Wave Measurement Evaluation and Testing

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ABSTRACT:

The JCOMM Expert Team on Wind Waves and Storm Surges (ETWS) is presently carrying out a Pilot Project (www.jcomm.info/WET) for the Data Buoy Cooperation Panel to address potential biases in in-situ wave measurements from buoys. Previous comparisons with satellite altimeter data suggest that there may be significant biases between operational buoy networks operated by different national agencies, even with the same platforms. Biases are a serious concern in climatology, especially in computation of trends, but are also relevant for example in wave forecast verification, comparisons of wave model performance and regional statistics.

The following paper will describe the principles of First-5, insights into the use of an analysis tool called WAVEVALTool, and provide preliminary results from various components of the wave measurement testing and evaluation program.

INTRODUCTION:

Wind generated surface gravity waves have been measured in some form or another for nearly a half-century. These reports have been used for ship routing, planning, operation, and investigations of the mechanisms in wave development including growth rate formulations. As the number of wave measurement sites has increased (Figure 1; and http://www.osmc.noaa.gov/osmc/index.jsp) over the past four decades, applications of the information have also increased.

Fifteen years have transpired since original directional spectral evaluations were performed off the Pacific coast (O'Reilly et al. 1996). Results from this pioneer study showed biases (Datawell, NDBC buoy) in wave energy (0.9-percent, -2.8-percent), mean direction (3.4-deg, 2.3-deg), directional spread (0.3-deg, 5.7-deg), skewness (3^{rd} directional moment, 0.14, -0.44), and kurtosis (4^{th} directional moment, 0.85, -0.55)), derived from a pressure array (relative reference), a Datawell Directional WaveRider and a NOAA National Data Buoy Center (NDBC) 3-m discus buoy. The biases may appear at first relatively small, however the higher order moment errors tended to increase. Since that time many operational wave measurement centers (e.g. NOAA/NDBC) have replaced their standard gimbaled Hippy with smaller, lighter robust electronic motion sensors (Teng, et al, 2009). More recently, Bender et al. (2010) found in wave measurements during Hurricane Katrina significant wave heights were on average over-estimated by 26-percent, and up to 56-percent (about a 3-m difference) during the peak of the storm using a strapped-down accelerometer. In addition, Durrant et al. (2009) evaluated long-term altimeter records from *Jason-1* and *Envisat* to point-source wave measurements (NOAA/NDBC and Environment Canada, Marine Environmental Data Service). Their results showed a difference of nearly 10-percent between the Canadian buoys and that of NOAA/NDBC, where the NDBC buoys reported higher significant wave heights; it is not possible to say from this which, if either, is correct, since the satellites are calibrated to the NOAA buoys. These studies can have a dramatic impact on recent climate studies using archived point source measurements (e.g. Ruggiero, et al. 2010, Allan and Komar, 2000). Changes in the buoy location, hull, sensor type and processing method, as well as breaks in the record (days up to years) and intermittent loss in data specifically during large storm events, could be misconstrued as climate variability. This observation has been more recently studied in a work by Gemmrich, Thomas and Bouchard

Wave measurements have been used in data assimilation; evaluation of numerical wave models, algorithms for satellite based altimeter wave estimates, and now because of archived long-term records climate variability. In most, if not all cases, we have blindly accepted the reliability and accuracy of these wave records. To address this concern, the National Oceanographic and Atmospheric Administration's (NOAA) Integrated Ocean Observing System Program (IOOS) developed *A National Operational Wave Observation Plan* (http://www.ioos.gov/library/wave_plan_final_03122009.pdf) where testing and evaluation of existing and future wave measurements assets should be performed. Swail et al. (2010) identified this concern:

> "***Continuous testing and evaluation of operational and pre-operational measurement systems is an essential component of a global wave observing system, equal in importance to the deployment of new assets**.*"

The Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) has initiated this effort. Over the past three years this project has been coordinated between Environment Canada, US Army Corps of Engineers, NOAA's National Data Buoy Center, along with the Alliance for Coastal Technologies (ACT, http://www.act-us.info/) the latter funded by NOAA/IOOS Program, and an international Steering Team, performing the field testing, generating the procedures to follow, development of analysis packages, and documenting the results. The challenges to accomplish these tasks are daunting, however the results derived from this project will benefit the entire wave measurement, wave modeling community.

The primary focus of this project is the evaluate point-source wave measurements. We acknowledge there are other platforms such as aircraft- and satellite-based altimeters, Synthetic Aperture Radar, Scanning Radar Altimeters, land-based HF- and X-Band Radar systems fully capable of estimating surface gravity waves. However, these systems all require referencing to point-source wave measurements. In addition, for coastal applications, there are alternate means to estimate waves, such as wire resistance gauges, pressure sensors, and acoustic Doppler current profilers. The focus for the initial effort of the JCOMM pilot project is the evaluation and testing of wave buoys located in intermediate and deep water (10's to 100's of meters).

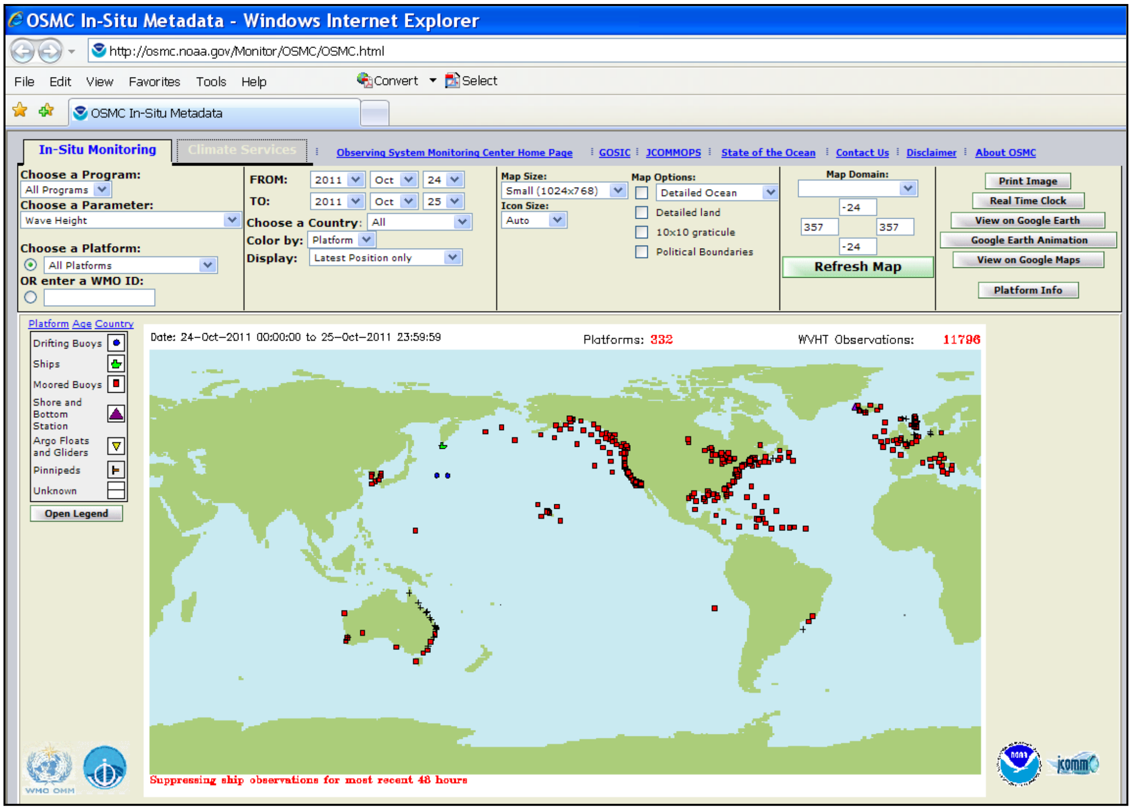

Figure 1. Summary of real-time surface gravity wave observation sites from the Observing System Monitoring Center.

FIRST-5 BASICS:

At the onset, we acknowledge that surface gravity waves are one of the most difficult oceanographic parameters to measure. Changes in the free surface occur very rapidly, unlike temperature, color, Sea-surface elevation. Spatially, waves can also be highly variable, where multiple meteorological events can influence a small confined area. Multiple wave systems defined in frequency and direction space influence the overall wave characteristics. We define the directional wave spectrum as $S(f,\theta)$, or energy that is functionally related to frequency, (f) and direction (θ). A point on the free surface at any time can be approximated as the linear superposition and sum of wave components that span all frequencies and directions.

Any wave measurement derived from a floating buoy is an estimate. Directional and non-directional wave information is derived from buoy motions and the power transfer functions, phase responses associated with the buoy including the super-structure, mooring, measurement systems and analysis packages. This dependency as will be shown is particularly important at low energy levels and at low and high frequencies where the wave signal being measured is weak and the potential for added signal contamination increases.

Determining the free surface from a buoy is generally achieved from three systems (Figure 2). They are all described and typically involve the concurrent measurement of three time series. The first is particle following (or translational) buoys (e.g. Datawell WaveRider Buoys) that use an accelerometer (doubly integrated) to determine the X, Y, and Z position of the free surface. Global Positioning Systems (GPS) also fit into this class of sensors. The second is slope following (pitch-roll) commonly used in NDBC buoys, where *dz/dx* and *dz/dy* is measured. The third system is a direct measurement of the orbital velocity from acoustic sensors and then transformed via linear wave theory to estimate the free surface.

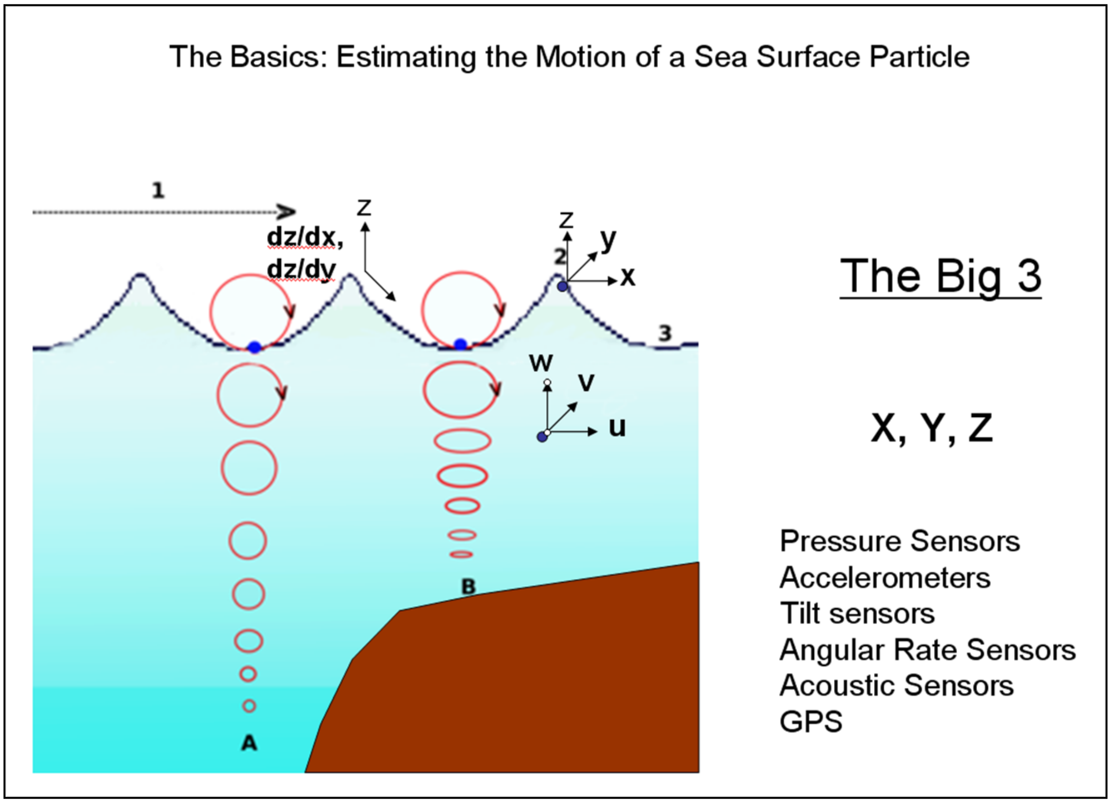

Figure 2. Schematic Representation of what is to be measured, from W. O'Reilly (Alliance for Coastal Technologies, Wave Sensor Technologies Workshop, March 2007).

A Fast Fourier Transform (FFT) of the vertical displacement time series yields an estimate of S(f). At discrete frequency bands the directional distribution (Figure 3) of wave energy S(θ) can be expressed as an infinite Fourier Series (equation in Figure 3). The normalized directional Fourier coefficients (a_1, b_1, a_2, b_2; or for translational buoys defined as α_1, α_2, r_1, r_2). We are attempting to define the spectral shape as shown in Figure 3, from the expansion of the Fourier series. At the minimum, any evaluation of the directional information is based on Fourier coefficients, or moments that can be mathematically defined (i.e. first moment is the mean direction, second moment the directional spread, third moment skewness, and fourth moment kurtosis). The generation of the line identified in Figure 2 is only achievable via some estimate such as the Maximum Likelihood, Maximum Entropy Methods (e.g. Benoit, 1992). These methods make an attempt to estimate the remaining Fourier coefficients. So any graphical representation of the directional shape or 2-dimensional directional wave spectrum is an interpretation of nature, and should not be construed as exact. Any evaluation technique decomposing an estimated S(f,θ) as the initial starting point will result in an intractable solution, that in fact is based purely on an approximation. A true evaluation method to determine differences in directional wave measurements (adopted by JCOMM, as well as ACT) is based on the five Fourier coefficients S(f) and a_1, b_1, a_2, b_2; or translational buoys defined as α_1, α_2, r_1, r_2, or the First-5. Then it becomes a true tractable, mathematically, and measurement pure wave evaluation with no a-priori assumptions governing the spectral characteristics.

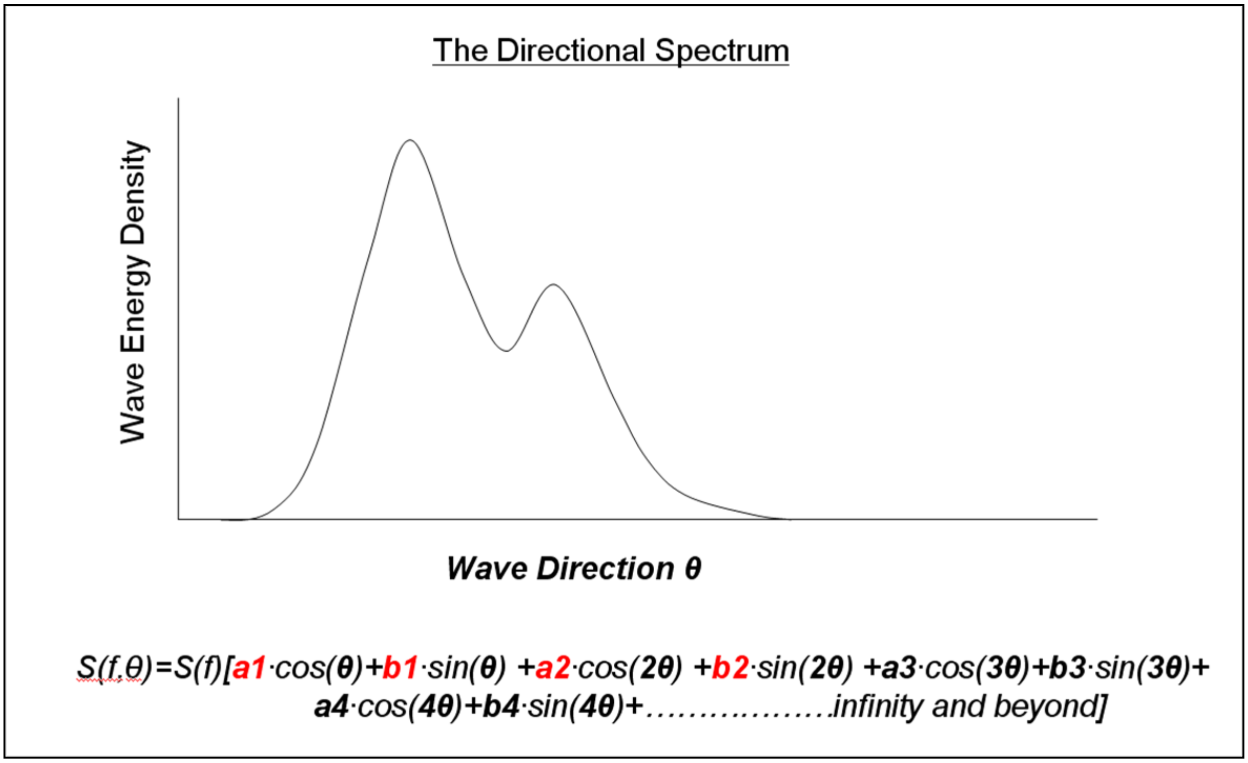

Figure 3. Schematic of the directional distribution, and Fourier series expansion.

FIRST-5 EVALUATION PROCEDURE:

There are many differences between wave measurement platforms, such as the hull, mooring, super-structure, sensor, and internal analysis package. Each will have an impact on the quality of the wave results. Any directional wave instrument can provide the First-5 Fourier coefficients. The degree of accuracy of the coefficients plays an important role in the evaluation process. Most, if not all instruments contain noise in the time series. It is the level of that noise compared to the real wave energy or in the directional coefficients that can contaminate any wave record. The signal-to-noise level provides that measure to determine the quality of the wave sensor output. O'Reilly (ACT, 2007) equates directional wave instruments to audio equipment, or the *fidelity*. Instruments with high fidelity can be used to resolve some of the finer details of S(f,θ), like the directional width at a particular frequency and can often determine if the directional characteristics at that frequency are bi-modal. Low fidelity instruments will generally return reasonable estimates of the mean wave direction, but will over-estimate the directional spread and under-estimate skewness and kurtosis. A common assessment of signal-to-noise levels is that sea surface displacement has a larger signal than sea-surface slope signals; increased wave energy will result in a larger signal; the lower the frequency the lower the acceleration, slope, and velocity signals and thus the potential for contamination from noise.

The evaluation procedure may appear at first very complicated, but in general it is not the case. There are two sets of data that are time varying defined by the frequency spectra S(f), and the estimator free statistical parameters: mean direction (1st moment), directional spread (2nd moment), skewness (3rd moment) and kurtosis (4th moment) at each frequency. The S(f) and accompanying directional moments are decomposed into discrete frequency bands at each time interval and evaluated. The only assumption made is to map the spectral data into one common discrete frequency range.

An analysis package has been developed to perform the intra-measurement evaluation. Originally called CDIPTool, and now called WAVEVALTool is written in Matlab® and can be executed on a standard PC. The software and documentation is accessible from the following website:

http://cdip.ucsd.edu/?nav=documents&sub=index&units=metric&tz=UTC&pub=public&map_stati=1,2,3&xitem=product&xdoc=cdiptool).

The most difficult portion of the analysis is to construct the input spectral file. Many have been developed for Datawell Directional files, NOAA/NDBC and Environment Canada archived data, to mention a few. It is anticipated that more will be needed as new data sets become available. New options are being developed (e.g. scatter plots, quantile-quantile analysis, and statistical tests). For a new toolbox, WAVEVALTool is fairly robust, however, with any software product problems may occur, and the authors welcome any feedback.

A series of the graphical products derived from WAVEVALTool and discussion are provided below. The first example (Figure 4) displays a time plot of two co-located buoys (both directional) significant wave height results for a seven month period. The top panel displays the total wave height for two co-located buoys. Integrating over the entire range of frequencies, the wave heights are relatively similar to one another. However, decomposing S(f) into discrete frequency ranges, and integrating illustrate large differences in the low (middle panel) and high (lower panel) frequency ranges. There are only four occurrences of observable wave energy for buoy 44255 during the seven month period of record (middle panel Figure 4) despite 44235 observing low but continuous wave energy. It is believed buoy 44255 (Environment Canada buoy) applies a filter to very low signal levels zeroing out all wave energy.

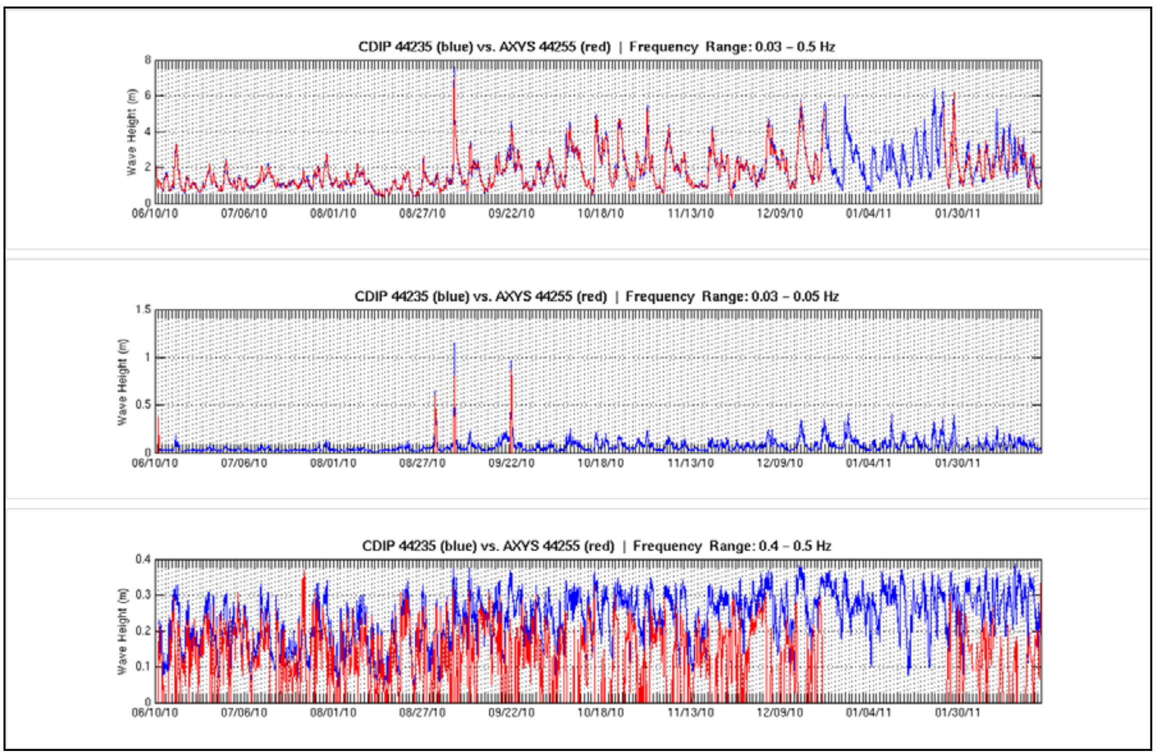

Figure 4. Evaluation of two co-located wave measurements over time, for total (top panel), low frequency (middle panel), and high frequency (lower panel) ranges. The CDIP 44235 is the Environment Canada Datawell Directional Waverider, AXYS 44255 is the 6-m MONAD hull and the TriAxys sensor. Note results were also compared to the 6-m NOMAD hull using the Environment Canada operational strapdown accelerometer payload. All figures refer to the two buoys indicated here.

However when the energy does exist at 44255 it clearly influences the total wave height estimates, where the under-estimation in the low frequency energy peaks will translates into under-estimation in the total. The lower panel of Figure 4 shows buoy 44255 under-estimates the energy level when it seems to exceed some threshold, then becomes zero.

This analysis can be carried out for the directional parameters, and higher order moments. Figure 5 contains the results for the two sites, where the top panel is the mean wave direction for the entire frequency range, the middle panel for the low frequency range (0.03- to 0.05-Hz), and the bottom panel for the high frequency range (0.4 to 0.5-Hz). Again, the overall mean wave direction for both buoys trend in a similar fashion, for multiple storms moving across the deployment region where the mean wave direction contains directional shifts of 180-deg. If only the top panel was evaluated, one would strongly suggest both buoys show excellent correlation. However, by decomposing S(f) and now its directional components in discrete frequency bands large differences are evident. The middle panel of Figure 5 contains the mean direction response for the low frequency range. As in the case of the wave height (middle panel of Figure 4), the number of observations is reduced, suggesting any energy contained in frequency bands from 0.03- to 0.05-Hz does not exist. However, buoy 44235 contends there is. In the high frequency range (bottom panel Figure 5), and despite under-estimating the wave heights, the mean wave direction derived from buoy 44255 performs relatively well compared to 44235.

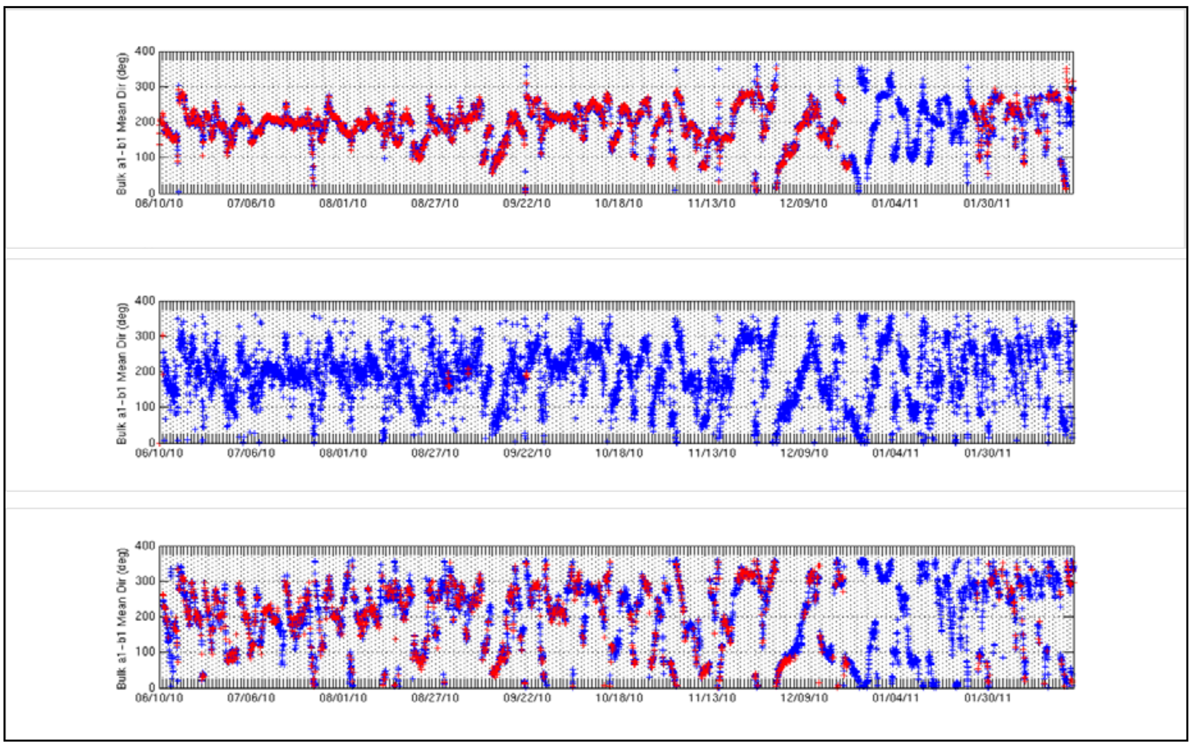

Figure 5. Evaluation of two co-located wave measurements over time, for mean wave direction, total (top panel), low frequency (middle panel), and high frequency (lower panel) ranges. Symbols and buoy types are defined in Figure 4.

WAVEVALTool is used to evaluate the higher order directional moments. Figure 6 displays the results of a continuation in the intra-measurement evaluation. The results are similar to the height and mean wave direction. However in the high frequency range there is a substantial positive bias in the spread of 44255. By dissecting the S(f) and the directional properties into discrete frequency ranges clearly show where two co-located directional wave measurements agree, and diverge. One last point of this discussion that is worthy to note. These comparisons were between a Datawell Directional Waverider and a 6-m NOMAD with an Tri-Axys© wave sensor capable of estimating directional information. The NOMAD hull is a non-symmetrical *ship* configuration located just offshore of the Island of Newfoundland.

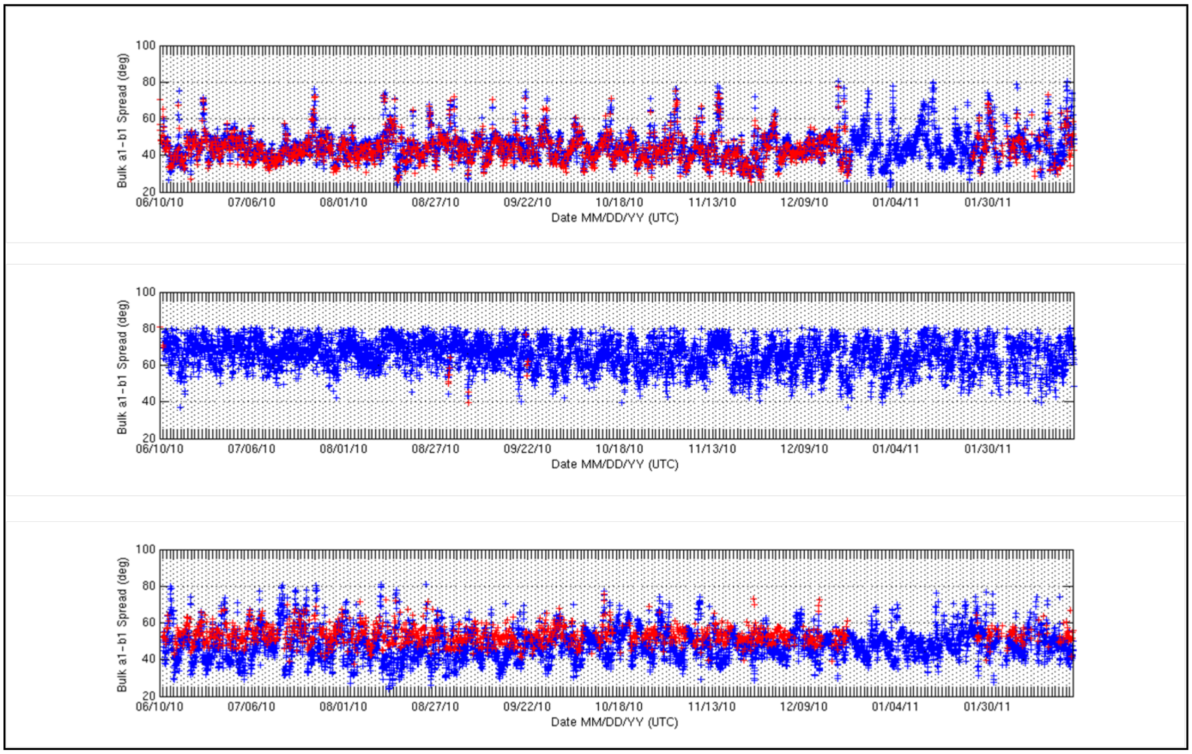

Figure 6. Evaluation of two co-located wave measurements over time, for directional spread, total (top panel), low frequency (middle panel), and high frequency (lower panel) ranges. Symbols and buoy types are defined in Figure 4.

Time plots provide an excellent way to evaluate buoy characteristics, drill down to specific frequency ranges in energy and the directional moments. Summarizing the information into one graphical form that is relatively easy to interpret is a challenge. WAVEVALTool has a provision to produce a wave component plot. Given the data set defined as a series of time paired S(f), and their directional moments we can decompose the estimates into a two-dimensional space, energy (or height) and frequency. Statistical testing is performed (bias, root mean square error) in terms of discrete *boxes* defined by a frequency range, and energy range. The statistical results are summed over time and color contoured, as relative boxes with distinct intervals. Examples are presented in Figures 7 through 9 displaying the bias between the two buoys for energy, mean wave direction and directional spread. Analyses were also performed on a_2, b_2 (for the mean direction and spread) and skewness for period of record but not presented. The results shown in the following figures emulates that of the time plots, however it summarizes the findings in one graphic. As indicated, buoy 44255 (the 6-m NOMAD) total energy compared in general favorably to 44235 (Directional WaveRider) for most occurrences during the seven month deployment. This is indicative of the dark blue boxes in the range of carrier frequencies observed during that time period. As the energy level or frequency range decreases there is a trend for the 6-m NOMAD to diverge from the Waverider. Finally for the low and high frequency range the zeroing of wave energy tends to overshadow any evaluation. However, it is very surprising to see a directional sensor fixed in a non-symmetric hull is capable of estimating the mean wave direction, and directional spread.

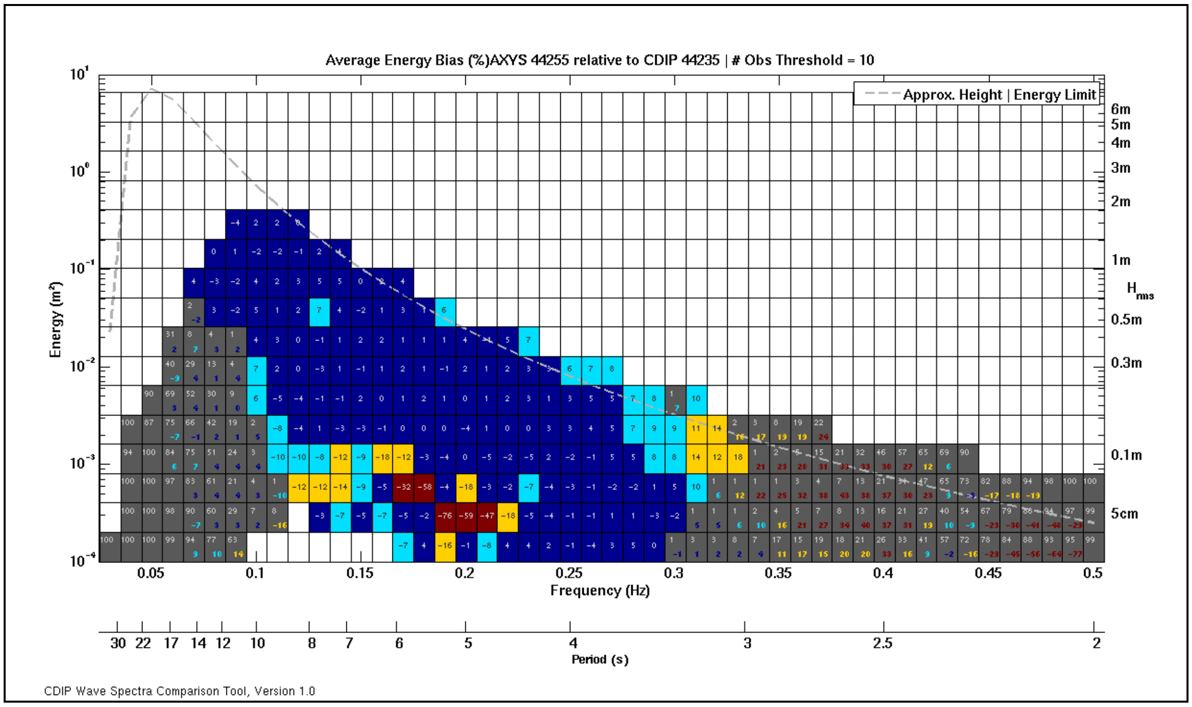

Figure 7. Energy bias between 44225 and 44235. Note biases less than 5-percent, (dark blue), from 5- to 10-percent (light blue), 10- to 20-percent (yellow), greater than 20-percent (red). Grey areas with values defined in the boxes indicate NO data from one of the two buoys (generally 44255).

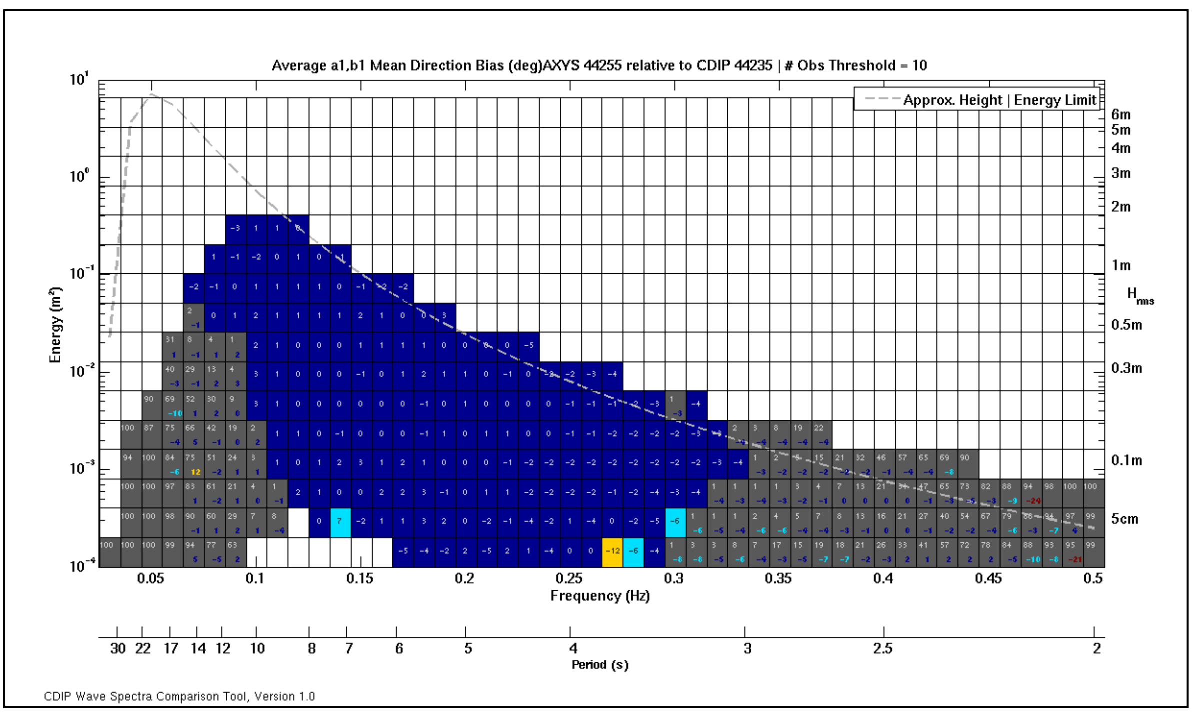

Figure 8. Mean direction bias between 44225 and 44235. Note biases less than 5-deg, (dark blue), from 5- to 10-deg (light blue), 10- to 20-deg (yellow), greater than 20-deg (red). Grey areas with values defined in the boxes indicate NO data from one of the two buoys (generally 44255).

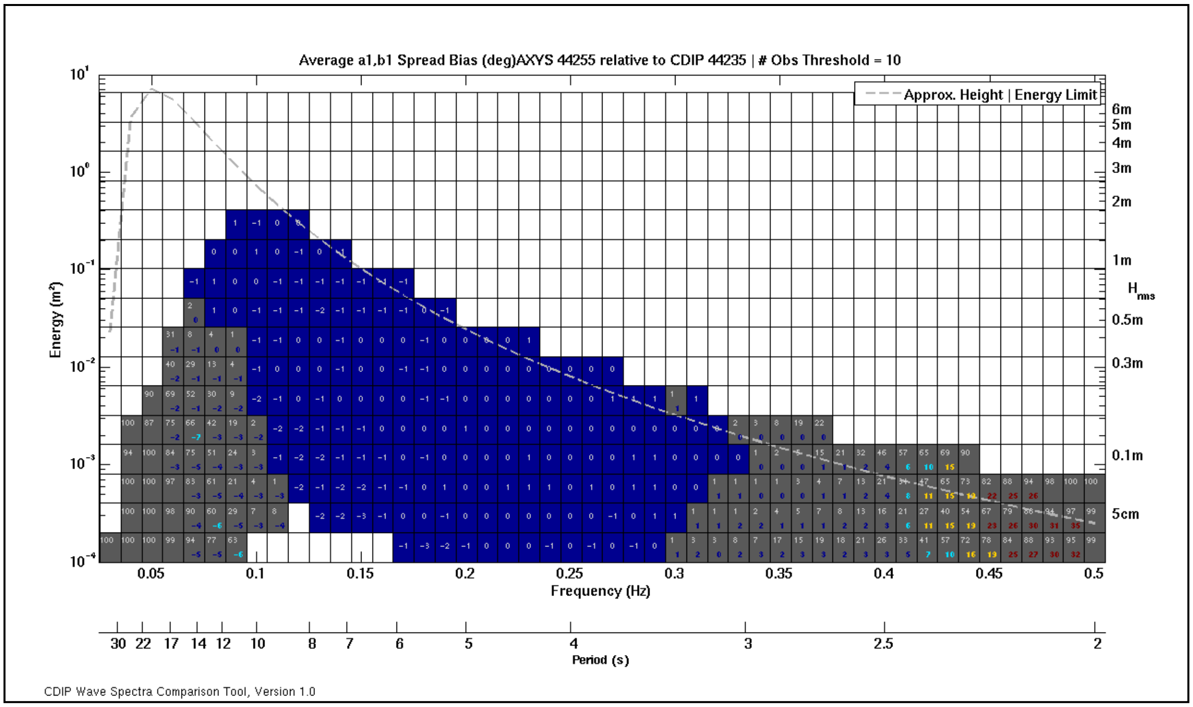

Figure 9. Directional spread bias between 44225 and 44235. Note biases less than 5-deg, (dark blue), from 5- to 10-deg (light blue), 10- to 20-deg (yellow), greater than 20-deg (red). Grey areas with values defined in the boxes indicate NO data from one of the two buoys (generally 44255).

INTRA-BUOY DEPLOYMENT AND EVALUATION:

The use of WAVEVALTool has been established as the software package JCOMM and the IOOS National Waves Plan will adopt to perform all intra-measurement evaluations. The other aspect to testing and evaluation are procedural. During a recent Alliance for Coastal Technologies workshop, a group of wave measurement experts, including the USACE, NOAA/NDBC, Environment Canada, JCOMM, Naval Research Laboratory (Stennis Space Center), ACT participants and many wave measurement manufacturers from the private sector, discussed means to evaluate wave measurements. There were two options, create a *buoy farm* where specific locations were selected, (Atlantic, Gulf of Mexico, Pacific and Great Lakes), where all participants deploy their respective instruments at one time. In part, this option was subject to certain constraints, mainly the availability of *in-kind* ship time, availability of a particular contributed asset, and coordination between multiple organizations to be successful. A second deployment plan would be to place one *relative reference* at specific locations where existing buoys are deployed in the wave network. This plan would only require multiple *relative reference* assets (mooring, batteries, communications), and dictated by pre-determined maintenance to a given buoy. The only impediment to this plan was to define the *relative reference*, and have all manufacturers present mutually agreed. The IOOS National Operational Wave Observation Plan selected a Datawell Directional Waverider as the *relative reference* to be used. At this meeting all participants agreed.

JCOMM, Environment Canada, NOAA/NDBC, and the USACE have been involved with this intra-measurement evaluation for the past two years. Results provided in the above discussion came directly from the Environment Canada collaborative effort where two directional Waveriders were deployed, one along the Atlantic seaboard, and one along the Pacific coast. These buoys will be re-deployed to alternate sites evaluating different buoy types. In addition, NOAA/NDBC has recently constructed a *buoy farm* in the Pacific Ocean just west of Monterey, California. Contained in this domain is one Directional

Waverider, a 3-m discus buoy with two sensors (Hippy and a *3DM* motion sensor), and a 2.4-m buoy containing a *3DM* motion sensor. In addition NOAA/NDBC has multi-sensor packages on three other buoys contained their wave measurement array (Atlantic, Gulf of Mexico and Pacific). JCOMM is also coordinating a site at the EkoFisk platform in the North Sea, where a directional laser system presently exists. This system is thought to be the most accurate of any wave measurement system available for deep water wave measurements. Information regarding this study will be forthcoming during the 12th International Workshop on Wave Hindcasting and Forecasting. Under the JCOMM umbrella, additional evaluations are also being carried out by Korea and India.

SUMMARY CONCLUSIONS AND RECOMMENDATIONS:

It has been well documented over the last decade or more, that differences between wave measurements arise from different buoy configurations. Originally the thought was most of these differences were evident in directional estimates. Changes in sensors and other dependencies in the power transfer functions and phase responses to map the buoy responses to the free surface have now affected the energy levels. Bender et al. (2010) found in extreme wind and wave events that standard 3-m discus buoys will over-estimate significant wave heights by 50-percent. The differences between NOAA/NDBC and Environment Canada historical records, and even within the historical record for one buoy location, are disconcerting because of the activity in the literature to use long-term buoy records for climate studies.

We cannot understate the need to evaluate wave measurements, not only newly developed systems, but historical as well. Only recently NOAA/NDBC has mentioned their 6-m NOMAD fleet of buoys will be retired using alternate platforms in their operational wave array. The time to initiate an intra-measurement evaluation and testing procedure is here, and will have a direct impact on all that use wave measurements, for operations, modeling, data assimilation, algorithm formulations for altimeter estimates.

We have documented a technique that is devoid of any assumptions, use of real wave estimates based on the First-5, developed a sophisticated analysis package dissecting those estimates in an extremely useful form. On a national and international framework with input from the private sector, one *relative reference* will be used in the evaluation for deep water moored buoys, and a plan for performing those comparisons. All we have to do is the work.

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