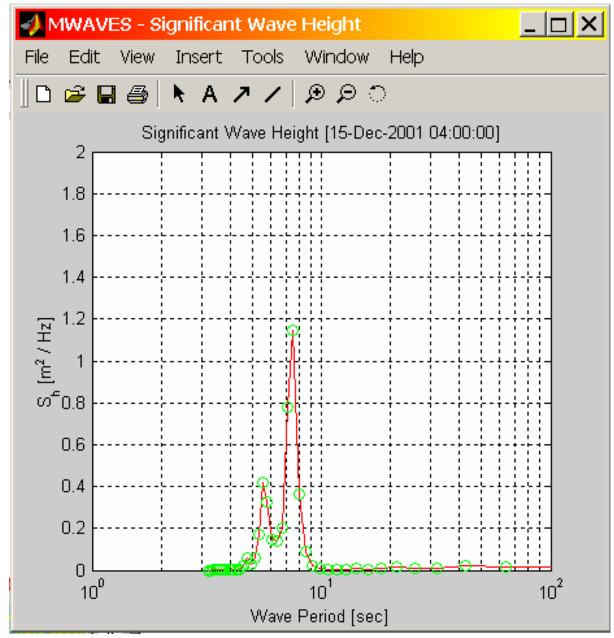


FIGURE 5 – Non-Directional Wave Height Spectrum

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