The Harvest Experiment:
Current Results from the 18-yr Calibration Record

Bruce Haines and Shailen Desai
Jet Propulsion Laboratory, California Inst. of Tech., Pasadena CA

George Born, Chuck Fowler and Scott Washburn
University of Colorado, Boulder

Steve Gill
NOAA CO-OPS

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Harvest Platform

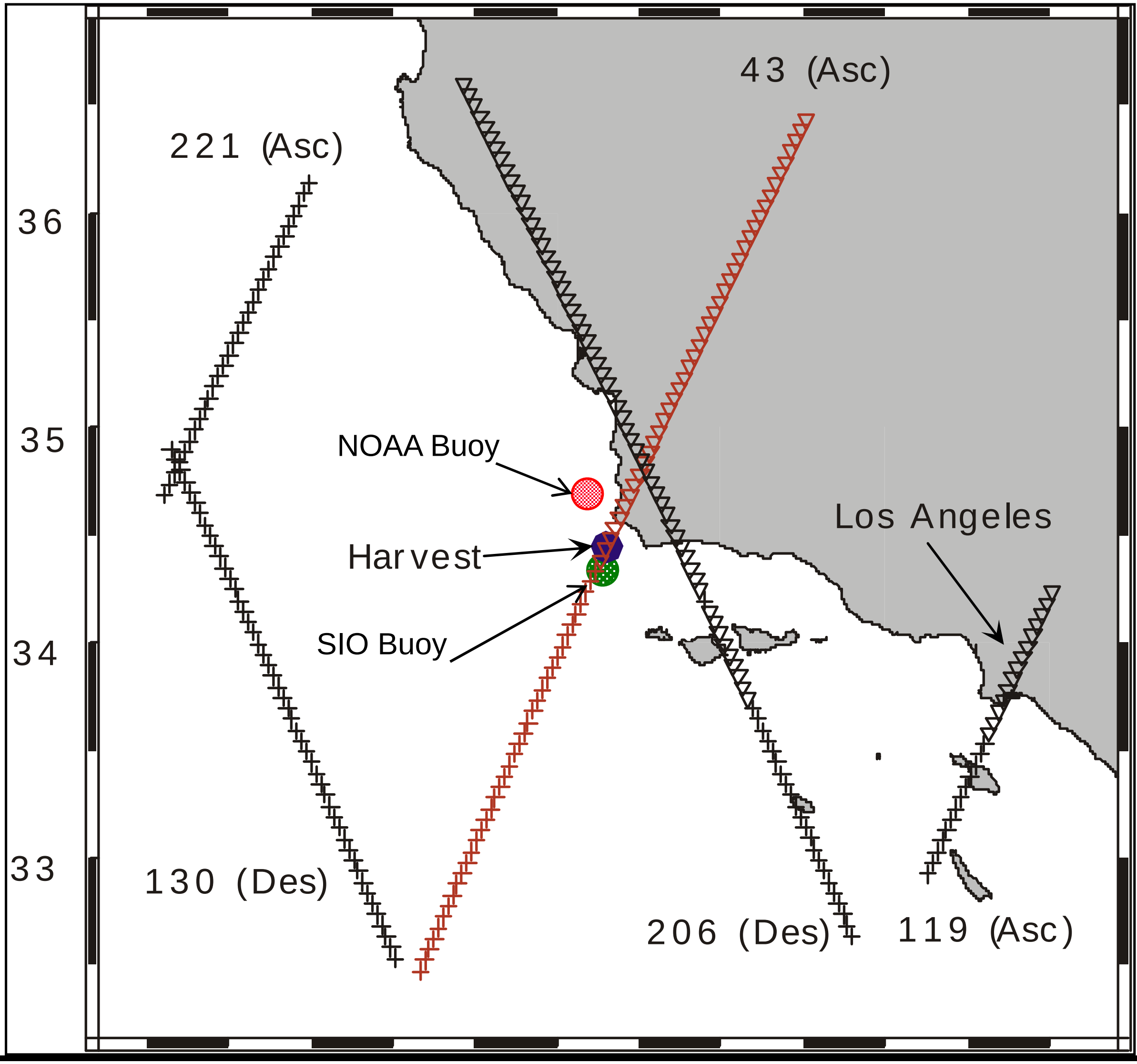
Owned by Plains Exploration and Production (PXP)

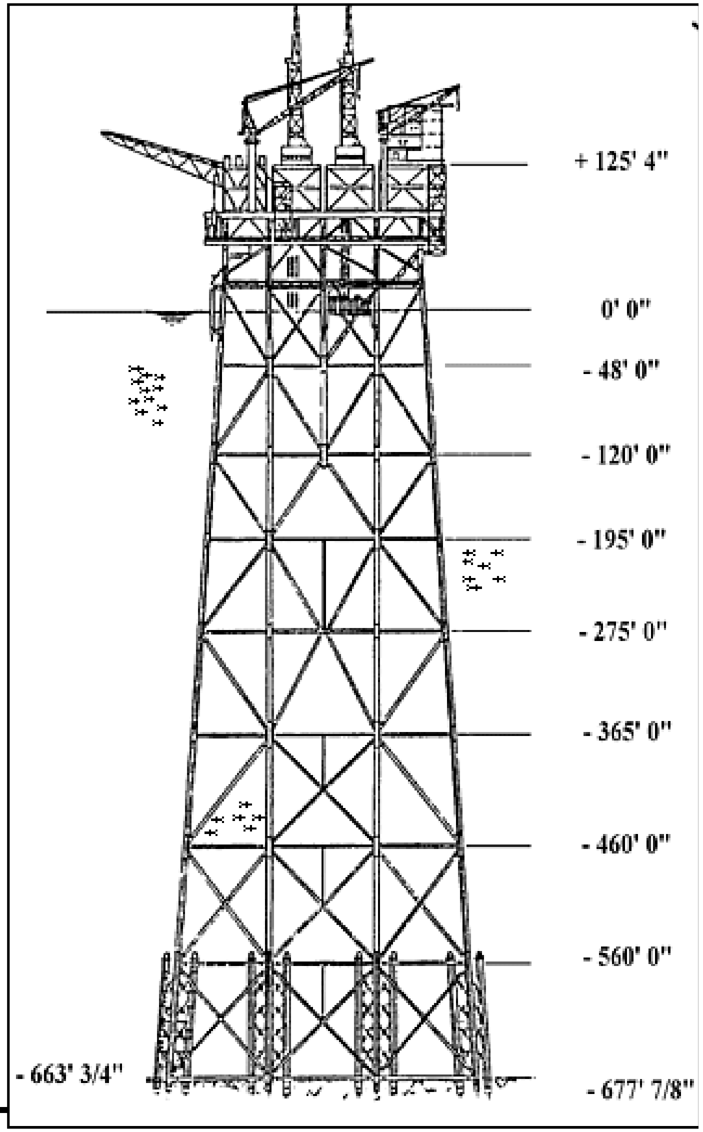
NASA Prime Verification Site for High-Accuracy (Jason-class) Altimetry: T/P (1992–2005), Jason-1 (2001–) and OSTM/Jason-2 (2008–).

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 18 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
- **84 Jason-2 overflights and counting…**
  - Over two years of monitoring
- **Nominal experiment operations status**
  - NOAA water level systems serviced (August)
  - CU lidar system maintenance upcoming
  - Routine underwater maintenance upcoming

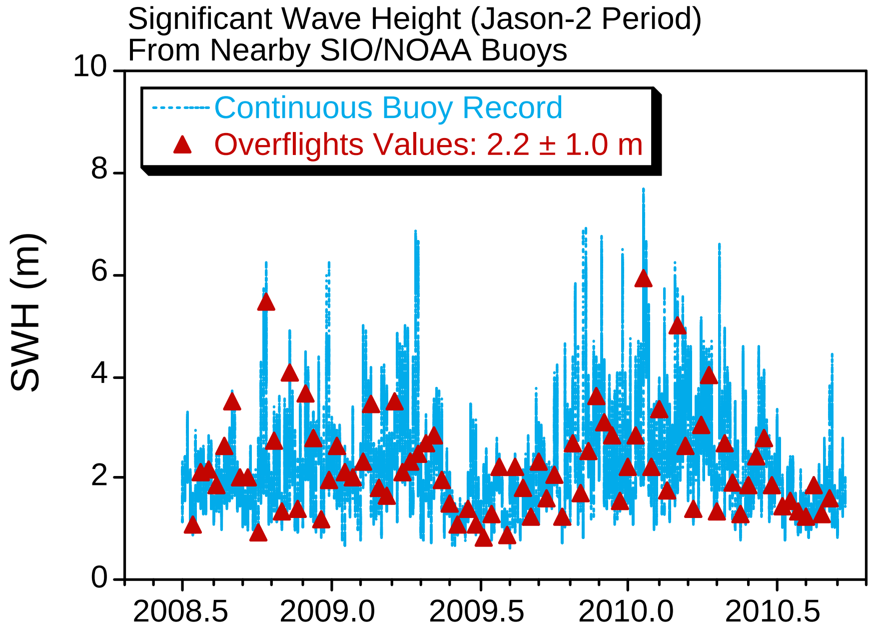
Map of Harvest Vicinity

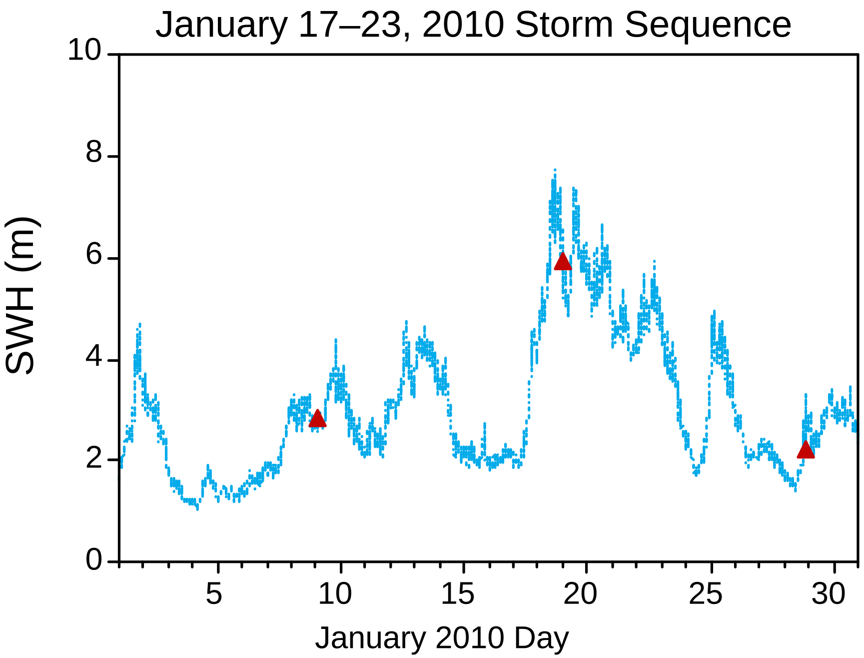




Courtesy PXP

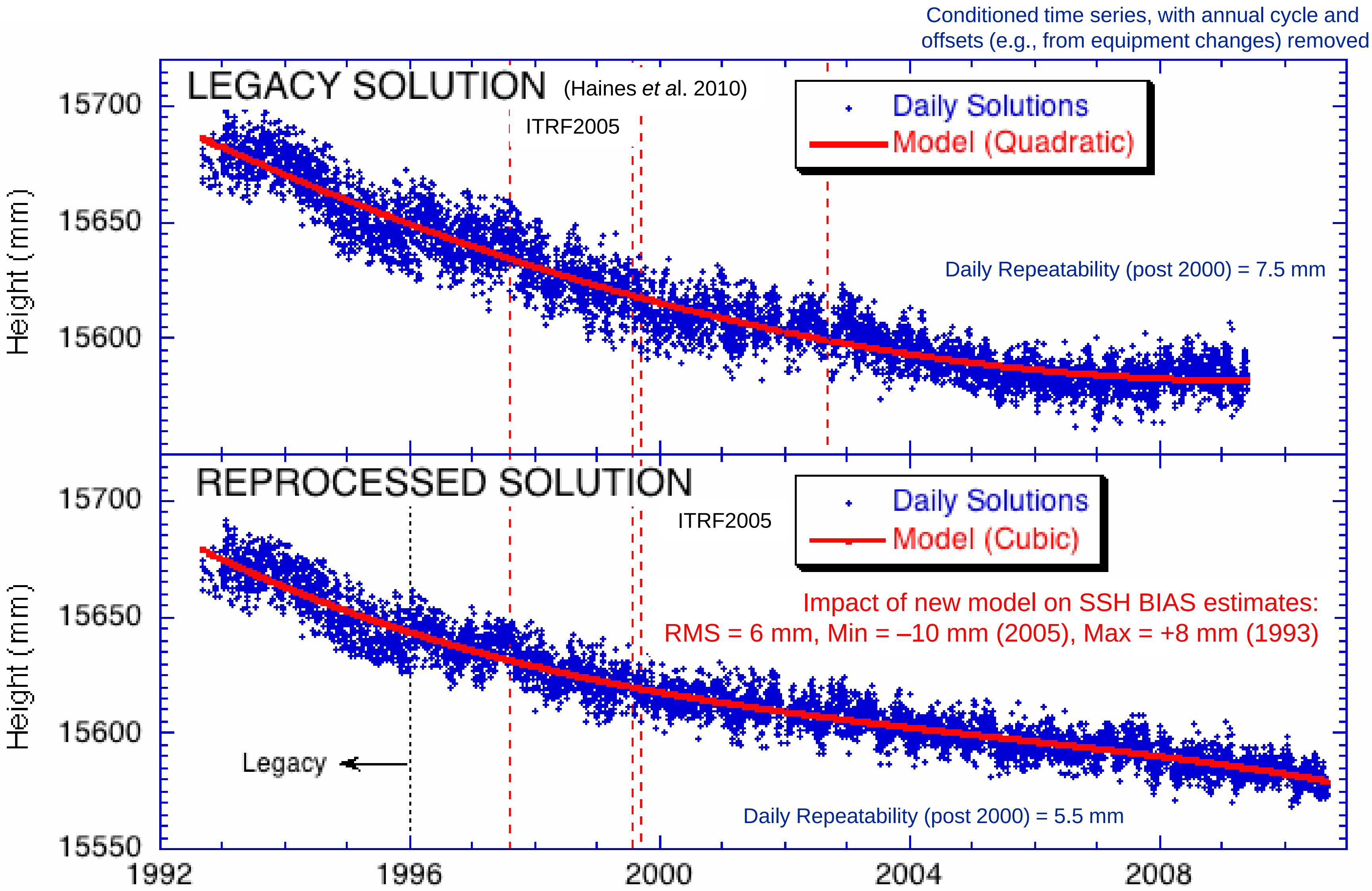
Harvest: Open-Ocean Conditions





Harvest Geodetic Height: A New Solution

Based on Reprocessed GPS Satellite Orbits and Clocks[1]

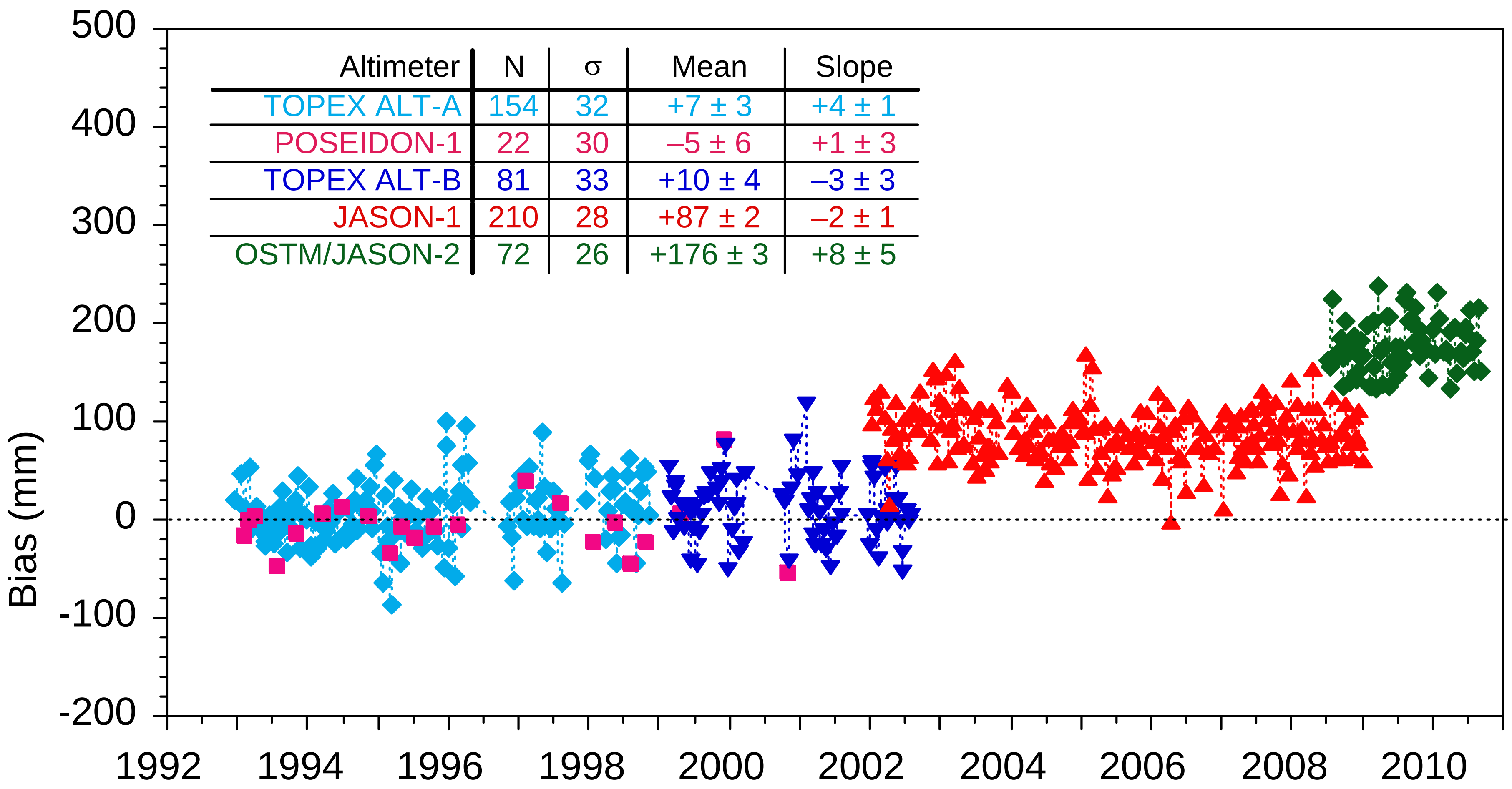


1 Desai *et al.*, The JPL IGS analysis center: Results from the reanalysis of the global GPS network, *EOS Trans*, AGU, 2009.

Harvest Closure Analysis: Assumptions for Altimeter Leg

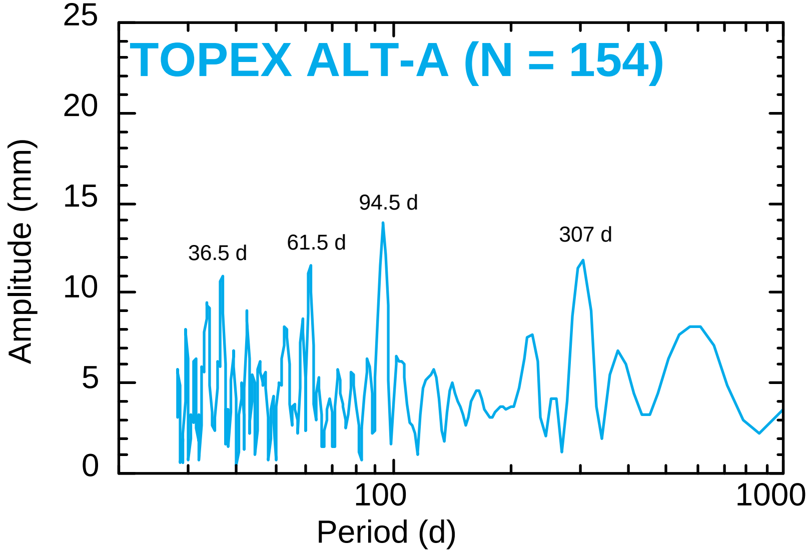
Model	**TOPEX/Poseidon**	**Jason-1**	**OSTM/ Jason-2**
Orbital Height	GSFC std0905 (Lemoine et al., 2010)	GDR-C	T/GDR
Altimeter Range	Ku (MGDR)	Ku (GDR-C)	T/GDR
Wet troposphere	Repro from Brown et al. (2009)	GDR-C	T/GDR
Dry troposphere	MGDR	GDR-C	T/GDR
Ionosphere	MGDR: Ku (ALT), DORIS (POS-1)	GDR-C	T/GDR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

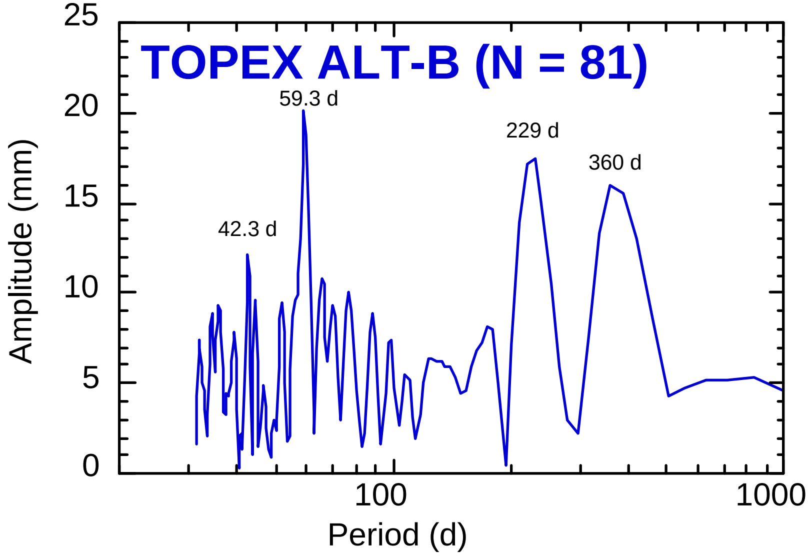
Harvest SSH Calibration Time Series

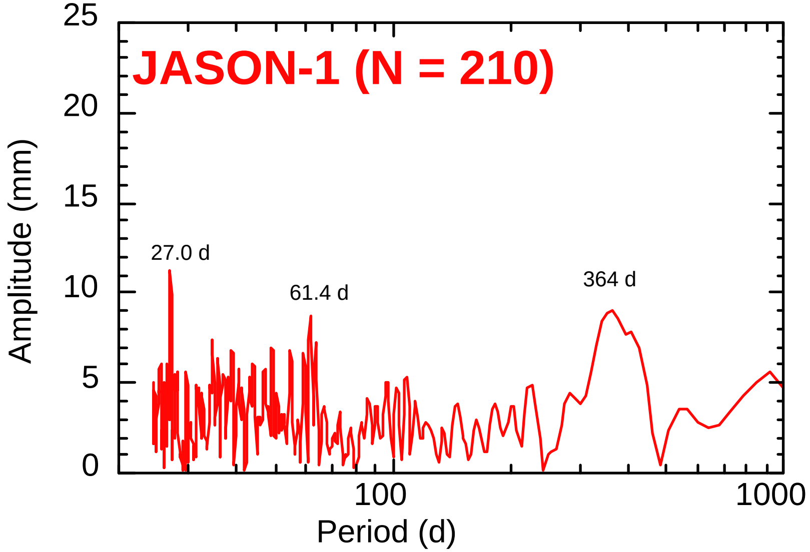


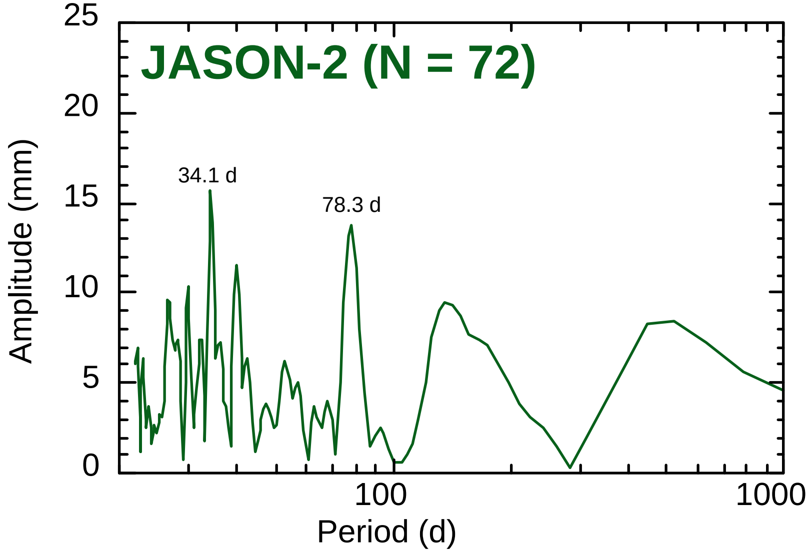
Altimeter	N	σ	Mean	Slope
TOPEX ALT-A	154	32	+7 ± 3	+4 ± 1
POSEIDON-1	22	30	–5 ± 6	+1 ± 3
TOPEX ALT-B	81	33	+10 ± 4	–3 ± 3
JASON-1	210	28	+87 ± 2	–2 ± 1
OSTM/JASON-2	72	26	+176 ± 3	+8 ± 5

Periodograms of SSH Bias Time Series





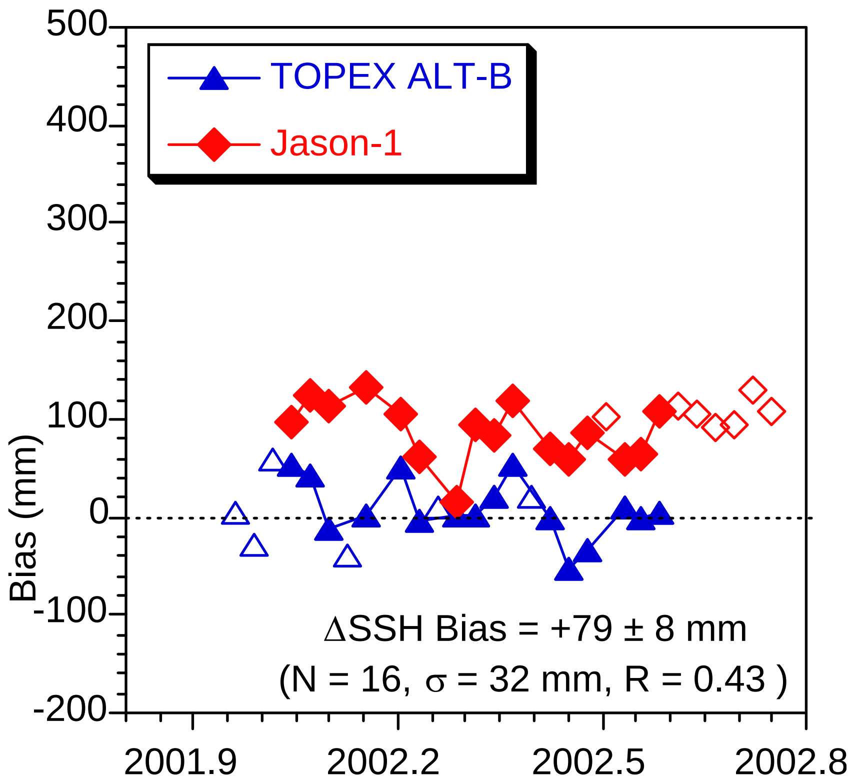


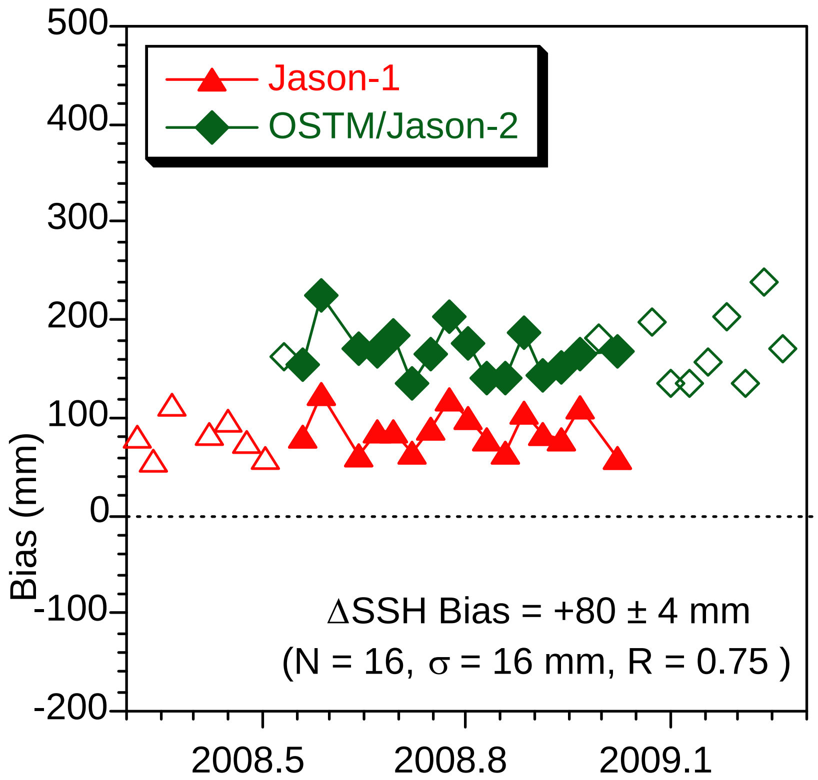


T/P : MGDR CG_CORR not applied.
S1/S2 atmospheric tide not applied to dry trop.

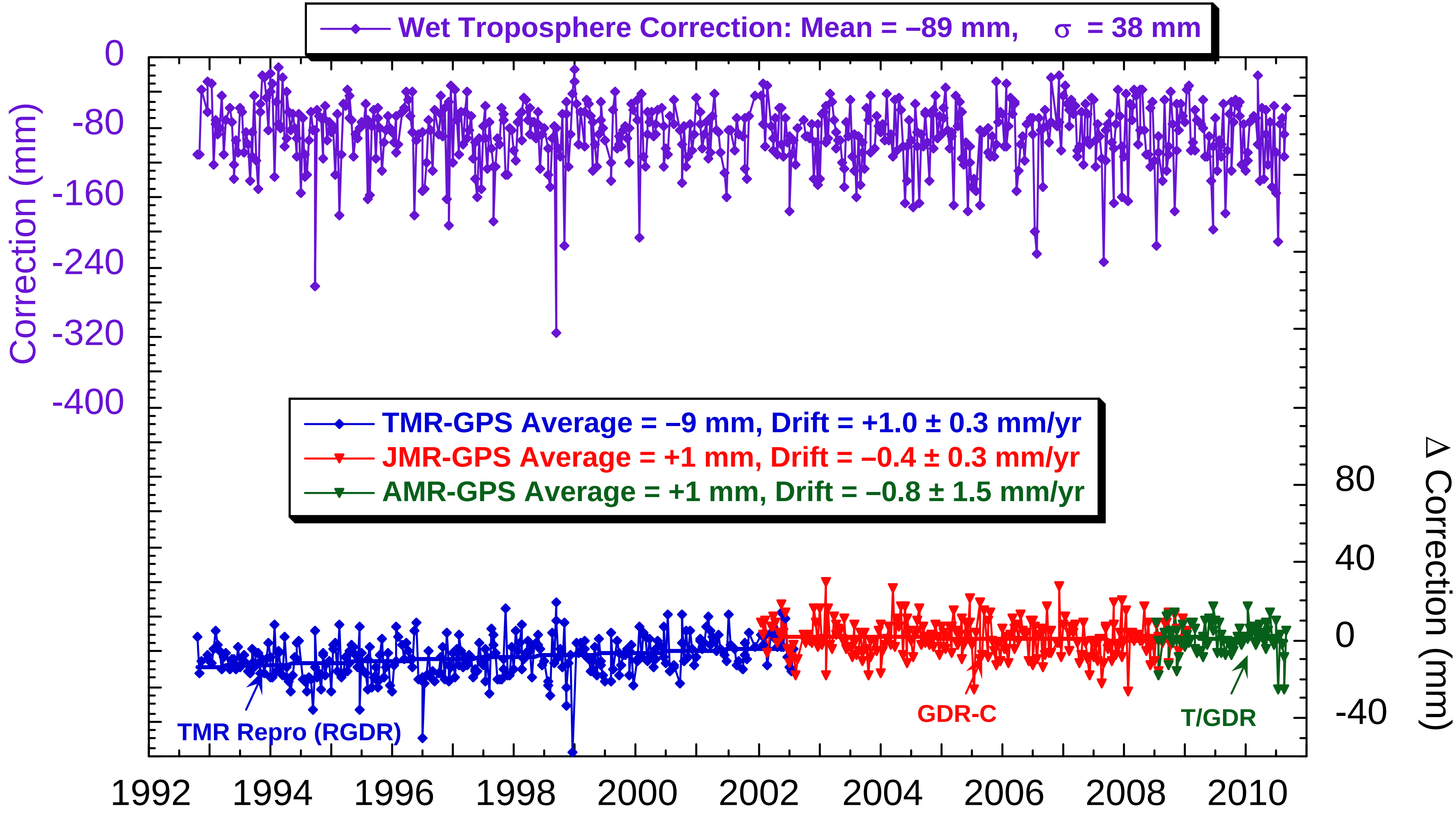
Harvest SSH Calibration Time Series

RELATIVE BIASES FROM DUAL OVERFLIGHTS





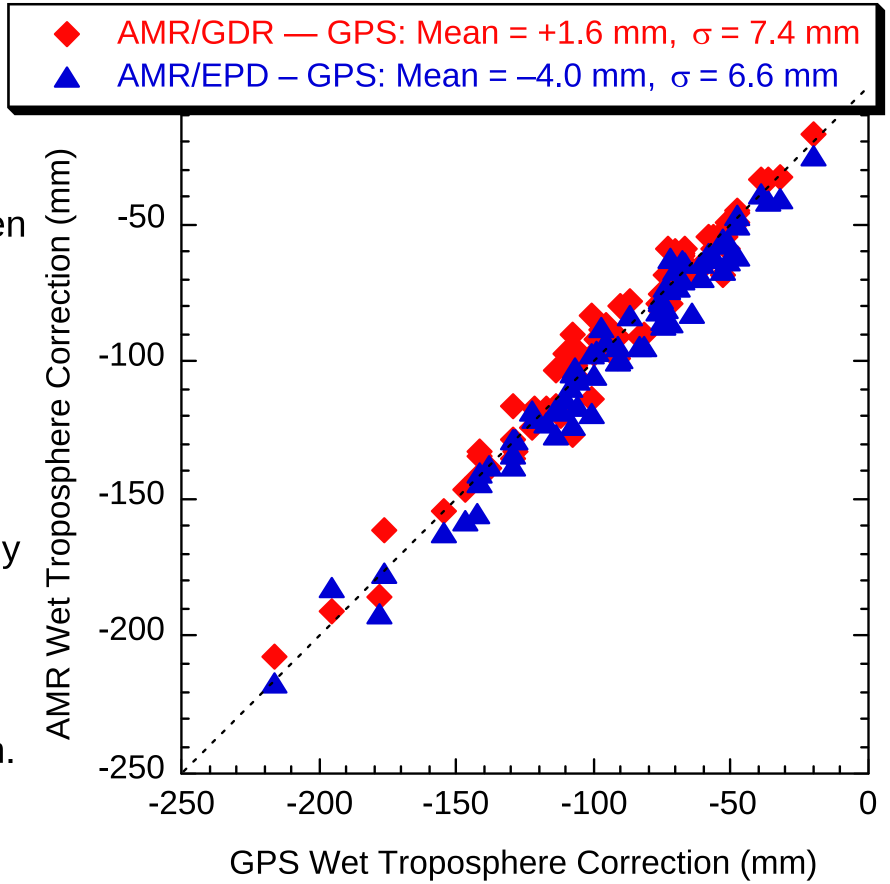
Wet Path Delay: Radiometer vs. GPS



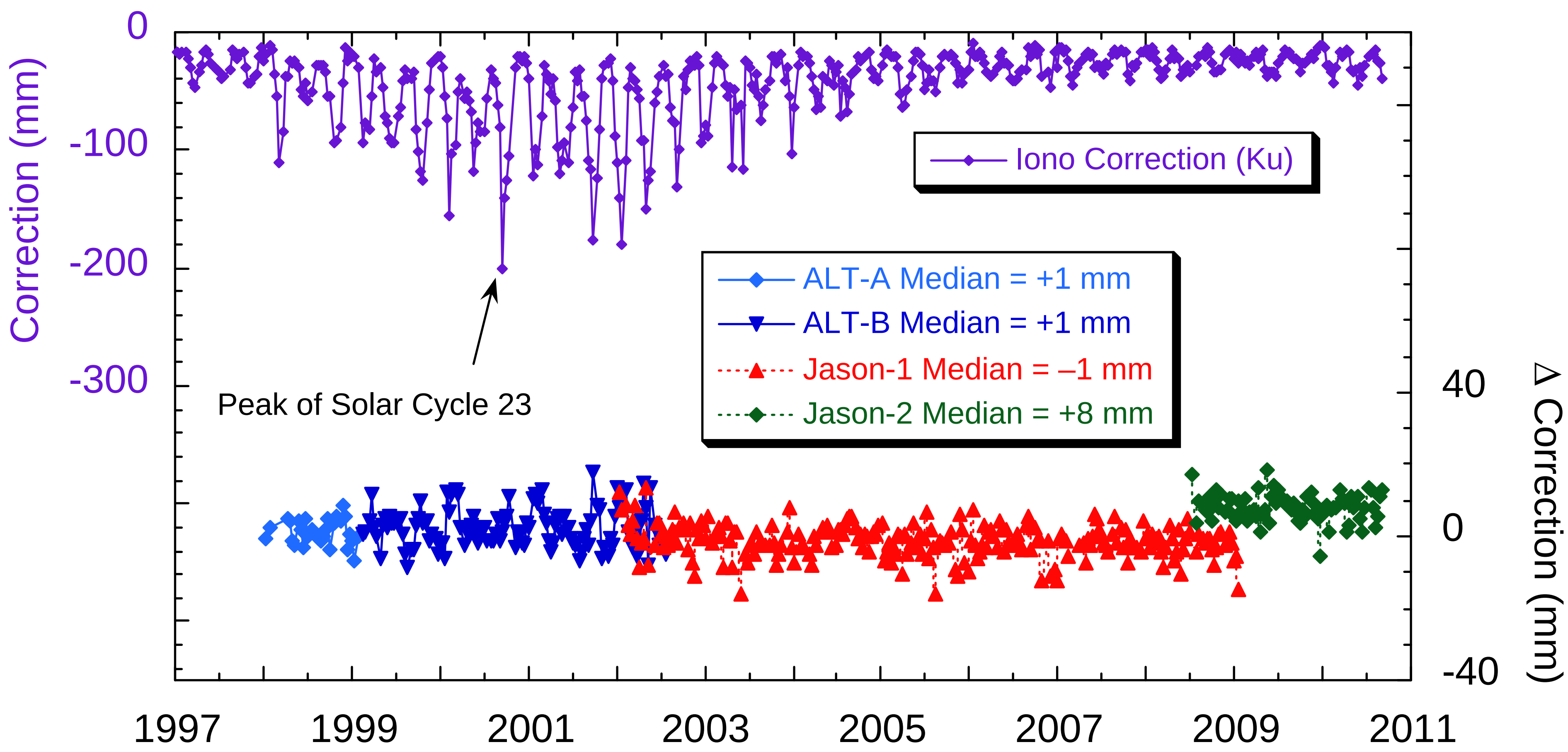
Radiometer Land Contamination: Performance of AMR/EPD Product at Harvest

- Use std. fit procedure for AMR GDR correction on approach to Harvest
  - Linear fit over 10-s terminating 5-s before platform overflight.
  - Avoids land contamination (e.g., Christensen et al., 1994).
- Use new fit procedure for AMR EPD
  - Linear fit over 10-s terminating at TCA.
  - Harvest ~10 km from land along pass 43
- AMR/EPD improves agreement with GPS
  - Bias value from GPS may not be trustworthy at few mm level (e.g, radome)
- AMR/EPD suggests troposphere over platform slightly wetter vs. 30 km offshore.
  - Would increase Jason-2 SSH bias by 6 mm.
- Analysis of JMR/EPD underway

Wet Troposphere Correction
AMR Enhanced Path Delay Product vs. GPS



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



Absolute Ku- and C-Band SSH Biases

	Jason-1 Ku-Band	Jason-1 C-Band	Jason-2 Ku-Band	Jason-2 C-Band
SSH Bias	+76 $\pm$ 5 mm	+84 $\pm$ 9 mm	+164 $\pm$ 8 mm	+191 $\pm$ 11 mm
Local SSB	3.5 $\pm$ 0.2 %	4.6 $\pm$ 0.4 %	3.5 $\pm$ 0.3 %	3.7 $\pm$ 0.5 %
Number of Overflights	202	202	66	66
Postfit σ	31 mm	50 mm	26 mm	36 mm

- **Begin with uncorrected Ku- and C-Band Ranges**
  - Compensate for troposphere using standard (GDR) approach
  - Compensate for ionosphere using GPS-based correction (JPL GIM).
- **Estimate SSH bias and local SSB on each frequency simultaneously**
  - SSB model (local to Harvest) is a simple percentage of SWH from buoy.
- **Jason-2 Ku- and C-Band SSH biases disagree by 3 cm**
  - C-band SSH bias higher than corresponding Ku-band estimate
- **Lends additional insight on results from global analysis**
  - Discrepancy of ~5-cm between Ku- and C-Band Δ "Orbit–Range" (J2–J1)
  - Relative bias of ~1 cm between Jason-1 and Jason-2 ionosphere corrections

Summary of Harvest Findings

- **Both Jason-2 and Jason-1 reading SSH too high, by +17 and +9 cm respectively**
  - OSTM/Jason-2: +176 ± 3 mm (N = 72, σ = 26 mm)
  - Jason-1: +87 ± 2 mm (N = 210, σ = 28 mm)
- **TOPEX/Poseidon systems unbiased (< 2 cm)**
  - T/P ALT-B: +10 ± 4 mm (N= 81, σ = 33 mm)
  - T/P ALT-A: +7 ± 3 mm (N = 154, σ = 32 mm)
  - T/P POS: –5 ± 6 mm (N = 22, σ = 30 mm)
- **Excellent agreement between Harvest & global estimates of relative (J2 – J1) SSH bias**
  - +80 ± 4 mm from 16 common overflights of Harvest
  - +77 ± 1 mm from global cycle-by-cycle comparisons
- **Jason-1 and OSTM/Jason-2 exhibit common behavior**
  - High correlation of bias estimates (R = 0.75)
  - 16-mm scatter (1σ) of individual relative bias estimates
  - Testifies to common heritage of measurement systems
- **Primary source of Jason-1 and Jason-2 biases is altimeter**
  - CNES corrections to Ku range (Seattle OST/ST) not included (pending confirmation + C-band results)
- **SSH drift estimates altered by new model for platform subsidence**
  - Drift estimates for ALT-B, POS-2, Jason-1 all statistically indistinguishable from zero
  - Jason-2 drift (+8 ± 5 mm/yr) of questionable significance (1.6σ)
  - ALT-A drift estimate (4 mm/yr) consistent in sign with PTR degradation.

Summary of Harvest Findings (cont.)

- **New AMR enhanced path delay (EPD) product yields promising results**
  - Enables use of AMR data at platform location (~10 km from shore)
  - Improves agreement with independent GPS-derived PD estimates
- **Poseidon-3 Ku-ionosphere delay smaller (9 mm) than Poseidon-2**
  - Poseidon-2 agrees better with GPS (GIM)
- **Cubic model for platform vertical motion now preferred**
  - New framework for platform position solutions: reprocessed orbits/clocks
- **Influence of radome to be revisited in upcoming campaign**
- **New approach to SSH bias computation lends insight on individual Ku, C contributions**
  - Jason-1 C- and Ku-band SSH biases agree at ~1 cm level
  - Jason-2 C SSH bias ~3 cm larger than corresponding Ku SSH bias.

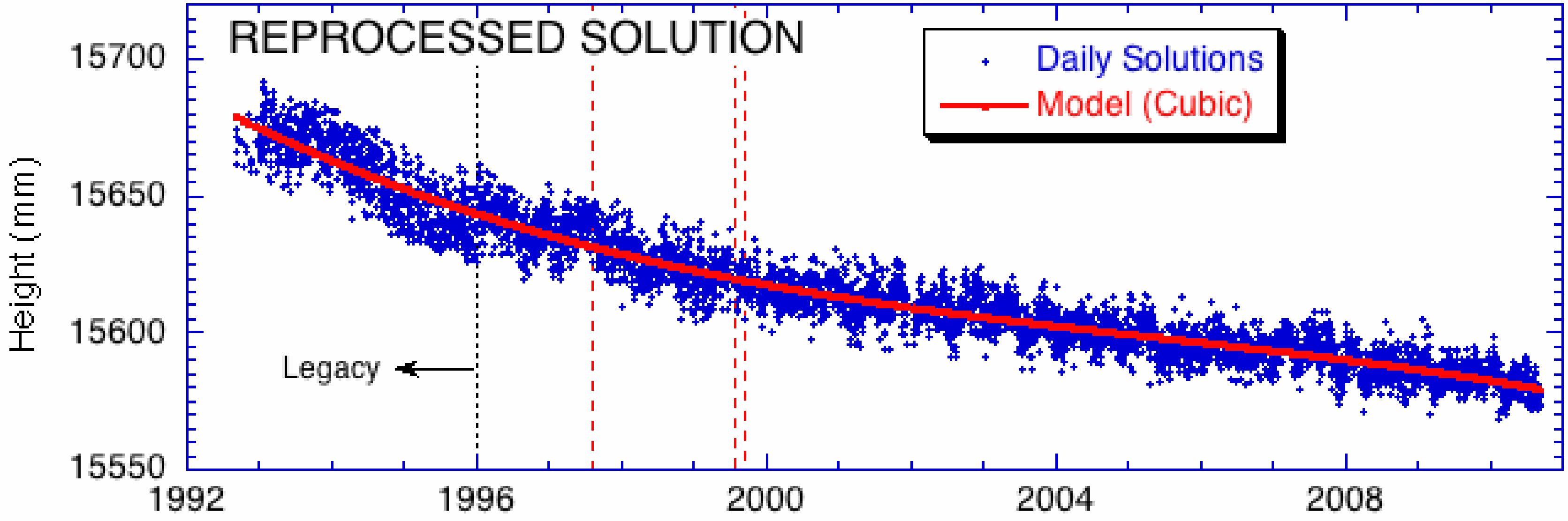
Evolution of Bias/Drift Estimates

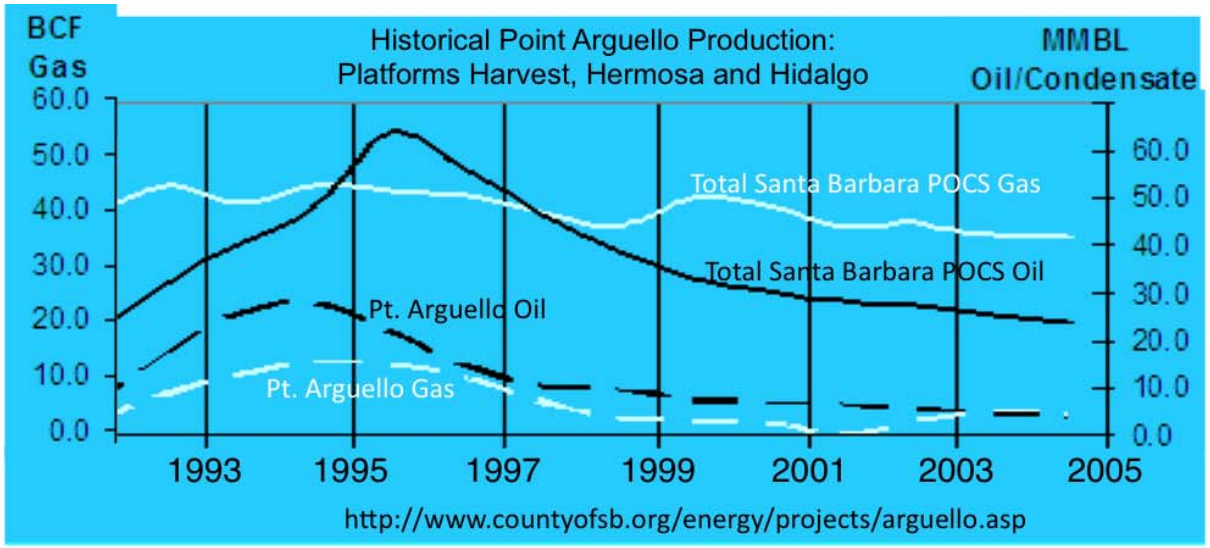
BIAS (mm)	Nice 2008	Seattle 2009	*Mar. Geod*. 2010	Lisbon 2010
Jason-2	+200	+174	+178	+176
Jason-1	+99	+94	+94	+87
ALT-B	+15	+14	+14	+10
Poseidon-1	+5	–10	–10	–5
ALT-A	+17	+1	+1	+7

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

- Impact of improved models for platform subsidence (from GPS measurements) is significant.
- Tide-gauge errors? See Washburn et al. (poster) for evaluation of primary (Bubbler) system against lidar

PXP Platform Harvest Geodetic Height From 18 Years of Continuous GPS Monitoring



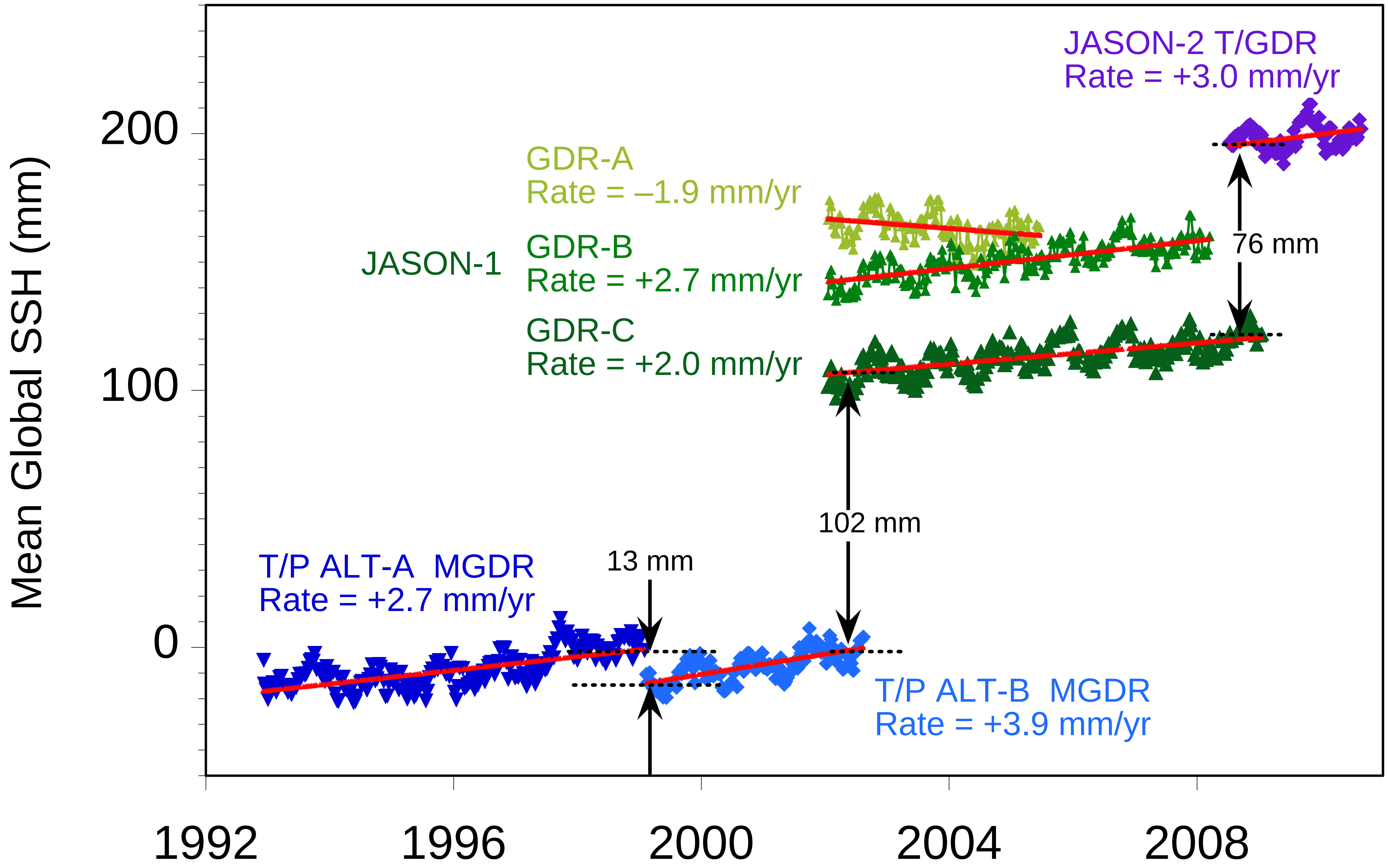


Oil/Gas Production from 1992–2005

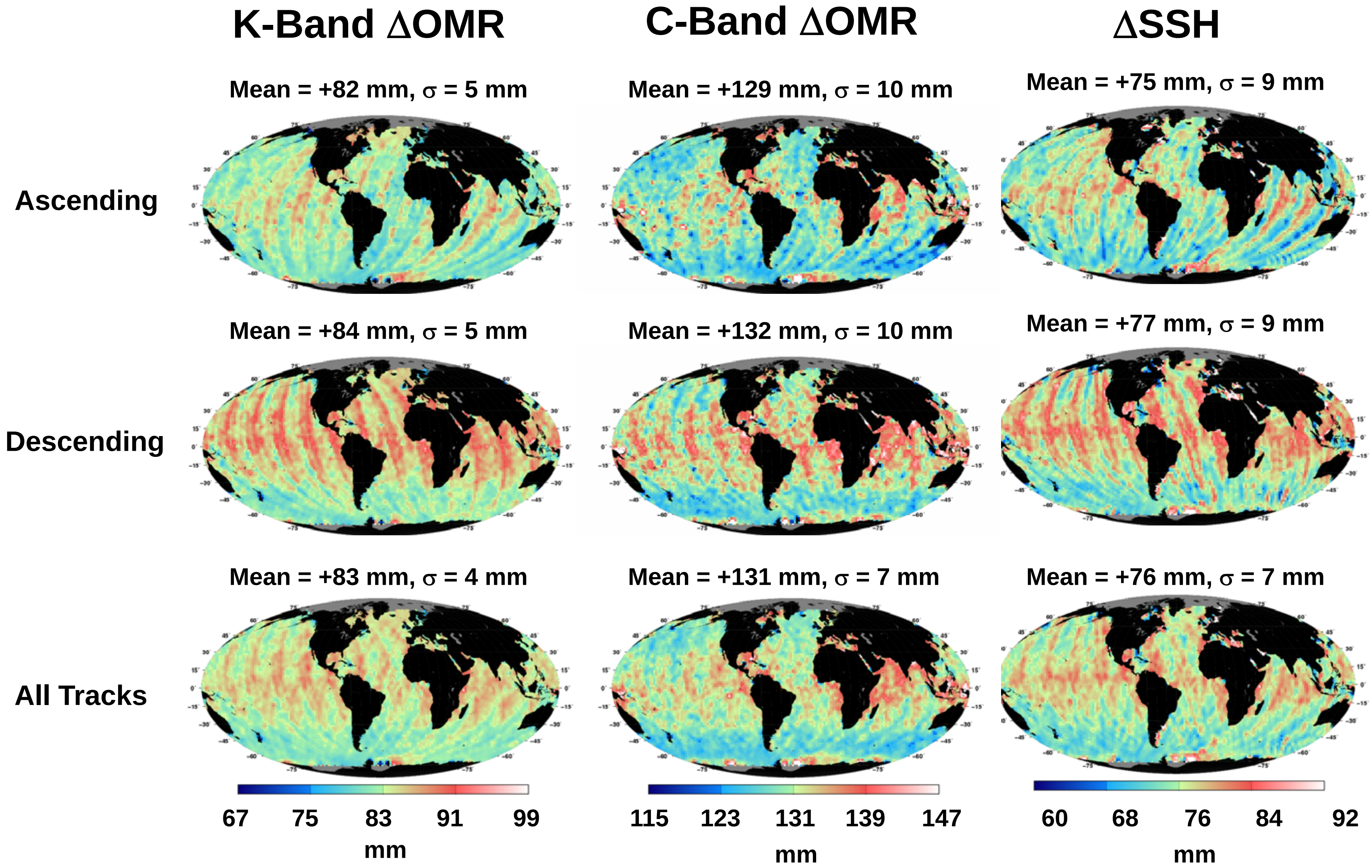
California Division of Oil, Gas and Geothermal Resources; Minerals Management Services

Backup Slides

Global Sea Level from T/P, Jason-1 and Jason-2:
UNCALIBRATED Record for 1992—2010



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

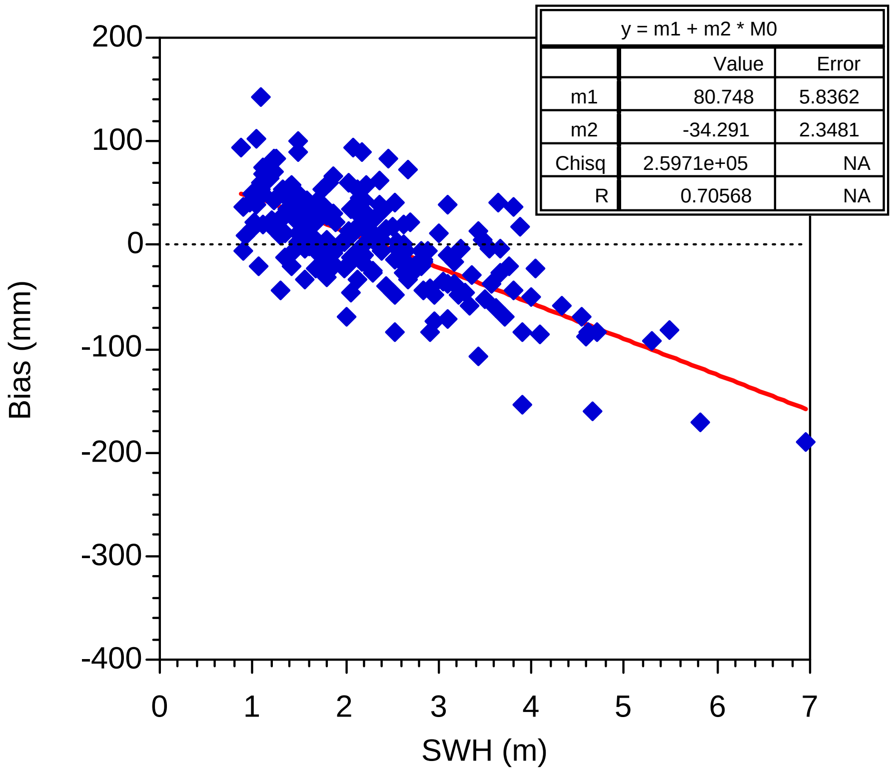


Absolute Ku- and C-Band SSH Biases

- **Begin with uncorrected Ku- and C-Band Ranges**
- **Compensate for troposphere using standard (GDR) approach**
  - Model dry troposphere
  - AMR/JMR wet troposphere
- **Compensate for ionosphere using independent measure**
  - GPS-based correction (JPL GIM; Mannucci et al.)
  - Ensure independence of potential inter-frequency altimeter bias (Ku-C) and ionosphere correction.
- **Do not compensate for sea-state bias (SSB)**
- **Do linear regression of SSH bias against SWH**
  - Use measurements from nearby buoy (Scripps) at Harvest.
- **Estimate SSH bias and local SSB simultaneously**
  - SSB model (local to Harvest) is a simple percentage of SWH.
  - Iterative 3-sigma edit (no other QC on closure data).
  - SSH Bias is intersection of model with SWH = 0.

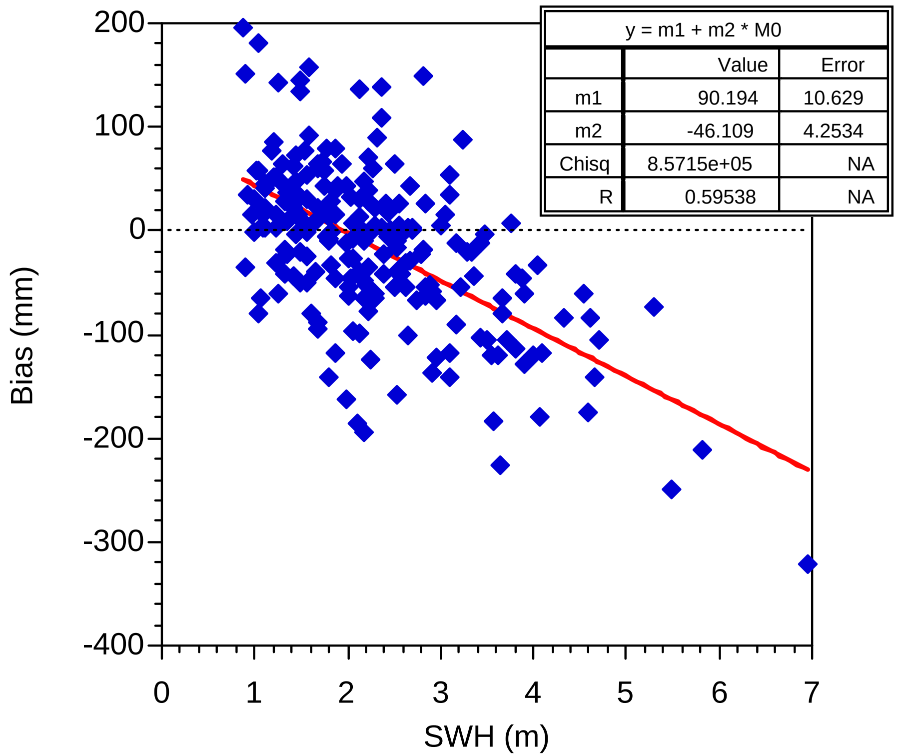
SSH uncompensated for sea-state bias

Jason-1 Ku-Band SSH vs SWH



y = m1 + m2 * M0		
	Value	Error
m1	80.748	5.8362
m2	-34.291	2.3481
Chisq	2.5971e+05	NA
R	0.70568	NA

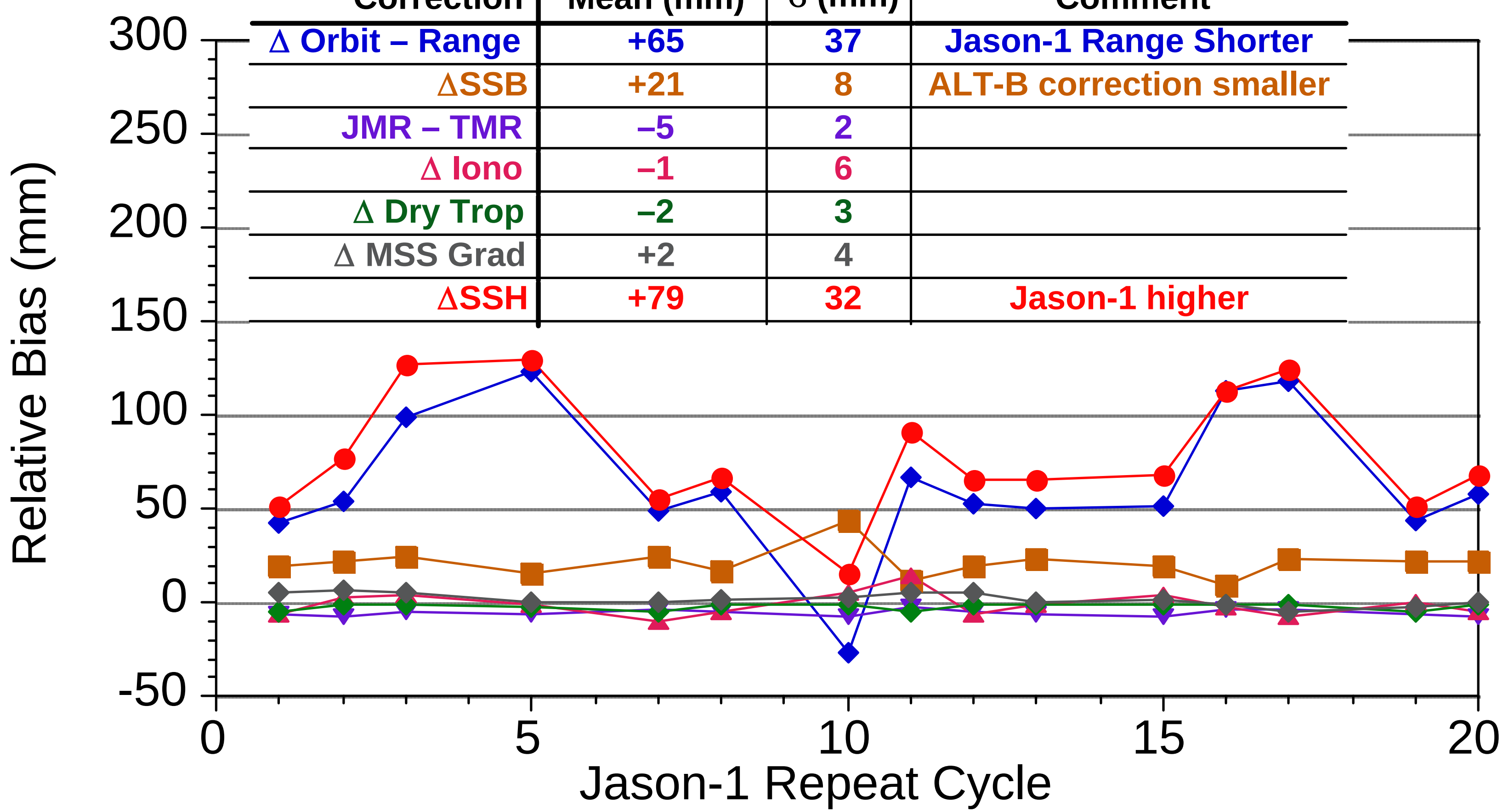
Jason-1 C-Band SSH vs SWH



y = m1 + m2 * M0		
	Value	Error
m1	90.194	10.629
m2	-46.109	4.2534
Chisq	8.5715e+05	NA
R	0.59538	NA

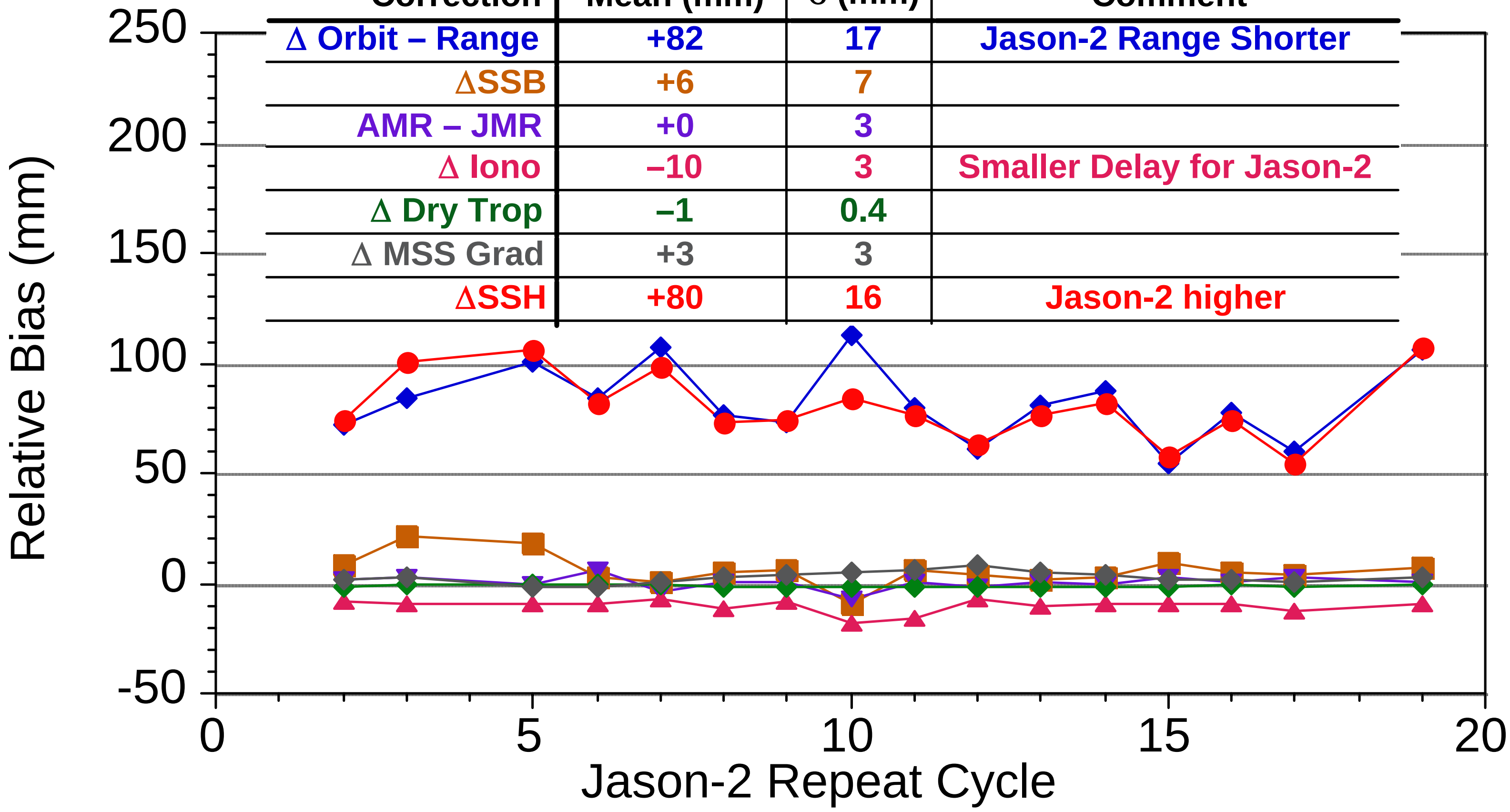
T/P Jason-1 Tandem Overflights of Harvest: Comparison of Correction Terms

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



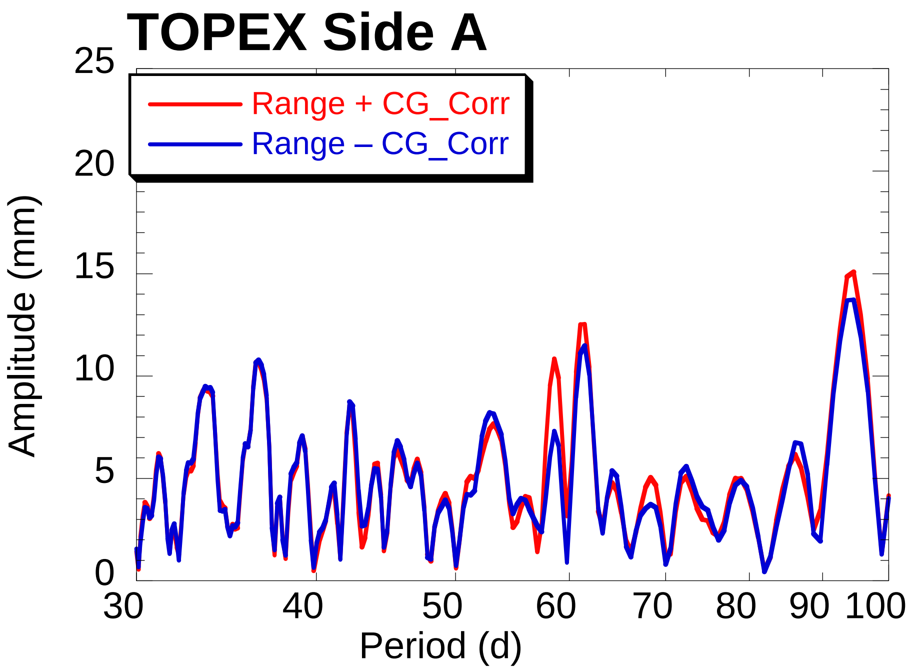
Jason 1/2 Tandem Overflights of Harvest: Comparison of Correction Terms

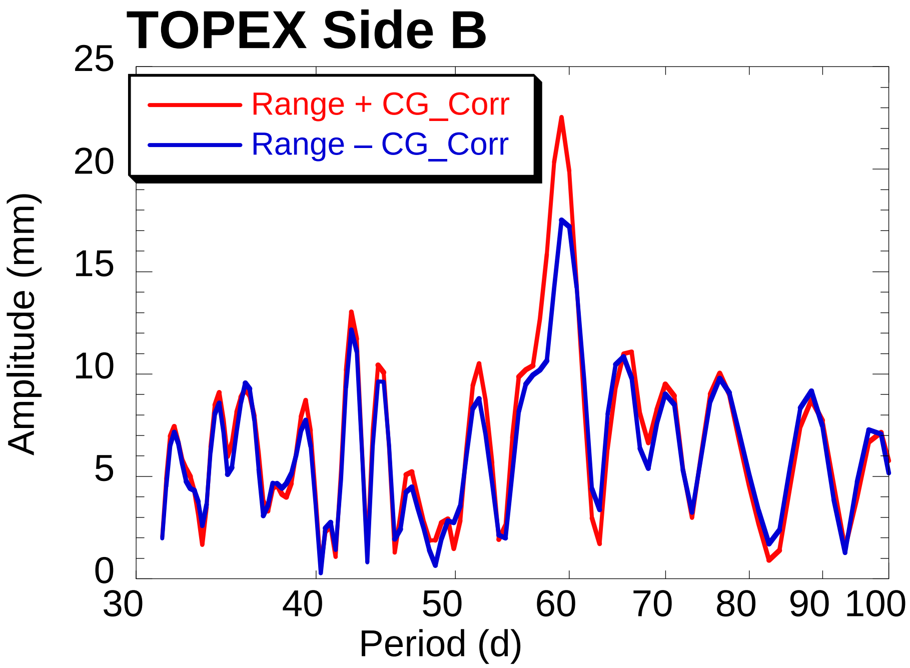
Correction	Mean (mm)	σ (mm)	Comment
Δ Orbit – Range	+82	17	Jason-2 Range Shorter
ΔSSB	+6	7	
AMR – JMR	+0	3	
Δ Iono	–10	3	Smaller Delay for Jason-2
Δ Dry Trop	–1	0.4	
Δ MSS Grad	+3	3	
ΔSSH	+80	16	Jason-2 higher



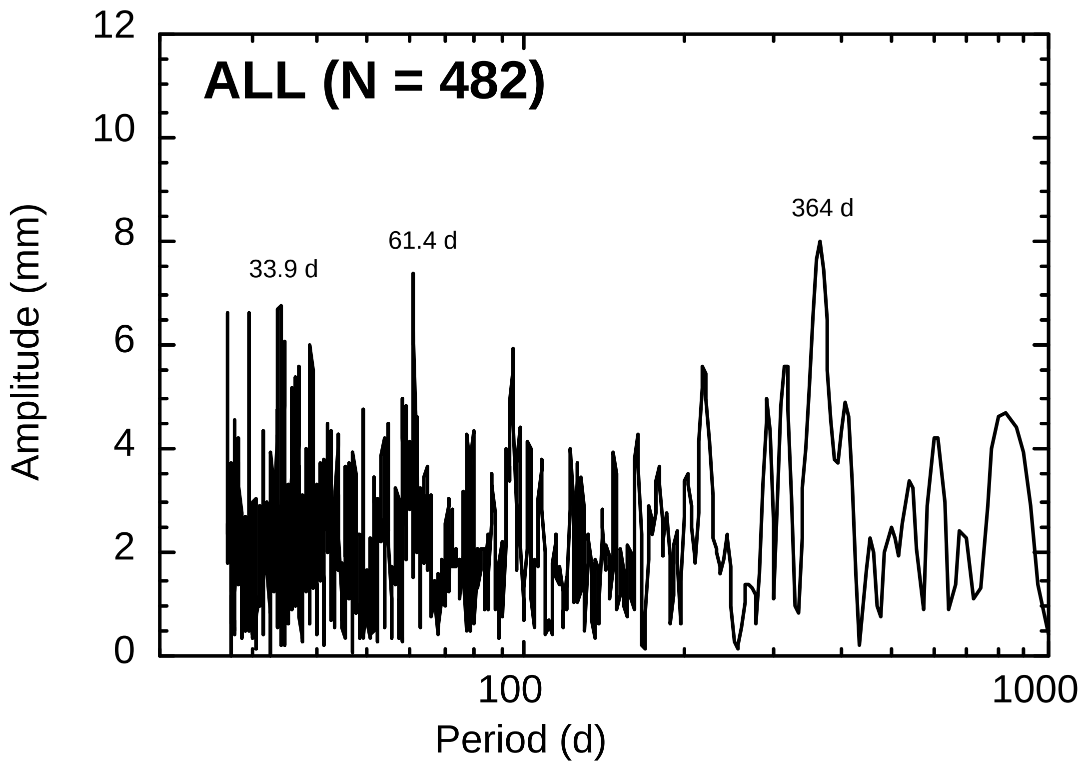
Jason-2 Radial Orbit Difference (POE vs GPS): σ = 6 mm; Mean = –1 mm (N = 79)

Impact of MGDR CG Correction for T/P





Periodogram of Combined SSH Bias Time Series



Evolution of Bias/Drift Estimates

BIAS	Nice 2008	Seattle 2009	Haines et al. (2010)	Mean (This Study)	Median (This Study)
Jason-2	+200	+174	+178	+176	+173
Jason-1	+99	+94	+94	+87	+87
ALT-B	+15	+14	+14	+10	+9
Poseidon-1	+5	–10	–10	–5	–6
ALT-A	+17	+1	+1	+7	+5

DRIFT	Nice 2008	Seattle 2009	Haines et al. (2010)	LSQ (This Study)	LAD (This Study)
Jason-2		–5	+15	+8	+10
Jason-1	+1	–2	–2	–2	–2
ALT-B	–2	–1	–1	–3	–4
Poseidon-1	–1	+3	+3	+1	–3
ALT-A	+0	+5	+5	+4	+4