The Harvest Experiment: New Beginnings

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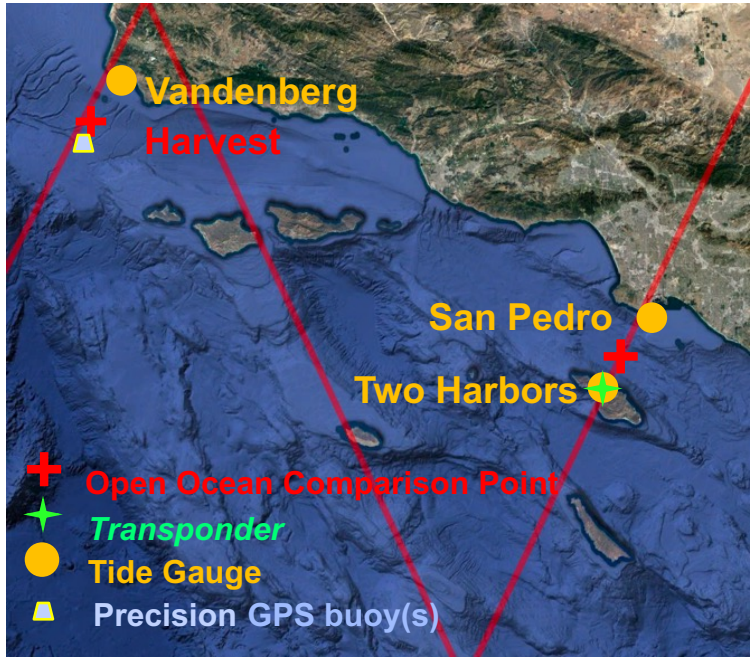
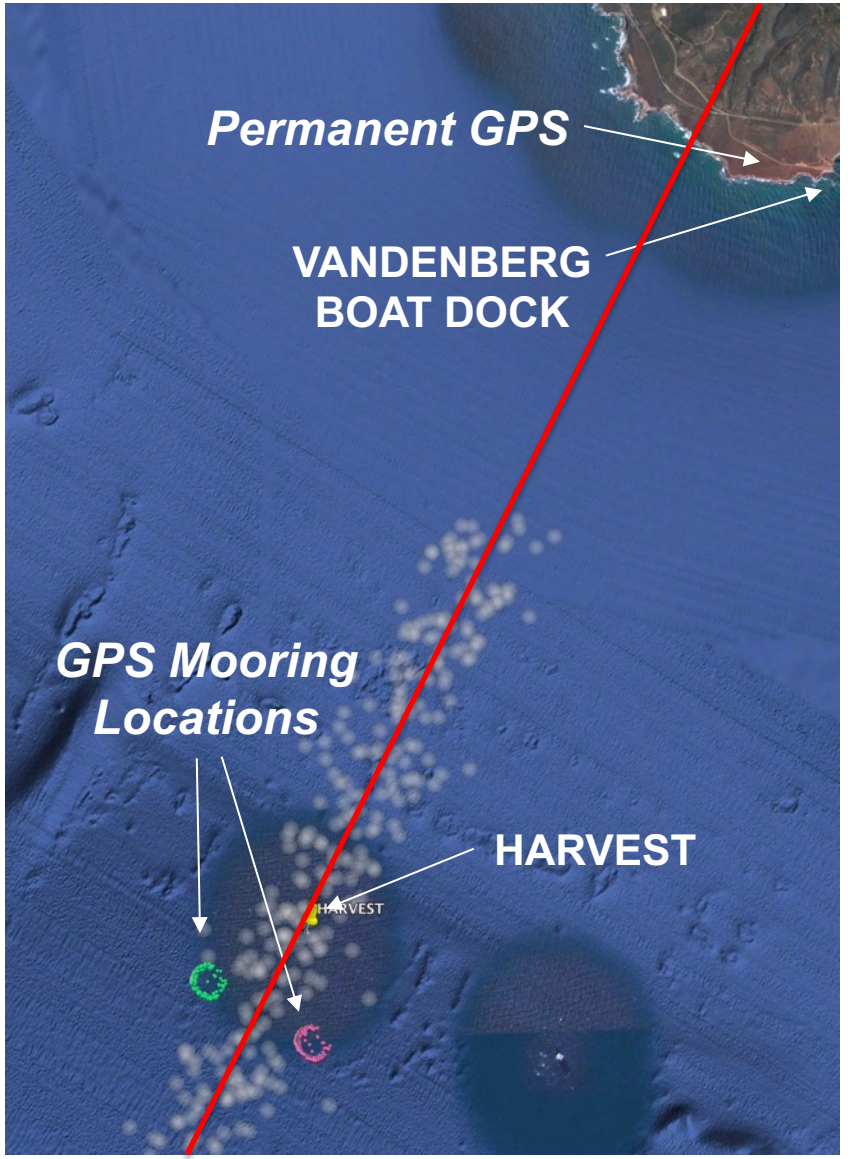
Platform Harvest: End of An Era

- **NASA Prime Verification Site for altimeter reference missions since 1992**
  - Supported continuous monitoring with redundant tide gauges and GPS.
  - Provided connection dating back to original TOPEX/Poseidon mission.
  - Supported accurate and durable verification record for Sentinel-6 before shut down.
- **Platform slated for decommissioning**
  - "Notice to vacate" received by JPL Summer 2022.
  - Instruments powered off November 2022.
  - Most instruments removed, including GPS station.
- **New observation systems to ensure continuity and preserve historical record.**
  - Harvest precise GPS buoy(s) deployed permanently near platform (yearly swap outs).
  - Tide gauge (UH/NOAA) installed at Vandenberg Space Force Base boat dock, along same ground track, about 12 km from the platform.
  - Catalina Island transponder and tide gauge along adjacent (ascending) ground track.



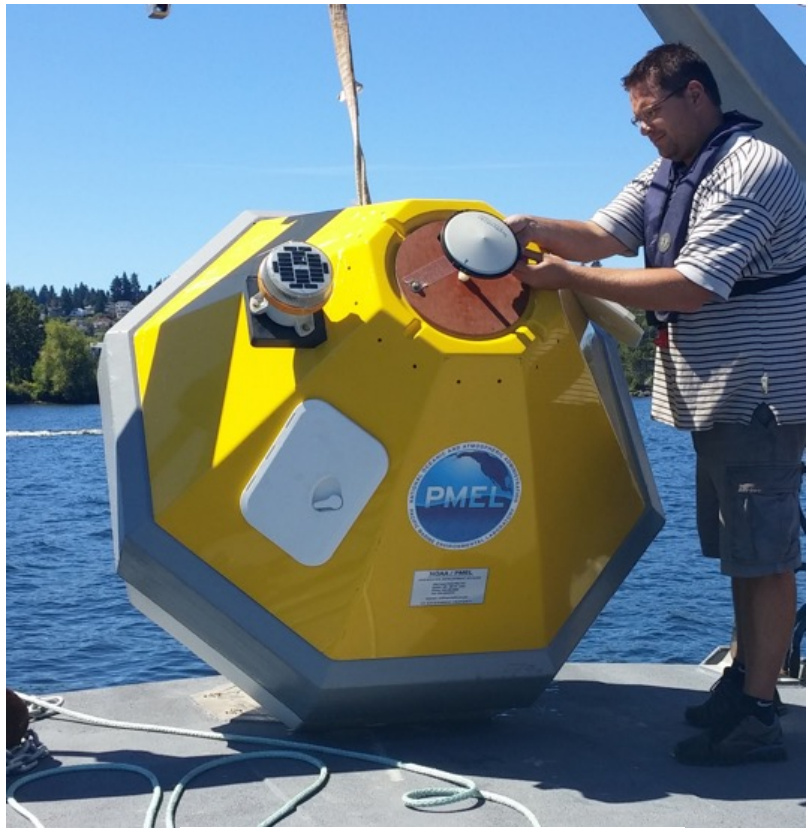
Vandenberg Tide Gauge

- **Installed by University of Hawaii SLC August 2023**
  - Under auspices of NOAA and JPL with US Space Force.
- **Radar gauge on Vandenberg Boat Dock**
  - ~1 km from Jason/S6 ground track and 12 km from Harvest Platform
- **Surveyed to nearby GPS (historic VLBI) site.**
  - Continuous GPS since 1992.
  - Also used as relay site for data from Harvest platform.
- **~60 cm geoid difference between Harvest and coast.**
  - Precise measure needed for connection to platform in open ocean.



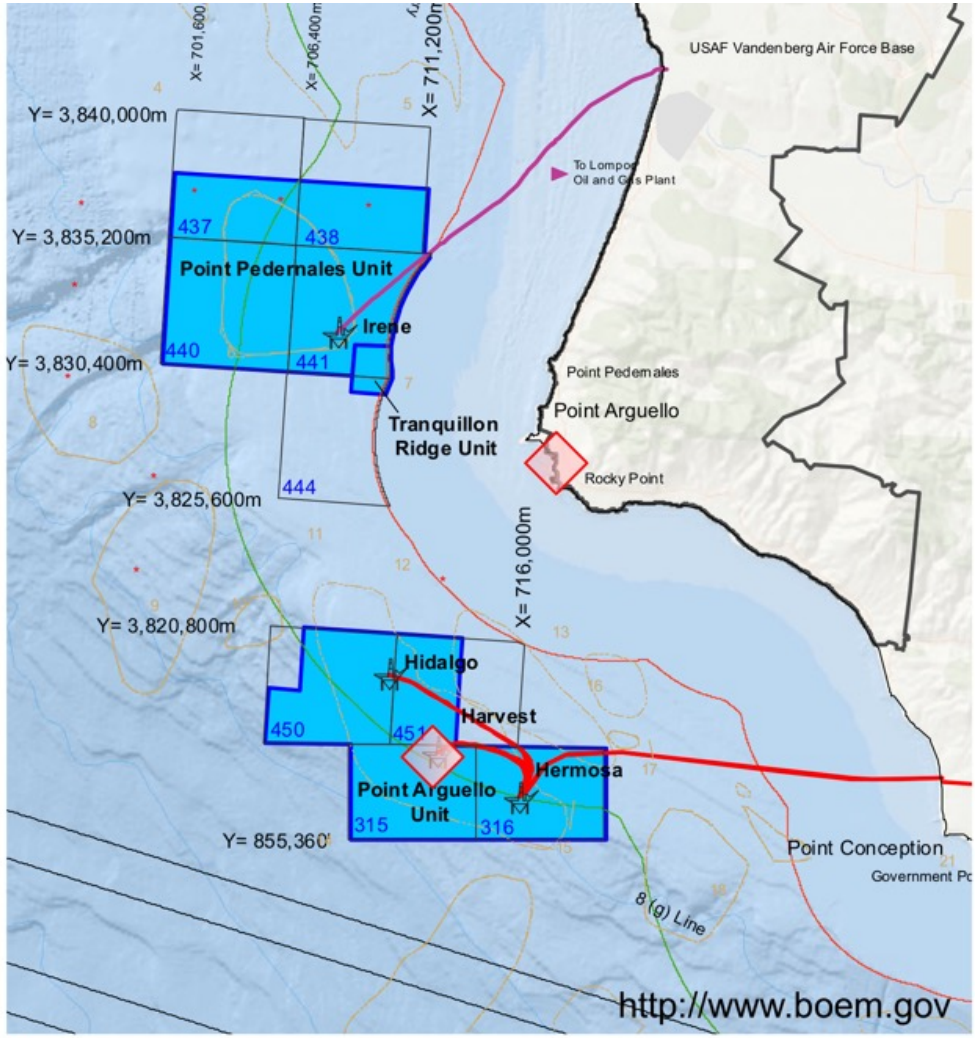
Precise GPS Buoys

- **NASA JPL & NOAA PMEL program initiated in 2013.**
  - Enable long-term continuous & accurate GNSS data collection in the open ocean.
  - Support precise measurements of SSH, SWH, troposphere and ionosphere.
  - Applications include seafloor geodesy, water vapor, space weather and natural hazards in addition to altimeter calibration.
  - Fundamental buoy design has been tested and evolved since 2015.
  - Over 2500 buoy days of data have been collected, with campaigns up to ~1 year.
- **First Harvest campaign in 2018.**
  - Better than 1 cm relative SSH (between buoys 1.5 km apart).
  - SSH bias and tropospheric estimates competitive with platform
  - Absolute water level challenging (2-3 cm static offsets with surveyed tide gauges).
  - High SWH (> 4 m) challenging.
- **Continuous occupation at Harvest began in 2020.**
  - Requires yearly swap outs of buoy.
  - Some operational challenges: vandalism, moorings breaking free (possible shark bites?)
- **GPS buoys are also key components of NASA ocean campaigns for SWOT.**
  - 1-2 cm agreement with steric height for SWH < 4 m (Wang et al, 2022).

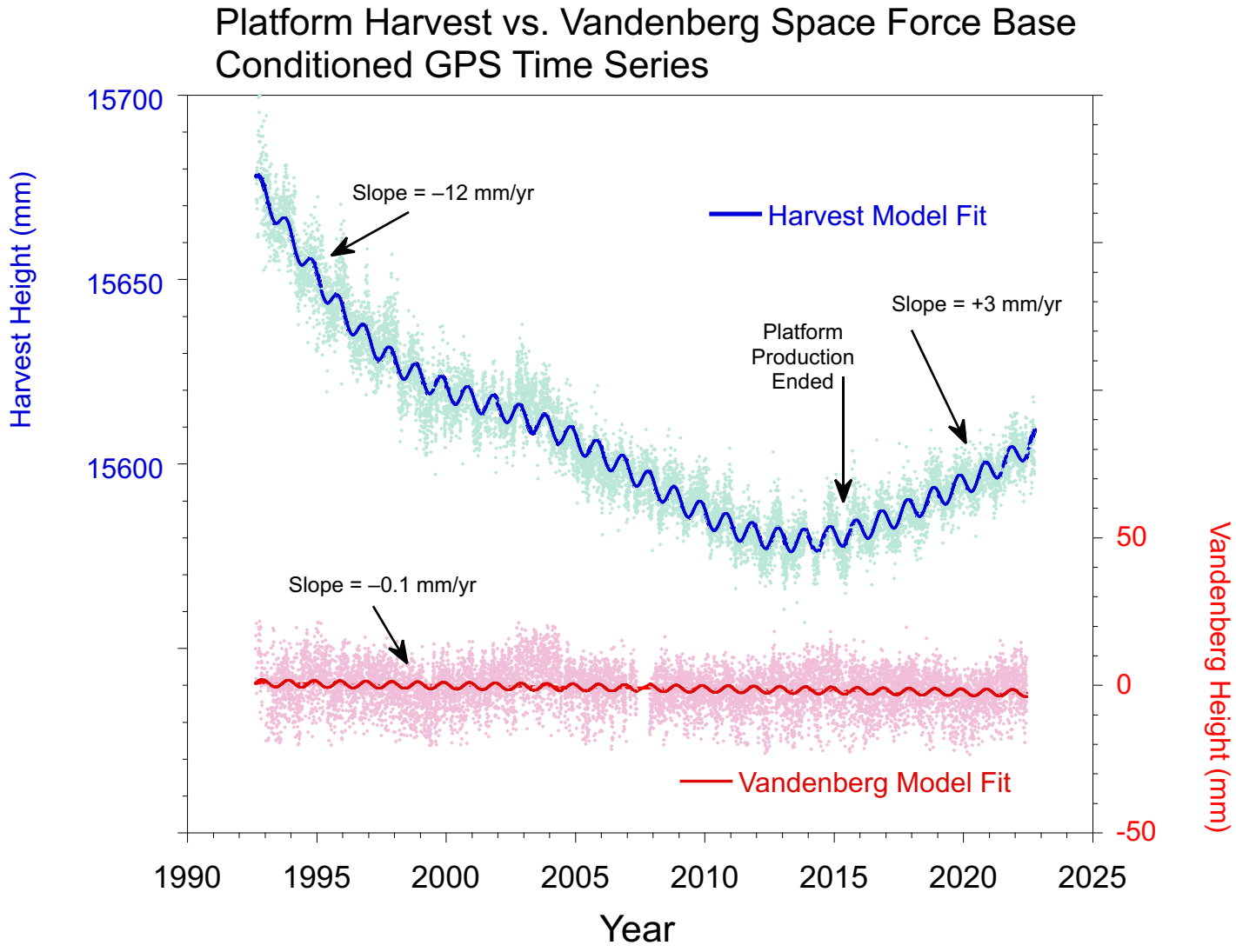


Septentrio AsterX GNSS Receiver

Vertical Land Motion from GPS: Platform Harvest vs. Vandenberg AFB



GPS Receivers

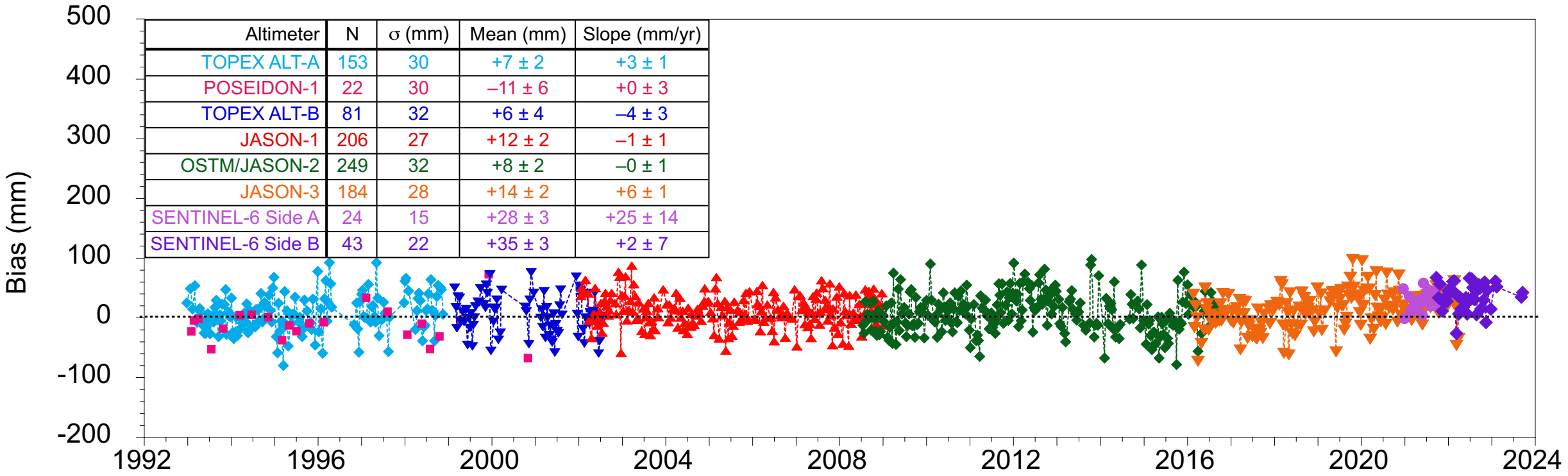


Vandenberg Results from JPL IGS Analysis Center
https://sideshow.jpl.nasa.gov/post/series.html

Harvest Long-Term SSH Calibration Record

T/P: MGDR + reprocessed orbits (*Lemoine et al.*) and wet trop. (*Brown et al.*); **Jason-1:** GDR-E; **Jason-2**: GDR-D; **Jason-3**: **GDR-F**; **Sentinel-6**: **NTC F08**

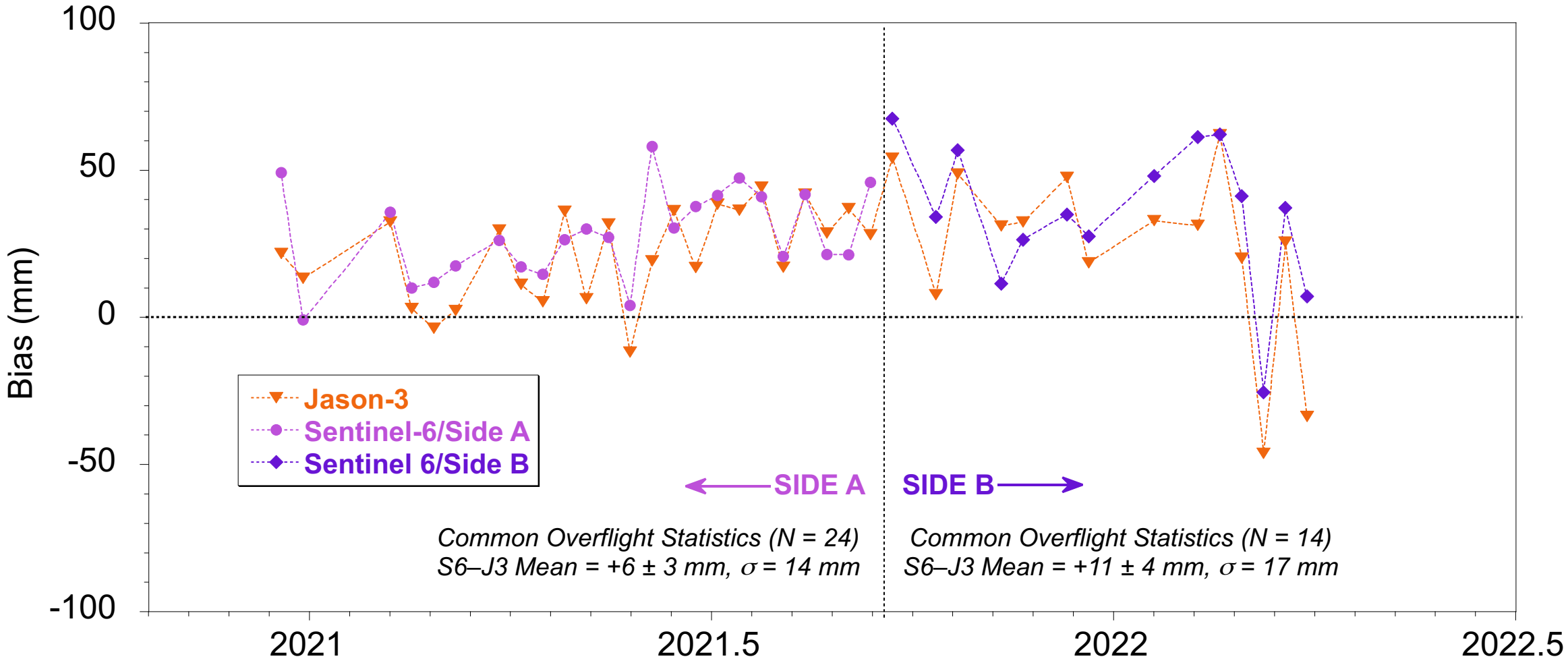
Altimeter	N	σ (mm)	Mean (mm)	Slope (mm/yr)
TOPEX ALT-A	153	30	+7 ± 2	+3 ± 1
POSEIDON-1	22	30	–11 ± 6	+0 ± 3
TOPEX ALT-B	81	32	+6 ± 4	–4 ± 3
JASON-1	206	27	+12 ± 2	–1 ± 1
OSTM/JASON-2	249	32	+8 ± 2	–0 ± 1
JASON-3	184	28	+14 ± 2	+6 ± 1
SENTINEL-6 Side A	24	15	+28 ± 3	+25 ± 14
SENTINEL-6 Side B	43	22	+35 ± 3	+2 ± 7



- Sentinel-6 SSH bias slightly positive for both Sides A and B (+3 cm).
- Recent uptick (since 2018) in time series remains a subject of investigation.
  - Effects of uncertain land motion and equipment changes (Bubbler to radar) may provide partial explanations.
- Repeatability of S6 and recent J3 SSH estimates superior to those from legacy missions.
  - May reflect improved performance of radar tide gauges.
- SSH bias estimates for legacy missions indistinguishable from zero
  - Systematic errors of 1–2 cm due principally to land motion.

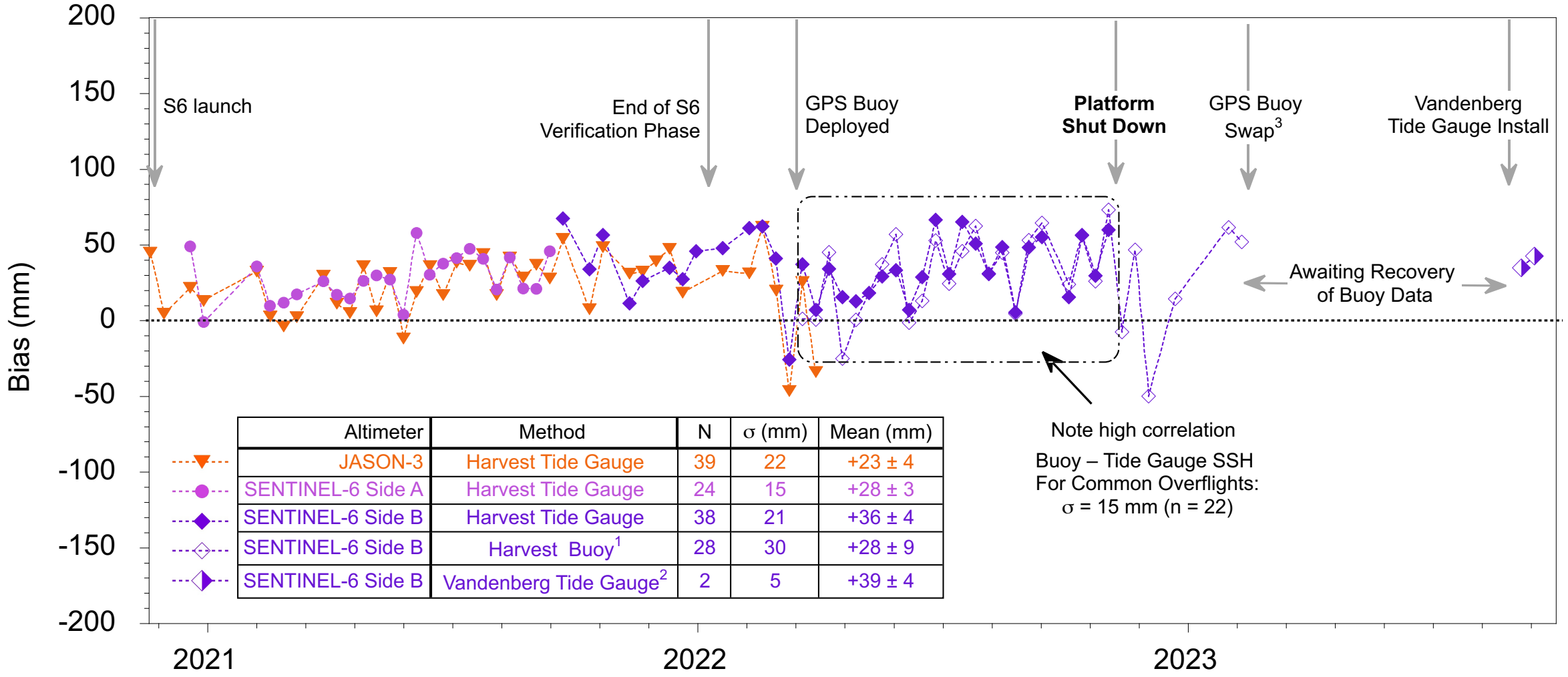
Harvest SSH Calibration Record

Focus on Sentinel-6/Jason-3 Formation Flight Phase



- Relative SSH bias (S6–J3) slightly positive (≤ 1 cm), consistent with global analysis.

Harvest SSH Calibration Time Series:
Closeup of Transition from Platform During Sentinel-6 Era

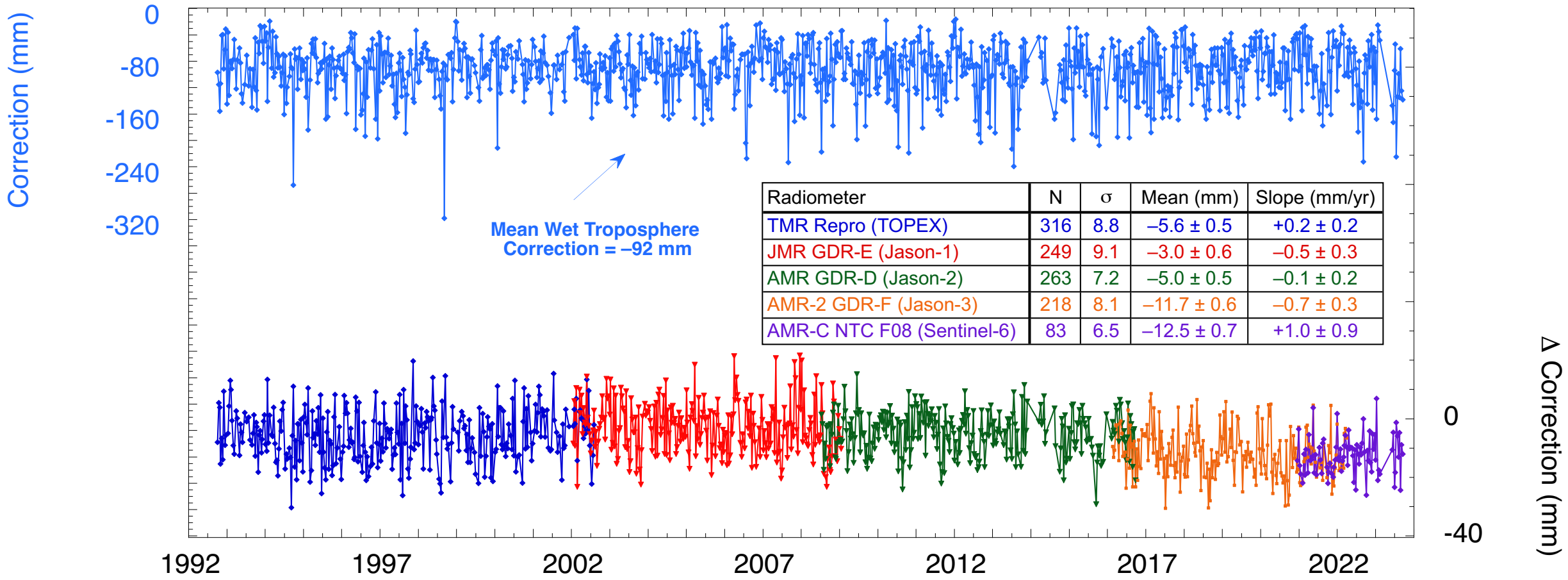


Altimeter	Method	N	σ (mm)	Mean (mm)
JASON-3	Harvest Tide Gauge	39	22	+23 ± 4
SENTINEL-6 Side A	Harvest Tide Gauge	24	15	+28 ± 3
SENTINEL-6 Side B	Harvest Tide Gauge	38	21	+36 ± 4
SENTINEL-6 Side B	Harvest Buoy[1]	28	30	+28 ± 9
SENTINEL-6 Side B	Vandenberg Tide Gauge[2]	2	5	+39 ± 4

1 After water level and sea-state bias calibrations of 25 mm and 1.9% respectively (cf., Wu et al. poster).
2 Leveled to Harvest using local survey (U. Hawaii) + CLS22 mean sea surface (Schaeffer et al.).
3 High-rate (1-Hz) GPS data collected in 2023 (after annual buoy swap) will be available after recovery of new buoy.

Harvest Wet Troposphere Calibration Record

Spaceborne Radiometer — Ground GPS

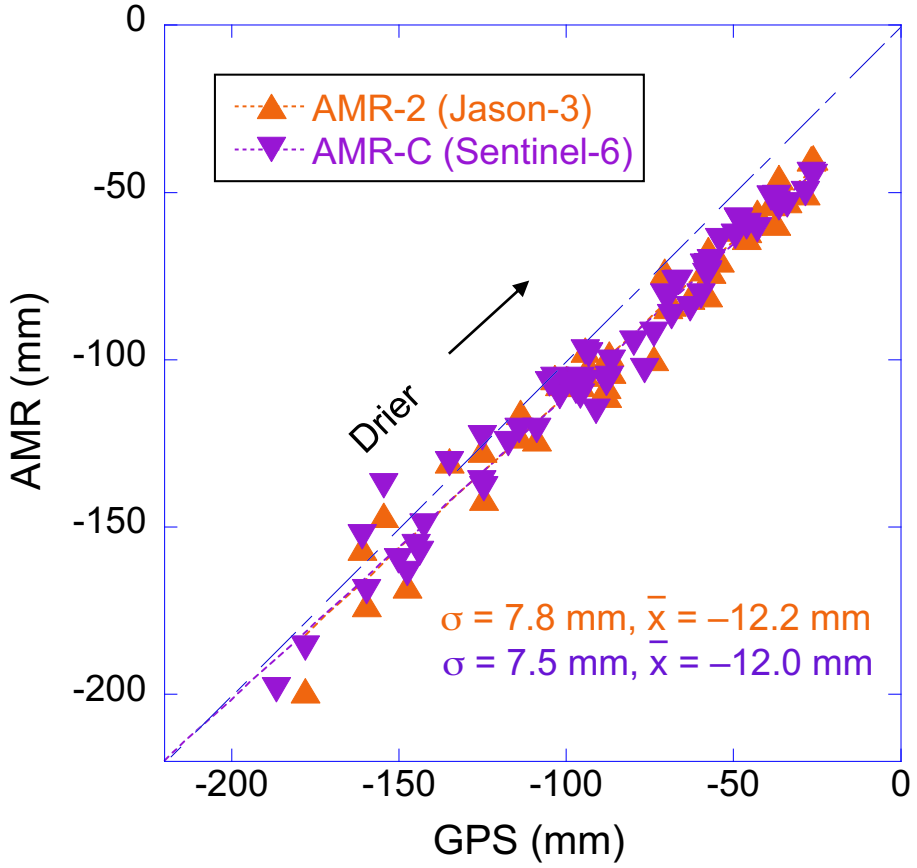


- Excellent stability of radiometer systems over platform for past 30 years.
  - Slight drift for AMR-2 on Jason-3.
- GPS consistently drier than radiometers (by 3–13 mm).

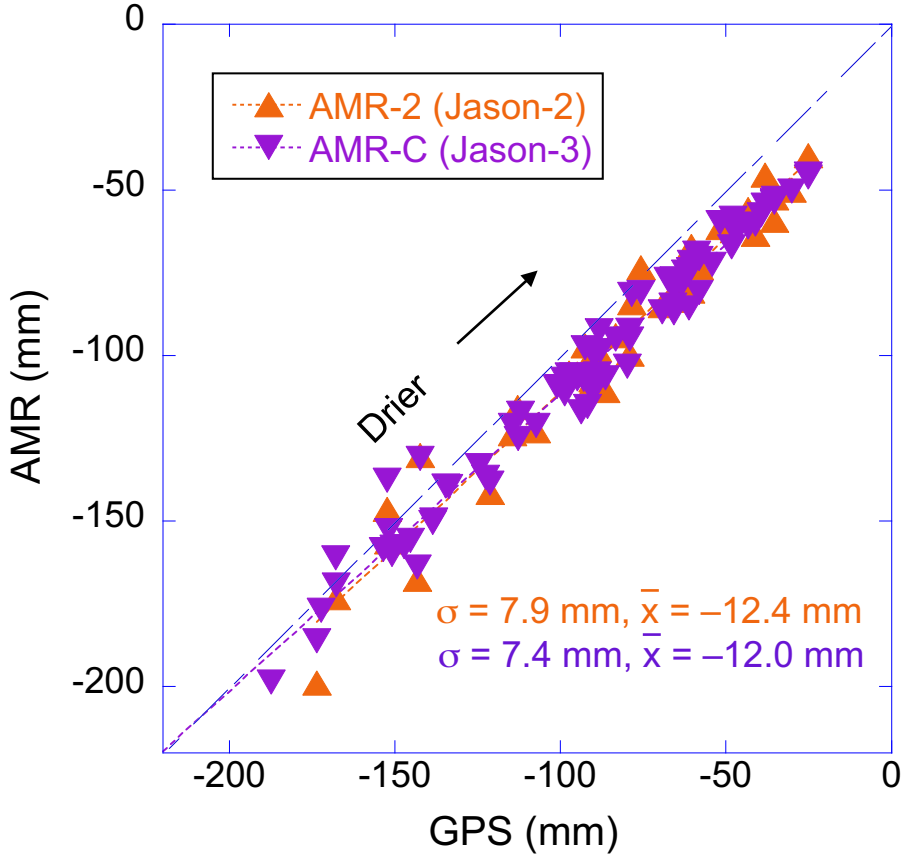
Harvest Wet Troposphere Comparisons for Sentinel-6 Era

Recoveries of Wet Troposphere from Floating (Buoy) and Fixed (Platform) GPS are Nearly Indistinguishable

Platform GPS vs. Radiometer



Buoy GPS vs. Radiometer



- AMR path delays (both Jason-3 and Sentinel-6) are wetter than GPS by ~1 cm.
- Comparisons hint at a scale error: differences larger for driest overflights.
- Excellent agreement between platform and buoy GPS (Mean = 0 mm, σ = 4 mm)

Summary

- **Sentinel-6 SSH (absolute, geocentric) slightly high at Harvest**
  - Side A F08 Product (LRM) +28 ± 15 mm[1]
  - Side B F08 Product (LRM): +35 ± 16 mm[1]
- **Sentinel-6 SSH slightly high relative to Jason-3**
  - Sentinel-6/Side A — Jason-3: +6 ± 3 mm
  - Sentinel-6/Side B — Jason-3: +11 ± 4 mm
  - Consistent with results from global analysis.
- **Good consistency between Sentinel-6 Sides A&B**
  - Indistinguishable differences at Harvest
- **Sentinel-6 AMR-C path delay remains wetter than GPS, by ~1 cm at Harvest.**
  - Harvest comparisons favor dry conditions (mean wet delay < 10 cm).
  - Results continue to hint at a scale error (differences are smaller for wet overflights).
  - Jason-3 AMR shows similar behavior.
  - Application of GPS path delays in place of AMR would reduce SSH biases for both S6 and J3 ~1 cm.
- **The Harvest Experiment is well positioned to move forward seamlessly, without the platform itself.**
  - Calibration metrics from GPS buoys are competitive with those from platform, except under high wave conditions.
  - Preliminary results from Vandenberg tide gauge show promise of this new sensor.
  - Stable land at Vandenberg is an advantage compared to the platform.
  - Coupled with assets on Catalina (e.g., Transponder), Harvest will continue to provide insights on current and future altimetric systems.

1 Error includes systematic uncertainty in platform vertical