Status of and Plans for the Wave Measurement Program at NOAA's National Data Buoy Center

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1. Introduction

Surface gravity waves (whose wave frequencies range from 1.0 to 0.033 Hz) entering and crossing the nation's waters, have a profound impact on navigation, offshore operations, recreation, safety, and the economic vitality of the nation's maritime and coastal communities. Although waves are a critical oceanographic variable and measurement assets exist, there are roughly 200 observation sites (about one-half estimate directional waves) around the U.S. leaving significant gaps in coverage.

In 2009, The National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center' Wave (NDBC) Wave Measurement Program reached unprecedented levels of buoys and directional waves measurements. The number of operational buoys reached 117 in mid-September 2009 and buoys making directional wave measurements have more than doubled since 2003. The increase in wave measurements is being driven by requirements and technology.

2. NDBC Wave Measurements

NDBC has made wave measurements from buoys since 1970 and directional wave measurements since 1972. NDBC buoys' primary purpose is to measure wind and pressure. Directional wave measurements are made from discus-hull buoys using pitch/roll/heave method. The wave measuring sensors are either the Datawell Hippy 40 or a strapped-down accelerometer to determine heave and magnetometers or angular rate sensors to determine pitch and roll. NDBC's directional wave measurements use the method of Longuet-Higgins *et al.* (1963) after transforming the time series data into the frequency domain using a Fast Fourier Transform (FFT). NDBC averages adjoining Fourier frequency bands to reduce the amount of data for transmission shoreside. Directional wave data are transformed from the buoy-hull coordinate system by using orthogonal magnetometers to determine the heading of the buoy's hull with respect to magnetic North. Finally, the earth's magnetic declination is applied to render the directional wave measurements in True North coordinates.

NDBC uses three approaches to determine pitch and roll: (1) The Datawell Hippy provides direct output of pitch and roll, (2) the magnetometer signals can be separated into time-invariant time-varying components which then can be used to determine pitch and roll, this approach is called the Magnetometer-Only (or MO) method, and (3) integrating three orthogonal angular rate sensors with an independent tilt sensor to determine the constants of integration, this approach is call the Angular Rate System (ARS).

Once shoreside, NDBC applies Response Amplitude Operators to correct for hull-mooring effects and heave sensor response. For strapped-down accelerometers, NDBC applies a low-frequency correction to the acceleration spectral density data to remove time-dependent noise component of tilting on the vertical acceleration. Without this correction, noise would be overly amplified when the acceleration spectra are integrated (divided by the very small numbers of the 4^{th} power of the radian frequency) to produce the displacement spectra. NDBC then calculates the bulk wave parameters – significant wave height, dominant (or peak) period, average period, and mean wave direction at the dominant period. NDBC also applies its swell-wind wave separation algorithm to produces bulk wave parameters for swell and wind waves.

NDBC performs automated quality control on the bulk wave parameters before distributing the data in real-time (NDBC, 2009). Real-time data are distributed in World Meteorological Organization message formats on the Global Telecommunication System and NOAAPORT. NDBC performs further analysis before submitting the data to the long-term archive at the National Oceanographic Data Center (http://www.nodc.noaa.gov/BUOY/buoy.html) and preserving them on the NDBC website (http://www.ndbc.noaa.gov/).

2. Requirement Drivers

The deployment of a worldwide Ocean Observing System is one goal within the three central science and technology elements of the Ocean Research Priority Plan issued by the Joint Subcommittee on Ocean and Science and Technology in January 2007. Since the U.S. Integrated Ocean Observing System (IOOS®) identified ocean surface waves as one of the most important ocean variables to be observed in real-time, NDBC partnered with the U.S. Army Corps of Engineers to develop a U.S. national operational plan for observing wind-generated surface gravity waves. The plan can be found at: http://ioos.gov/program/wavesplan.html

Existing locations were determined based on local weather forecast office requirements, resulting in a useful, but *ad hoc* wave network with limited integration of the observations into user products. The proposed system will increase the wave observation spatial coverage along and across the US coasts to about 300 sites (upgrading approximately 130 existing platforms to directional capabilities); and will serve a large and increasing user community. The design will complement existing and future remote sensing programs (land and satellite based systems). This effort will also coordinate with and leverage related international efforts, such as the Global Earth Observing System of Systems (GEOSS).

All NDBC buoys make non-directional (or omnidirectional) wave measurements. However, the number of directional wave measurements has more than doubled since 2003 (Figure 1). The National Weather Service has recognized the increased need for measurements in areas of demanding weather and sea conditions in Alaska, under the Alaska Buoy Network Expansion Project (ABNE), and in the tropics, under the Hurricane Supplemental Buoy Project (HSB). ABNE expanded the number of buoys in Alaskan waters from 5 to 19 during a six-year period completed in 2007 (Figure 2).

In May 2009, NDBC deployed the final three buoys of the 15-buoy HSB that spans the Gulf of Mexico, Caribbean Sea, and the tropical Atlantic (Figure 3). Other individual projects brought new buoys to Hawai'i, the Straits of Juan De Fuca, New England, Florida Straits, and the Gulf of Mexico. In addition NDBC has replaced non-directional measurements at a number of Coastal-Marine Automated Network (C-MAN) stations with directional wave buoys.

The increase has occurred despite the loss of the sponsorship by the Department of the Interior's Minerals Management Service for its buoys in the Santa Barbara Channel and the Gulf of Mexico, and the loss of sponsorship for the Christmas Island buoy (Station 51028).

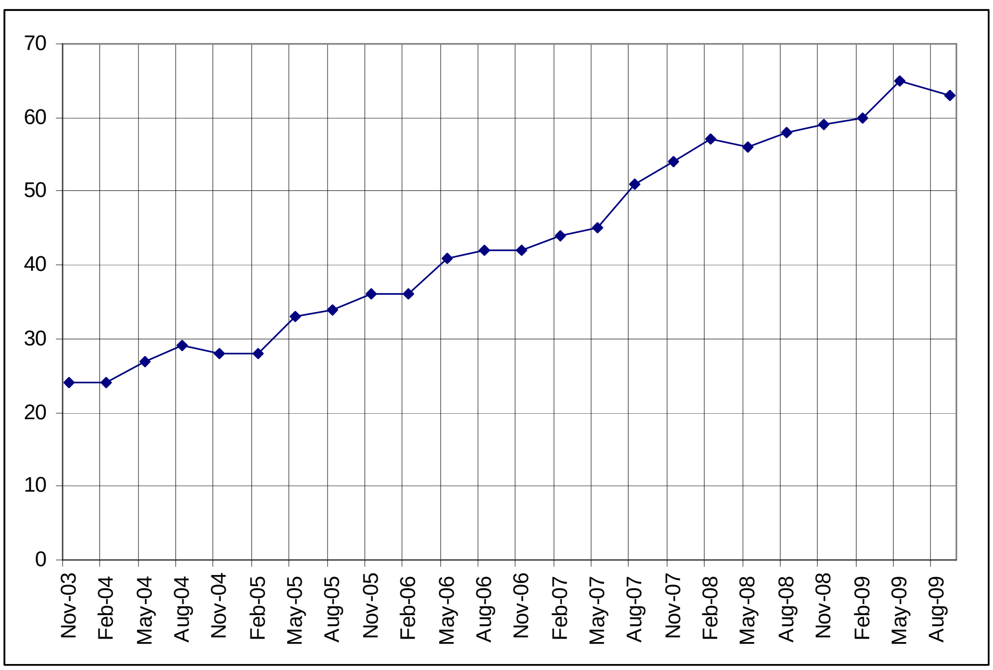

Figure 1: Growth in the Number of NDBC Directional Wave Buoys

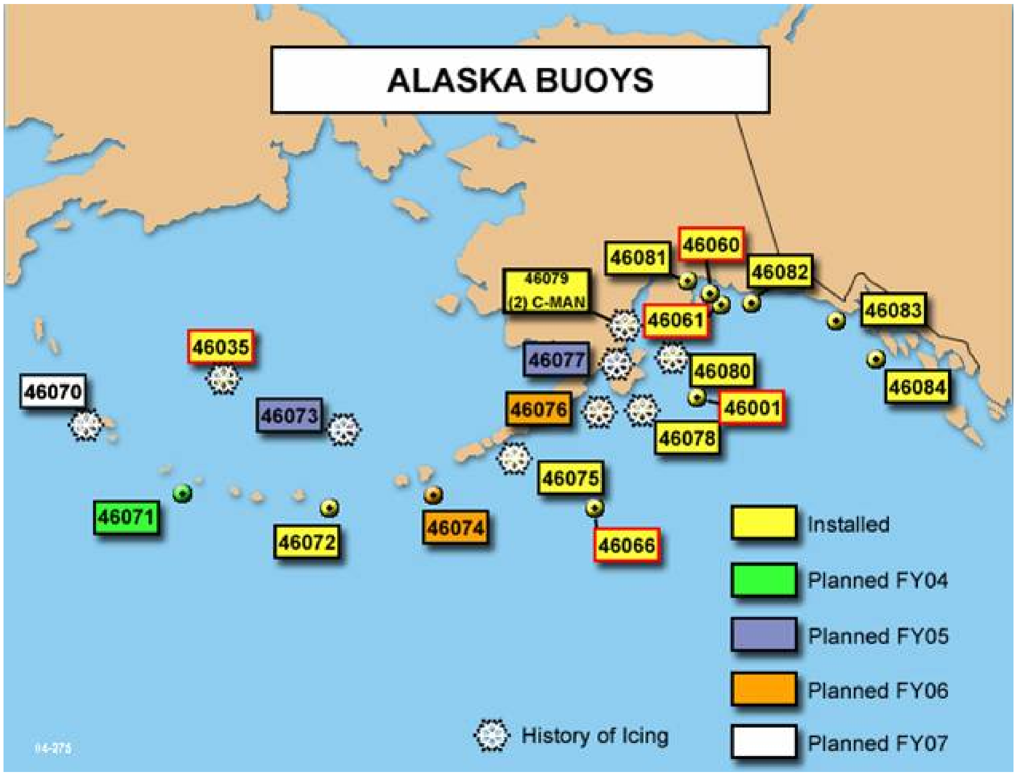

Figure 2: Alaska Buoy Expansion Network

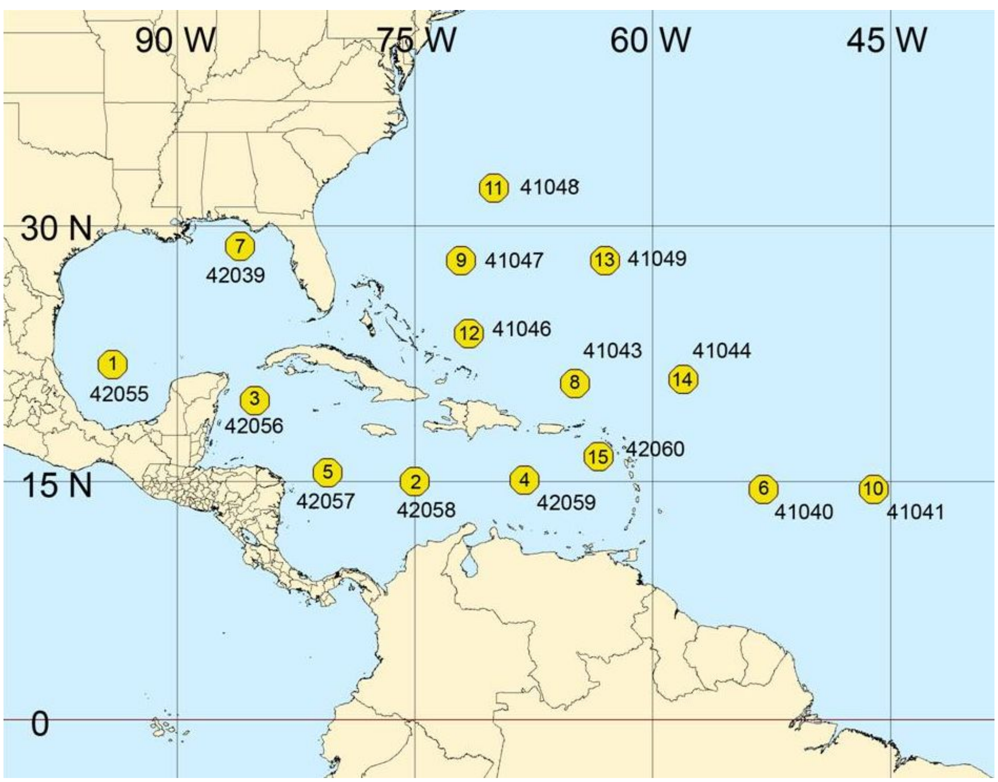

Figure 3: Hurricane Supplemental Buoys

3. Technology Drivers

The overriding goal of the National Wave Measurement Plan is to provide the US with a seamless coverage along and offshore system of consistent directional wave measurements comprised by a level of accuracy that will serve the requirements of the broadest range of IOOS® wave information users. To achieve this goal requires that the observations satisfy a *First-5* standard. Setting the standard to a *First-5* level will directly lead to improved estimates in height, period, direction, and provide better information to all users of wave information. *First-5* refers to 5 Fourier coefficients defining variables at the entire range of energy carrying frequencies. The first variable is the wave energy, related to the wave height, and the other four are the first four coefficients of the Fourier series that defines the directional distribution of that energy.

Less expensive hulls and wave measurement systems allow NDBC to add directional wave measurements to more buoys than ever. NDBC uses a newly-developed, low-cost 1.8-m foam hull to provide directional wave measurements in proximity to C-MAN stations, such as Buzzards Bay, MA (BUZM3), Sand Key, FL (SANF1), or Cook Inlet, AK.

The development that will have the most long-term impact on NDBC directional Wave measurements is the fielding of the Digital Directional Wave Module (DDWM). DDWM is the latest descendant of the Wave Processing Module (WPM) (Chaffin *et al*., 1992) – which samples at 1.0766 Hz to provide higher-resolution low-frequency measurements and extend the high-frequency bands up to 0.485 Hz. The DDWM's motion sensor is a model 3DM-GX1 manufactured by MicroStrain Inc. The 3DM-GX1 provides measurements from three orthogonal angular rate sensors, three orthogonal acceleration sensors, and three orthogonal earth magnetometers.

DDWM uses the ARS method to determine directional wave measurements with several important modifications to accommodate the digital output of the 3DM-GX1 sensor, reduction of the longest sampling duration from 40 minutes to 20 minutes, the removal of the independent tilt senor, and the use of mean measured Earth magnetic fluxes for pre-determined model output fluxes. Without an independent tilt sensor, the mean pitch and roll are derived from the ratios of the horizontal components of accelerations to the vertical accelerations.

NDBC conducted a preliminary field evaluation consisting of a Datawell Hippy 40 and a DDWM co-located on a 3-m discus hull anchored to the northeast of Hawai'i. After approximately one month of data with significant wave heights ranging from 0.8 to 3.0 m, the first evaluation indicates good agreement between the two systems (Table 1).

TABLE 1: DDWM Compared to Hippy, May 2009, Sample Size 744 (Teng *et al.*, 2009).

Measurement	Mean Difference	Root Mean Square Difference	NDBC Goal
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 s	±1.01 s	±1.0 s
Energy-weighted Wave Direction	-0.53 °	±5.34 °	±10 °

The 3DMG-X1 reduces the size (Figure 4) and costs of making directional wave measurements, thus allowing more buoys to make directional wave measurements. That the 3DM-GX1 integrates all 9 sensors can lead further improvements in wave measurements, such as using a hybrid approach that uses particle following (orbital velocities) in the lower frequencies to improve the detection of low-frequency, small-slope swell waves and slope-following in the higher frequency, steeply-sloped waves.

The integrated sensors of the 3DMG-X1 will also allow the application of a true tilt correction to the strapped-down accelerometer measurements to overcome the problems with phase lag between tilt and heave sensors in NDBC's early attempts. In 2009, NDBC hosted a multi-sensor evaluation using its Ocean Wave Instrument Facility (OWIF) and Desk-Top Wave Simulator (DTWS, Figure 5) with participation by the Naval Research Laboratory and Texas A&M University. The evaluation demonstrated promising results for the direct application of a tilt correction. NDBC's OWIF (Steele *et al.*, 1985) provides realistic testing of directional wave measurements in a controlled environment down to 5-second periods. NDBC developed the DTWS to extend the test range to less than 3 s.

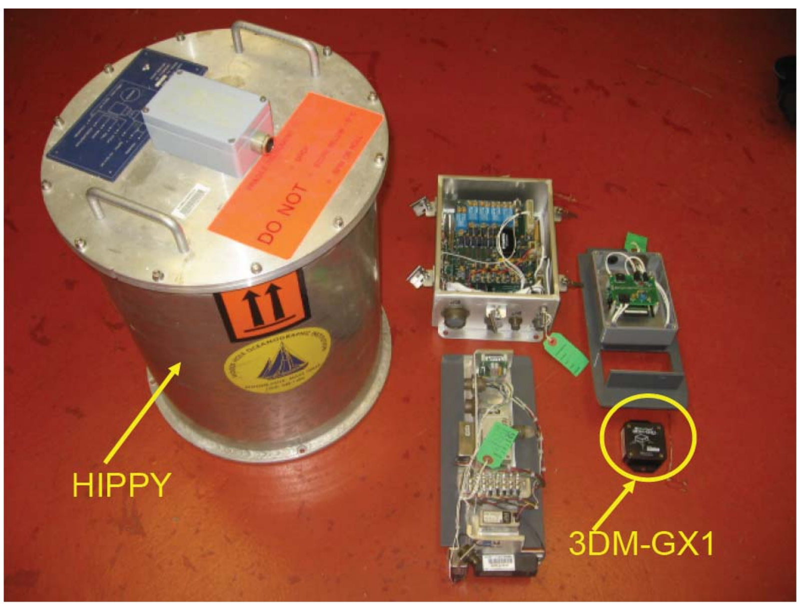

Figure 4: Hippy vs 3DM-GX1

4. Plans

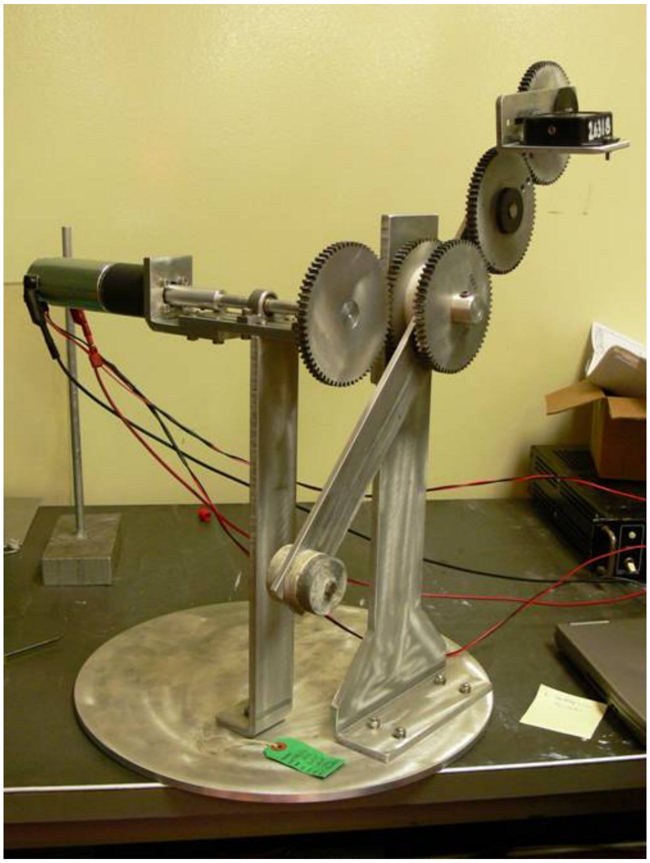

Figure 5: Desk-Top Wave Simulator (DTWS). The radius of the arm is 24 cm.

NDBC's role in the National Waves Plan cover many areas: (1) upgrade existing sensors; (2) add additional observations in critical "gap" locations; (3) implement a continuous technology testing and evaluation program; (4) support the Quality Assurance / Quality Control (QA/QC) and data integration of wave observations from a large number of IOOS operators; (5) support the operation and maintenance requirements of the system; (6) include the training and education of IOOS wave operators; and (7) promote the development of new sensors and measurement techniques.

In terms of upgrading sensors, in the near-term, NDBC is phasing out the remaining Magnetometer-Only directional wave stations and replacing them with DDWM. In the longer-term, NDBC will replace all of its wave systems with DDWM. The Datawell Hippy will remain in the NDBC inventory.

To fill key gap areas and enhance the network, NDBC is developing a standard, multi-purpose hull, called NDBC Standard Buoy. The Standard Buoy's foam hull and interchangeable electronics housings reduce manufacturer, maintenance, logistics, training, and deployment costs. The Standard Buoy has the potential to make wave measurements from any of NDBC's three systems (Figure 6) – the traditional weather buoys, the 55 buoys of the Tropical Atmosphere Ocean Array (TAO) that straddle the equatorial Pacific, and from 39 buoys of the Tsunami Detection Network that use the Deep-ocean Assessment and Reporting of Tsunamis (DART) technology. NDBC is also maintaining a vigorous test and evaluation program to ensure that wave observations from the Standard Buoy will meet First-Five requirements.

NDBC is a leader in developing improved QA/QC algorithms and techniques for marine observations. NDBC, collaborating with other wave quality control centers like Scripps Coastal Data Information Program (CDIP) and IOOS Regional Associations, has either chaired or co-chaired four Quality Assurance of Real-Time Ocean Data (QARTOD) meetings to focus on standardization and improvements of wave quality control. The next QARTOD meeting will be held in Atlanta, GA on 17 – 19 November 2009. Waves will continue to be a focus for this and future meetings.

Figure 6: NDBC Standard Buoy in its Major Configurations

Acknowledgments.

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