California's Offshore Harvest Platform: Twenty Five Years of Monitoring the Altimetric Record

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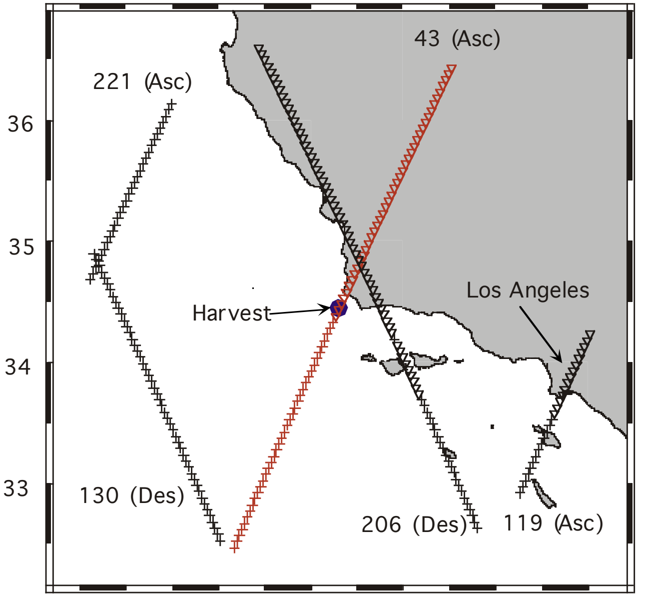
Harvest Platform

- **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)
- **Supports rich in-situ data set representing over 25 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)
  - 82 Jason-3 overflights and counting (2016–)
- **Informs important evolutions to GDRs**
  - Together with partner sites, exposed bias errors in SSH
  - TOPEX oscillator error (Zanife et al., 1996)
  - Jason-1/2 antenna reference errors (Desjonqueres)

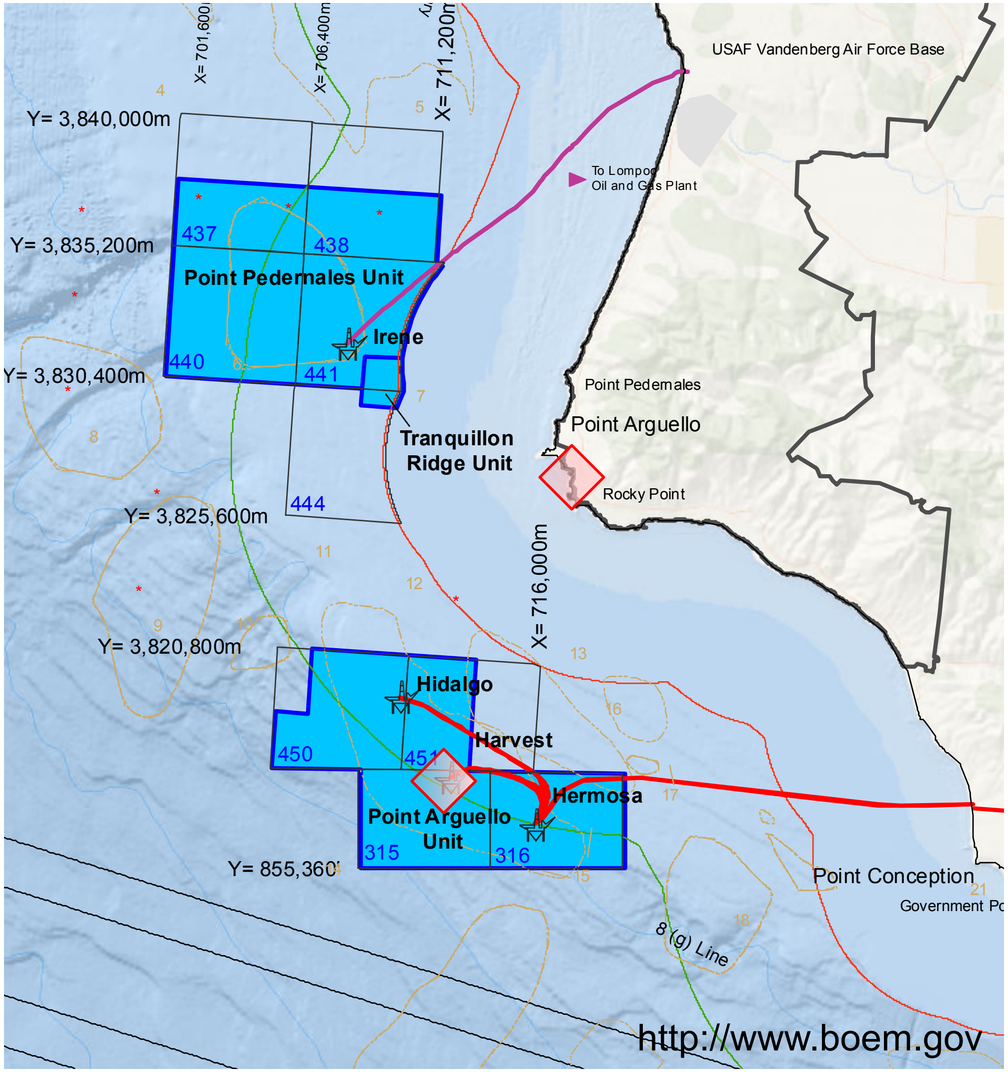


Outline

- **Focus on two most significant challenges for Harvest**
  1. **Using GPS to measure subsidence of seafloor from fluid withdrawal**
  2. **Using tide gauges to measure local (platform) water level in heavy seas**
- **Describe past experiences**
  - **How have these challenges informed the evolution of the Harvest Experiment?**
- **Discuss future plans**
  - **Expanding the calibration footprint**
  - **Reducing sensitivity to leading error sources**

Vertical Land Motion from GPS

- Harvest (est. 1985) is the central of three oil platforms located over the Point Arguello offshore reservoir.
- Production began in 1991, peaked in 1994, and halted in 2015.
- Continuous GPS since 1992: one of the oldest GPS/tide gauge co-locations in the world.
- GPS at nearby Vandenberg AFB (est. 1992) provides onshore fiducial point away from reservoir subsidence bowl.
- Non-linear seafloor motions present significant challenge for altimeter calibration.



GPS Receivers

Early Estimate of Vertical Seafloor Motion from GPS

First Results Showed No Evidence of Subsidence

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. C12, PAGES 24,465–24,485, DECEMBER 15, 1994

Calibration of TOPEX/POSEIDON at Platform Harvest

E. J. Christensen,[1] B. J. Haines,[1] S. J. Keihm,[1] C. S. Morris,[1] R. A. Norman,[1] G. H. Purcell,[1] B. G. Williams,[1] B. D. Wilson,[1] G. H. Born,[2] M. E. Parke,[2] S. K. Gill,[3] C. K. Shum,[4] B. D. Tapley,[4] R. Kolenkiewicz,[5] and R. S. Nerem[5]

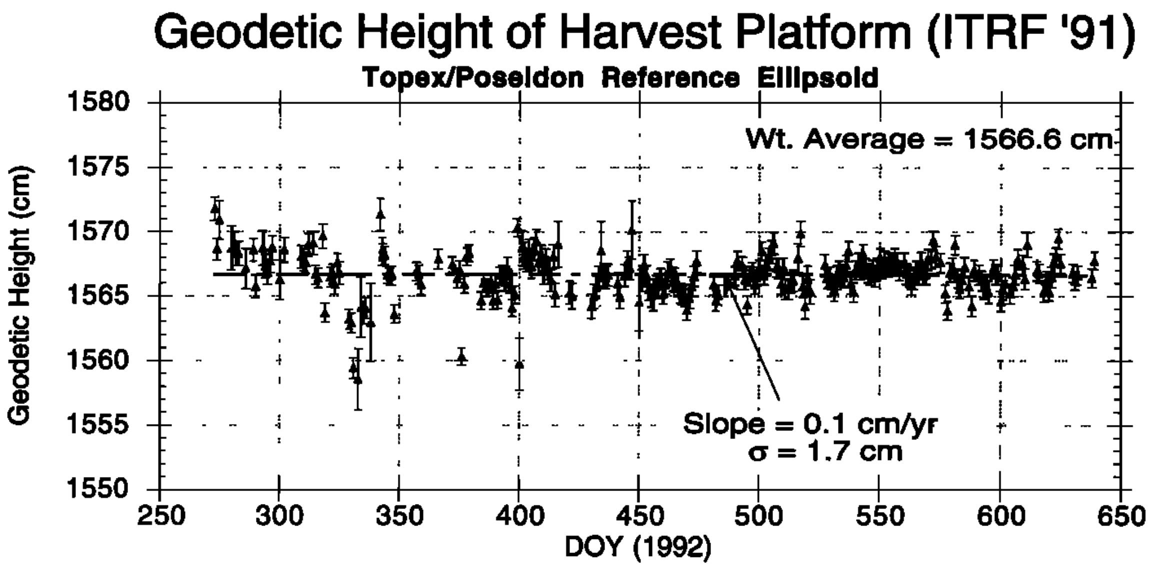
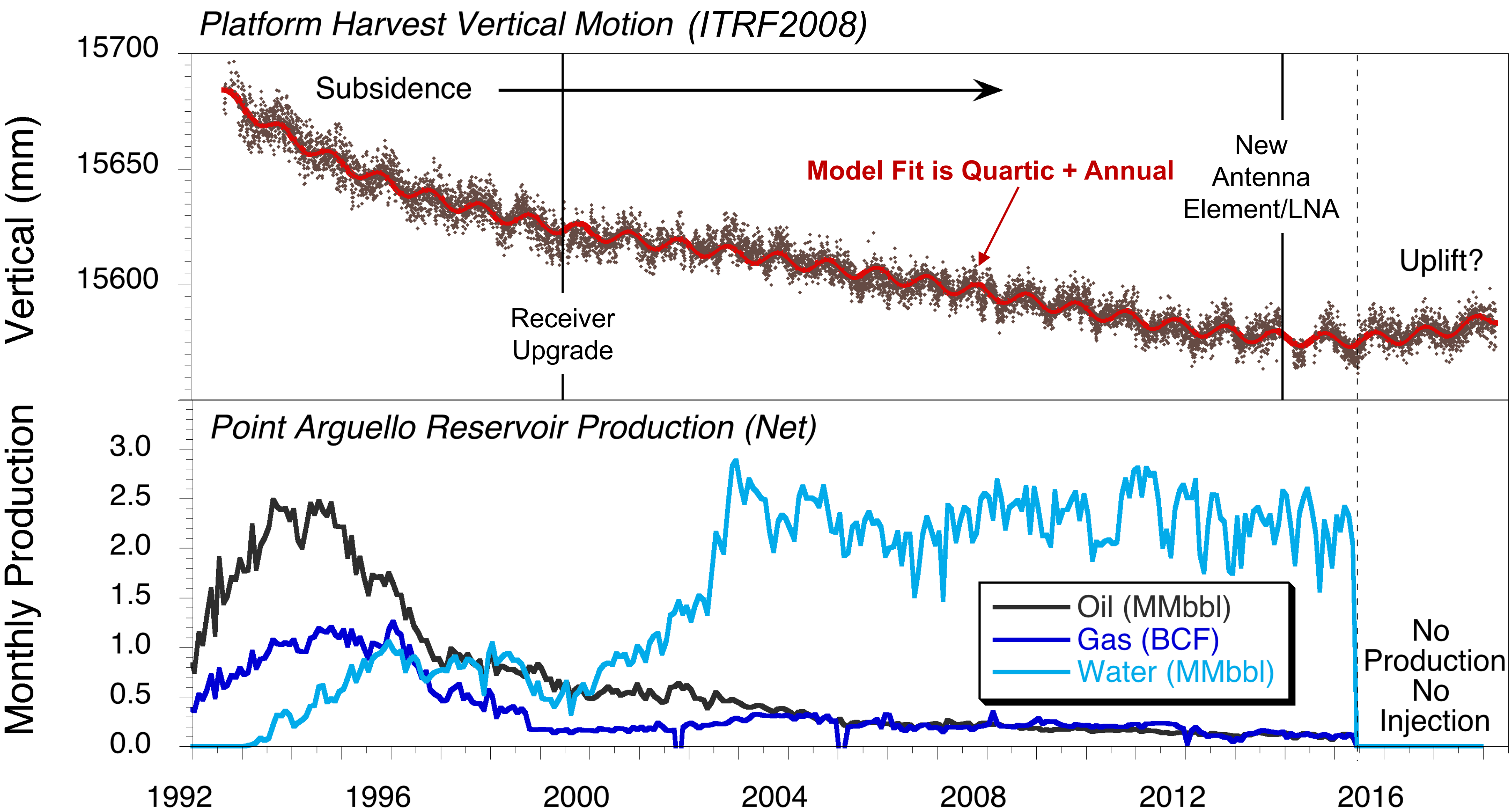


Figure 5. Geodetic height of the Harvest Platform determined by GPS in ITRF91 coordinates relative to the TOPEX/POSEIDON standard reference ellipsoid.

Current Estimate of Vertical Seafloor Motion from GPS

Complex Pattern of Subsidence and Rebound

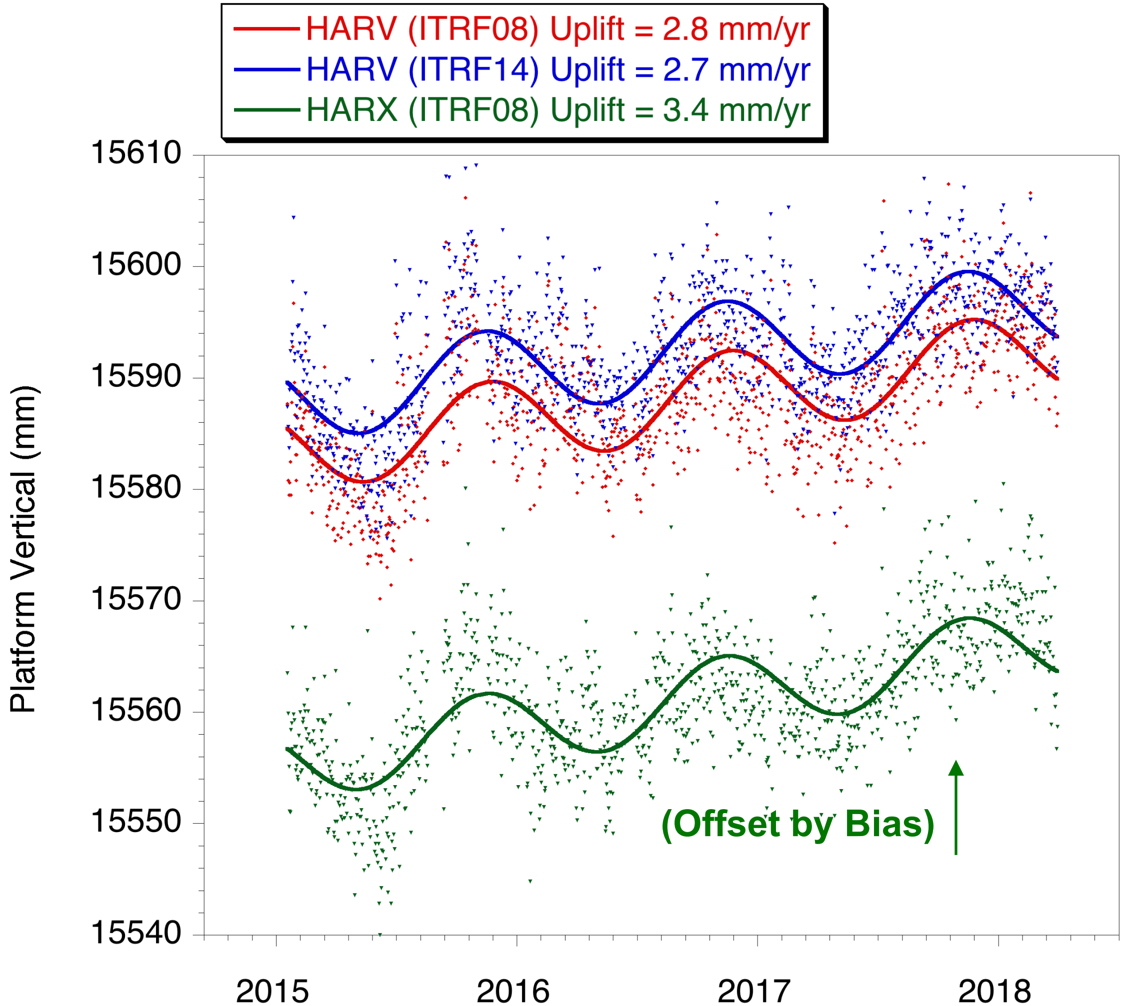


https://www.data.boem.gov/Main/PacificProduction.aspx

Current Estimate of Vertical Seafloor Motion from GPS

Recent Uplift Corroborated by Independent GPS Receiver/Antenna

Second GPS (Monitor) Station Installed Early 2015



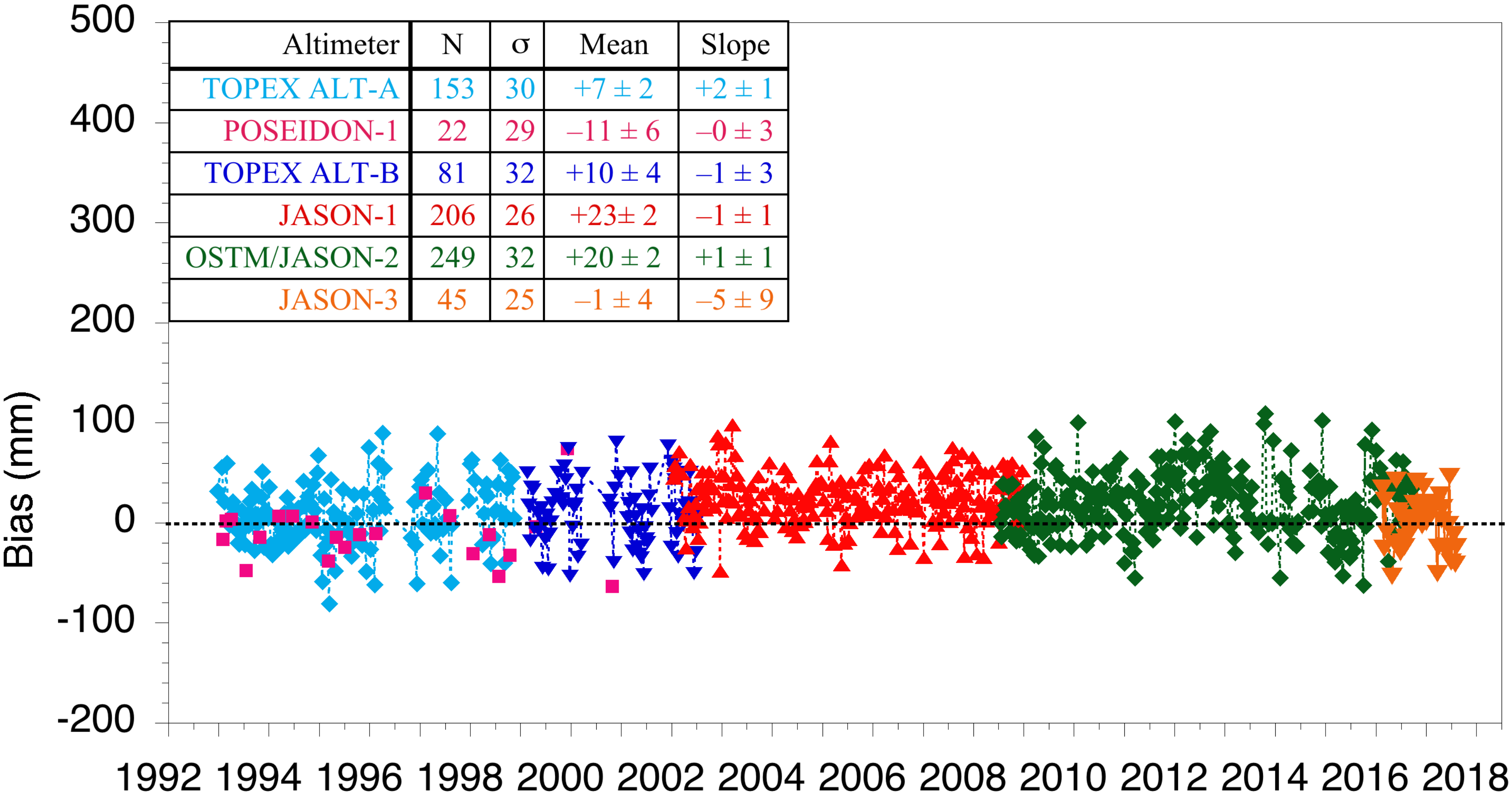
Harvest Long-Term SSH Calibration Record

Circa October 2017 (Miami OSTST)

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-E

Altimeter	N	σ	Mean	Slope
TOPEX ALT-A	153	30	+7 ± 2	+2 ± 1
POSEIDON-1	22	29	–11 ± 6	–0 ± 3
TOPEX ALT-B	81	32	+10 ± 4	–1 ± 3
JASON-1	206	26	+23± 2	–1 ± 1
OSTM/JASON-2	249	32	+20 ± 2	+1 ± 1
JASON-3	45	25	–1 ± 4	–5 ± 9

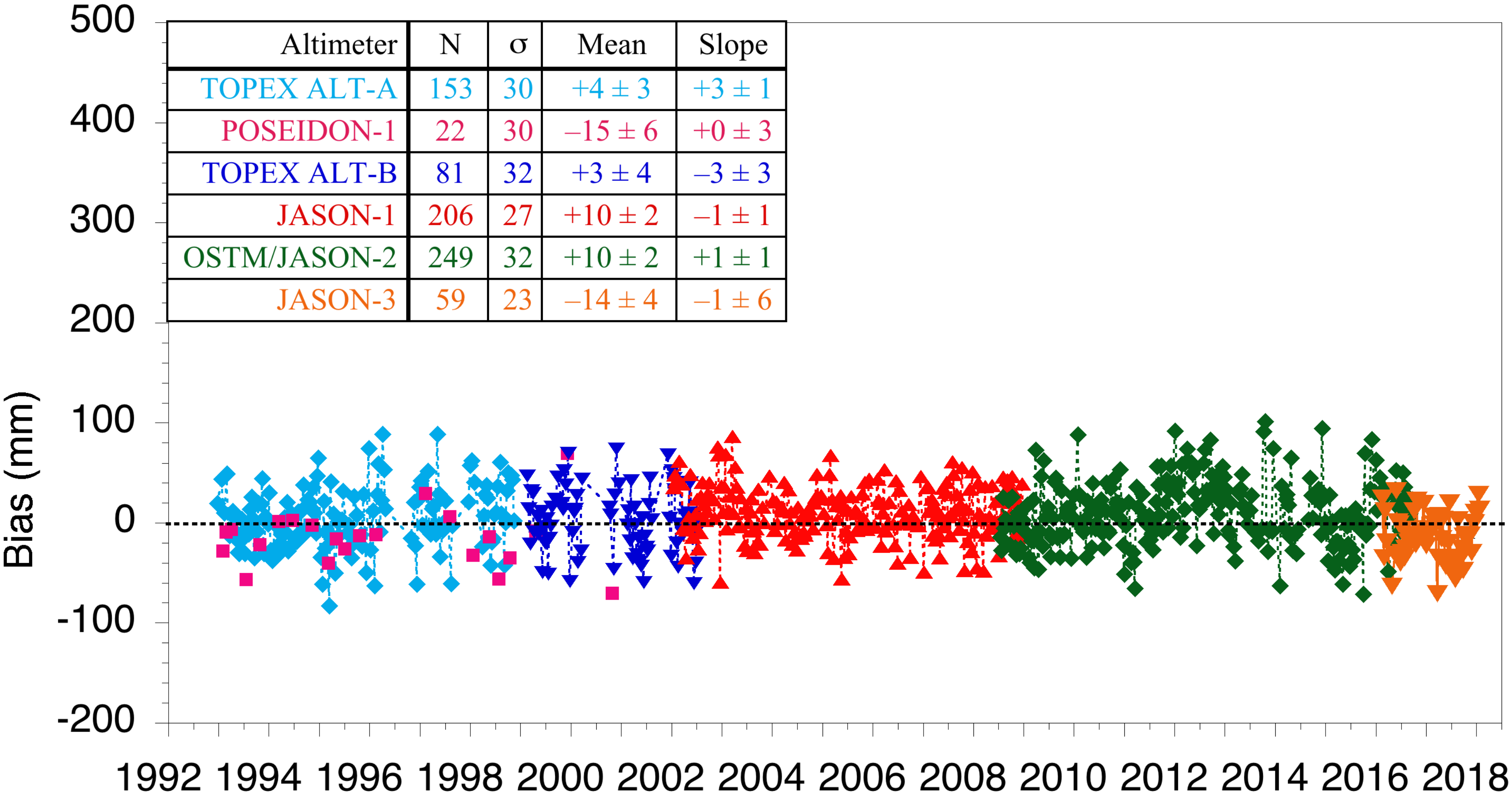


Harvest Long-Term SSH Calibration Record

Current Best Estimate (Using New Estimate of Seafloor Motion)

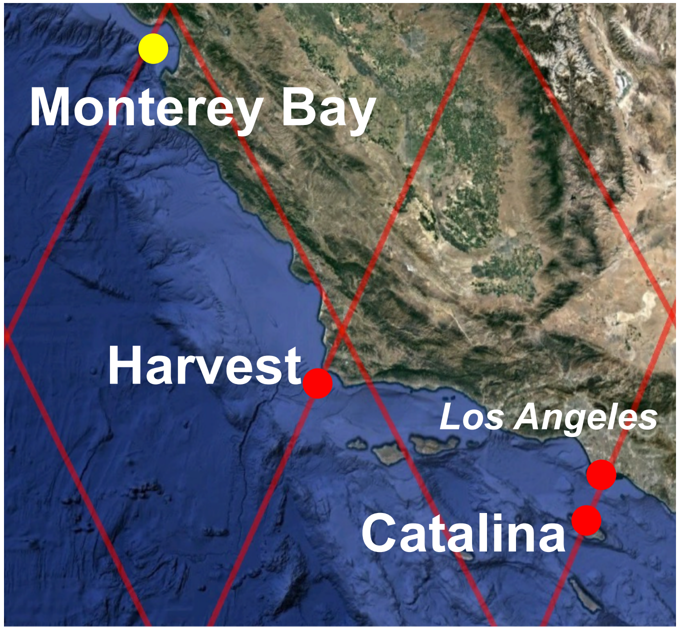
Nominal Time Series:

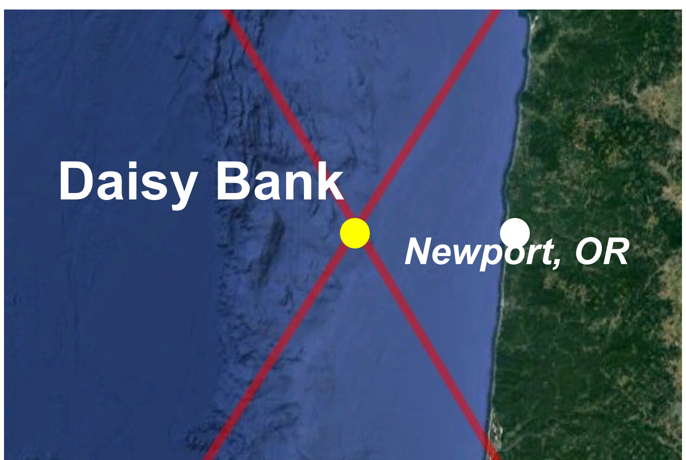
T/P: MGDR + reprocessed orbits (*Lemoine et al.*, 2010) and wet trop. (*Brown et al.*, 2009); **Jason-1:** GDR-E; **Jason-2**: GDR-D; **Jason-3**: GDR-E

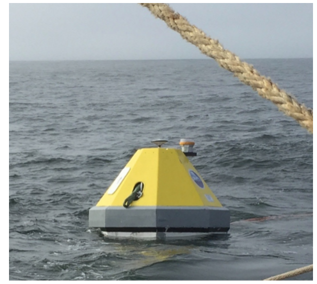


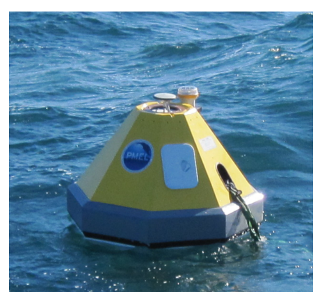
Altimeter	N	σ	Mean	Slope
TOPEX ALT-A	153	30	+4 ± 3	+3 ± 1
POSEIDON-1	22	30	–15 ± 6	+0 ± 3
TOPEX ALT-B	81	32	+3 ± 4	–3 ± 3
JASON-1	206	27	+10 ± 2	–1 ± 1
OSTM/JASON-2	249	32	+10 ± 2	+1 ± 1
JASON-3	59	23	–14 ± 4	–1 ± 6

Regional Campaigns: Expanding the Calibration Footprint









Monterey Bay

Summer 2017 GPS Buoy Campaign for SWOT (but also near Jason pass).

Harvest

NASA Prime Verification Site for High-Accuracy (Jason-class) Altimetry.

Stable and Accurate Calibration Record Spanning 25 Years.

Catalina Island

Provisional calibration site est. 6/17 (lidar tide gauge + existing GPS).

Daisy Bank

Summer 2016 GPS Buoy Campaign at Jason Crossover Location

GPS Buoy Project

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

OBJECTIVES:

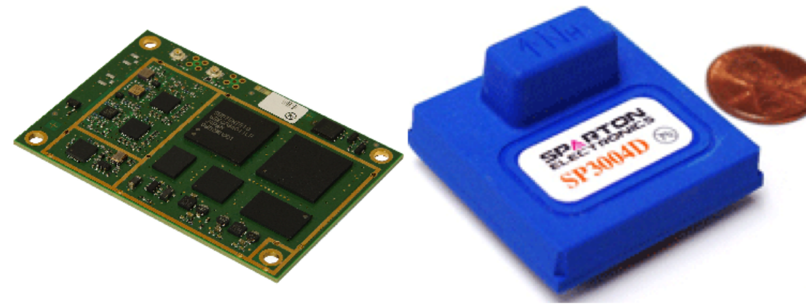
- Design, build and test a modular, low-power, robust, high-accuracy GNSS measurement system for long-term, continuous and autonomous operations on ocean- and cryosphere-observing platforms.
- Probe the limits of new kinematic precise-point positioning (PPP) techniques for accurately determining sea-surface 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.

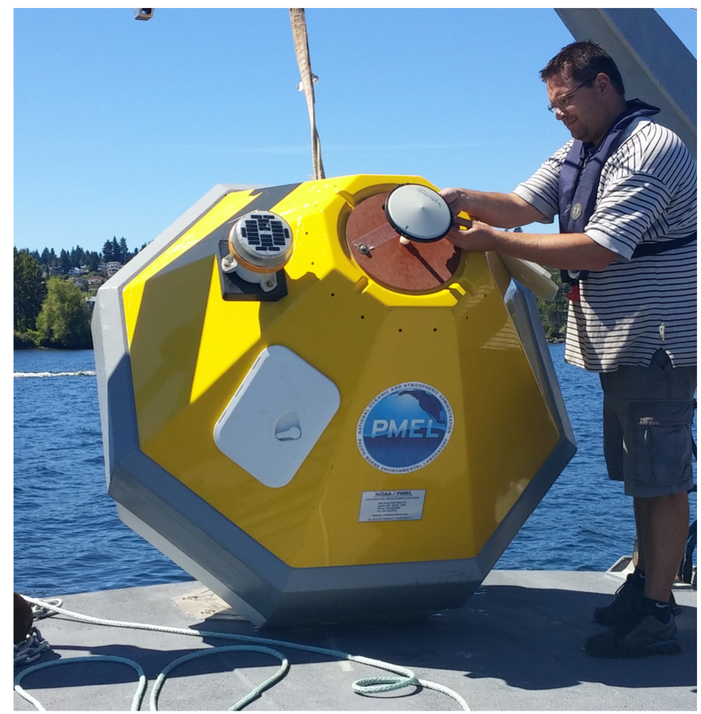
***Extending the Reach of the Global GNSS Network to the World's Oceans: A Prototype Buoy for Monitoring Sea Surface Height, Troposphere and Space Weather*, B. Haines, S. Brown, S. Desai, A. Komjathy, R. Kwok, D. Stowers, C. Meinig and J. Morison.

Prototype Precision GPS Buoy

FEATURES

- Integrated low-power (~1 W), dual-frequency GPS system (Septentrio)
- Miniaturized digital compass/accelerometer.
- Iridium communications (presently used for basic heartbeat information).
- Adaptable to multiple floating platforms (e.g., buoys, wave gliders).
- Enables geodetic quality solutions without nearby reference stations.





DEVELOPMENT AND TESTING

- Buoy tested successfully under progressively more challenging conditions:

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

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

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

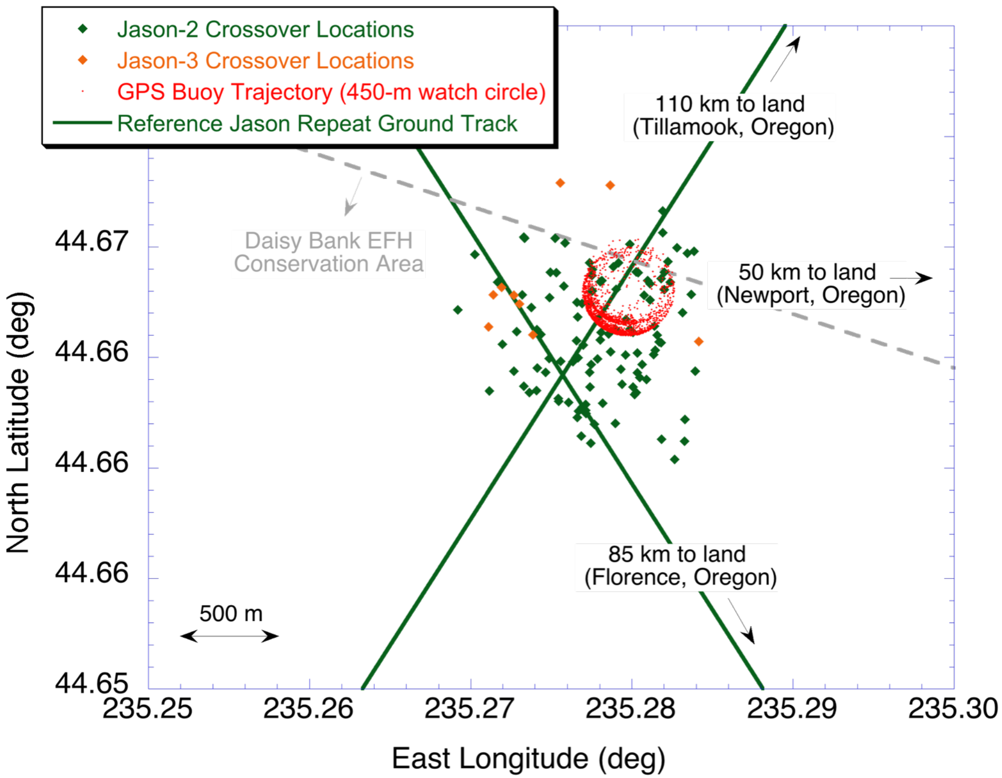
✓ *Monterey Bay: SWOT Pilot Experiment (June 22 to September 7, 2017).*

⇨ **Total of 236 days in the water** (20 days of data from Monterey Bay data lost due to failed USB drive).

GPS Buoy Campaigns

DAISY BANK CLOSEUP

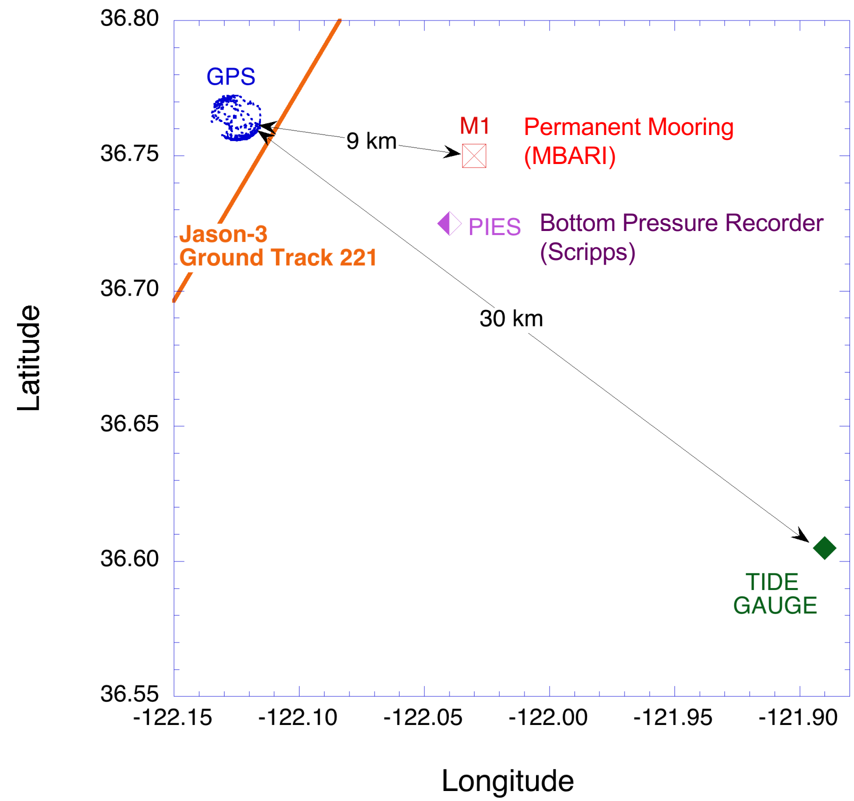
~200-m depth



Deployment spanned 24 dual Jason-2/3 overflights

MONTEREY BAY CLOSEUP

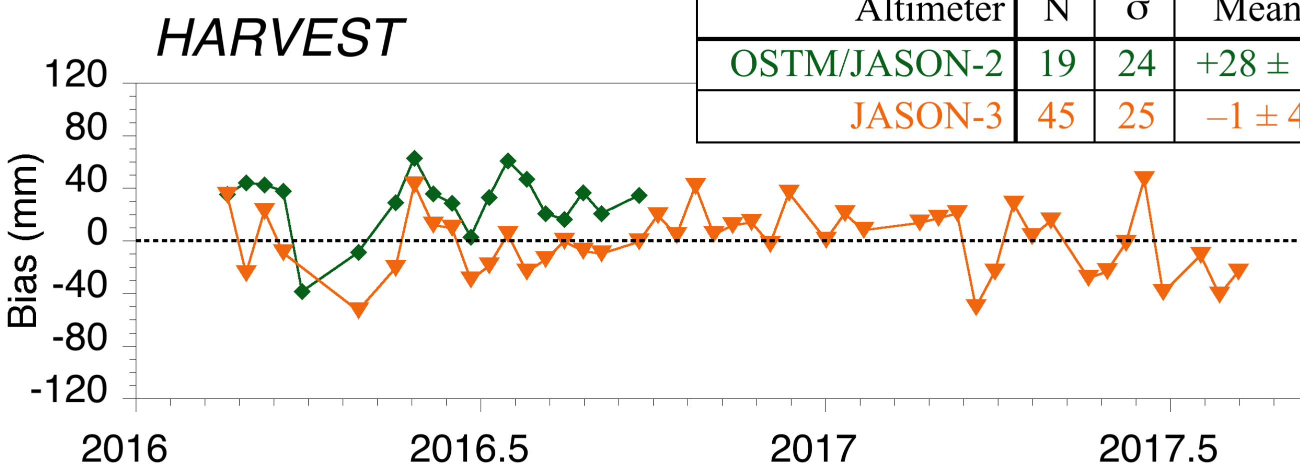
~1000-m depth



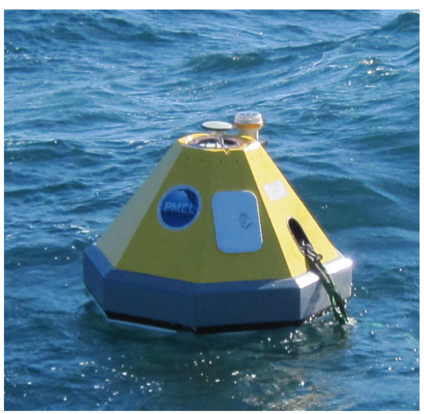
Deployment spanned 6 Jason-3 overflights

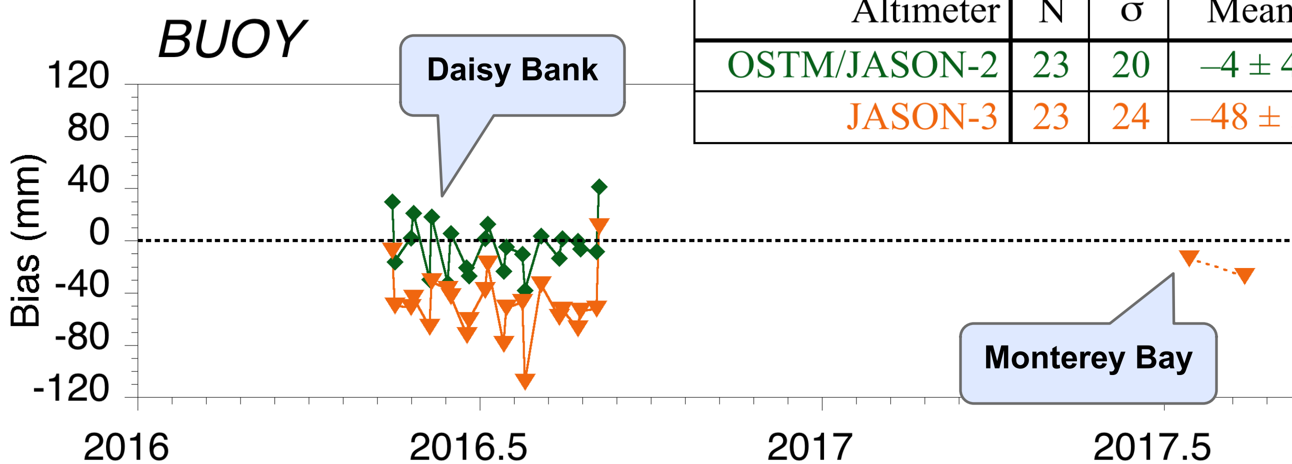
SSH Bias: Harvest vs. Buoy

Comparable Results for the Jason-3 Era



Altimeter	N	σ	Mean
OSTM/JASON-2	19	24	+28 ± 5
JASON-3	45	25	–1 ± 4

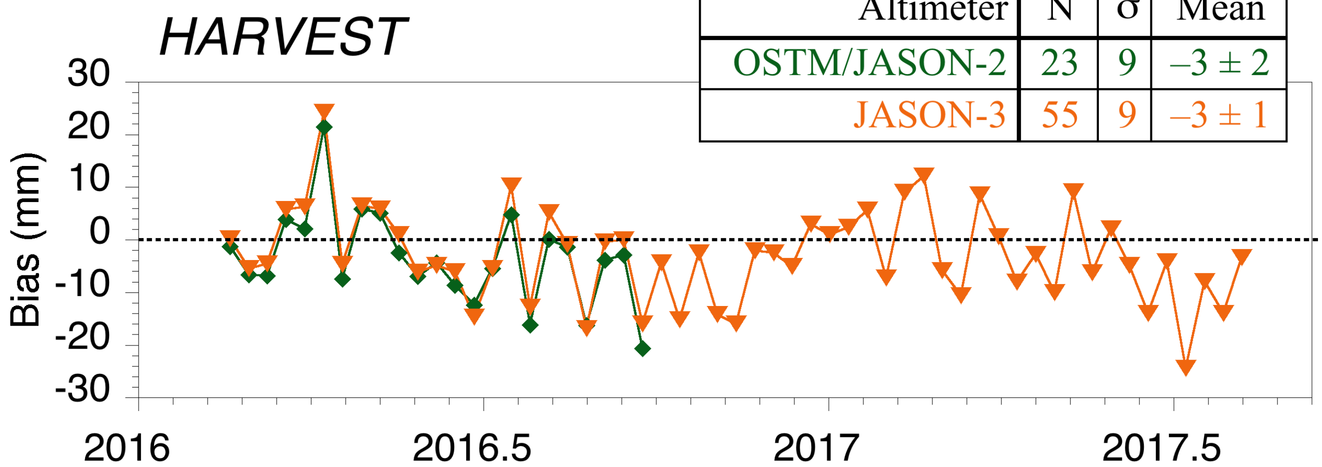




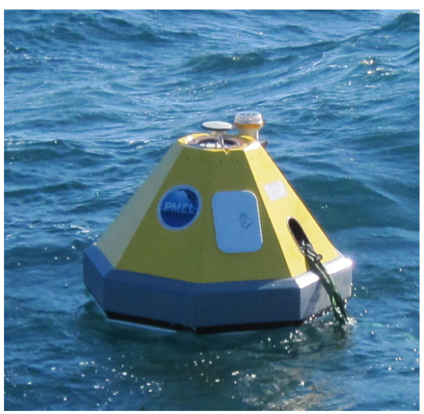
Altimeter	N	σ	Mean
OSTM/JASON-2	23	20	–4 ± 4
JASON-3	23	24	–48 ± 5

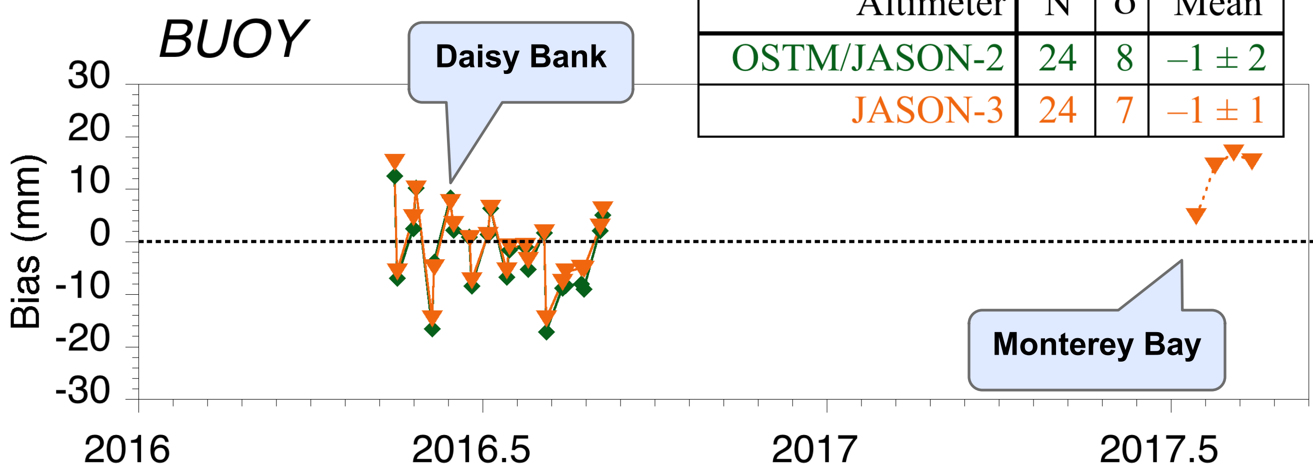
GPS Wet Path Delay Calibration: Harvest vs. Buoy

Comparable Results for the Jason-3 Era



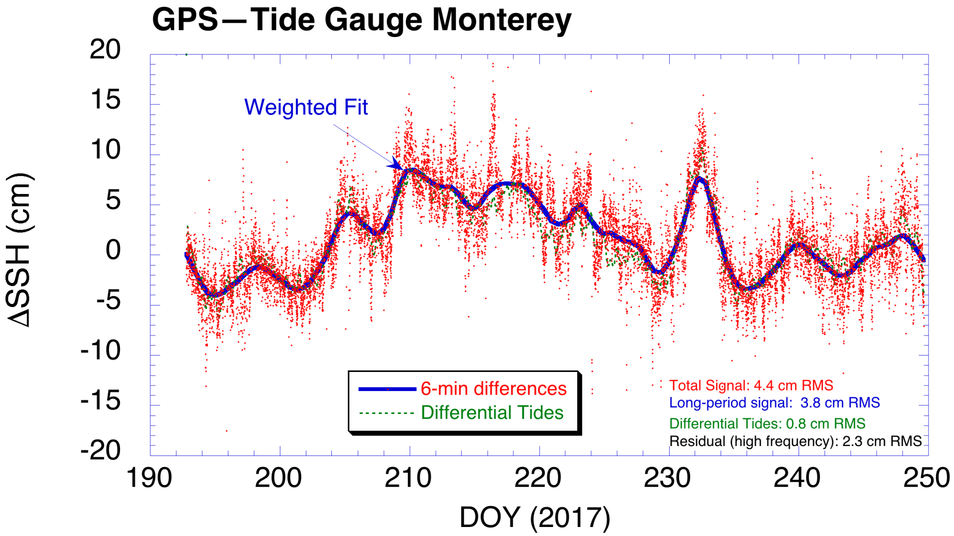
Altimeter	N	σ	Mean
OSTM/JASON-2	23	9	–3 ± 2
JASON-3	55	9	–3 ± 1

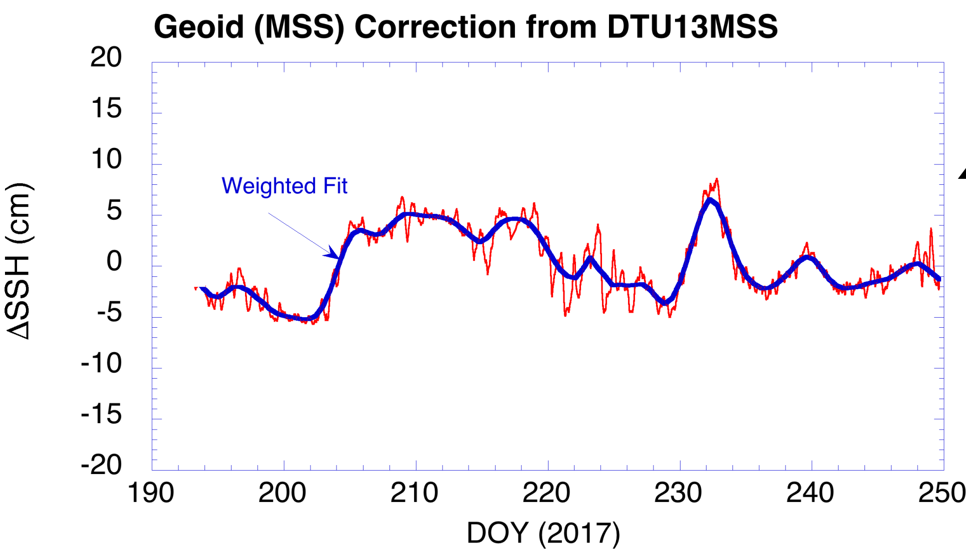




Altimeter	N	σ	Mean
OSTM/JASON-2	24	8	–1 ± 2
JASON-3	24	7	–1 ± 1

Buoy Results Underscore Importance of Geoid Signal

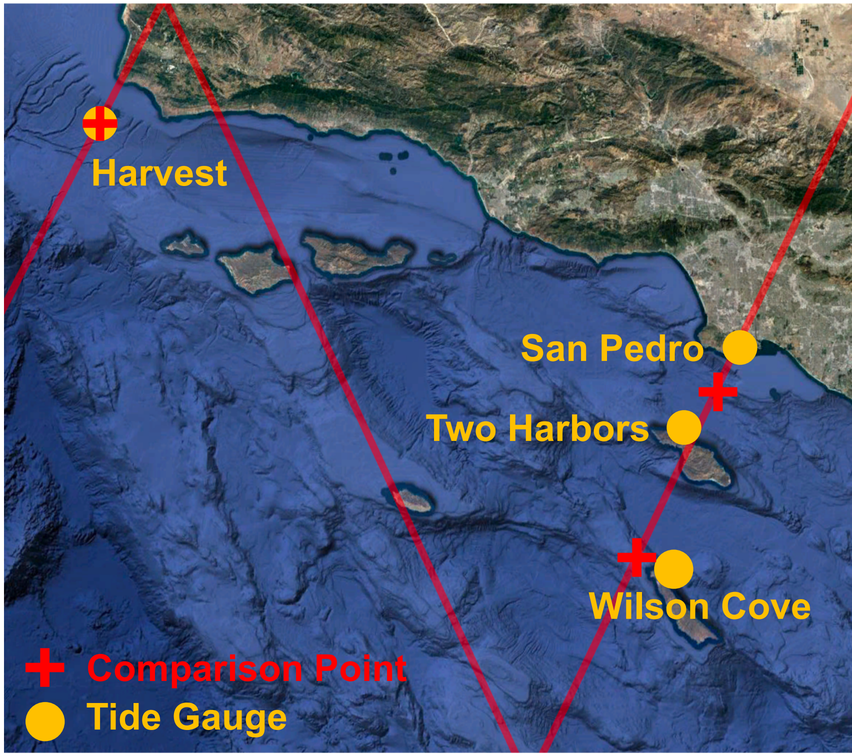




- In Monterey Experiment, buoy was moored in ~1000 m of water over the wall of Monterey Canyon.
- Significant small-scale geoid features observed as buoy traced out its path within 2-km watch circle.
- Stationary, small (spatial) scale features in the geoid manifest as long (temporal) scale SSH anomalies, due to persistence of buoy in certain locations (driven by prevailing currents.)
- Simple correction from MSS (DTU13) captured anomalous signal observed in buoy vs. tide gauge differences.
    - Reduced variance of long-term SSH anomaly difference by 80%.
- Additional geoid signal remains (and could be measured using a dedicated buoy survey).

Towards a Permanent Regional Network:
Provisional Sites on Santa Catalina and San Clemente Islands

- **Lidar tide gauge installed June 2016 on Catalina Island**
  - USC Wrigley Inst. for Environmental Studies near Two Harbors.
  - ~20 km (along Jason pass 119) to center of San Pedro Channel.
- **Preliminary altimeter vs. TG comparisons show promise**
  - 30-mm repeatability (N = 14 overflights) for comparison point in San Pedro channel.
  - But 45% of overflight opportunities eliminated on account of high backscatter (low winds).
- **Radar gauge installed March 2017 on San Clemente**
  - NOAA/NOS COOPS sensor in Wilson Cove for 90 d (VDatum)
  - Comparison point is along unobstructed open-ocean approach.
  - Wind/wave conditions are intermediate (more active than San Pedro Channel, but less active than Harvest).



Summary

- **Absolute SSH bias from Harvest***
  - Jason-3: –14 ± 15 mm for GDR-E (Cycles 1 to 72 with N = 59)
  - Jason-2: +10 ± 15 mm for GDR-D (Cycles 1 to 303 with N = 249)
  - Jason-1: +10 ± 10 mm for GDR-E (Cycles 1 to 259 with N = 206)
- **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.
- **Provisional tide gauges in Channel Islands**
  - Supplement Harvest for future studies (e.g., SWOT).
  - Provide some insurance against possible loss of platform.
- **Preliminary results from GPS buoy very promising**
  - Returned continuous, high accuracy data for Daisy Bank and Monterey Bay
  - Supported accurate retrievals of SSH, SWH, wet path delay and ionosphere.
  - Competitive with Harvest for all altimeter calibration metrics.
  - Next planned deployment: Summer 2018 at Harvest with two buoys.

** Error includes uncertainty in platform vertical*