Recent Advances in the NDBC Wave and Tsunami Measurement Programs

Richard H. Bouchard[1], Rodney Riley[1], Richard Dinoso[1], Karen Grissom[1], Walt McCall[1], George Mungov[2], and Thomas Ryan[3]

[1]National Data Buoy Center, Stennis Space Center, MS, USA 39503

Corresponding Author: richard.bouchard@noaa.gov

[2]National Geophysical Data Center, Boulder, CO, USA 80305

[3]National Oceanographic Data Center, Silver Spring, MD, USA 20910

NDBC Wave Program

1. NDBC last presented the Status and Plans for its Wave Measuring Program at the 11th Workshop in 2009 (Bouchard *et al.*, 2009). Since then NDBC has seen a number of significant accomplishments and events. These include, (a) Growth in the number of directional wave systems, (b) Development and deployment of dual wave measurement systems, (c) Development of the capability to record wave measurements on-board a buoy, (d) the establishment of a Field Laboratory for wave system intercomparisons and evaluation near Monterey Bay, CA, and (e) Field Evaluation of a tilt compensated vertical acceleration measurements.

   a) Since 2009, the number of NDBC stations making directional wave measurements decreased to a low of 52 stations in late 2011, but since then has rebounded to its highest level in history of 71 stations in late 2013 **(Figure 1)**. Directional wave measurements are now made on 65% of NDBC buoys compared to 30% in 2003.The rebound since 2011 is due to:
      i. Replacement of non-directional 6-m NOMAD hulls with 3-m discus hulls,
      ii. Reduction in costs of procuring and calibrating directional wave systems now make directional wave measurements economically viable for all discus hulls, and
      iii. Addition of Datawell Waveriders to NDBC's inventory, and collaboration with Monterey Bay Aquarium Research Institute on a multi-purpose buoy.

   b) In April 2011, NDBC deployed a dual directional wave measuring system at Station 44014, Virginia Beach. The system is sponsored by the U.S. Army Corps of Engineers and allows NDBC to evaluate wave systems on the same hull, which can accommodate both a Datawell Hippy 40 and an NDBC system. Data is returned from both systems in real-time and recorded on-board for use when the buoy is recovered. Since then, NDBC has added dual wave measurements at Stations 46042, Monterey Bay, and 46029, Columbia River Bar.

   c) NDBC wave systems now have the capability to record wave measurements on-board the buoy on memory cards. Once NDBC develops the necessary documentation and corrects the clock drift, it will work with the National Oceanographic Data Center (NODC) to archive the data. NDBC will only provided limited access to the data until the documentation is mature and the clock drift understood.

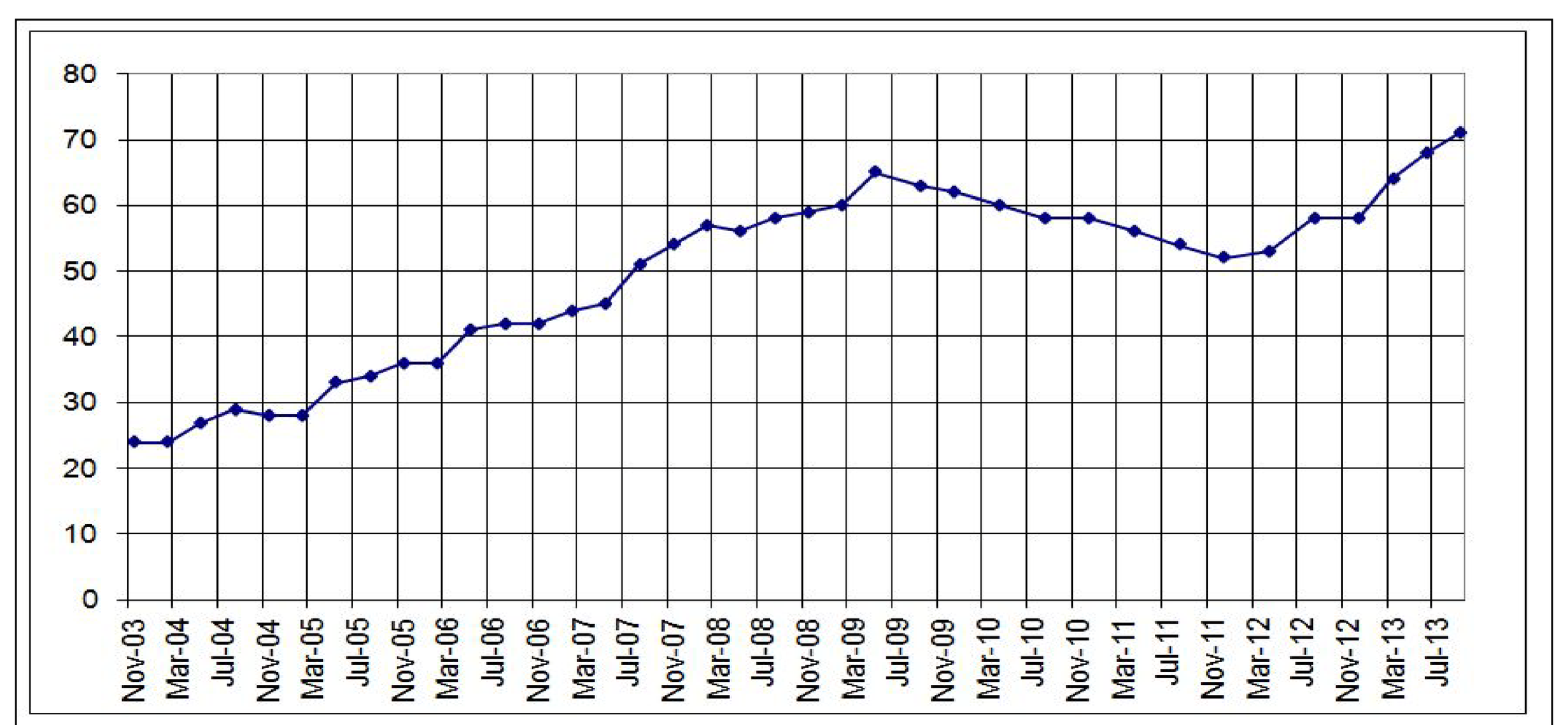


Figure 1: Number of NDBC Stations with Directional Wave Measurements

Figure 2: Monterey Field Laboratory

   d) As an adjunct to the JCOMM Data Buoy Cooperation Panel's (DBCP) Pilot Project Wave measurement Evaluation and Test (PP-WET), in 2011 NDBC deployed its own Datawell Waverider buoy as Station 46114, near an NDBC dual wave system at Station 46042, Monterey, CA. The stations are approximately 50 km west of Monterey, CA and are separated by about 14 km **(Figure 2)**. In addition to conducting intercomparisons with NDBC systems, NDBC and Monterey Bay Aquarium Research Institute are conducting a field evaluation of a multi-purpose buoy in the area. NDBC has also conducted a field evaluation of its Digital Directional Wave Module (DDWM) mounted on a Liquid Robotics Wave Glider with the buoys in the field laboratory.

   e) Following the work of Bender *et al.*, (2009, 2010) showing that a small discus buoy using a one-dimensional strapped-down accelerometer in shallow-water could lead to overestimated wave heights, NDBC examined the phenomena at its dual wave system buoy at Station 46029. In November 2009, a high seas event showed that in seas less than 6 m both systems were in good agreement. However, as the waves exceeded 6-7 m, the strapped-down accelerometer of the DDWM exceeded the wave heights of tilt-dampened Datawell Hippy **(Figure 3)**. In response, NDBC undertook a change to its DDWM system to incorporate tilt compensation (Riley et al., 2010) to the vertical acceleration time series, and field evaluations indicate during Hurricane Irene showed promising results **(Figure 4)**.
   Comparisons are underway for data collected at the dual wave systems at 44014, 46029, and 46042. Using almost 3 years of data at 46029 without tilt compensation, indicated growth of wave height error with increasing wave height, and extending the least squares fit line from the measured data to heights of 16 m indicates a possible 2 m or 12% error. Meanwhile, data collected at 46042 with tilt compensated DDWM indicated little growth in error with increased wave height, but showed an underestimation of the waves in the 2 -5 m range.

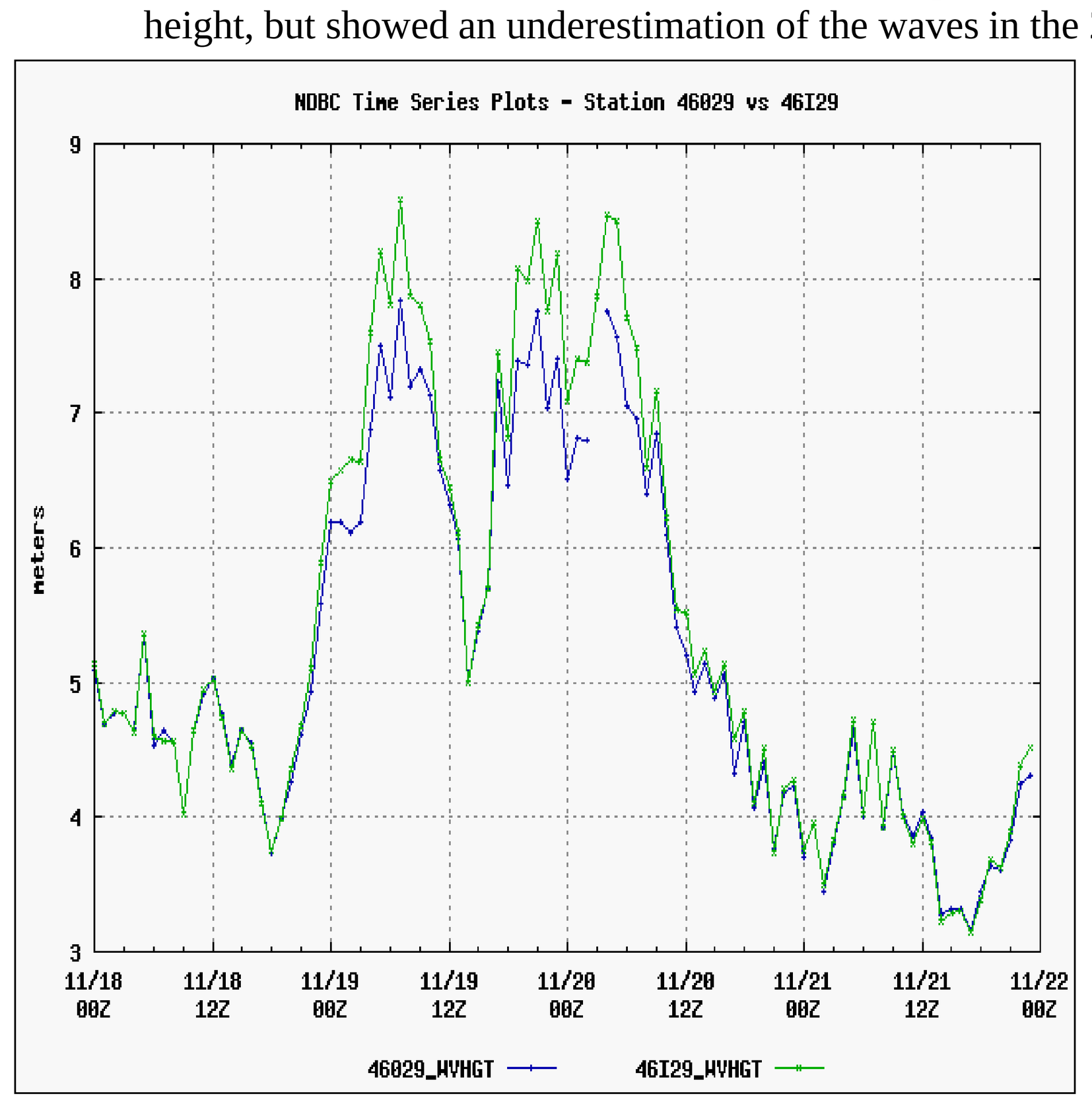


Figure 3: Dual Wave Systems, 46029 is Datawell Hippy and 46I29 is DDWM. Tear is 2009.

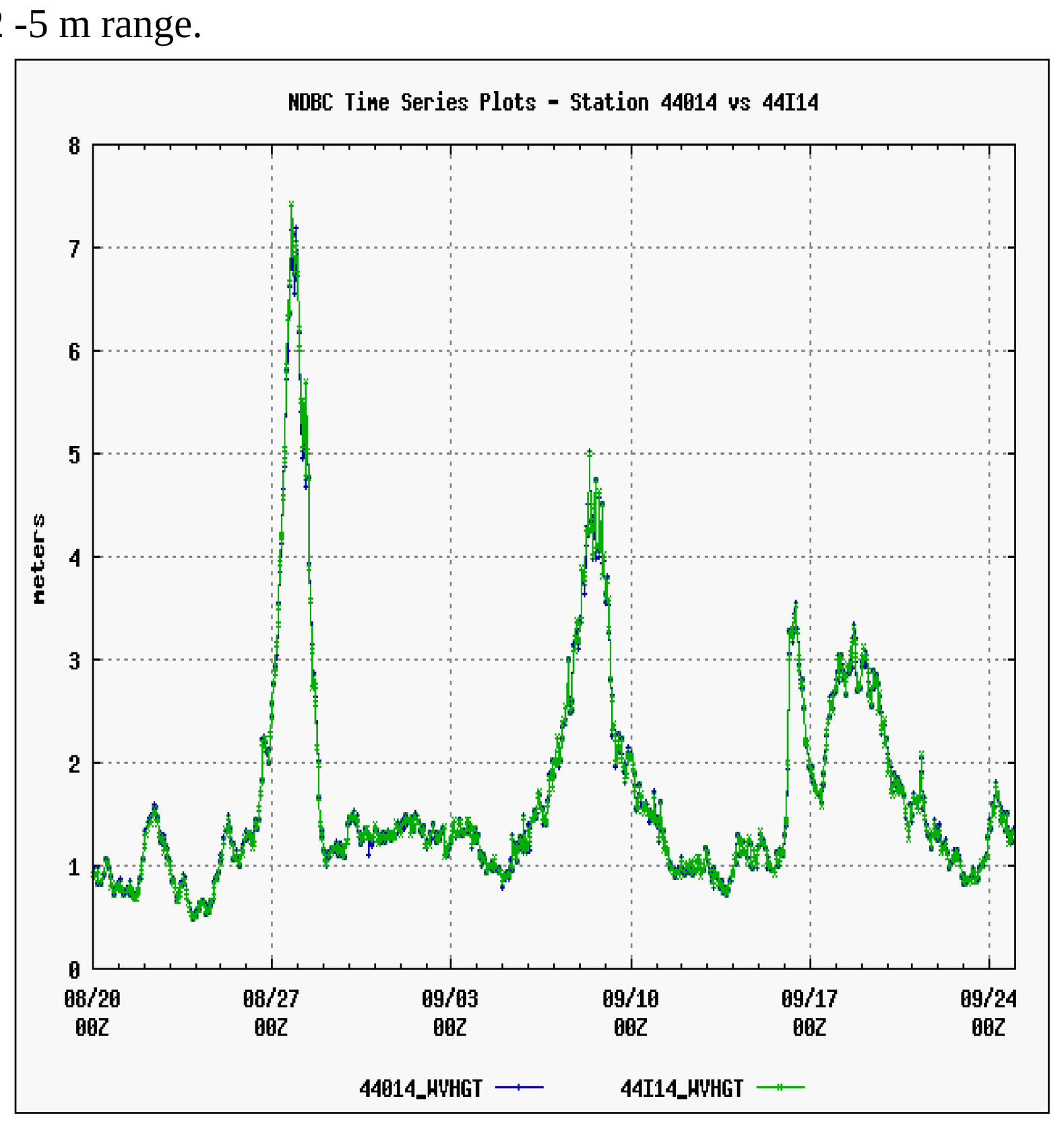


Figure 4: Dual Wave Systems, 44014 is Datawell Hippy and 44I14 is DDWM. Year 2011

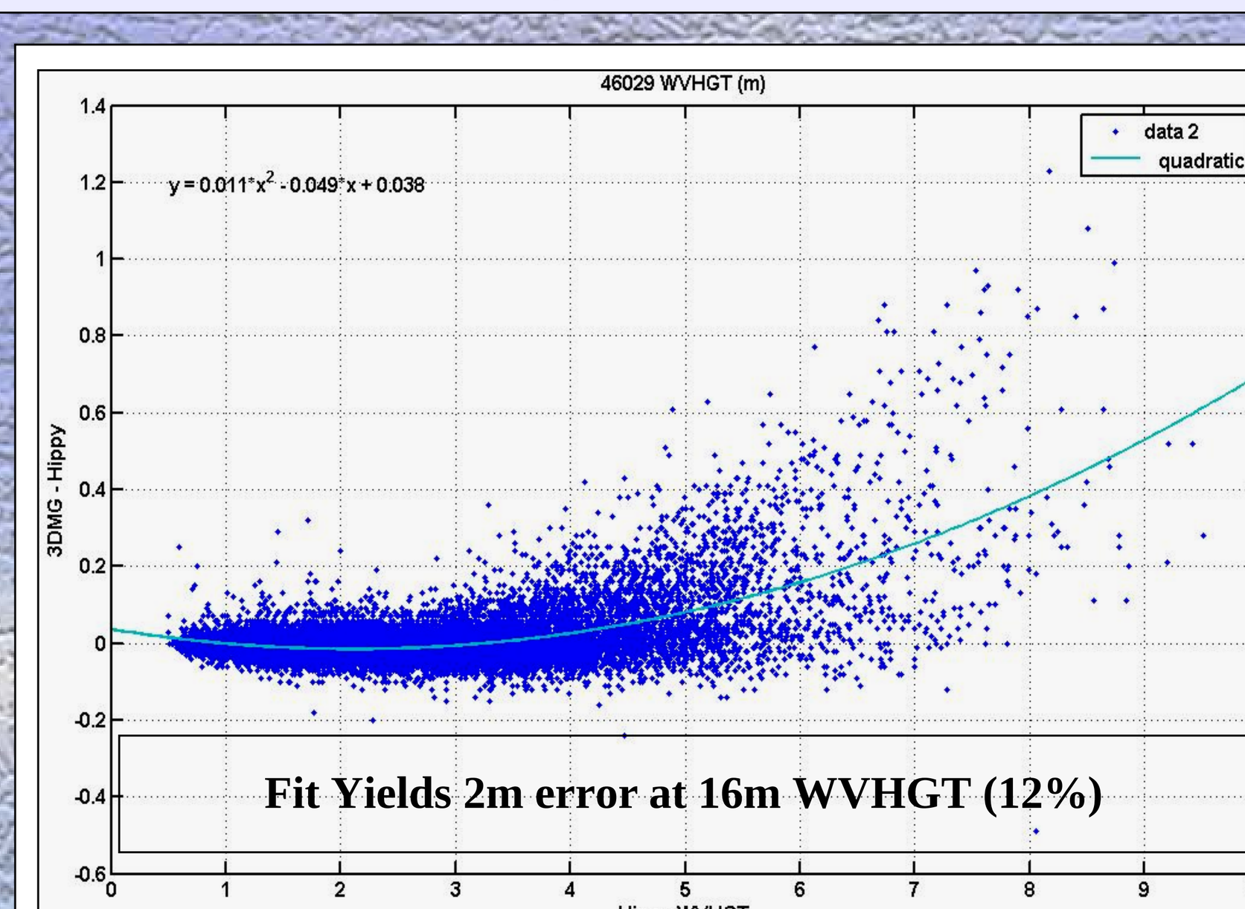


Figure 5: 46026 comparison between Datawell Hippy and DDWM (3DMG) *WITHOUT* tilt compensation

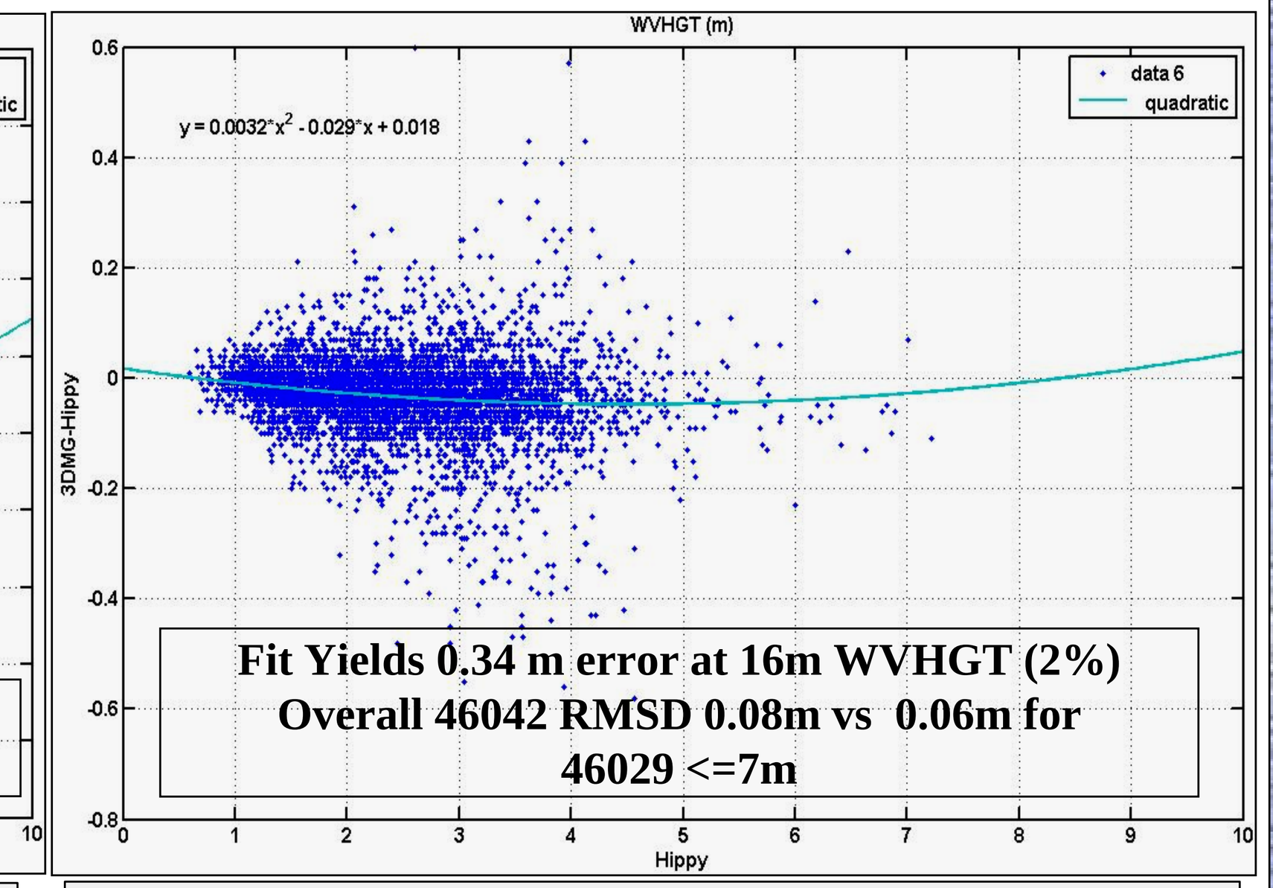


Figure 6: 46042 comparison between Datawell Hippy and DDWM (3DMG) *WITH* tilt compensation

NDBC also conducted an evaluation of its DDWM mounted on a Liquid Robotics Wave Glider. No changes to the DDWM or DDWM processing were made for the evaluation. The directional measurements proved unsatisfactory, but some encouraging results were seen with the wave heights (**Figure 7** and **Table 1**).

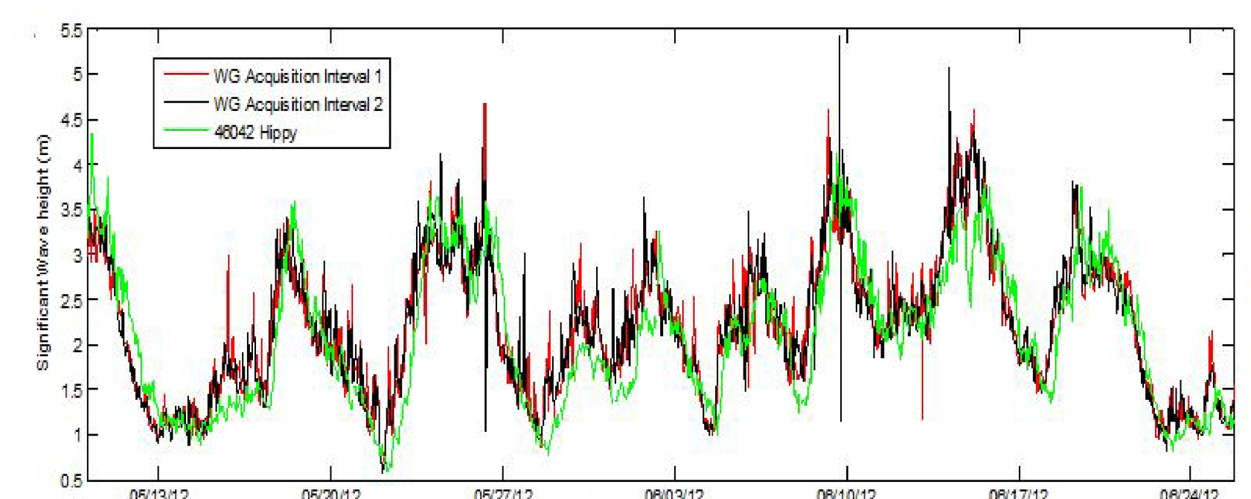


Figure 7: WaveGlider – Buoy Wave Heights

	NDBC Spec.	Mean Diff	Std Diff	RMSD	Bias	MAE
Significant Wave Height (m)	38.9%	0.102	0.435	0.446	0.102	0.341
Average Period (s)	55.7%	0.932	0.813	1.236	0.926	1.004
Dominant Period (s)	46.7%	3.548	5.029	6.153	3.522	4.009
Mean Wave Direction (deg)	21.6%	-60.050	98.160	115.030	-59.597	77.025

Table 1: WaveGlider – Buoy Wave Statistics

NDBC Buoy Wave Archives at the National Oceanographic Data Center

The official, long-term archive of NDBC's Wave Measurements is at the National Oceanographic Data Center (NODC, http://www.nodc.noaa.gov, **Figure 8**). Data are uploaded by month and are generally available about 30 days after the end of the month. As of September 2013, the archive held 44426 *Buoy-Months* of data, which are about 20 million wave observations, going back to 1972. In 2011 the format was changed from F291, a text-record format (**Figure 9**), to netCDF (Network Common Data Form), version 4 with Groups compliant with Climate and Forecast (CF) metadata standards (Burnett *et al.*, 2011). NDBC and NODC took advantage of the format change to add more metadata to the records. Additional information in the netCDF include:

- Quality Indicators of the data,
- Metadata down to the sensor level,
- All data from a station, including back-up or redundant systems, and
- Identification of new deployments (**Figure 10**) to aid in assessing the homogeneity of data.

The additional data and metadata assists researchers in determining the applicability of the data to their specific research needs, and assist researchers in understanding any possible effects upon long-term records caused by changes to the measurement systems (Gemmrich *et al.* 2010).

Presently, all archived data are from the real-time transmission from the buoys. Sometimes the transmitting system fails while the wave measurement system continues to work, but the data are lost. NDBC is undertaking an engineering and data management effort to record and store the wave measurements on-board the buoys, thus preserving the data even if transmissions fail. This will also allow NDBC or future researchers to reprocess the data as new techniques and applications are developed.

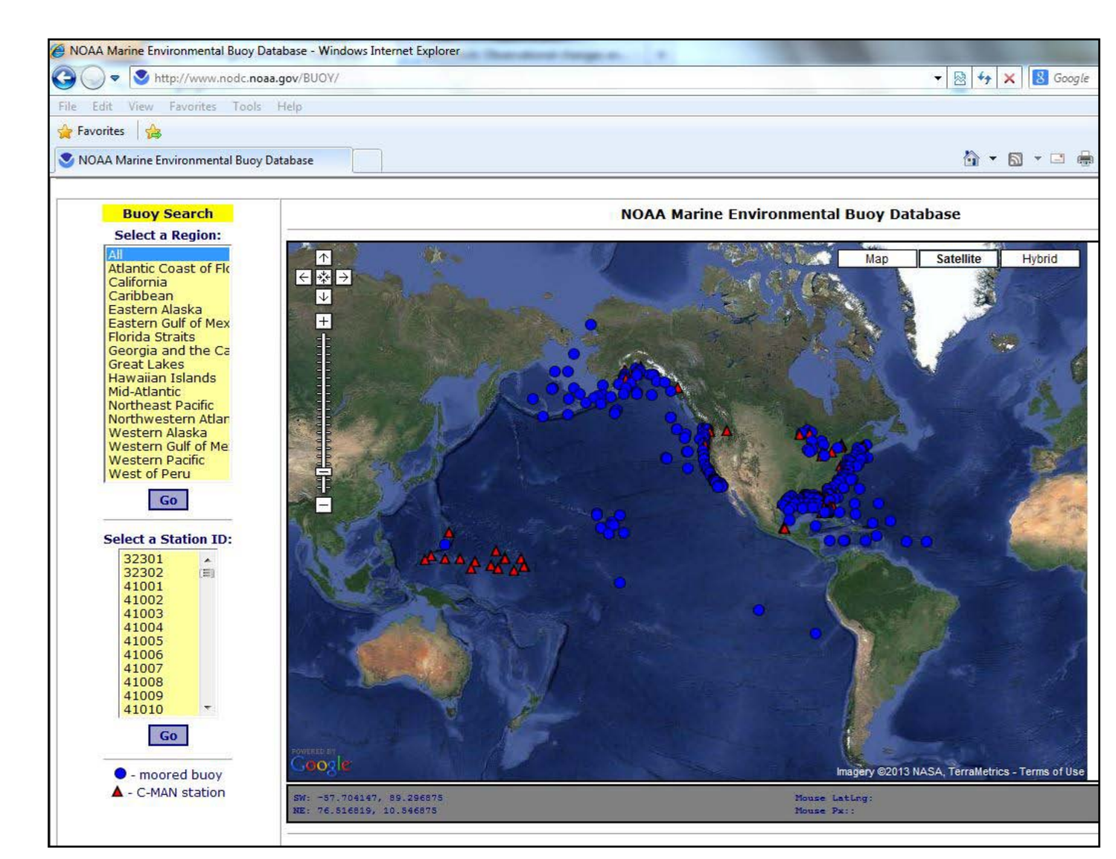
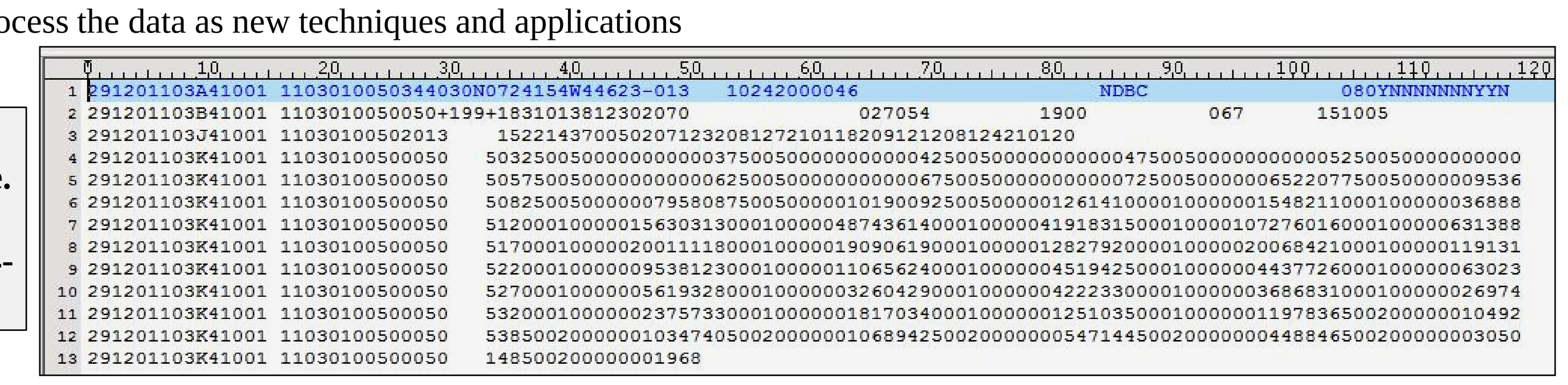
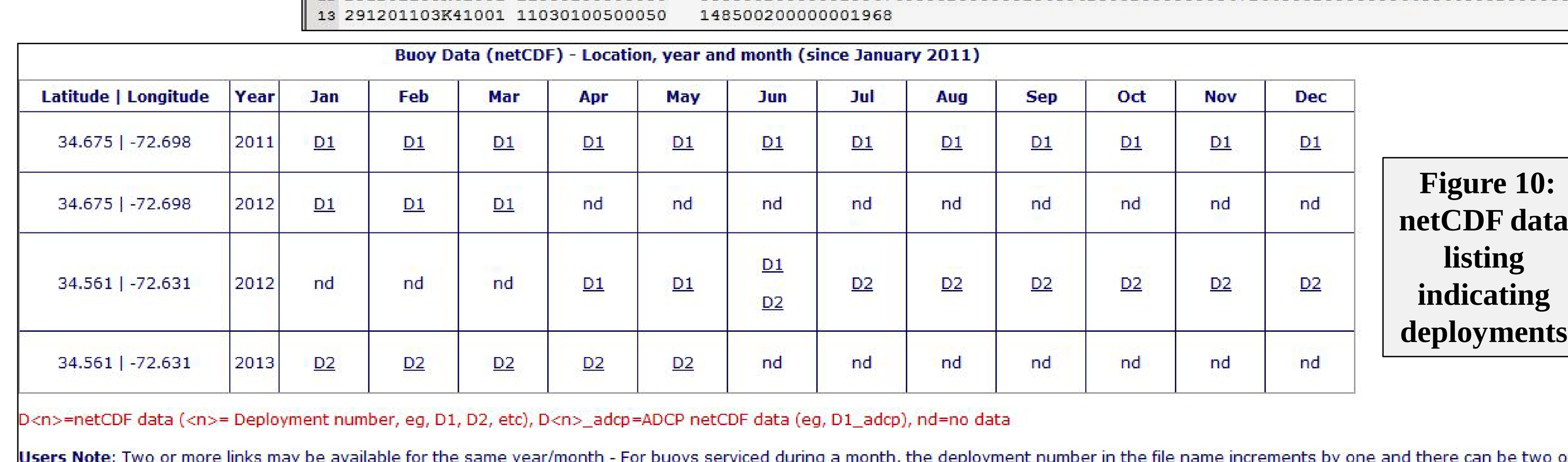


Figure 8: Buoy Archives Page at NODC




```
1 291201103A41001 110301005034403 0N0724154W44623-013    10242000046                     NDBC              080YNNNNNNNYYN
2 291201103B41001 1103010050050+199+1831013812302070              027054          1900          067        151005
3 291201103J41001 11030100502013    15221437005020712320812721011820912120812421012 0
4 291201103K41001 11030100500050   50325005000000000003750050000000000042500500000000000475005000000000000525005000000000
5 291201103K41001 11030100500050   50575005000000000006250050000000000067500500000000000725005000000652207750050000009536
6 291201103K41001 11030100500050   50825005000000795808750050000001019009250050000001261410000100000015482110001000003688 8
7 291201103K41001 11030100500050   51200010000015630313000100000487436140001000004191831500010000107276016000100000631388
8 291201103K41001 11030100500050   51700010000020011118000100000190906190001000001282792000010000020068421000100000119131
9 291201103K41001 11030100500050   52200010000009538123000100000110656240001000000451942500010000004437726000100000063023
10 291201103K41001 11030100500050   52700010000005619328000100000032604290001000000422233000010000003686831000100000026974
11 291201103K41001 11030100500050   53200010000002375733000100000018170340001000000125103500010000001197836500200000010492
12 291201103K41001 11030100500050   53850020000001034740500200000010689425002000000054714450020000000448846500200000003050
13 291201103K41001 11030100500050   148500200000001968
```


Figure 9: Example F291 file. Wave spectral data are on lines 4-13



Buoy Data (netCDF) - Location, year and month (since January 2011)

Latitude | Longitude	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
34.675 | -72.698	2011	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1
34.675 | -72.698	2012	D1	D1	D1	nd	nd	nd	nd	nd	nd	nd	nd	nd
34.561 | -72.631	2012	nd	nd	nd	D1	D1	D1 D2	D2	D2	D2	D2	D2	D2
34.561 | -72.631	2013	D2	D2	D2	D2	D2	nd	nd	nd	nd	nd	nd	nd

D<n>=netCDF data (<n>= Deployment number, eg, D1, D2, etc), D<n>_adcp=ADCP netCDF data (eg, D1_adcp), nd=no data

Users Note: Two or more links may be available for the same year/month - For buoys serviced during a month, the deployment number in the file name increments by one and there can be two or more D<n> links (eg, D1, D2..etc) for that buoy. For buoys with ADCP data, there is an additional ADCP link for separate ADCP data (eg, D1_adcp).

Figure 10: netCDF data listing indicating deployments

References: Bender, L. C., N. L. Guinasso, J. N. Walpert, and S. D. Howden, 2009: A Comparison of Two Methods for Determining Wave Heights from a Discus Buoy with a Strapped-Down Accelerometer. *Proc. 11th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symposium, JCOMM Technical Report 52, WMO/TD-No. 1533, IOC Workshop Report 232*, Halifax, Canada October 18-23, 2009. Available on-line at: http://www.waveworkshop.org/11thWaves/index.htm; Bender, L. C., N. L. Guinasso, J. N. Walpert, and S. D. Howden, 2010: A Comparison of Methods for Determining Significant Wave Heights—Applied to a 3-m Discus Buoy during Hurricane Katrina. *J. Atmos. Oceanic Technol.*, 27, 1012–1028. doi: http://dx.doi.org/10.1175/2010JTECHO724.1; Bouchard, R., C-C. Teng, R. Riley, and W.H. Burnett, 2009: Status of and Plans for the Wave Measurement Program at NOAA's National Data Buoy Center. *Proc. 11th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symposium, JCOMM Technical Report 52, WMO/TD-No. 1533, IOC Workshop Report 232*, Halifax, Canada October 18-23, 2009. Available on-line at: http://www.waveworkshop.org/11thWaves/index.htm; Burnett, W.H., K. Casey, R. Bouchard, T. Ryan, and R.V. Hervey, 2011. The National Oceanographic Data Center and National Data Buoy Center: Operational, in-situ observations – real-time and archived, Abstract, *Proc. First Conference on Transition of Research to Operations*, Seattle, WA, American Meteorological Society, https://ams.confex.com/ams/91Annual/webprogram/Paper182103.html; Gemmrich, J., B. Thomas, and R. Bouchard, 2011. Observational changes and trends in northeast Pacific wave records, *Geophys. Res. Lett.*, 38, L22601, doi:10.1029/2011GL049518; Gower, J.,and F. González, 2006. US warning system detected the Sumatra Tsunami. *Eos, Transactions American Geophysical Union*, 87(10), 105-108; Riley, R., C. Teng, R. Bouchard, R. Dinoso, and T. Mettlach, 201: Enhancements to NDBC's Digital Directional Wave Module. In *OCEANS 2011* (pp. 1-10). IEEE.

NDBC Tsunami Measurement Program

2. NDBC maintains and operates the National Oceanic and Atmospheric Administration's (NOAA) buoy-based, deep-sea tsunami monitoring network. The network consist of 39 strategic located stations across the Pacific, mainly in the vicinity of subduction zones that serve as source regions for earthquake-generated tsunamis **(Figure 11)**. The systems employ the NOAA-developed Deep-ocean Assessment and Reporting of Tsunamis II (DART II) technology. The technology measures the pressure at the bottom of the ocean and can communicate those measurements to the Tsunami Warning Centers in less than 3 minutes **(Figure 12)**. The technology has a tsunami detection algorithm that will put a station into rapid reporting mode. The network grew from 6 stations in 2003 to 39 in 2008. The system has detected every tsunami generated in the Pacific Ocean and even the Indonesian Tsunami of 2004 was detected by the Pacific tsunami stations (Gower and González, 2006).
   During the 2011 Japanese earthquake and tsunami, The Tsunami warning Centers initiated 20 rapid reporting modes and detected a tsunami signal in 10 stations, including 51406 **(Figure 13)** almost 11,000 km from the earthquake. On June 13, 2013, Station 44402's detection algorithm triggered rapid reporting mode with no evidence of seismic activity **(Figure 14)**. During that day and early on the 14th, tsunami-like waves were observed along the Northeast Atlantic Coast of the US. NOAA is presently investigating this phenomenon as a possible meteostsunami associated with a weather system that moved off the East Coast (see *http://wcatwc.arh.noaa.gov/previous.events/?p=06-13-13* for more details).

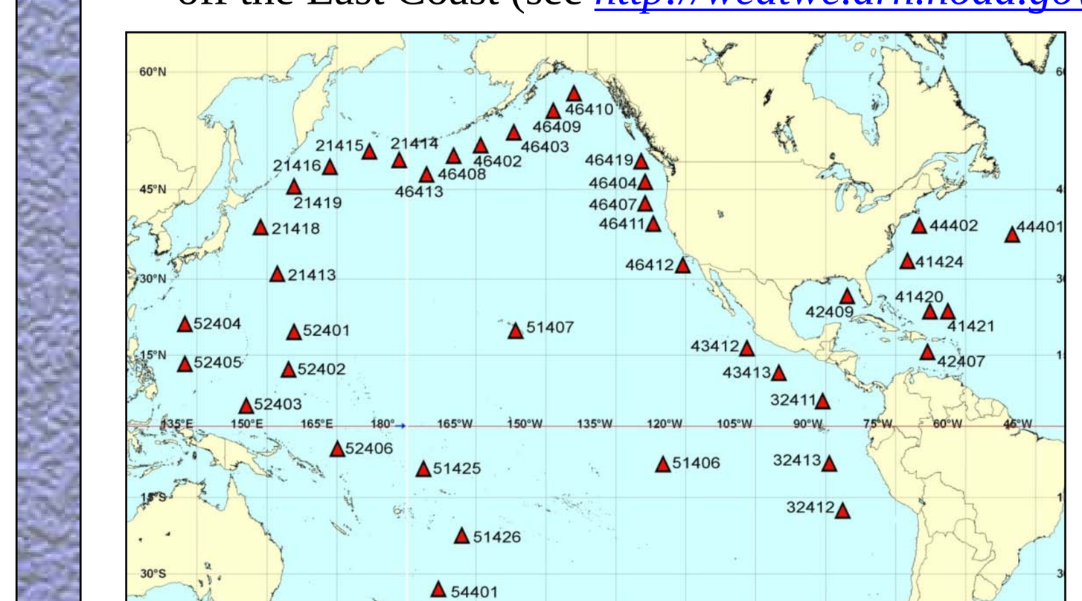
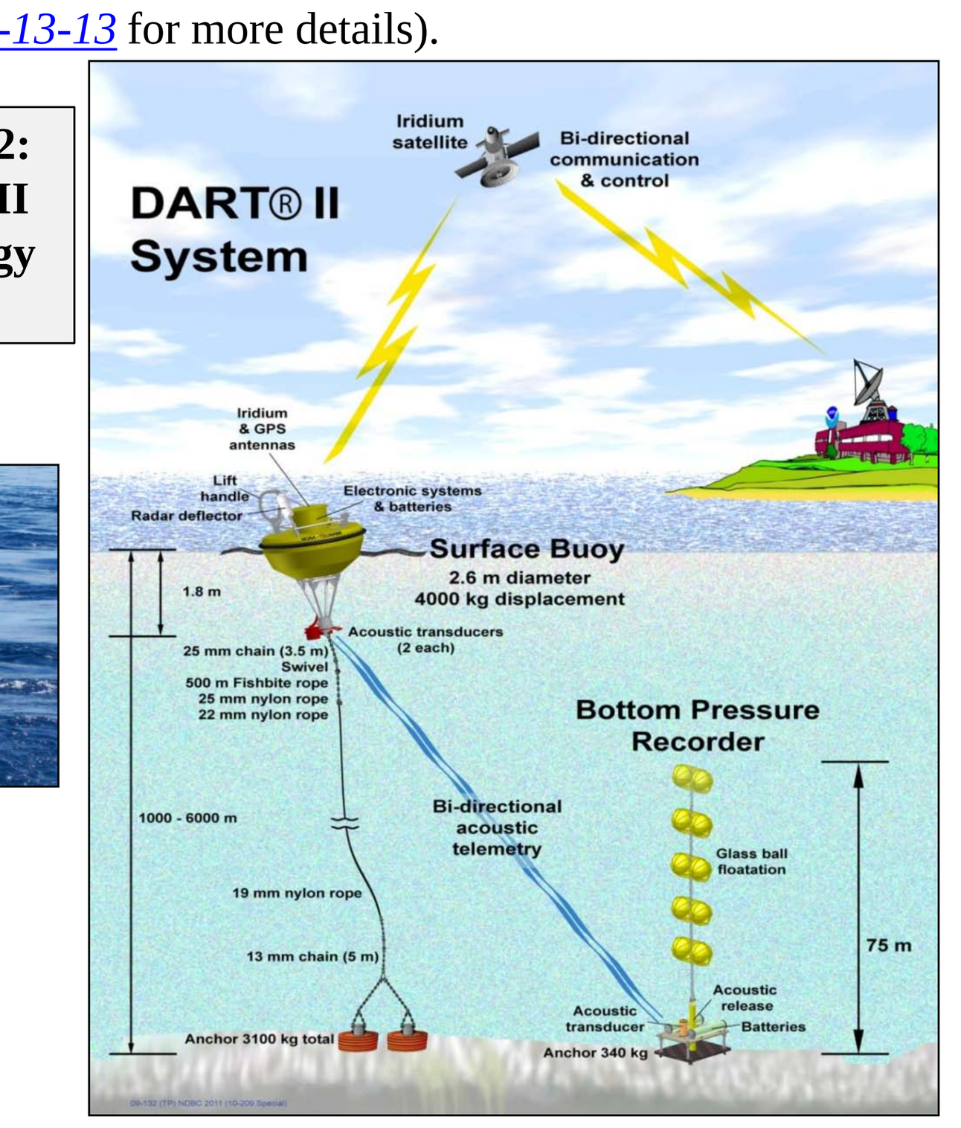


Figure 11: NOAA buoy-based, Deep-sea Tsunami Network (above)

Figure 12: DART® II Technology (right)



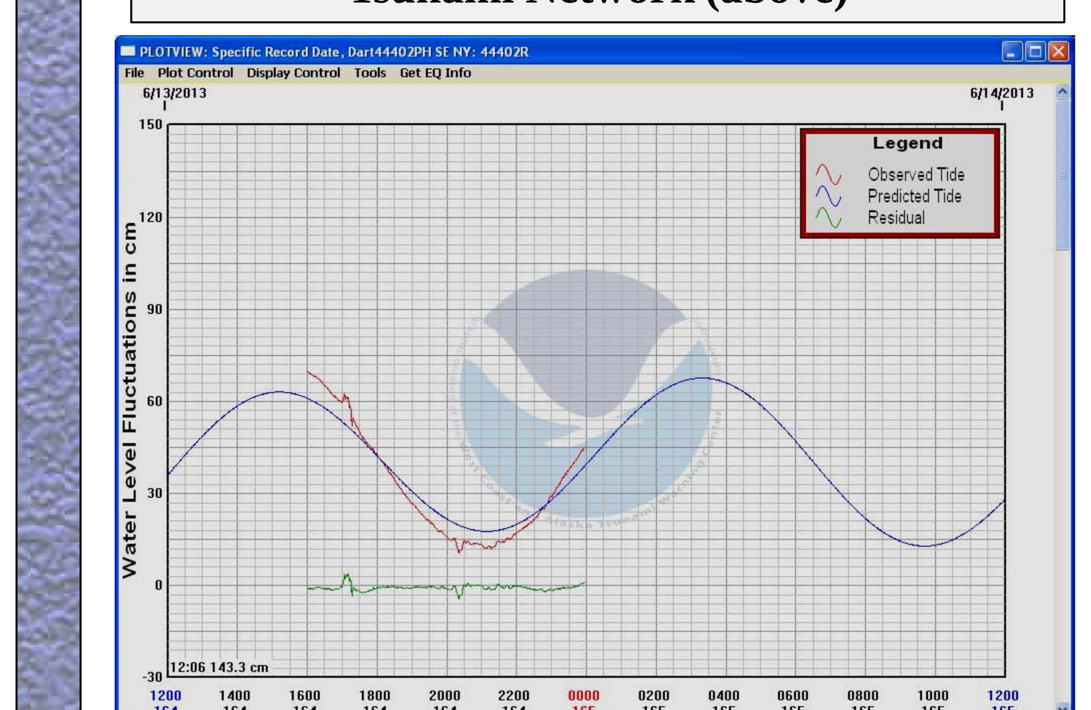


Figure 14: Water-level measurements and de-tide residuals from Station 44402 for June 13 (Day 164). Image courtesy of the National Tsunami Warning Center. (above)

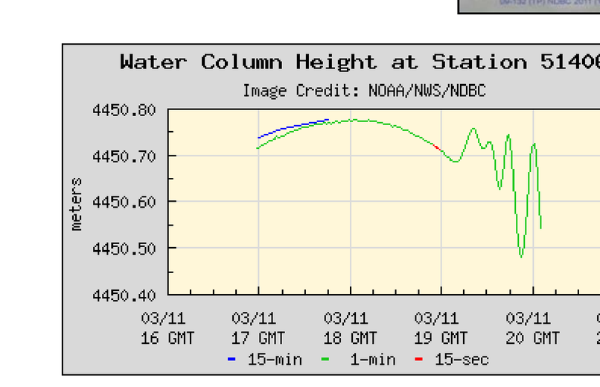


Figure 13: 2011 Japanese Tsunami Signal at 51406 (left)

NOAA Global Water-Level Data Supporting Natural Hazards Research and Global Ocean Monitoring

NOAA's **National Geophysical Data Center (NGDC)** and co-located World Data Service for Geophysics (WDS) is responsible for the assimilation, processing, quality assurance, and integration of deep-ocean (DART®) and coastal water level data. The original and processed data are managed in a standards-compliant data archive and available through the NGDC/WDC global historical on-line tsunami database.

The NOAA/NGDC data archive includes:

- 15-second DART® data after retrieval of bottom recorders
- Real-time data from DART® ETD systems
- Archived BPR records from pre-DART® era provided from PMEL
- 1-minute processed and un-processed data from coastal tide-gauge stations
- Data for historical tsunami events, run-ups, deposits, photos, publications, reports from post-tsunami field surveys, etc.

Data acquisition:

- DART® - NGDC archives, processes, and distributes the high-resolution records following retrieval of the BPR by NDBC
- Real-time DART® data are available from NDBC and post-processed by NGDC for tsunami events or by special request
- Coastal tide-gauge 1-minute data are available in real-time from CO-OPS and archived, processed for tsunami events, available from and archived by NGDC.

Data processing: All data are processed to the level of "scientific quality" removing trends, fixing spikes and other instrumental issues, and de-tide using a customized version of the tidal package of the Institute of Ocean Sciences (IOS, Sidney, BC, Canada) developed by Foreman (2009).

Data distribution: Data are available from the NGDC Natural Hazards web site, recent events ***http://www.ngdc.noaa.gov/hazard/*** Additional access to other data is under development and data are provided on request to ***haz.info@noaa.gov***