The Harvest Experiment:
Connecting Jason-3 to the Long-Term Sea Level Record

….with additional results from the Daisy Bank GPS Buoy

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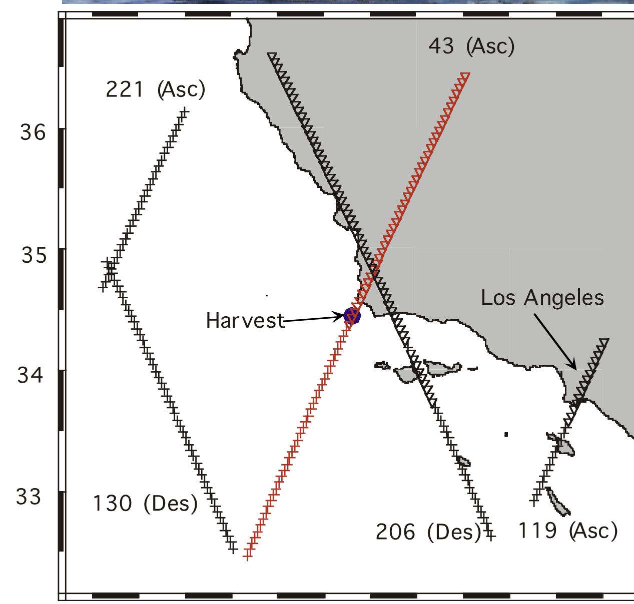
Harvest Platform

- **NASA Prime Verification Site for High-Accuracy (Jason-class) Altimetry**
  - Open-ocean location along 10-d repeat track
  - 10-km off coast of central California
- **Provides independent measure of local geocentric sea level**
  - Precise GPS receivers
  - Redundant tide gauges (Bubbler, radar, lidar)
  - Local survey
- **Yields absolute SSH bias**
  - Also provides for monitoring of ancillary parameters (e.g., wet troposphere delay)
- **Rich in-situ data set representing over 24 years of continuous monitoring**
  - 365 T/P overflights spanning 10 years (1992–2002)
  - 259 Jason-1 overflights spanning 7 years (2002–2009)
  - 303 Jason-2 overflights spanning 8 years (2008–2016)
  - First Jason-3 overflight on February 19, 2016
    - In formation 80 seconds after Jason-2
    - 23 dual overflights until…
    - Jason-2 began shift to new orbit on Oct. 2.

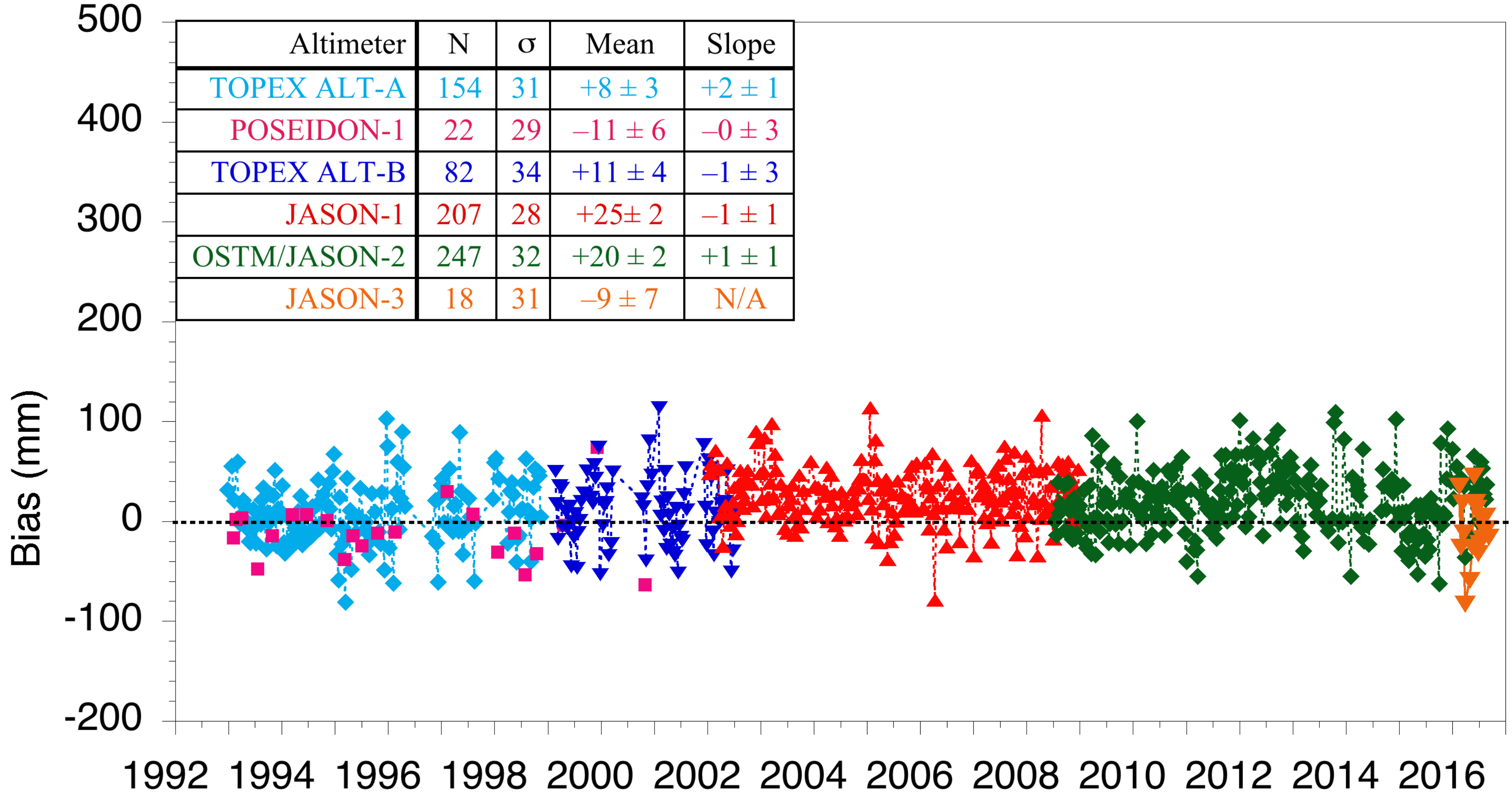


Harvest Long-Term SSH Calibration Record

With Early Jason-3 Overflights

Nominal Time Series:

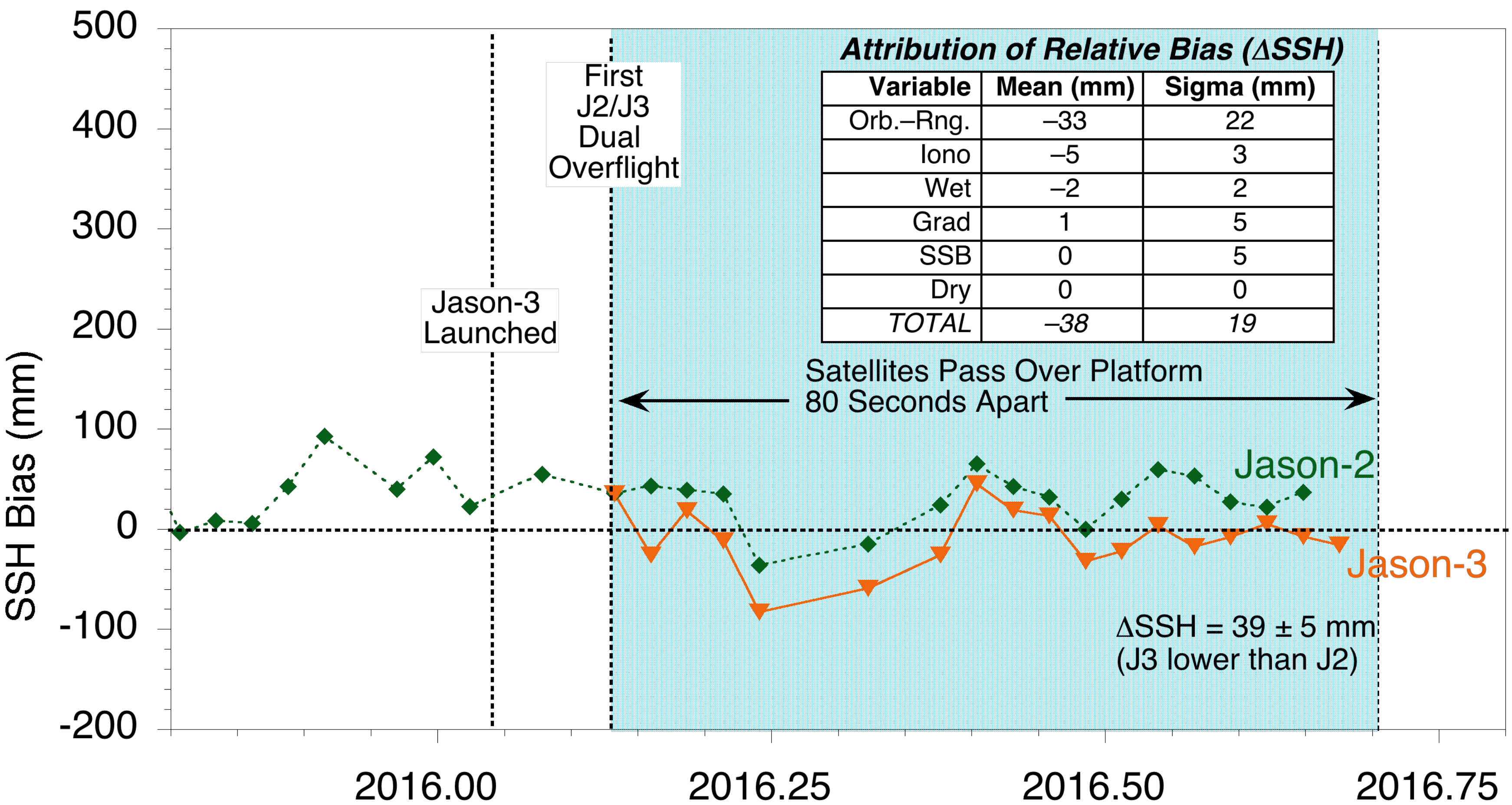
T/P: MGDR + reprocessed orbits (*Lemoine et al.*, 2010) and wet trop. (*Brown et al.*, 2009); **Jason-1:** GDR-E; **Jason-2**: GDR-D; **Jason-3**: GDR-T



Altimeter	N	σ	Mean	Slope
TOPEX ALT-A	154	31	+8 ± 3	+2 ± 1
POSEIDON-1	22	29	–11 ± 6	–0 ± 3
TOPEX ALT-B	82	34	+11 ± 4	–1 ± 3
JASON-1	207	28	+25± 2	–1 ± 1
OSTM/JASON-2	247	32	+20 ± 2	+1 ± 1
JASON-3	18	31	–9 ± 7	N/A

Harvest Calibration Time Series:

Closeup of Recent Jason-2 and -3 Data

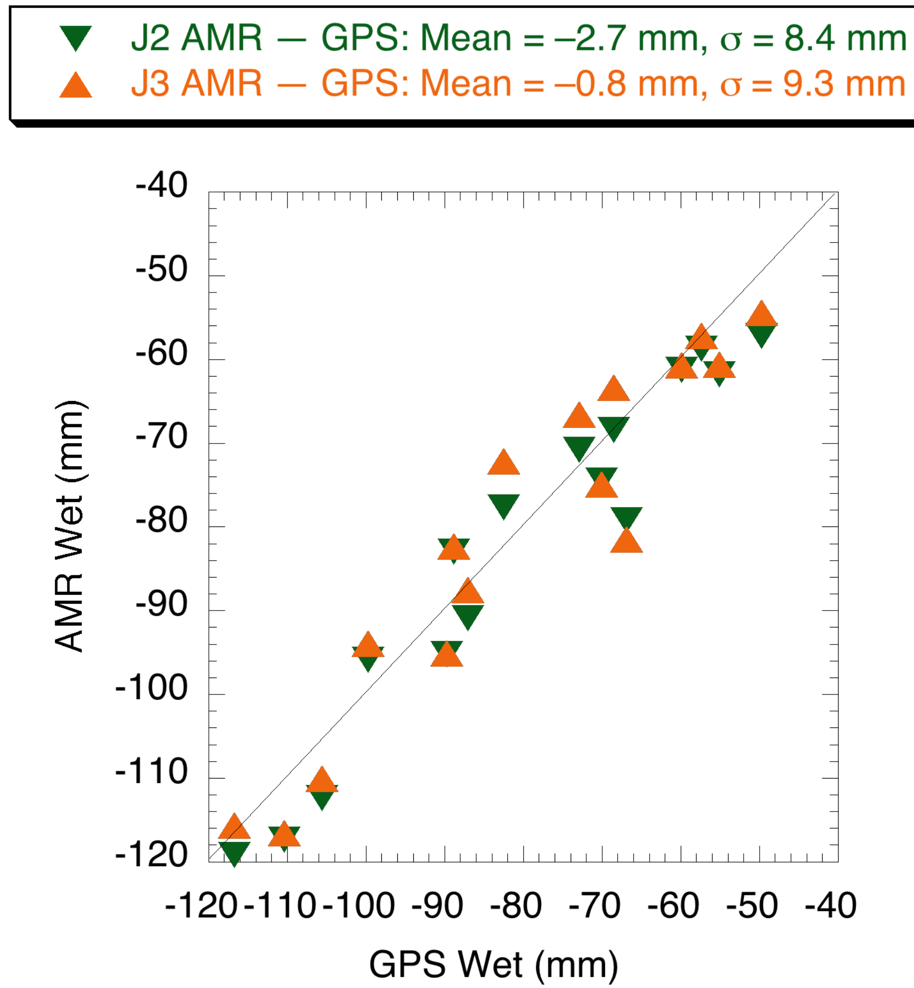


Variable	Mean (mm)	Sigma (mm)
Orb.–Rng.	–33	22
Iono	–5	3
Wet	–2	2
Grad	1	5
SSB	0	5
Dry	0	0
TOTAL	*–38*	*19*

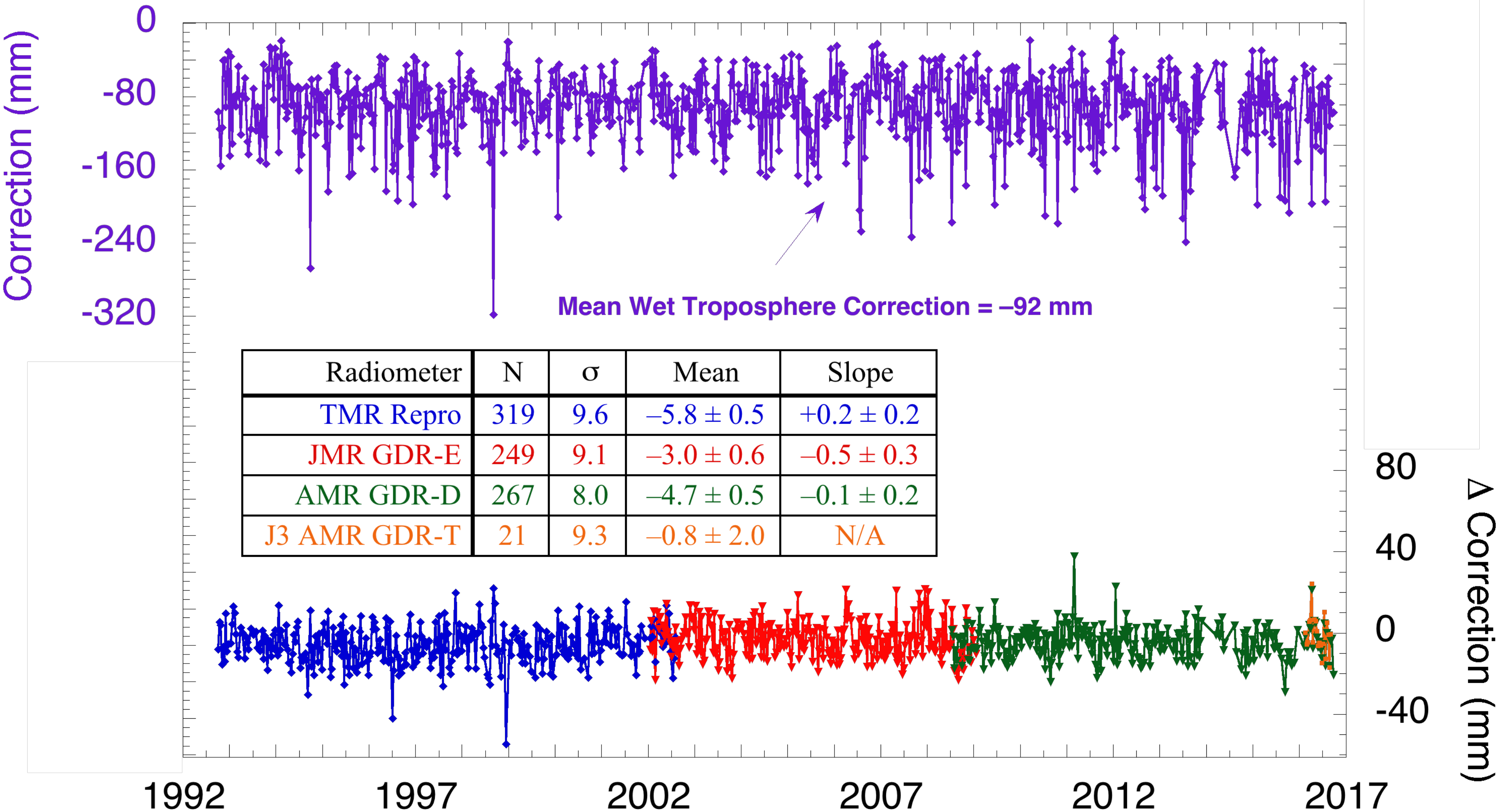
- Relative SSH bias from 17 dual overflights is 38 ± 5 mm (1 std. error, with J3 SSH lower than J2)
- Most of ΔSSH bias due to altimeter range (replacing POE with JPL GPS orbits impacts mean by only 1 mm.)
- Jason-3 iono. delay smaller than Jason-2.

Wet Troposphere: AMR vs. GPS Dual Overflights

- **Wet troposphere estimates from platform GPS used to monitor AMR path delay measurements.**
- **Large drift (~3 cm/yr) in J3 AMR IGDR reduced to insignificance (<1 mm/yr) with GDR-T.**
- **Long-term MR vs. GPS time series (next slide) provides another perspective.**
- **Note that typical wet path delay at Harvest is ~9 cm**
  - **Drier than global average**



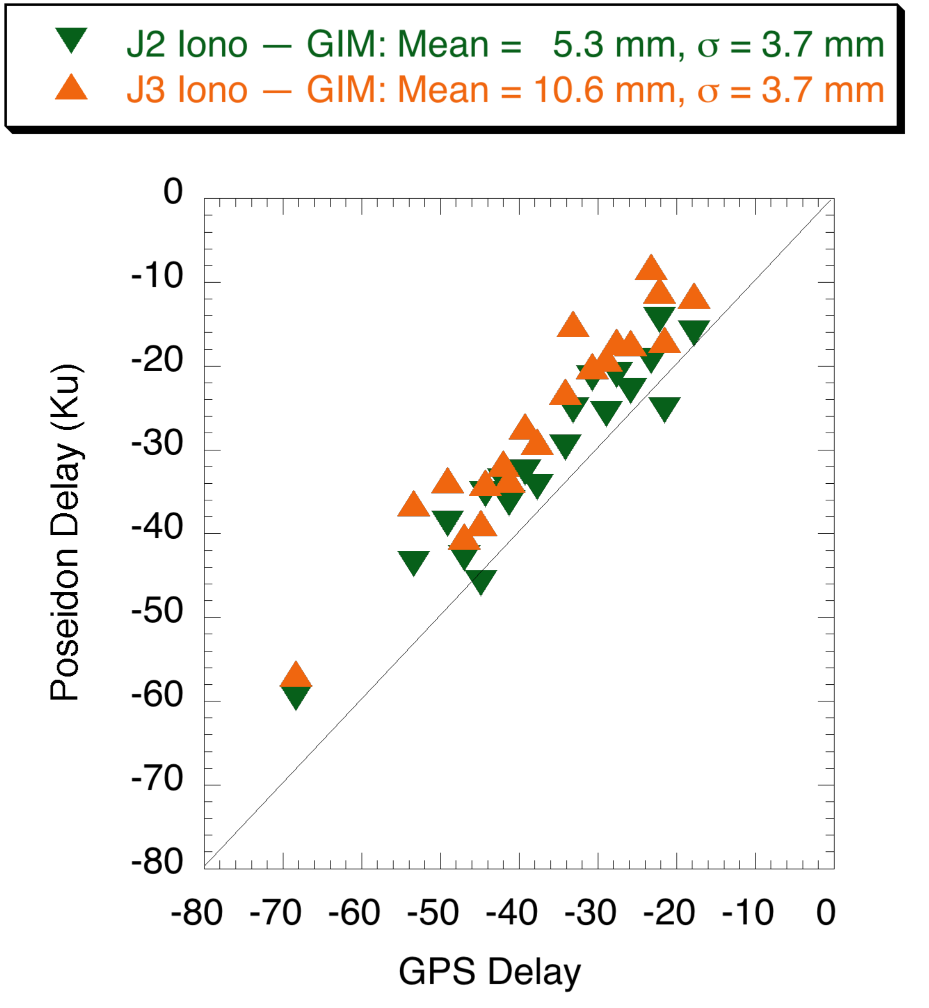
Wet Troposphere: MR vs. GPS



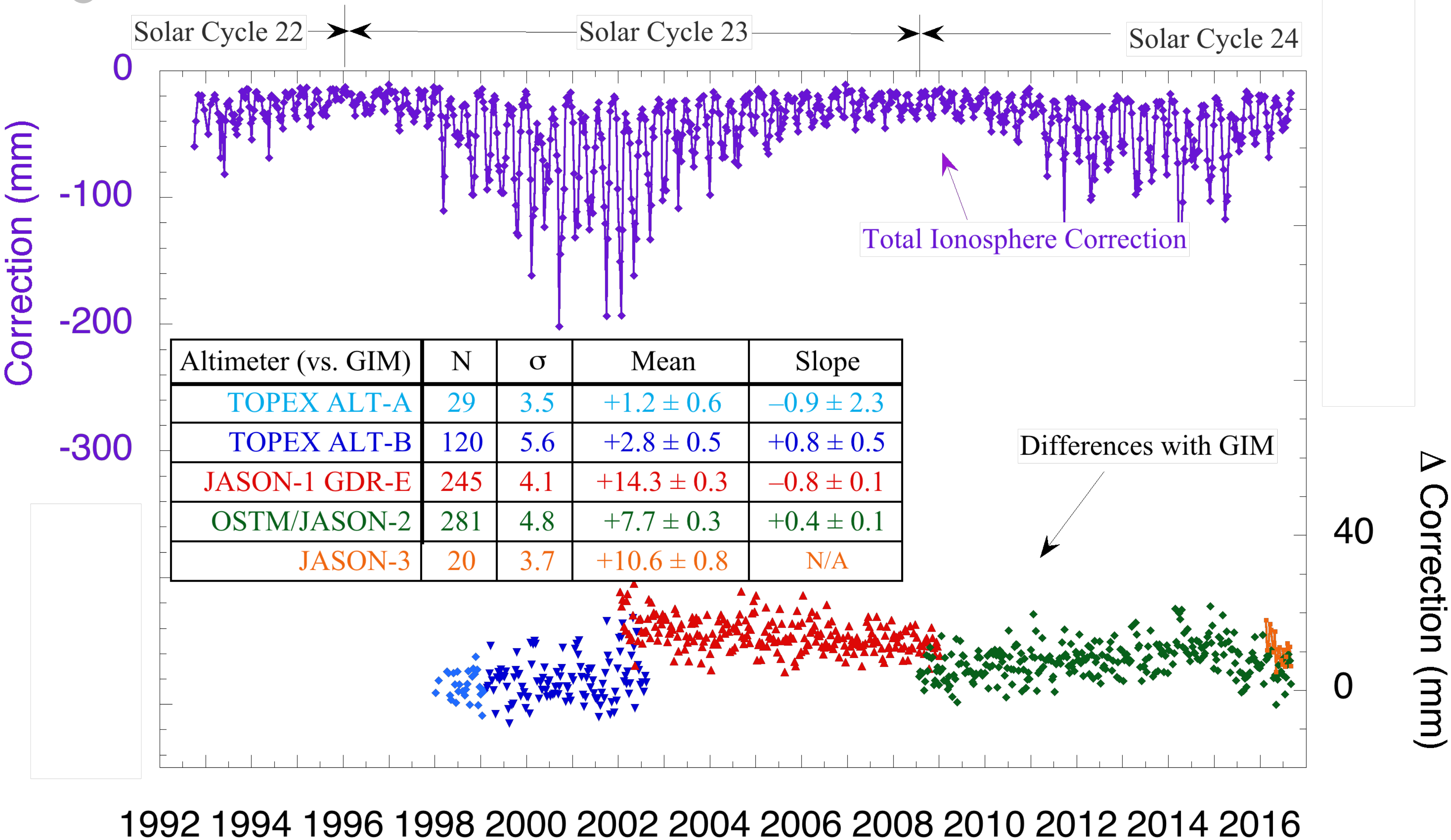
Radiometer	N	σ	Mean	Slope
TMR Repro	319	9.6	–5.8 ± 0.5	+0.2 ± 0.2
JMR GDR-E	249	9.1	–3.0 ± 0.6	–0.5 ± 0.3
AMR GDR-D	267	8.0	–4.7 ± 0.5	–0.1 ± 0.2
J3 AMR GDR-T	21	9.3	–0.8 ± 2.0	N/A

Ionosphere: Ku-Band Altimeter vs. GIM Dual Overflights

- **Ionosphere delay estimates from GIM used to monitor Ku-band altimeter correction.**
- **GIM delays larger (in magnitude) than both Jason-2 and -3 corrections.**
  - **GPS Mean = –38 mm**
  - **J2 Mean = –31 mm**
  - **J3 Mean = –25 mm**
- **Long-term ionosphere calibration time series (next slide) provides another perspective.**
  - **Provides backdrop of long-term solar cycle.**
  - **Delays for all Jason missions smaller than GIM.**
  - **GIM errors may also contribute**



Ionosphere: Ku-Band Altimeter vs. GPS



Altimeter (vs. GIM)	N	σ	Mean	Slope
TOPEX ALT-A	29	3.5	+1.2 ± 0.6	–0.9 ± 2.3
TOPEX ALT-B	120	5.6	+2.8 ± 0.5	+0.8 ± 0.5
JASON-1 GDR-E	245	4.1	+14.3 ± 0.3	–0.8 ± 0.1
OSTM/JASON-2	281	4.8	+7.7 ± 0.3	+0.4 ± 0.1
JASON-3	20	3.7	+10.6 ± 0.8	N/A

GPS Buoy Project

- Joint NASA JPL, NOAA PMEL and U. Washington project funded through NASA ROSES call (Physical Oceanography)*

OBJECTIVES:

- Design, build and test a modular, low-power, robust, high-accuracy GNSS measurement system for long-term, continuous and autonomous operations on ocean- and cryosphere-observing platforms.
- Probe the limits of new kinematic precise-point positioning (PPP) techniques for accurately determining sea-surface height, and recovering neutral and charged atmosphere characteristics.
- Explore potential scientific benefits—in the fields of physical oceanography, weather and space weather—of accurate GNSS observations from a global ocean network of floating platforms.

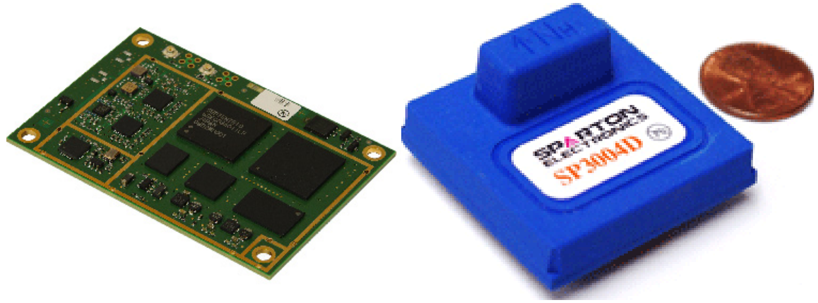
Prototype buoy successfully completed open-ocean testing at Jason crossover location near Daisy Bank off Oregon coast (120 days from May 11–Sept. 8, 2016).

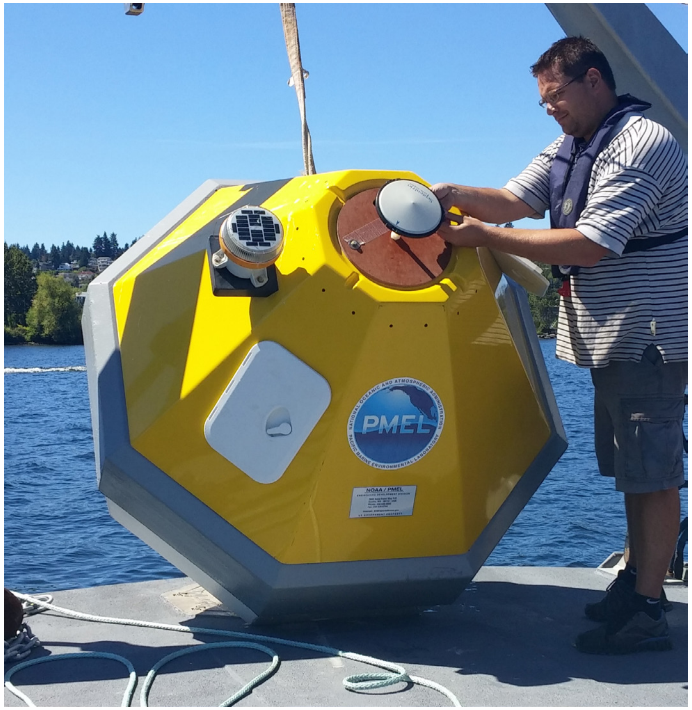
**Extending the Reach of the Global GNSS Network to the World's Oceans: A Prototype Buoy for Monitoring Sea Surface Height, Troposphere and Space Weather*, B. Haines, S. Brown, S. Desai, A. Komjathy, R. Kwok, D. Stowers, C. Meinig and J. Morison.

Prototype Precision GPS Buoy

FEATURES

- Integrated low-power (~1 W), dual-frequency GPS system: Septentrio AsteRX-m credit-card sized receiver + PolarNt-x MF Antenna.
- Miniaturized digital compass/accelerometer.
- Iridium communications (presently used for basic heartbeat information).
- Adaptable to multiple floating platforms (e.g., buoys, wave gliders).
- Delivers geodetic accuracies without nearby reference stations.





DEVELOPMENT AND TESTING

- Buoy tested successfully under progressively more challenging conditions in US Pacific Northwest:

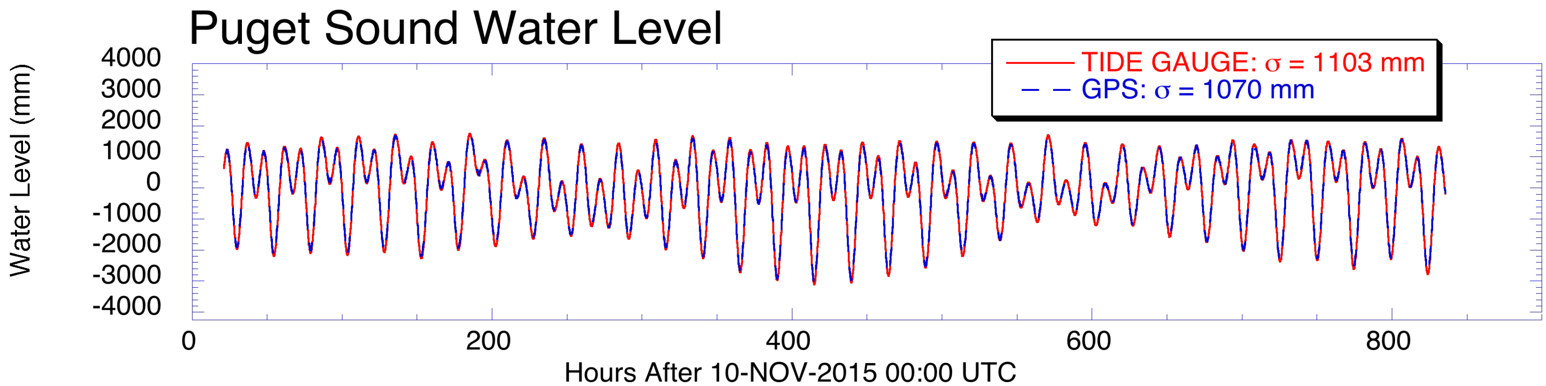
✓ *Lake Washington (Aug. 7–12, 2015).*

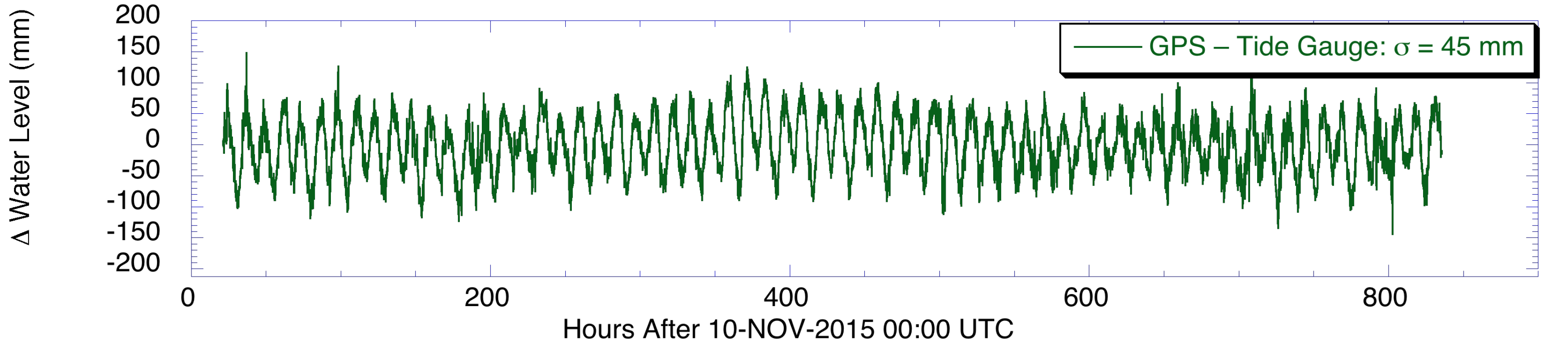
✓ *Puget Sound (Nov. 10 to Dec. 14, 2015).*

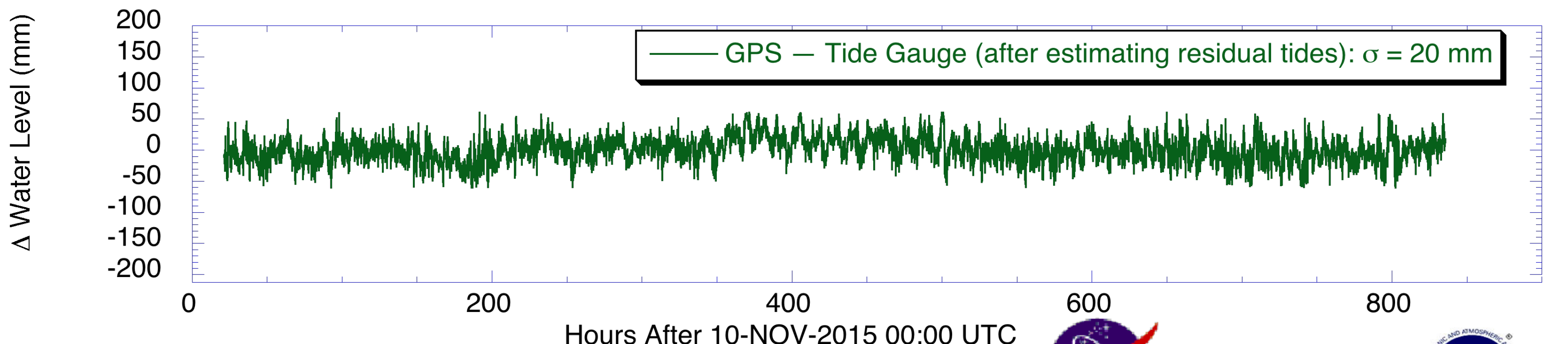
✓ *Daisy Bank off Oregon Coast: open ocean Jason crossover location (May 11 to Sep. 8, 2016).*

Puget Sound Test Results

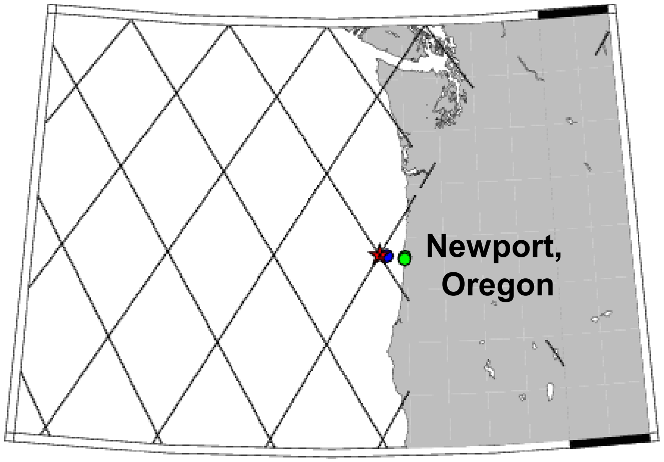
Buoy vs. Tide Gauge Water Level (14 km separation)

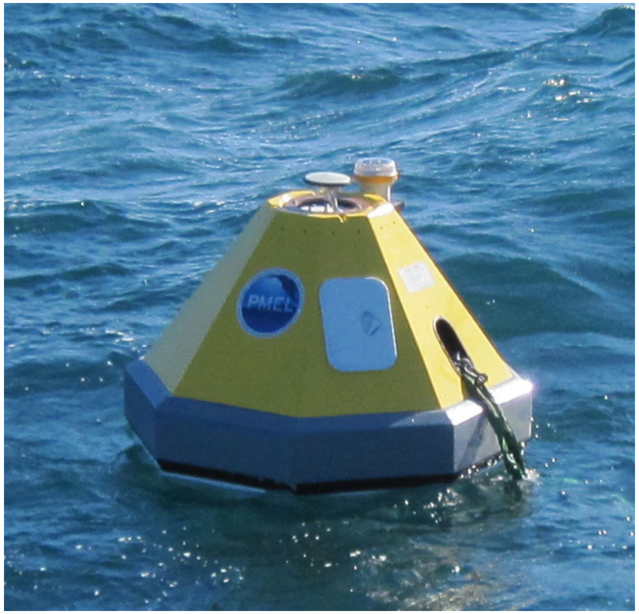




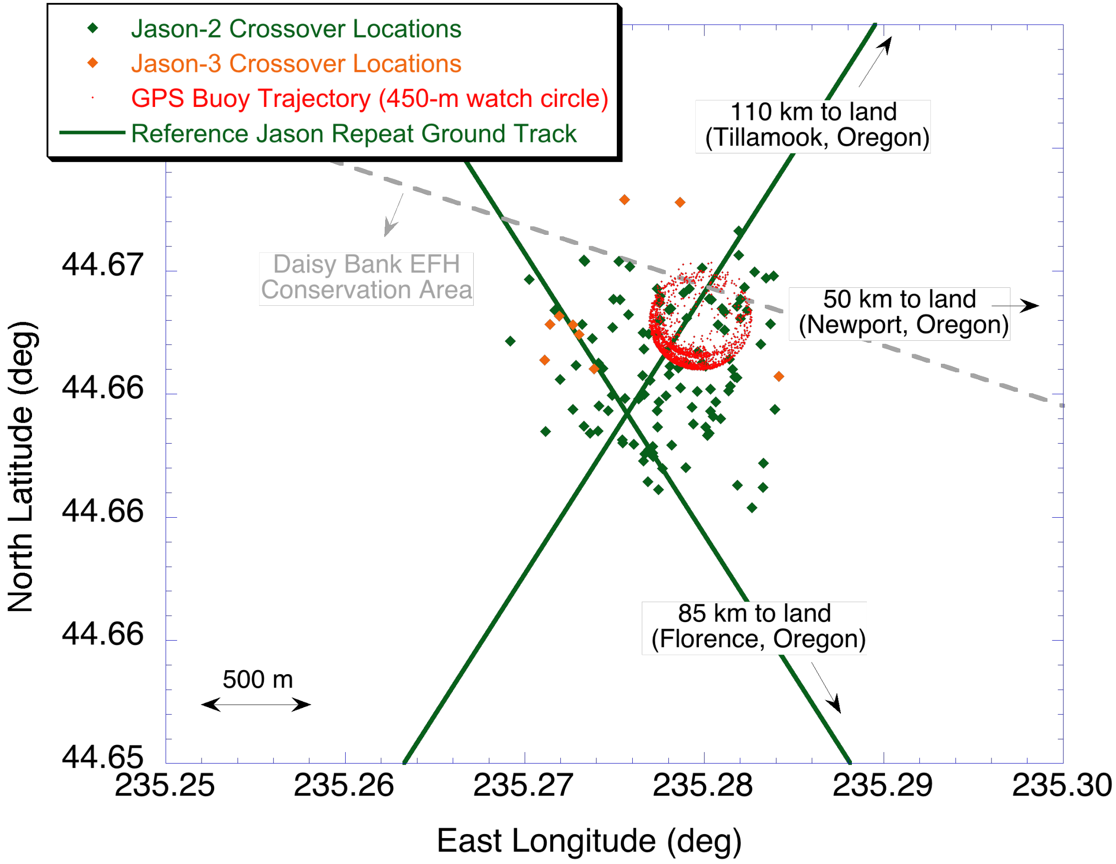


Daisy Bank GPS Buoy



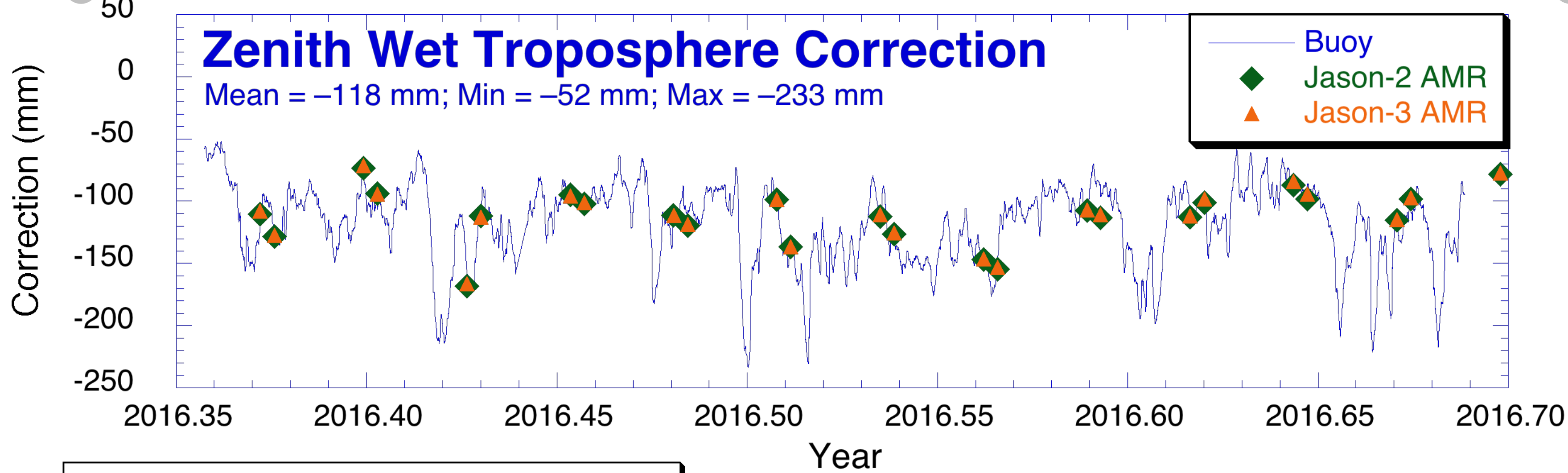


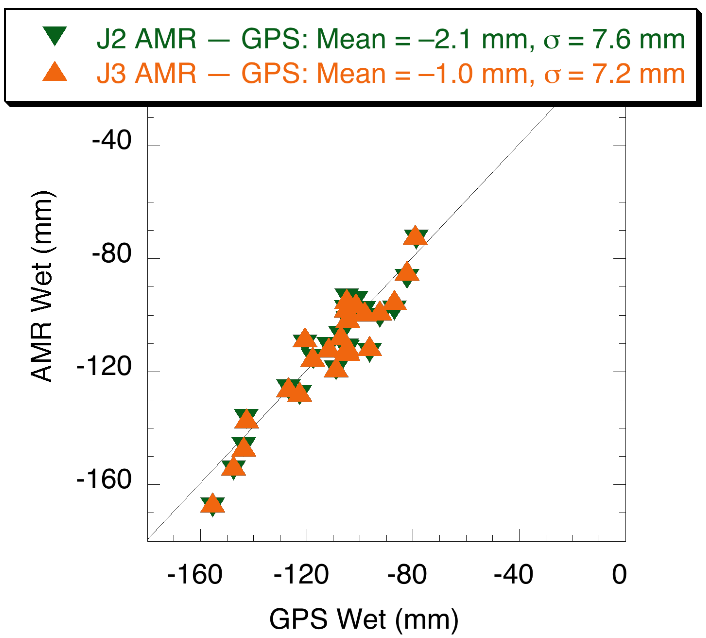
CLOSEUP OF BUOY LOCATION



Deployment spanned 24 dual Jason-2/3 overflights

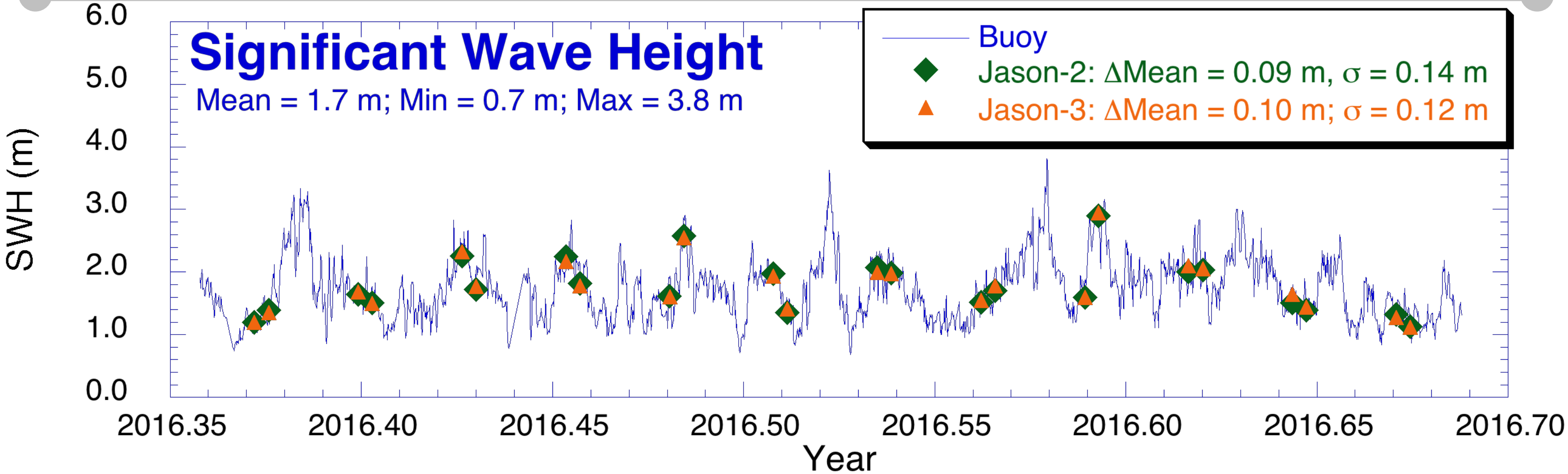
GPS Buoy vs. Radiometer at Daisy Bank: Wet Troposphere

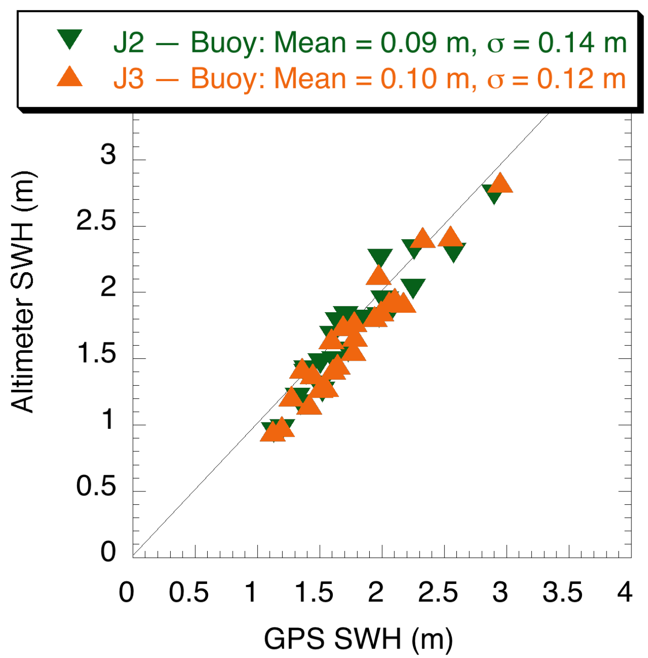




- **Buoy zenith wet troposphere estimated (as random walk) simultaneously with buoy position and clock.**
- **Excellent agreement between buoy and radiometer delay**
  - Bias at mm level
  - Scatter of 7–8 mm

GPS Buoy vs. Altimeter at Daisy Bank: SWH

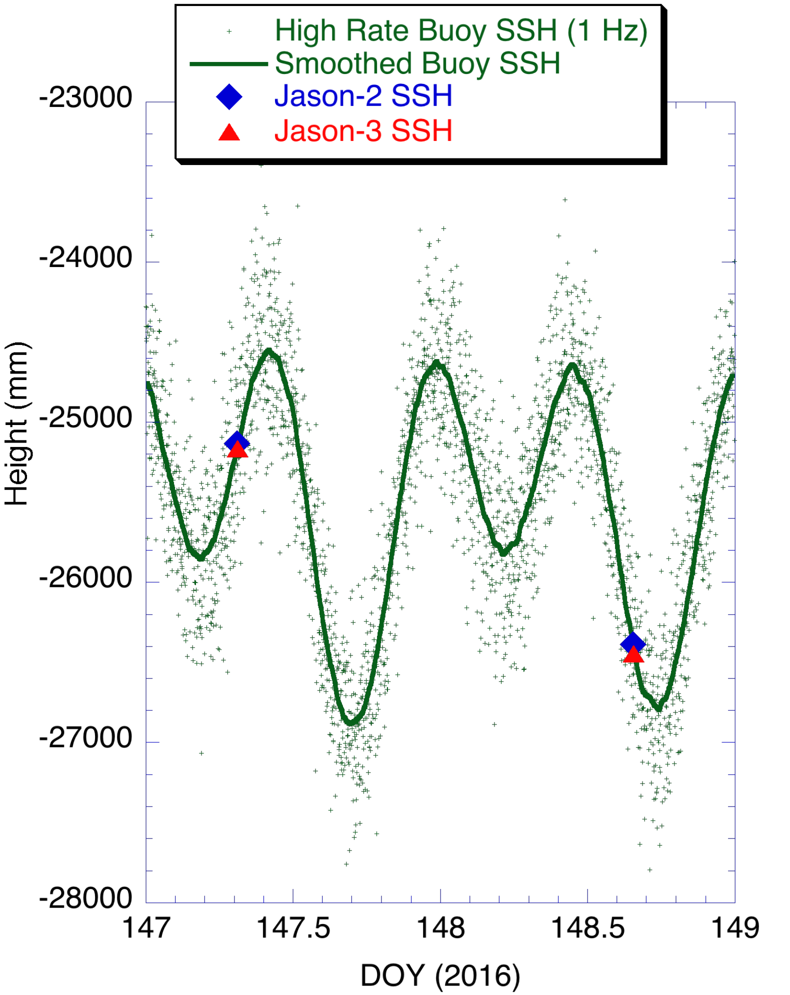


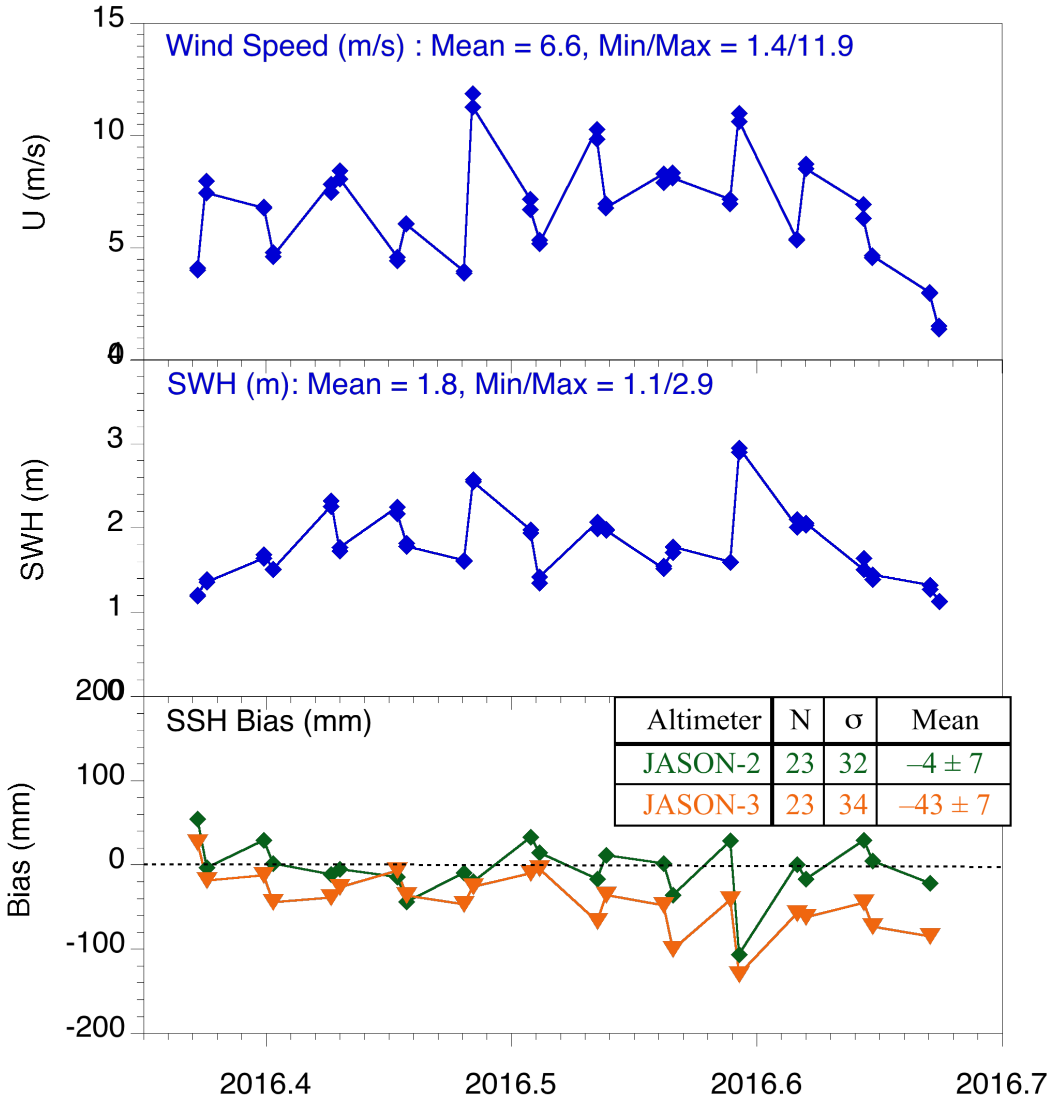


- **Buoy SWH derived from scatter of 1-Hz height estimates over ten minutes.**
  - SWH = 4σ
- **Excellent agreement between buoy and radar altimeter**
  - ~10-cm bias
  - ~10-cm scatter

GPS Buoy vs. Altimeter at Daisy Bank: Sea Surface Height

Buoy vs. Altimeter SSH: May 26–27, 2016





Altimeter	N	σ	Mean
JASON-2	23	32	–4 ± 7
JASON-3	23	34	–43 ± 7

Summary

- **Absolute SSH bias from Harvest***
  - Jason-3: –9 ± 12 mm for GDR-T (Cycles 1 to 21 with N = 18)
  - Jason-2: +20 ± 10 mm for GDR-D (Cycles 1 to 300 with N = 247)
  - Jason-1: +25 ± 10 mm for GDR-E (Cycles 1 to 259 with N = 206)
- **Relative Jason-2 vs. Jason-3 SSH bias *<u>from dual Harvest overflights</u>*:**
  - Jason-3 SSH lower (by 38 ± 5 mm) than Jason-2 SSH.
  - Comparisons with “orbit-range” suggest SSH bias comes mainly from range.
  - Smaller Jason-3 ionosphere delay (~5 mm).
- **SSH drift at Harvest indistinguishable from zero for all legacy systems**
  - ≤ 1 mm/yr for all systems except TOPEX (Side A). Jason-3 time series too short.
- **Preliminary results from Daisy Bank GPS buoy very promising**
  - Returned high-quality, uninterrupted data for entire open-ocean test (~120 d).
  - Supported accurate retrievals of SSH, SWH, wet path delay and ionosphere.
  - Competitive with Harvest for all altimeter calibration metrics.
  - Assimilation of attitude from digital compass/accelerometer underway: improved modeling of platform rotations, water level offset, and multipath should further reduce errors in buoy time series.

** Error includes uncertainty in platform vertical*

George H. Born

November 10, 1939 – January 21, 2016