Introduction

This *WaveExtract* software is designed to process wave data collected on one of several of Nortek's instruments. *WaveExtract* supports data collected from the *Vector*, *Aquadopp Profiler*, and *Aquadopp*; and uses PUV processing for these instruments. The wave height, period and spectra estimates are based on the pressure (P) signal and the wave directional estimates are based on the wave's orbital velocity (U and V) measurements.

This easy to use program simply reads in the data file and outputs the results from each burst measurement in the form of two files. The first output file contains the estimated wave parameters such as wave height, period, and direction. The second output file provides the wave frequency spectra. Since there is no graphical presentation of the results and limited input requirements, it represents Nortek's simplest solution to post processing of wave data. The user needs to only specify the file to be processed and the distance the instrument was off the bottom.

This documentation provides an overview of how estimates are performed, defines the output estimates, and indicates how to avoid some of the common mistakes *prior* to the data collection exercise. Since each instrument has its own setup, it is critical that the following text is well noted for successful deployments and the subsequent wave processing.

This following text is broken down into the following sections (1) PUV background, (2) Deployment Planning, (3) Wave Processing, (4) and the Appendices which describes wave mechanics in greater detail.

Figure 1 Nortek family of PUV instruments*, Aquadopp, Vector,* and *Aquadopp Profiler*

How the PUV Method Works

Collecting wave data with Nortek's instruments utilizes a well known approach known as the PUV technique. More specifically, waves are measured using their associated dynamic pressure (P) and orbital velocities (U and V for the *x* and *y* directions). The pressure signal is utilized to estimate the frequency spectrum. This energy in the spectrum is then used to estimate wave height and period. The measurements of the waves' orbital velocities provide us with an estimate for the wave direction.

Since these estimates are based on the wave energy distribution and are not a direct measure of the free surface they are considered inferred estimates. The process by which we arrive at wave estimates from the energy distribution requires special attention to the transformation process.

Both the dynamic pressure and orbital velocities are driven by the surface waves. The signals associated with these properties are complicated by the fact that they attenuate exponentially with depth. The exact behavior of the attenuation has to do largely with the depth of the water and the wavelength. In a nutshell the behavior is as follows, (1) as we move down in the water column the signal is increasingly attenuated, (2) as the wave length decreases (shorter period or higher frequency) the signal again experiences increasing attenuation. The take home is that waves become more difficult to estimate when they are measured from great depths or the waves are short in period. The exact mechanics is described in greater detail in Appendix A.

The above explanation of signal attenuation is exactly why we are both depth *and* frequency limited when measuring waves. The table to the right provides a general guideline for the limitations of the measurable waves with regard to depth, frequency, and height.

Table 0 Minimum measurable wave heights for several different Depth and Peak Period senarios.

Depth	Peak Period	H_s
20	5,8	0,75
20	6,4	0,60
20	7,2	0,35
20	8,3	0,30
20	10,1	0,20
15	5,0	0,50
15	5,5	0,40
15	6,2	0,25
15	7,1	0,20
15	8,7	0,15
10	4,1	0,40
10	4,5	0,30
10	5.0	0,20
10	5,8	0,15
10	7,1	0,10
5	2,9	0,20
5	3,2	0,15
5	3,6	0,10
5	4,1	0,07
5	5,0	0,05
3	2,3	0,12
3	2,5	0,10
3	2,8	0,05
3	3,2	0,04
3	3,9	0,03

Deployment Planning

Knowing the frequency limitations and having a sense of the waves that are to be captured is critical to determining the instrument's depth and ultimately successful data collection and post-processing. Therefore we aim to achieve a 'Target Depth'. This is a deployment depth for which we capture as much of the wave spectrum as possible with the greatest amount of accuracy.

Prior to deployment, one must consider the target waves to be captured. Knowing the types of waves the instrument is likely to be exposed to makes it much easier to decide upon a deployment depth. For instance, will you be measuring large waves in the Pacific Ocean or within a sheltered bay? Keep in mind what the peak period is expected to be and the depth that this wave is measurable (See Table 1).

For the Pacific, I would begin with the assumption that the waves have the potential to be several meters high and the peak period would be approximately 10 seconds. After consulting Table 1, I would target the deployment depth at 15 meters.

For a bay or sheltered body of water, I would expect the peak period to lay around 5 seconds and height not to be too great. Therefore it is advisable to deploy the instrument in 5-10 meters of water.

When selecting the number of samples in a burst, the sampling should be set up such that the wave record is "well sampled." This generally means the burst is greater than 15 minutes in duration. This can easily be achieved if the instrument is set to 1 Hz and 1024 samples, or 2 Hz and 2048 samples. This provides over 17 minutes of data and both examples are encouraged setups.

Requirements Particular to Each Instrument

Vector:

The *Vector* has the greatest sampling options since it can sample at 1, 2, 4, 8 Hz, etc. However note that if one is only interested in measuring waves then it is probably not necessary to sample any higher than 2 Hz. Therefore the upper limit for the length of the data record is 2048 samples. This is due to the fact that the PUV approach can not detect waves much higher than 1 second in period due to the attenuation effects associated with the deployment depth and wave frequency.

Setting the instrument up for wave data collection is performed in the Deployment Planning dialog box. Here you will find the option of collecting data continuously or in burst mode. In order to use the WaveExtract software the instrument must be set in burst mode. The number of samples should be set to 1024, 2048, or a number consistent with the chosen sampling rate to ensure over 15 minutes of data is collected.

It is also suggested to set the nominal velocity to no more than +/- 1.0 m/s; where the associated horizontal velocity range is 2.1 m/s (the horizontal and vertical ranges are provided in the Deployment Planning dialogue box). The orbital velocity associated with large waves can reach this speed in shallow water. This may be adjusted downward if waves are expected to be small, or adjusted upwards if waves are expected to be exceptionally large.

Keep in mind that the location of the pressure sensor is located where the stem is connected to the unit. This is the location from which one measures the distance off the bottom. It is later entered as a parameter for the wave processing.

Special consideration must be taken when using a Vector with a cabled transducer array (opposed to the firmly attached stem type). For the cabled type, it is critical that during deployment the instrument's array relative to its body (cylinder) is the same as it is with the *Vector* with the stem. This is because the internal tilt sensor determines up or down, and ultimately ensures that the correct coordinate system is used for the directional estimates.

Aquadopp Profiler

Similar considerations should be used here as was done with the *Vector*. However here we have fewer sampling rates to choose. The location of the pressure sensor is at the transducer head and therefore the location from where to measure the mounting height.

When setting up the Aquadopp Profiler for wave measurements, the user must select the "Use Advanced Settings" within Deploy Plannning. Once in advanced settings, check the "Wave Burst" box. Again the setup should be chosen such that the data collection period is over 15 minutes.

Note that when specifying the number of samples and measurement interval, one shoule take into consideration that both current and wave measurements are made in turn (or cycle). Therefore there must be enough time to make a wave and current measurement for each interval. A warning message will appear if there is a conflict.

Since the Aquadopp Profiler measures waves using the current cells above it, care should be taken to ensure that the cell does not touch the surface. The measurement volume begins 0.5 meters above the transducer head and ends at a distance two times the cell size. The user has the option to choose the cell size to use. It is advisable to choose a cell size as close to 2 meters as possible, where the limitation should only be proximity to the surface and power usage.

Aquadopp

Similar considerations should be used here as was done with the *Vector*. Here we have fewer sampling rates to choose. The location of the pressure sensor is at the transducer head and therefore the location from where to measure the mounting height.

When setting up the *Aquadopp* for wave measurements, the user must select the "Use Advanced Settings". Then once in advanced settings, check the "Diagnostics" box. The Aquadopp uses a sampling rate of 1 Hz so it is encouraged to use 1024 samples. **NOTE:** the first sample in the burst is the noise floor and therefore not used in the wave measurements. This means that the number of samples must be set to 2^n+1. For example the number of samples could be 513, 1025, or 2049 (n = 9,10,11).

Deployment Considerations and Cautionary Notes

The PUV approach is based on linear wave theory; occasionally situations arise where linear theory is no longer valid and second order effects become increasingly significant. Such situations occur when one attempts to improve the instrument's response by placing it in increasingly shallower water. Long waves in shallow water become *solitary*, and hence have a nonlinear profile that is not accounted for by the PUV transformation. The result is that waves are properly sensed but the wave height is slightly underestimated.

Perhaps the most difficult aspect of classifying sea state via spectral based estimation is the realization of wave energy at high frequencies. These types of spectra prove to be quite tricky. Amongst the problems are the errors in the calculation of moments and cutting off peaks at higher frequency. One scenario is that an instrument placed in 15 meters of water may never detect the energy up above 0.25 Hz.

Usually we aim to classify the incident wave field and therefore it is critical that we deploy the instrument in a location that exposes it to an incident wave environment that is undisturbed by its surroundings. Some neighboring structures that influence the incident waves could include piers, breakwaters, unusual changes in bathymetry, as well as rivers (or exposure to high currents). Such structures affect the local wave field (reflections, diffraction, refraction, evanescent modes, etc.) and are not the best representation of the incident wave field. For example an instrument deployed in front of a breakwater would be exposed to the combined incident and reflected waves. The PUV approach does not have the ability to separate these two fields. Therefore close proximity to any of the above listed is discouraged, unless of course the object of the data collection exercise is to measure the locally influenced wave environment at the particular location of deployment.

Things that can go wrong

The instrument is not setup in burst mode. If data was collected in continuous mode and not in the diagnostic/burst mode, then the data can not be processed with WaveExtract.

If the deployment depth is too great then it may difficult to measure small, short waves. Be mindful of the limitations listed in Table 1.

Once deployed, care should be taken to keep it away from anything that can affect the magnetic field (e.g. iron), and hence influence the internal compass.

When selecting a depth one should also include any local tidal variations in the expected operating depth. The cell size should be chosen so the beam never touches the surface.

WaveExtract: Steps in Data Processing

The processing software has been designed so that there is minimal input required from the user. The only necessary input parameter is the distance the pressure sensor is off the bottom. This means the distance from the pressure sensor to the ocean bottom.

The WaveExtract software has four options for processing methods. The default method is the PUV method. Obviously the method for PUV should be chosen if not already. Other options are available for processing of other data types.

The pressure and compass offsets are simply available to adjust for possible biases (e.g. local magnetic declination). There is also a checkbox for "waves to" in the event the user wants to output the directions "from". The default wave direction for the output is the direction the waves are traveling "to".

Aside from these parameters, all the user needs to do is "add files" and then initiate processing by clicking on "Go".

Output format

There are two output files, one which outputs the wave estimates and the other outputs the wave spectra. The estimate output file (*.wap) is present in the form of a table with the estimates for each of the burst measurement. These estimates are defined as follows:

Time Stamp	(Month, day, year, hour, minute, second)
Significant Wave Height	(Meters)
Peak Period	(Seconds)
Mean Period	(Seconds)
Direction at Peak	(Degrees)
Spreading	(Degrees)
Mean Direction	(Degrees)
Unidirectivity Index	(Dimensionless)
Error Code	(See text on Error Messages)

In addition to the wave parameters, the frequency spectrum is also output in a separate file (*.was). The first row is the frequency vector and the subsequent rows are the spectrum for each of the bursts. The spectrum is based on the pressure signal and output in units of meter^2/Hz.

The specific setup for the instrument can be viewed in the header file (*.hdr). In addition to specifics about the instrument and its setup, there is a listing of the data types output (as listed above).

MatLab users may find the three scripts "GetWAP.m" , "GetWAS.m", and "PlotWAP.m" a useful starting point for extracting and plotting the wave estimates from the *.wap and *.was files. The MatLab scripts are bundled with WaveExtract.

Error Messages

Presently we have incorporated into the processing some simple checks on the data quality. If the burst of data has one of these errors, it will be indicated in the output file by an error code (listed below). If the burst is in error then the estimates are set to a value of "-1". After processing has been completed, a message box will appear if there are any errors. Within this message box the number of errors and their types will be listed.

The quality checks include the following with the corresponding error code. A value of *0* indicates no detected data errors.

No Errors (0)
Processing of burst was successful and had no detectable errors.

No Pressure (-1)
This would appear if the pressure is too low, and indicates that the instrument was most likely out of the water or unreasonably close to the surface.

Low Pressure (-2)
This error suggests that there was no dynamic pressure detected in the time series, and means that the waves are not measurable (i.e. a constant pressure). This would occur if the instrument was deployed at a depth that is too deep to measure the waves or simply that there were no measurable waves.

Low Amplitude (-3)
This indicates that the amplitude of the Doppler signal was too low to measure the orbital velocity.

White Noise Test (-4)
This test is to determine if the estimated spectrum is purely white noise. Such a spectrum does not contain information about the surface waves.

Unreasonable Estimate (-5)
If it appears that there is an unreasonable estimate then the burst is flagged as bad.

Never Processed (-6)
The wave processing cleans up some corrupt data (ie checksum errors) however if number of bad points exceeds 10% of the burst data, then the data is not processed and it is tagged with this error message. Usually this error message suggests that the wave burst was incomplete or damaged

Appendix A

Wave induced properties

Waves on the ocean surface are clear to us all, however less obvious are the subsurface dynamics generated by these waves. Beneath the surface, waves generate an orbital motion as they pass by a point (indicated in Figure 2). The motion associated with the waves penetrates down into the water column. The ability to measure these dynamics below the surface allows for us to interpret the waves on the surface and therefore provides the means to estimate many of the wave parameters that are commonly used to describe a sea state, such as height, period, and direction.

Nortek provides three instruments (*Aquadopp, Aquadopp Profiler,* and *Vector*) which allow one to use the 'PUV' technique to measure waves. The 'PUV' approach for estimating wave height and direction measures both the dynamic pressure and the velocity in two directions (orthogonal), U and V.

As a wave propagates there is an induced particle motion. The trajectory of this motion is presented in Figure 1. Additionally there is also dynamic pressure that is associated with the combined effect of the vertical acceleration and the change with depth of the water column (Figure 2).

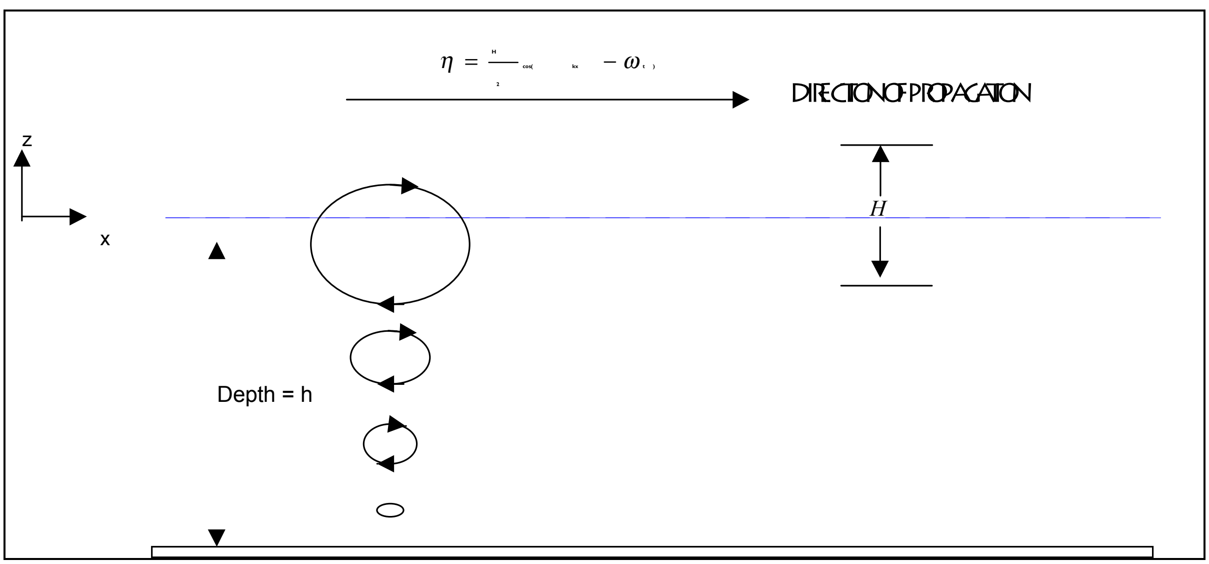

Figure 2 Wave Particle Trajectories

The known relationship, or transfer function of these quantities allows us to estimate the surface elevation indirectly. Therefore the PUV approach measures both pressure and particle velocities to arrive at the power spectrum and the subsequent wave statistics/estimates.

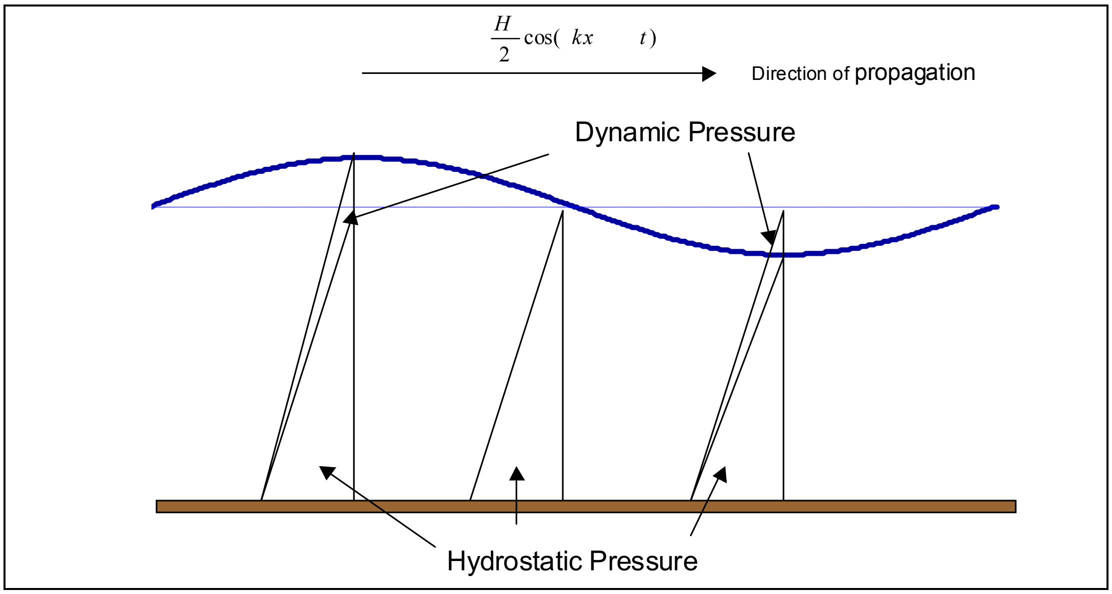

Figure 3 Daynamic Pressure Beneath a Wave

Estimating Sea State

Processing Steps

The Processing is relatively simple and are composed of the following steps (further description is provided in the subsequent text):

1) First perform the transformation on the time series (e.g. Pressure, Velocity) from the time domain to the frequency domain using a standard FFT.
2) Calculate the Auto and Cross Spectra for the pressure and two velocities.
3) Apply the transfer functions to the Auto Spectra to arrive at the Power Spectra for the free surface.
4) Apply quality control to the spectra (Determine a cutoff frequency and extrapolate).
5) Estimate the wave statistics for height and period using the moments calculations.
6) Calculate the Fourier arguments which will ultimately be used for the directional estimates.

Transfer Functions

The transfer functions relating the quantities in the subsurface to the surface elevation are given as,

$$T_p = \frac{\cosh k(h+z)}{\cosh kh}$$ for the pressure

$$T_v = \frac{\omega \sinh k(h+z)}{\cosh kh}$$ for the velocity.

Where h is the water depth, z is the position in the water column, ω is the circular frequency, and k is the wavenumber ($k = 2\pi/\lambda$). The wave number is calculated from the following equation both in terms of frequency and wavelength λ,

$$\omega^2 = gk \tanh kh \qquad \text{or} \qquad \lambda = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{\lambda}\right).$$

If we try to solve for the wavenumber k, we realized that we can not easily isolate and solve for k. Therefore this transcendental relationship requires a recursive solution in order to converge upon a solution.

Cross Spectral

The full cross spectra is presented as, $C_{xy} = S_x S_y^*$, where the * indicates the conjugate. The cross spectra are ultimately used for the directional estimates, whereas the auto spectra is used to estimate wave height and period.

The following relationships are used in order to arrive at the surface power spectra for the surface (from quantities measured in the subsea), $C_{\eta\eta} = \frac{C_{pp}}{T_p^2} = \frac{C_{vv}}{T_v^2}$.

Waves as a random process

Distributions

In the PUV method, we use the frequency distribution of wave energy as the starting point to estimate waves at the sea surface. The spectrum provides a description of the sea state since it inherently contains information about the wave period and height. These parameters are amongst the parameters we are interested in estimating.

The two spectra that are often used to describe the sea surface are the Pierson-Moskowitz and the JONSWAP Spectra. The former is generally best suited for waves which are generated in deep water and are fully developed. These limitations led to a better description that could account for a noted 'peak enhancement', in field data collected. The JONSWAP is better suited for coastal areas and for developing seas. These spectra are mentioned here since they are the basis for our extrapolation approach in the higher frequencies.

Typical Spectra are presented in the following diagram. Notice that the overlaying spectra represent different peak frequencies and amplitudes, but maintain a characteristic shape. Later this will prove valuable since it allows us to extrapolate the spectra beyond the measurable frequency.

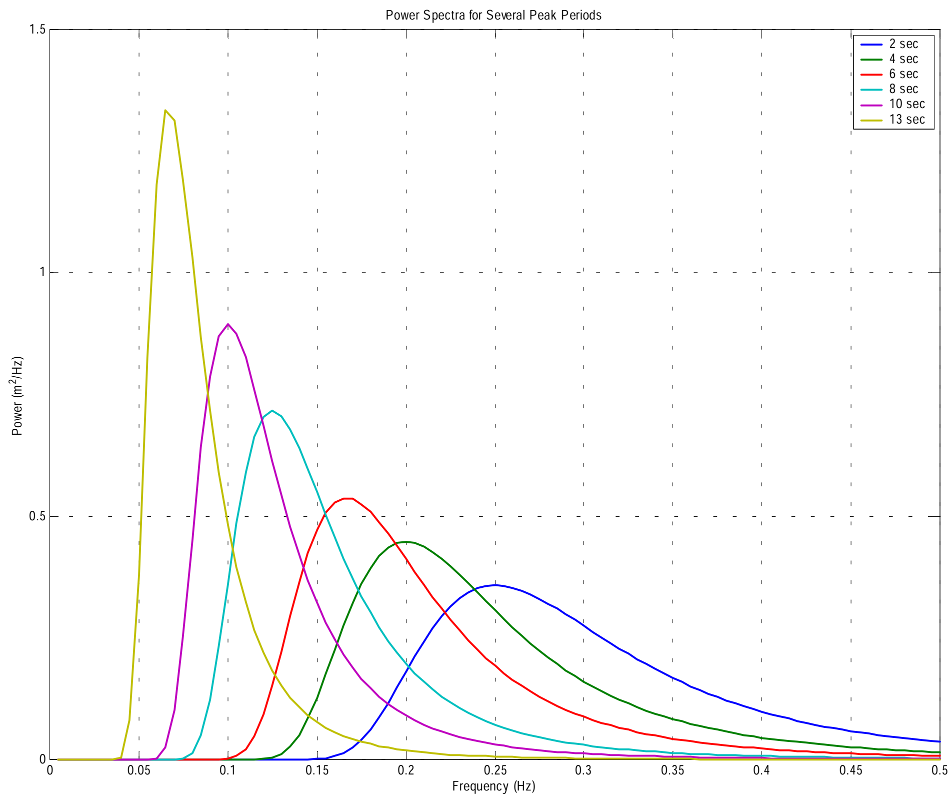

Figure 4 Various Spectra showing the characteristic shape for a Pierson-Moskowitz spectrum.

Heights

Wave heights are generally classified by a standard known as the *Significant Wave Height*, H_s. This is defined by the average height of the top 1/3 largest wave heights. Classically, this estimate is performed by sorting all waves in a time record according to height. Once this has been done the estimate may be calculated.

However in our approach, we utilize the spectrum of the sea surface to approximate this value. A generally accepted approximation of H_s is, $H_{m0} = 3.8\sqrt{m0}$. The *m0* represents the first moment of the power spectrum. The k^{th} moment is defined by, $m_k = \int f^k C(f)df$, where *C* is the power spectrum, and *f* is the frequency.

Other wave height estimates are often reported such as the mean of the top 10% (H_{10}), the mean of the top 1% (H_1), and maximum height. These estimates are more often used for long term statistics. These statistics can also be defined in terms of H_s follows (Shore Protection Manual);

$H_{10} = 1.27H_s$,

$H_1 = 1.67H_s$.

Period

There are two commonly reported estimates for the wave period, *Peak Period* (T_p), and *Mean Period* (T_m). The peak period is simply defined as the period associated with the peak in the spectrum. The mean period is defined by the average of all periods in the data record. It is generally accepted that the following relationship approximates the mean period, using the zero and second moments of the power spectrum: $T_{m02} = \sqrt{m0/m2}$.

Direction

Commonly we describe the distribution of wave energy over frequency and direction with the following relationship; $E(f,\theta) = S(f)D(f,\theta)$. Where *S* is the distribution for the frequency domain and the Directional distribution *D* is a normalized distribution such that the following conditions must be met;

$$\int_0^{2\pi} D(f,\theta)d\theta = 1,$$

$D > 0$ for $[0, 2\pi]$.

The directional distribution, *D* can be approximated by a Fourier expansion according to,

$$D(f,\theta) = \frac{1}{\pi}\left[\frac{1}{2} + \sum_n \{a_n \cos n\theta + b_n \sin n\theta\}\right]$$ (Longhuet-Higgins 1963)

Generally the two parameters defining the directional distribution is the mean direction θ_1, and the spread of the distribution, σ.

The mean direction is expressed in terms of the first pair of Fourier coefficients:

$\theta_1(f) = \arctan(b_1(f)/a_1(f))$.

The spreading is expressed in terms of the Fourier coefficients as $\sigma = \sqrt{2(1-r_1)}$, where $r_1 = \sqrt{a_1^2 + b_1^2}$.

Directional Spectra Estimates

As it was stated earlier, the two common directional estimates, mean direction and spreading can be expressed in terms of the Fourier coefficients. It has been shown that the first two pairs of Fourier coefficients can be expressed in terms of the cross spectra; (Krogstad, H.)

$$a_1(f) = \frac{C_{pu}}{\left[C_{pp}(C_{uu} + C_{vv})\right]^{1/2}},$$

$$b_1(f) = \frac{C_{pv}}{\left[C_{pp}(C_{uu} + C_{vv})\right]^{1/2}},$$

$$a_2(f) = \frac{C_{uu} - C_{vv}}{C_{uu} + C_{vv}},$$
$$b_2(f) = \frac{2C_{vu}}{C_{uu} + C_{vv}}.$$

Cutoff & Extrapolation

At deeper waters or higher frequency waves, the induced dynamic velocity and pressure also decrease. The problem arises when the perturbation is less than the sensitivity of the sensor. This leads to a false growth with the spectral level as we increase frequency. The reason for this false growth is that as we move up in frequency, the signal drops into the noise floor while the transfer function decays exponential. The end result is the power spectrum at high frequencies becomes a fixed noise floor divided by a very small value transfer function. The behavior is presented in Figure 5 by the dashed line.

This behavior at high frequencies necessitates the need for defining a cutoff frequency and an extrapolation from this frequency onward. Since we will ultimately integrate the spectra for the moment calculations, we require spectra that are unambiguous and bounded. We assume that the spectrum follows a Pierson-Moskowitz or JONSWAP type spectrum, and therefore extrapolate in terms of frequency at a rate of $f^{-4.5}$.

The frequency at which the cutoff is selected is determined by finding the last local minima above a maximum amplification factor in the spectrum as we sweep up in frequency.

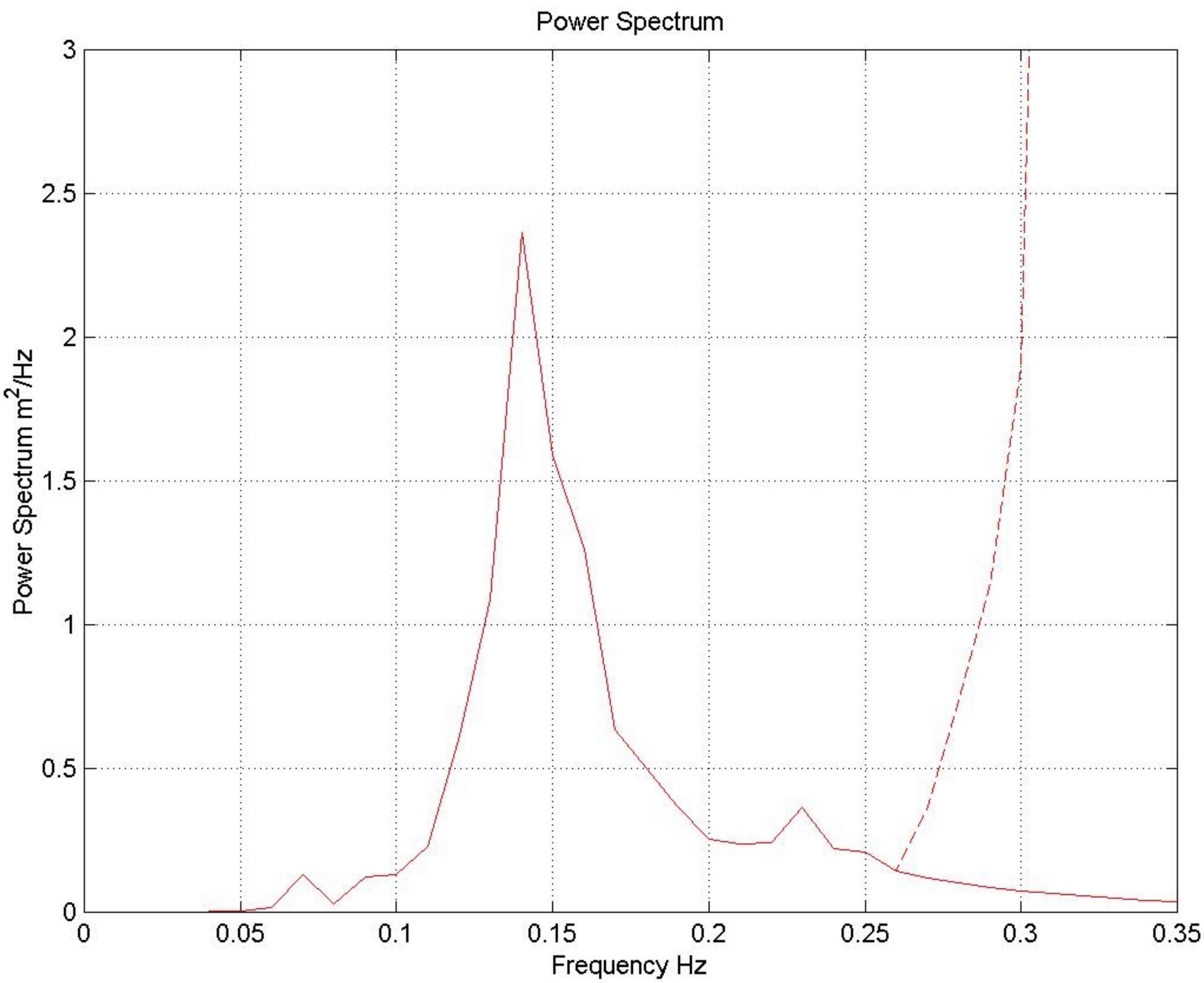

Figure 5 Example of high frequency extrapolation. Note original signal is represented by the dashed line

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