The Harvest Experiment: Status and New Results from the Sentinel-6 Mission

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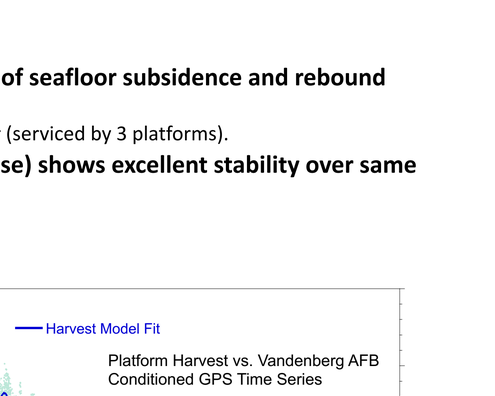
Abstract

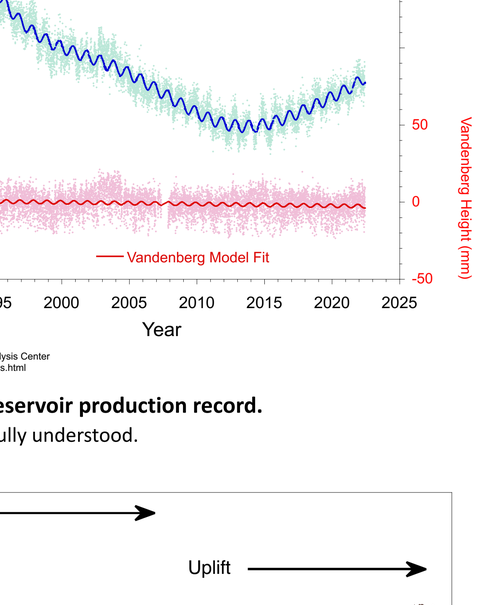
We describe the latest satellite radar altimeter CALVAL results from the Harvest offshore platform. Located 10 km off the coast of central California near Point Conception, Harvest has served as the NASA prime verification site for the TOPEX/POSEIDON (T/P) and Jason series of altimeter reference missions for 30 years. The T/P repeat ground track was designed to take the satellite directly over Harvest every 10 days, enabling the development of a continuous verification record based on direct, overhead passes of the platform. The crucial role of T/P in developing a climate-quality record of sea level and ocean circulation has been inherited by the Jason series of reference missions, which have traced out the same 10-d repeat ground track passing by the platform. With the beginning of the routine operations phase in November 2021, the Sentinel-6 Michael Freilich mission assumed the mantle for extending this valuable scientific observation record.

The Harvest platform is being decommissioned, and activities are underway for the long-planned transition of the CALVAL function to regional infrastructure in the Southern California bight. Against this backdrop, however, the Harvest observational record has been accurately maintained throughout these crucial, early phases of the Sentinel-6 Michael Freilich mission. We describe the outcomes from this last chapter of the Harvest story, and provide a preview of new observing systems.

Platform Harvest: End of an Era

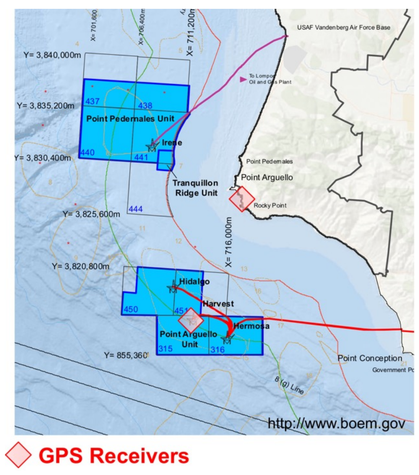
- **NASA Prime Verification Site for altimeter reference missions since 1992**
  - Supports continuous monitoring with redundant radar tide gauges and GPS.
  - Provides connection dating back to original TOPEX/Poseidon mission.
  - Exceptional verification record has been established for Sentinel-6.
- **Platform to be decommissioned**
  - Notice to vacate received summer 2022.
  - Platform to be placed on “cold standby” (TBD date): unmanned, except for inspection visits.
  - Plans for instrument removal awaiting approval.
  - Instruments continue to operate in interim.
- **Transition plan being followed**
  - New Harvest precise GPS buoy successfully deployed March 2022, following cadence of yearly swapouts.
  - Vandenberg tide gauge (recently approved) to be installed ASAP to enable overlap with Harvest.
  - Catalina buildout continues (transponder, new radar gauge in September 2022).





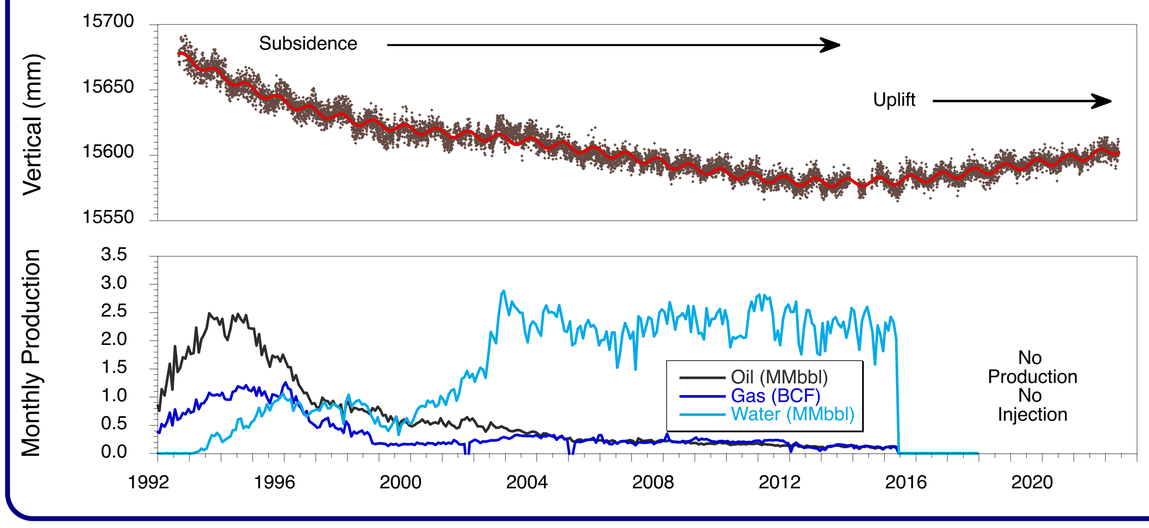
Vertical Land Motion

- **Offshore GPS (Platform Harvest) reveals complex pattern of seafloor subsidence and rebound over the past three decades.**
  - Likely confined to immediate vicinity of offshore Arguello reservoir (serviced by 3 platforms).
- **Onshore GPS only ~10 km away (Vandenberg Air Force Base) shows excellent stability over same time period.**
  - Negligible vertical land motion at new tide gauge location

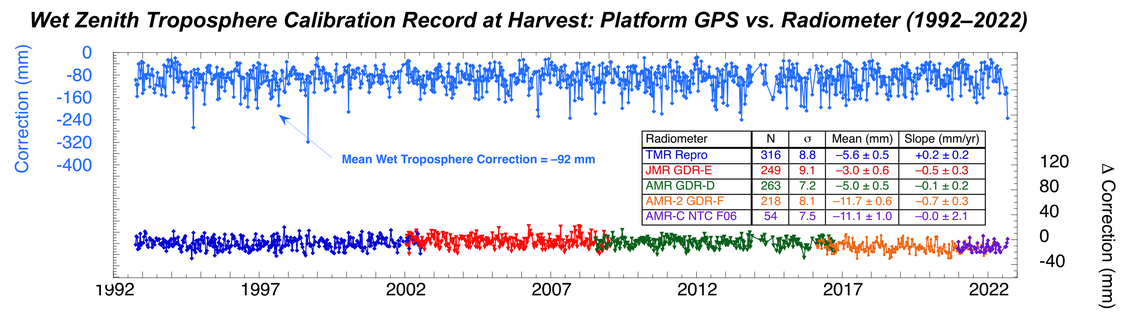


Vandenberg Results from JPL IGS Analysis Center
https://sideshow.jpl.nasa.gov/post/series.html

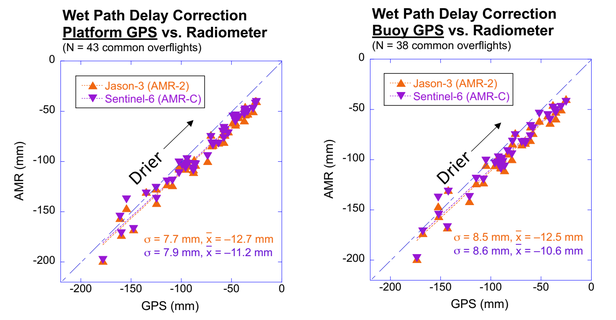
- **Pattern of vertical seafloor motion correlates with Arguello Reservoir production record.**
  - Rapid rebound of seafloor since cessation of drilling in 2015 not fully understood.

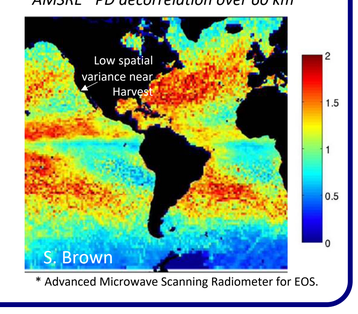


Wet Troposphere Delay



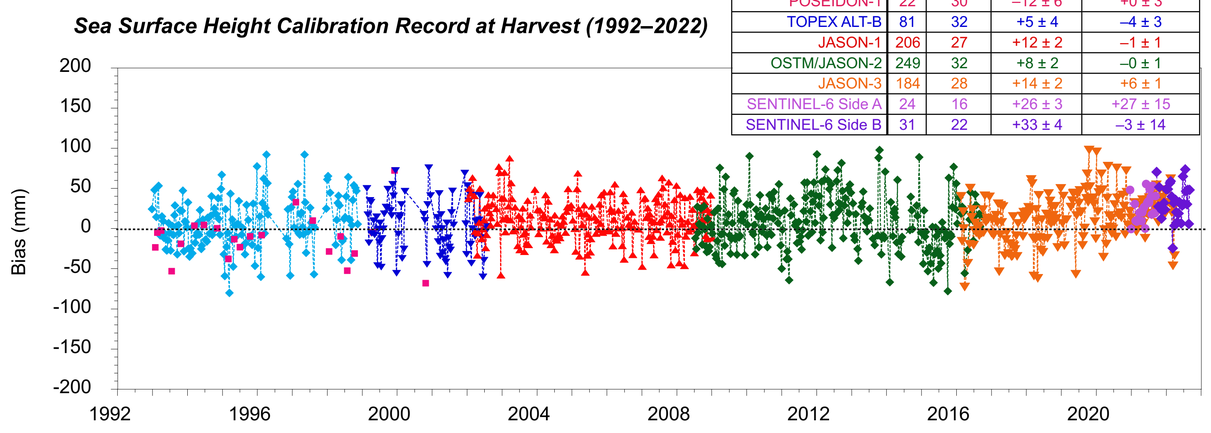
- **Long-term calibration time series**
  - Compares recoveries from platform GPS and spaceborne radiometers.
  - Shows typical dry conditions (mean delay < 100 mm).
  - Illustrates excellent stability of radiometer systems over platform for past 30 years (slight drift for AMR-2 on J3).
  - Provides connection dating back to original TOPEX/Poseidon (TMR) system.
- **Sentinel-6/Jason-3 Formation Flight**
  - AMR path delays wetter than GPS by ~1 cm.
  - Comparisons hint at a scale error: differences slightly larger for drier overflights.
  - Excellent agreement between platform and buoy GPS
    - Mean = 0.2 mm, σ = 4 mm.
  - Buoy ready to replace platform for troposphere recoveries.
- **High resolution (HRMR) data**
  - Performance of hybrid HRMR/AMR data similar to traditional AMR data at platform.
  - Potential HRMR advantage may be somewhat diminished in this area (S. Brown, private communication, 2022).
    - Low spatial variance in wet path delay off central CA
    - Platform located sufficiently far offshore (10 km)
    - Dry conditions prevail





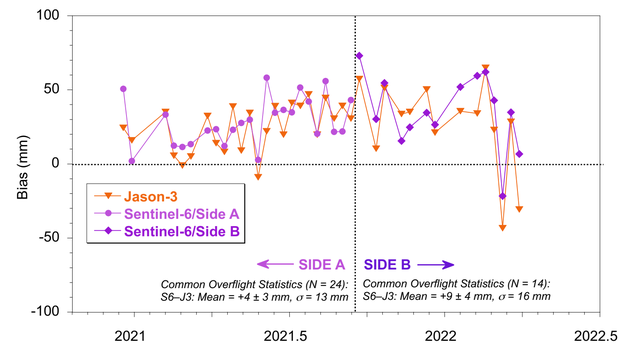
* Advanced Microwave Scanning Radiometer for EOS.

Sea Surface Height



Altimeter	N	σ (mm)	Mean (mm)	Slope (mm/yr)
TOPEX ALT-A	153	30	+7 ± 2	+3 ± 1
POSEIDON-1	22	30	–12 ± 6	+0 ± 3
TOPEX ALT-B	81	32	+5 ± 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	16	+26 ± 3	+27 ± 15
SENTINEL-6 Side B	31	22	+33 ± 4	–3 ± 14

- **Long-term calibration time series**
  - Sentinel-6 SSH bias slightly positive for both Sides A and B (+3 cm).
  - Recent uptick (since 2018) under investigation.
    - Effects of uncertain land motion model and tide gauge swap (from Bubbler to radar) may provide partial explanations.
  - Repeatability of SSH bias estimates from S6 era (including recent J3) superior to those from legacy time series.
    - May reflect performance of new radar tide gauges.
  - SSH bias estimates for legacy missions indistinguishable from zero
    - Systematic errors of 1–2 cm due principally to land motion
  - Large estimated drifts in S6 SSH reflect small sample size.
- **Sentinel-6/Jason-3 Formation Flight**
  - Relative SSH bias (S6–J3) slightly positive (< 1 cm), consistent with global analysis.
- **Impact of alternate S6 orbit/range products**
  - SSH bias for SAR smaller by ~6 mm
  - SSH bias with JPL GPS-based orbit (Desai et al.) smaller by ~3 mm.
  - Both SAR range and JPL orbit slightly improve repeatability.



Sentinel 6 Side A	N	Mean (mm)	σ (mm)	Slope (mm/yr)
Nominal	23	+26 ± 3	16	+25 ± 16
Nominal with SAR Range	23	+20 ± 3	14	+25 ± 13
Nominal with JPL GPS Orbit	23	+23 ± 3	15	+16 ± 16

Sentinel 6 Side B	N	Mean (mm)	σ (mm)	Slope (mm/yr)
Nominal	31	+33 ± 4	22	–3 ± 14
Nominal with SAR Range	31	+26 ± 4	20	–2 ± 13
Nominal with JPL GPS Orbit	31	+30 ± 4	21	–7 ± 14

Summary

- **Sentinel-6 SSH (absolute, geocentric) slightly high at Harvest**
  - Side A LRM: +26 ± 15 mm[1]
  - Side B LRM: +33 ± 16 mm[1]
  - Side A SAR: +20 ± 15 mm[1]
  - Side B SAR: +26 ± 16 mm[1]
- **Sentinel-6 SSH slightly high relative to Jason-3**
  - Sentinel-6/Side A (LRM) — Jason-3: +4 ± 3 mm
  - Sentinel-6/Side B (LRM) — Jason-3: +9 ± 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 wetter than GPS (by ~1 cm at Harvest).**
  - Harvest comparisons favor dry conditions (mean wet delay < 10 cm).
  - Results 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.
- **Preliminary HRMR results at Harvest inconclusive.**
  - Could be due to low spatial variance of PD in Harvest vicinity, coupled with inherent noise of HRMR.
  - GPS comparisons could lead to improved HRMR algorithms (e.g., regional blending approaches).

1 Error includes systematic uncertainty in platform vertical

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