IGS Clock Products Working Group Report

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18th Meeting of the Consultative Committee for Time and Frequency (CCTF)

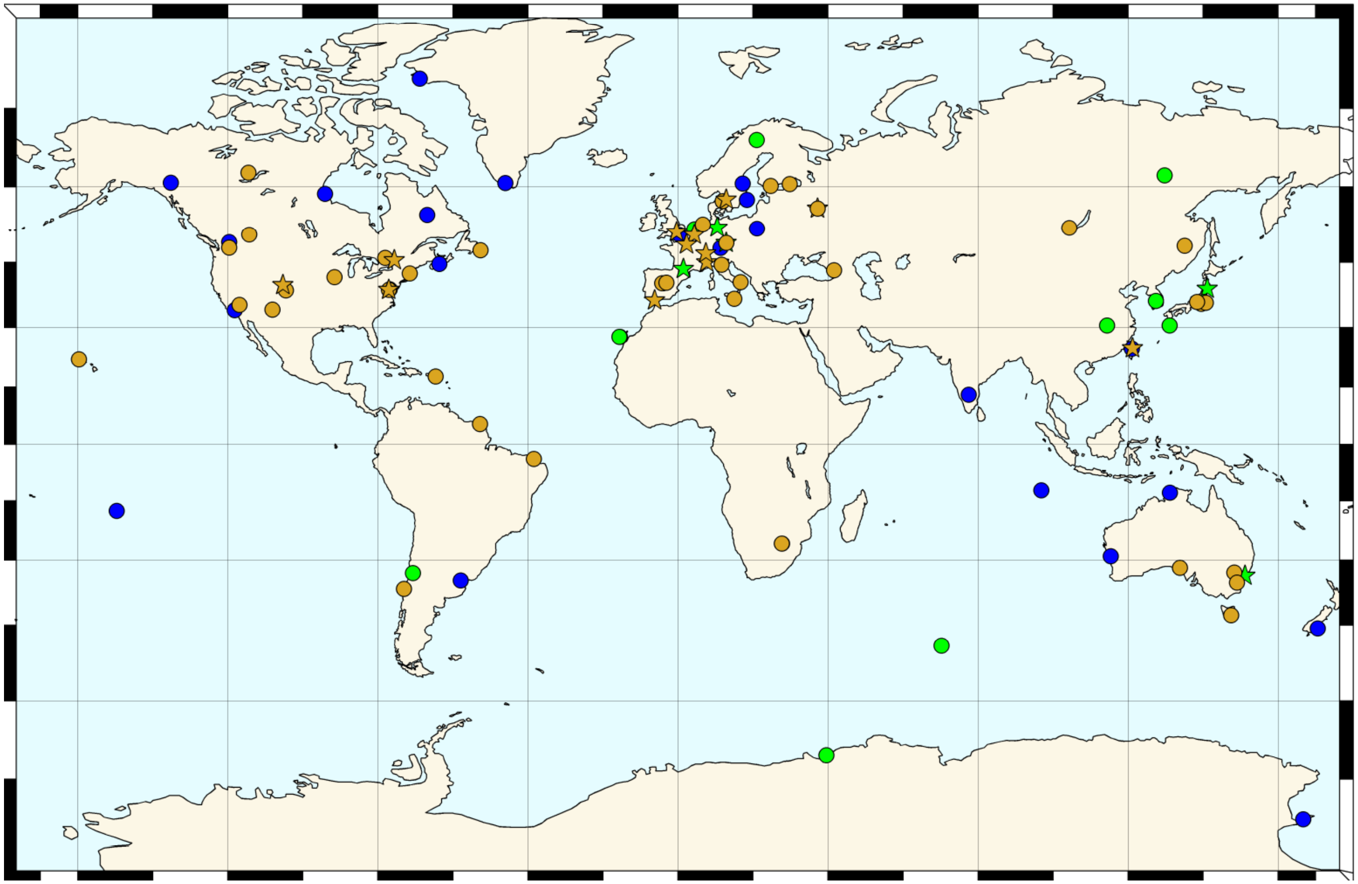
4-5 June 2009

Outline

- *IGS Product Status*
  - *Ultra-Rapid/Rapid/Final Products*
  - *New Real-Time Products*
- *Analysis of Subdaily GPS Satellite Clock Variations*
- *Day Boundary Monitoring & Antenna Installations*
- *New IGS Timescale Schedule*

IGS High Performance Clocks

IGS Site @ Labs	Time Lab	Freq. Std.
AMC2	AMC	H-Maser
BOR1	AOS	Cesium
BRUS	ORB	H-Maser
IENG	IEN	H-Maser
KGN0	CRL	Cesium
MDVJ	VNIIM	H-Maser
MIZU	NAO	Cesium
NISU/T	NIST	H-Maser
NPLD	NPL	H-Maser
NRC1/2	NRC	H-Maser
NRL1	NRL	H-Maser
OBE2	DLR	Rubidium
OPMT	OP	H-Maser
PENC	SGO	crystal
PTBB	PTB	Cesium
SFER	ROA	H-Maser
SPT0	SP	H-Maser
SYDN	NMI	Cesium
TLSE	CNES	Cesium
TWTF	TL	H-Maser
USNO/1	USNO	H-Maser
WAB2	CH	H-Maser
WTZA	IFAG	Cesium
WTZR	IFAG	H-Maser



masers (63) cesiums (43) rubidiums (25)

☆ time lab stations (22)

+ GPS space clocks …

SUMMARY OF IGS CORE PRODUCTS

PRODUCT SUITES	# ACs	CURRENT ACCURACY	LATENCY	UPDATES	SAMPLE INTERVAL	QUALITY ASSESSMENT
Ultra-Rapid *(predicted)*			real time	03, 09, 15, 21 UTC		
• orbits	7 (2)*	< 5 cm			15 min	marginally robust
• SV clocks	4	~5 ns			15 min	extremely poor
• ERPs	7 (2)*	< ~1 mas			6 hr	very weak
Ultra-Rapid *(observed)*			3 - 9 hr	03, 09, 15, 21 UTC		
• orbits	7 (2)*	~3 cm			15 min	fairly robust
• SV clocks	4	~0.2 ns			15 min	weak
• ERPs	7 (2)*	~0.1 mas			6 hr	fairly robust
Rapid			17 - 41 hr	daily		
• orbits	8	~2.5 cm			15 min	robust
• SV, stn clocks	5	~0.1 ns			5 min	marginally robust
• ERPs	8	~0.06 mas			daily	robust
Final			13 - 20 d	weekly		
• orbits	8	~2.5 cm			15 min	robust
• GLO orbits	4	< ~10 cm ?			15 min	not robust
• SV, stn clocks	6	~0.1 ns			5 min, 30 s	robust for 5 min
• ERPs	8	~0.03 mas			daily	robust
• terr frame	8	3 (h), 6 (v) mm			weekly	robust

** indicates AC contributions that are weaker than others*

IGS Real Time (IGS RT) Pilot Project

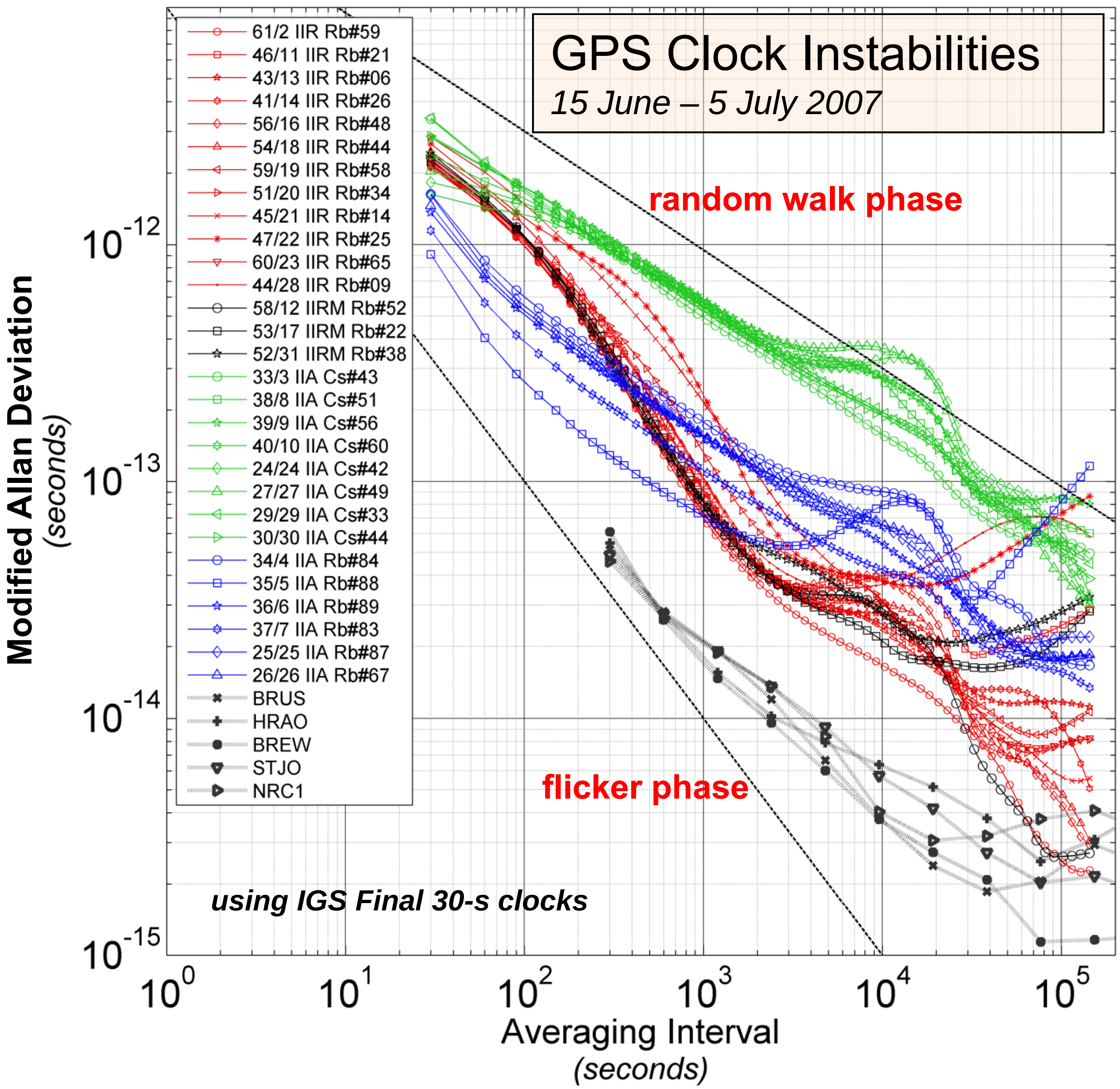
- Pilot began in 2008
- Goal: produce near-real time products with very frequent update
- 1 Hz data from ~60 global IGS real-time tracking stations
- 5 RT ACs participating in product generation
- Essentially utilizes IGU orbit predictions
- Expected update interval for clocks ~few seconds *(not yet determined)*
- *Not yet available to the public, but soon ….*

Sample orbit+clock results for Week 1534, Day 0 (31 May 2009)

Summary Table

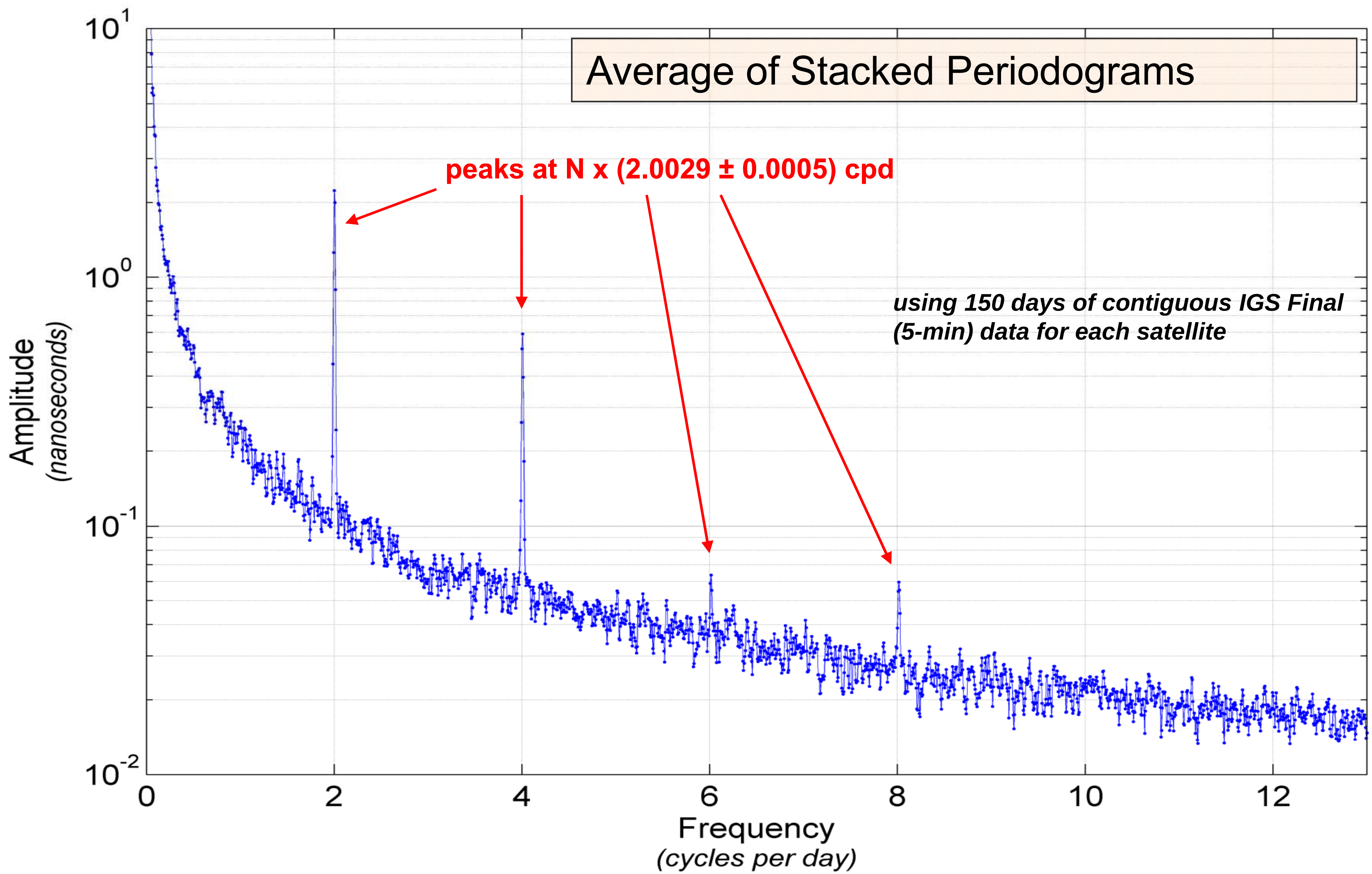
AC	nSats	OrbRMS(mm)	nSatClk	nUsed	SatRMS(ns)	SatSig(ns)
comb	30	0.0	8639	8430	0.26	0.15
bkg	30	66.9	8637	8428	0.76	0.15
bkg2	46	130.7	8616	8407	0.96	0.35
dlr	30	73.7	8640	8431	0.81	0.16
esoc	30	60.9	8640	8431	0.22	0.19
esoc2	30	63.7	8622	8413	0.23	0.19
nrc	30	46.2	8397	8192	0.27	0.18
gmv	30	64.0	8640	8431	0.86	0.84

Sub-daily Characteristics of GPS Clocks

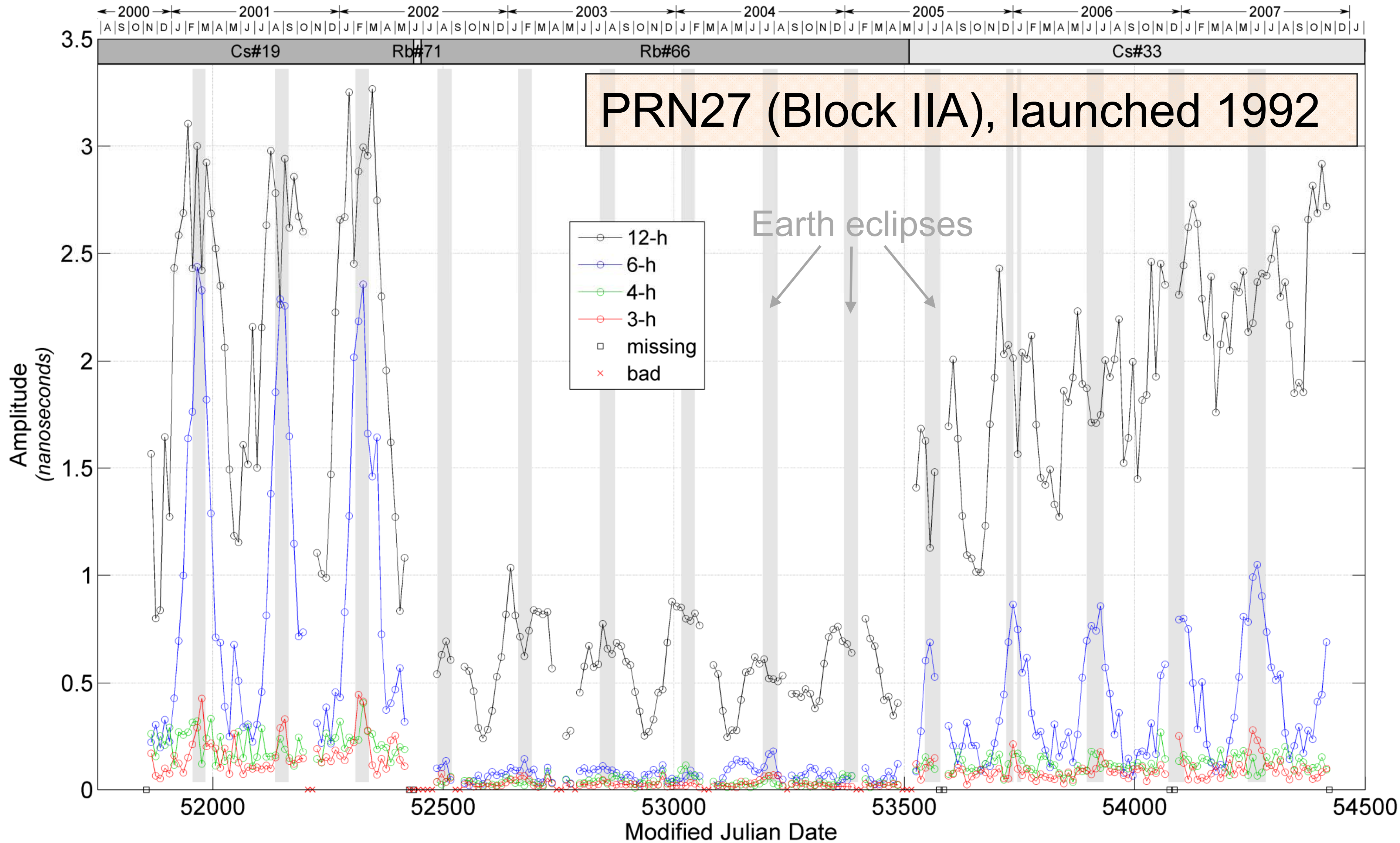


- IIA cesiums
  - poorest overall stability
  - behave mostly as random walk phase noise
  - MDEV power-law slope -1/2
  - excess deviations near 13,600 s
- IIA rubidiums
  - similar to Cs clocks but much more stable
  - flicker phase component for intervals < 100 s
  - also with excess near 13,600 s
- IIR & IIR-M rubidiums
  - newer generation clocks less stable than IIA Rb up to 1000 s
  - complex high-frequency behavior due to onboard Time Keeping System (TKS)
  - some excess near 13,600 s

12-hr Harmonics Pervasive in GPS Constellation



Temporal Variation of GPS Spectral Peaks

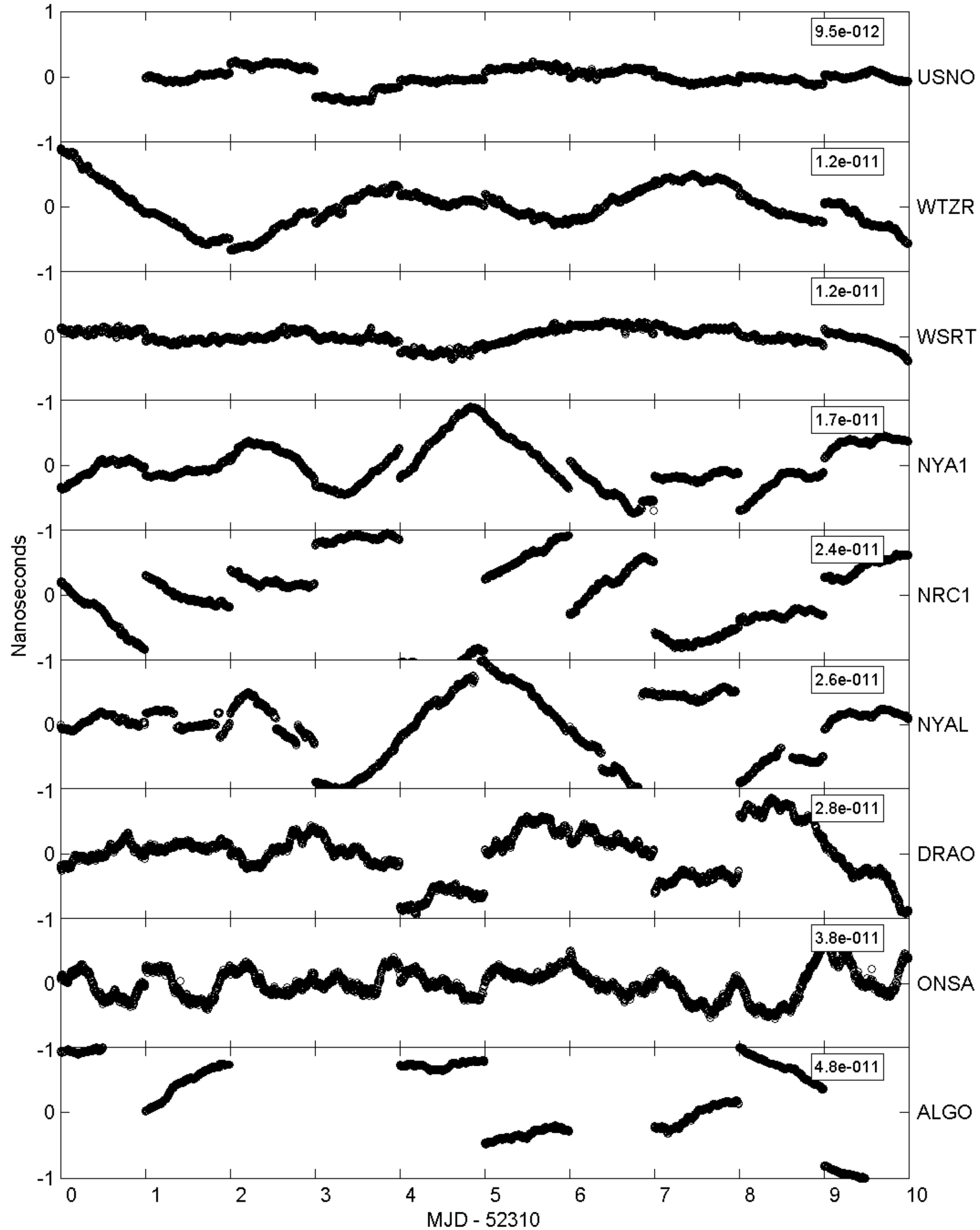


Summary of GPS Clock Variations

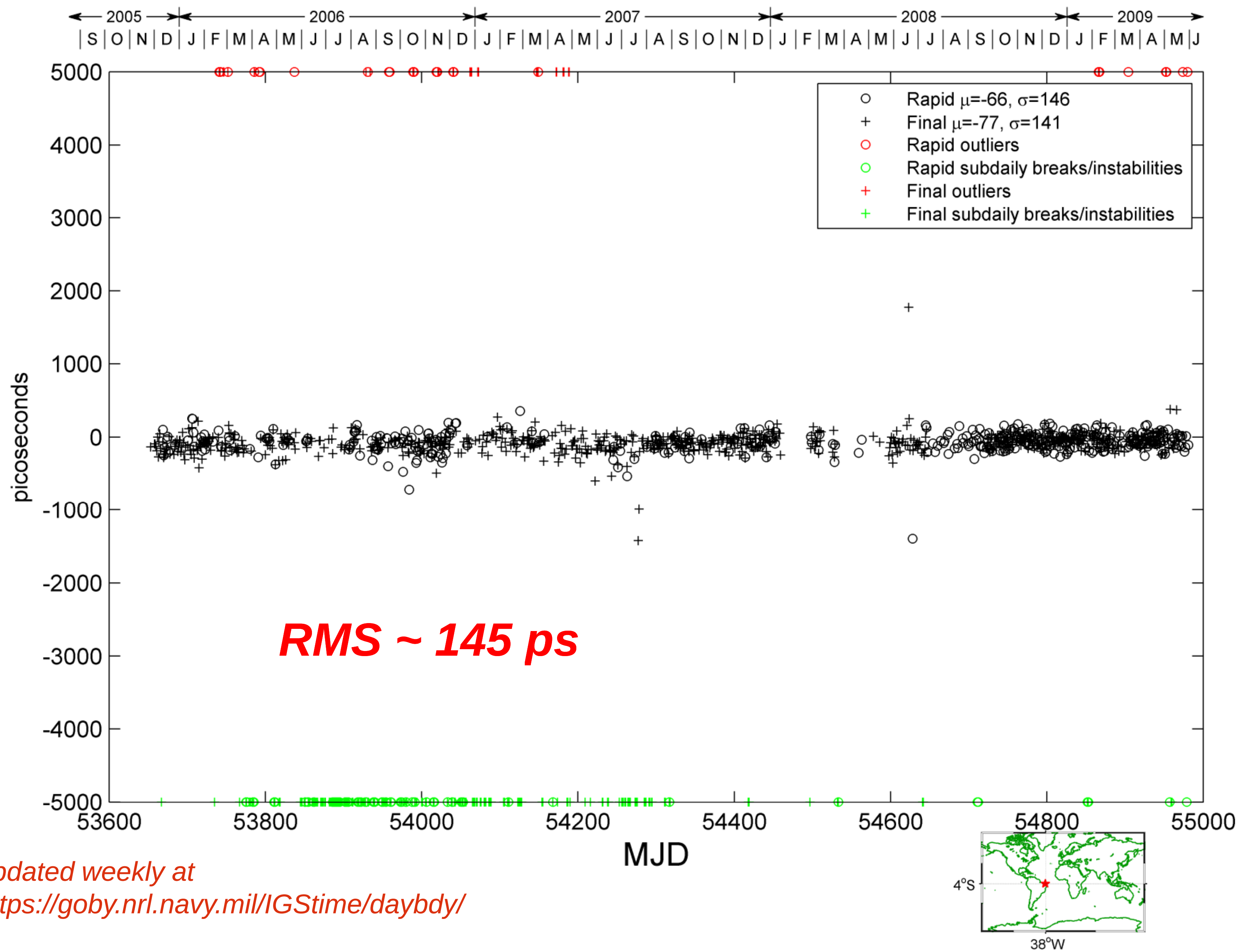
- IIA Cs clocks closely follow random walk behavior with poorest stability
- IIA Rb clocks similar but have much better stability plus high-frequency flicker phase component
- Newest IIR/IIR-M Rb clocks less stable than IIA Rb over intervals <1000 s but better for longer times
- GPS clocks show periodics at N x (2.0029 ± 0.0005) cpd or periods of (11.9826 ± 0.0030) / N hr for N = 1,2,3,4
  - —must be related to orbital dynamics but periods differ by 60 ± 11 s
- Prediction errors >100 ps (IGS accuracy) @ 40-50 s for IIA Cs & IIR Rb
- Prediction errors >100 ps (IGS accuracy) @ ~200 s for IIA Rb
- Latency for real-time clock service should be <50 s for errors <~100 ps

Examples of IGS estimated clocks w.r.t. IGST

- **Day-boundary clock discontinuities studied for all IGS H-maser sites**
- **Provide estimate of time transfer accuracy**
- **Clock bias accuracy is determined by mean code noise per arc**
- **For 24-hr arc with code σ = 1 m, clock accuracy should be ~120 ps**
- **Actual variances are highly site-dependent**
- **Some sites have seasonal variations**
- **Presumably caused by variable local code multipath conditions**
- **Long-wavelength (*near-field*) code multipath most important**
- **Performance depends on overall station data quality, esp cables & receivers & antenna installations**
- **Best sites have no discontinuities**

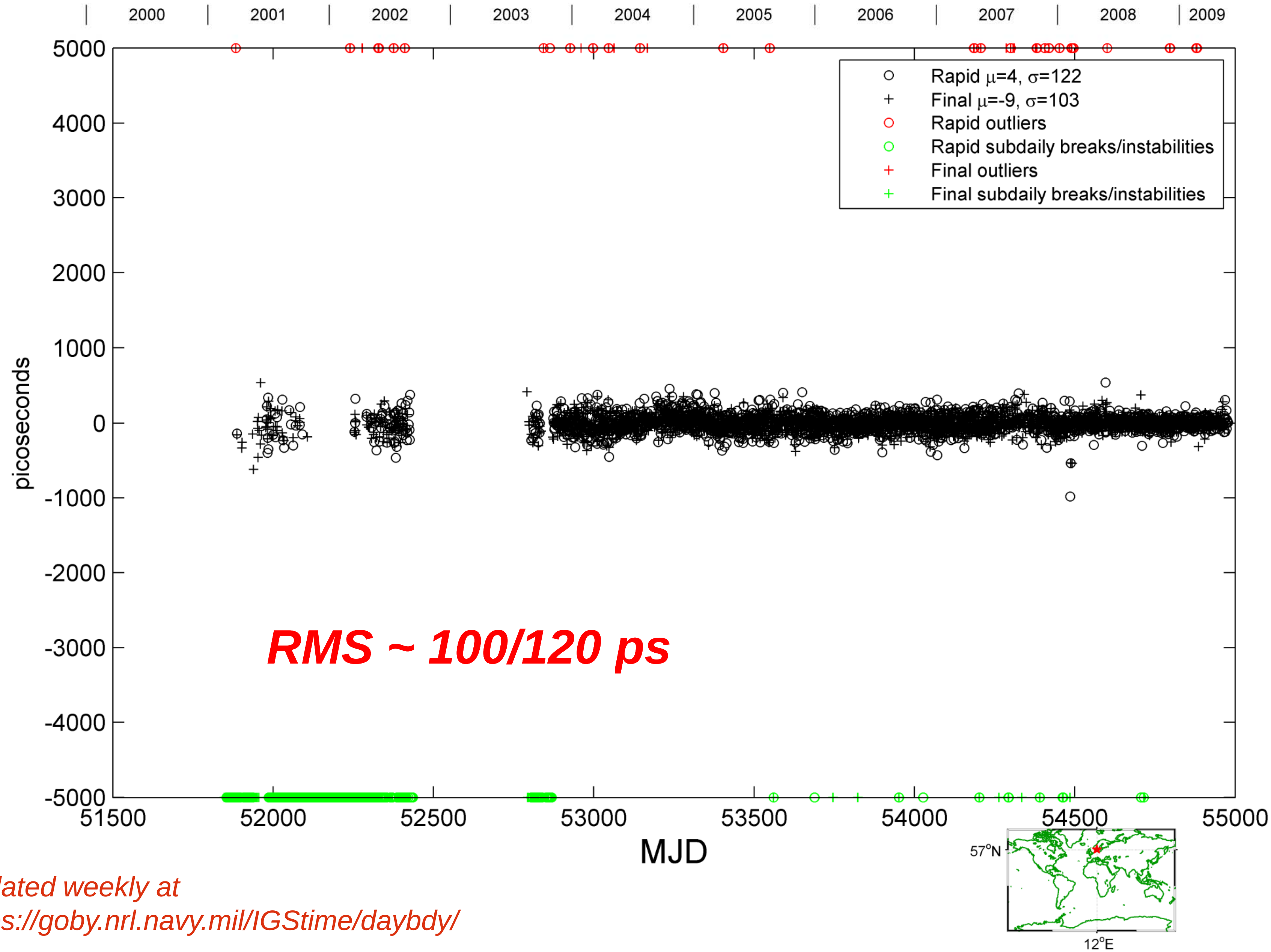


Day Boundary Discontinuities at BRFT



updated weekly at
https://goby.nrl.navy.mil/IGStime/daybdy/

Day Boundary Discontinuities at ONSA



updated weekly at
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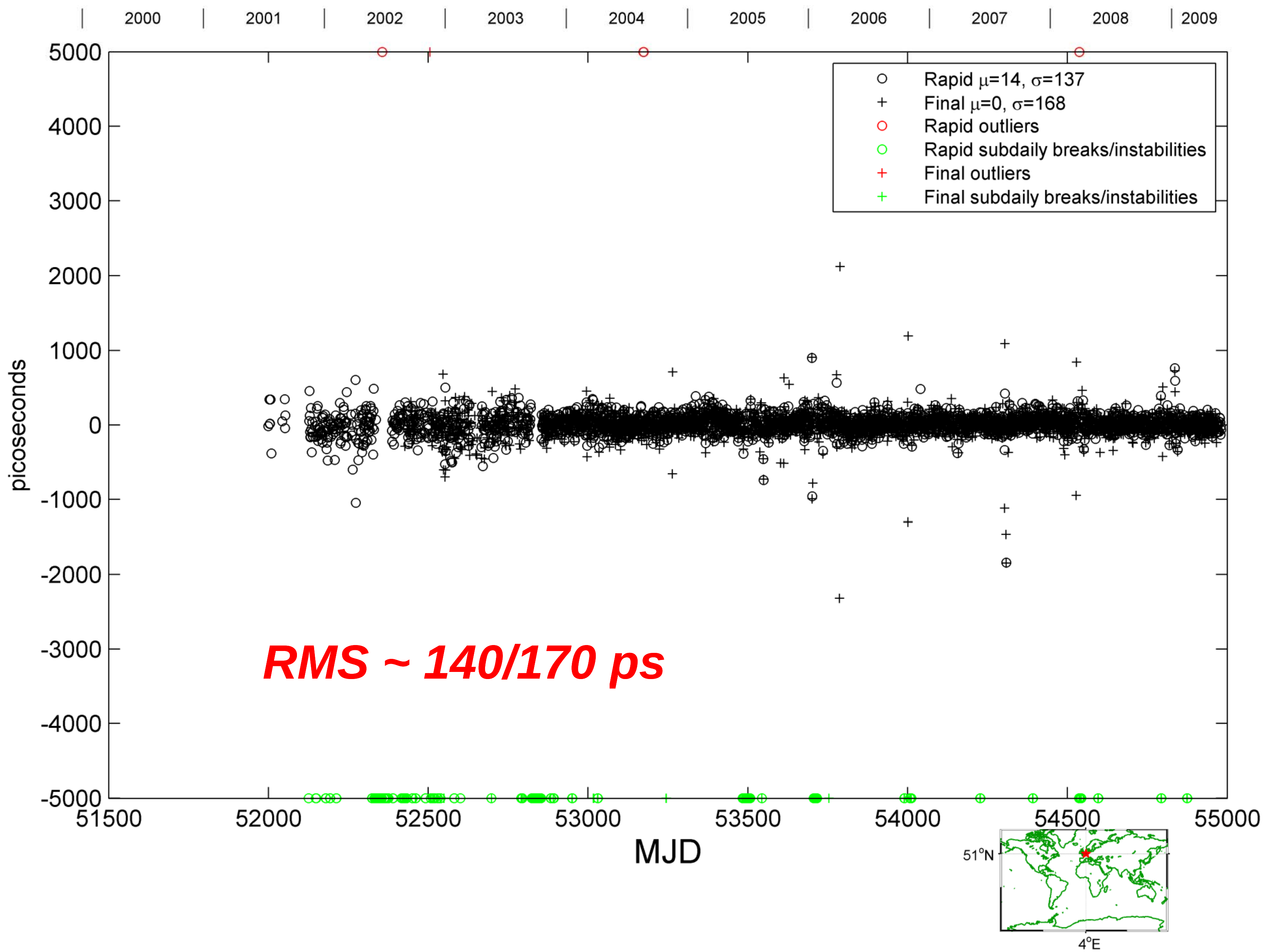
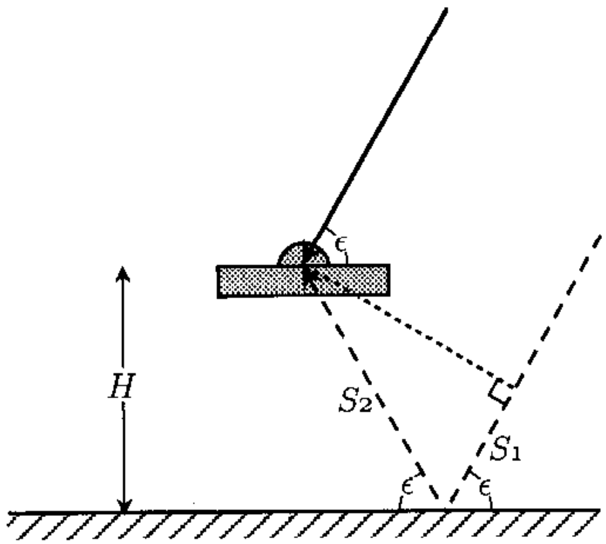
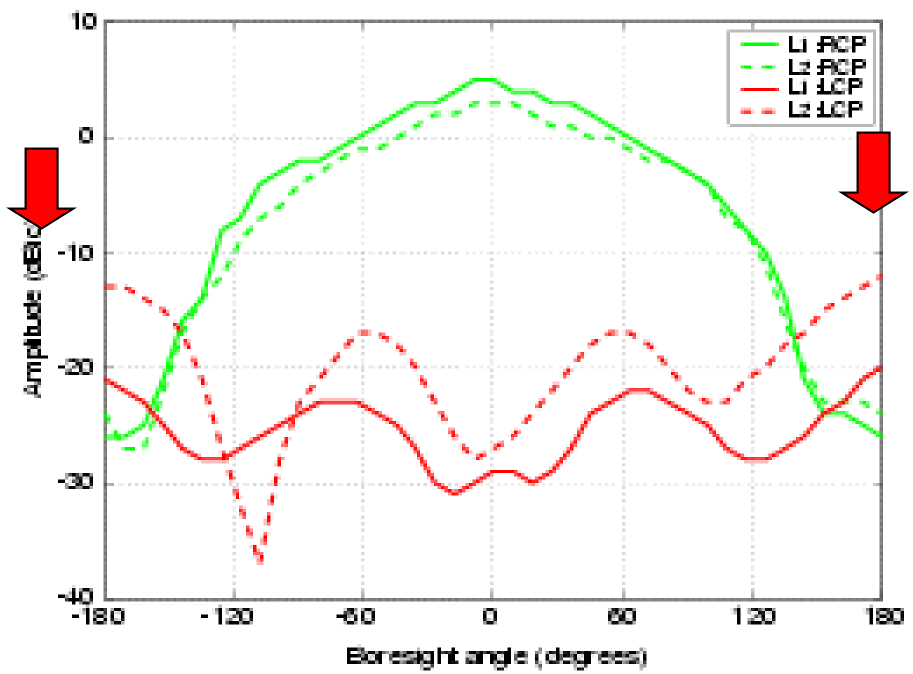
Day Boundary Discontinuities at BRUS



Near-field Multipath Hypothesis

- **Hypothesis: (J. Ray, 2005) Near-field standing-wave back reflection a likely cause of day-boundary discontinuities at many sites**
- **Expect longest-period MP errors when H (phase center to back surface) is smallest [Elósegui et al., 1995]**
- **Choke-ring design especially sensitive to L2 reflections from below [Byun et al. 2002]**
- **Most IGS RF stations use antenna mount over surface!**
- **Antenna installations should follow examples of best timing labs, such as BRFT, WAB2, ONSA & BRUS**





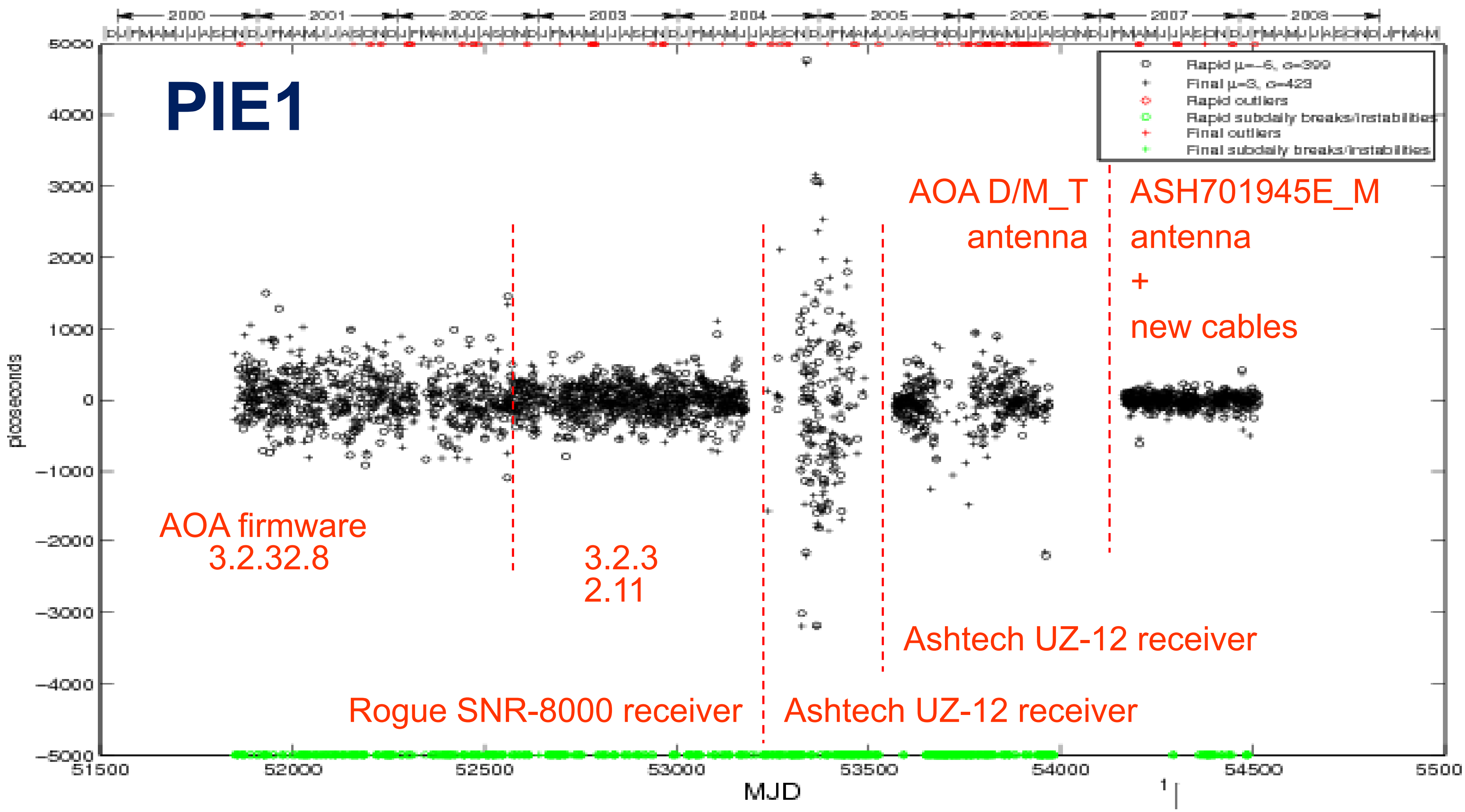
Poor Antenna Mounts



Good Antenna Mounts

choke-ring rests in a matrix of microwave absorbing material

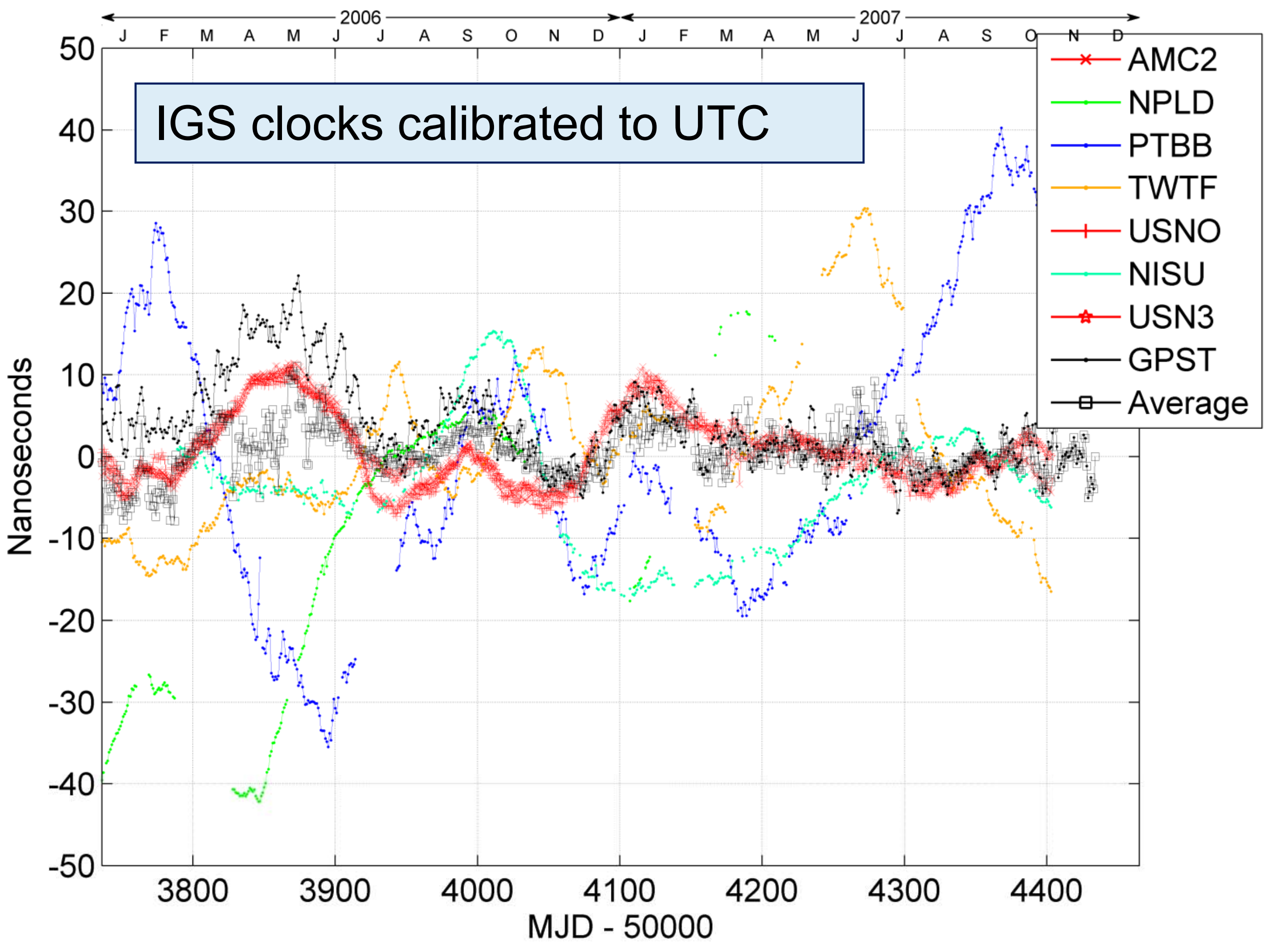
Other Hardware Choices Also Important



receiver health, firmware, antenna model, & cables also affect day-boundary clock jumps *(J. Ray , EGU 2008)*

New Timescale - Tie to UTC

- Current version relies on GPS Time as sole reference to UTC
- Multiple stations colocated at timing labs will provide a better quality & robust link to UTC; relatively calibrated to UTC using CircularT
- Stability of the average of these clocks suggests that a steering time constant of about 70 days will be appropriate.



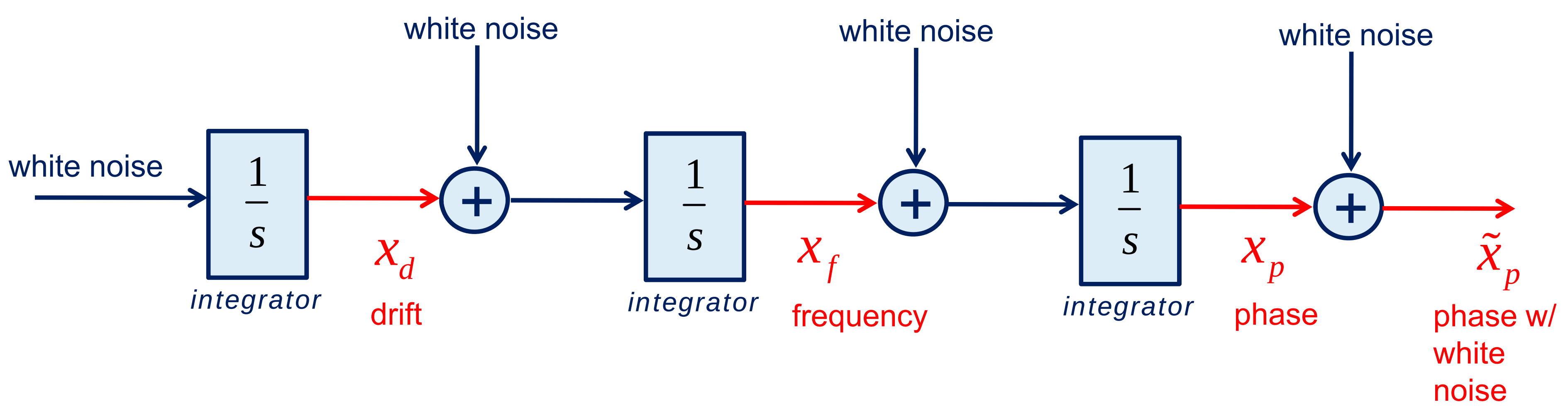
New Timescale Schedule

- Re-processing effort within the IGS still underway
  - Re-analysis of all GPS data back to 1994
  - First combined product results expected in late FY09/FY10
- New IGS timescale will be used in the reprocessed products, provided enough ACs contribute clocks
- IGS will eventually transition to new products as the official operational ones
- Paper on new timescale expected FY09/FY10

THANK YOU

BACKUPS

New Timescale Model – 8 states per clock



$$\mathbf{x} = \begin{bmatrix} \tilde{x}_p & x_p & x_f & x_d & a_{\omega_1} & b_{\omega_1} & a_{\omega_2} & b_{\omega_2} \end{bmatrix}^T$$

additional states to model two harmonics (e.g., 6- & 12-hour)

Process noise models:
- WH phase
- RW phase
- RW freq.
- RW drift

Timescale Constraints

Stein, '94

- Observability problem
  - Only clock (phase) ***differences*** are measured.
  - 4 independent excitations per clock implies 4 new constraints necessary to isolate *individual* clock excitations:

multiple clock weights

$$\sum_{i=1}^{N} a_i \left(\tilde{x}_p^{(i)}(t+\delta \mid t) - \tilde{x}_p^{(i)}(t+\delta) \right) = 0$$

$$\sum_{i=1}^{N} b_i \left(x_p^{(i)}(t+\delta \mid t) - x_p^{(i)}(t+\delta) \right) = 0$$

$$\sum_{i=1}^{N} c_i \left(x_f^{(i)}(t+\delta \mid t) - x_f^{(i)}(t+\delta) \right) = 0$$

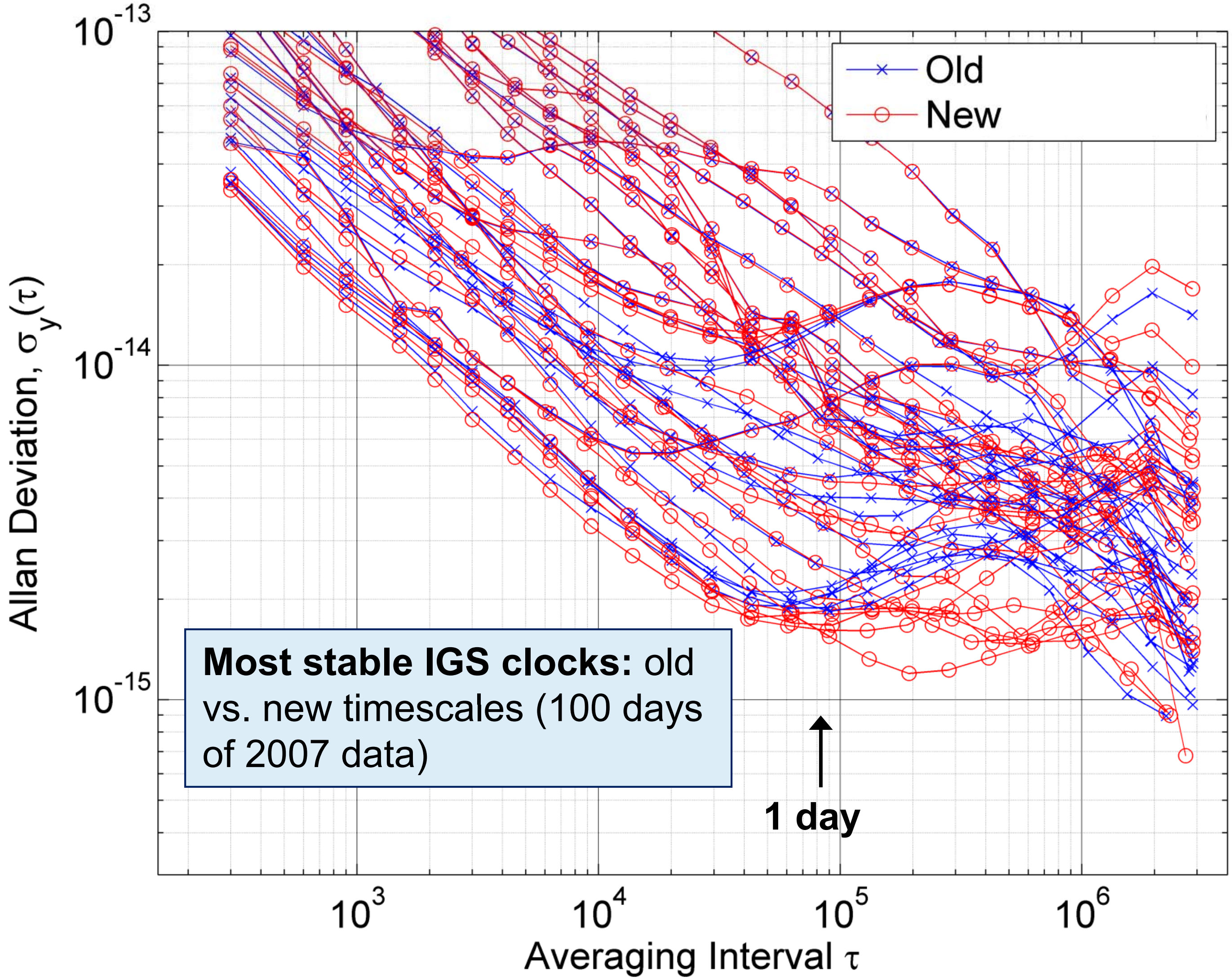
$$\sum_{i=1}^{N} d_i \left(x_d^{(i)}(t+\delta \mid t) - x_d^{(i)}(t+\delta) \right) = 0$$

Solves the observability problem by assuming that each collection of noise inputs are zero on weighted average.

Note that three of the four will suffice to constrain the solution; also, measurement noise & WHPH are not distinguishable., so care must be taken w/ large measurement noise.

New Timescale Results

New version shows improved stability from 1 day to ~10 days; however, steering of new scale not completely implemented



Multiple Per Clock Weighting

- New multiple weighting per clock allows a timescale which is optimized over a wide range of intervals:

  e.g., ~ 1 day,

  ~ 10 days, &

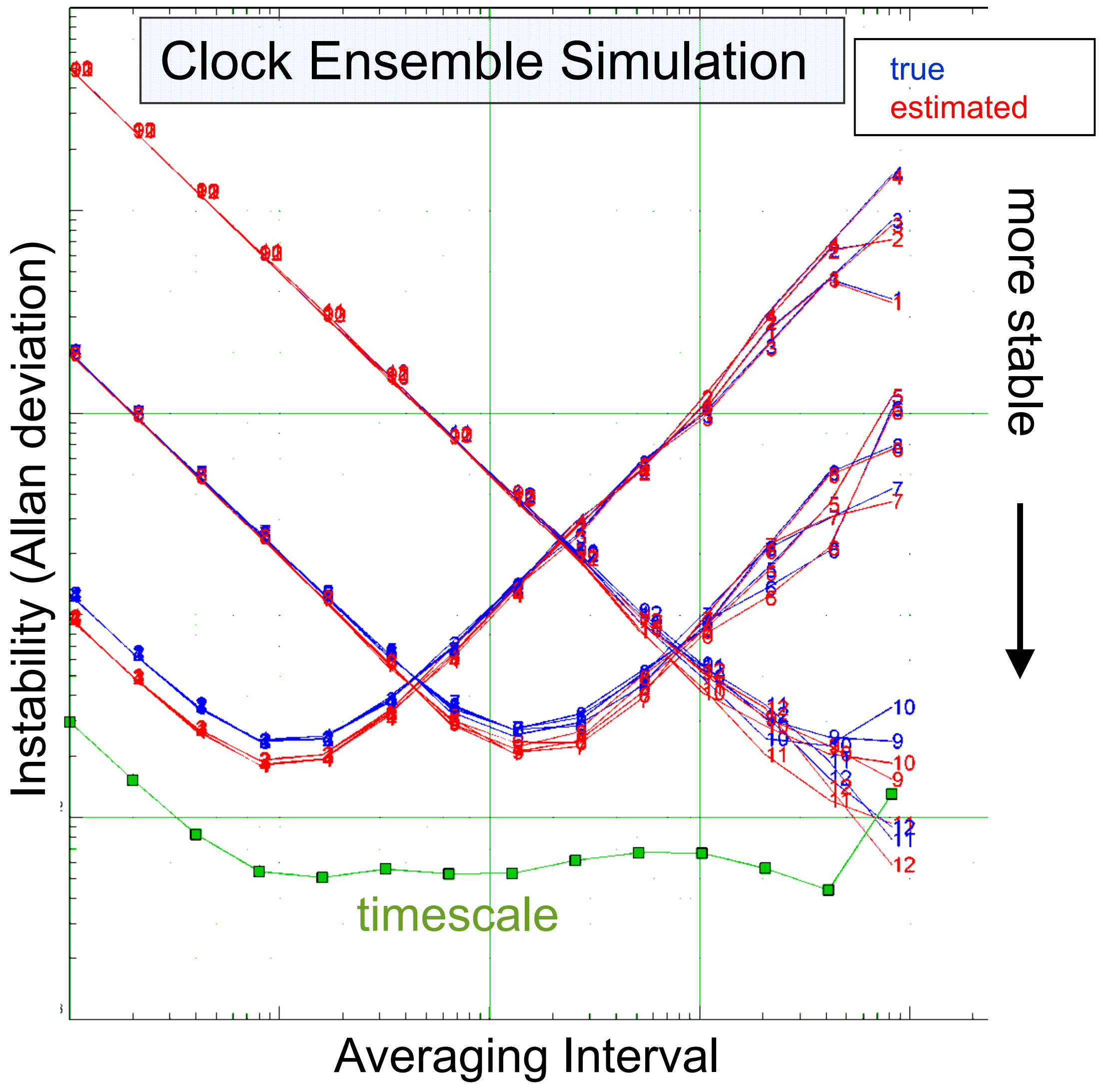
  ~ months)

a_i ~ inverse WH ph level for clock i

b_i ~ inverse RW ph level for clock i

c_i ~ inverse RW fr level for clock i

d_i ~ inverse RW dr level for clock i



4 cpd Peak – Neglected Relativistic J_2 Effect

- GPS clock frequencies aligned approximately to Terrestrial Time (IS-GPS-200), for convenience
- Users should account for effect of orbit eccentricity using $-2(\mathbf{r}\cdot\mathbf{v})/c^2$ correction
- Unmodeled J_2 (oblateness) effect is ~70 ps variation with 6-hr period (+ longer-period effects) – *J. Kouba (2004)*

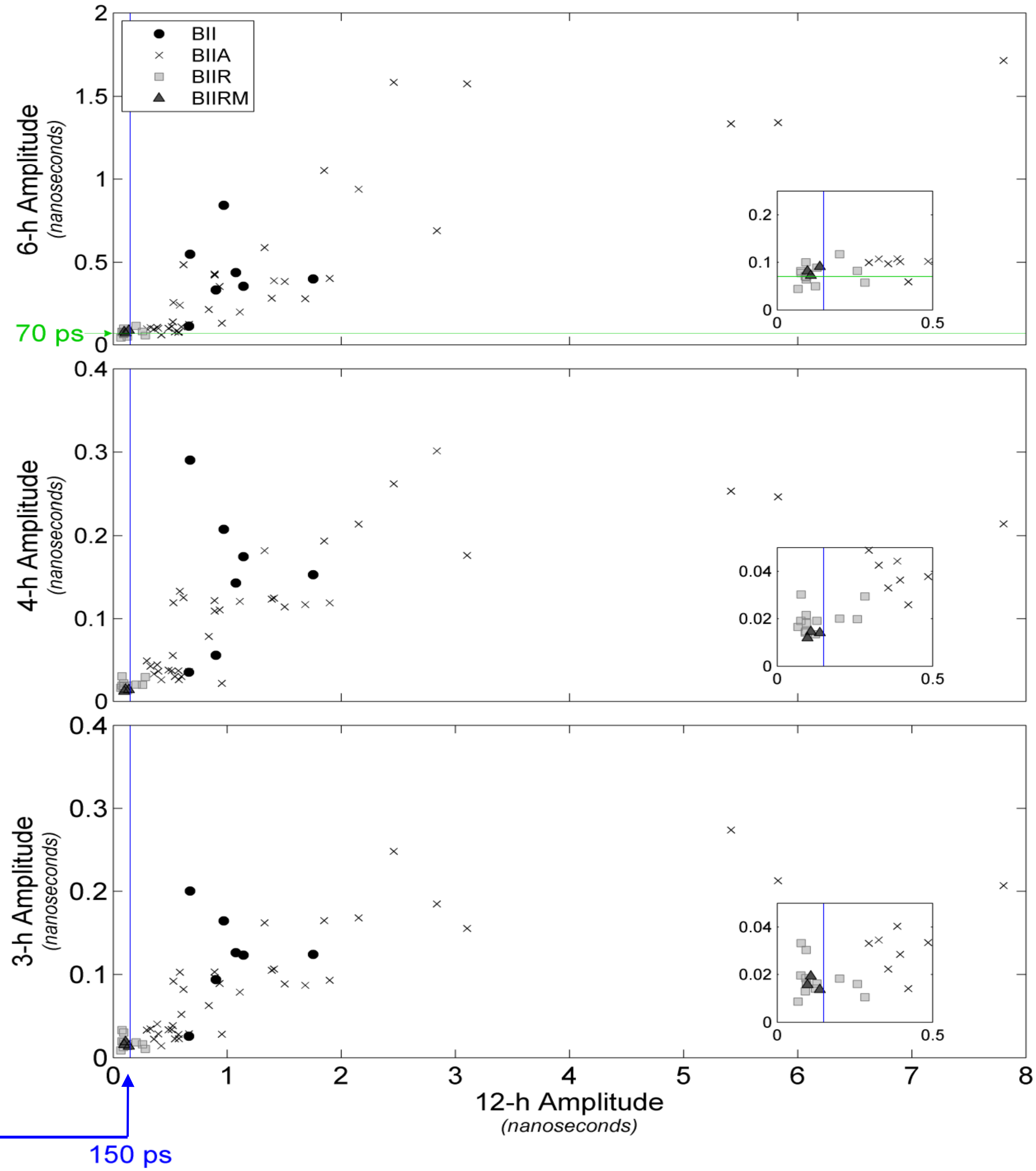
Approximate (~90%) correction can be made using:

$$\Delta t^{\mathrm{rel}} = \left[446.47\times10^{-12} + \delta\Delta t_{\mathrm{con}}(a_0)\right]t - 2(\mathbf{r}\cdot\mathbf{v})/c^2 + \delta\Delta t^{\mathrm{per}}$$

$$\delta\Delta t^{\mathrm{per}} = -\frac{a_E^2}{2a^2c^2}J_2\left[3\sqrt{GMa}\sin^2(i)\sin(2u) - 7\frac{GM}{a}\left(1-\frac{3}{2}\sin^2 i\right)t\right]$$

a semi-major axis u argument of latitude i inclination $J_2 = 1.083\times10^{-3}$

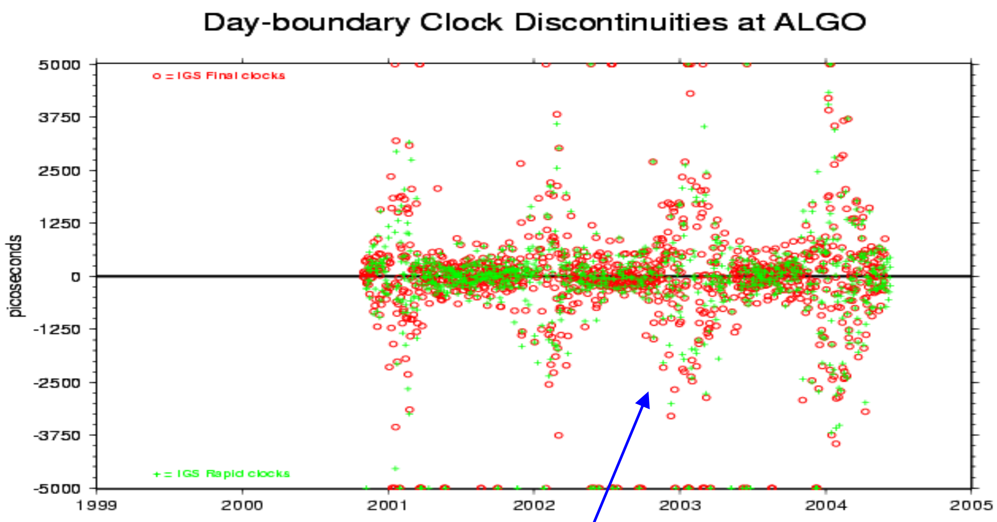
Correlations Between Spectral Peaks

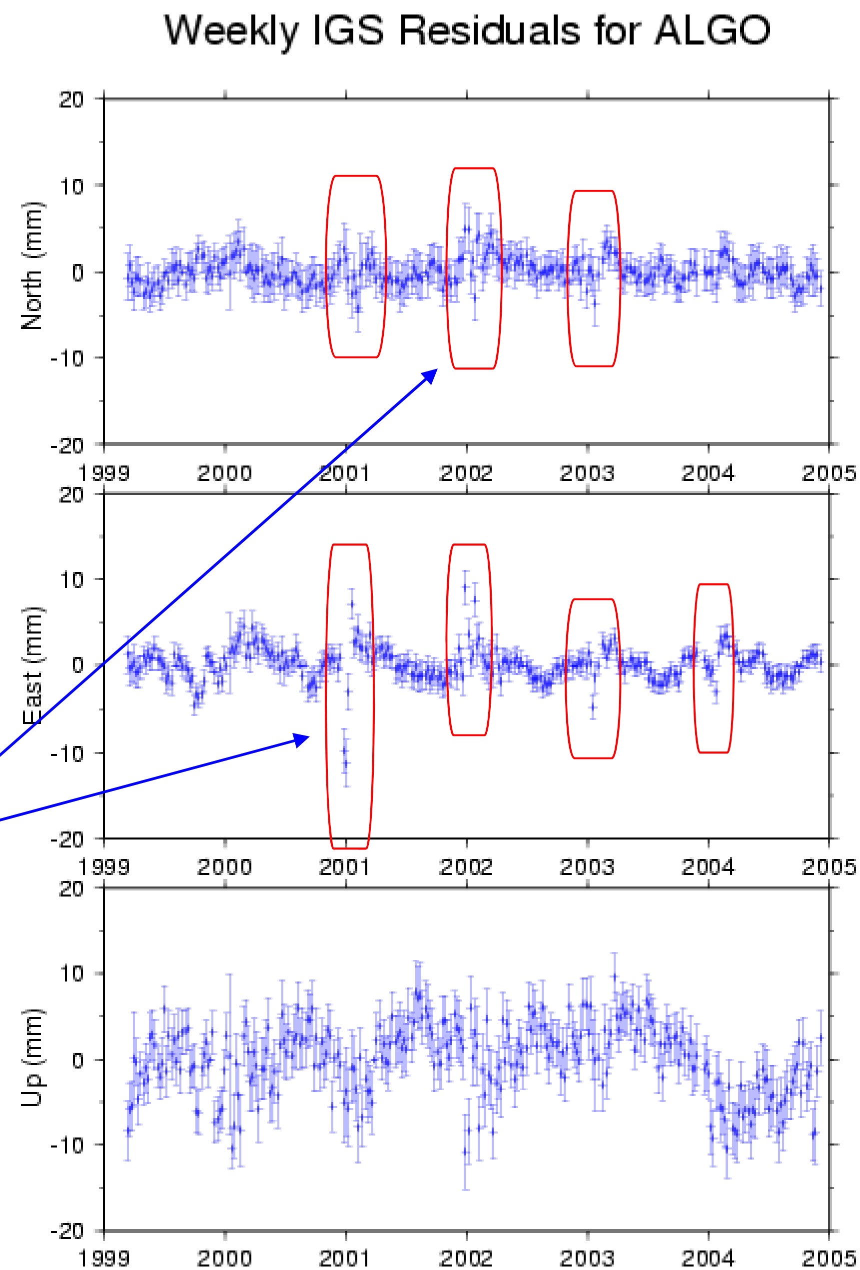


Neglected J_2 effect not large enough to fully account for observed 6-hr periodic

Max average orbit inaccuracy

Correlated Clock & Position Effects:





- ALGO day-boundary clock jumps increase in winters
- every winter ALGO also has large position anomalies
  - IGS deletes outliers >5 σ
- implies common near-field multipath effect is likely (phase & code)

J. Ray, EGU 2008