The Harvest Experiment:
New Results from the Platform and Moored GPS Buoys

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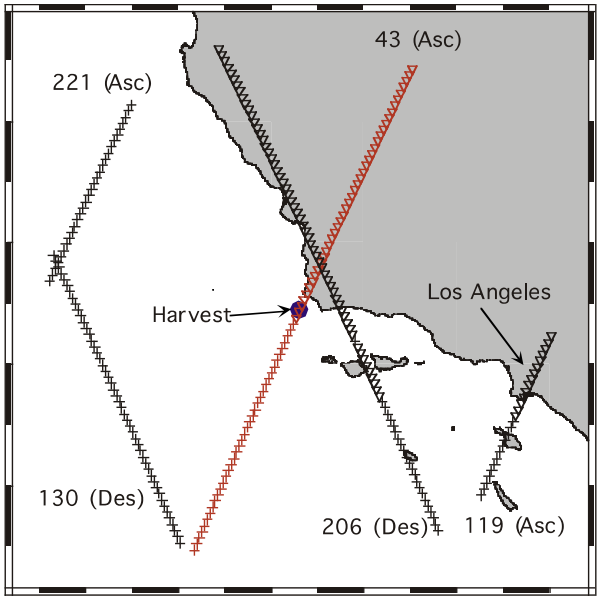
Harvest Platform

- **NASA Prime Verification Site for High-Accuracy, Jason-class Altimetry (est. 1992)**
  - 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 collection of rich in-situ data set representing over 27 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)
  - 136 Jason-3 overflights and counting (2016–)
- **Platform production ended in May 2015**
  - Platform to be decommissioned (date unknown).
  - Risk reduction activities underway

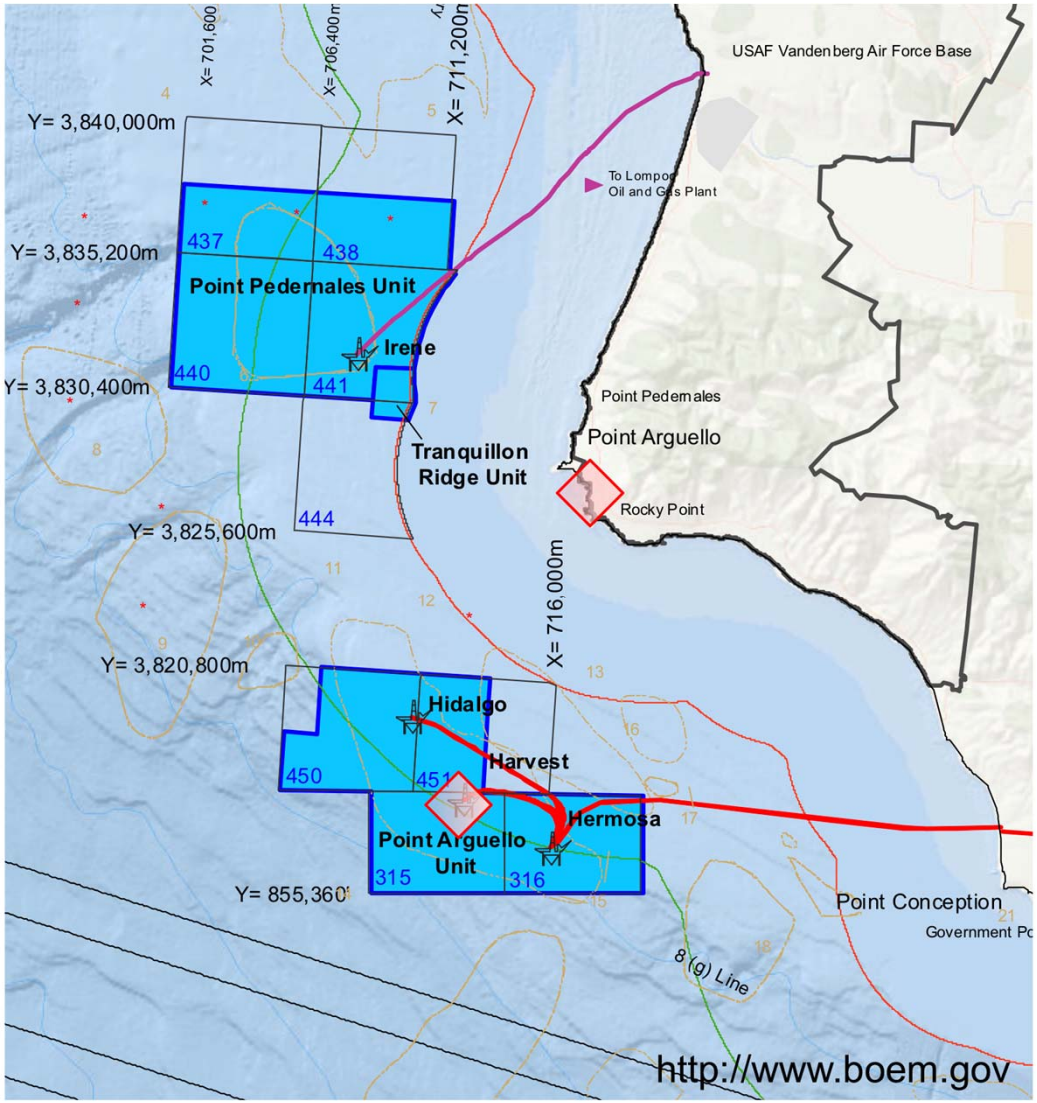


Highlights

- New Vertical Seafloor Motion Model (ITRF2014)
- Updated Harvest SSH Time Series
- Early Results from TOPEX Retracked Data
- 2018 Harvest GPS Buoy Campaign

Vertical Land Motion from GPS

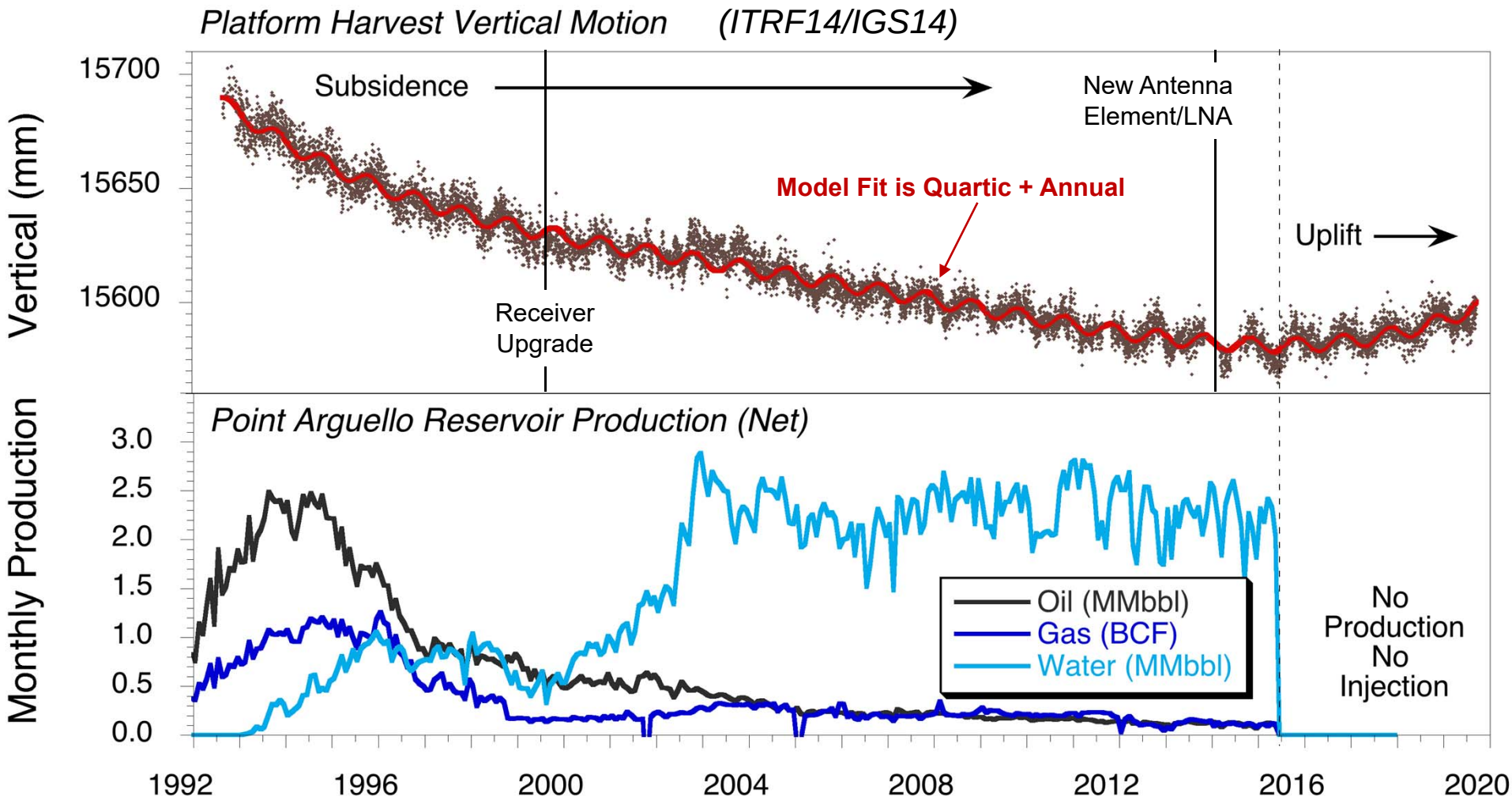
- Harvest (est. 1985) is the central of three oil platforms located over the Point Arguello offshore reservoir.
- Production began in 1991, peaked in 1994, and halted in 2015.
- Continuous GPS since 1992: one of the oldest GPS/tide gauge co-locations in the world.
- GPS at nearby Vandenberg AFB (est.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



GPS Receivers

New Estimate of Vertical Seafloor Motion from GPS

Complex Pattern of Subsidence and Rebound



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

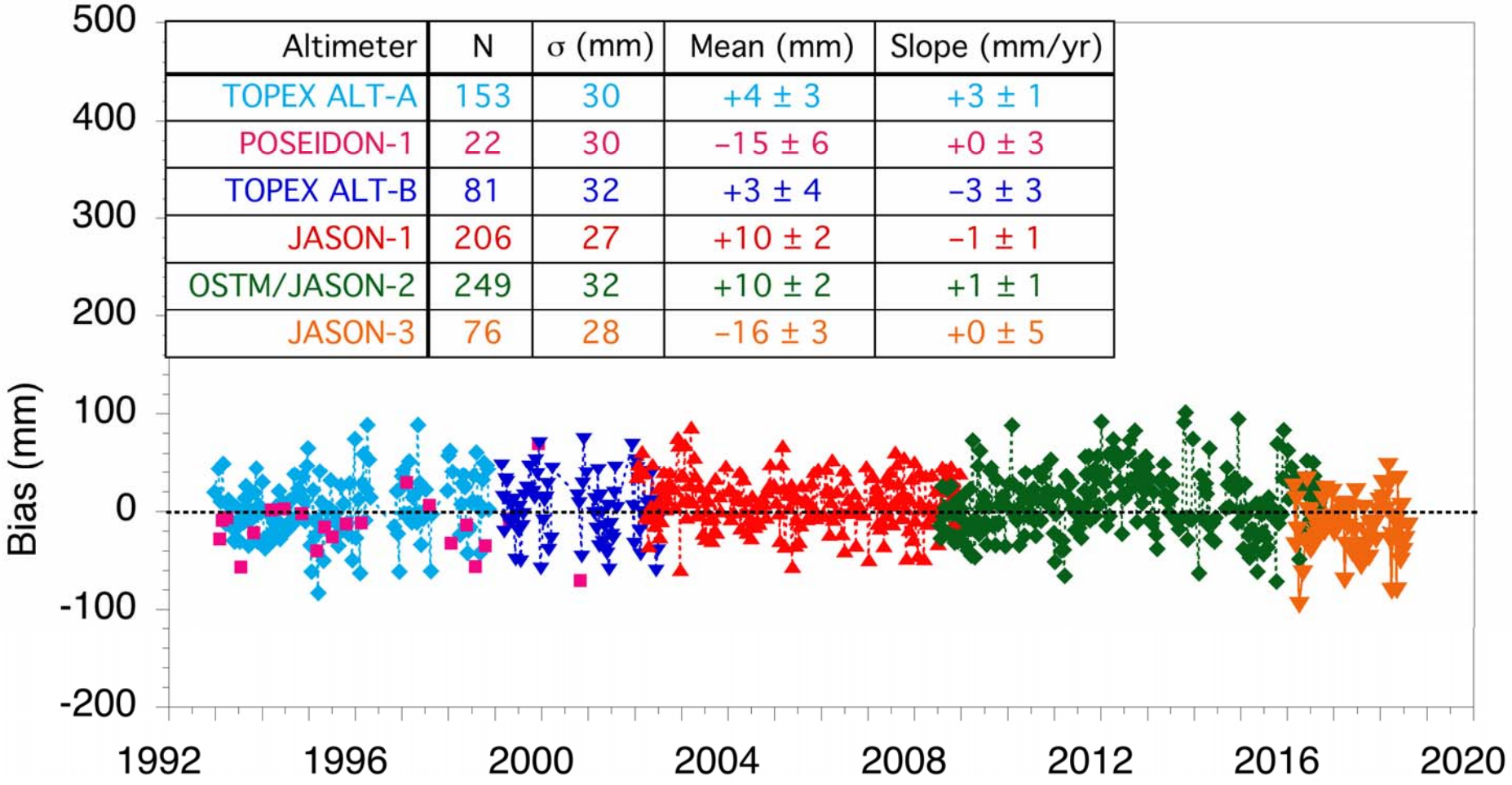
Harvest Long-Term SSH Calibration Record

Circa September 2018 (Azores OSTST)

Legacy 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 (mm)	Mean (mm)	Slope (mm/yr)
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	76	28	−16 ± 3	+0 ± 5



Harvest Long-Term SSH Calibration Record

Current Best Estimate: Update Seafloor Motion (ITRF2014) and Extend Jason-3 Time Series

Current (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

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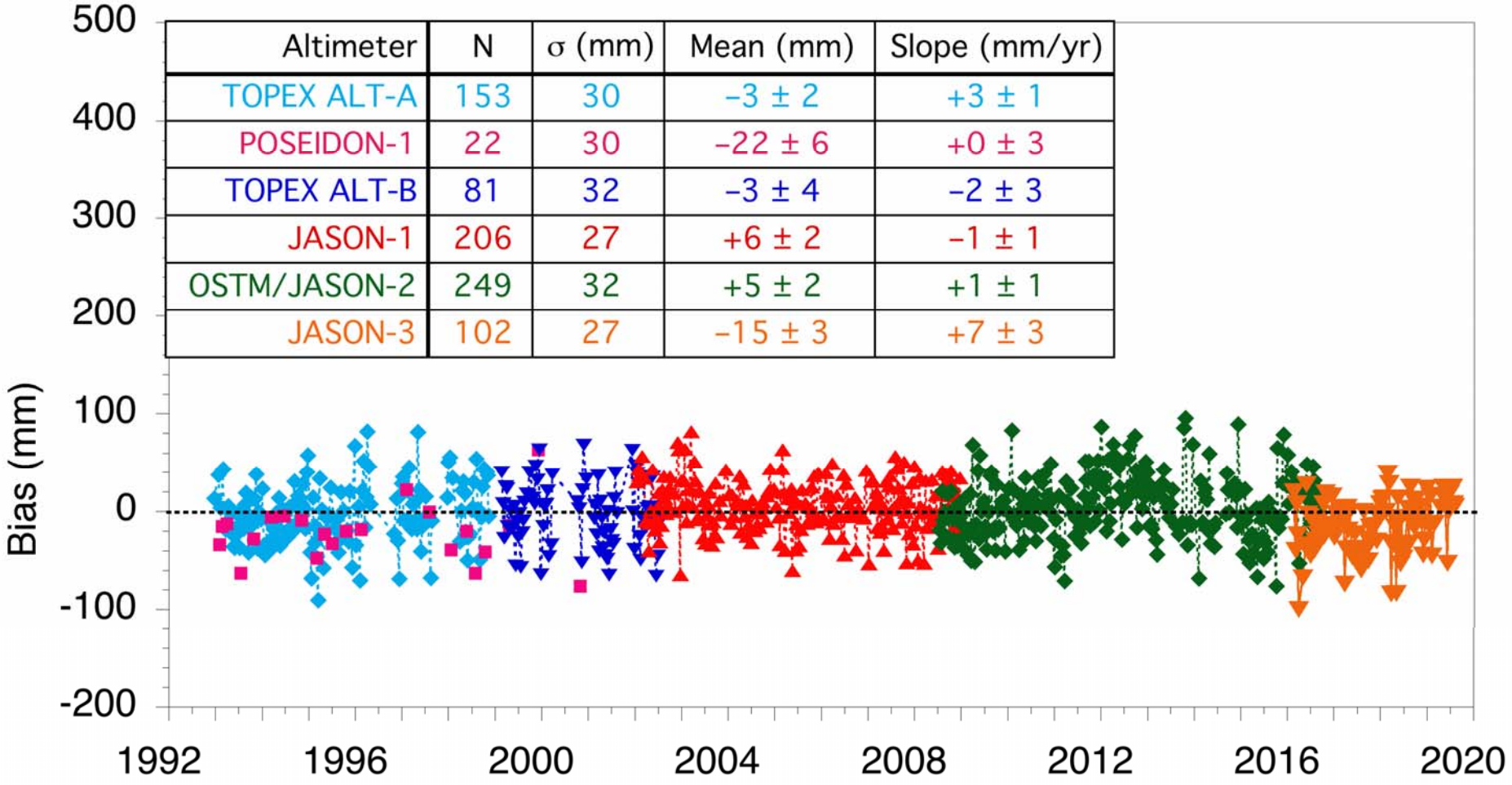
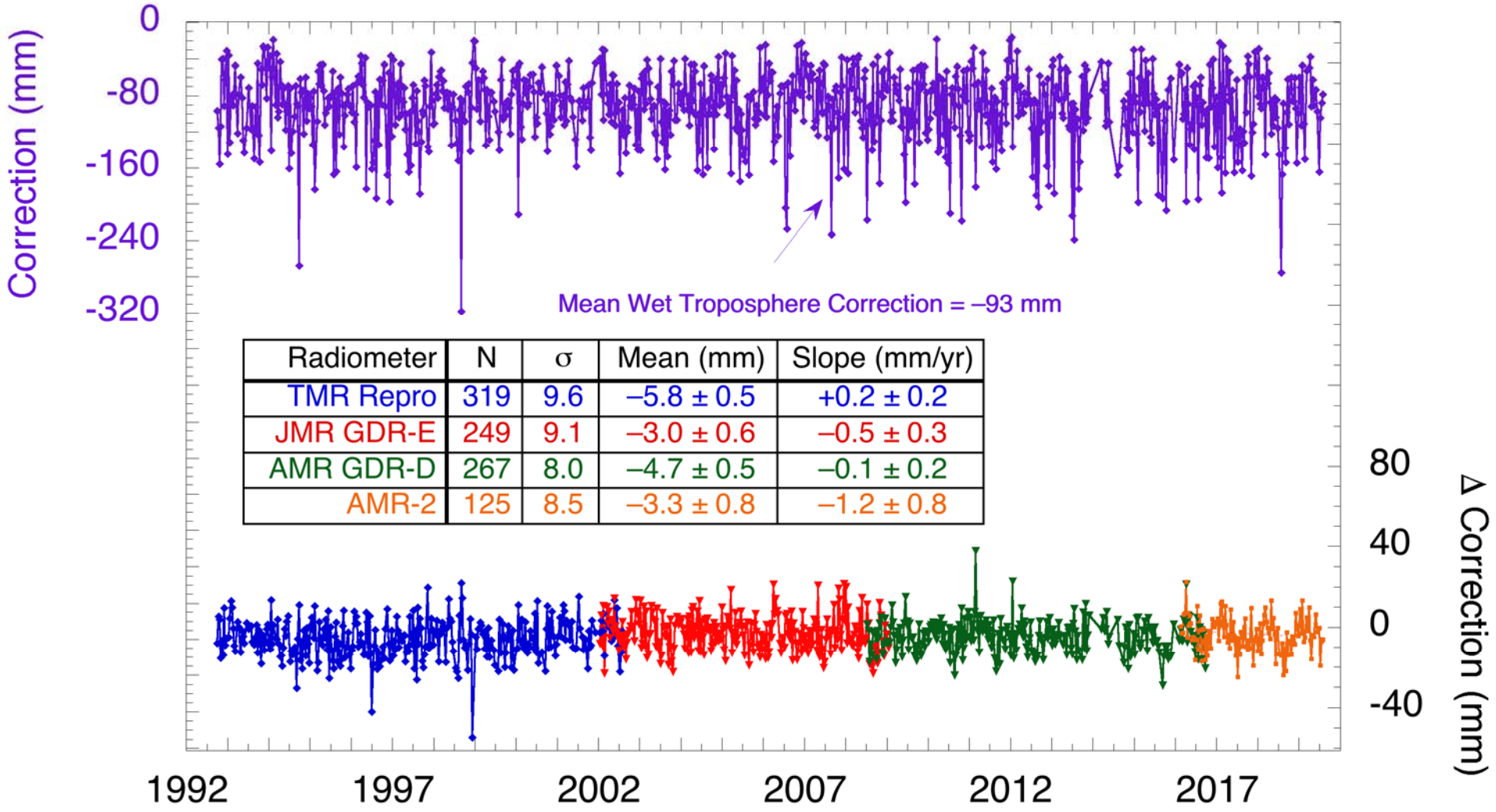
JASON-3	102	27	−15 ± 3	+7 ± 3

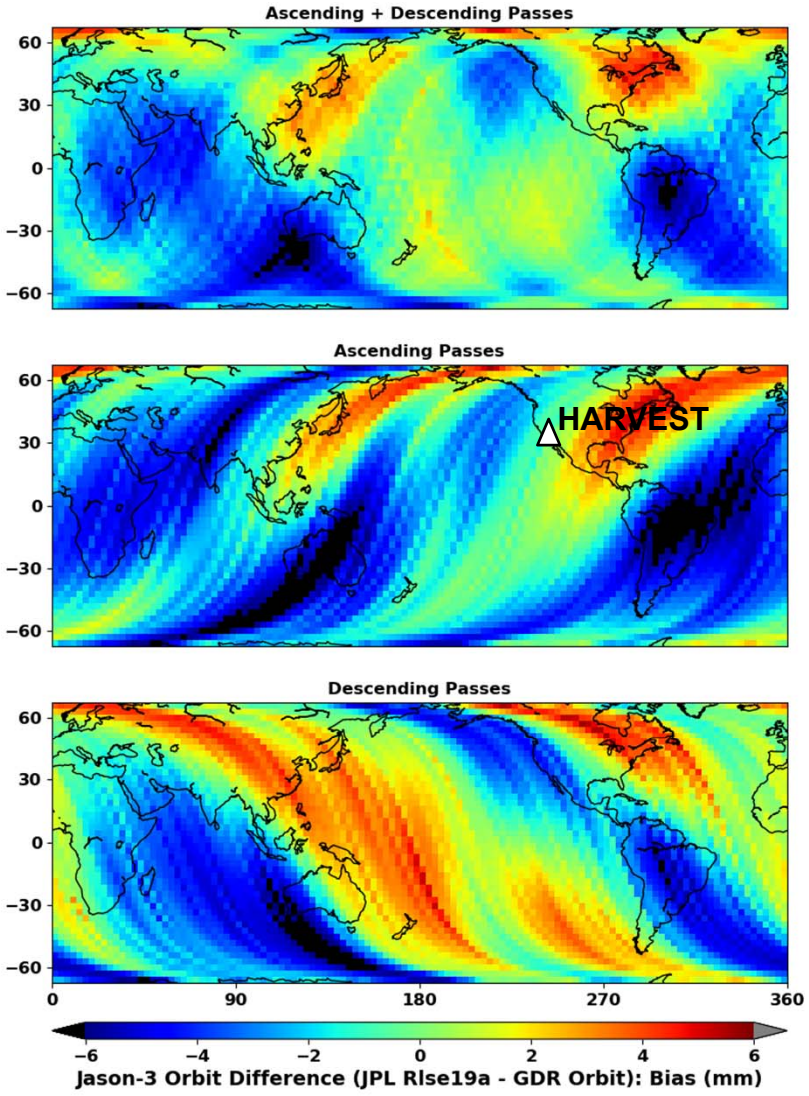


Wet Troposphere: Radiometer vs. GPS

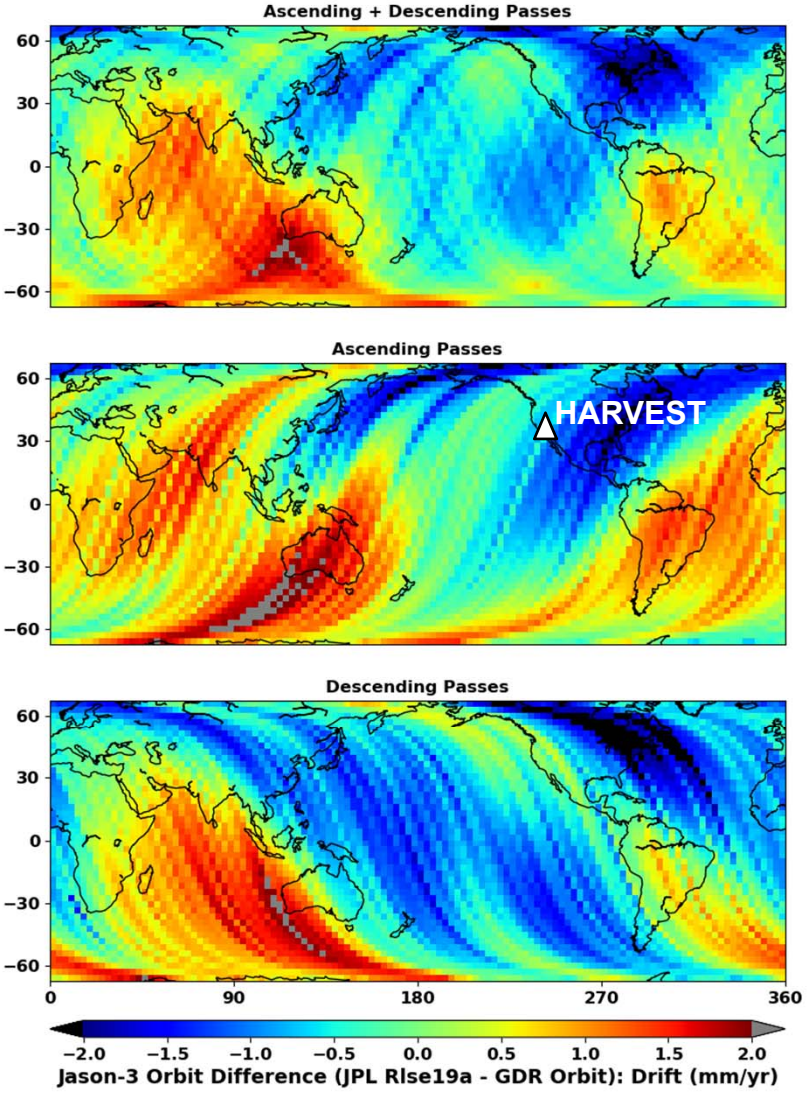


GPS Reduced Dynamic Orbit Solutions Reveal Geographically Correlated Errors (JPL GPS RLS19a vs. GDR)

Mean (–2 mm at Harvest)



Drift (–0.8 mm/yr at Harvest)



Harvest Long-Term SSH Calibration Record

Current Best Estimate: Update Seafloor Motion (ITRF2014) and Extend Jason-3 Time Series

Current (Nominal) Time Series:

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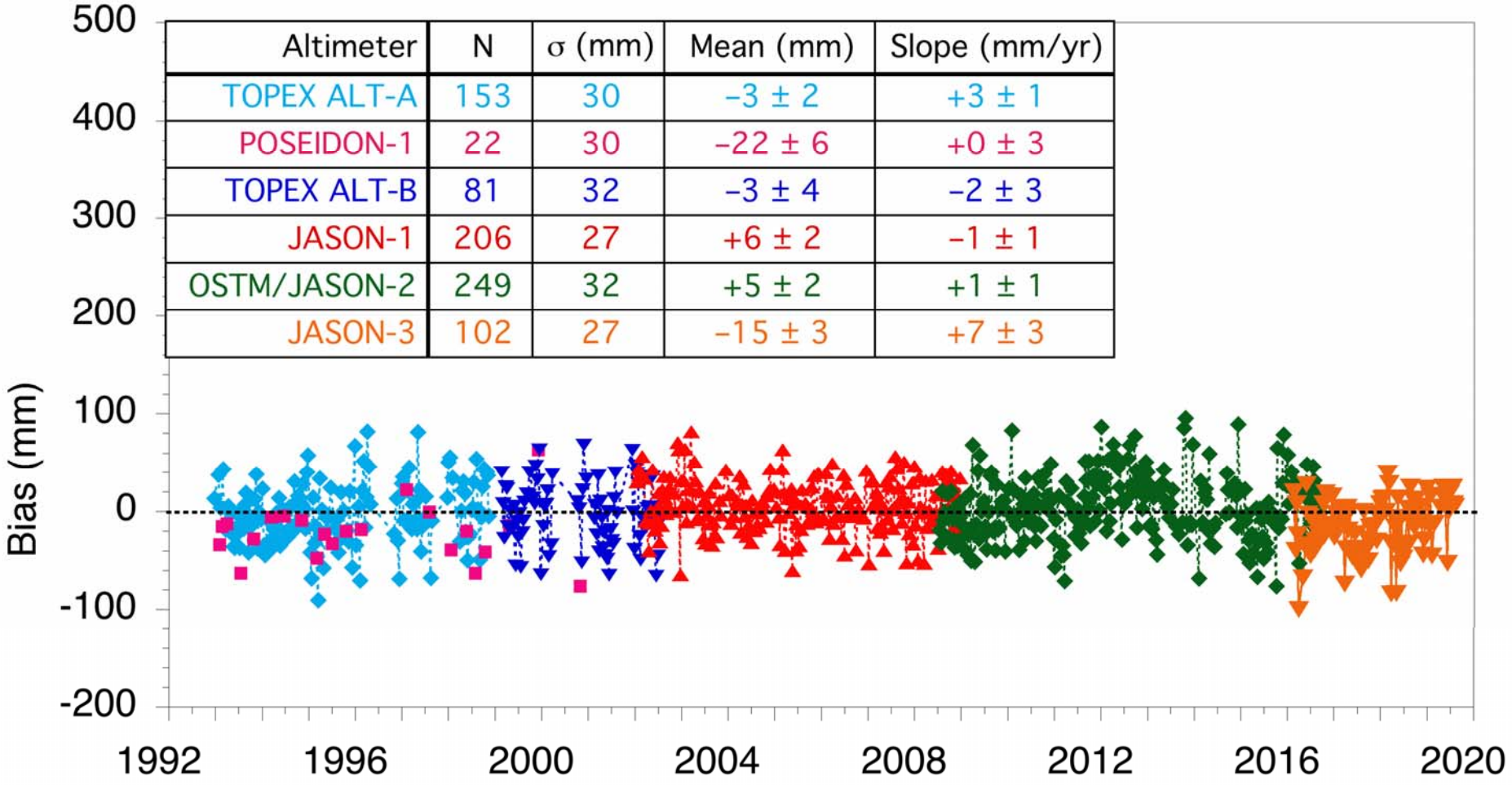

Harvest Long-Term SSH Calibration Record

Use Alternative Orbit and Wet Path Delay Correction for Jason-3

Current (Enhanced) 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 with GPS wet trop and JPL GPS-based (RLSE19a) orbit.

Altimeter	N	σ (mm)	Mean (mm)	Slope (mm/yr)
TOPEX ALT-A	153	30	−3 ± 2	+3 ± 1
POSEIDON-1	22	30	−22 ± 6	+0 ± 3
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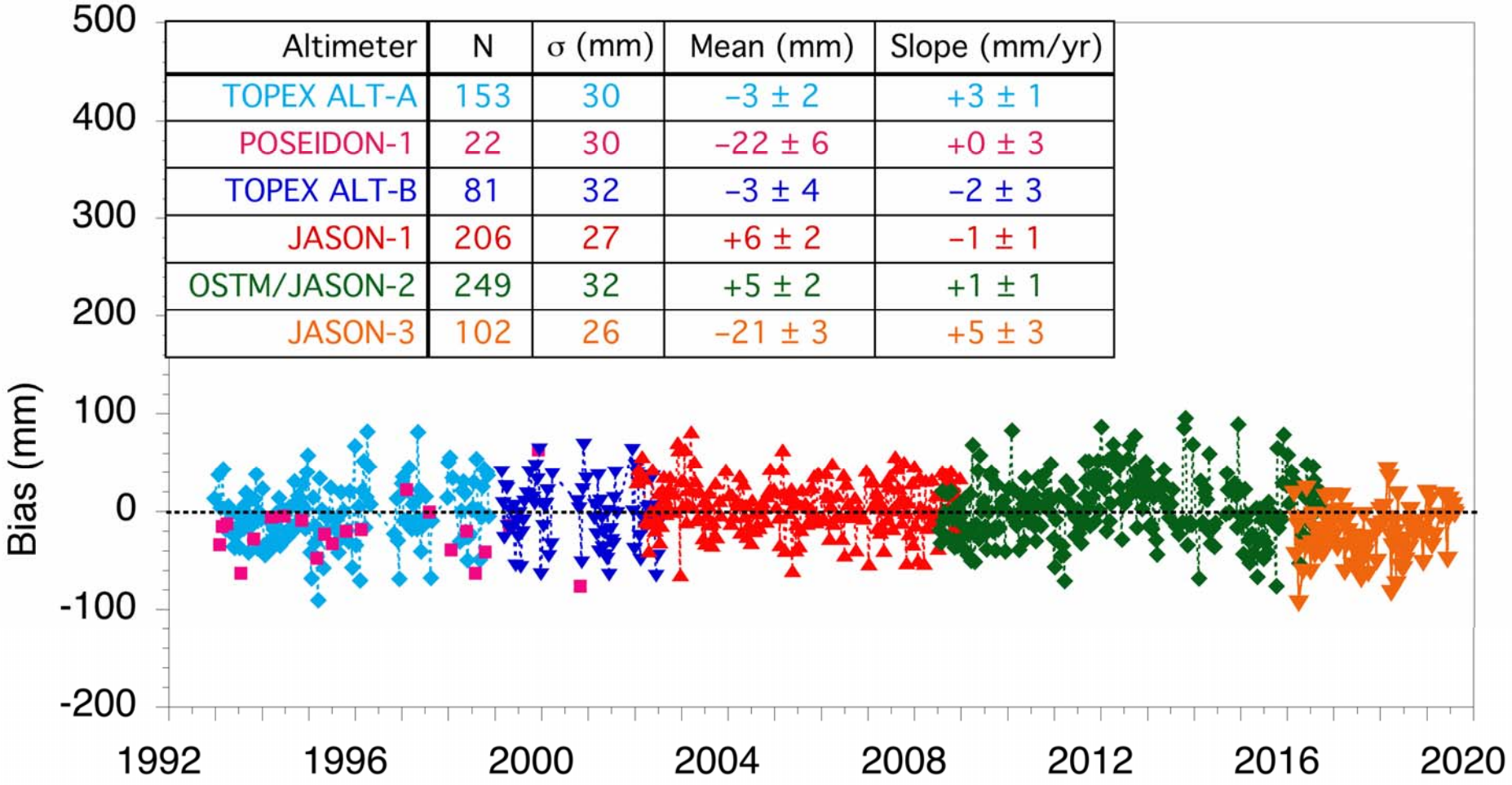
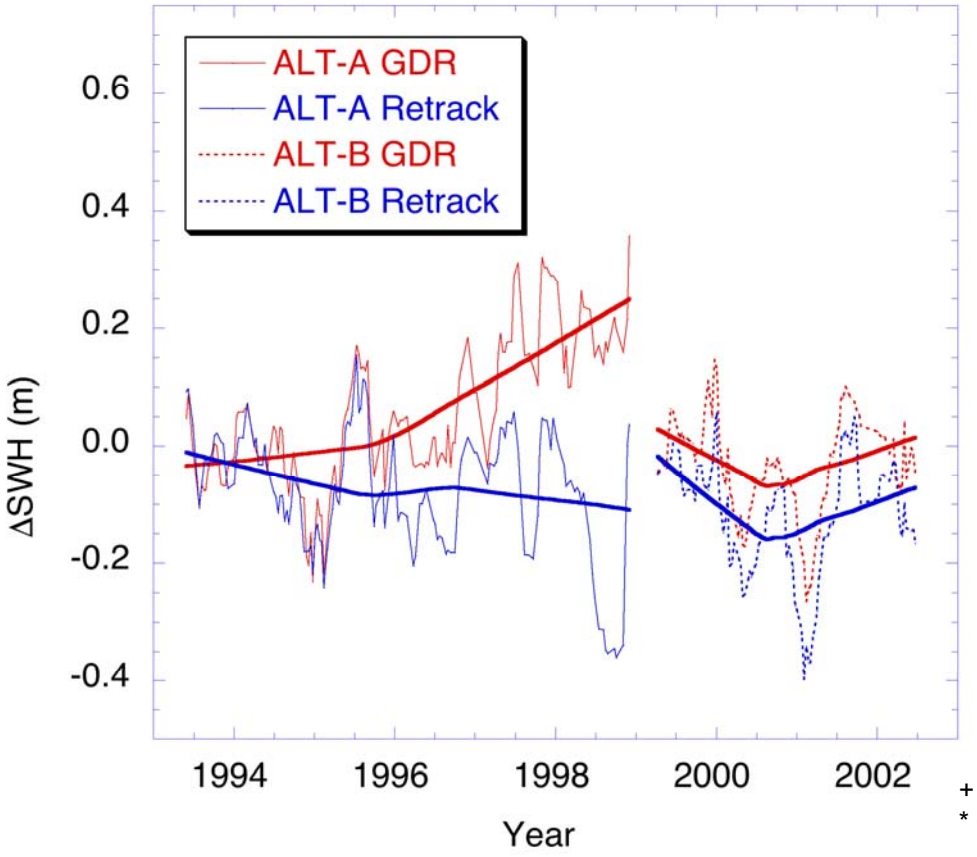
JASON-1	206	27	+6 ± 2	−1 ± 1
OSTM/JASON-2	249	32	+5 ± 2	+1 ± 1
JASON-3	102	26	−21 ± 3	+5 ± 3



TOPEX Retracked Data: Preliminary Harvest Results

- Long-term behavior of SWH significantly improved.
- Preliminary impact on SSH bias at cm level (***updates pending, e.g., for Side A SSB***).
- Decreased drift magnitude $|dSSH/dT|$ for Sides A and B, but with questionable significance.

TOPEX – BUOY SWH AT HARVEST



TOPEX SSH BIAS AT HARVEST

Side A (N=147)	MGDR+	Retracked*
Mean (mm)	–4.1 ± 2.6	*+9.1 ± 2.7*
Rate (mm/yr)	+4.4 ± 1.5	+3.1 ± 1.6
σ (mm)	29.7	32.3

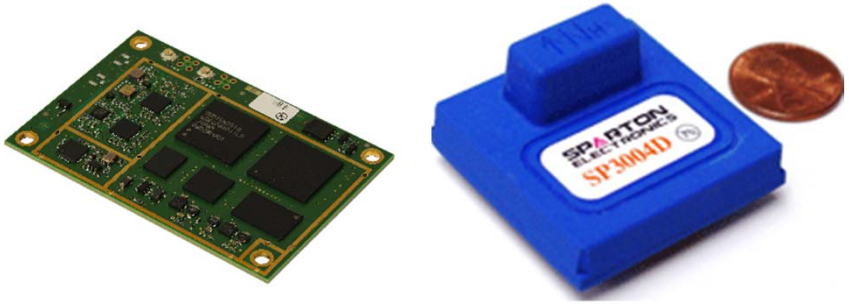
Side B (N=81)	MGDR+	Retracked*
Mean (mm)	–2.7 ± 3.5	*–7.9 ± 3.5*
Rate (mm/yr)	–2.4 ± 3.1	–0.9 ± 3.1
σ (mm)	31.9	31.2

+ Nominal time series is based on MGDR + improved (GSFC) orbit and TMR.
* Considers only altimeter-derived parameters (i.e., Range, Iono. and SSB).

Precision GPS Buoy System

FEATURES

- Integrated low-power (~1 W), dual-frequency GNSS
- Miniaturized digital compass/accelerometer.
- Iridium communications.
- Load cell (for modeling water line displacement)
- Enables geodetic quality solutions without nearby reference stations.



DEVELOPMENT AND TESTING

- Buoy system design evolves under progressively more challenging conditions:

✓ *Lake Washington (2015).*

✓ *Puget Sound (2015).*

✓ *Daisy Bank: open-ocean Jason satellite crossover location off coast of Oregon (2016)*

✓ *Monterey Bay: SWOT Pilot Experiment (2017).*

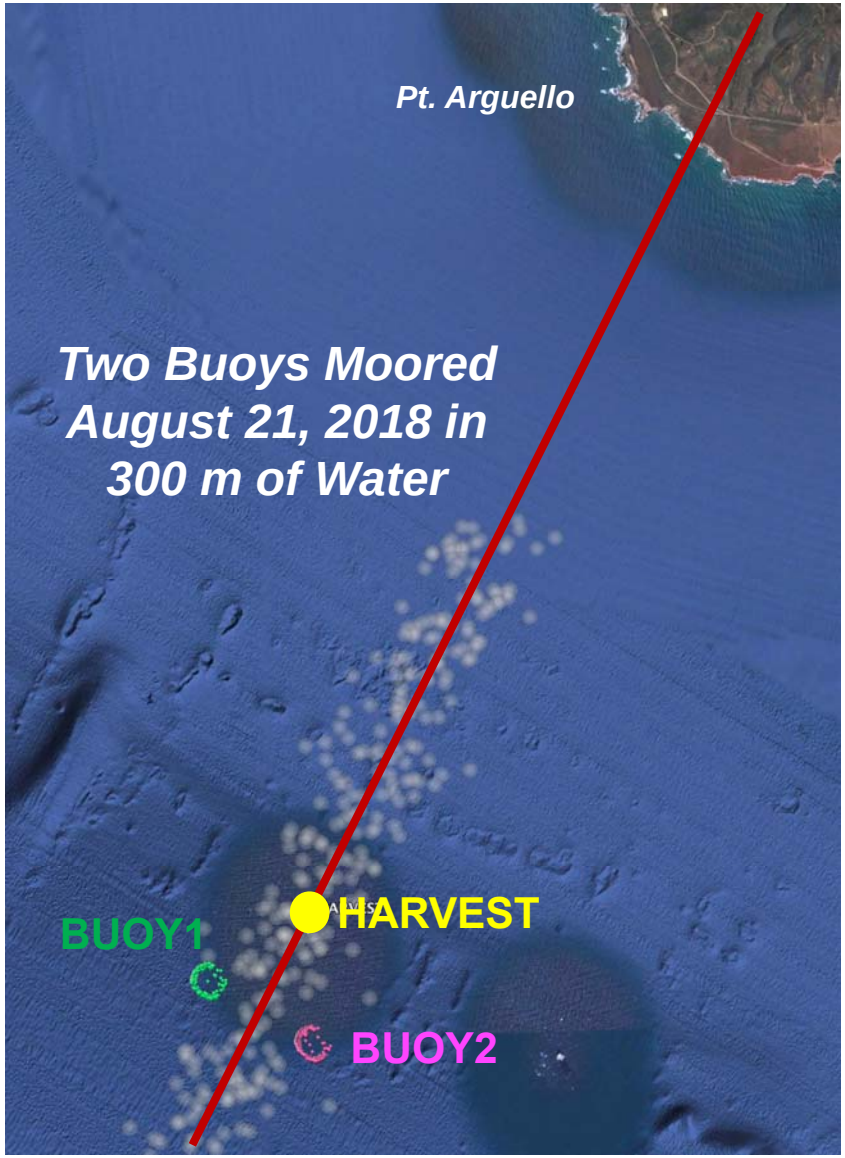
✓ ***Harvest Platform Tandem Campaign (2018).***

✓ *SWOT Prelaunch Tandem Campaign: Sentinel 3A deep water crossover (underway)*

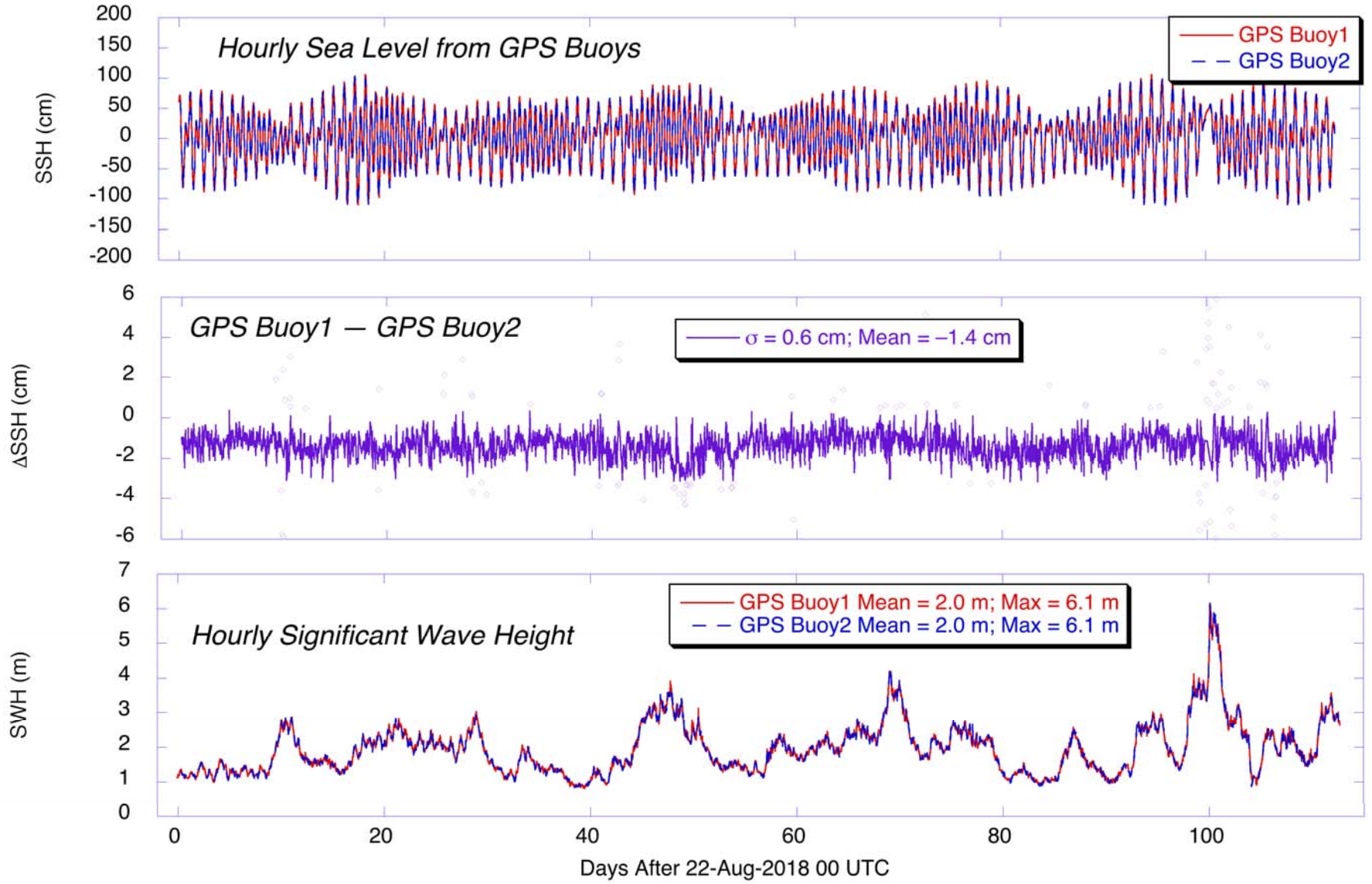
⇨ **Over 450 successful buoy days in the water**

Joint NASA/NOAA Harvest Buoy Campaign
Aug. 2018 – Mar. 2019

- Main goal: examine potential of precision GPS buoy systems to replace NASA Harvest verification site.
  - Risk reduction exercise for Jason-3 and Sentinel-6.
  - Anticipates possible platform loss or abandonment.
  - Buoys close to platform (~1.5 km) to support comparisons with platform tide gauges and overhead altimetry from Jason-3.
- Secondary goal: probe limits of GPS-based relative sea-surface height determination in open ocean.
  - Features similarly equipped surface buoys (new buoy modeled after prototype, except adds Prawler system).
  - Buoys separated by ~1.5 km.
  - Short baseline lends insight on impacts of waves and on potential of GPS array for SWOT CALVAL.
- Campaign enhancements
  - New longevity goal of 150 days: operate through higher (winter) sea states (GPS data collection ended after 114 d).
  - Buoys equipped with load cells to measure force on mooring (to study movement of buoy water line).
  - NOAA Prawler for taking CTD and dissolved oxygen measurements along mooring.
  - Telemetry upgrade: 1-min snapshots of GPS tracking data + Prawler, load cell and orientation data. (High-rate GPS observations—500 million in total—recovered with buoys.)

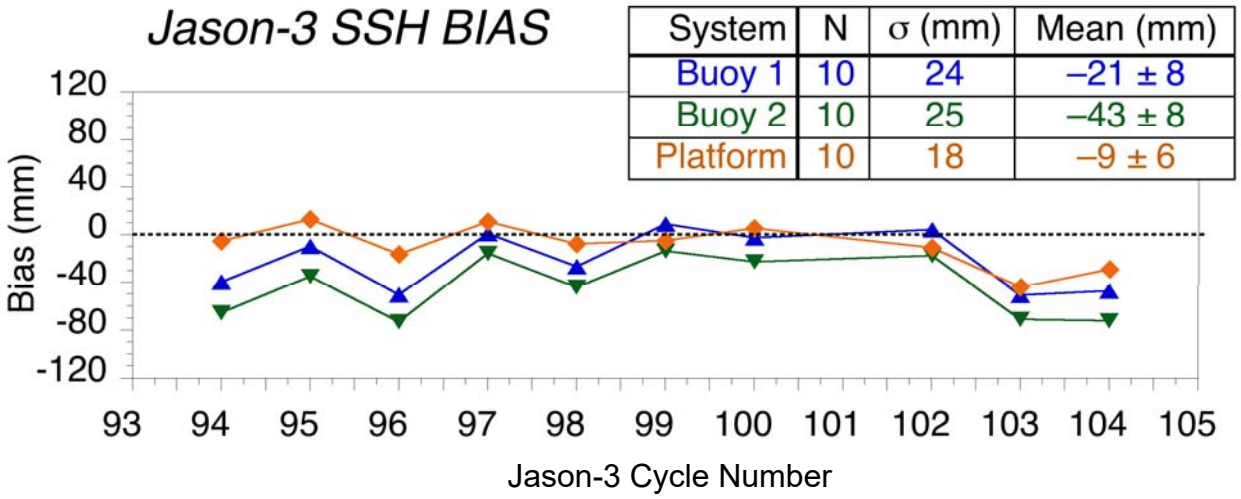


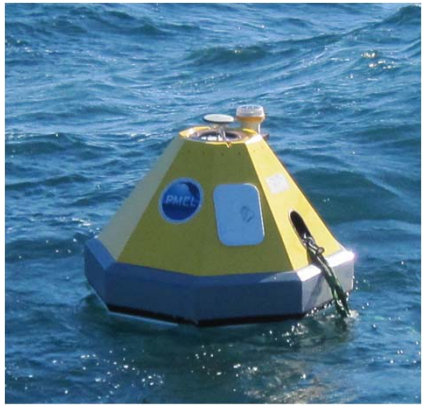
Sea Surface Height Time Series from Harvest Campaign: Comparing Two GPS Buoys Separated by 1.5 km

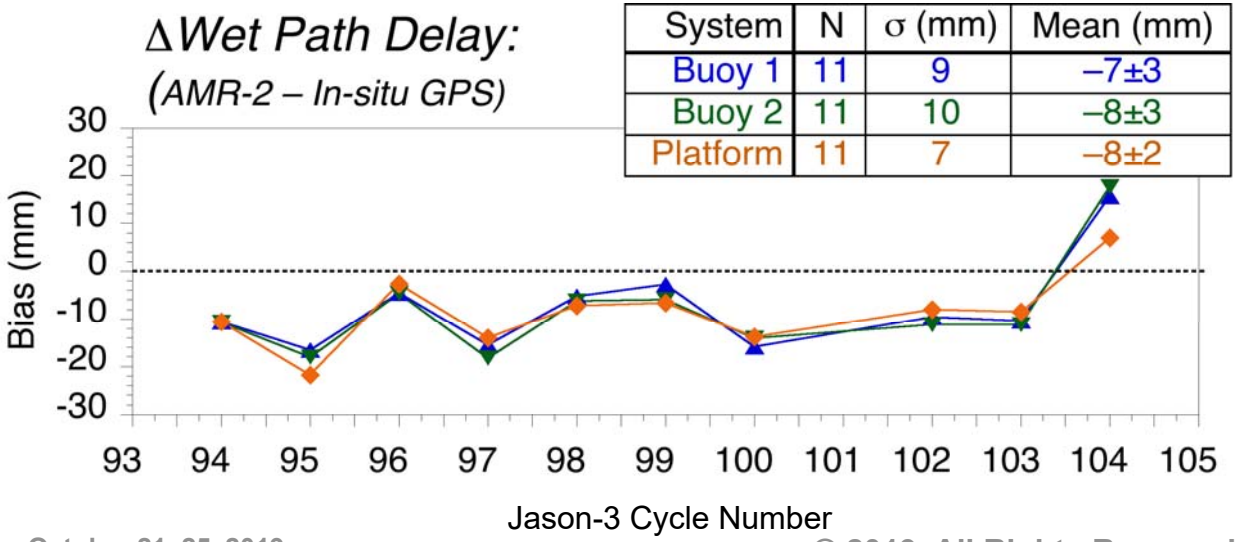


Verification of Altimeter Sea Surface Height and Wet Path Delay

Platform Harvest (Tide Gauge and Fixed GPS) vs. GPS Buoys







Summary

- **Latest SSH bias estimates from Harvest***
  - Jason-3: –15 ± 12 mm for GDR-E
  - Jason-2: +5 ± 10 mm for GDR-D
  - Jason-1: +6 ± 10 mm for GDR-E
  - ALT–B: –3 ± 10 mm for MGDR+
  - ALT–A: –3 ± 12 mm for MGDR+
  - POS–1: –22 ± 12 mm for MGDR+
- **Promising Results from Harvest Tandem GPS Campaign**
  - Supported accurate retrievals of SSH, SWH, wet path delay (corroborating early results from Daisy Bank in 2016 and Monterey Bay in 2017.)
  - 6-mm repeatability for hourly ΔSSH between two buoys separated by 1.5 km (for SWH < 4 m).
  - Mean height difference (1.4 cm) is in keeping with uncertainty in relative buoy weights.
  - Competitive with Harvest for all altimeter calibration metrics.
  - Candidate for replacing Harvest when platform decommissioned.
- **For more on Harvest Regional Campaigns:**
  - *In Situ Measurements for Satellite Altimeter Calibration and Validation using LiDAR Systems, Dodge et al. (CVL003 Poster)*
  - *Regional in situ CalVal of Sentinel-3 altimeter range at non-dedicated sites, Cancet et al., (CVL001 Poster)*

** Error includes uncertainty in platform vertical*

Backup

Harvest Long-Term SSH Calibration Record

TOPEX Control Set: Nominal (MGDR+) for Cycles Common to Retracked Data

TOPEX Control Set

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 with GPS wet trop and JPL orbit

Altimeter	N	σ (mm)	Mean (mm)	Slope (mm/yr)
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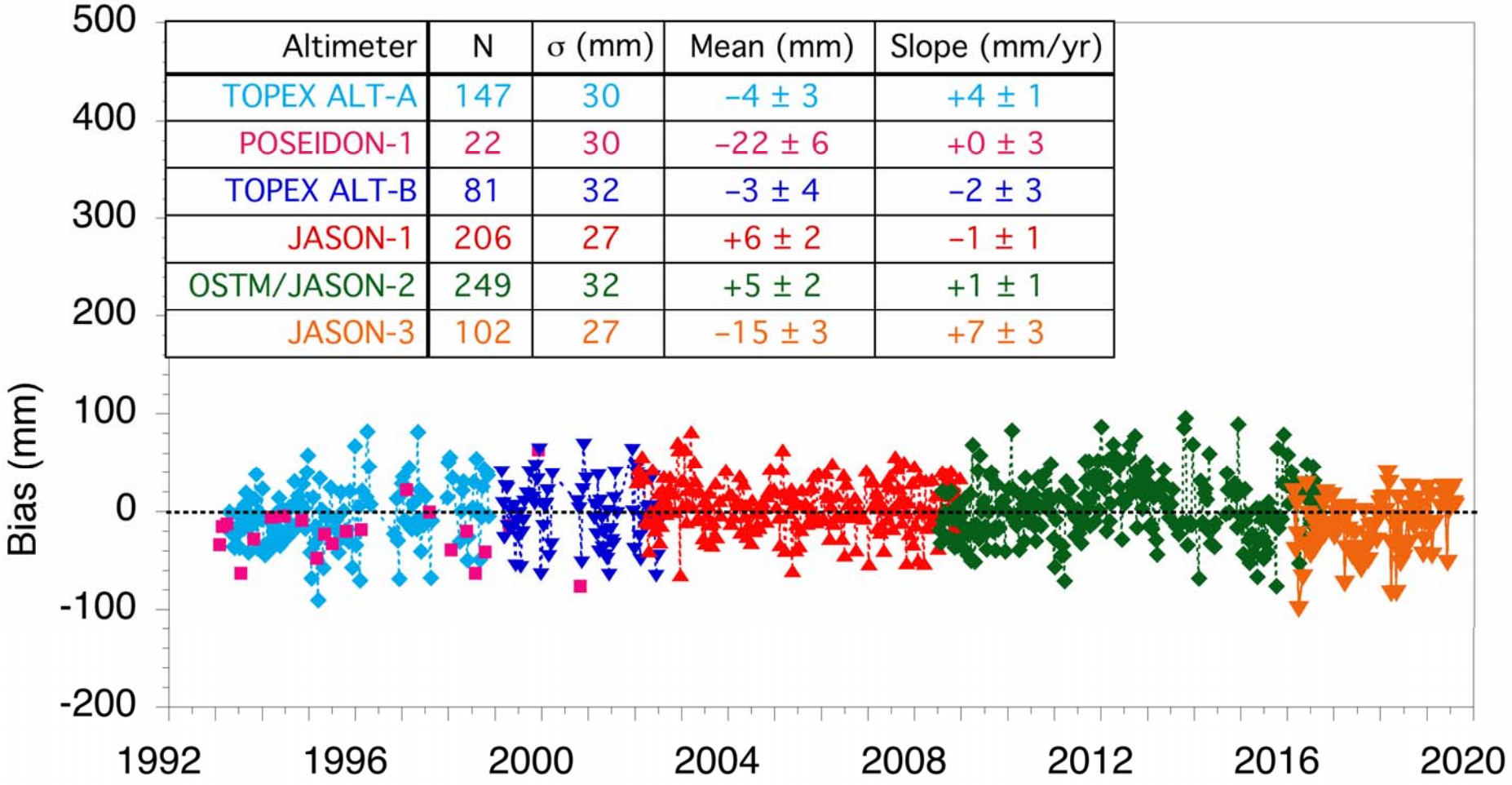


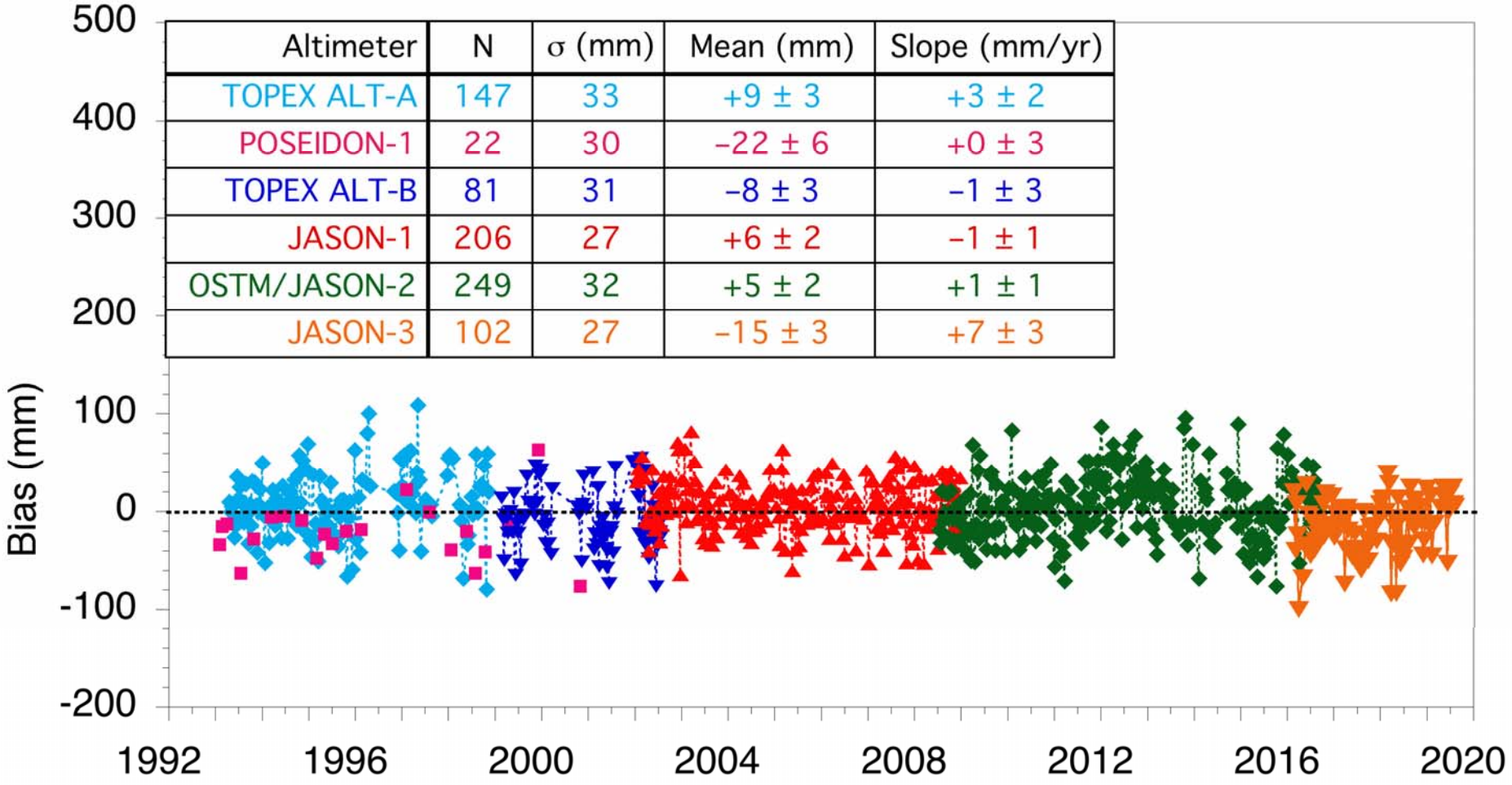
Harvest Long-Term SSH Calibration Record

TOPEX Retracked Data: Replace Ku Range, Ionosphere and SSB

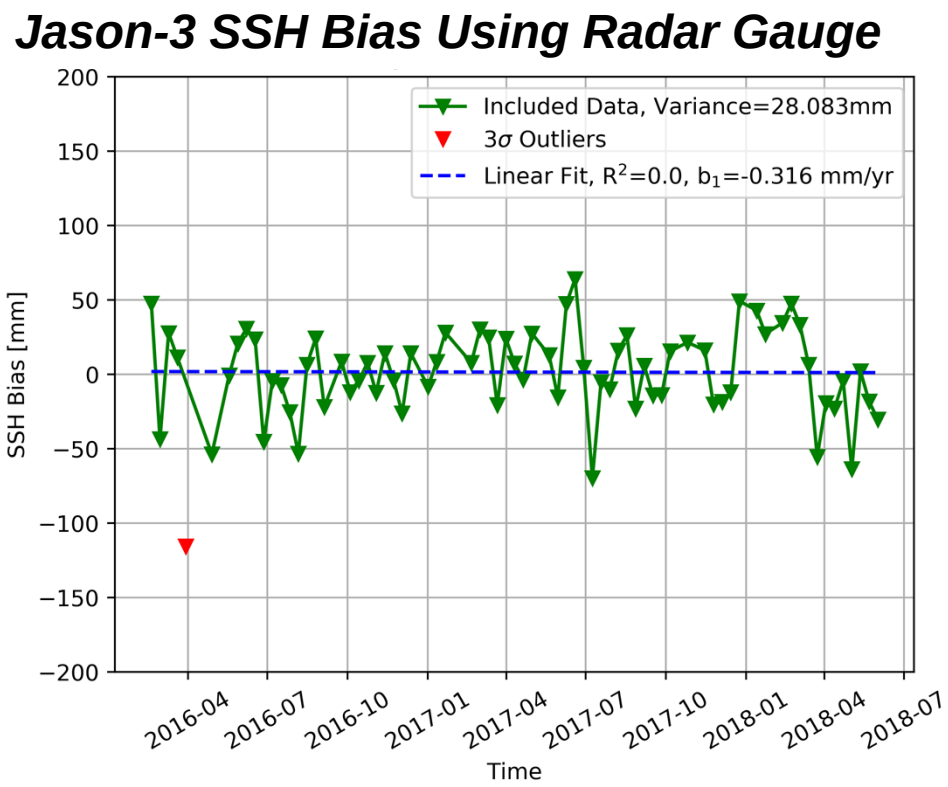
TOPEX Retracked Data

T/P: Retracked Data + 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 with GPS wet trop and JPL orbit

Altimeter	N	σ (mm)	Mean (mm)	Slope (mm/yr)
TOPEX ALT-A	147	33	+9 ± 3	+3 ± 2
POSEIDON-1	22	30	−22 ± 6	+0 ± 3
TOPEX ALT-B	81	31	−8 ± 3	−1 ± 3
JASON-1	206	27	+6 ± 2	−1 ± 1
OSTM/JASON-2	249	32	+5 ± 2	+1 ± 1
JASON-3	102	27	−15 ± 3	+7 ± 3



Platform Water Level from Tide Gauges
Update on Tide Gauge Performance in Heavy Seas



- Pressure (Bubbler) gauge has served as the standard at Harvest for many years, but has significant sea-state dependence and presents maintenance challenges.
- Radar gauges stable, accurate, and easy to maintain: gradually replacing submerged systems in NOAA network.
- Studies are ongoing to characterize remaining systematic errors from, e.g. wind waves, swell, sea spray and spume.
- Plan is to maintain pressure (Bubbler), radar and lidar systems operating simultaneously as long as practical.