Sea Surface GPS: Recent Advances

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New Opportunities to Study Tectonic Precursors
Meeting of the NASEM Committee on Seismology and Geodynamics
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Precision GPS Buoy Project

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

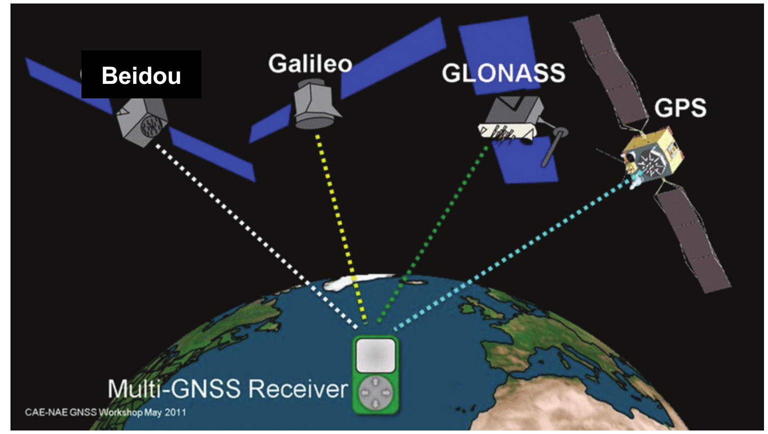
OBJECTIVES:

- 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, space weather, sea floor geodesy and natural hazards—of accurate GPS observations from a global ocean network of floating platforms.

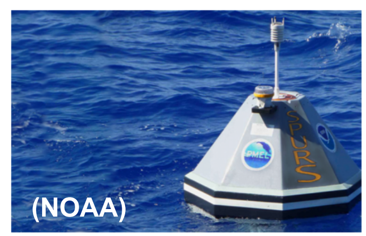
**Extending the Reach of the Global GNSS Network to the World's Oceans: A Prototype Buoy for Monitoring Sea Surface Height, Troposphere and Space Weather*, B. Haines, S. Brown, S. Desai, A. Komjathy, R. Kwok, D. Stowers, C. Meinig and J. Morison.

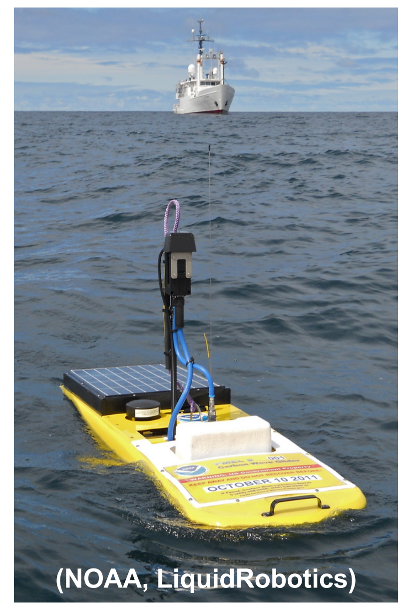
The Time is Ripe for the Development of a Global GNSS Ocean Network

- Emerging Global Navigation Satellite Systems (GNSS).
  - Provide improved framework to support demanding kinematic applications.
- Advances in miniature, high-accuracy GNSS receivers (e.g., OEM boards).
  - Coupled with improved telemetry (e.g., IridiumNEXT) and data compression.
- Innovations in precise point positioning.
  - Enable high accuracies without dedicated reference stations (e.g., Bertiger at al., 2010).
  - Supported by real-time GPS products (e.g., http://www.gdgps.net).
- New ocean-faring platforms and advanced mooring systems.
  - LiquidRobotics Wave Glider
  - SailDrone
- Broad scientific/societal benefits.
  - Sea level and satellite altimeter cal/val
  - Atmospheric rivers (precipitable water)
  - Space weather (ionosphere from GPS TEC)
  - Sea floor geodesy, seismology
  - Natural hazards (e.g., Tsunamis)




(NOAA, SailDrone)

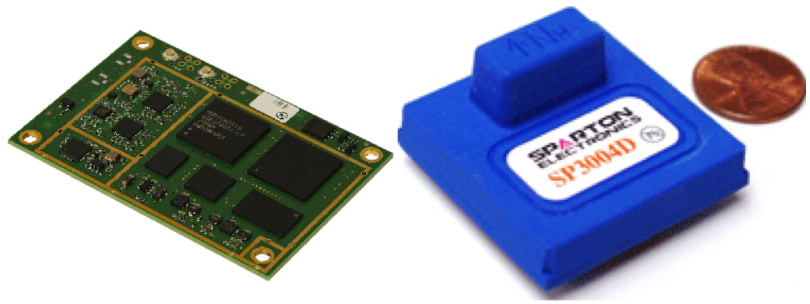

(NOAA)

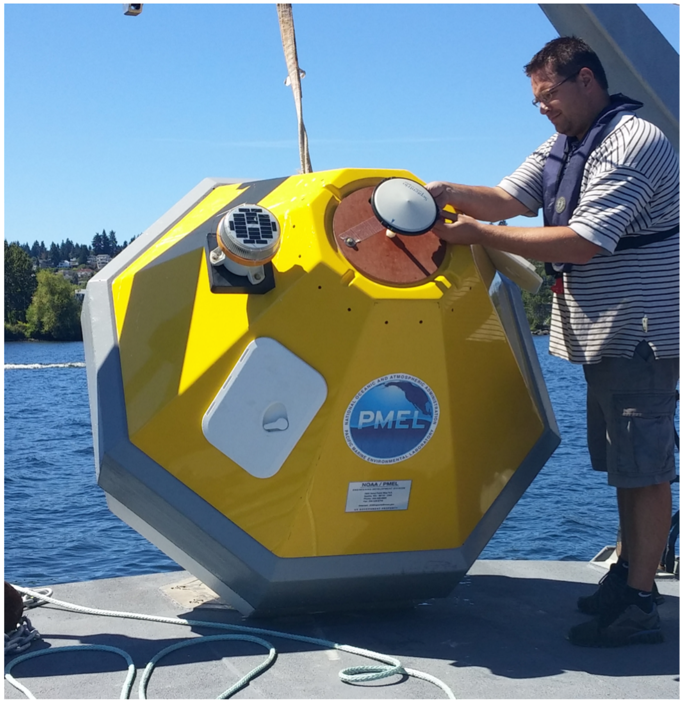

(NOAA, LiquidRobotics)

Prototype Precision GPS Buoy

FEATURES

- Integrated low-power (~1 W), dual-frequency GPS system (Septentrio)
- Miniaturized digital compass/accelerometer.
- Iridium communications.
- Adaptable to multiple floating platforms (e.g., buoys, sail drones, wave gliders).
- 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).*

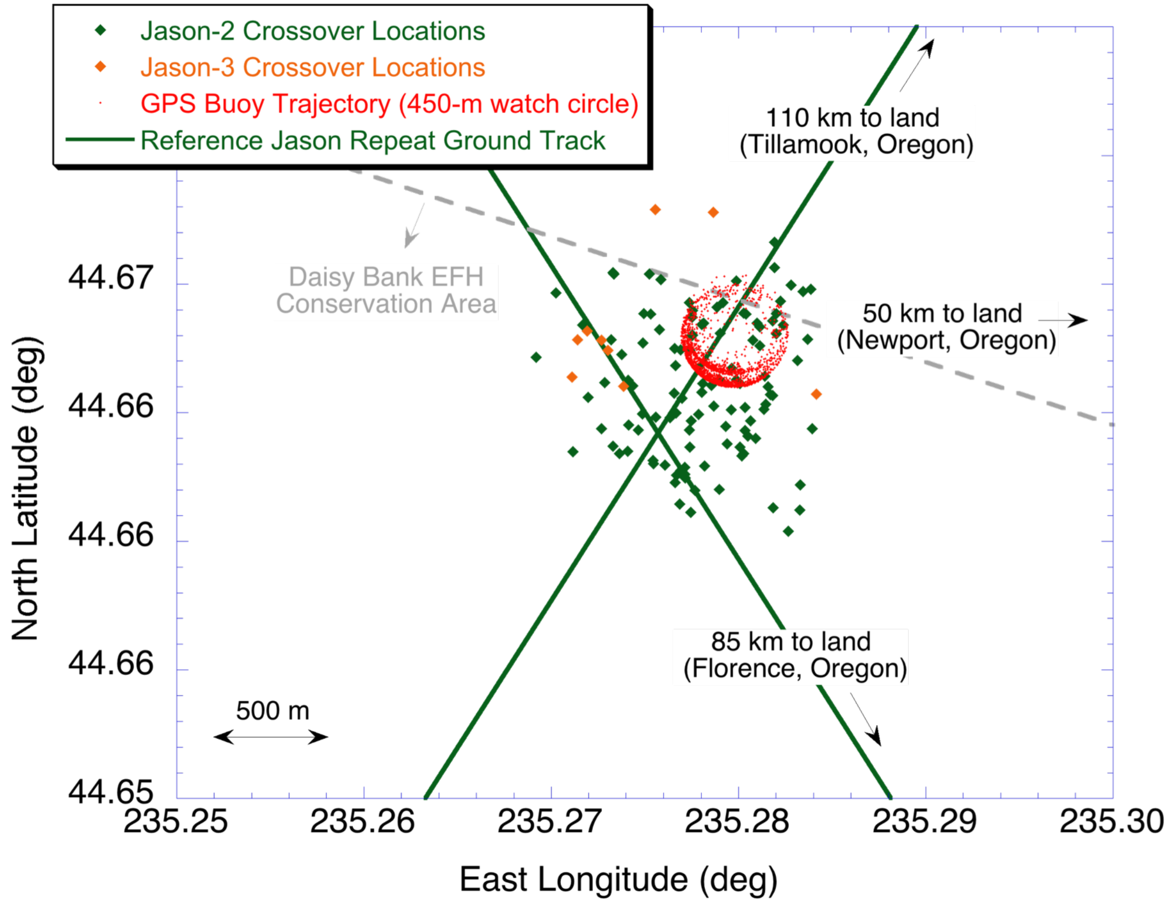
✓ *Harvest California Offshore Platform: tandem buoy experiment (2018).*

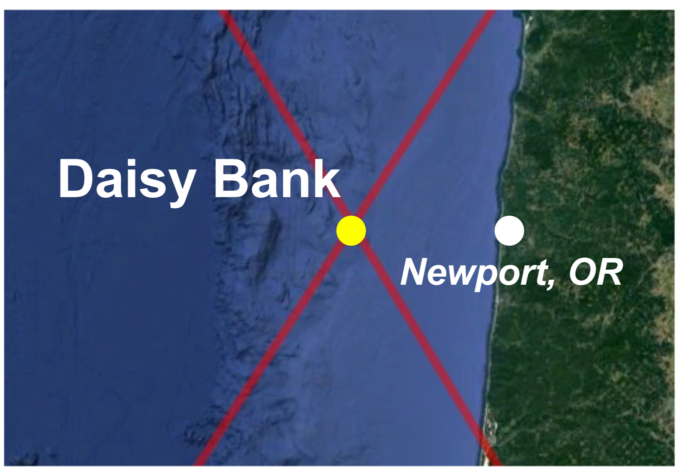
⇨ **Total of 464 successful buoy days in the water**

Daisy Bank (2016)
First Open Ocean Campaign

Daisy Bank

- Summer 2016 GPS Buoy Campaign at Jason Crossover Location
- Buoy moored 50 km offshore over submarine rock outcrop (shallow water).
- Typical SWH of 1–3 m.
- Operated continuously for 120 days (May thru Sep).
- Deployment spanned 24 dual Jason 2/3 overflights.



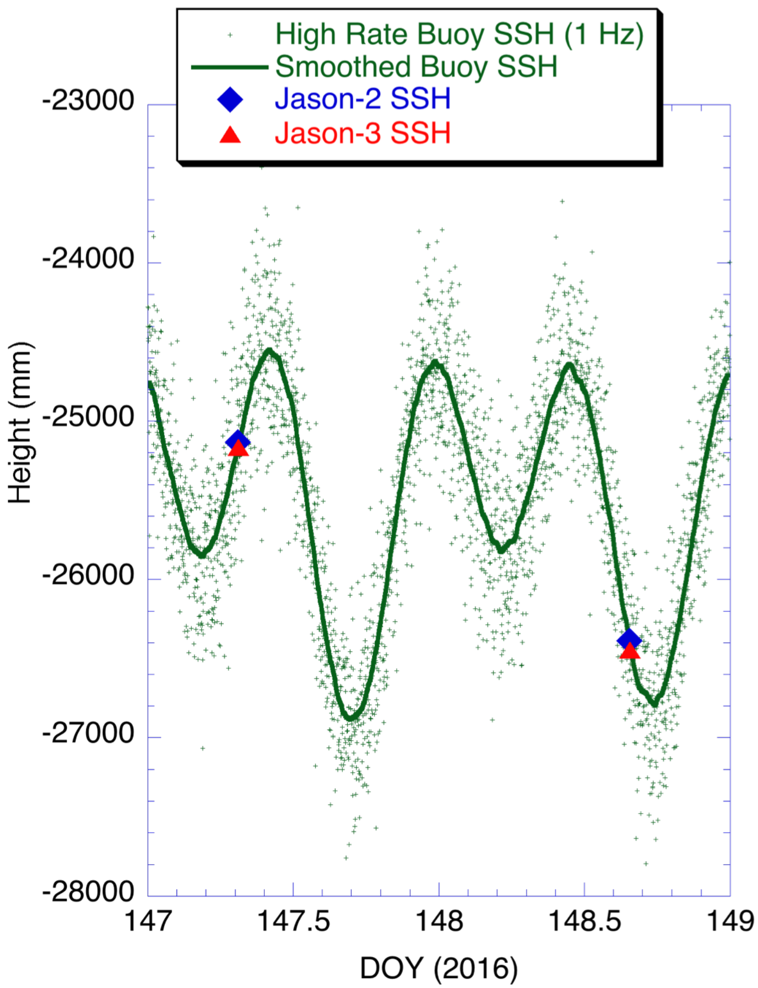


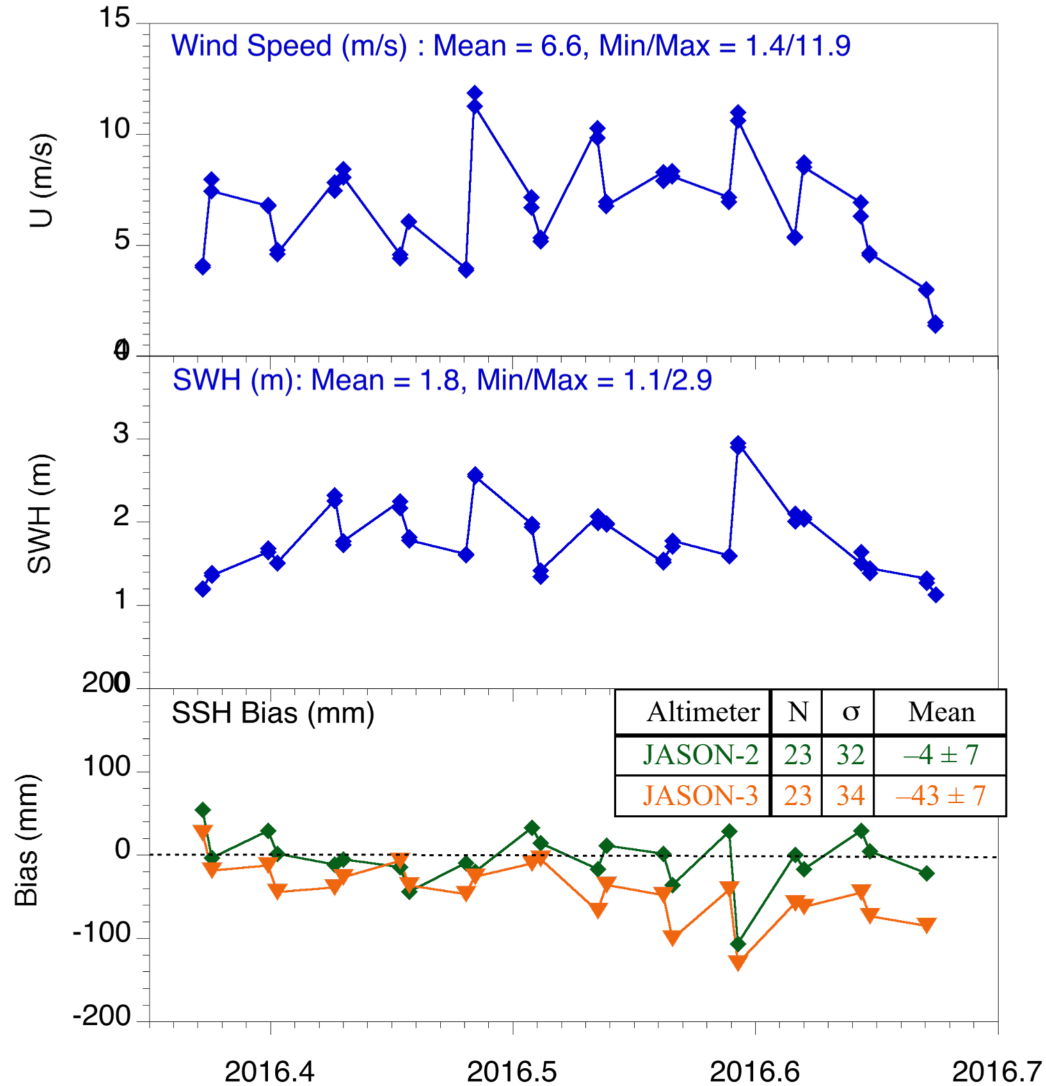
DAISY BANK CLOSEUP

~200-m depth

Daisy Bank (2016)
Comparison to Jason Sea Surface Height

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



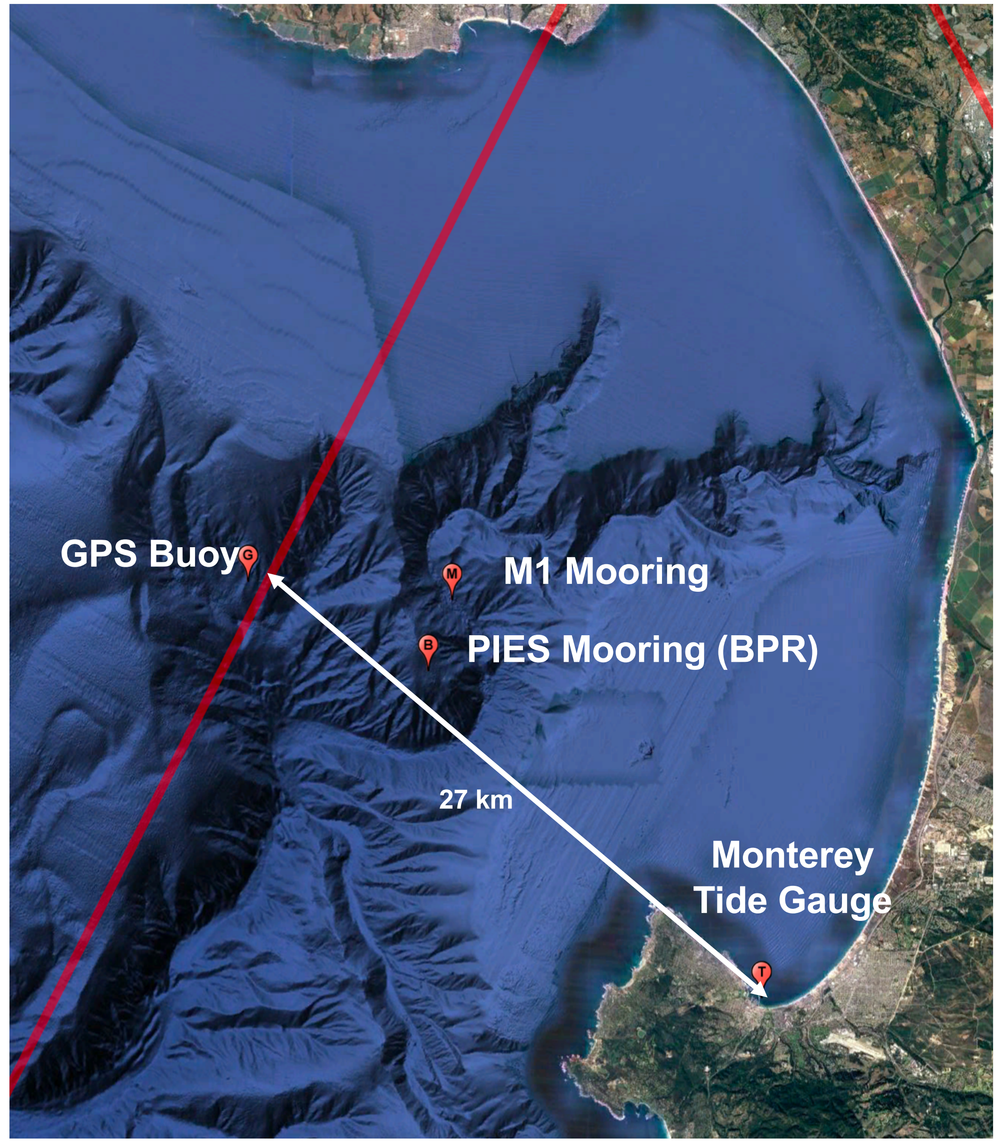


Altimeter	N	σ	Mean
JASON-2	23	32	−4 ± 7
JASON-3	23	34	−43 ± 7

Monterey Bay (2017):
SWOT Pilot Experiment

Monterey Bay

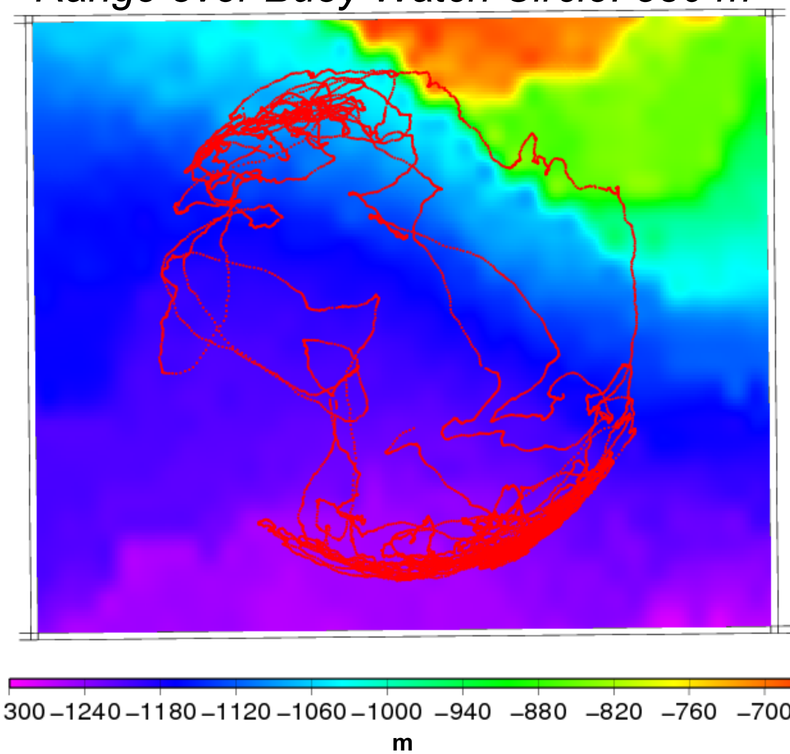
- Summer 2017 GPS Buoy deployment to complement SWOT glider campaign.
- Buoy moored 20 km offshore over steep wall of Monterey Canyon.
- Mooring depth of ~1000 m, with watch circle diameter of ~2 km
- Operated continuously for ~60 days (after repair of failed USB drive).
- Adjacent to ascending Jason track.
- Deployment spanned 6 Jason-3 overflights.



Monterey Buoy Results Underscore Importance of Geoid Signal

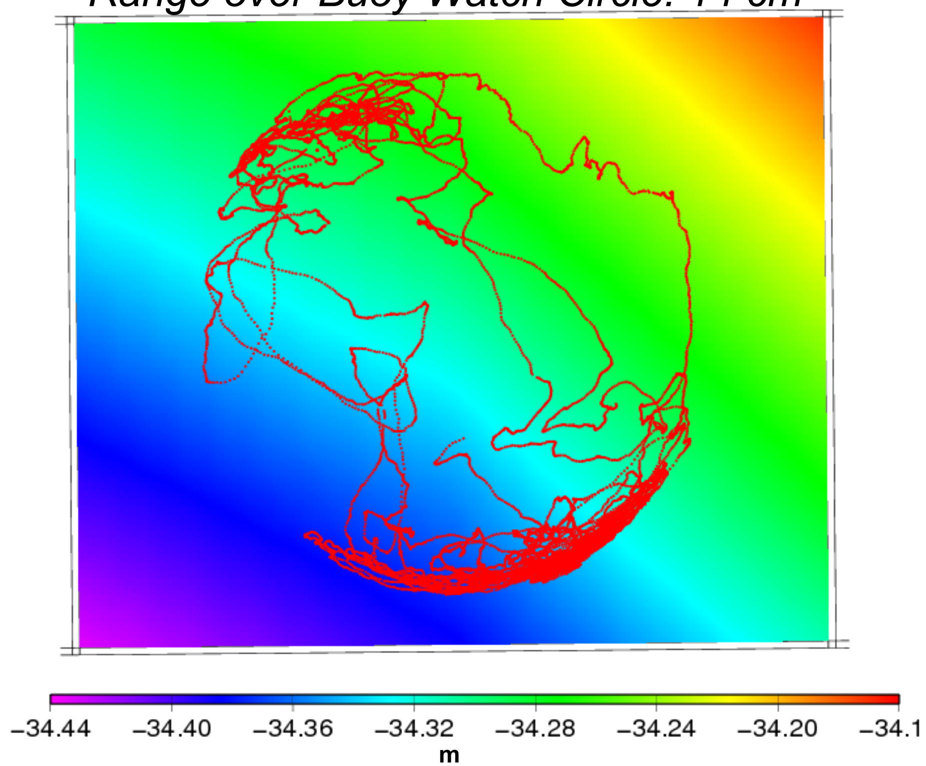
In Monterey Experiment, buoy was moored in ~1000 m of water over the steep walls of Monterey Canyon, the largest submarine canyon along the west coast of North America.

Bathymetry
Range over Buoy Watch Circle: 530 m



Divins, D.L., and D. Metzger, NGDC Coastal Relief Model
http://www.ngdc.noaa.gov/mgg/coastal/coastal.html
http://sccoos.org/data/bathy

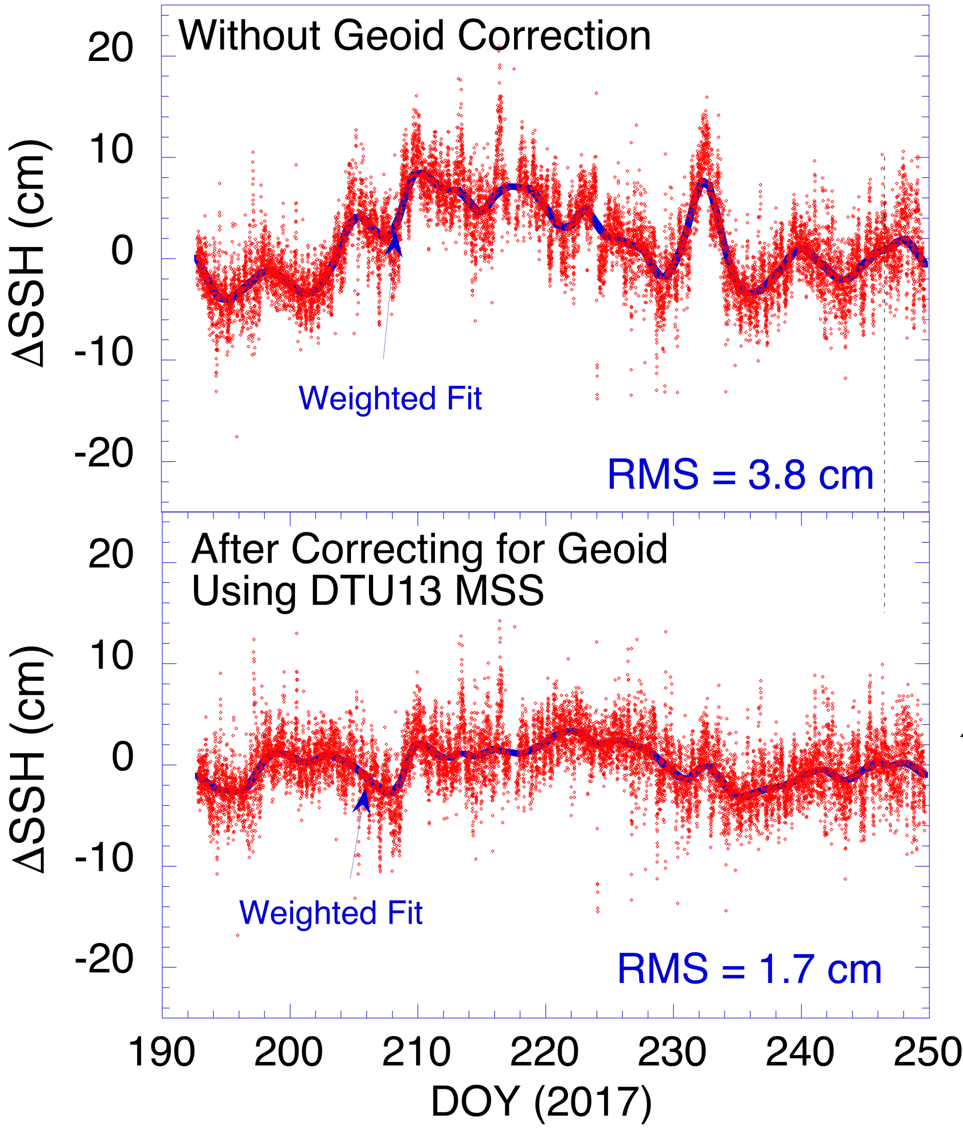
***Geoid** (from MSS Model)*
Range over Buoy Watch Circle: 14 cm



Andersen, O., P. Knudsen and L. Stenseng, The DTU13 MSS (Mean Sea Surface) and MDT (Mean Dynamic Topography) from 20 Years of Satellite Altimetry, IGFS 2014.

Monterey Buoy Results Underscore Importance of Geoid Signal

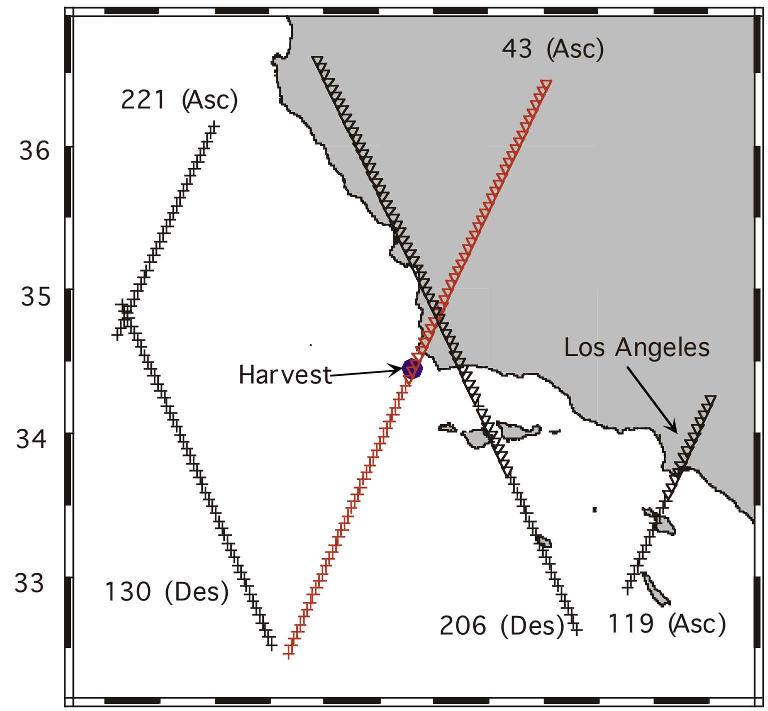
Strong Geoid Signal Observed in Time Series of GPS Buoy – Tide Gauge SSH



- 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 (diameter) 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 GPS survey (Bonnefond et al., 2003),

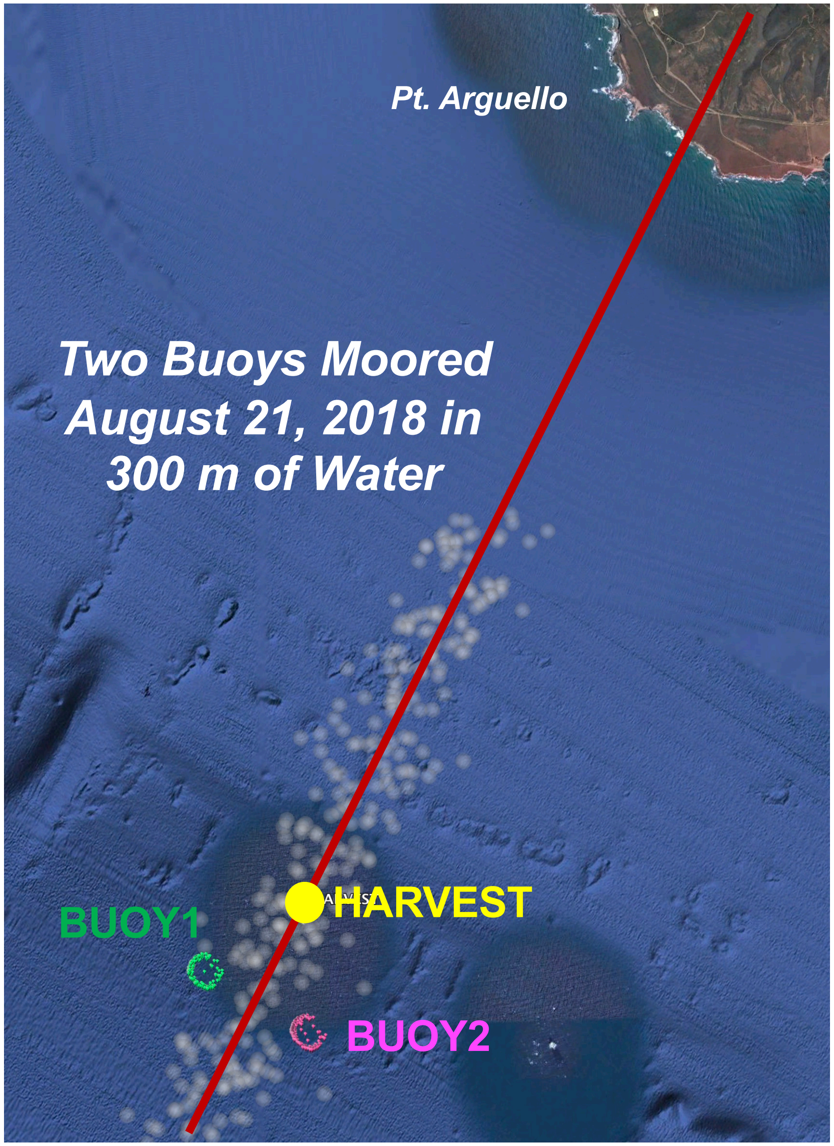
Harvest Platform

- **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
  - Conditions typical of open ocean
- **Provides independent measure of local geocentric sea level**
  - Precise GPS receivers + local survey
  - Redundant tide gauges (Bubbler, radar, lidar)

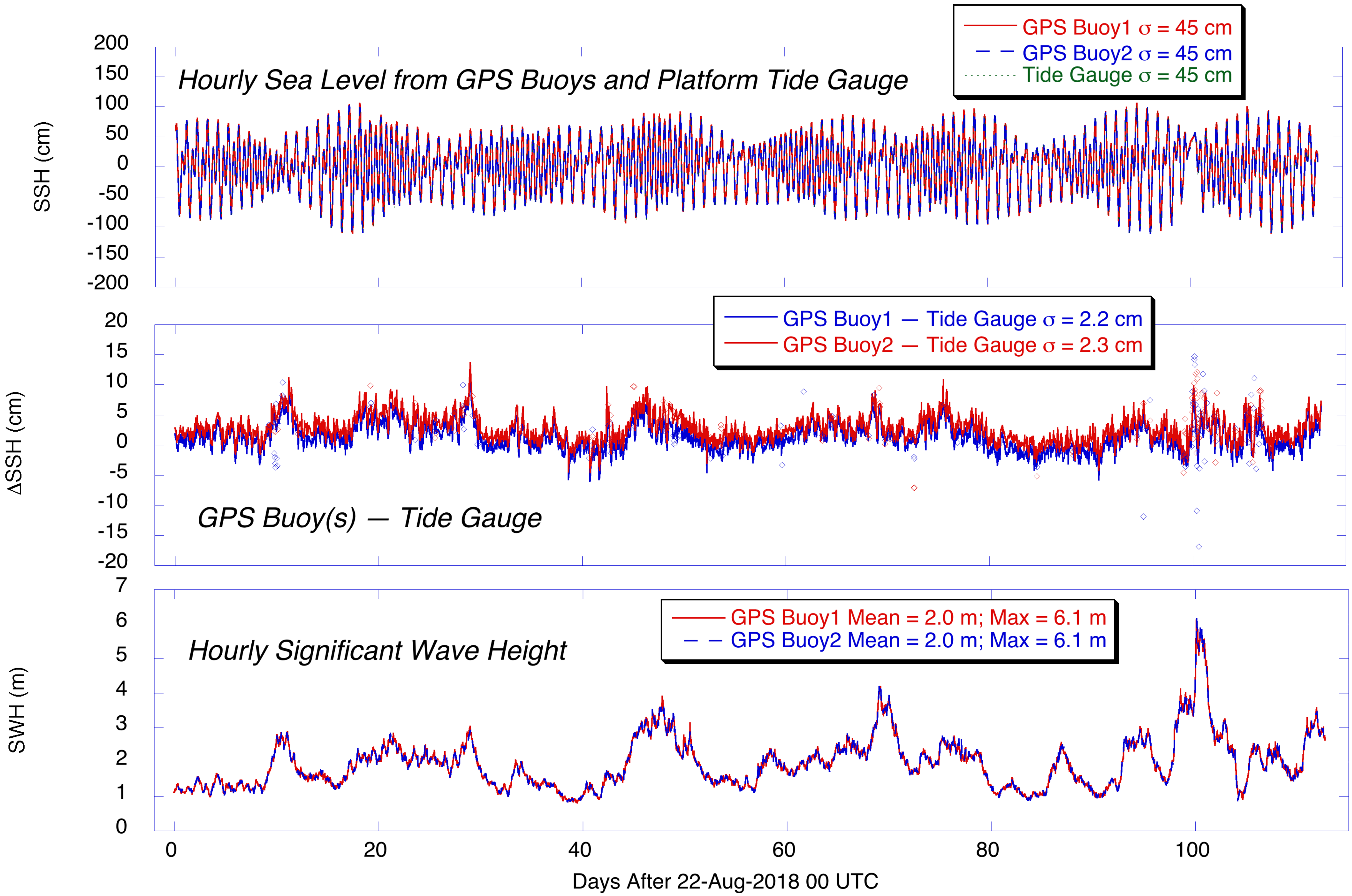


Joint NASA/NOAA Harvest Buoy Campaign
Aug. 2018 – Mar. 2019

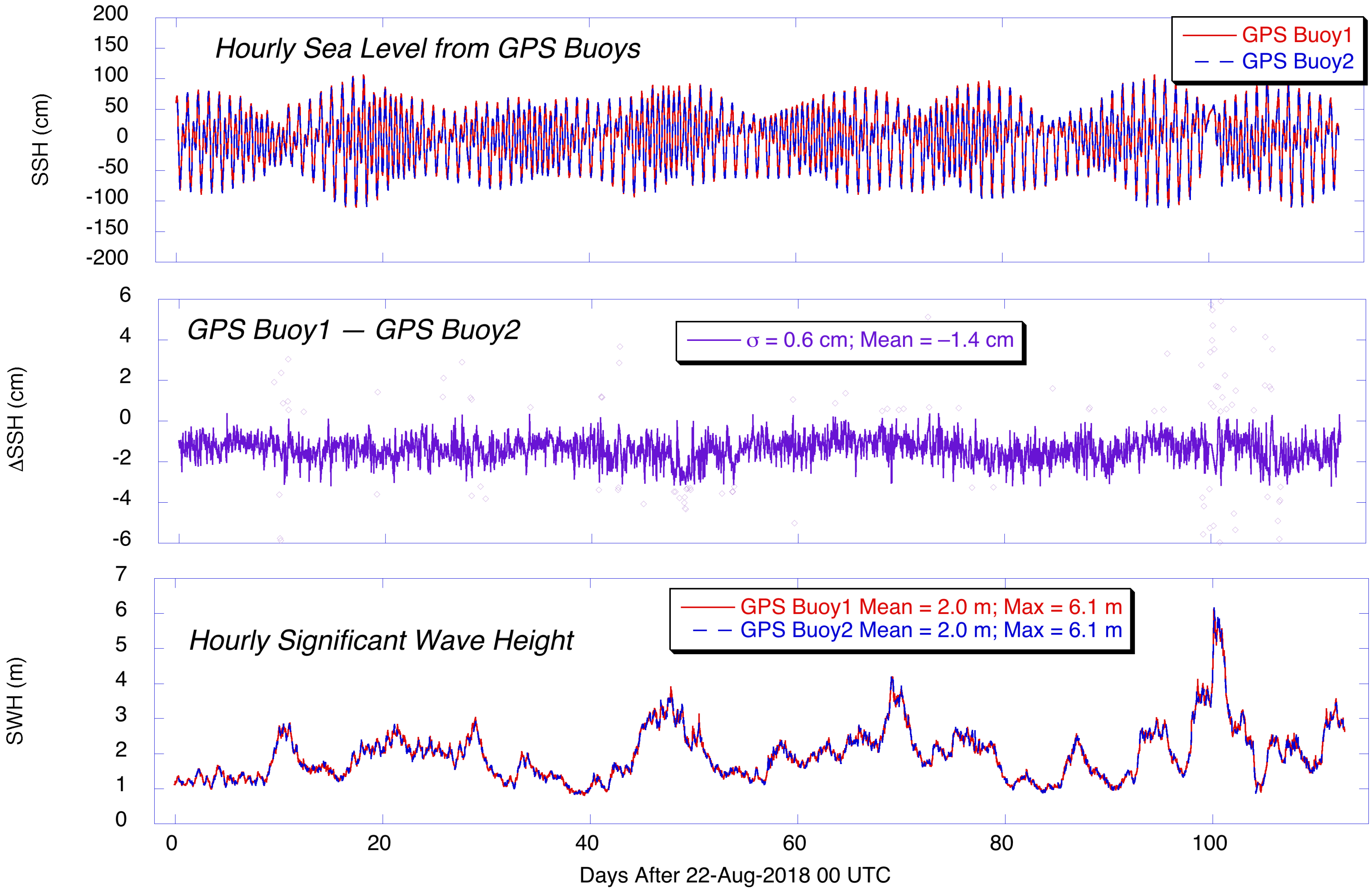
- Main goal: examine potential of precision GPS buoy systems to replace NASA Harvest verification site.
  - Risk reduction exercise for Jason-3 and Sentinel-6.
  - Anticipates possible platform loss or abandonment.
  - Buoys close to platform (~1.5 km) to support comparisons with platform tide gauges 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: Platform Tide Gauge vs. GPS Buoys



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



Summary

- **Preliminary results from GPS buoy very promising.**
- **Comparisons with independent obs. suggest SSH accuracy close to 2 cm.**
  - Horizontal accuracies probably similar, but difficult to validate.
- **Accuracy of relative (between-buoy) SSH is < 1 cm.**
  - Quantifies impact of waves in averaging scheme (holds for SWH < 4 m).
  - Based on comparisons of two similarly-equipped buoys deployed 1.5 km apart.
  - Assumes sufficient averaging of 1-Hz data (~6 minutes to 1 hour).
- **System may provide model for an improved acoustic (GPS-A) observation system for seafloor geodesy.**
  - Enables accurate and continuous access to the global terrestrial reference frame.
  - Does not require dedicated (reference) GPS stations on land.
  - Capitalizes on a simple power-conserving design—single GPS and digital compass on compact buoy—to provide accurate positioning and orientation for hydrophone.
  - Reduces burden on costly, campaign-style ship-based GPS-A measurements.
  - Adaptable to other platforms (e.g., wavegliders, SailDrones).
- **System provides additional GPS-based observations of interest.**
  - Total electron content from GPS enables characterization of traveling ionospheric disturbances (from tsunamis and/or possible precursory events).
  - High-rate SSH enables direct detection of Tsunamis.

Some Challenges

- **Telemetry**
  - 1-Hz data desired for best sea-surface height and geolocation.
  - Current system transmits (via Iridium) raw GPS observations collected at 1-min rate.
  - High-rate (1-Hz) GPS data stored on board for recovery with buoy.
  - IridiumNEXT may enable 10X improvement in transmission throughput.
  - Additional data reduction/compression strategies under evaluation.
- **Power**
  - Current design uses batteries (no solar).
  - Preparing to test new batteries in 1-year deployment.
  - Solar panels for longer deployments.
- **Buoy orientation data**
  - Need to evaluate whether current system is adequate for positioning hydrophone relative to GPS antenna

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University of Tasmania: Christopher Watson

Scripps Institute of Oceanography: Fred Spiess (1919–2006)

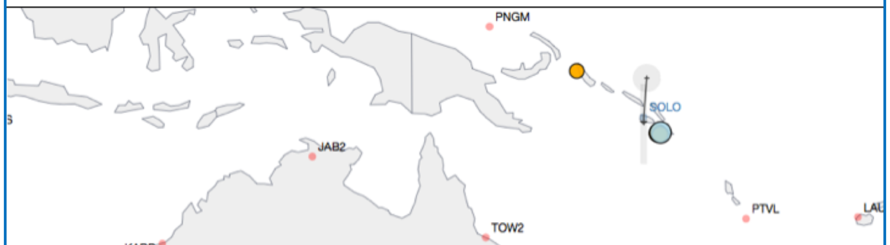
University FAF Munich: Günter Hein

GDGPS Real-Time Natural Hazard Monitoring

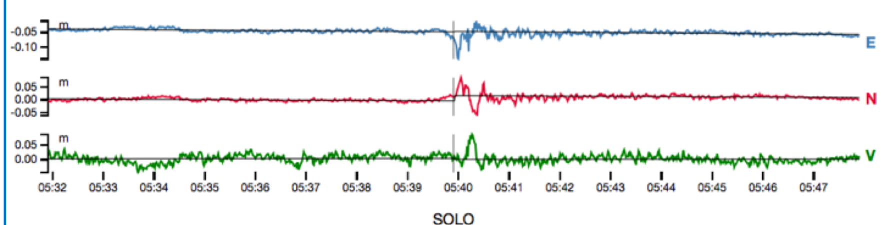
Earthquake displacement monitoring for 200+ sites

https://ga.gdgps.net

Solomon Island M7.8 earthquake, Dec 8, 2016



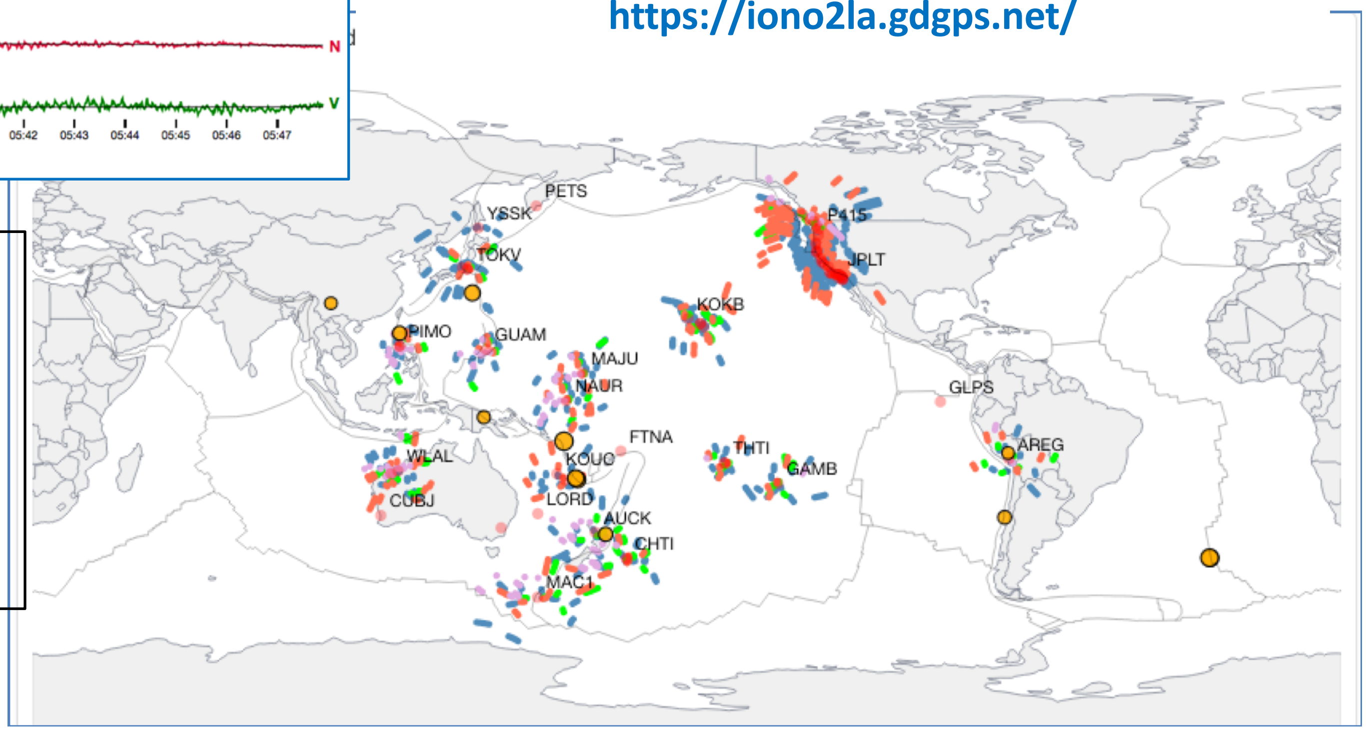
Station	Distance (km)	E (cm)	N (cm)	V (cm)	Significance
SOLO	204	0.16 ± 0.69	2.03 ± 0.75	−0.36 ± 2.04	75% (EN); 12% (V)



Real-Time detection of tsunami-driven ionospheric disturbances with GNSS ground tracking

(Savastano et al., Nature, 2017)

https://iono2la.gdgps.net/



RT iono tracks (past 20 min):
- GPS (MEO)
- Galileo (MEO)
- GLONASS (MEO)
- BeiDou (MEO+GEO+IGSO)

USGS EQ feed (past day):
- M4.5+ Earthquakes