The Harvest Altimeter Calibration Experiment: Recent Results

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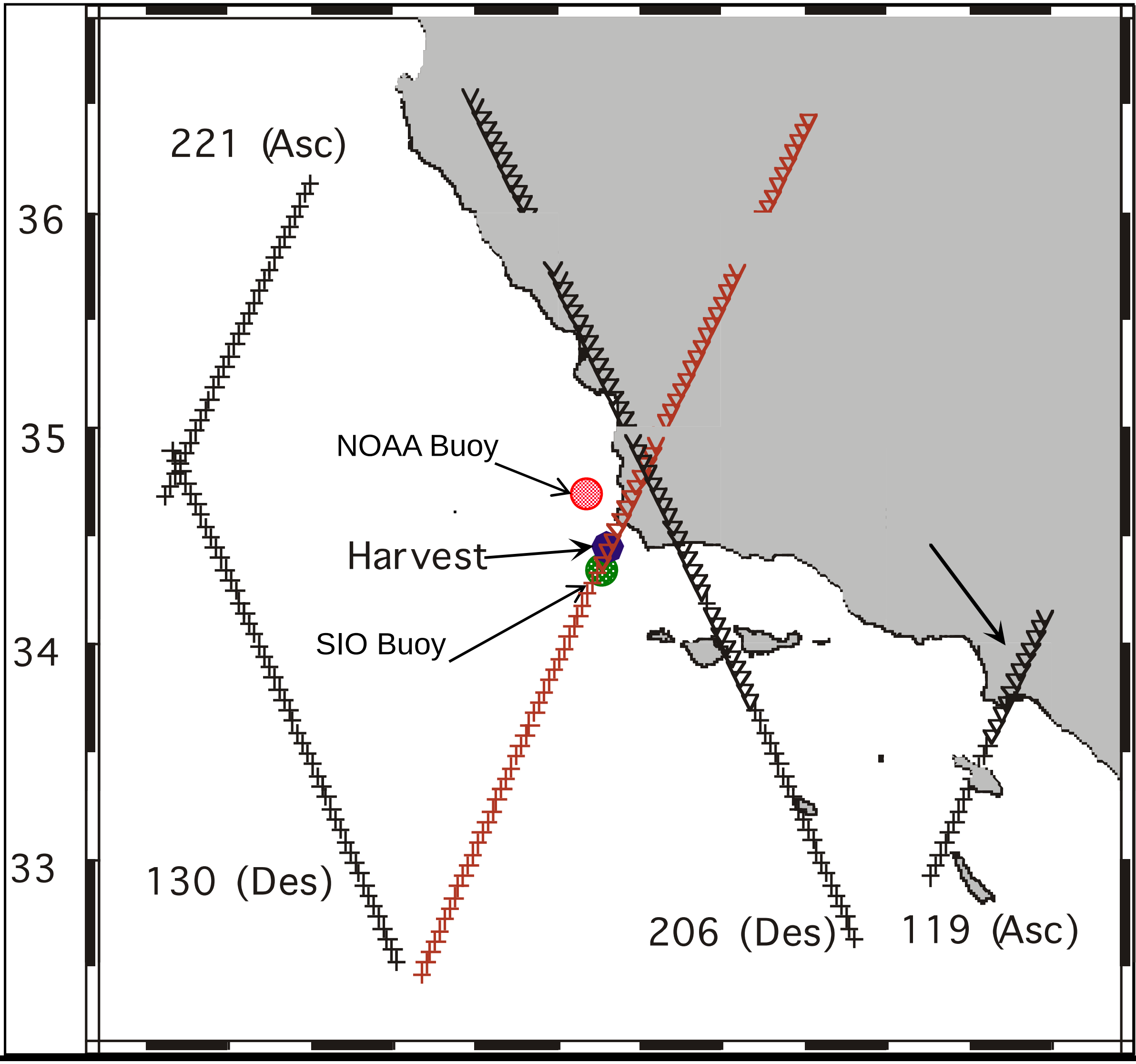
Harvest Platform

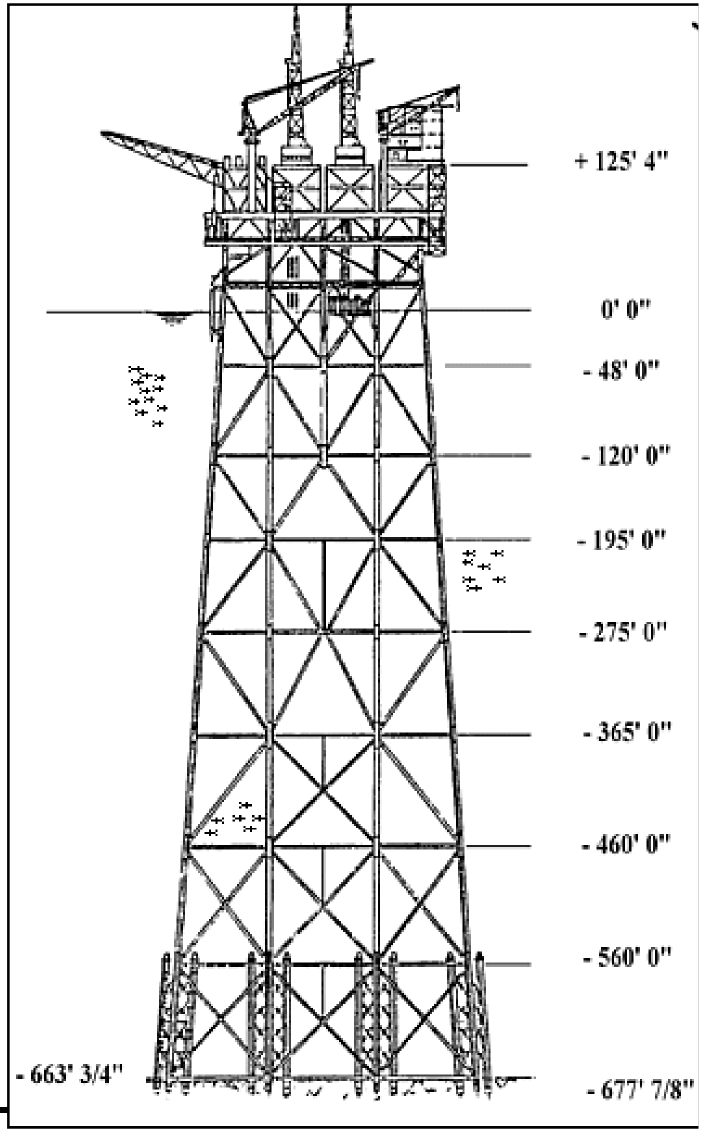
NASA Prime Verification Site for High-Accuracy (Jason-class) Altimetry: T/P (1992–2002), Jason-1 (2001–2009) and OSTM/Jason-2 (2008–).

Courtesy PXP

- **Open-ocean verification site located 10-km off coast of central California**
- **Ground track passes directly through this location by design (T/P heritage)**
- **Rich in-situ data set representing 19 years of continuous monitoring**
- **365 T/P overflights spanning 10 years**
  - 22 in formation with Jason-1 (2002)
  - Final overflight on August 13, 2002
- **259 Jason-1 overflights spanning 7 years**
  - 20 in formation with Jason-2 (2008–2009)
  - Final overflight on January 18, 2009
- **121 Jason-2 overflights and counting…**
  - Over three years of monitoring
- **Experiment operations status**
  - Underwater maintenance: 9/2011
  - CU Lidar upgrade: 9/2011
  - NOAA maintenance: 8/2010
  - Tide gauge outage: 4/2011(antenna repaired)

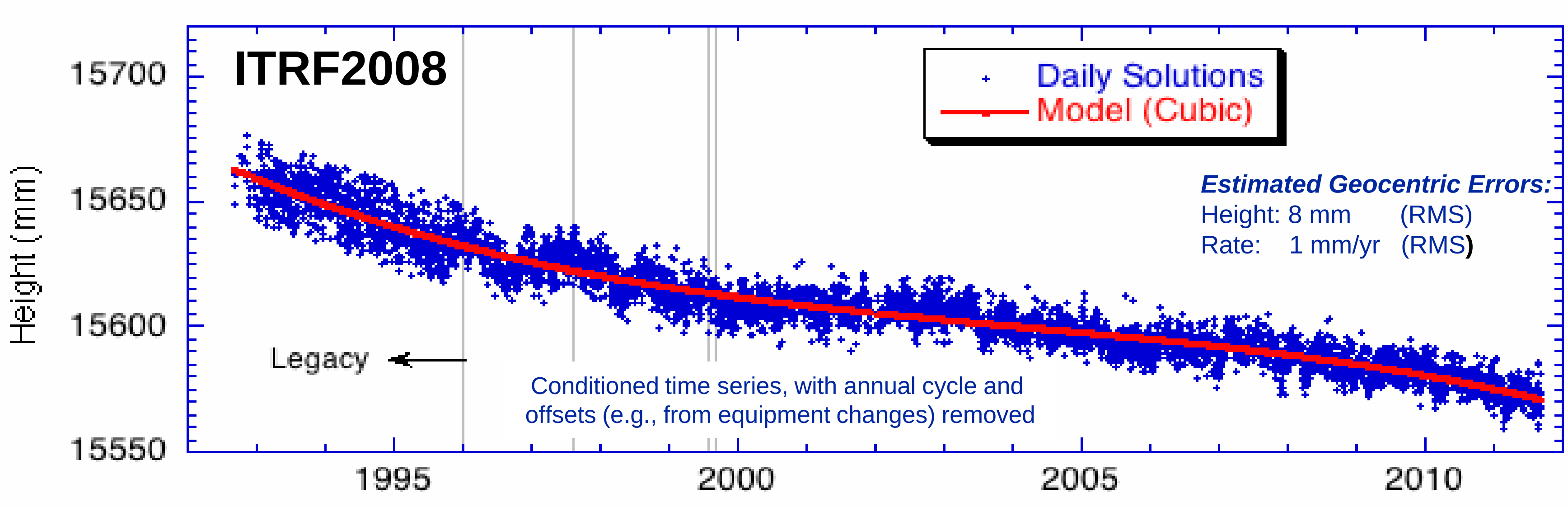
Map of Harvest Vicinity

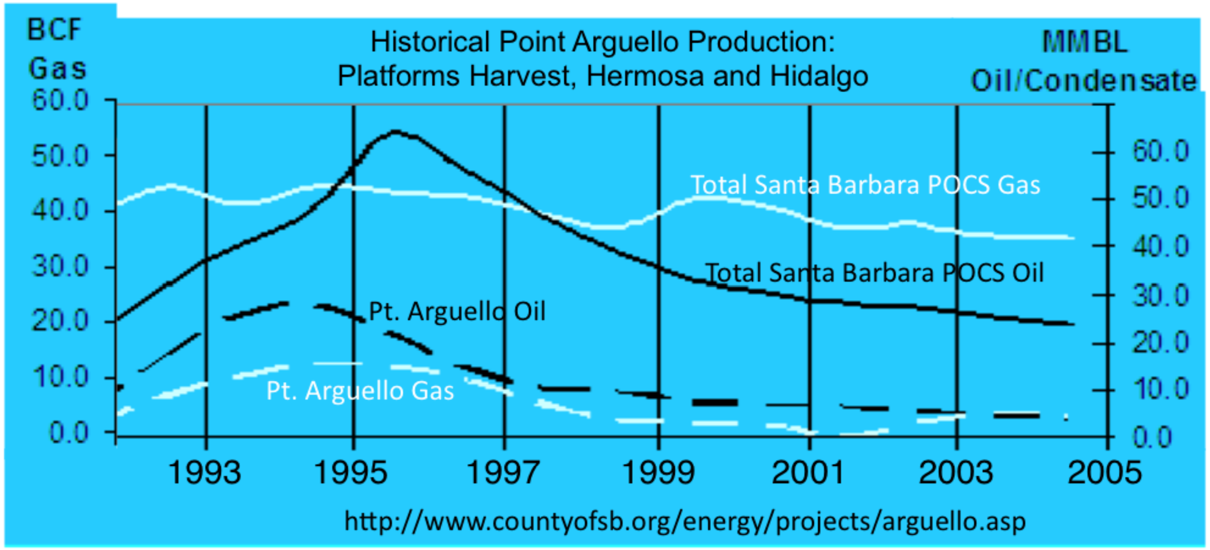




Courtesy PXP

Platform Harvest Geodetic Height From 19 Years of Continuous GPS Monitoring





Oil/Gas Production from 1992–2005

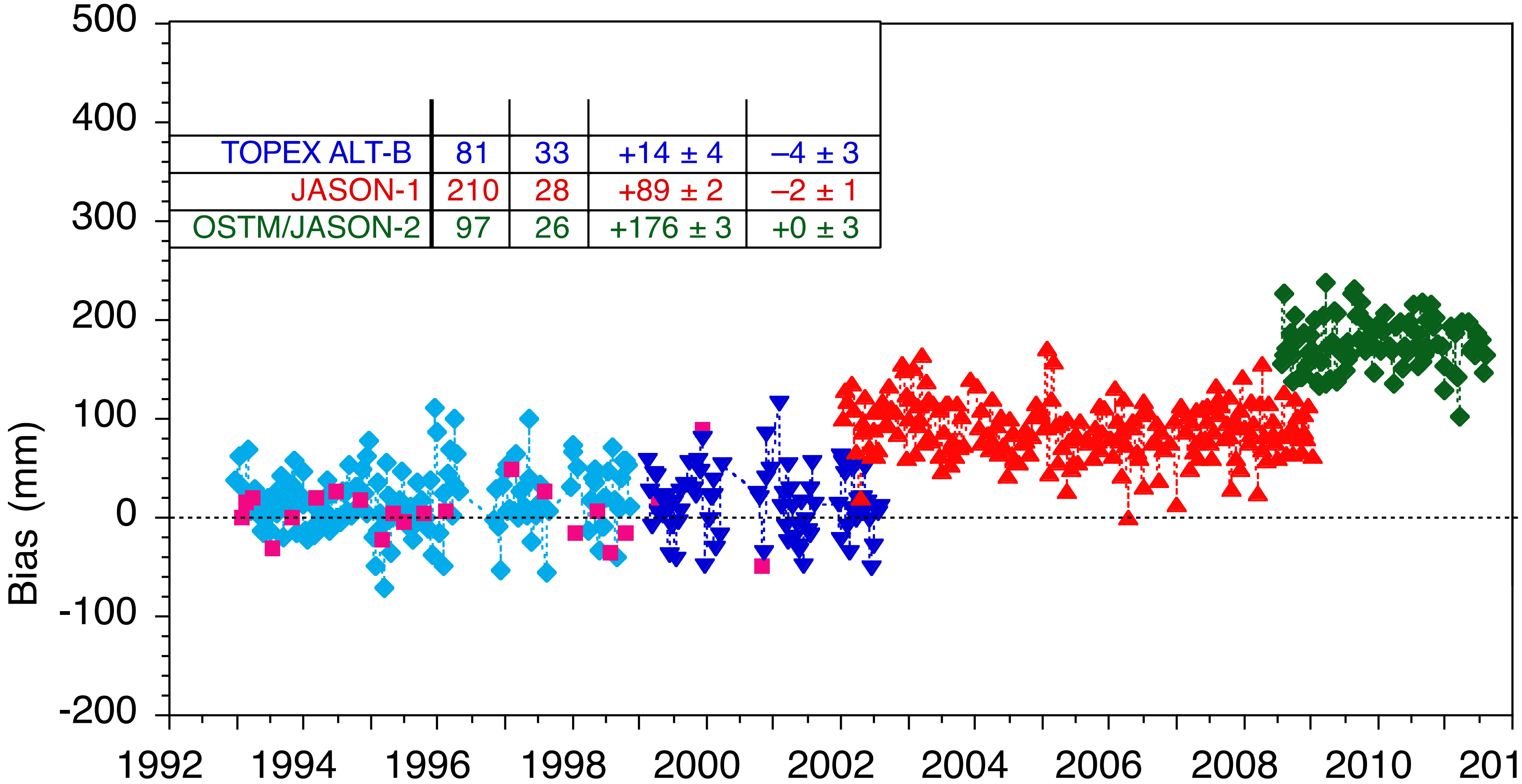
California Division of Oil, Gas and Geothermal Resources; Minerals Management Services

Harvest Closure Analysis: Assumptions for Altimeter Leg

Model	TOPEX/Poseidon	Jason-1	OSTM/ Jason-2
Orbital Height	GSFC std0905 (Lemoine et al., 2010)	GDR-C	T/GDR
Altimeter Range	Ku (MGDR)	Ku (GDR-C)	T/GDR
Wet troposphere	Repro from Brown et al. (2009)	GDR-C	T/GDR
Dry troposphere	MGDR	GDR-C	T/GDR
Ionosphere	MGDR: Ku (ALT), DORIS (POS-1)	GDR-C	T/GDR
Sea-state bias	MGDR	GDR-C	T/GDR

Nominal Time Series:

T/P: MGDR + reprocessed orbits (*Lemoine et al.*, 2010) and wet trop. (*Brown et al.*, 2009); **Jason-1:** GDR-C; **Jason-2**: GDR-T

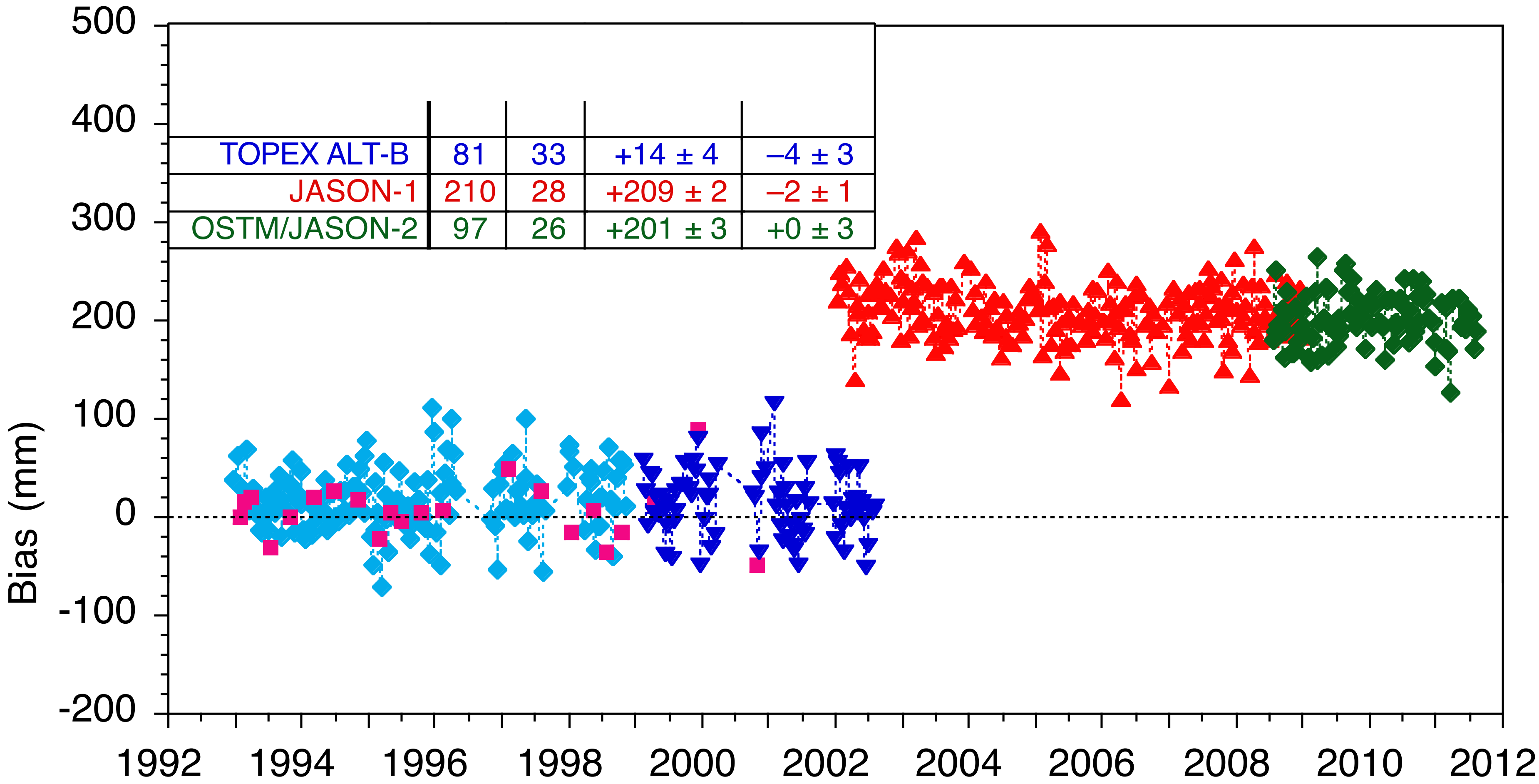


TOPEX ALT-B	81	33	+14 ± 4	–4 ± 3
JASON-1	210	28	+89 ± 2	–2 ± 1
OSTM/JASON-2	97	26	+176 ± 3	+0 ± 3

Harvest SSH Calibration Time Series

Update 1:

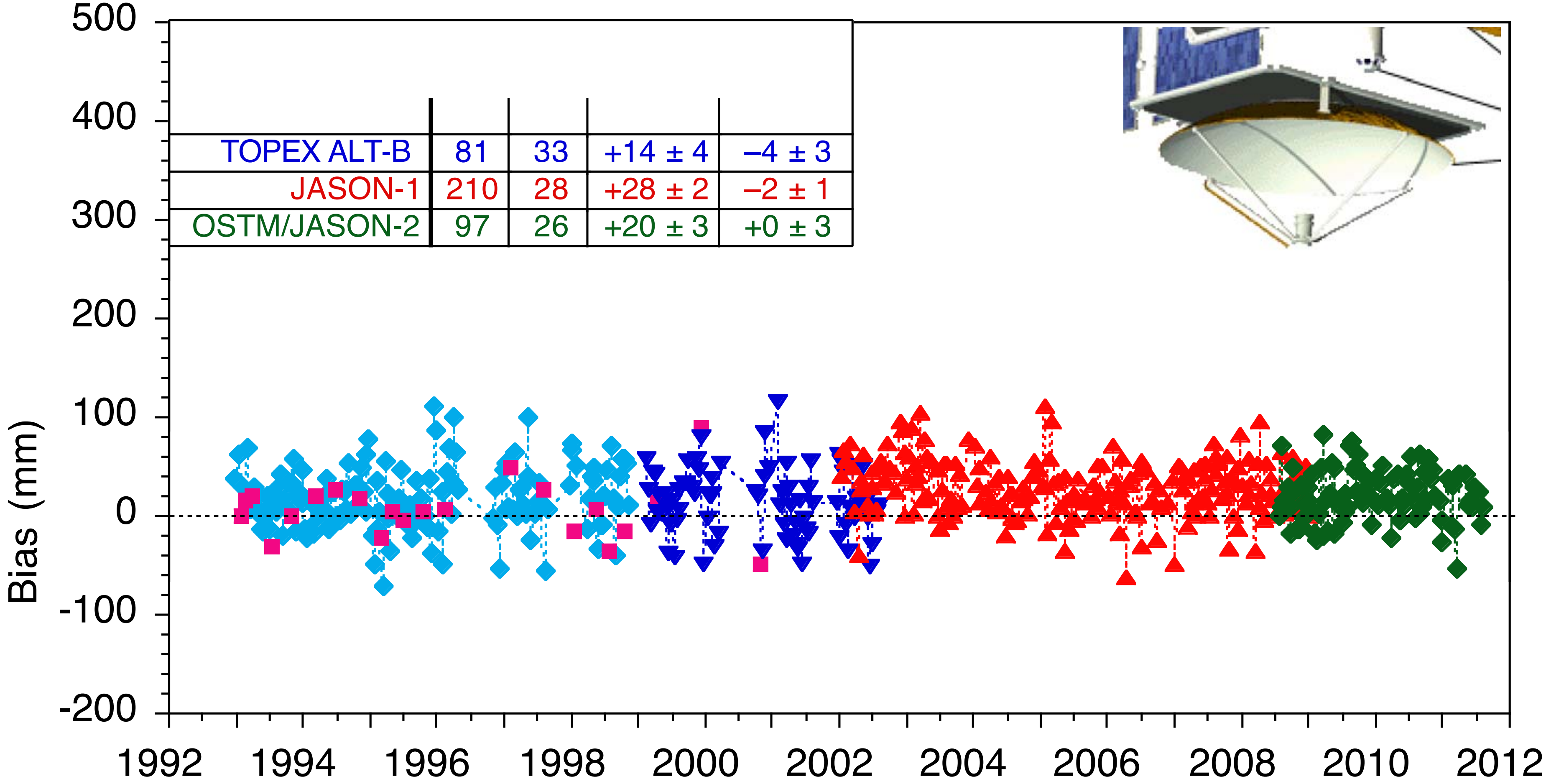
Correct Jason-1 and Jason-2 ranges for errors (biases) from altimeter characterization files (*Desjonquères et al.*, 2009)



Harvest SSH Calibration Time Series

Update 2:

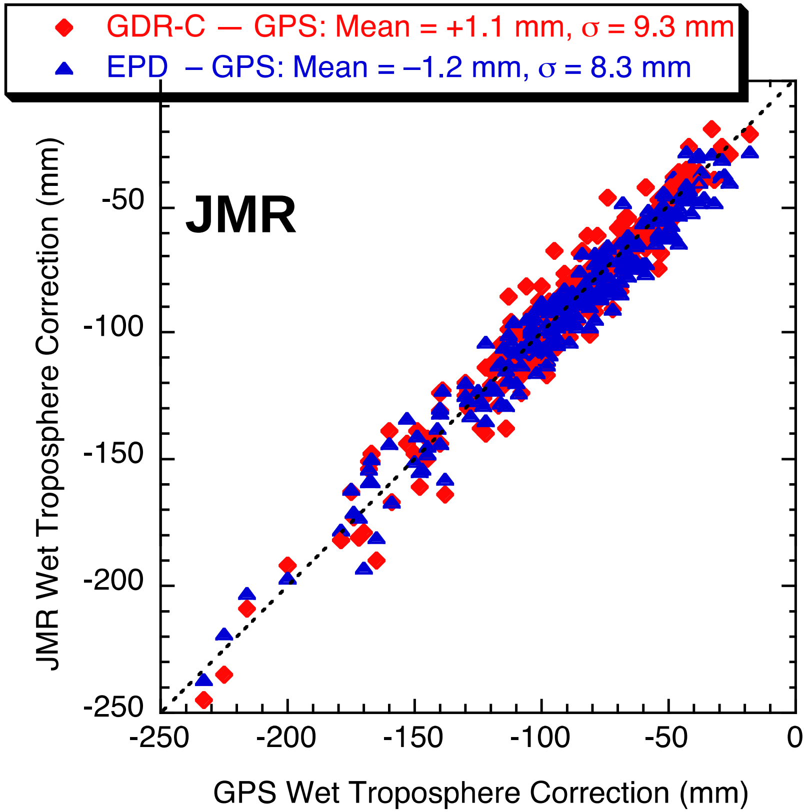
Correct Jason-1 and Jason-2 ranges due to inconsistent definition of antenna reference point (*Desjonquères et al.*, 2011)

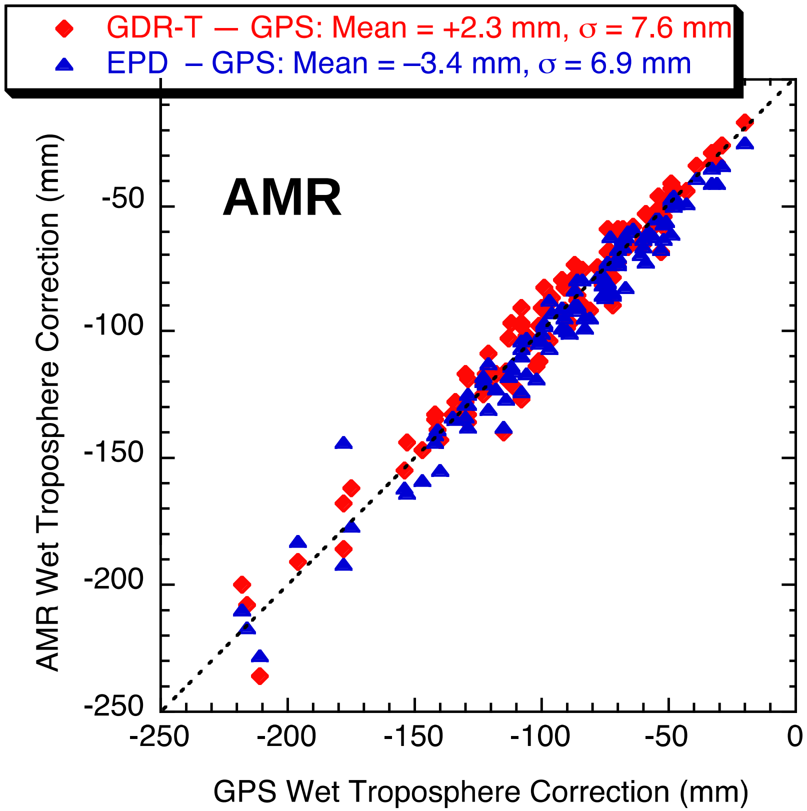


TOPEX ALT-B	81	33	+14 ± 4	–4 ± 3
JASON-1	210	28	+28 ± 2	–2 ± 1
OSTM/JASON-2	97	26	+20 ± 3	+0 ± 3

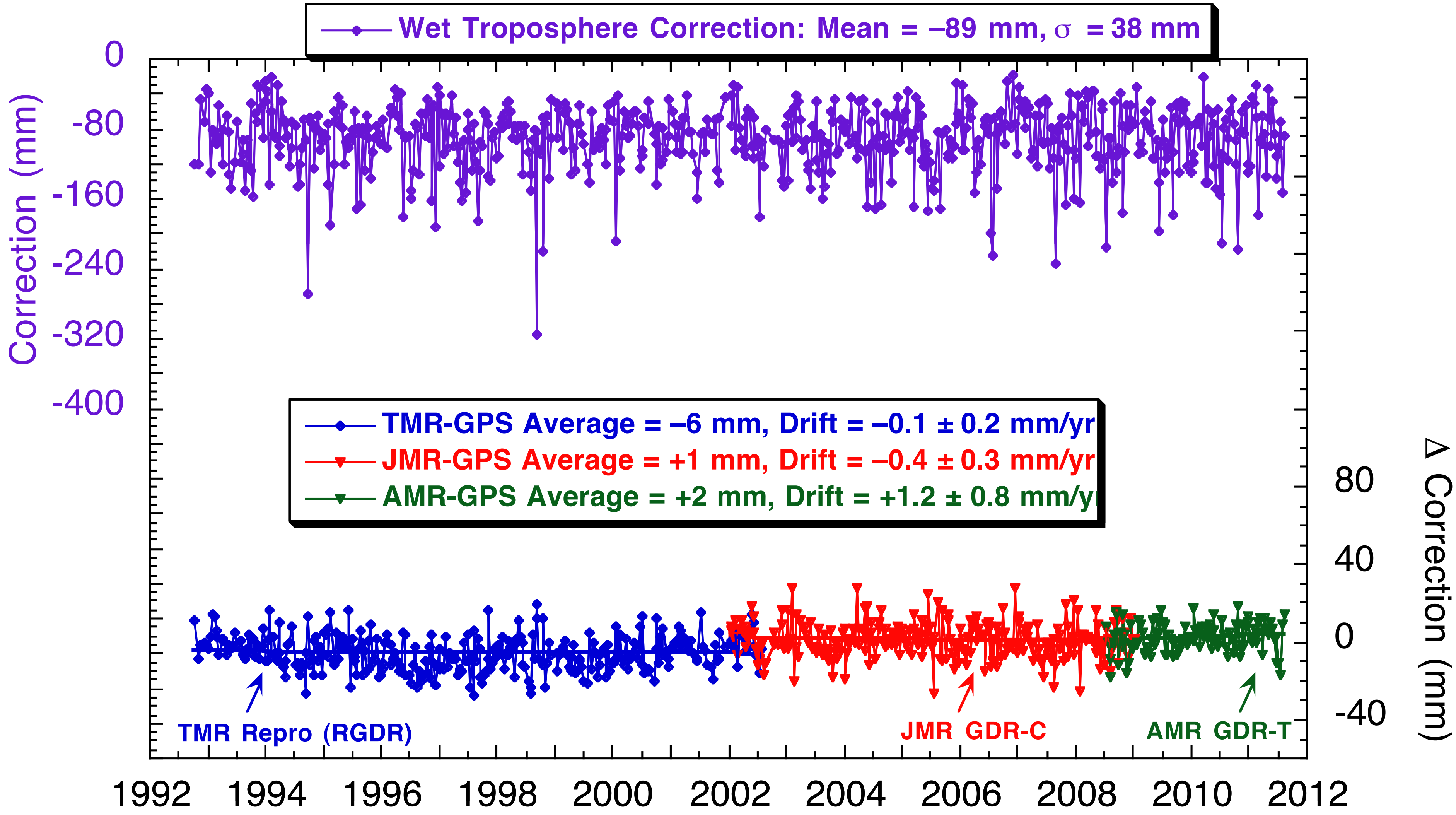
Radiometer Land Contamination: Performance of EPD Product at Harvest

- Standard GDR correction evaluated 5-s before platform overflight
- EPD evaluated at TCA
  - Improves agreement with GPS
  - Bias values from GPS may not be trustworthy at few-mm level (e.g., radome)





Wet Path Delay: Radiometer vs. GPS



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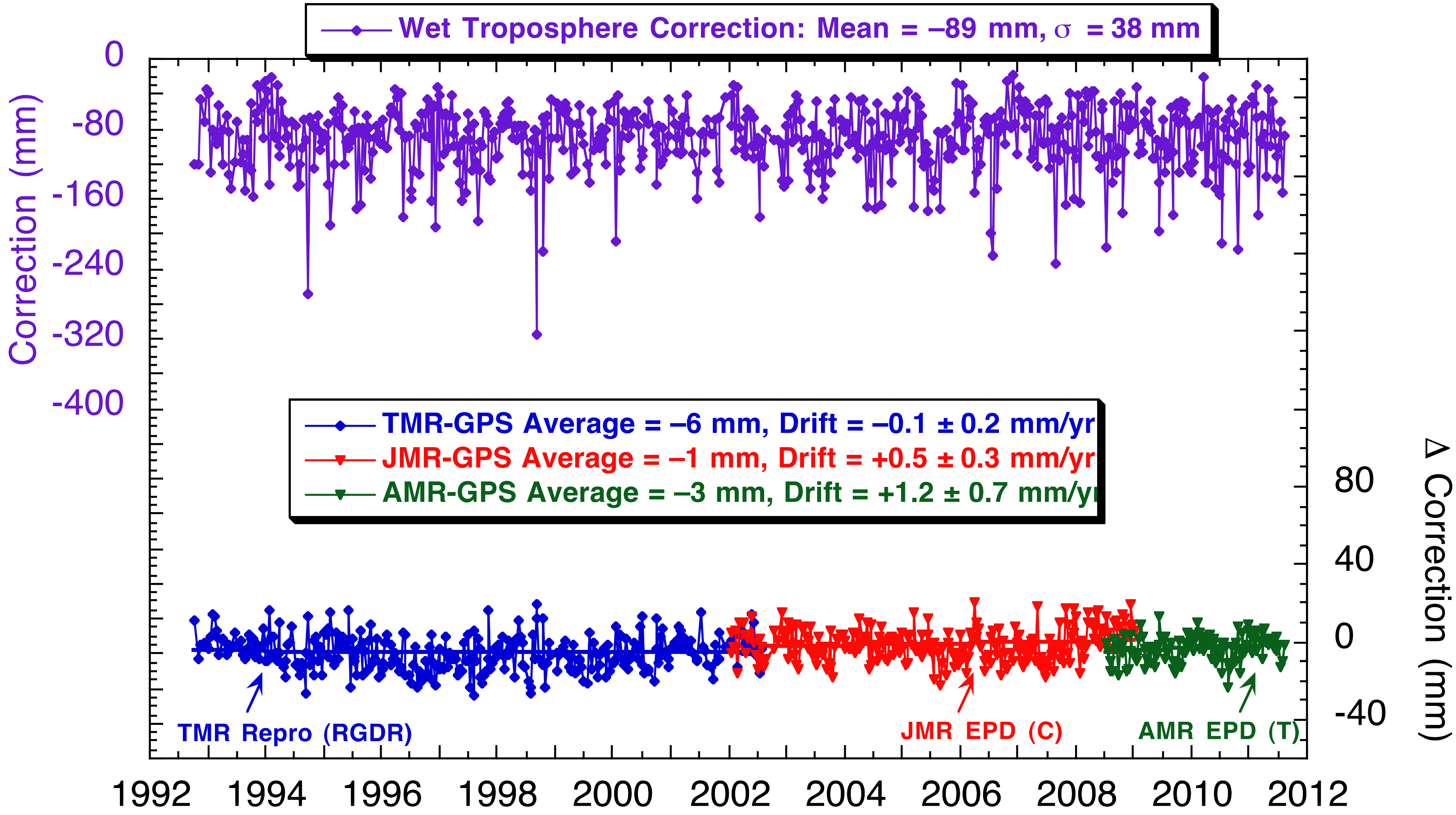
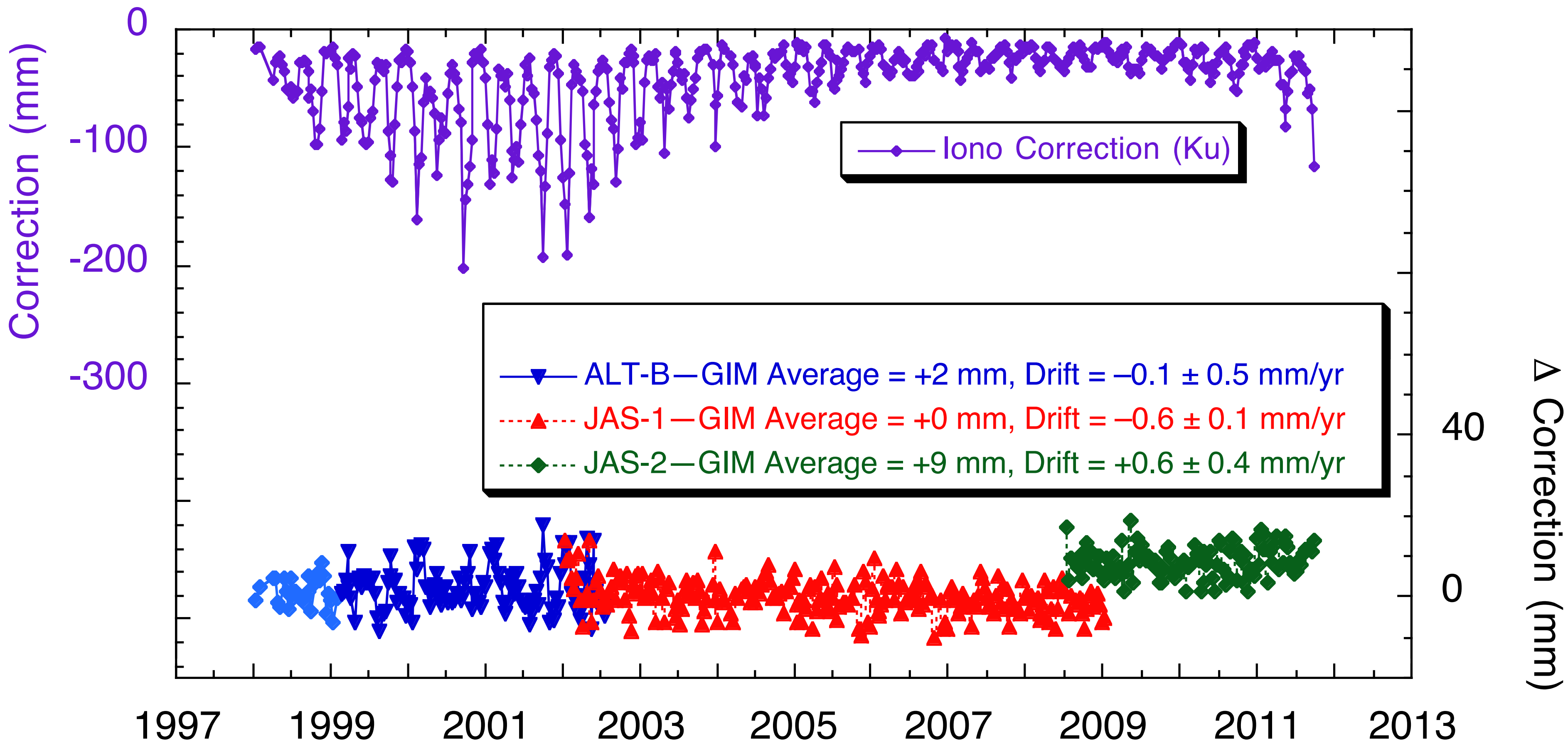


Harvest: Ku-Band Ionosphere Calibration Using JPL GPS Ionosphere Maps



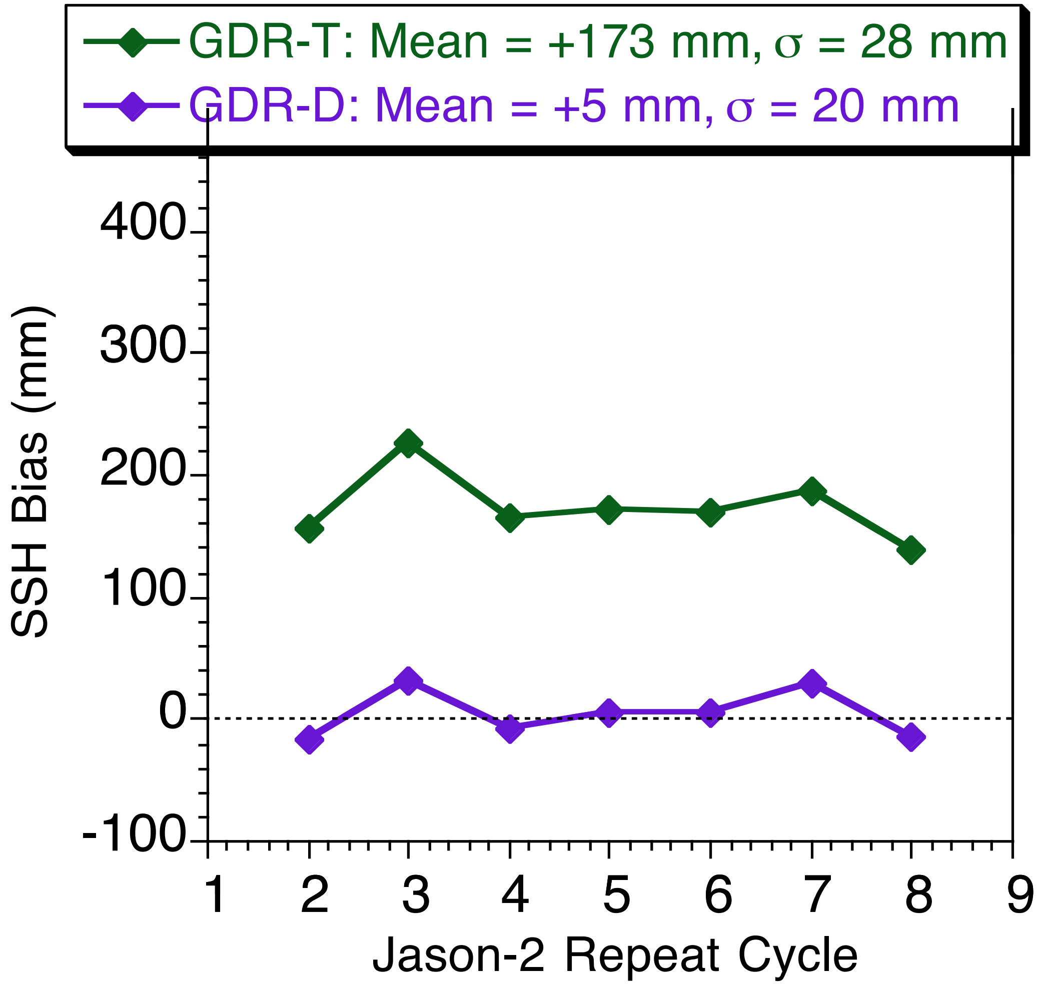
Absolute Ku- and C-Band SSH Bias/Drift

- **Begin with uncorrected Ku- and C-Band Ranges**
  - Compensate for troposphere using standard (GDR) approach
  - Correct ranges for characterization (e.g., PRF, internal delay) and ARP errors.
- **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(s)
  - Ionosphere is a scaling of TECU from GIM (GPS-based).
- **Only Jason-2 C-band SSH bias (+4 cm) significantly different from zero**
- **C-band SSB shows higher sensitivity to SWH**
- **Ionosphere scale factors slightly lower than theoretical values: 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)	+11 ± 7	–1 ± 10	+14 ± 10	**+43 ± 16**
SSH Drift (mm/yr)	–1 ± 1	–2 ± 2	–2 ± 3	+9 ± 5
Local SSB (%)	3.4 ± 0.2	4.4 ± 0.3	3.6 ± 0.3	4.1 ± 0.5
Iono. (mm/TECU)	2.0 ± 0.2	12.9 ± 0.3	1.4 ± 0.6	13.1 ± 0.9
Number	208	205	98	92
Postfit σ (mm)	31	48	28	42

An Early Glimpse at the OSTM/Jason-2 Preliminary GDR-D

Features corrected Jason-2 ranges, new SSB, orbit, ionosphere and wet troposphere (including EPD)



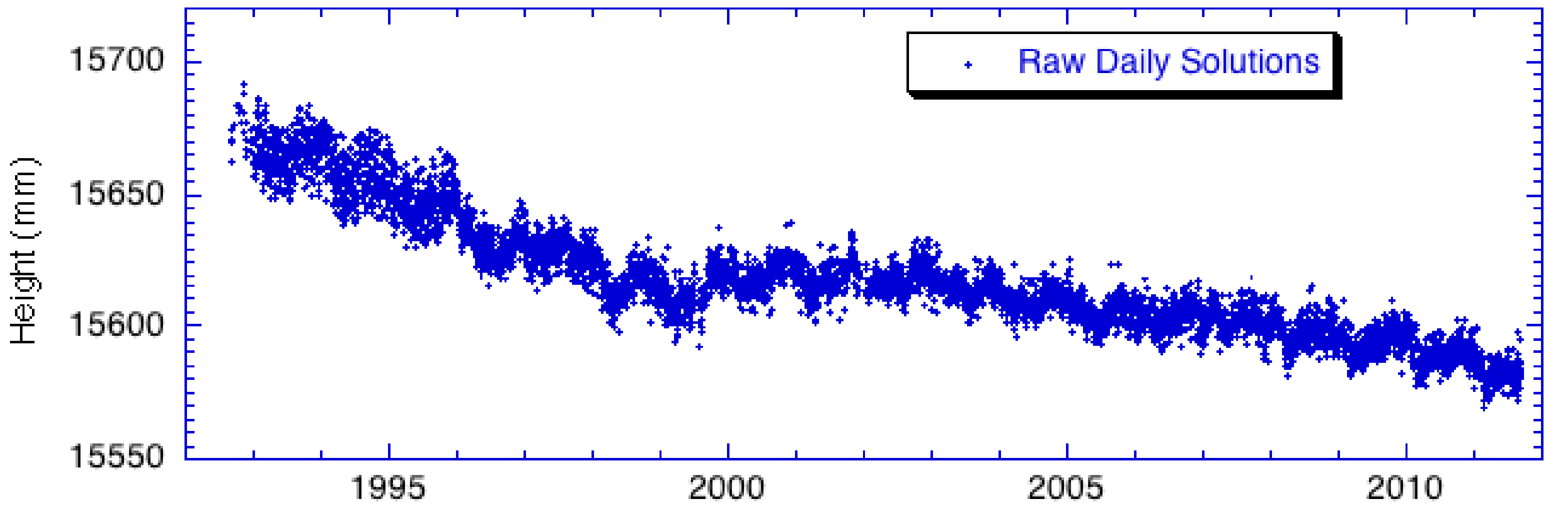
Source of ΔSSH Bias (GDR-T to GDR-D):

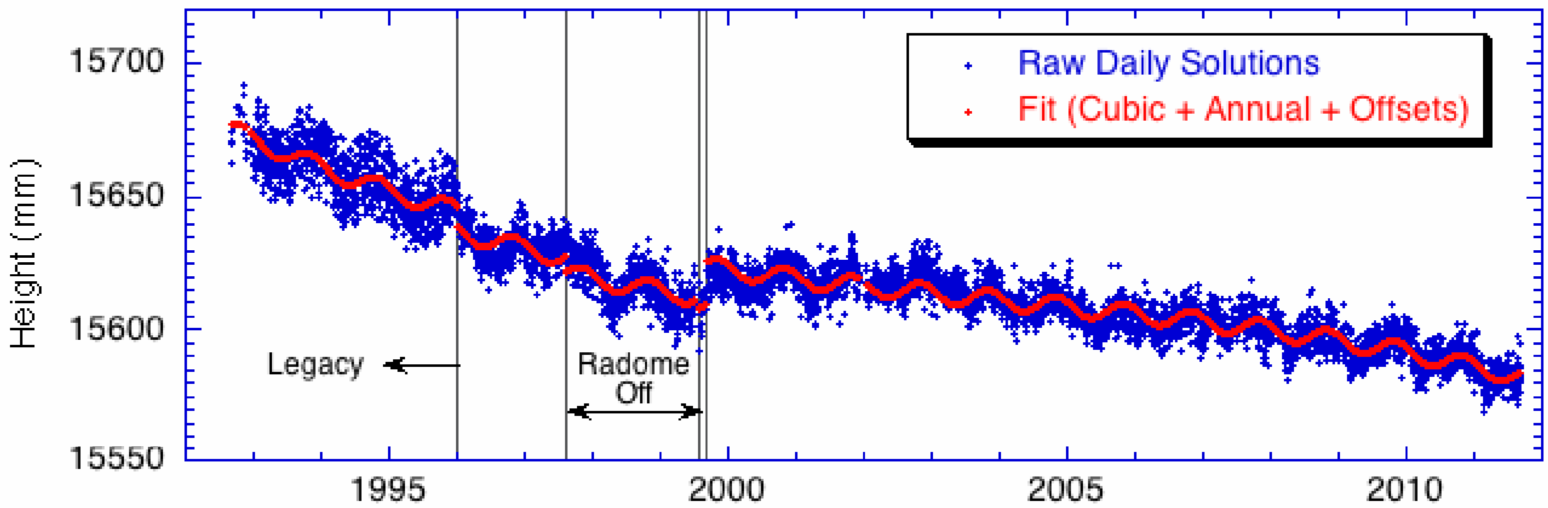
Parameter	Bias (mm)	σ (mm)
Range_Ku	–151	1
SSB_Ku	–33	7
Iono_Ku	+7	2
Wet_Rad	+6	8
Orbit	+2	2
NET	**–169**	

Summary of Harvest Findings

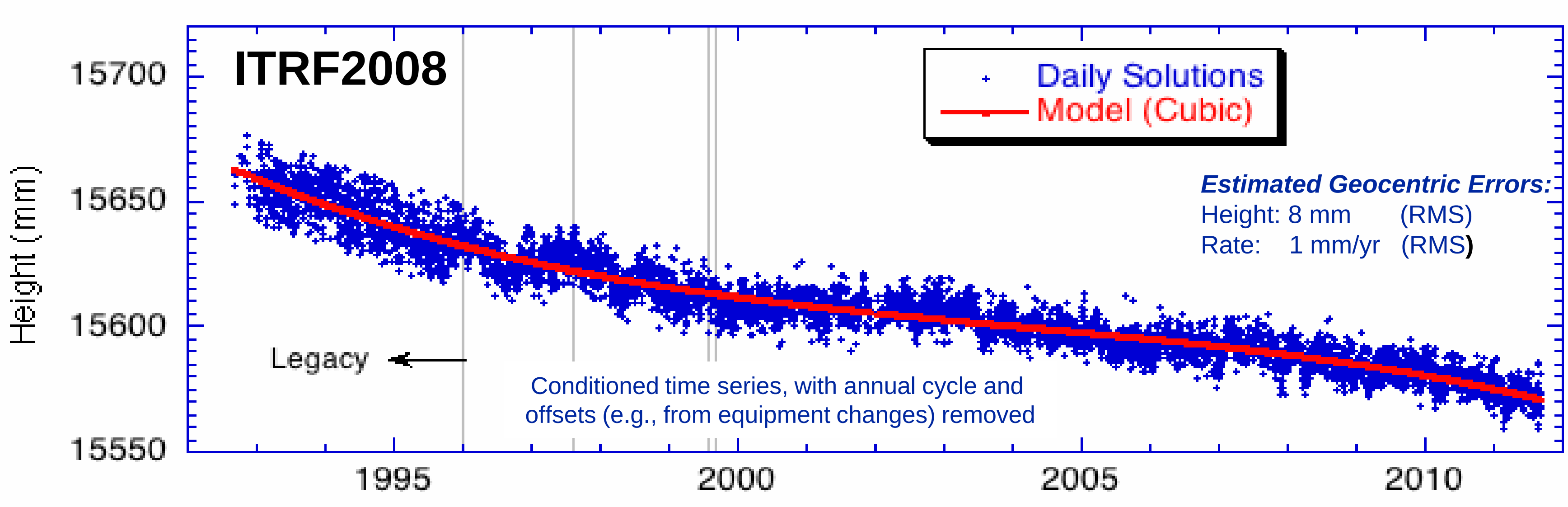
- **Current Jason-2 and Jason-1 GDR SSH too high, by +18 and +9 cm respectively**
  - OSTM/Jason-2: +176 ± 3 mm (N = 97, σ = 26 mm)
  - Jason-1: +89 ± 2 mm (N = 210, σ = 28 mm)
- **Primary source of Jason-1 and Jason-2 biases is altimeter**
  - CNES corrections to altimeter range (*Desjonquères et al*., 2009; 2011) reduce biases to 2–3 cm level.
  - Preliminary Jason-2 GDR-D yields ~5 mm bias (statistically indistinguishable from zero).
  - Additional 3-cm Jason-2 SSH bias shift from new (preliminary GDR-D) SSB model
- **Jason-2 Ku-ionosphere (GDR-T) delay smaller (9 mm) than Jason-1**
  - Jason-1 agrees better with GPS (GIM)
  - New (GDR-D) ionosphere correction reduces bias.
- **New approach to SSH bias computation lends insight on individual Ku, C contributions**
  - Jason-2 C-band SSH bias slightly positive (~4 cm)
- **TOPEX/Poseidon systems unbiased (< 2 cm)**
  - T/P ALT-B: +14 ± 4 mm (N= 81, σ = 33 mm)
  - T/P ALT-A: +18 ± 3 mm (N = 154, σ = 32 mm)
  - T/P POS: +6 ± 6 mm (N = 22, σ = 30 mm)
- **SSH drift estimates for all systems statistically indistinguishable from zero**
  - Modeling of vertical land motion still limiting systematic error source.
- **Enhanced path delay (EPD) product yields promising results**
  - Enables use of JMR/ AMR data at platform location (~10 km from shore)
  - Improves agreement with independent GPS-derived PD estimates

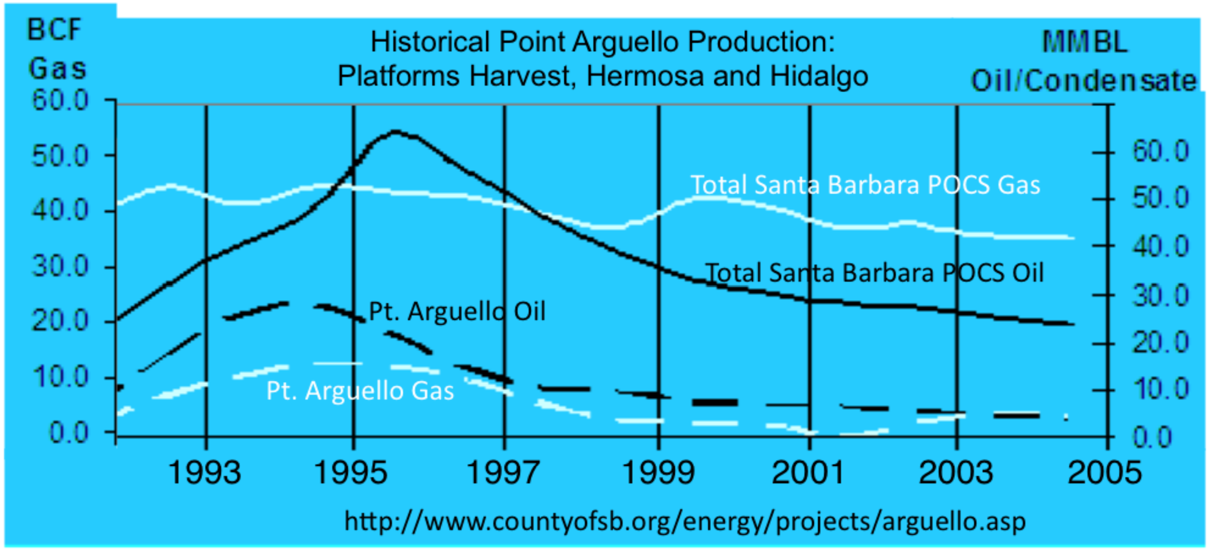
Using GPS to Monitor Vertical Land Motion at Harvest





Platform Harvest Geodetic Height
From 19 Years of Continuous GPS Monitoring





Oil/Gas Production from 1992–2005

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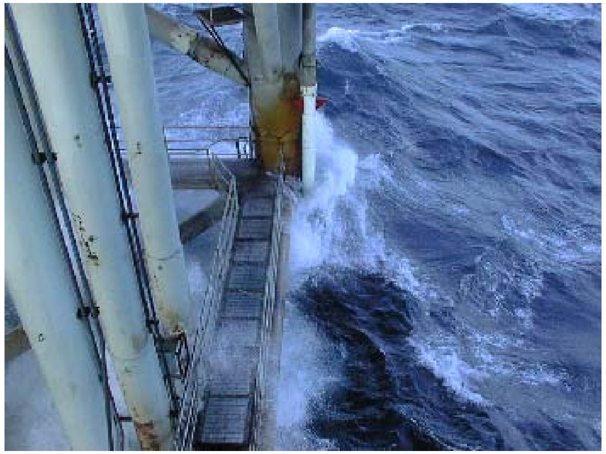
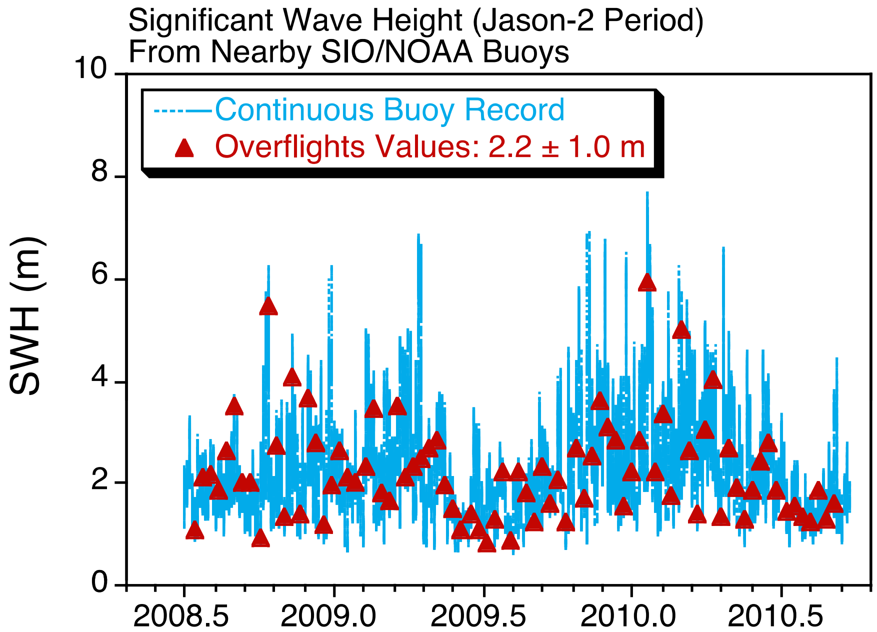
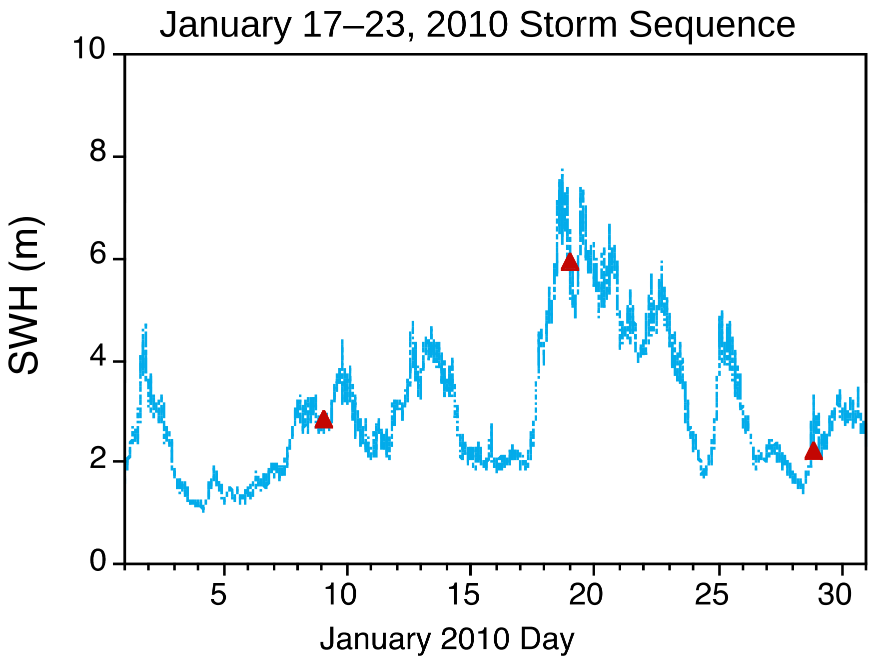
Harvest: Open-Ocean Conditions







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

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

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

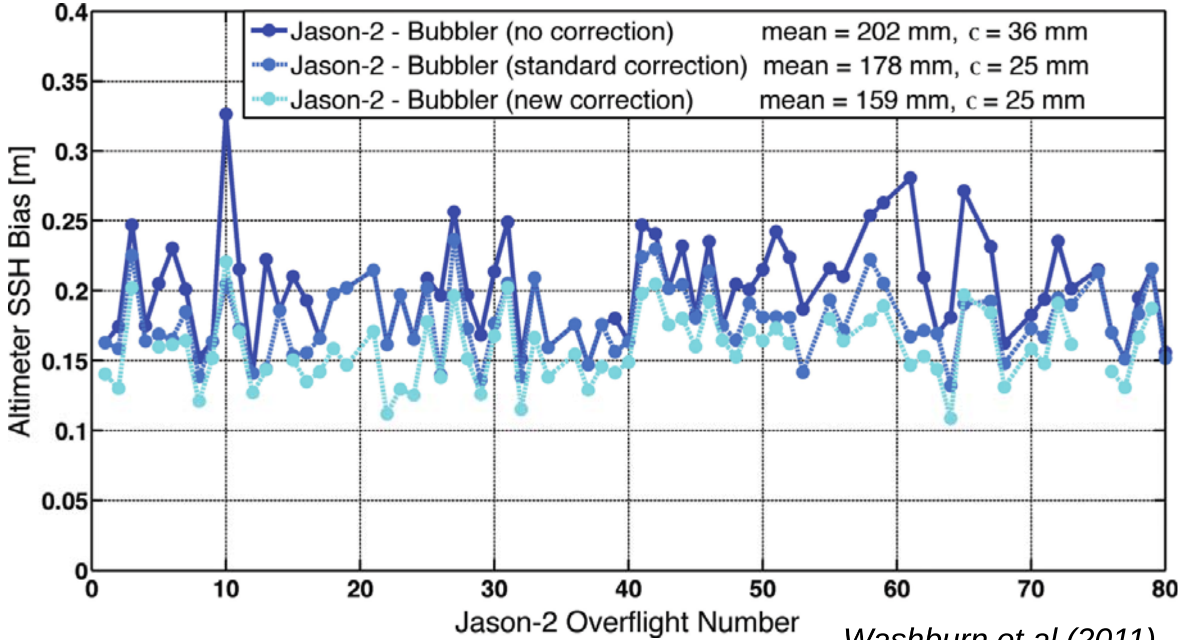
Standard Bubbler Correction *Parke and Gill (1995)*

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

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

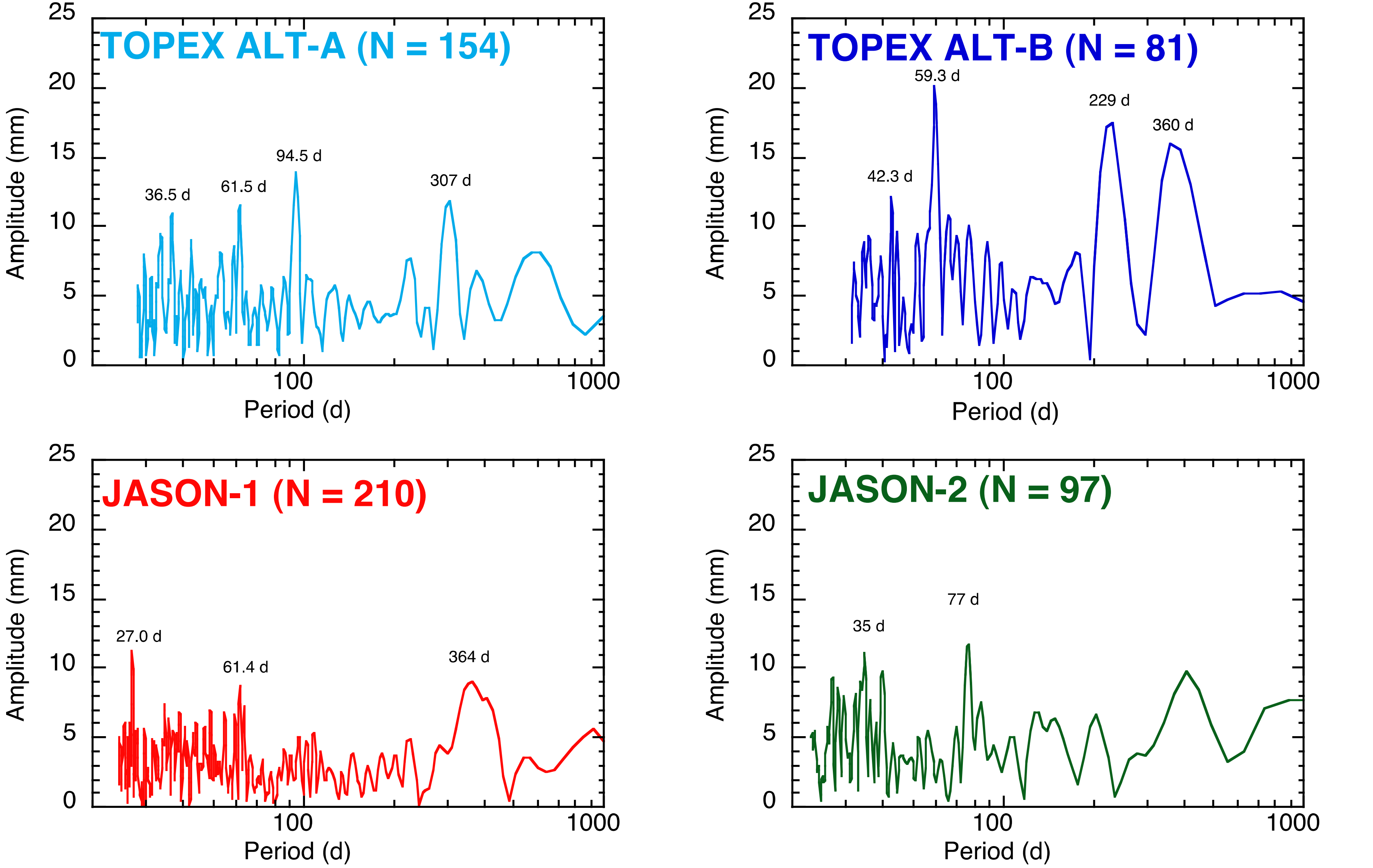
New Bubbler Correction

Washburn et al (2011)



Washburn et al (2011)

Periodograms of SSH Bias Time Series



T/P : MGDR CG_CORR not applied.
S1/S2 atmospheric tide not applied to dry trop.

Harvest SSH Calibration

				Mean	Err	sd	Bias	Err	Drift	Err	sd	Median	Bias	Drift	MAD
SSH: JASON-1 ABSOLUTE SERIES															
Jason-1 GDR-C	1-259	210	2002.0	89.4	2.0	28.3	96.3	3.9	-1.9	0.9	28.1	87.8	97.3	-2.2	21.9
Jason-1 GDR-C (GPS tropo)	1-259	206	2002.0	89.5	1.9	27.6	97.2	3.9	-2.1	0.9	27.3	88.2	94.8	-1.8	21.0
Jason-1 GDR-C (JMR/EPD)	1-259	208	2002.0	91.1	1.9	27.4	100.6	3.8	-2.7	0.9	26.9	89.9	104.2	-3.6	20.8
Jason-1 GDR-C (GIM)	1-259	210	2002.0	93.4	2.0	28.8	102.7	3.9	-2.6	1.0	28.4	91.6	104.7	-3.0	22.2
SSH: JASON-2 ABSOLUTE SERIES															
Jason-2 GDR-C	1-114	97	2008.5	176.0	2.6	25.6	175.5	5.1	0.4	2.9	25.7	173.4	170.4	2.5	19.9
Jason-2 GDR-C (GPS tropo)	1--114	97	2008.5	177.2	2.5	24.3	175.7	4.9	1.0	2.8	24.4	176.9	171.6	2.9	19.0
Jason-2 GDR-C (AMR/EPD)	1-114	96	2008.5	181.0	2.6	25.8	182.2	5.1	-0.8	3.0	26.0	180.3	180.8	-0.5	20.2
Jason-2 GDR-C (GIM)	1-114	97	2008.5	187.5	2.6	25.3	186.2	5.1	0.9	2.9	25.5	186.7	181.3	3.4	19.6
Jason-2 GDR-C (001-107)	1-107	86	2008.5	175.8	2.8	26.0	174.6	5.6	0.8	3.5	26.2	173.4	170.6	2.4	20.4
Jason-2 GDR-C (CNES GDRD)	1-107	86	2008.5	179.1	2.8	25.7	178.1	5.5	0.7	3.4	25.9	178.6	174.2	3.3	19.8
Jason-2 GDR-C (JPL rlse11a)	1-107	86	2008.5	177.8	2.9	26.7	177.7	5.7	0.0	3.5	26.8	177.5	173.1	2.9	21.0
Jason-2 GDRC (001-008)	1 to 8	7		173.2	10.5	27.7						170.1			
Jason-2 GDRD (including test GDRD orbit)	1 to 8	7		4.6	7.5	19.8						5.0			
TOPEX/POSEIDON ABSOLUTE SERIES															
TOPEX-B MGDR++ (TMR-rp + GSFC std0905)	237-365	81	2002.0	14.1	3.7	33.0	10.1	5.2	-3.5	3.3	33.0	13.1	10.3	-4.8	25.1
TOPEX-A MGDR++	1-235	154	1993.0	17.5	2.5	31.1	12.1	4.7	2.0	1.4	31.0	15.2	13.0	1.0	23.7
POSEIDON-1 MGDR++	1-365	22	2002.0	6.0	6.3	29.4	4.7	17.1	-0.2	2.7	30.1	5.9	-21.3	-4.3	20.4

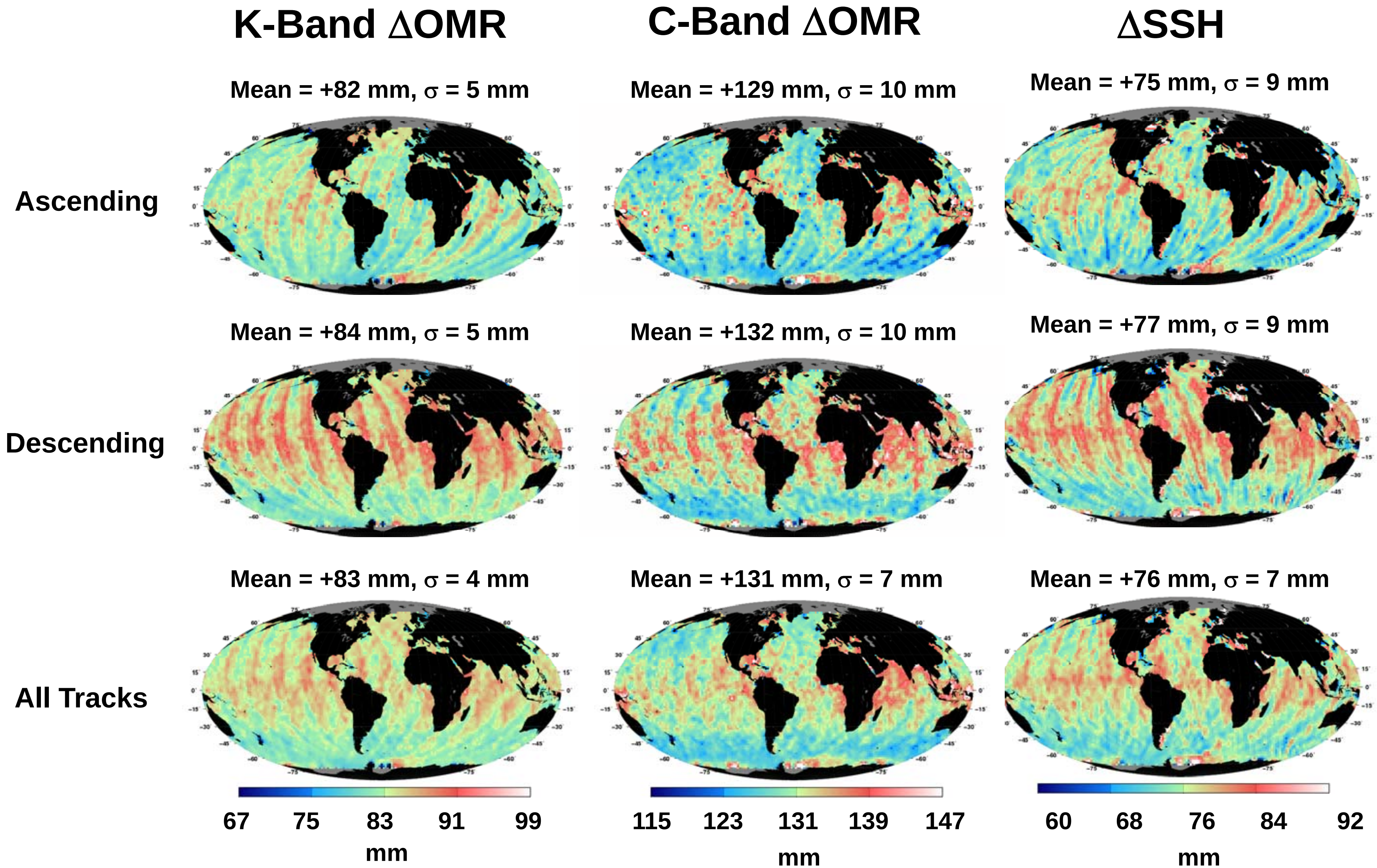
Evolution of Bias/Drift Estimates

BIAS (mm)	Nice 2008	Seattle 2009	*Mar. Geod.* 2010	Lisbon 2010	San Diego 2011
Jason-2	+200	+174	+178	+176	+176
Jason-1	+99	+94	+94	+87	+89
ALT-B	+15	+14	+14	+10	+14
Poseidon-1	+5	–10	–10	–5	+6
ALT-A	+17	+1	+1	+7	+18

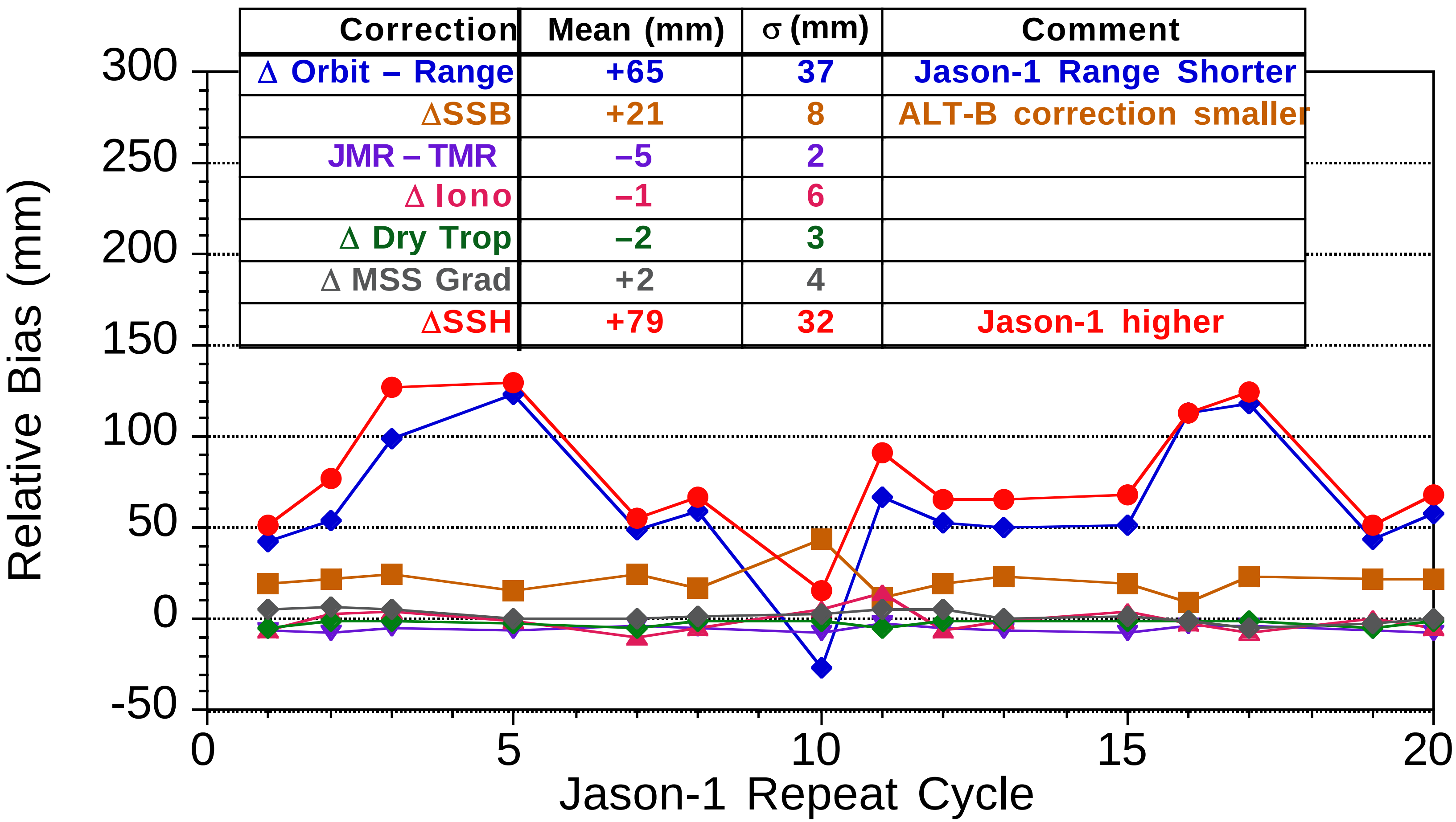
DRIFT (mm/yr)	Nice 2008	Seattle 2009	*Mar. Geod.* 2010	Lisbon 2010	San Diego 2011
Jason-2	n/a	–5	+15	+8	+2
Jason-1	+1	–2	–2	–2	–2
ALT-B	–2	–1	–1	–3	–4
Poseidon-1	–1	+3	+3	+1	–0
ALT-A	+0	+5	+5	+4	+2

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

Jason-2 – Jason-1 Geographically Correlated Errors From Tandem Calibration Phase (J2 Cycles 8–20)



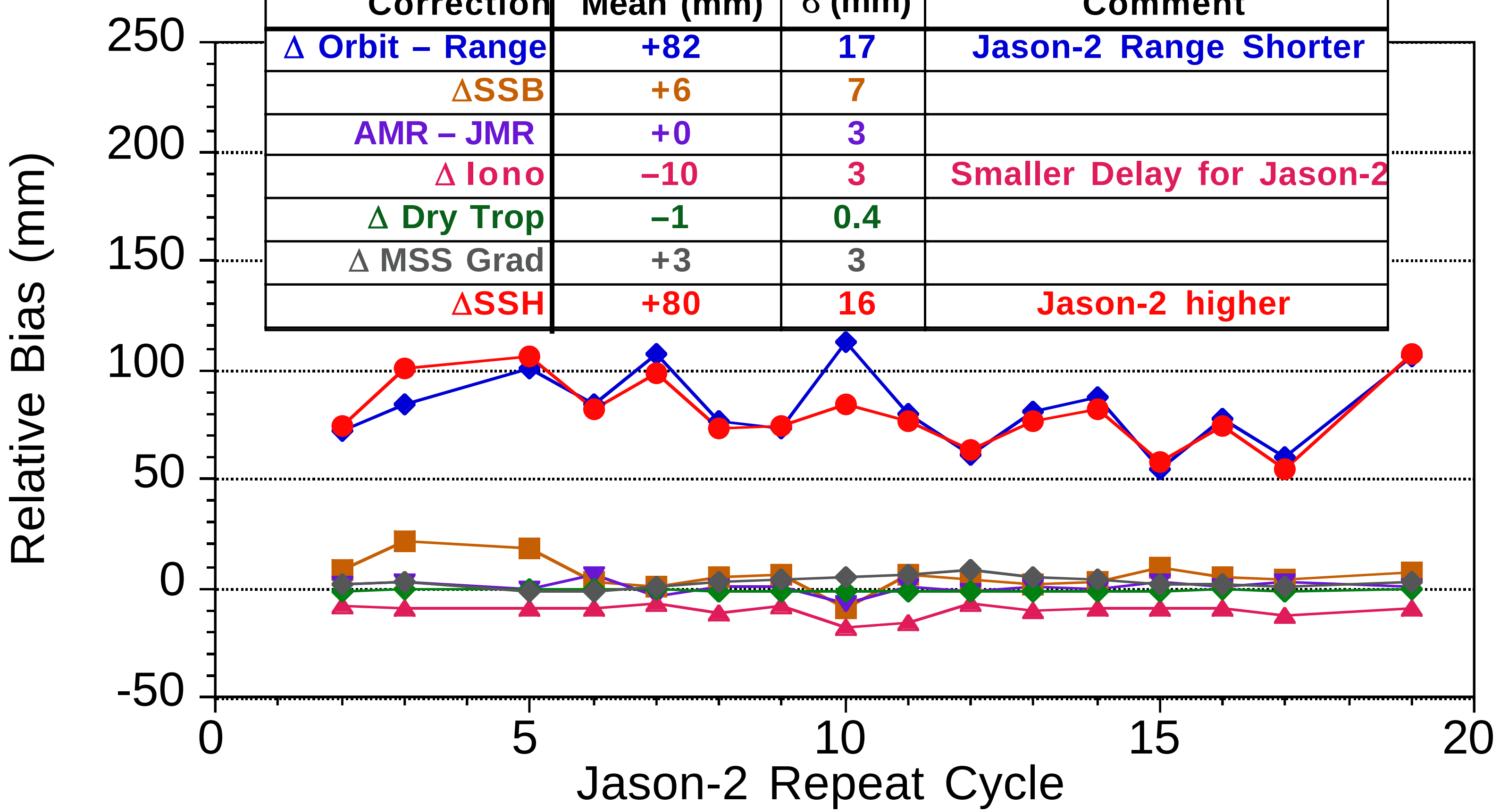
T/P Jason-1 Tandem Overflights of Harvest: Comparison of Correction Terms



Correction	Mean (mm)	σ (mm)	Comment
Δ Orbit – Range	+65	37	Jason-1 Range Shorter
ΔSSB	+21	8	ALT-B correction smaller
JMR – TMR	–5	2	
Δ Iono	–1	6	
Δ Dry Trop	–2	3	
Δ MSS Grad	+2	4	
ΔSSH	+79	32	Jason-1 higher

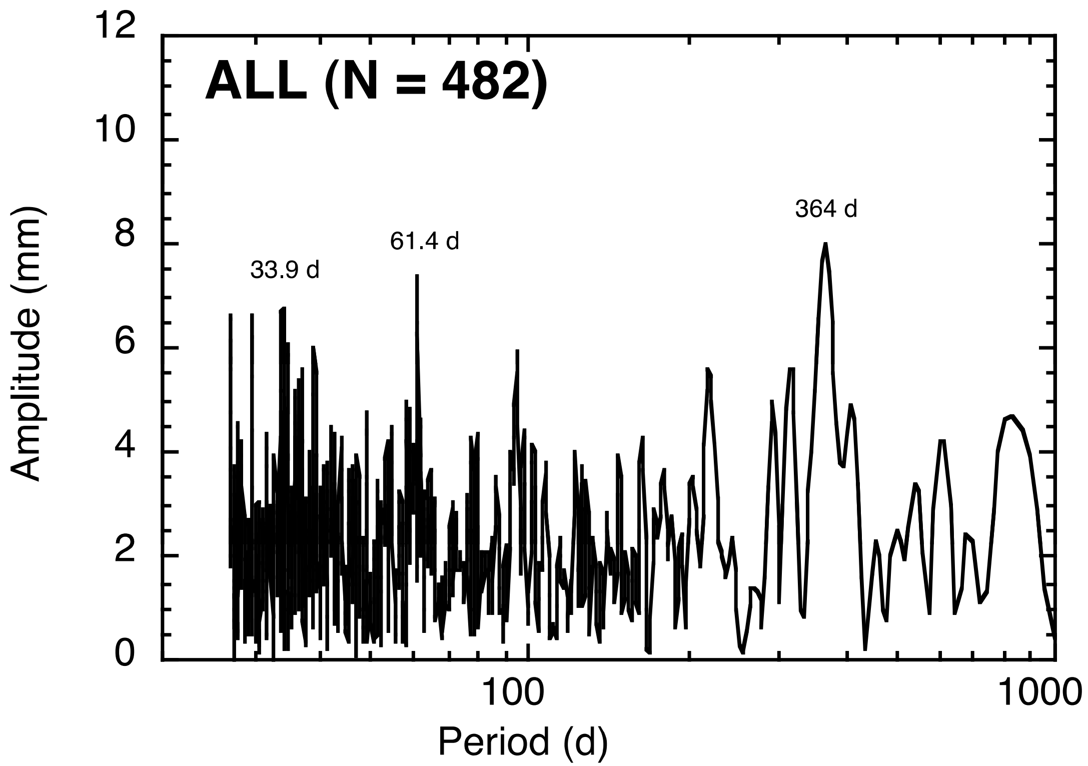
Jason 1/2 Tandem Overflights of Harvest: Comparison of Correction Terms

Correction	Mean (mm)	σ (mm)	Comment
Δ Orbit – Range	+82	17	Jason-2 Range Shorter
ΔSSB	+6	7	
AMR – JMR	+0	3	
Δ Iono	–10	3	Smaller Delay for Jason-2
Δ Dry Trop	–1	0.4	
Δ MSS Grad	+3	3	
ΔSSH	+80	16	Jason-2 higher



Jason-2 Radial Orbit Difference (POE vs GPS): σ = 6 mm; Mean = –1 mm (N = 79)

Periodogram of Combined SSH Bias Time Series



Jason-1 vs Jason-2 Global Statistics