# Extreme Wave Height Reports from NDBC Buoys during Hurricane Sandy

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# Mother Nature Piles It On

*Additionally, many EMs expressed **surprise at the large and damaging waves** Sandy caused. Of coastal residents surveyed after Sandy, 77 percent described **the impact of waves as more than they expected** (Gladwin, Morrow & Lazo, 2013). Even small to moderate storm surges can cause life-threatening and damaging conditions because of **severe coastal waves on top of surge**.*

– *NWS Sandy Assessment* (2013)

*Katrina had already generated large northward-propagating swells, leading to **substantial wave setup** along the northern Gulf coast, when it was at Category 4 and 5 strength during the 24 hours or so before landfall.*

– Knabb, *et al.* (2005), *Tropical Cyclone Report, Hurricane Katrina*

# Uncertainties

1. *What was the highest wave?*
2. *Were the waves really that high?*

## Hurricane Sandy Smashes Ocean Wave Records

OurAmazingPlanet Staff | November 14, 2012 05:26pm ET

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A striking image of Verrazano Bridge in Brooklyn as Hurricane Sandy approaches on Oct. 29, 2012. Pin it

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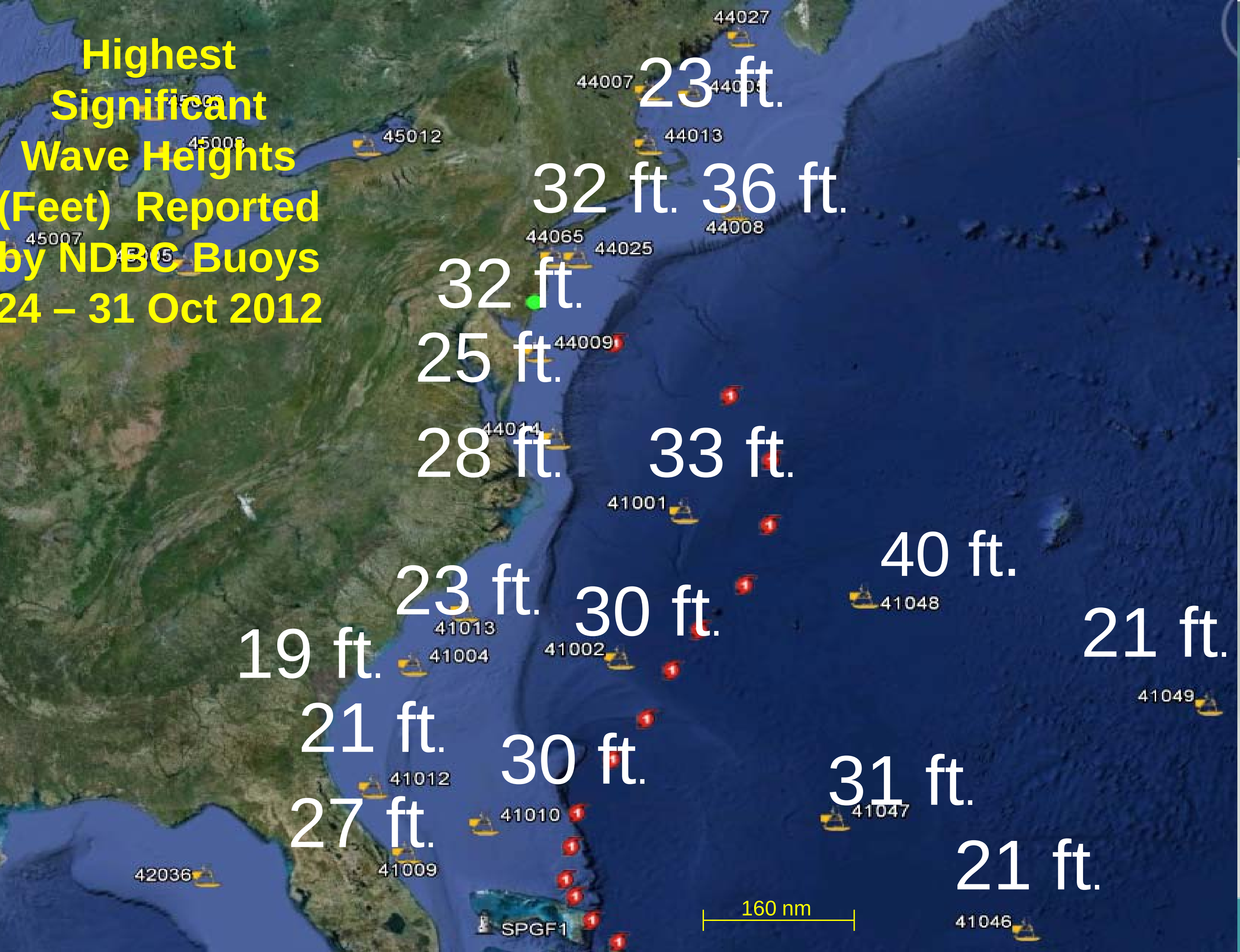
# Highest Significant Wave Heights (Feet) Reported by NDBC Buoys 24 – 31 Oct 2012



# What NDBC Measures and Reports

Details in NDBC Technical Document 96-01

- **Reports** significant wave height ($H_s$): an estimate of the distance from trough to crest of the average of the highest one-third of the waves
- **Measures** the vertical acceleration of the buoy hull (1.7066 Hz, for 20 minutes), from an accelerometer perpendicular to the buoy's deck
- **Transform** into the frequency domain by a Fast Fourier Transform (FFT)
- **Correct** for hull/mooring response (Steele *et al*. 1985) and dynamic tilting (Lang, 1987)
- **Double integration** (~ f^-4) to displacement spectrum, S(*f*)
- **Calculate** $H_s = 4^* \text{sqrt}\left[\sum S(f)^* d(f)\right]$

# NDBC Wave Measurement Systems

Accuracy

Datawell Waverider: 2 (1)


Datawell Hippy: 15, (4)

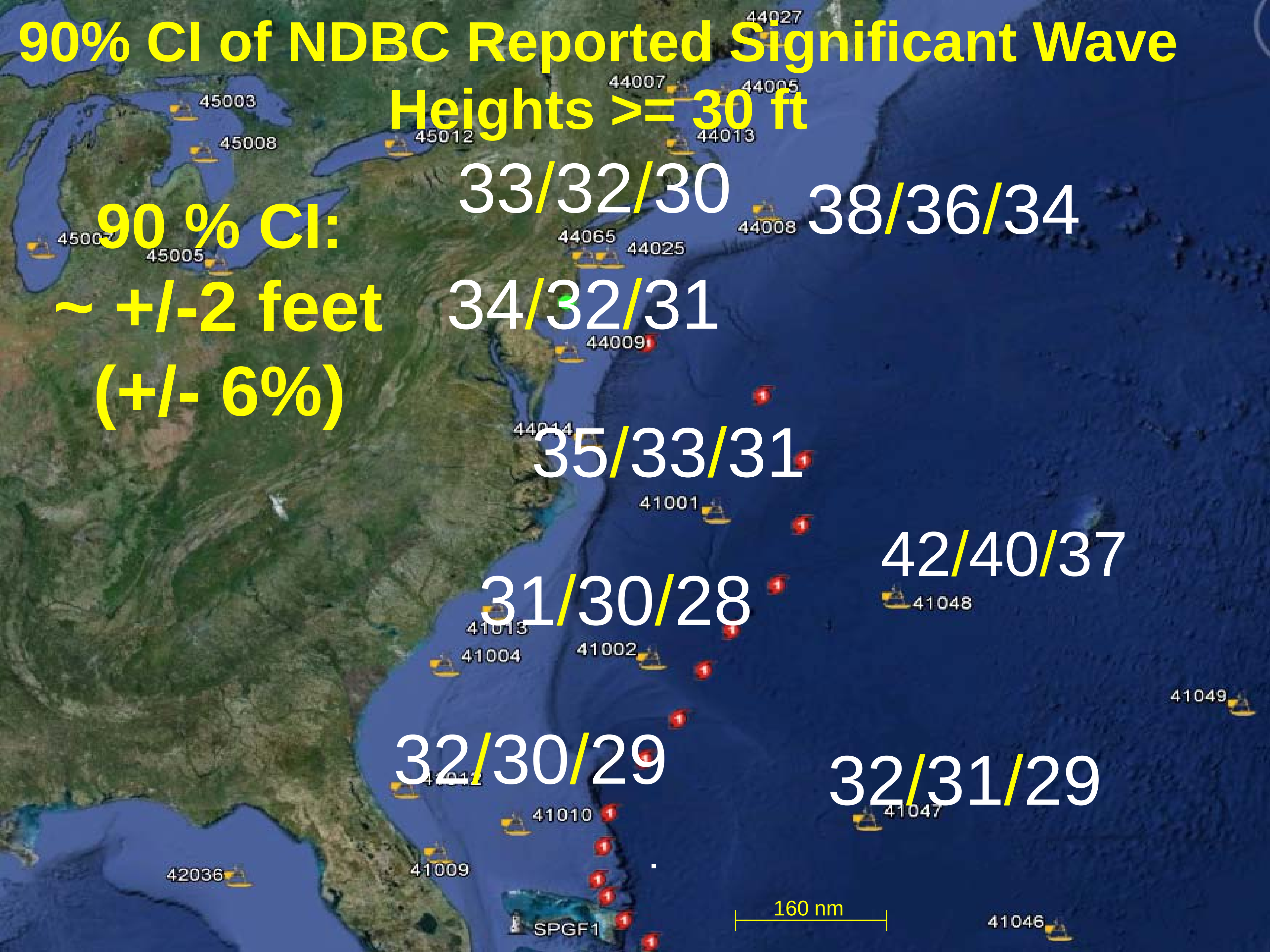

Strapped-down accelerometer: 100+

Cost

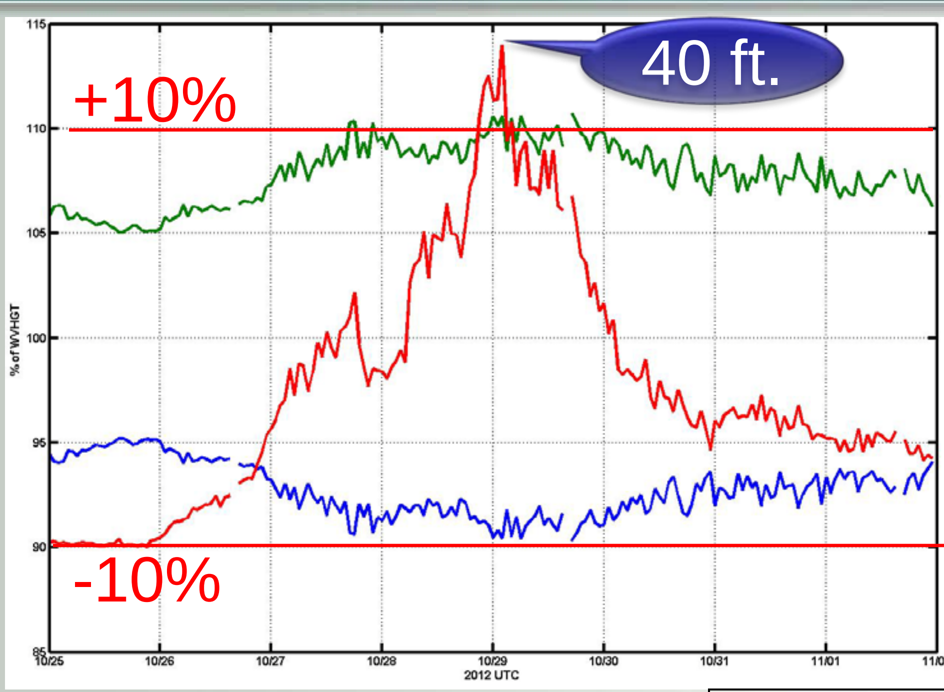
# Confidence Intervals (CI)

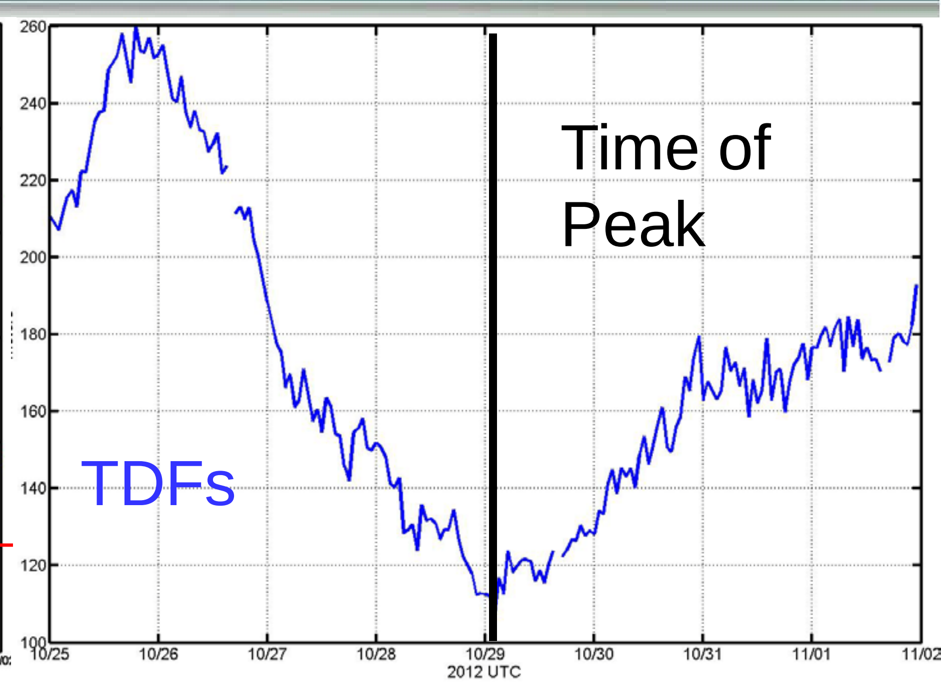
- Uncertainty due to Sample Variability because Waves are a Random Process
- NDBC considered confidence intervals as early as Earle (1983) and in NDBC (1996).
- Follow Donelan and Pierson (1985) for 90 % CI
- Total Degrees of Freedom Product of Sampling Period and Statistical Bandwidth (Bendat and Piersol, 2010, also NDBC, 1996)
- Assume Stationary over One Hour, then Sampling Period = 3600 s

# 90% CI of NDBC Reported Significant Wave Heights >= 30 ft



# 90 % CI with 20-Minute Sampling Example 41048




20-minute Sampling Increases Uncertainty. Now ~ +/- 10% as TDFs decrease

However, for either sampling duration:

- As Seas Build
  - -Bandwidth Narrows
  - -Uncertainty Increases
  - - Interval Spreads

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## Superstorm Sandy vs. The Perfect Storm

### A Comparison with Focus on Ocean Waves

**Ross Van Til, National Weather Service, Training Division**
**Hugh McRandal, National Weather Service, Ocean Prediction Center**
**Andrew Shashy, National Weather Service, WFO Jacksonville, FL**
**The authors are with the NWA Specialized Operational Services Committee – Marine Section**

As Superstorm Sandy evolved, comparisons were made to the 1991 Perfect Storm, but how similar were they really? The root of these comparisons came from the fact that both events involved the phasing of tropical and mid-latitude energy to produce extremely powerful systems. In addition, they both occurred at the end of October. However, the '91 storm would best be described as a rapidly intensifying extratropical low that absorbed a tropical system (Hurricane Grace), while the case with Sandy was such that the original tropical system's circulation remained fully intact while absorbing an injection of mid-latitude energy. For a closer look at Sandy's evolution via an innovative satellite imagery analysis technique, see this GOES-R and JPSS National Centers Perspective blog entry.

waves. Therefore, peak individual waves for each of these historic storms were certainly much higher than the significant wave height numbers mentioned above. NOAA buoys do not measure nor report the peak height of individual waves, and questions have been raised regarding Canadian buoy observations during extreme conditions, though individual waves of approximately 100 feet were reported by a Canadian buoy with the Perfect Storm, which helped to cement its status as a legendary marine weather event. Sandy, on the other hand, will be



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# Highest, Peak, Maximum Wave

- Drawbacks to actual maximum wave height measurement (direct integration of acceleration time series) because of:
  - Lag in buoy response
  - Noise, especially strapped-down accelerometers
  - Corrections apply in frequency domain
  - Limited battery power to either bring back time series or do additional calculations on board
- Rayleigh Multiplier:

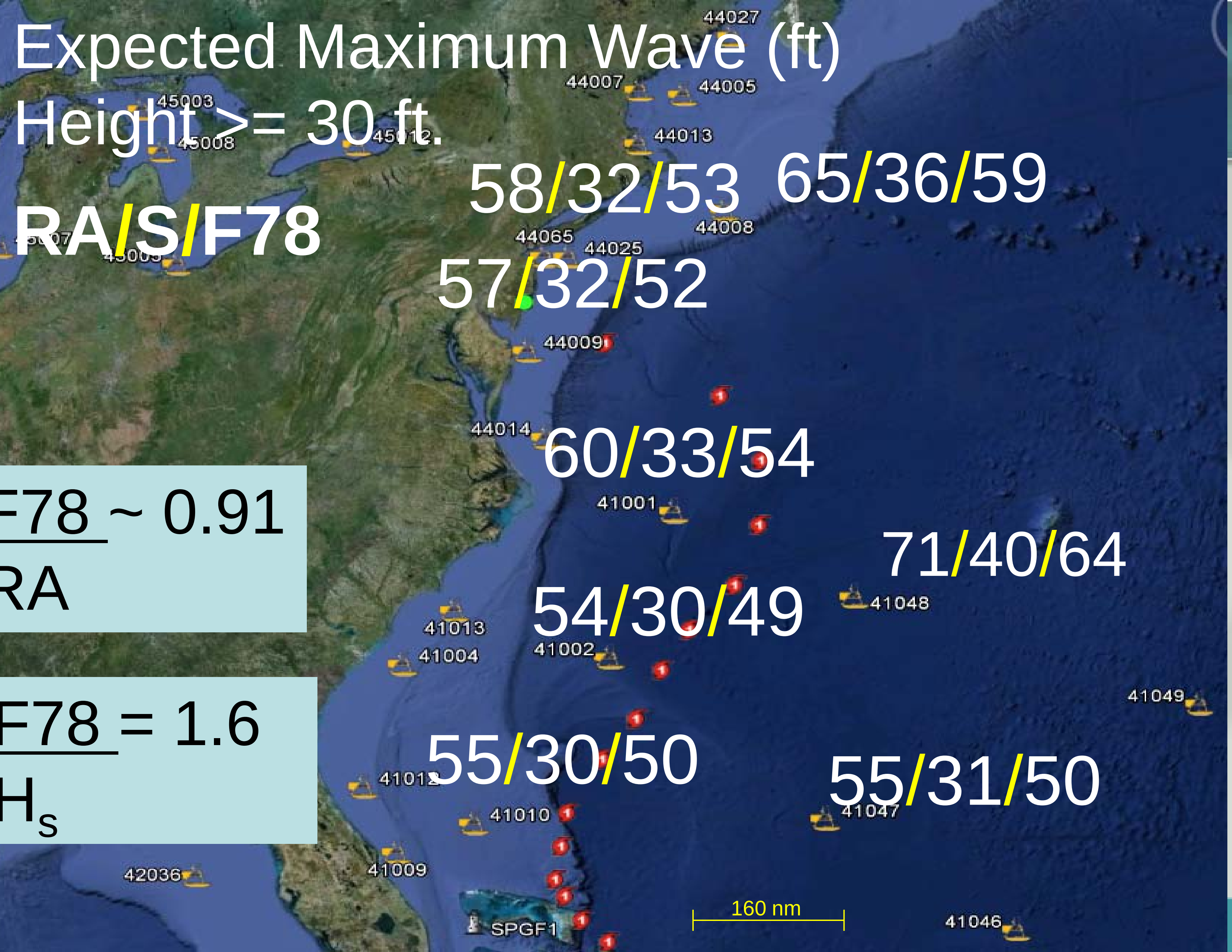
  2 * Mean Significant Wave Height over the period needed to acquire 2000-5000 records; ~2 - 6 hours (WMO, 1988)
- *A single peak height is a poor estimate of overall severity of wave conditions* – Earle (1983)

# Highest Wave

- The Rayleigh distribution is approximately correct, but slightly overestimates wave heights.
- Rayleigh overestimates the wave heights because the trough preceding a large crest is very likely to be on a lower part of the envelope.
- The empirical distribution suggested by Forristall (1978) accounts for the observed reduction in wave height
- ***Most Probable Maximum****: Modal Value*
- ***Expected Maximum****: The expected value or ensemble average in a record of given length*

Expected Maximum Wave (ft) Height >= 30 ft.

**RA/S/F78**




F78 ~ 0.91
RA

F78 = 1.6
$H_s$

# Bender Effect, Bender *et al.*, 2009 & 2010

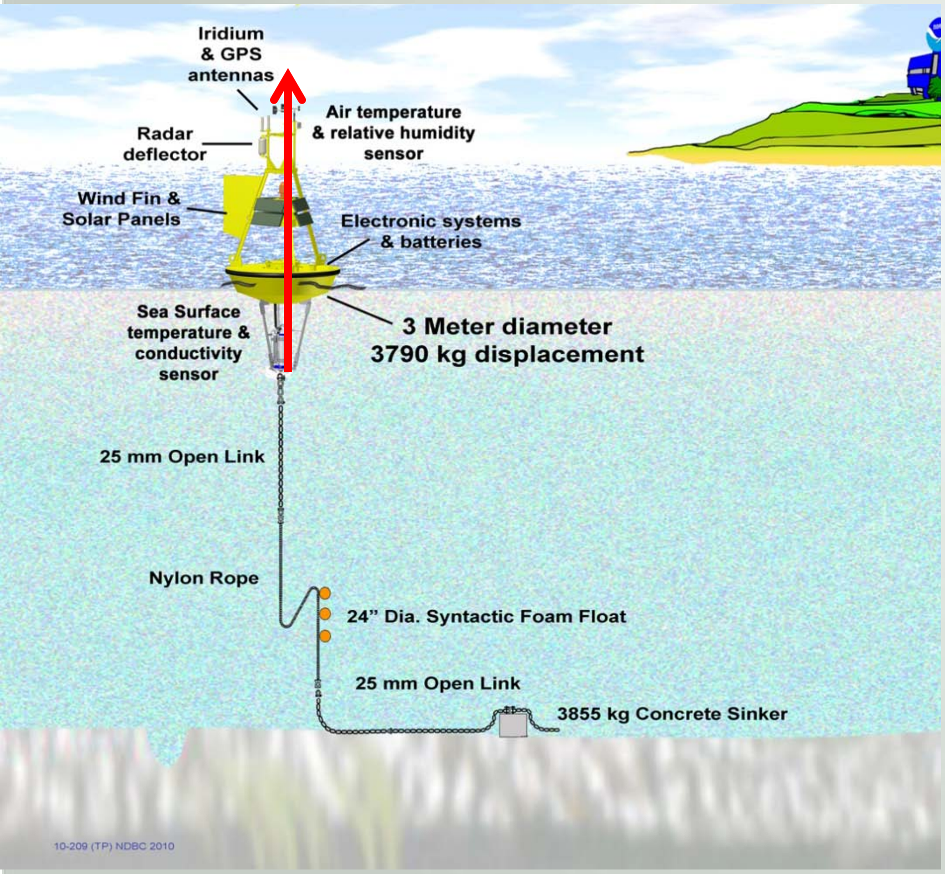
Strapped-Down Accelerometer, Small Hull, Shallow Water, and Large, Persistent Tilt

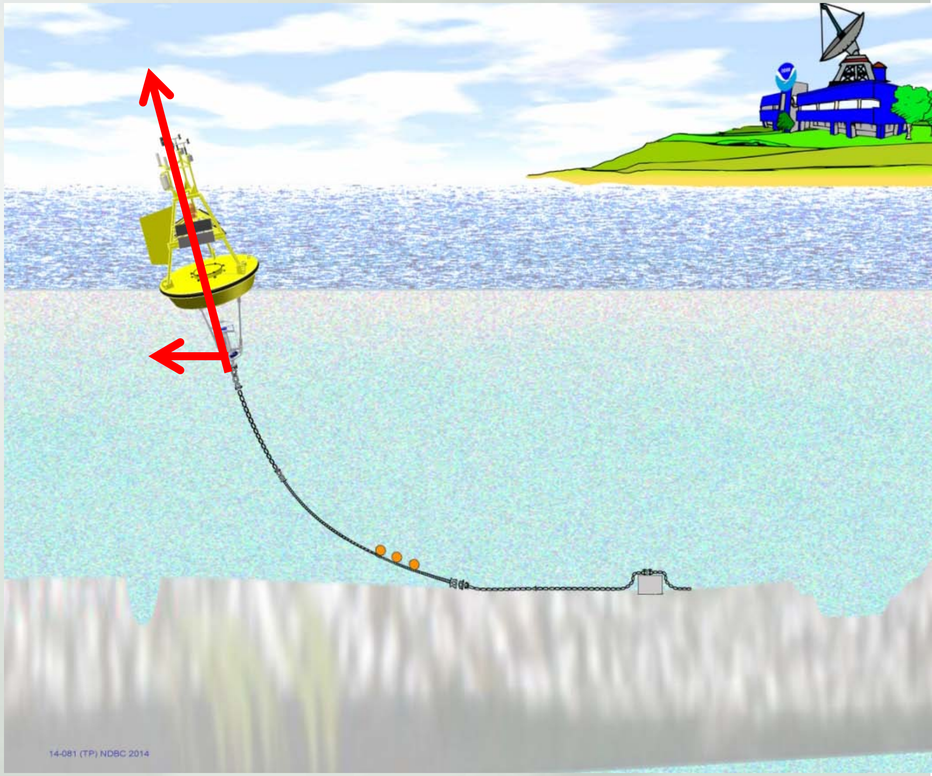
Bender, Mettlach, and Wang reproduced at NDBC Test Facility

**Slack mooring to respond to waves**

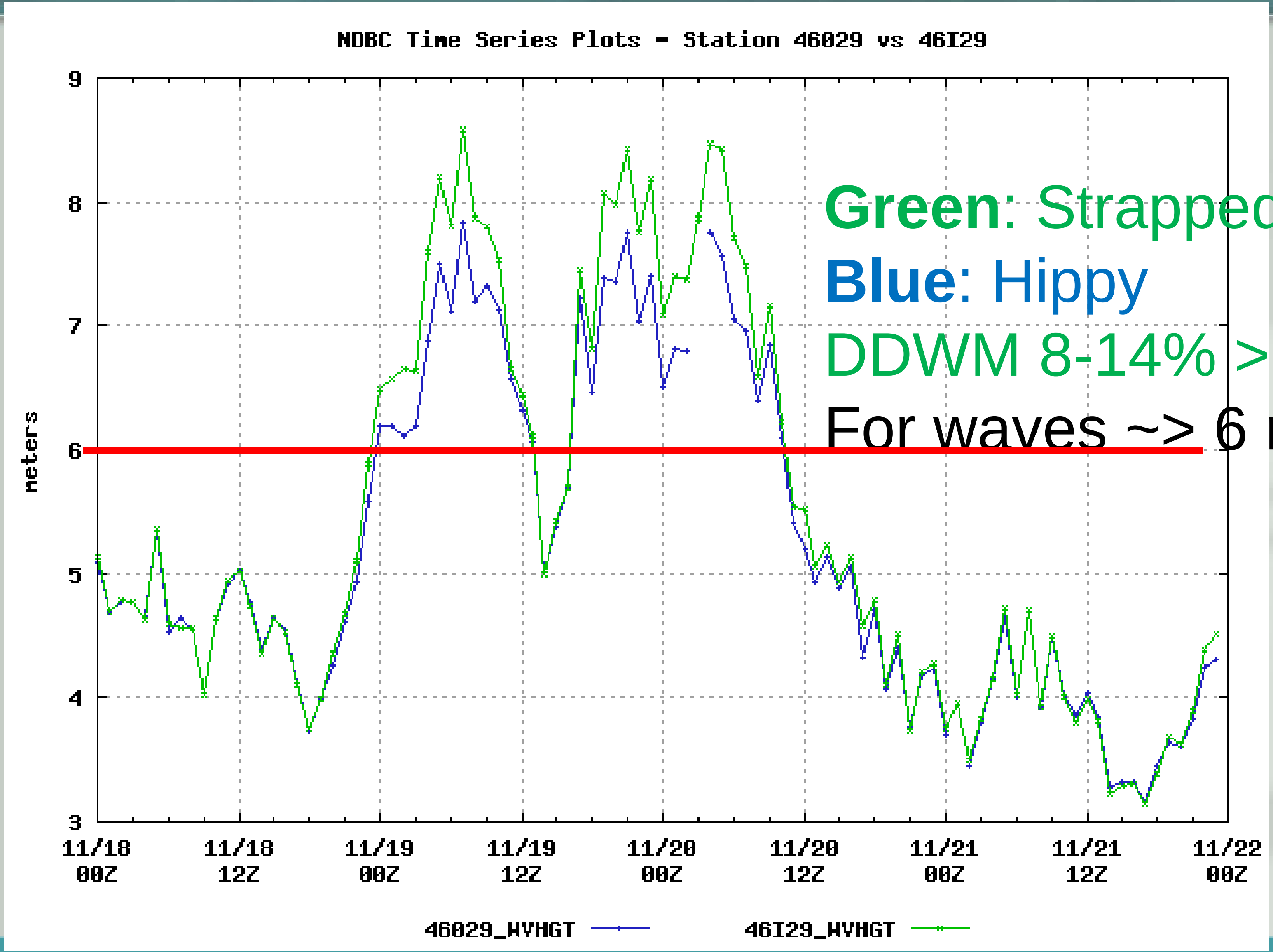
**Horizontal forces mapped into "vertical" accelerometer**

**Results in overestimation**



# Dual Wave System Shows Bender Effect November 2009 at Columbia River Bar




**Green**: Strapped-down

**Blue**: Hippy

DDWM 8-14% > Hippy

For waves ~> 6 m

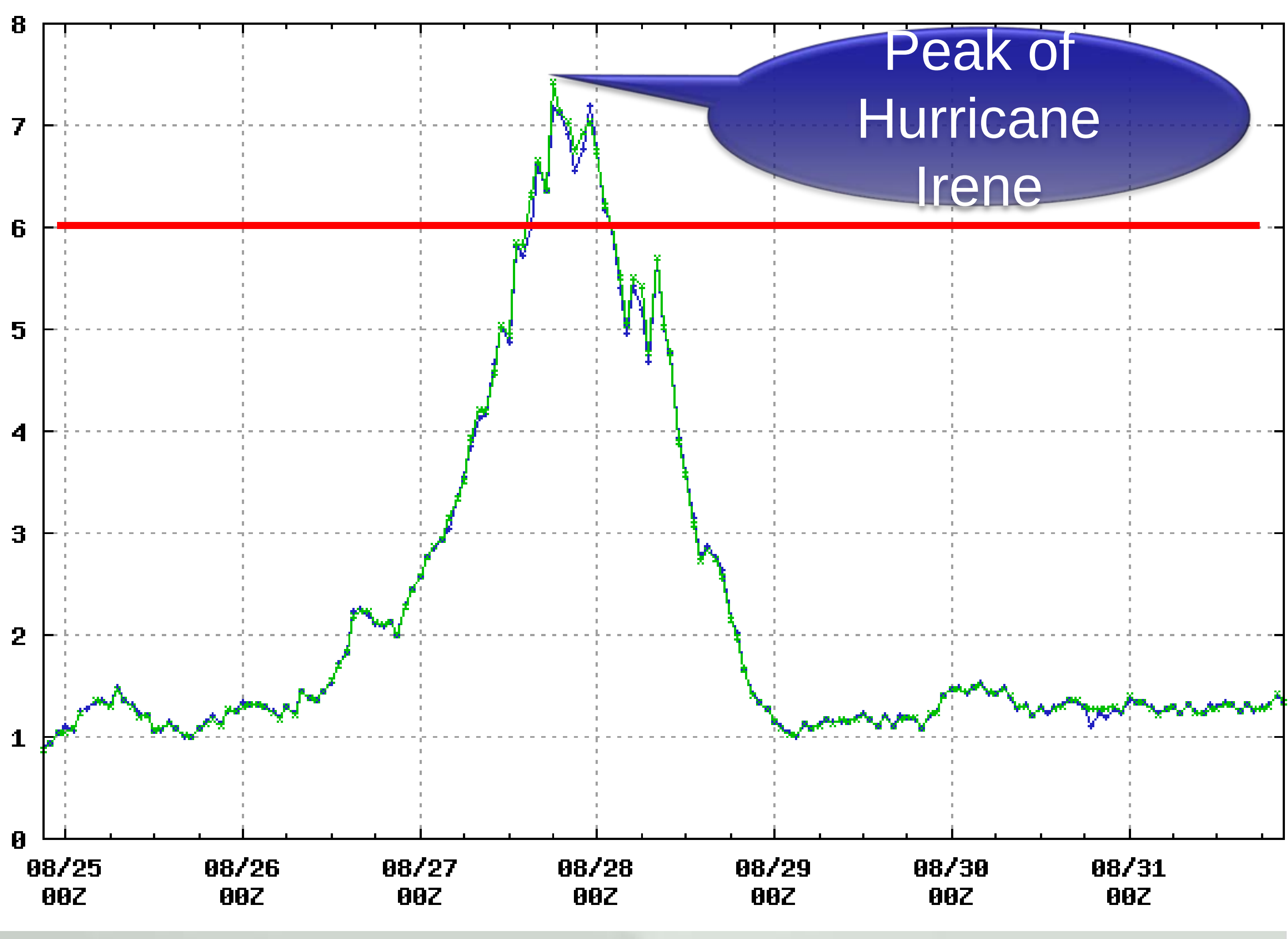
# *Tilt Correction Algorithm applied to Acceleration Times Series*

Dual Wave System at 44014 during Hurricane Irene

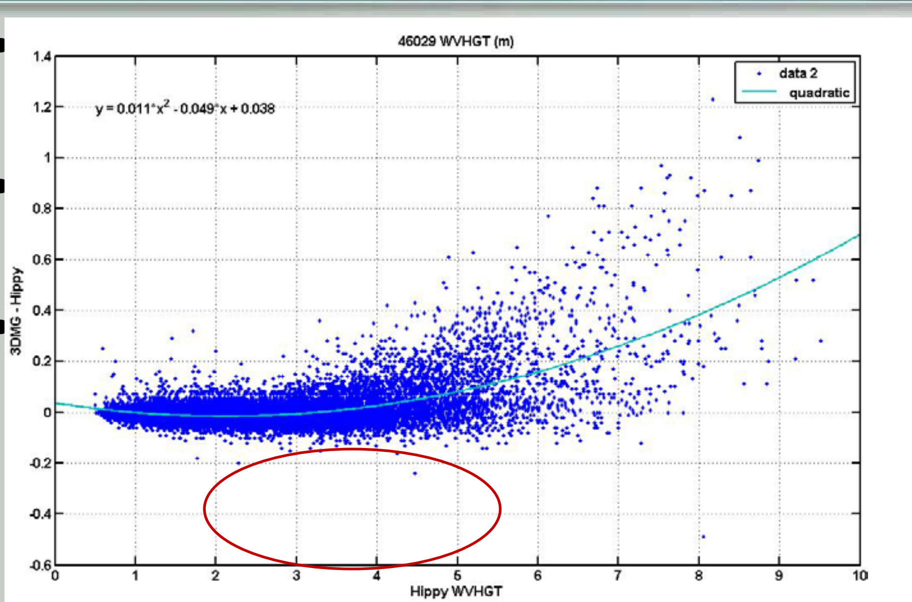
Tilt Correction:

(Riley *et al*., 2011) requires:

Pitch and roll sensors and 3 orthogonal accelerometers

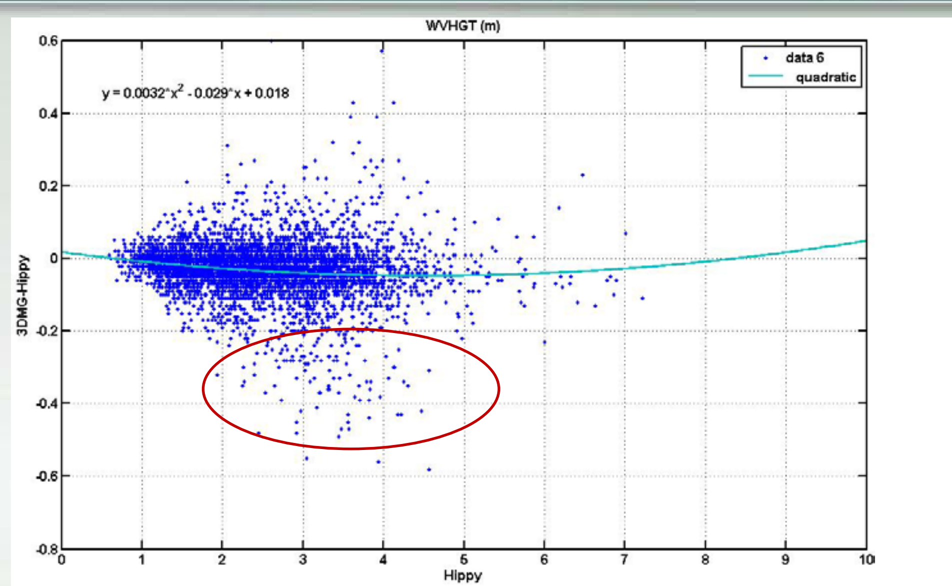


# Monterey Wave Testbed



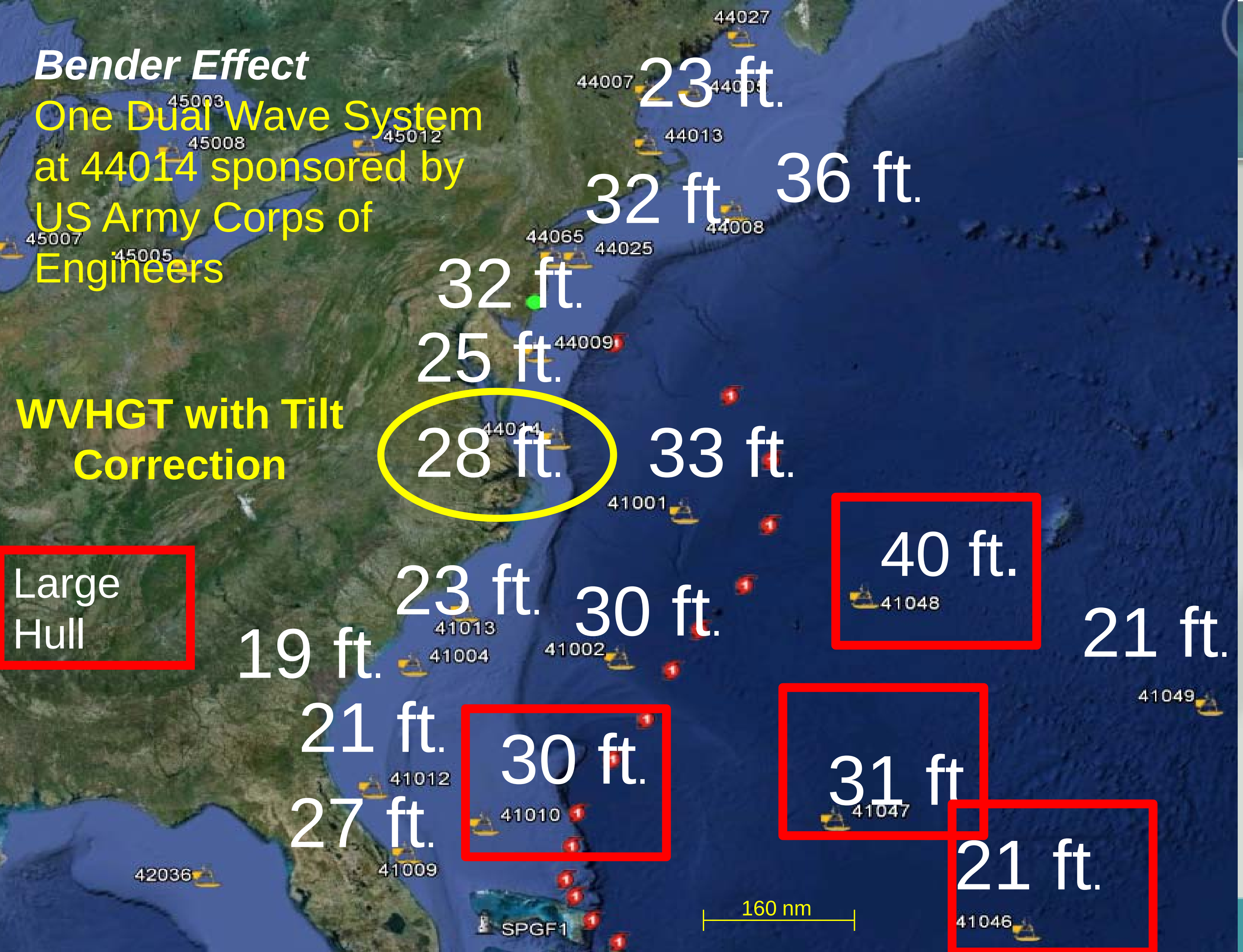

Fit Yields 2m error at 16m WVHGT (12%)

Strapped-down accelerometer vs Hippy No Tilt Correction




Fit Yields 0.34 m error at 16m WVHGT (2%)
Overall 46042 RMSD 0.08m vs 0.06m for 46029 <=7m

Strapped-down accelerometer vs Hippy With Tilt Correction



Bender Effect
One Dual Wave System at 44014 sponsored by US Army Corps of Engineers
WVHGT with Tilt Correction
Large Hull
23 ft.
36 ft.
32 ft.
32 ft.
25 ft.
28 ft.
33 ft.
40 ft.
23 ft.
30 ft.
21 ft.
19 ft.
21 ft.
30 ft.
31 ft.
27 ft.
21 ft.
160 nm
44027
44007
44005
44013
44008
44065
44025
44009
44014
45003
45012
45008
45007
45005
41001
41048
41013
41004
41002
41049
41012
41010
41047
42036
41009
SPGF1
41046

For more information: richard.bouchard@noaa.gov

# Further Research

- **There are more contributors to uncertainty**
  - e.g., crest chopping, system changes (Gemmrich *et al.,* 2011), etc.

- **Tentative efforts to gage accuracies and uncertainties:**
  - JCOMM Pilot Project for Wave Evaluation and Testing (Swail *et al*., 2010), e.g.., Monterey TestBed
  - Limited Dual Wave systems
  - FLOSSIE: Intergenerational Field Comparison
  - Time Series Data will be available to test theories of wave height distribution and measurements of the maximum wave.

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# Supplementary Slides

# Supplementary Slide
# Confidence Intervals

- Statistical Spectral Bandwidth ($B_s$), Bendat and Piersol, 2010:

$$B_s = \frac{(\sum S(f)df)^2}{\sum S^2(f)df}$$

- Total Degrees of Freedom (TDF), Earle 1983:

$$2 * B_s * \text{Sampling Duration}$$

- 90% CI (Donelan and Pierson, 1983)

The confidence interval for the estimate of the variance is given by (24)

$$P(10^{-(\mathrm{TDF})^{-1/2}}\, \hat{\mathrm{var}} < \mathrm{var} < 10^{+(\mathrm{TDF})^{-1/2}}\, \hat{\mathrm{var}}) = 0.90 \quad (24)$$

# Supplementary Slide
# Expected (mean) Maximum

- Rayleigh

$E(x_{max}) = m_0^{½} * (8.00* \ln N)^{½} * ( 1+ (0.577/2*\ln N)$

- Forristall (1978)

$E(x_{max}) = m_0^{½} * (8.42* \ln N)^{1/\alpha} * ( 1+ (0.577/\alpha*\ln N)$

Where:

$m_0= \sum S(f)*d(f)$; $m_2 = \sum f^2*S(f)*d(f)$;

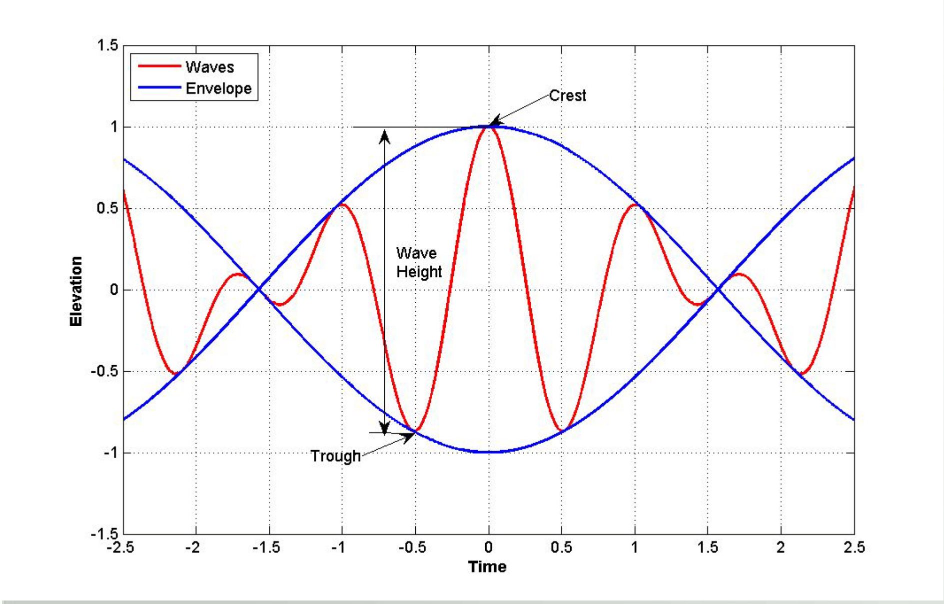
$N = 3600/T_z$; $T_{zero} = (m_0/m_2)^{½}$

$\alpha = 2.126$

# Forristall, 1978 (F78)

*..trough preceding a large crest is very likely to be on a lower part of the envelope.*

F78 (--) fits data △ better than Rayleigh (——



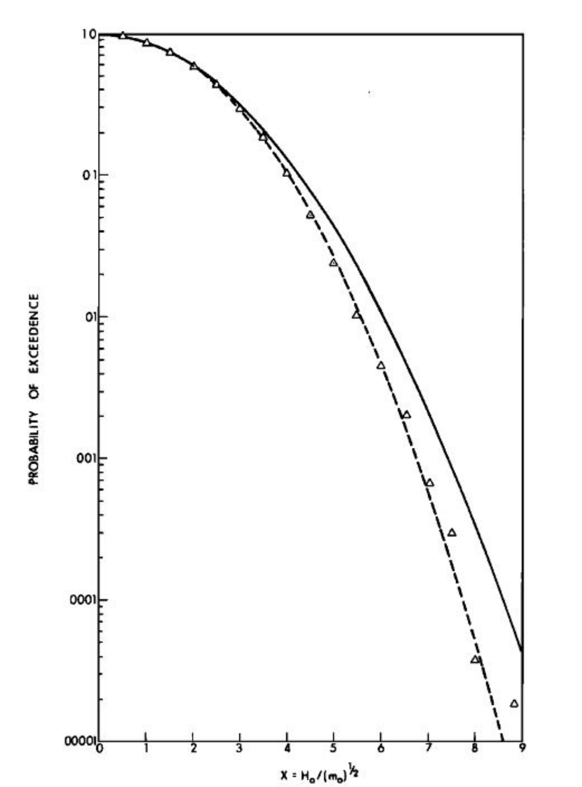
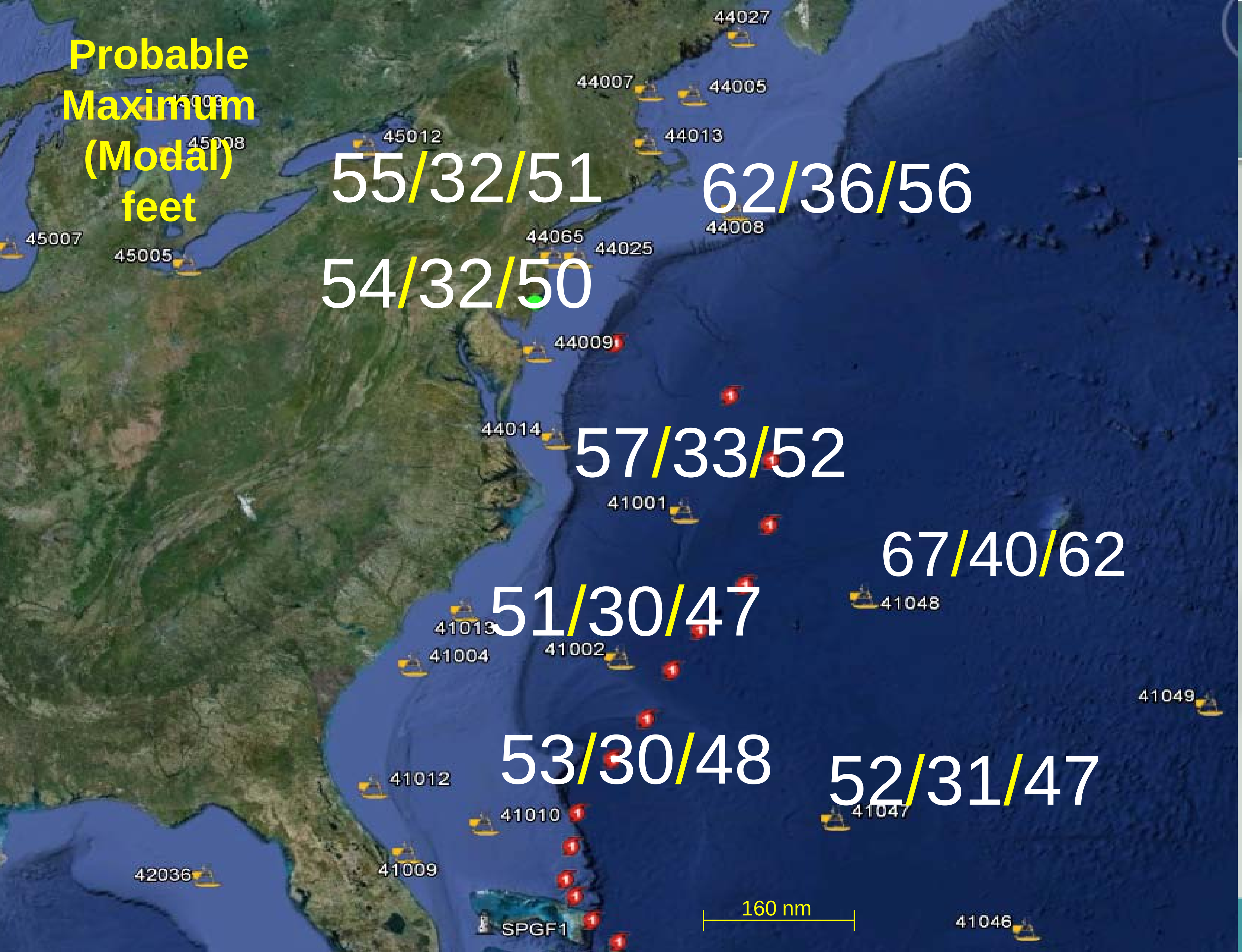




Fig. 2. Probability of exceeding a given normalized wave height. The triangles are data, the solid line is the Rayleigh distribution, and the dashed line is the empirical Weibull distribution.



Probable
Maximum
(Modal)
feet
55/32/51
62/36/56
54/32/50
57/33/52
67/40/62
51/30/47
53/30/48
52/31/47
44027
44007
44005
45012
44013
44008
45007
45005
44065
44025
44009
44014
41001
41048
41013
41004
41002
41049
41012
41047
41010
42036
41009
SPGF1
41046
160 nm

# Supplementary Slide
# Tilt Correction for Vertical Acceleration ($A_{corrected}$)

- Need pitch and roll sensors & 3 orthogonal accelerometers
- NDBC early development:
  - *Bender Effect* not evident on large hulls
  - Lacked integrated sensors to overcome phase lag between stand-alone sensors

$$A_{corrected} = A_{surge}*\sin(p) – A_{sway}*\cos(p)*\sin(r) – A_{uncorrected}*\cos(p)*\cos(r)$$

Where:

p = Buoy Pitch

r = Buoy Roll

Riley, R., C-C., Teng, R. Bouchard, R. Dinoso, and T. Mettlach, 2011: "Enhancements to NDBC's Digital Directional Wave Module." In *OCEANS 2011*, pp. 1-10. IEEE.