# NDBC's Digital Directional Wave Module

Chung-Chu Teng, Richard Bouchard, Rodney Riley
NOAA National Data Buoy Center
Stennis Space Center, Mississippi 39529, U.S.A.

Theodore Mettlach, Richard Dinoso, Joel Chaffin
Science Applications International Corporation
NOAA National Data Buoy Center
Stennis Space Center, Mississippi 39529, U.S.A.

*Abstract-* **The National Data Buoy Center (NDBC) has developed a compact, low power, directional wave measurement system called the Digital Directional Wave Module (DDWM). It represents the latest advance in NDBC's 30-year history of producing wave measurement systems. The DDWM consists of embedded electronics; a commercial off-the-shelf (COTS) motion sensor; custom, embedded software and hardware; and a mounting plate. The COTS sensor measures the earth's magnetic flux density and the buoy's, acceleration and angular rate about three orthogonal axes, aligned with its bow, starboard beam and mast. The module uses the Angular Rate System (ARS) method of determining pitch and roll angles, from which wave directions are derived. Using the same wave-data processing techniques, algorithms, and software as those from earlier NDBC wave systems has reduced development and operating costs and has avoided problems associated with changing data message formats. The DDWM's small size and weight, compared to previous systems, has reduced shipping costs and eased handling, thereby facilitating safe and efficient at-sea servicing. The module's high tolerance for extreme environmental conditions has allowed NDBC to loosen its special handling procedures associated with less robust sensors. New quality assurance tests and test equipment were developed for the digital sensor, the integrated processing package, and digital sensor output. This paper presents DDWM's development strategy, system description, quality assurance, laboratory tests and field tests. Test results show that primary wave parameters from DDWM are within NDBC accuracy standards.**

## I. INTRODUCTION

The National Data Buoy Center (NDBC) has successfully used Datawell's Hippy 40 Mk II sensor in its directional wave systems since 1976 [1]. In the past five years, NDBC's network of wave-measuring buoys has grown, whereas base funding has tightened. While the Hippy sensor, a proven, trusted sensor, has performed very well, it comes with three disadvantages. First, its high cost restricts its use to only select stations. Second, the Hippy is definitely intolerant to frigid temperatures and to unusually hot temperatures. It cannot be deployed in the Gulf of Alaska or the Bering Sea. Third, its weight and size are too much for NDBC's smaller, coastal buoys.

To avoid the constraints associated with the Hippy, NDBC began looking for a less expensive, more heat-tolerant and smaller wave sensor. In 1994, NDBC integrated several motion sensors into a single package, producing what has been named the Angular Rate System (ARS). It consists of a bi-axial magnetometer for determining direction, three angular rate sensors for deriving pitch and roll angles, a mast-aligned accelerometer for obtaining the wave-energy spectrum and a tilt sensor of getting average pitch and roll angle. The tilt sensor is required because the algorithm for obtaining pitch and roll angle developed by Steele *et al.* [2] makes the assumption that mean pitch and roll angles are zero. The ARS package has provided a much smaller, less costly replacement for the Hippy. Mettlach and Teng documented its performance, finding that it is as sensitive as the Hippy is to low-amplitude, long-period Pacific swell waves. [3]

In 2007, NDBC began testing the MicroStrain® (MicroStrain, Inc.) motion sensor 3DM-GX1. The sensor, comprised of Micro-ElectroMechancial System (MEMS) sensors from Honeywell International Inc. and Analog Devices Inc, produces nine measurement channels: acceleration, angular rate and magnetic flux density along three orthogonal axes at a rate of 35 hertz. The channels provide everything needed to replicate the ARS. Additionally, these provide potential for matching the vertically stabilized accelerations of the Hippy. NDBC has integrated the 3DM-GX1 with a small electronics package, producing the Digital Directional Wave Module (DDWM). It replaces the older analog system called the Directional Waves Processing Module (DWPM). DDWM is part of an overall strategy that will allow NDBC to make cost-effective directional wave measurements from its buoy network that has expanded with the increased demand for buoy observations in harsh environments and distant locations such as Alaska and the hurricane-prone areas of the tropical Atlantic.

The present paper provides detailed descriptions of the components of DDWM, its advantages over existing sensors and systems, NDBC's development strategy and process, and quality assurance procedures. Laboratory tests conducted on

0-933957-38-1/09/$20.00 

DDWM and the motion sensors at NDBC's compass rose and wave instrument facility are presented and discussed. A field evaluation, which compared a Datawell Hippy-based system to the DDWM with both systems mounted on the same hull, and its results are presented.

## II. Development Strategy

In developing the new directional waves system, much of the existing system was leveraged to reduce the development effort and risks to the success of the project and health of the operational network.

### *2.1 Re-use of System Structure: Formats, Processing, Data Management*

Much of the entire NDBC directional waves system, both platform and shoreside, remained unchanged. Thus, data message formats, data reporting schemes and methods, data processing on shore, data management and display were untouched. Much of the existing embedded processes for the pitch-roll-heave acceleration system were re-used. This approach minimized development cost and risks, allowing for development, integration, and testing of the new system while not disrupting an operational network system.

### *2.2 DDWM Advantages*

Table I shows a comparison of the key specifications that give the 3DM-GX1 sensor an advantage over the Datawell Hippy 40. Two big factors are size and price. The smaller size is attractive in that the system can be changed during a buoy hop at sea. A Hippy can not be exchanged due to its large size and being mounted under the first equipment rack level. Removal would require lifting the buoy to the deck of a large vessel.

TABLE I
3DM-GX1 Advantages vs. Hippy 40

| | Hippy-40 [(1)] | 3DM-GX1 [(2)] |
|---|---|---|
| Weight | 36 Kg | 0.0746 Kg |
| Size | 73,010 $cm^3$ | 146.25 $cm^3$ |
| Temp. | -5°C to 35°C (55°C [(3)]) | -40 °C to 70°C |
| • Price | $25,000 (US) | $1200 (US) |

[1] – Source: Datawell Web site
[2] – Source: MicroStrain Web site
[3] – Short term or a few weeks

Shipping costs for NDBC across a 100-buoy network will be less. The smaller size also allows other systems to be installed or makes service easier since there is more room.

The temperature specification for the Hippy can be easily exceeded in the summer environment with a buoy on concrete surfaces. This has occurred at NDBC facilities where a buoy has completed production and testing but was waiting for ship availability, necessitating special handling.

Finally, a new Hippy is several thousand dollars more than the 3DM-GX1. The relative high cost of the Hippy limits its use.

Due to the small size and cost, the same DDWM hardware and software can be used for a directional wave or non-directional wave system. Thus, there are fewer systems to learn and maintain.

## III. DDWM System Description

The DDWM consists of an electronics box and the commercial off-the-shelf (COTS) motion sensor fixed to a phenolic plate, as shown in Figure 1. The plate has a cutout area that forms a handle and slides into NDBC's 3-meter buoy electronics rack. The embedded computer in the electronics box contains the processing firmware and provides a user menu for control and configuration.

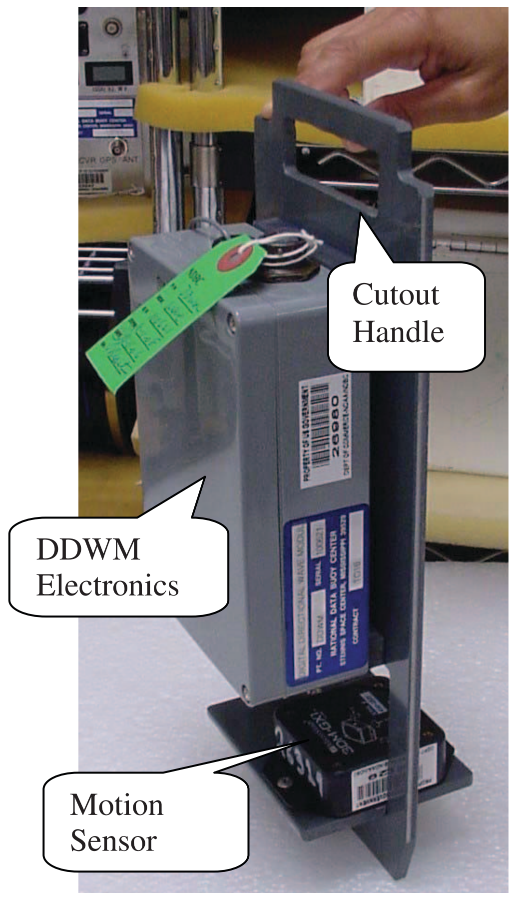


Figure 1. Digital Directional Wave Module

### *3.1 Electronics*

Figure 2 shows a block diagram of the DDWM electronics. It consists of a custom-designed circuit board for signal and power conditioning and provides connectors for internal connections. A plug-in COTS central processing unit board provides the processing hardware. An add-on COTS analog-to-digital board measures the analog gyrocompass signal, which is used for finding hull magnetic correction coefficients, used in buoy azimuth computations. A removable flash memory card records raw time series and processed data. An external connector connects to power and serial communications. The motion sensor connects to the electronics enclosure through a feed-through-type connection.

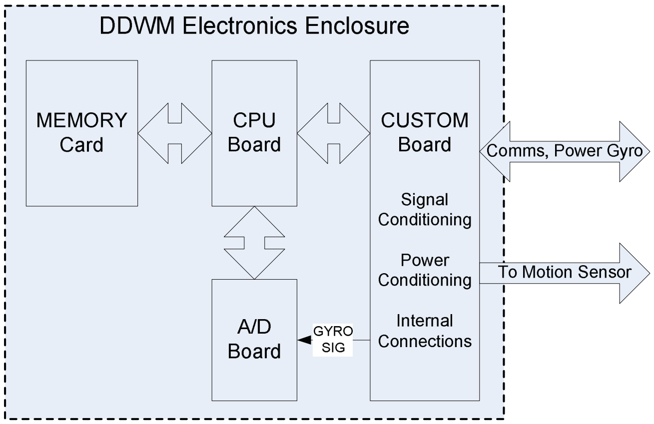


Figure 2 DDWM electronics block diagram

*3.2 Sensor*

The motion sensor is a model 3DM-GX1 manufactured by MicroStrain Inc. ([http://www.microstrain.com/3dm-gx1.aspx](http://www.microstrain.com/3dm-gx1.aspx)). It is purchased as a single package from the manufacturer. The 3DM-GX1 integrates six sensors from two different U.S. manufacturers: three single-axis angular rate sensors, each an XRS300 from Analog Devices, two dual axis accelerometers, each an ADXL210 from Analog Devices; and, a single 3-axis magnetometer, the Honeywell® HMC 1053 (Honeywell International Inc.).

Nine channels of information stream out of the unit at a rate of approximately 35 hertz, depending on the mode of operation selected. Early testing of the DDWM revealed that the *gyro-stabilized* mode of operation gives energy spectra with considerably less low-frequency noise than the *instantaneous* mode of operation. The DDWM software subsamples the data stream at a rate of 1.7066 hertz, which has been the NDBC standard rate since 1994.

The sensor is configured to continually sample and output data on an RS-232 serial port.

It is mounted on the DDWM frame in a fixed position such that, when installed in NDBC's 3-meter discus buoy, it is in the center of the buoy and at the water line.

*3.3 Software*

Software flow is shown in Figures 3. The core wave processing algorithm is derived from [2].

The user menu, given in Figure 4, provides operator control to load a new configuration or read an existing configuration. Various testing functions are provided, including the menus to conduct buoy magnetic system compensation.

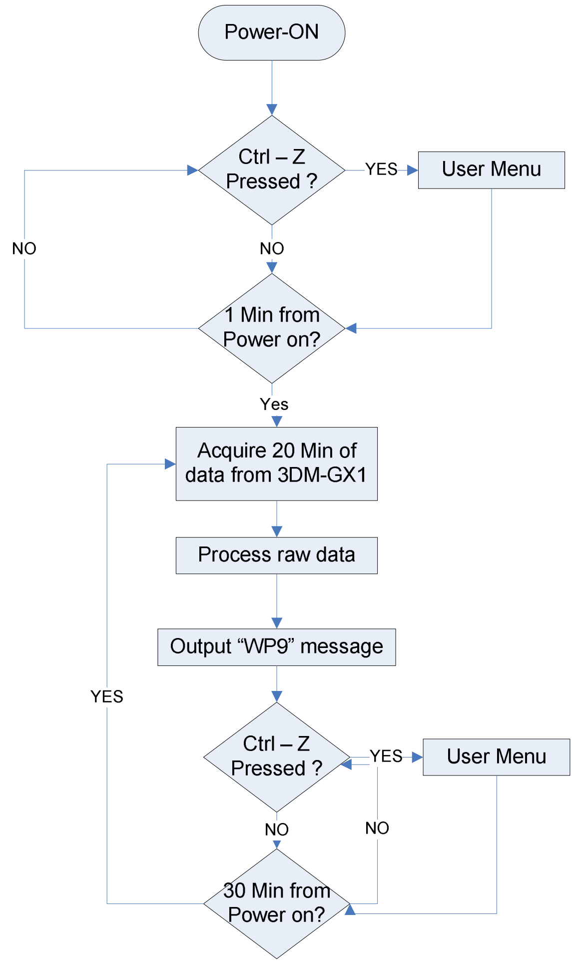


Figure 3. Simplified view of software flow

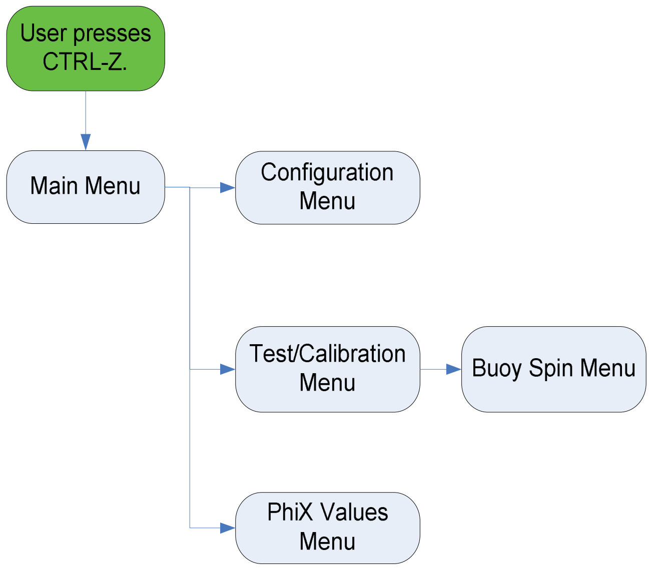


Figure 4. User Menu Organization

NDBC based the DDWM on the DWPM, which, in turn, is based on the Wave Processing Module (WPM) [4]. The DDWM preserves many of the hallmark characteristics first developed in the WPM: (1) 1.0766 hertz (Hz) sampling rate; (2) 20-minute sampling duration for longer period swell and 10-minute duration for wind waves; (3) band-averaging of wave spectra to produce 47 frequency bands, ranging from .0325 to .485 Hz.

However, the DDWM includes significant adaptations from the DWPM. First, NDBC uses a spline interpolation to step-down the sampling rate of the 3DM-GX1 to the 1.0766 Hz sampling rate of wave processing software, whereas the DWPM samples analog voltages directly. The DDWM uses a 20-minute sampling duration at and below 0.350 Hz and a 10-minute sampling duration in the bands above 0.35 Hz. The 10-minute sampling duration covers the last 10 minutes of the full 20-minute sampling duration. DDWM employs overlapping bin-averaging below 0.10 Hz to preserve the same number of degrees of freedom used in earlier systems

DDWM computes directional wave parameters using the ARS with some significant changes. [2]

Fundamentally, ARS separates pitch and roll into time-dependent and time-independent components. The time-dependent components are computed by a series of forward and inverse integrations of angular rates from three, orthogonal, angular rate sensors until the algorithm converges to a solution. Then, the mean pitch and roll are added to the result. DDWM does not use an independent tilt sensor to compute the means of the pitch and roll. Instead, the later versions of DDWM take advantage of the three, independent, acceleration measurements and use the ratio of the mean mast acceleration to both the bow and starboard accelerations to estimate mean pitch and roll.

## IV. Quality Assurance

### *4.1. Functional Verification*

The DDWM undergoes a laboratory test to ensure all the electronics and sensors function. The flash memory card is cleared and initialized. Once tests are complete and documented, a quality assurance (QA) representative verifies the paperwork. Each unit is returned to inventory with a green tag stamped by QA. The green tag is a visual indication to property control and technicians conducting buoy integrations that this unit has been functionally tested and verified to be ready for field use.

### *4.2. System Verification*

Once the DDWM is integrated into a buoy, a procedure is conducted to compensate for magnetic influences from the buoy and other equipment. The test consists of spinning the buoy while also recording headings from a gyrocompass. An embedded process in the DDWM computes and stores hull magnetic correction coefficients. This compensation information is stored in the DDWM and is logged into NDBC configuration management systems.

The entire buoy system is allowed to operate in its normal operational mode, but with no actual waves, for a minimum of 48 hours at Stennis Space Center and then an additional 12 hours at the deployment port dockside. Once deployed, three hours of on-site testing are conducted prior to releasing the deployment team from the deployment site. On-site testing includes comparing visual observations of wave height, period and direction by a trained observer with those reported by the station

### *4.3. QA/QC Process and Procedures*

Because DDWM uses the same message format to encode data for transmission from the buoy to NDBC, NDBC can seamlessly apply its established quality control (QC) procedures [5] to the DDWM data. NDBC has developed both automated and manual QC techniques. Trained and experienced analysts perform the manual techniques. These include examining statistics, various data plots, and the results of the automated QC. NDBC has two modes of automated QC termed hard-flags and soft-flags. Hard-flag tests control the release of the data, and soft-flag tests provide further post-release diagnostics.

The hard-flag tests consist of a message-integrity check to ensure the messages have not been corrupted during the transmission, a range check and a time rate of change check. In addition, related measurements can be hard-flagged. For example, when the wave height is hard-flagged, the wave periods are automatically hard-flagged. Hard-flag uses a hierarchical system to apply the tests – that is, they are performed in a set order and once a parameter fails a hard-flag test, then the other tests – the lower order hard-flag and all soft-flag tests – are not performed. The hard-flag is preserved in the database.

Among the soft-flag tests are range and rate-of-change tests that use more refined limits, comparisons of wind speed with spectral densities at higher frequencies, wind direction with wind wave directions, swell wave fetch limit tests, and the check-ratio test. All soft-flag tests are performed and results recorded in the database unless the measurement has been hard-flagged.

Shoreside processing remains unchanged from WPM and DWPM. Acceleration spectra are transformed into displacement spectra by first removing low-frequency noise and then applying the Response Amplitude Operator for the hull and mooring, then dividing by the fourth power of the frequency.

The low-frequency noise correction uses the Hervey-Lang algorithm (Rex Hervey, personal communication), which is the Lang noise correction algorithm [6] adapted to the single noise band. DDWM also uses the Hervey-Lang algorithm to determine the lowest frequency at which to start the integration of the angular rates to determine pitch and roll.

Wave data from buoys with DDWM systems are available in real time via the Global Telecommunication System (GTS), NOAAPORT, and the NDBC Web site (http://www.ndbc.noaa.gov/).

NDBC preserves the measurements on its Web site, and permanent archives are at the National Ocean Data Center (http://www.nodc.noaa.gov/BUOY/buoy.html).

## V. LABORATORY TESTS

The DDWM with the 3DM-GX1 sensor and DWPM system with the Hippy have been tested in NDBC's lab to check sensor performance and to debug and verify various changes to the processing code. Some of the tests that have been conducted that provide a more direct comparison and sensor verification are discussed below.

### *5.1. 3DM-GX1 Sensor Magnetometer Verification*

The 3DM-GX1 sensor is the wave-motion sensing device in the DDWM. Therefore, it was tested to confirm sensor outputs. The magnetometer outputs were verified on NDBC's compass rose, which is an outdoor area free from magnetic interference of earth's magnetic field. Table II below compares measured values with those a few miles away at the Stennis Space Center Geomagnetic Observatory which were $B_z = 0.427$ and $B_{total} = 0.491$ *Gauss*. The test was conducted on September 18, 2007.

TABLE II
3DM-GX1 MAGNETOMETER COMPARISON

| Heading (Deg) | $B_x$ | $B_y$ | $B_z$ | $B_{total}$ |
|---|---|---|---|---|
| 0 | 0.263 | -0.006 | 0.457 | 0.5273 |
| 45 | 0.183 | -0.189 | 0.457 | 0.5273 |
| 90 | -0.003 | -0.263 | 0.459 | 0.5290 |
| 135 | -0.188 | -0.181 | 0.458 | 0.5271 |
| 180 | -0.260 | 0.006 | 0.458 | 0.5267 |
| 225 | -0.179 | 0.189 | 0.456 | 0.5251 |
| 270 | 0.007 | 0.261 | 0.456 | 0.5255 |
| 315 | 0.191 | 0.180 | 0.456 | 0.5261 |
| 360 | 0.263 | -0.006 | 0.457 | 0.5273 |
| Mean | | | 0.4571 | 0.5268 |
| Standard Deviation | | | 0.0011 | 0.0012 |

The discrepancy between the high values from the sensor and the true values from the observatory was traced to calibration procedures by the manufacturer, MicroStrain. The difference is not an important factor in wave direction calculations because the direction is derived simply from the arctangent of the bow ($B_x$) and starboard ($B_y$) magnetic measurements, which, even if equally mis-scaled, will yield accurate results.

### *5.2. 3DM-GX1 and Hippy Significant Wave Height Verification and Comparison*

For wave heights, a series of tests have been conducted. In one such test, the Datawell Hippy 40 Mk II was mounted beside a 3DM-GX1 for several minutes of operation on NDBC's Ocean Wave Instrument Facility (OWIF), which has a radius of motion of one meter. Ideal wave height H should be 2.83 meters. Several runs were made for seven wave periods $T$ with one of three wave slopes $\varphi$. Going counterclockwise, the maximum $\varphi$ and minimum slopes $-\varphi$ occur at the 3 o'clock and 9 o'clock positions in the wave orbit, respectively. At the 12 o'clock and 6 o'clock position, wave slope is horizontal. The results are shown in Table III. The test is somewhat artificial in that the wave slopes are much greater than would occur naturally, according to linear wave theory. This may explain the high variance in the results.

TABLE III
WAVE HEIGHT COMPARISONS

| $T$ (sec) | $\varphi$ (Deg) | $H$ Hippy (m) | $H$ 3DM-GX1 (m) | Error Hippy (%) | Error 3DM-GX1 (%) |
|---|---|---|---|---|---|
| 6 | 8 | 2.94 | 3.10 | -0.04 | -0.10 |
| 9 | 0 | 3.01 | 2.87 | -0.06 | -0.01 |
| 9 | 8 | 2.91 | 2.85 | -0.03 | -0.01 |
| 9 | 24 | 3.19 | 2.84 | -0.13 | -0.003 |
| 12 | 0 | 2.88 | 2.94 | -0.02 | -0.04 |
| 12 | 8 | 2.87 | 2.98 | -0.01 | -0.05 |
| 12 | 24 | 2.99 | 3.04 | -0.06 | -0.07 |
| 15 | 0 | 2.79 | 2.87 | 0.01 | -0.01 |
| 15 | 8 | 2.75 | 2.82 | 0.03 | 0.004 |
| 15 | 24 | 2.79 | 3.44 | 0.01 | -0.22 |
| 18 | 0 | 2.93 | 2.92 | -0.04 | -0.03 |
| 18 | 8 | 1.81 | 2.92 | 0.36 | -0.03 |
| 18 | 24 | 2.93 | 4.08 | -0.04 | -0.44 |
| 21 | 0 | 2.75 | 2.72 | 0.03 | 0.04 |
| 21 | 8 | 2.69 | 2.77 | 0.05 | 0.02 |
| 21 | 24 | 2.86 | 4.76 | -0.01 | -0.68 |
| 24 | 0 | 2.69 | 2.59 | 0.05 | 0.08 |
| 24 | 8 | 2.76 | 2.61 | 0.02 | 0.08 |
| Mean | | 2.81 | 3.10 | 0.01 | -0.08 |
| Standard Dev. | | 0.28 | 0.54 | 0.10 | 0.19 |

A limitation of the OWIF, and a reason for the artificiality of the simulated waves, is that it cannot be turned faster than 4.5 seconds per revolution, due to its relatively large size. For this reason, a smaller Desk Top Wave Simulator (DTWS) was developed. It can be turned considerably faster. It has a radius of motion of 0.245 meter, which produces wave heights of 0.69 meter, and a tilt angle of 14 degrees. Table IV gives results from a series of tests at frequency *f*. These were conducted to see if there is any frequency dependency in the sensor, that is, a rise or decline in wave heights depending on waved period. From the results, we see a small variation in wave height but no definite trend with frequency.

TABLE IV
3DM-GX1 WAVE HEIGHT TEST USING DTWS

| $H$ (m) | $f$(Hz) |
|---|---|
| 0.728 | 0.2404 |
| 0.745 | 0.2884 |
| 0.756 | 0.3495 |
| 0.712 | 0.3545 |
| 0.659 | 0.4356 |
| 0.696 | 0.4361 |
| 0.716 | 0.4384 |
| 0.802 | 0.4800 |
| 0.793 | 0.4885 |
| 0.657 | 0.6246 |
| 0.729 | 0.6269 |
| Mean = 0.727 | |
| Standard Dev. = 0.047 | |

## VI. FIELD TESTS

The DDWM was deployed with a DWPM–-Hippy system on a 3-meter buoy platform north of Hawaii at station 51000. The area was open-ocean with a depth of about 4,755 meters. Both systems were configured to collect data during the same 20 minutes each hour. The systems were mounted on the same buoy platform. The sensing elements are mounted in the hull with the 3DM-GX1 mounted just above the Hippy sensor. Data were reported once an hour through the onboard data acquisition and reporting system.

Table V below summarizes the comparison of the DDWM to the DWPM-Hippy and the NDBC requirements. The comparison period was from May 1, 2009 to May 30, 2009. The energy-weighted directions were calculated by using data in which the wave heights exceeded 25 centimeters.

Therefore, if one assumes the Hippy system is the standard, then the DDWM measures NDBC's bulk wave parameters within NDBC accuracies requirements.

TABLE V
DDWM COMPARED TO DWPM-HIPPY

| Measurement | Mean Difference | rms Difference | NDBC Requirement |
|---|---|---|---|
| Significant Wave Height | -0.02 m | 0.03 m | ±0.2 m or ±10% |
| Average Period | 0.19 s | ±0.08 s | ±1.0 s |
| Peak Period | 0.13 | ±1.01 s | ±1.0 s |
| Energy-weighted wave direction | -0.53 ° | ±5.34 ° | ±10 ° |

A characteristic of the 3DM-GX1, which NDBC has found with previous deployments, is its tendency to give reduced wave energy on the high end of the spectrum. This is also seen in the deployment of 51000. There are two reasons for this. The more important reason is that the sensor picks up less energy than does the Hippy. The second reason is that the accelerations of the 3DM-GX1 are not tilt-compensated. There is a slight cosine error when using mast accelerations instead of true vertical accelerations, as from the Hippy. Mean spectral energy density and the relative difference, DDWM-DWPM, are given in Figure 5. The reduced high-frequency energy of the DDWM has little effect on the wave height measurement; the mean difference in wave height between the DWPM-Hippy and DDWM-3DM-GX1 is a very small -2 centimeters. The relative differences on the low end of the spectrum can be attributed to the low-frequency noise correction used. Two coefficients in the Lang-Hervey noise correction can be adjusted to bring the two curves closer together on the low end.

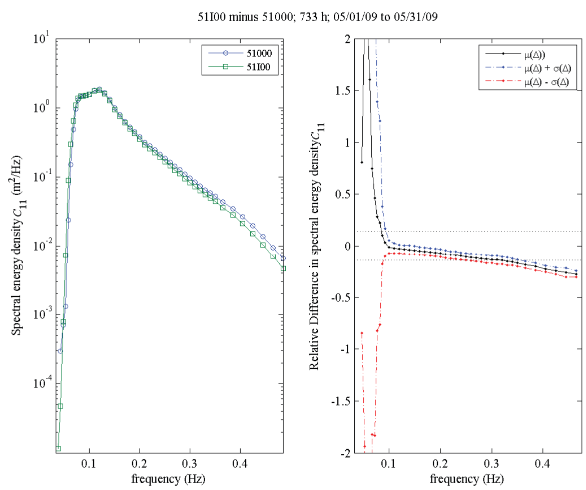


Figure 5 Left panel: average spectral energy density from DWPM Hippy from 51000 and 51I00. Right panel: Mean $\mu$ and standard deviation $\sigma$ of relative difference $\Delta$ of spectral energy density, 51I00 minus 51000, by frequency for the time noted. Threshold for energy used in computations of relative difference is 0.001 m$^2$/Hz. Dotted lines at -0.14 and 0.14 denote range of acceptability in difference.

One interesting instance of low-amplitude, long-period swell waves reaching the station is used to verify sensitivity to swell waves and its directional accuracy. In this case, the energy spectra of both the DWPM and DDWM detected wave energy of 1 m$^2$/Hz at frequency of 0.0725 hertz at 1300 UTC 11 May 2009. An energy level of 1.0 m$^2$.Hz corresponds to wave amplitude of 10 cm, from which we can conclude that the buoy was tilting no more than ±0.12º at that frequency.[1]

The direction of the energy components from the DDWM and DWPM were 178°N and 171°N, respectively. Using the ridgeline technique of Mettlach and Teng [3], the energy was propagated back to the respective points of swell origin, as shown in Figure 6. Also plotted on the map is a best estimate of swell origin based on a visual inspection of wind speed and direction at a distance of 5,771 nautical miles, yielding errors from 51000 and 51I00 to be -2º and +5º, respectively.

Although this was the only swell case during the field test period, it dramatically proves the accuracy of the DDWM with respect to the DWPM-Hippy and natural conditions.

[1] Wave length $L$ of a 0.0725-hertz wave = 297 m. Wave number $k$ = 0.0212 radians per meter. Amplitude $a$ = 0.10 m Maximum wave slope = $ak$, amplitude times wave number. $\arctan(ak)\times 180/\pi = .12°$

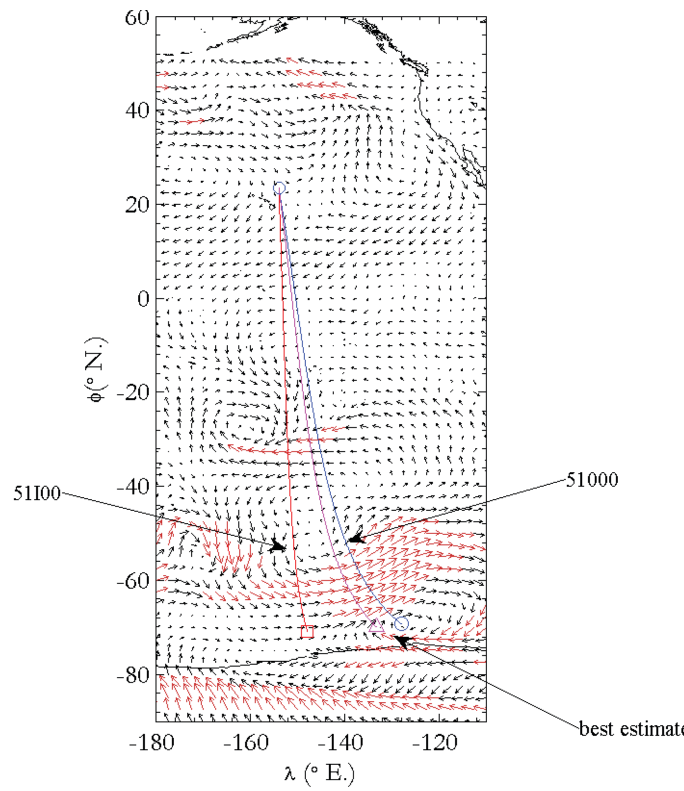


Figure 6 Map of central-east Pacific Ocean 0600 UTC 30 April 2009, time of swell origin, and paths of wave energy estimated from wave parameters from the two systems 51000 and 51I00. Between the two buoy trajectories is estimated best path based on wind direction in the Ross Sea, Antarctica. Arrows in red denote a wind exceeding 15 m/s. Arrow size is proportional to wind speed, direction is direction toward. (Wind field obtained from NOAA/OAR/ESRL.)

## VII. CONCLUDING REMARKS

NDBC has completed development and fielding of a directional wave measurement system that is more compact and more economical to use in its national network of ocean observing systems than earlier systems. This system uses a small COTS sensor that measures angular rate, acceleration, and magnetism on three orthogonal axes. The DDWM uses a unique processing algorithm to convert the angular rate to pitch and roll angles and then processes the results into the NDBC wave products. The DDWM re-uses many system and data architectural components to deliver, manage and QC the wave data. Because of its economic advantage, the DDWM will allow NDBC to measure directional waves on many more stations than it could if only the Hippy-based system were used. Tests have shown that the DDWM meets NDBC bulk wave parameter requirements. The Hippy system will remain in NDBC's inventory of wave systems for special-case use only.

NDBC strives to continually improve its wave products through market research and quality assurance testing. Future plans will involve more stringent tests of the DDWM's response before and after deployment using the DTWS and fielding of a non-directional mode of the DDWM. The non-directional mode will be used on platforms that are not discus shaped, can not be easily compensated for magnetic influences, or where directional waves are not funded. Using the DDWM in those cases will further reduce the different types of wave equipment to maintain, test, repair, etc., thus further improving budget efficiency.

Future development opportunities include using all three accelerations to resolve the true vertical acceleration. OWIF testing has demonstrated that doing so will dramatically improve wave measurements during extreme high waves. Also for certain smaller, spherical hulls, the three accelerations, instead of pitch and roll angles, can be used to resolve wave directions. Flash memory card data from 51I00 has been used to test the approach.

## ACKNOWLEDGMENTS

DDWM development was done under the general NDBC technical services contract with Sciences Applications International Corporation, Advanced Science and Engineering Operation (ASEO). Reanalysis data in Figure 6 provided by the National Oceanic and Atmospheric Administration's Office of Oceanic and Atmospheric Research Earth Systems Research Laboratory, Physical Science Division (NOAA/OAR/ESRL PSD), Boulder, CO USA from their Web site at www.cdc.noaa.gov

## REFERENCES

[1] Steele, K.E, E.L. Burdette and A. Trampus, 1978: A System for the Routine Measurement of Directional Wave Spectra from Large Discus Buoys, Proceedings of Oceans '78, Washington D.C., 6-8 September 1978, 94-102

[2] Steele, K.E., Wang, D.W., Earle, M.D., Michelena, E.D., Dagnall, R.J., 1998, Buoy Pitch and Roll Computed Using Three Angular Rate Sensors, *Journal of Coastal Engineering,* IEEE, Vol. 35, pp. 123-139.

[3] Mettlach, Theodore and Chung-Chu Teng, 2006: Validation of National Data Buoy Center Directional Wave Measurements Using Swell Waves from Distant Storms, *Proceedings of Oceans '06*, Boston.

[4] Chaffin, J.N., Bell, W., and Teng, C.C., 1992, Development of NDBC's Wave Processing Module, *Proceedings of MTS 9*2, MTS, Washington, D.C. pp. 966-970.

[5] NDBC, 2003: *NDBC Technical Document 03-02, Handbook of Automated Data Quality Control Checks and Procedures of the National Data Buoy Center,* 54 pp. [Available on-line at: http://www.ndbc.noaa.gov/handbook.pdf].

[6] Lang, N., 1987. The empirical determination of a noise function for NDBC buoys with strapped-down accelerometers," *Proceedings of OCEANS 87*, IEEE, New York, NY, pp. 225-228.