Establishing the Provenance of NDBC’s Accuracy Statement for Directional Waves

Richard H. Bouchard and Rodney E. Riley
National Data Buoy Center (NDBC), Stennis Space Center, MS USA

Ocean Waves Workshop, New Orleans, 15 January 2015
Provenance
• the place of origin or earliest known history of something.
• the beginning of something's existence; something's origin.
• a record of ownership of a work of art or an antique, used as a guide to authenticity or quality.
Several recent studies reported long-term trends extracted from these records. However, significant modifications of the wave measurement hardware as well as the analysis procedures since the start of the observations result in inhomogeneities of the records.
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Increase In Directional Wave Platforms
The payload (on-board computer system) presently installed at each station is given in the opening paragraph of each station’s present data page. For information on what payloads were used historically at each station, consult the NDBC data inventory.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>RANGE</th>
<th>FREQ.</th>
<th>AVG. PERIOD</th>
<th>RESOLUTION</th>
<th>ACCURACY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Dir.</td>
<td>0 to 360  deg</td>
<td>1.71 Hz</td>
<td>40/20 min</td>
<td>0.1 deg</td>
<td>+/- 10 deg</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>0 to 62 m/s</td>
<td>1.71 Hz</td>
<td>2/8 min</td>
<td>0.1 m/s</td>
<td>+/- 1.0 m/s or 10% ***</td>
</tr>
<tr>
<td>Wind Gust</td>
<td>0 to 82 m/s</td>
<td>1.71 Hz</td>
<td>3 &amp; 5 sec</td>
<td>0.1 m/s</td>
<td>+/- 1.0 m/s or 10% ***</td>
</tr>
<tr>
<td>Air Temp.</td>
<td>-40 to +60 °C</td>
<td>1.71 Hz</td>
<td>2/8 min</td>
<td>0.1 °C</td>
<td>+/- 1.0 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>800 to 1100 hPa</td>
<td>1.71 Hz</td>
<td>2/8 min</td>
<td>0.1 hPa</td>
<td>+/- 1.0 hPa</td>
</tr>
<tr>
<td>Sea Surface Temp.</td>
<td>-5 to +40 °C</td>
<td>1.71 Hz</td>
<td>2/8 min</td>
<td>0.1 °C</td>
<td>+/- 1.0 °C</td>
</tr>
<tr>
<td>Rel. Humidity</td>
<td>0 to 100%</td>
<td>1.71 Hz</td>
<td>2/8 min</td>
<td>0.1%</td>
<td>+/- 3%</td>
</tr>
<tr>
<td>Wave Height</td>
<td>0 to 35 m</td>
<td>1.71 Hz</td>
<td>40/20 min</td>
<td>0.1 m</td>
<td>+/- 0.2 m</td>
</tr>
<tr>
<td>Wave Period</td>
<td>0 to 30 SEC</td>
<td>1.71 Hz</td>
<td>40/20 min</td>
<td>1.0 sec</td>
<td>+/- 1 sec</td>
</tr>
<tr>
<td>Wave Spectra</td>
<td>0 to 99 m^2/m^2</td>
<td>1.71 Hz</td>
<td>40/20 min</td>
<td>0.01 Hz^1</td>
<td>NA</td>
</tr>
</tbody>
</table>
What Do We Mean by Wave Direction?

NDBC (1996) for details

• NDBC uses the method of Longuet-Higgins, Cartwright and Smith (1963) for heave, pitch, and roll from a moored DISCUS buoy

• Pitch and Roll from:
  – Datawell Hippy 40
  – Integration of three orthogonal angular rate sensors (ARS)
  – Partitioning Magnetometer Measurements (MO)

• NDBC then makes slopes in the buoy frame of reference

• Determine the buoy heading with respect to Magnetic North from the earth’s magnetic fluxes as measured by three orthogonal magnetometers and pitch and roll

• Magnetic declination then rotates to True North

• Slopes are passed through an FFT -> Co and quadrature spectra

• Use the first and second order Fourier Coefficients to determine directional wave spectra
HIPPY: 66,000 cm³, 36 kg, US$17,500
3DMG: 145 cm³, 0.075 kg, US$ 1,300
First and Second Order Fourier Coefficients:

\[ \tilde{a}_1(f) , \bar{b}_1(f) , \tilde{a}_2(f) , \bar{b}_2(f) \]

First order are functions of the quad-spectra; Second order, co-spectra

Mean Wave Direction (alpha1), WMO (1995):

\[ \alpha_1(f) = \frac{3\pi}{2} - \tan^{-1}(b_1(f), a_1(f)) \]

Principal Wave Direction (alpha2), WMO (1995):

\[ \alpha_2(f) = \frac{3\pi}{2} - \tan^{-1}(b_2(f), a_2(f)) \] + 0 or \( \pi \), closest to \( \alpha_1 \)

\( \alpha \) follows the IAHR (1997) convention:

As the angle between true north and the direction from where the waves are coming.
Clockwise is positive…
First and Second Normalized (wrt zeroth order Fourier Coefficient(spectral density) ) Polar Coordinates, WMO (1995)

\[
r_1(f) = \frac{\sqrt{b_1(f)^2 + a_1(f)^2}}{a_0(f)}
\]

\[
r_2(f) = \frac{\sqrt{b_2(f)^2 + a_2(f)^2}}{a_0(f)}
\]

From O’Reilly, 2008
• Fourier Coefficients:

\[ S(f, \theta) = \frac{a_0}{2} + \sum_{n=1}^{2} [a_n \cos(n\theta) + b_n \sin(n\theta)] \]

• Or in WMO terms:

\[ S(f, \alpha) = C_{11}(f) \ D(f, \alpha) \]

\[ D(f, \alpha) = \left[ \frac{1}{2} + r_1 \cos(\alpha - \alpha_1) + r_2 \cos(2(\alpha - \alpha_2)) \right] \frac{1}{\pi} \]

Note: Because of trig function properties and differences, this can yield negative \( S(f) \).
• Longuet-Higgins (1963) angular distribution

\[-D(f,\theta) = G(s) |\cos[(\theta-\theta)/2]^{2s}\]

• Where: \( S = r_1/(1 - r_1) \)

• Directional Width = \((2-2r_1)^{1/2}\)
Wave Direction Statistic Used in Certification or Commissioning is the Mean Wave Direction (at the Peak Frequency (Dominant Period)): \( \alpha_1(f=\text{max } C_{11}) \)

MWD also is:
- Wind Wave Direction (WWD)
- Swell Wave Direction (SWD)
in Spectral Partitioning
• Accuracy criteria used to certify/commission systems for operational use
• Other parameters are evaluated, and errors on the same order
• Field evaluations over a limited time
• Comparison with operational standard
• Generally:
  – Eliminate failed QC reports
  – Limited to cases when Peak Frequencies match
  – Statistic is either Root Mean Square Deviation (RMSD) or Functional Precision (Hoehns, 1977 & Gilhousen, 1987)

\[ FP = \sqrt{BIAS^2 + STDDiff^2} \]
<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Short Name</th>
<th>First Deployed</th>
<th>Last Deployed</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directional Wave Data Analyzer</td>
<td>DWDA</td>
<td>~1980</td>
<td>?</td>
<td>Steele <em>et al.</em>, 1985</td>
</tr>
<tr>
<td>Directional Wave Analyzer</td>
<td>DWA</td>
<td>~1986</td>
<td>MO, Dec 2010, Great Lakes</td>
<td>NDBC, 1996</td>
</tr>
<tr>
<td>Directional Wave Processing Module</td>
<td>DWPM</td>
<td>~1999</td>
<td>Analog, still used with Hippy 40</td>
<td>NDBC, 1996</td>
</tr>
<tr>
<td>Wave and Marine Data Acquisition System</td>
<td>WAMDAS</td>
<td>March 2006</td>
<td>~2010 NDBC 1.8m &amp; still on WHOI ASI</td>
<td>Teng <em>et al.</em>, 2007; Crout <em>et al.</em>, 2008</td>
</tr>
<tr>
<td>Digital Directional Wave Module</td>
<td>DDWM</td>
<td>April 2007</td>
<td>Operational</td>
<td>Teng <em>et al.</em>, 2009; Riley <em>et al.</em>, 2011</td>
</tr>
<tr>
<td>Candidate System</td>
<td>Reference Station</td>
<td>PoR</td>
<td># Samples</td>
<td>Statistic Type</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------</td>
<td>--------------</td>
<td>-----------</td>
<td>----------------------</td>
</tr>
<tr>
<td>DDWM 2.03</td>
<td>46042, Hippy, co-Hosted</td>
<td>Jan - Jun 2012</td>
<td>3510</td>
<td>MWD, RMSD</td>
</tr>
<tr>
<td>DWPM 20-minute</td>
<td>42056, DWPM 40-minute, Co-host</td>
<td>May - Sep 2008</td>
<td>3417</td>
<td>MWD, FP</td>
</tr>
<tr>
<td>DWPM, ARS</td>
<td>Gulf of Mexico</td>
<td>~ 2003</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>DWPM, Hippy</td>
<td>42003, GoM, WPM-MO</td>
<td>Sep-Oct 2003</td>
<td>253</td>
<td>MWD, FP</td>
</tr>
<tr>
<td>DWA, MO (Wang, 1995)</td>
<td>Monterey Bay, DWA Hippy</td>
<td>Oct 91-Mar 92</td>
<td>4268</td>
<td>MWD, Bias and STDDiff</td>
</tr>
<tr>
<td>DWA, Hippy (Gilhousen, 1990)</td>
<td>42015 &amp; 42016 (Mobile) &amp; 44006 (Duck)</td>
<td>1988</td>
<td>?</td>
<td>alpha1 at high frequencies; consistency between buoys and wind direction</td>
</tr>
</tbody>
</table>
Other Comparisons

• Pre-SWADE (Anctil et al., 1993)
  – 3-m discus with wind vane, DWA using Hippy 40 sensor
  – Deep-water evaluation in Gulf of Mexico with Bullwinkle platform
  – Mean Wave Direction, directional width, skewness and kurtosis
  – May – June 1989, 68 measurements
  – Poor correlation with skewness and kurtosis, better in higher seas
  – Direction and width: ~45/68 within 90% confidence limits!
Harvest Platform (O’Reilly et al., 1996)
• 3-m discus - DWA Hippy 40 & Datawell Waverider & pressure array at the platform
• Focused on Pacific swell; MWD integrated over the swell band (0.06 – 0.14 Hz)

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Datawell</td>
<td>NDBC</td>
</tr>
<tr>
<td>Energy</td>
<td>0.98 (0.98)</td>
</tr>
<tr>
<td>Direction</td>
<td>0.98 (0.97)</td>
</tr>
<tr>
<td>Spread</td>
<td>0.96 (0.96)</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.88 (0.87)</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>0.89 (0.88)</td>
</tr>
</tbody>
</table>
BUOY DIRECTIONAL WAVE OBSERVATIONS IN HIGH SEAS
Wang and Teng (1989)
14 – 18 December 1987, Monterey Bay, $H_s \sim 9$ meters
Hippy 40 DWA
MWD and S
Wave response to wind

As a result, we have increased confidence in the utility and quality of the data produced by NDBC's directional wave measurement buoys.
10 & 12-m Discus Hulls affected by currents

Based on Steele, 1997: Ocean Current Kinematic Effects on Pitch–Roll Buoy Observations of **Mean Wave Direction** and Nondirectional Spectra

- NDBC does not release in real-time directional wave measurements for frequencies above 0.20 Hz (< 5 sec)
- NDBC does archive (NODC) and preserve directional spectra at all frequencies
- **10-m anemometer height indicates hull in pre-2011 NODC records**
• Yaw induced by swell opposing wind increased errors
• Generally restricted to Gulf of Mexico and Great Lakes, a couple on the West Coast
• Notorious deviation occurred during Hurricane Ivan, 2004
## How Stable is the Accuracy Claim over Deployment

- Before leaving SSC, buoy heading accuracy < 4°
- Brought back four undamaged DDWM systems intact
- Reran buoy heading check
- Small sample, but found error ~ 6°, with largest 8.2°
- 8.2° - longest deployed, oldest battery and instrument ages, and hottest recal

<table>
<thead>
<tr>
<th>Buoy Hull Number</th>
<th>3D87</th>
<th>3DV13</th>
<th>3D33</th>
<th>3DV11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Cal Age (years)</td>
<td>2.8</td>
<td>3.2</td>
<td>1.9</td>
<td>4.2</td>
</tr>
<tr>
<td>Wave Instrument Age (years)</td>
<td>2.2</td>
<td>2.8</td>
<td>4.4</td>
<td>7.7</td>
</tr>
<tr>
<td>Battery Age (years)</td>
<td>3</td>
<td>4</td>
<td>2.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Air Temperature at Pre-Cal (°C)</td>
<td>18-22</td>
<td>16-24</td>
<td>16-27</td>
<td>17-32</td>
</tr>
<tr>
<td>Air Temperature at Post-Cal (°C)</td>
<td>2-10</td>
<td>2-16</td>
<td>2-16</td>
<td>23-29</td>
</tr>
<tr>
<td>Maximum Post-Cal Heading Error (°)</td>
<td>6.7</td>
<td>-6</td>
<td>-6</td>
<td>8.2</td>
</tr>
</tbody>
</table>
Summary

• 10° accuracy claim based on Mean Wave Direction at the Peak Frequency using RMSD or FP

• Field evaluation intercomparison with operational system for limited time

• Other directional parameters qualitatively reviewed, but are not Pass/Fail criteria for operational designation

• Limited Post-deployment calibrations show stability of heading calculations

• Provenance is a work in progress
Thanks

• Title slide picture courtesy of Weather Forecast Office Portland, OR

• Journal articles & Conference Proceedings:
  – NOAA Library, Boulder, CO
  – Maury Oceanographic Library, Naval Oceanographic Office, Stennis Space Center

• Chung-Chu Teng, Ken Steele, Dave Gilhousen, David Wang, Rex Hervey, Ted Mettlach, Bob Jensen
References


