The Long-Term Altimeter Calibration Record From the Harvest Platform

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Harvest Platform

- **NASA Prime Verification Site for High-Accuracy (Jason-class) Altimetry**
  - Open-ocean location along 10-d repeat track (by design)
  - 10-km off coast of central California
- **Continuous monitoring for over two decades**
  - 365 T/P overflights spanning 10 years (1992–2002)
  - 259 Jason-1 overflights spanning 7 years (2002–2009)
  - 194 Jason-2 overflights and counting… (2008–).
- **Experiment status**
  - New platform owner/operator
  - NOAA water level systems
    - Underwater service trips: 10/2012 and 08/2013
    - Orifice corrosion/comm. issues being addressed
    - Topside maintenance coming in early November
  - CU Lidar upgrade: 09/2011
- **New this year**
  - Additional Jason-2 (GDR-D) results.
  - Complete reprocessing of GPS time series (trop, height).
  - Regional calibrations for ENVISAT (Cancet et al., 2012).
  - First SARAL/AltiKa results
  - Successful retrieval of SWH from digital communications satellite signals (Shah et al., 2013)

Harvest Closure Analysis: Assumptions for Altimeter Leg

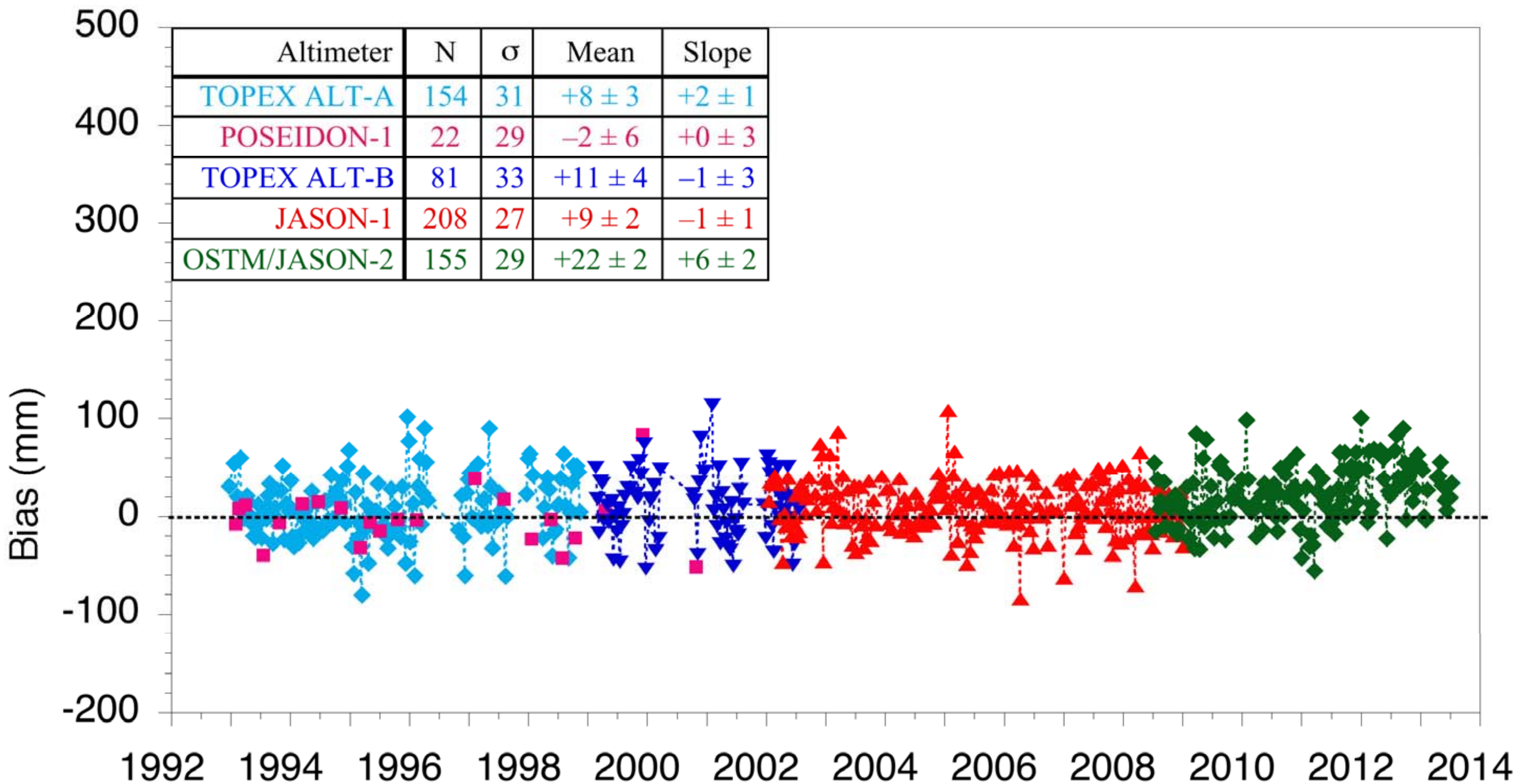
MODEL	NOMINAL			Jason-1 UPDATE
	TOPEX/Poseidon	Jason-1	OSTM/ Jason-2	Jason-1
Orbital Height	GSFC std0905 (Lemoine et al., 2010)	GDR-C	GDR-D	GDR-C
Altimeter Range	Ku (MGDR)			Corrected GDR-C*
Wet troposphere	Repro (Brown et al., 2009)			JMR EPD (Brown)
Dry troposphere	MGDR			GDR-C
Ionosphere	MGDR: Ku (ALT), DORIS (POS-1)			GDR-C
Sea-state bias	MGDR			MLE4 from J2

* Provisionally corrects for errors in antenna reference point and altimeter characterization (*Desjonquères and Picot, 2011*)

Harvest Long-Term Calibration Record

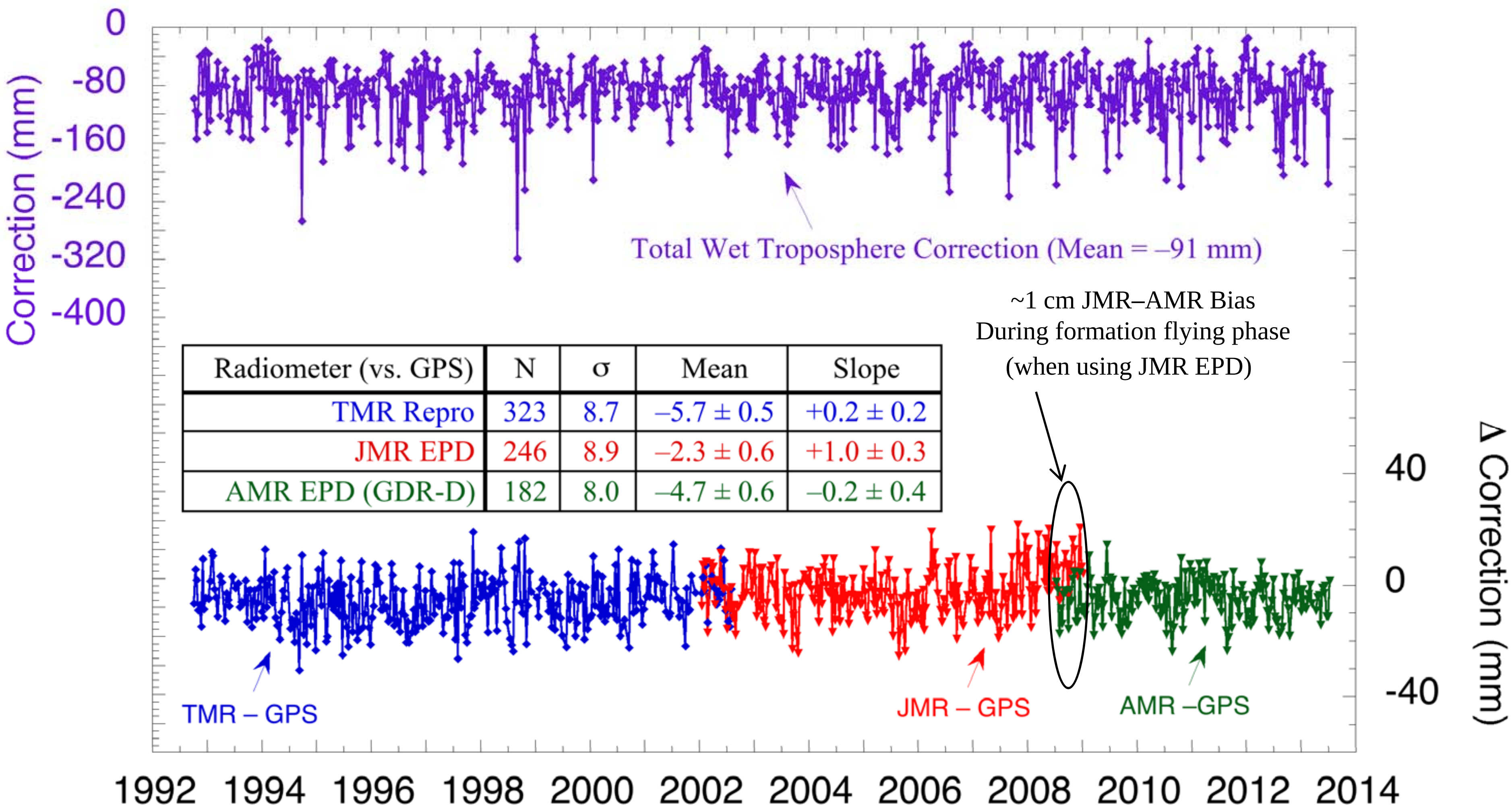
Update Jason-1 to GDR-D Standard

Includes most GDR-D standards: e.g., provisional range corrections for J1 (Desjonqueres and Picot, 2011); new MLE4 SSB model (based on Jason-2 data); Enhanced path delay correction for JMR (Brow et al.)



Altimeter	N	σ	Mean	Slope
TOPEX ALT-A	154	31	+8 ± 3	+2 ± 1
POSEIDON-1	22	29	–2 ± 6	+0 ± 3
TOPEX ALT-B	81	33	+11 ± 4	–1 ± 3
JASON-1	208	27	+9 ± 2	–1 ± 1
OSTM/JASON-2	155	29	+22 ± 2	+6 ± 2

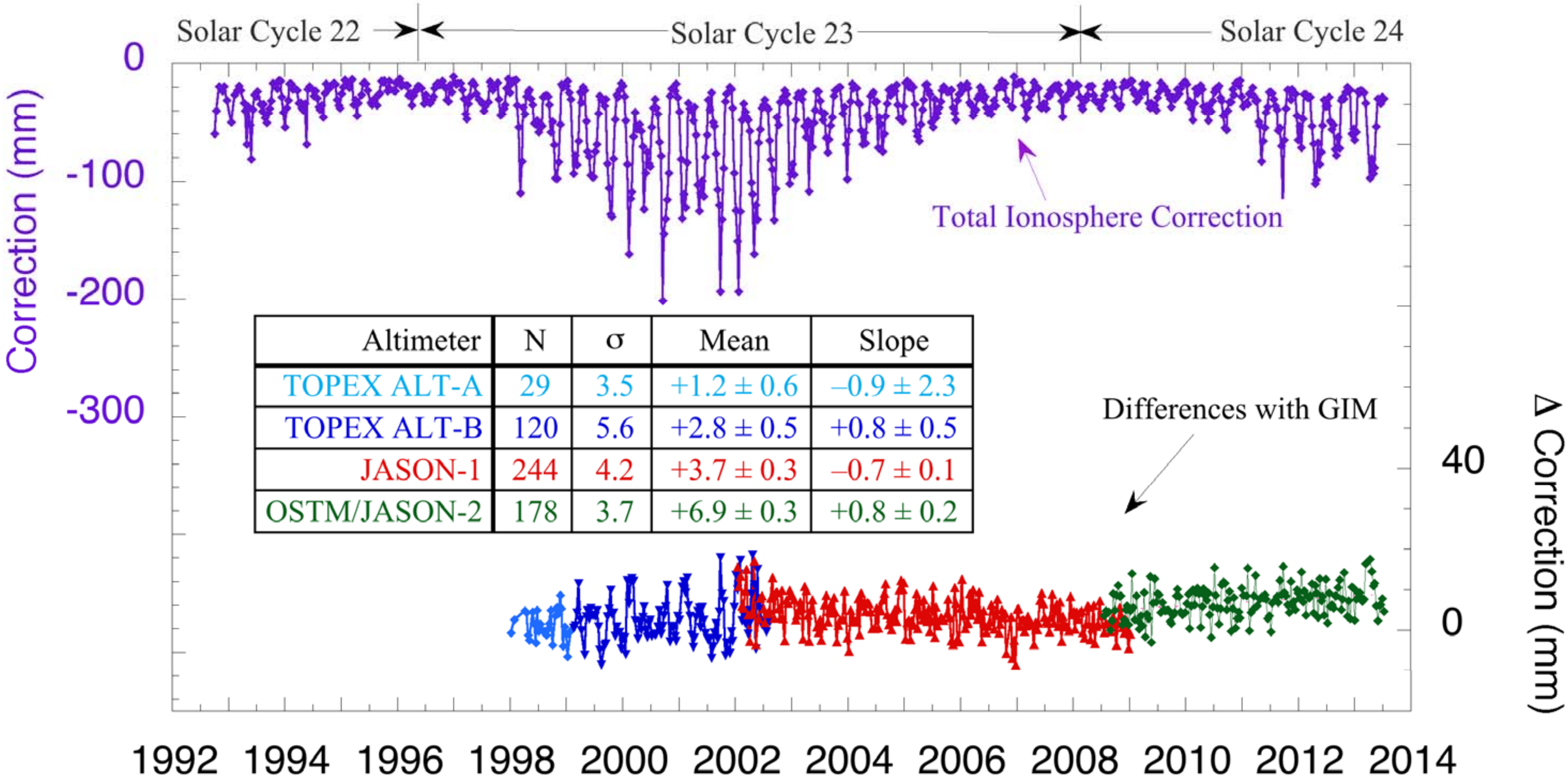
Wet Path Delay: Radiometer vs. GPS



Radiometer (vs. GPS)	N	σ	Mean	Slope
TMR Repro	323	8.7	–5.7 ± 0.5	+0.2 ± 0.2
JMR EPD	246	8.9	–2.3 ± 0.6	+1.0 ± 0.3
AMR EPD (GDR-D)	182	8.0	–4.7 ± 0.6	–0.2 ± 0.4

EPD correction (Brown) interpolated directly to platform TCA (vs. t–5 s for std. correction)

Harvest: Ku-Band Ionosphere Calibration Using JPL GPS Ionosphere Maps

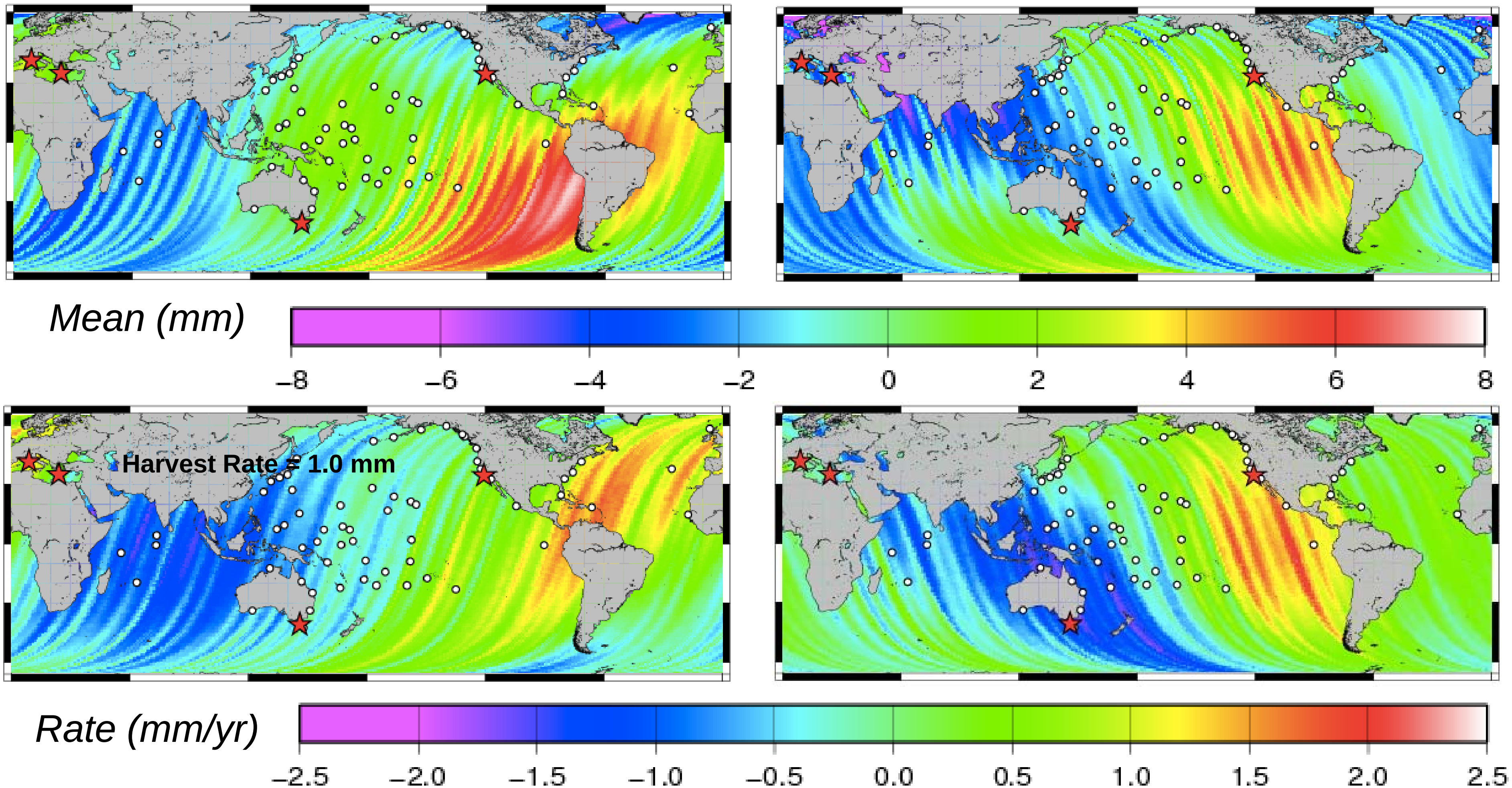


Altimeter	N	σ	Mean	Slope
TOPEX ALT-A	29	3.5	+1.2 ± 0.6	–0.9 ± 2.3
TOPEX ALT-B	120	5.6	+2.8 ± 0.5	+0.8 ± 0.5
JASON-1	244	4.2	+3.7 ± 0.3	–0.7 ± 0.1
OSTM/JASON-2	178	3.7	+6.9 ± 0.3	+0.8 ± 0.2

Jason-2 Radial Orbit Differences

GDR-D POE — JPL GPS

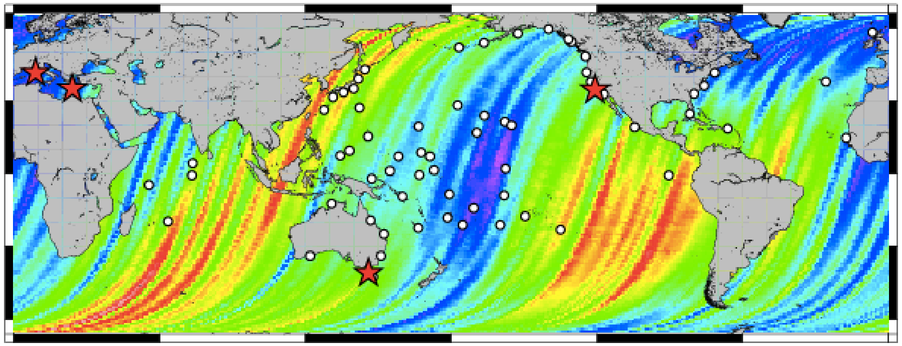
Ascending Passes Harvest Mean = 1.2 mm ***Descending Passes***



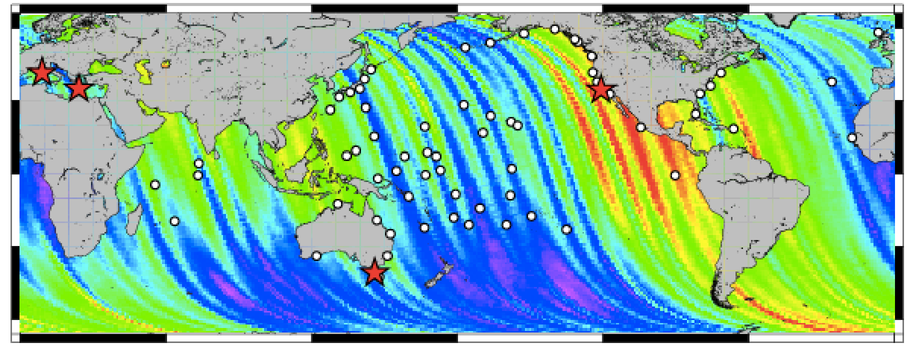
1) Red stars: dedicated calibration site; White circles: Tide gauges typically used for monitoring stability (Beckley et al., 2011)
2) Mean at Harvest = 1.2 mm (POE high). Rate at Harvest = 1.0 mm (POE higher in time)

Jason-2 Radial Orbit Differences
GDR-D POE — JPL GPS

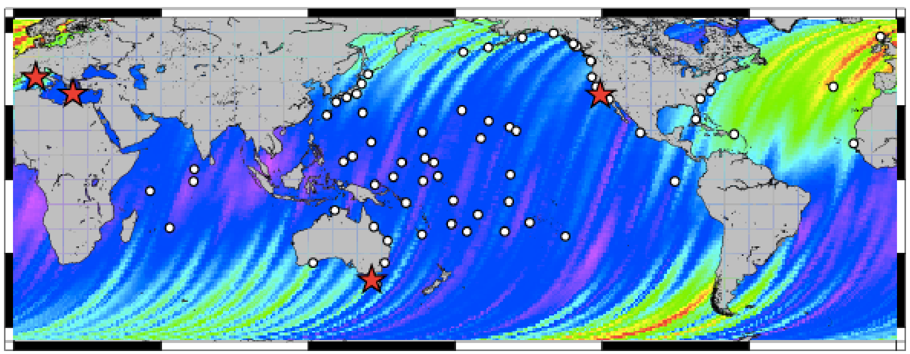
Ascending Passes

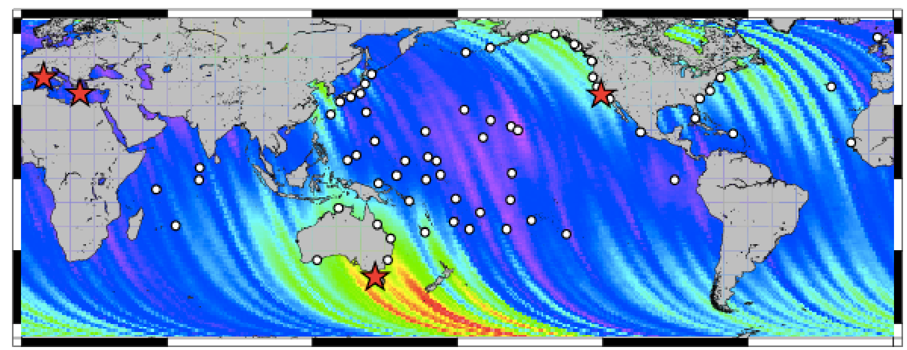


Descending Passes



Annual Amp. (mm)



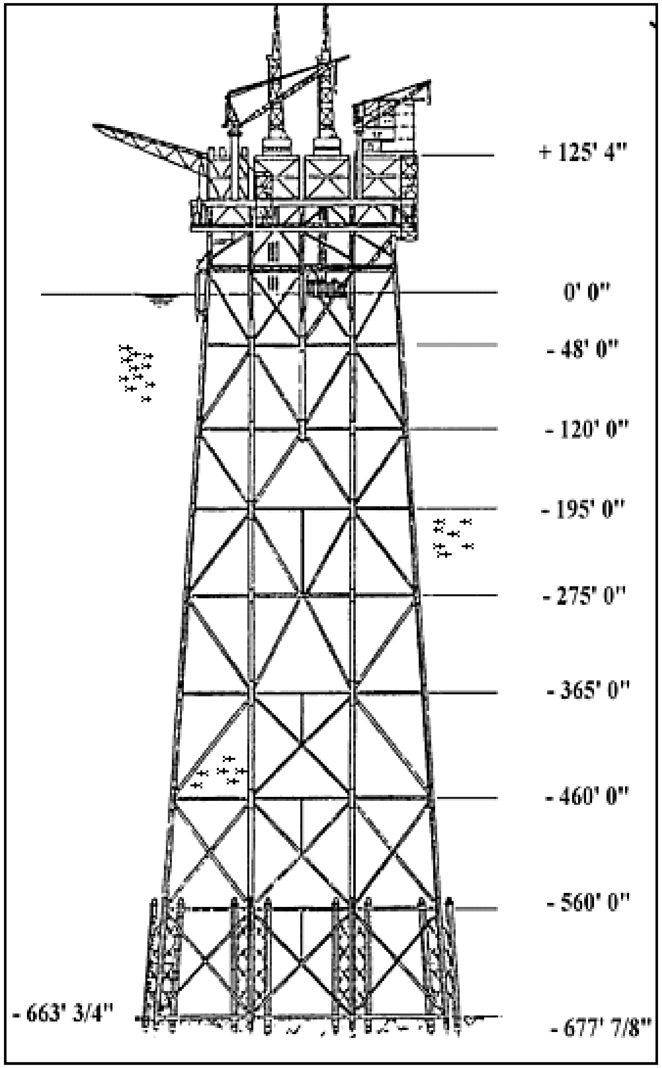


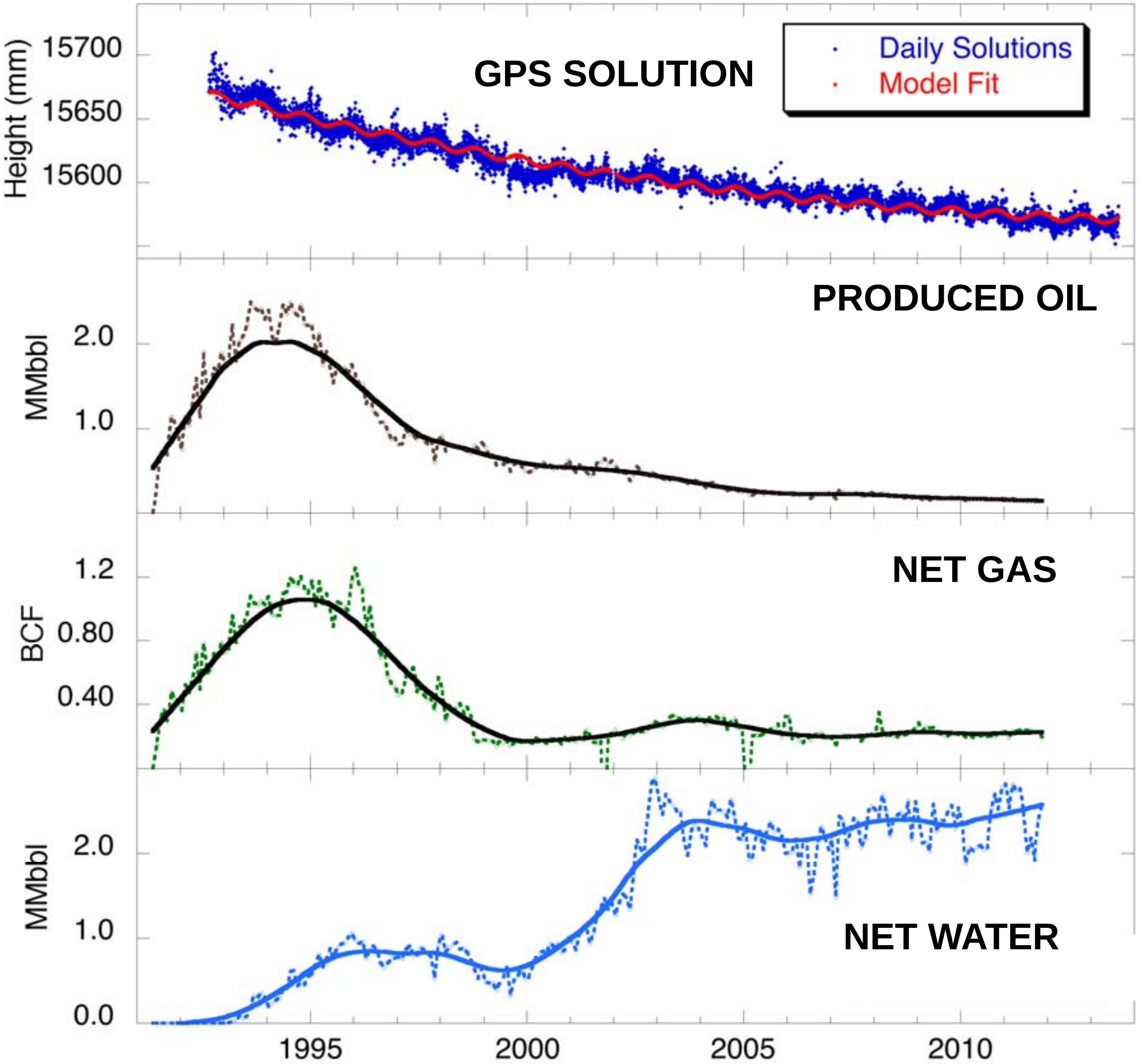
120-d Amp. (mm)

1) Red stars: dedicated calibration site; White circles: Tide gauges typically used for monitoring stability (Beckley et al., 2011)

Platform Harvest Geodetic Height From Two Decades of Continuous GPS Monitoring

Jet Propulsion Laboratory
California Institute of Technology



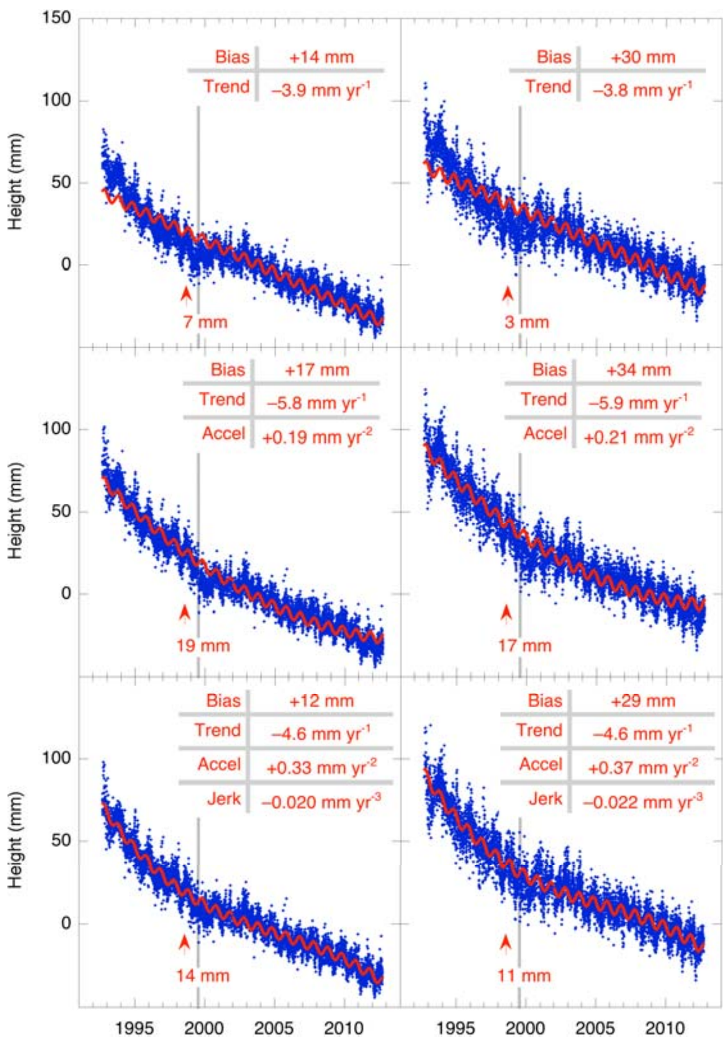


Production Statistics for Pt. Arguello Field from http://www.boem.gov

Uncertainty in Platform Vertical Motion

Jet Propulsion Laboratory
California Institute of Technology

- Uncertainties in platform height and vertical (seafloor) motion among limiting error sources.
- Recent analysis[1] develops error budget from competing GPS solutions & fit strategies.
- Overall error budget for SSH bias and drift now includes this systematic error source.



Altimeter	*Years*	*N*	*Bias (mm)*		
			$\sigma_{\bar{x}}$	σ_V	*Estimate*
ALT-A	1992–1999	154	3	14	+8 ± 14
Poseidon	1992–2000	22	6	14	−2 ± 15
ALT-B	1999–2002	81	4	14	+11 ± 15
Jason-1	2002–2009	208	2	15	+96 ± 15
Jason-2	2008–2013	155	2	15	+22 ± 15

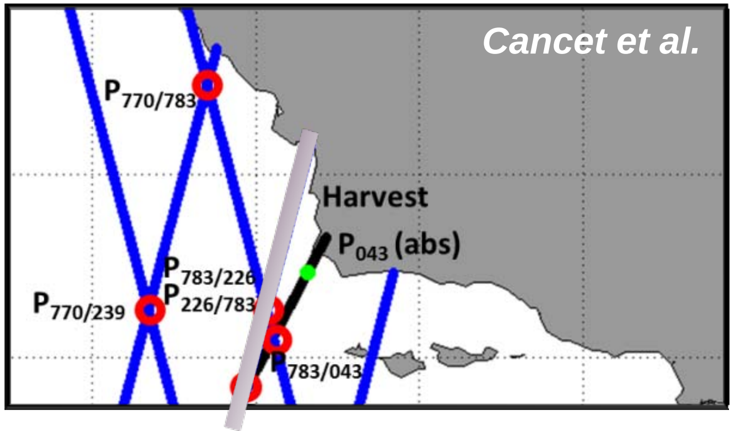
Altimeter	*Years*	*N*	*Drift (mm yr^{-1})*		
			$\sigma_{\bar{x}}$	σ_V	*Estimate*
ALT-A	1992–1999	154	1.4	2.8	+2.1 ± 3.1
Poseidon	1992–2000	22	2.7	2.5	+0.2 ± 3.7
ALT-B	1999–2002	81	3.3	1.1	−1.2 ± 3.5
Jason-1	2002–2009	208	0.9	0.6	−0.2 ± 1.1
Jason-2	2008–2013	155	1.6	2.0	+6.2 ± 2.6

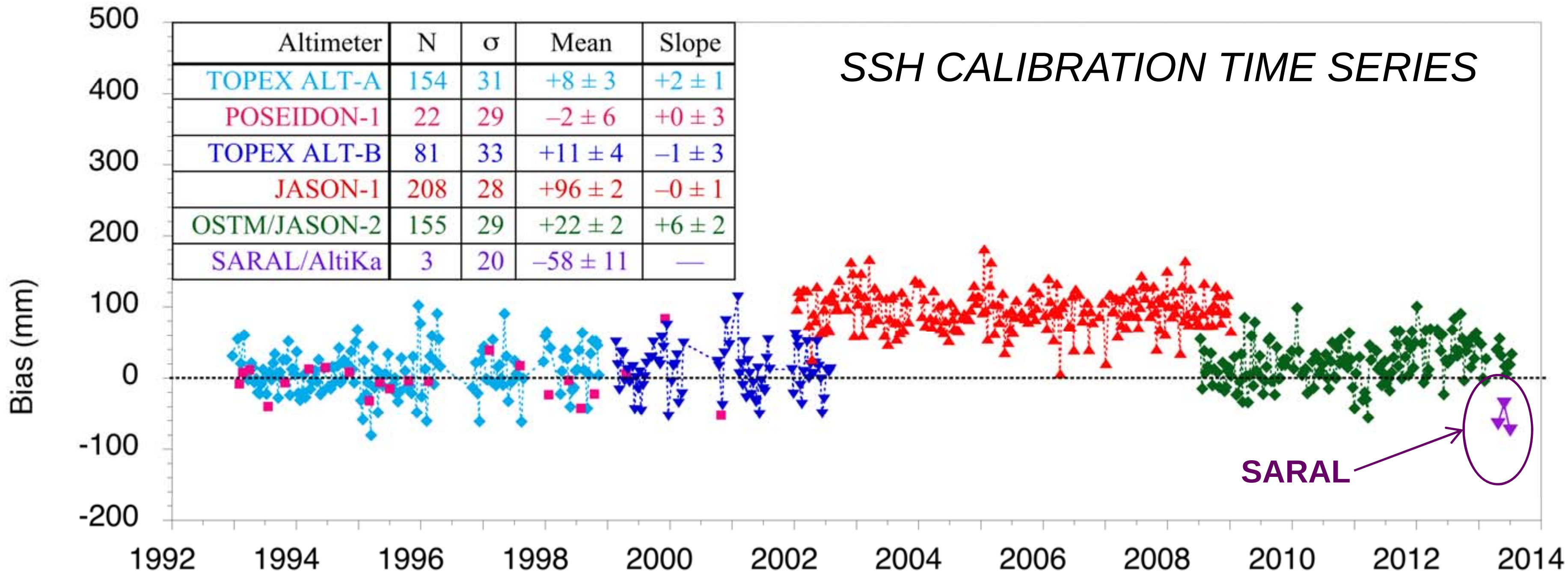
$\sigma_{\bar{x}}$: one standard error from linear regression to time series of SSH biases.
σ_V: estimated error from uncertainty in vertical location and motion of seafloor (Haines et al., 2013).
Estimate: estimate of bias or drift with total error (quadrature sum of $\sigma_{\bar{x}}$ and σ_V).

1 Haines et al., Adv. Space Res., Volume 51, Issue 8, 2013

Regional Calibration: First SARAL/AltiKa Results

- Regional calibration approach developed for Harvest by Cancet et al.
  - Use neighboring inter-satellite crossovers.
  - Successfully demonstrated for ENVISAT.
- For SARAL, direct (PCA) approach used.
  - Des. pass 226 only 18 km from platform (open ocean).
  - Gradient from CLS2011 MSS (GDR-D/T).





Altimeter	N	σ	Mean	Slope
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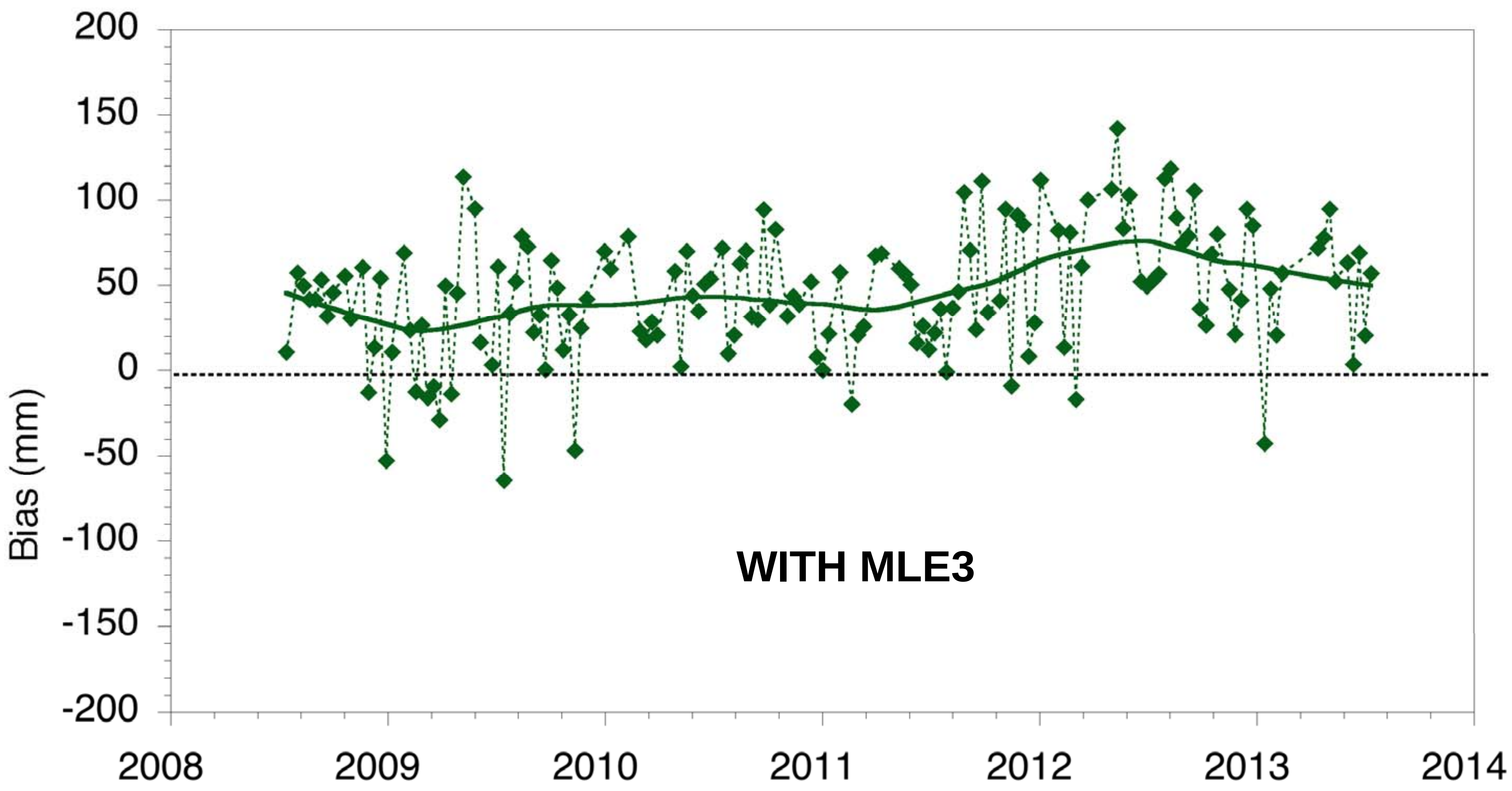
OSTM/JASON-2	155	29	+22 ± 2	+6 ± 2
SARAL/AltiKa	3	20	−58 ± 11	—

Summary

- **Current (GDR-D) Jason-2 SSH slightly biased** (low confidence).
  - +22 ± 15 mm, including error in platform vertical
- **Current (GDR-C) Jason-1 SSH biased high.**
  - +96 ± 15 mm, including systematic error from platform vertical.
  - Upgrades for next (GDR-D) product expected to reduce bias to 1-cm level.
- **TOPEX/Poseidon systems unbiased.** (Uncertainties include error in platform vertical.)
  - T/P ALT-B: +8 ± 15 mm
  - T/P ALT-A: +11 ± 16 mm
  - T/P POS: –2 ± 17 mm
- **First SARAL/AltiKa bias estimates from three open-ocean passes (PCA ~ 18 km).**
  - SSH bias of –58 ± 15 mm (formal error)
- **No signs of significant SSH instabilities for legacy missions**
  - Uncertainties in drift estimate range from 1 mm yr^{-1} (for Jason-1) to 3 mm yr^{-1} (for TOPEX ALT-A)
  - Small Jason-1 drift uncertainty due to long (7-yr) time series and good land-motion estimates.
  - Based on GPS retrievals, ~1 mm/yr drift persists in JMR EPD at Harvest.
- **Increasing Jason-2 SSH biases warrant further investigation.**
  - Drift of +6 ± 3 mm yr^{-1} for nominal (GDR-D) calibration time series (including land motion uncertainty).
  - Drift reduced by 1 mm yr^{-1} (to +5 ± 3 mm yr^{-1}) by using GPS-based reduced-dynamic orbits.
  - Developments on tide-gauge front may provide insight on systematic in-situ errors.
    - Upcoming (November) servicing mission
    - Thorough rescrub of past data from redundant (Bubbler) and lidar sensors.
  - Recent data (since mid-2012) suggest possible return of lower bias estimates.
  - Other potential altimetric sources should not be discounted.

Closeup of Jason-2 SSH Time Series



Evolution of Bias/Drift Estimates

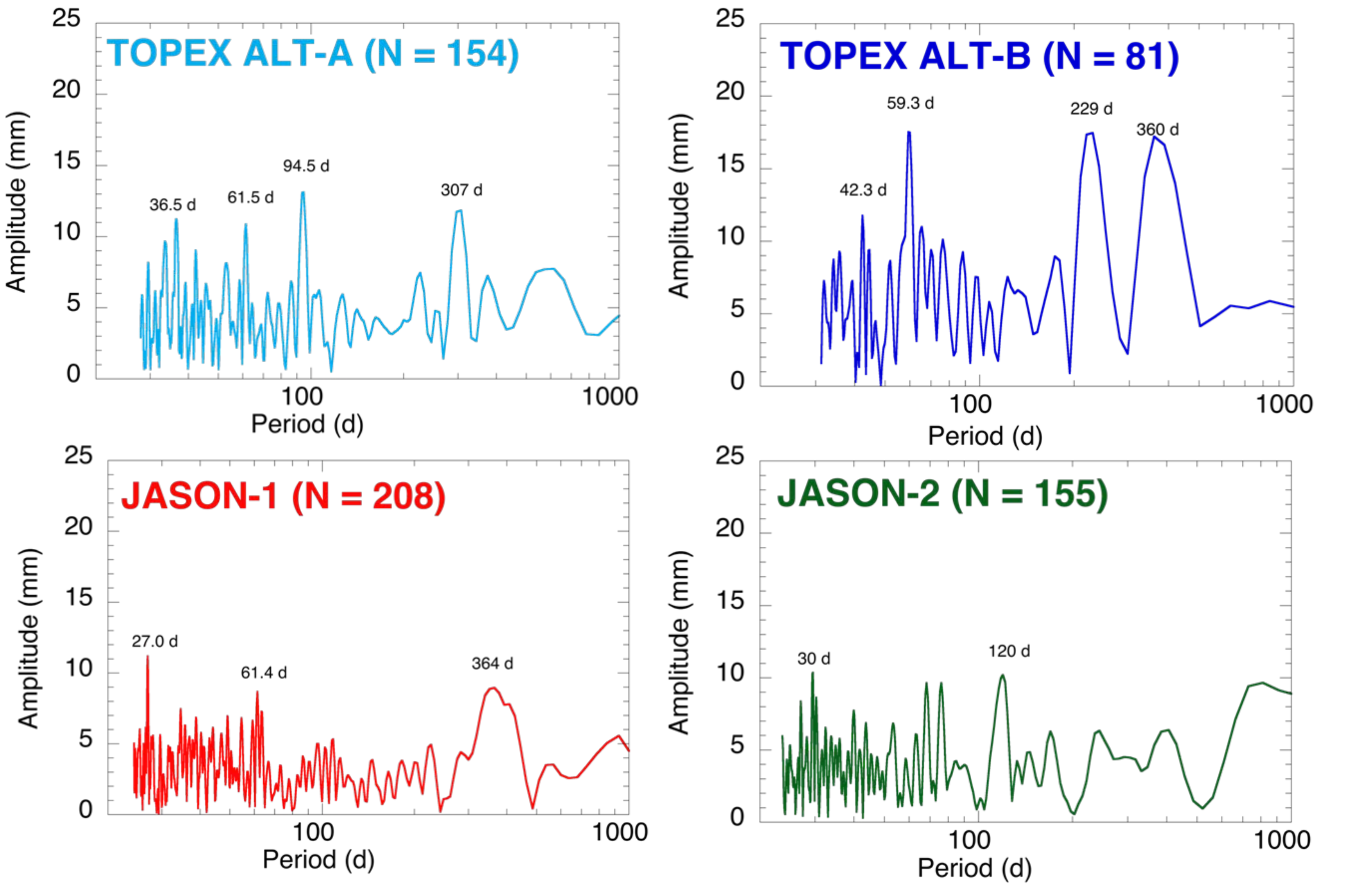
BIAS (mm)	Seattle 2009	*Mar. Geod.* 2010	Lisbon 2010	San Diego 2011	Venice 2012	Boulder 2013
Jason-2	+174	+178	+176	+176	+15	**+22**
Jason-1	+94	+94	+87	+89	+94	**+96**
ALT-B	+14	+14	+10	+14	+12	**+11**
Poseidon-1	–10	–10	–5	+6	+0	**–0**
ALT-A	+1	+1	+7	+18	+11	**+8**

DRIFT (mm/yr)	Seattle 2009	*Mar. Geod.* 2010	Lisbon 2010	San Diego 2011	Venice 2012	Boulder 2013
Jason-2	–5	+15	+8	+2	+5	**+6**
Jason-1	–2	–2	–2	–2	–1	**–0**
ALT-B	–1	–1	–3	–4	–2	**–1**
Poseidon-1	+3	+3	+1	–0	–0	**+0**
ALT-A	+5	+5	+4	+2	+2	**+2**

- Impact of improved models for platform subsidence (from GPS measurements) is significant.
- Tide-gauge errors also contribute

Backups

Periodograms of SSH Bias Time Series



Absolute Ku- and C-Band SSH Bias/Drift

- **Begin with uncorrected Ku- and C-Band Ranges**
  - Compensate for troposphere using standard (GDR) approach
  - Use GDR-D range for Jason-2 (Jason-1 range corrected for ARP and characterization).
- **Estimate SSH bias, drift and local SSB & iono. on each frequency simultaneously**
  - SSB model (local to Harvest) is a simple percentage of SWH from nearby buoy (“BM1”)
  - Ionosphere is a scaling of TECU from GIM (GPS-based): theoretical values are 2.2 (Ku) and 14.3 (C).

	Jason-1 Ku-Band	Jason-1 C-Band	Jason-2 Ku-Band	Jason-2 C-Band
SSH Bias (mm)	+25 ± 6	+10 ± 10	+24 ± 8	–20 ± 19
SSH Drift (mm/yr)	–2 ± 1	–2 ± 2	+4 ± 2	–18 ± 4
Local SSB (%)	4.0 ± 0.2	4.9 ± 0.3	3.7 ± 0.3	3.2 ± 0.7
Iono. (mm/TECU)	2.2 ± 0.2	13.2 ± 0.3	1.1 ± 0.3	11.1 ± 0.6
Number	207	203	155	149
Postfit σ (mm)	29	46	29	59

Lidar Leads to New Insight on Behavior of Primary (Bubbler) Tide Gauge

Standard Bubbler Correction

Parke and Gill (1995)

$$SSH_{Bubbler_{Corrected}} = SSH_{Bubbler} + 0.031 \times (SWH - 1.5)$$

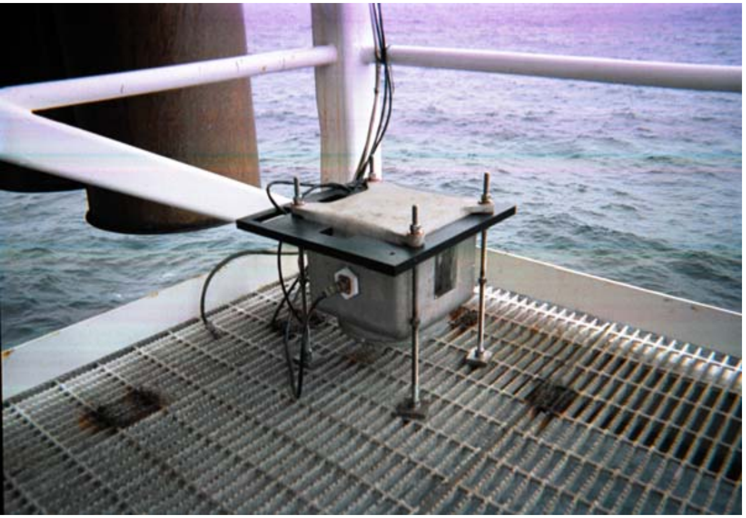
- For SWH > 1.5 m, else $SSH_{Bubbler_{Corrected}} = SSH_{Bubbler}$,

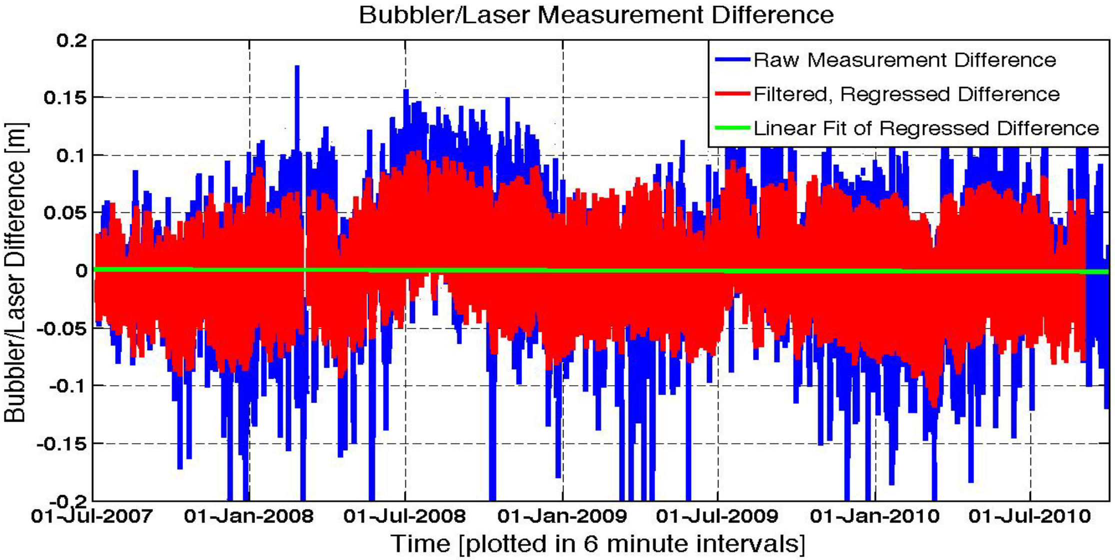
New Bubbler Correction

Washburn et al (2011)

$$\Delta SSH = SSH_{Bubbler} - SSH_{Laser} + SSH_{Correction}$$

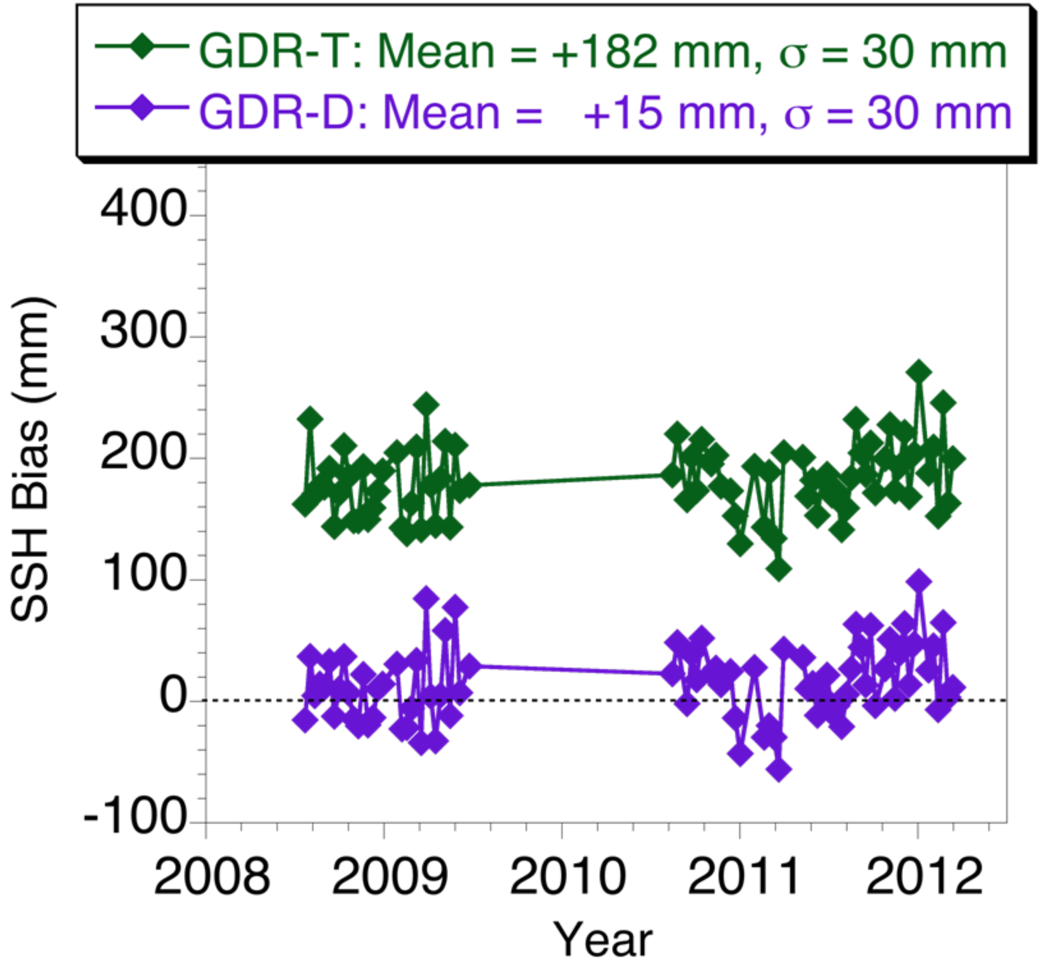
$$SSH_{Correction} = -B_0 + B_1 \times \left(\frac{1}{50\,\text{Hz average}} \right) + B_2 \times (SWH) + B_3 \times (\text{Wind Speed})$$





Harvest SSH Calibration Time Series: GDR-D vs. GDR-T

Comparison of GDR-D and GDR-T for Common Cycles (N = 80)



Source of ΔSSH Bias (GDR-T to GDR-D):

Parameter	Bias (mm)	σ (mm)
ΔRange_Ku*	–151	1
ΔSSB_Ku	–31	4
ΔIono_Ku	+6	1
ΔWet_Rad	+5	6
ΔOrbit	+4	5
TOTAL	**–167**	**11**

* ΔRange_C = –149 mm

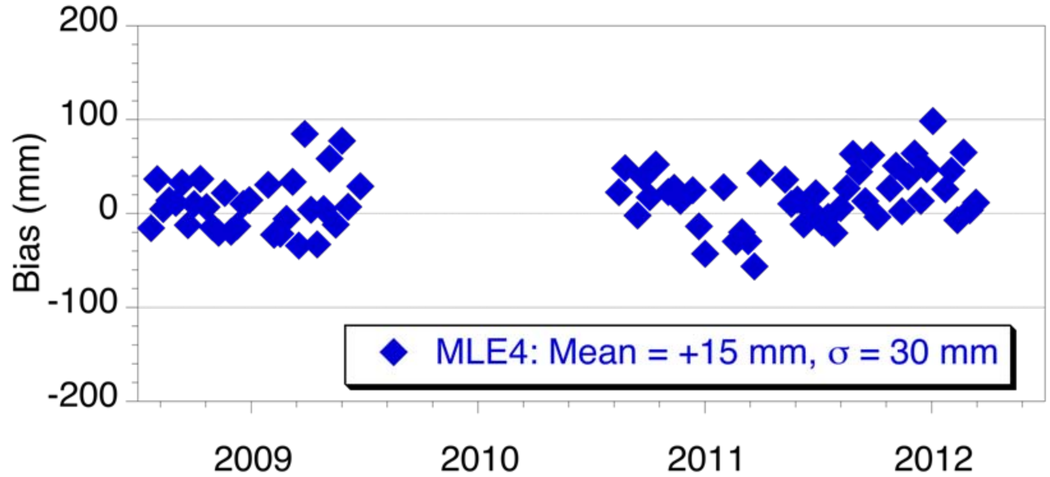
Alternative Retracking on Jason-2 GDR-D

- **GDR-D contains both MLE3 and MLE4 retracked data.**
  - MLE4 is nominal
- **MLE3 data increase scatter of SSH bias estimates**
  - Due mainly to Ku range
- **MLE3 data shift SSH bias upward**
  - Due mainly to SSB

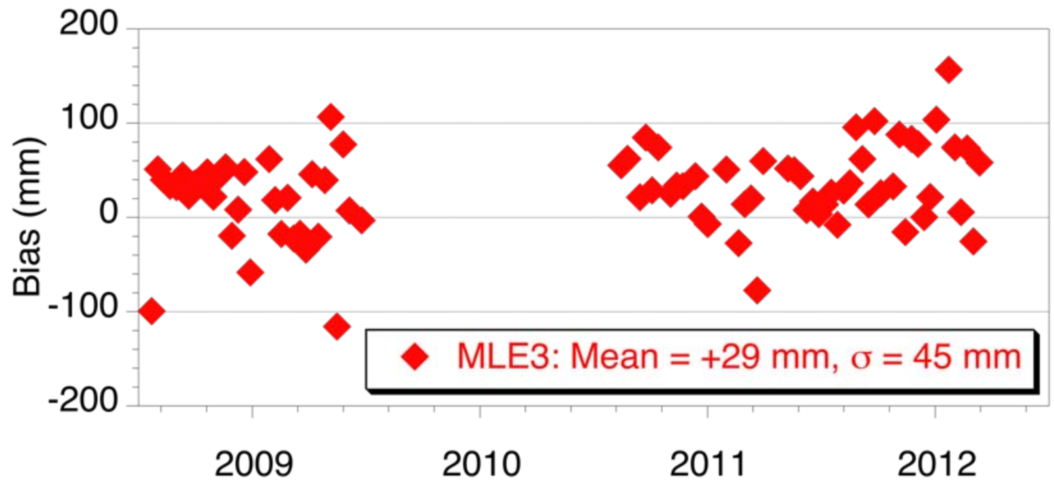
Source of ΔSSH Bias (MLE-4 to MLE-3):

Parameter	Bias (mm)	σ (mm)
ΔRange_Ku	–9	32
ΔSSB_Ku	+31	4
ΔIono_Ku	–6	6
TOTAL	**+16**	**35**

SSH Calibration Time Series with MLE4



SSH Calibration Time Series with MLE3



Harvest Calibration vs. GMSL Curve