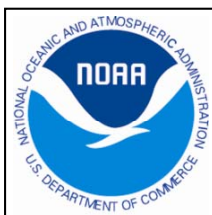


STATUS OF IGS CORE PRODUCTS

- Summary of current IGS core product attributes
- Ultra-Rapid, Rapid, & Final product series
 - orbits, ERPs, clocks, & station positions
 - some issues & concerns
 - accuracy & precision assessments
 - opportunities for improvements
- Goals for 2nd IGS Reprocessing Campaign



Jim Ray, NOAA/NGS
Jake Griffiths, NOAA/NGS



IGS Core Product Lines (2010)

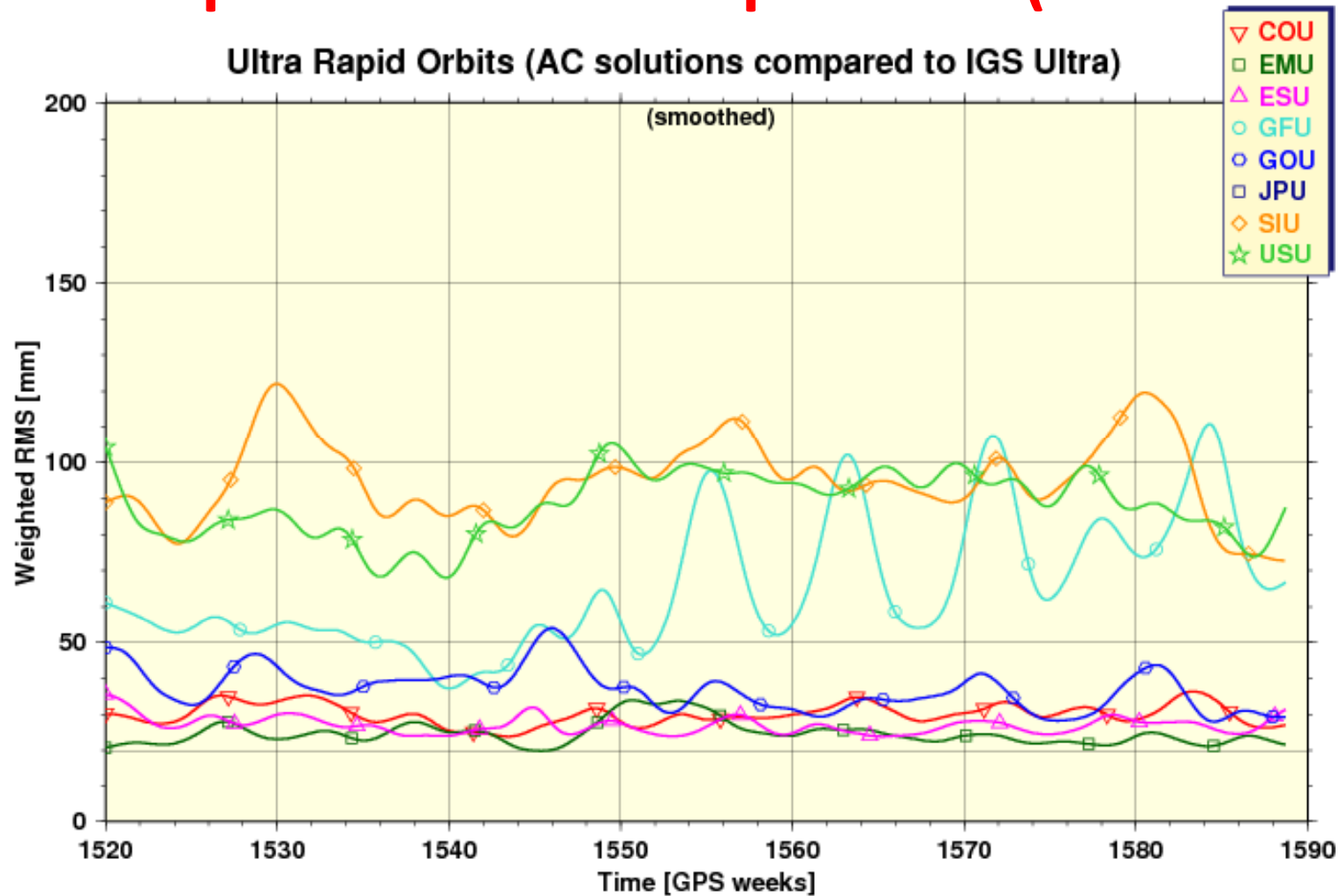
Series	ID code	Latency	Issue times (UTC)	Data spans (UTC)	Remarks
Ultra-Rapid (predicted half)	IGU	real-time	@ 03:00, 09:00, 15:00, 21:00	+24 hr @ 00:00, 06:00, 12:00, 18:00	<ul style="list-style-type: none"> ● for real-time apps ● GPS only ● issued with prior IGA
Ultra-Rapid (observed half)	IGA	3 - 9 hr	@ 03:00, 09:00, 15:00, 21:00	-24 hr @ 00:00, 06:00, 12:00, 18:00	<ul style="list-style-type: none"> ● for near real-time apps ● GPS only ● issued with following IGU
Rapid	IGR	17 - 41 hr	@ 17:00 daily	±12 hr @ 12:00	<ul style="list-style-type: none"> ● for near-definitive, rapid apps ● GPS only
Final	IGS	11 - 17 d	weekly each Thursday	±12 hr @ 12:00 for 7 d	<ul style="list-style-type: none"> ● for definitive apps ● GPS & GLONASS

IGS Product Types & ACs (June 2010)

Series	Product types	# of contributing ACs			Output sample interval
		Submit	Reject	Used	
Ultra-Rapid (IGA + IGU)	• GPS orbits	7	3	4	15 min
	• GPS SV clocks	4	1	3	15 min
	• ERPs: PM / LOD	6 / 6	2 / 3	4 / 3	6 hr
Rapid (IGR)	• GPS orbits	8	0	8	15 min
	• GPS SV clocks	6	1	5	5 min
	• station clocks	6	1	5	5 min
	• ERPs: PM / LOD	8 / 8	2 / 1	6 / 7	daily
Final (IGS)	• GPS orbits	9	~1	~8	15 min
	• GPS SV clocks	7	1	6	5 min
	• station clocks	5	1	4	30 s
	• GLO orbits	7	1	6	5 min
	• GLO SV clocks	6	1	5	15 min
	• GLO SV clocks	3	3	0	none
• ERPs: PM / LOD	9 / 9	~2 / ~3	7 / 6	daily	
• Terrestrial frame	9	~1	~8	weekly	

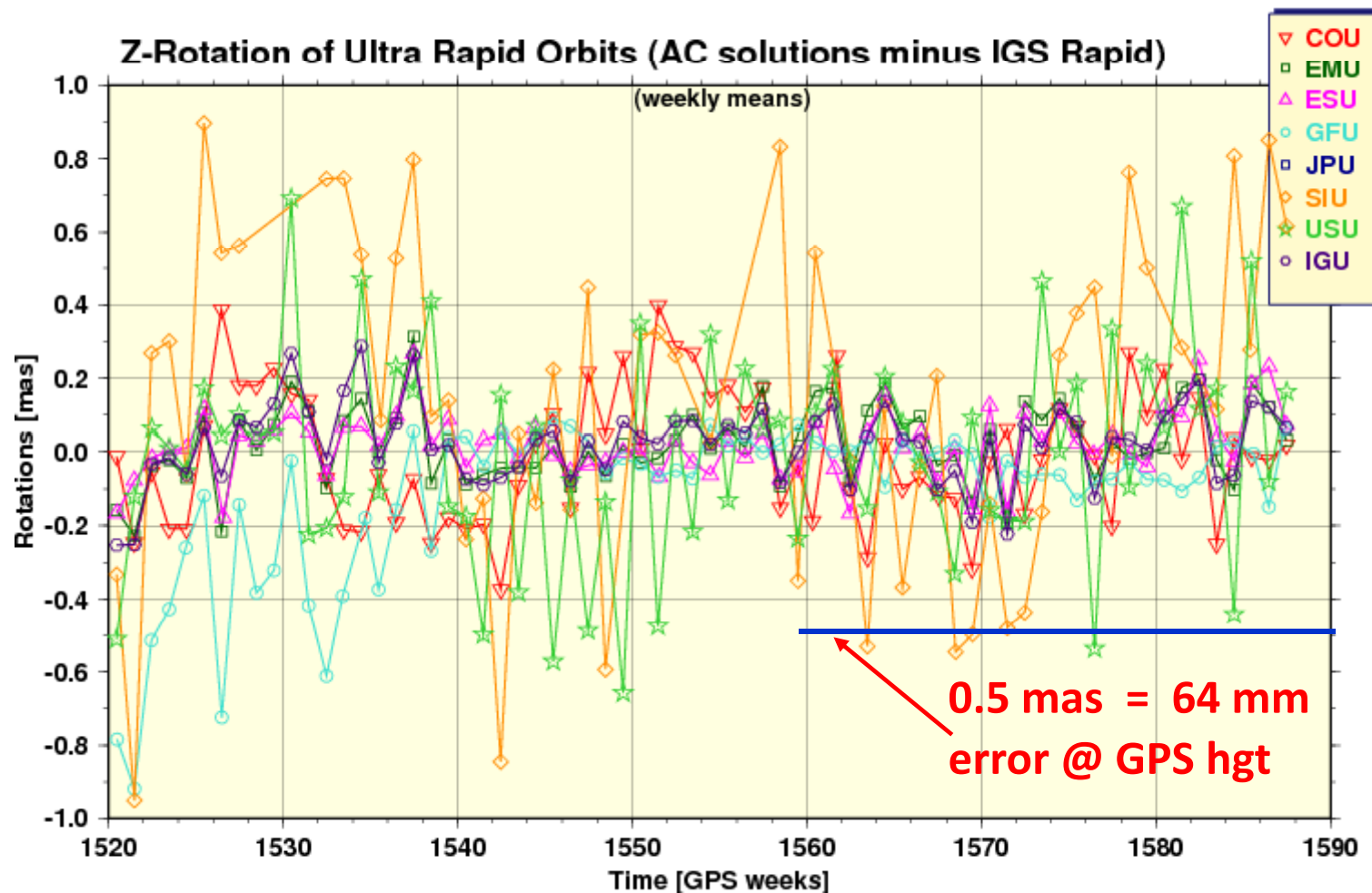
Ultra-Rapid Products

Ultra-Rapid AC Orbit Comparisons (over 48 hr)



- Performance among ACs has become bimodal & widely dispersed
 - SIO, USN, & GFZ have been rejected during most of past year
 - AC quality is more uniform over first 6 hr of predictions
 - biggest differences come from 6 – 24 hr predictions

Some IGU AC Orbits Have Large Rotations



- SIO & USN have large Y rotational errors, as well as Z rotations
 - GFZ has improved
 - CODE sometimes has moderately large Z rotations

Ultra-Rapid Orbit Diffs (mm) wrt IGR (2009)

	DX	DY	DZ	RX	RY	RZ	SCL	RMS	WRMS	MEDI	TOTAL ERR
IGU 6-hr predictions:											
mean	3.5	-0.6	0.3	0.3	0.8	3.1	-0.7	28.9	21.3	15.6	41.7
std dev	4.7	4.9	3.4	13.8	16.3	27.2	2.6	19.7	8.0	2.6	
IGU 24-hr predictions:											
mean	1.1	0.3	-0.1	-0.5	-0.6	-0.9	-1.3	64.7	47.3	30.2	80.2
std dev	1.8	2.0	3.8	21.9	31.2	52.0	1.9	33.3	16.3	6.0	
IGA observations:											
mean	1.2	0.3	0.1	-0.2	0.9	2.6	-1.2	9.0	8.0	7.2	16.3
std dev	0.8	0.9	1.3	3.4	3.4	12.7	1.5	1.6	1.3	1.2	

- Orbit errors double when prediction interval increases by x4
- IGA total err only ~40% worse than IGRs (but 175% worse for RZ)

Ultra-Rapid Orbit Diffs (mm) wrt IGR (2009)

	DX	DY	DZ	RX	RY	RZ	SCL	RMS	WRMS	MEDI	TOTAL ERR
IGU 6-hr predictions:						Z rotation errors are largest RT error – from UT1 prediction errors					
mean	3.5	-0.6	0.3	0.3	0.8	3.1	-0.7	28.9	21.3	15.6	41.7
std dev	4.7	4.9	3.4	13.8	16.3	27.2	2.6	19.7	8.0	2.6	
IGU 24-hr predictions:											
mean	1.1	0.3	-0.1	-0.5	-0.6	-0.9	-1.3	64.7	47.3	30.2	80.2
std dev	1.8	2.0	3.8	21.9	31.2	52.0	1.9	33.3	16.3	6.0	
IGA observations:											
mean	1.2	0.3	0.1	-0.2	0.9	2.6	-1.2	9.0	8.0	7.2	16.3
std dev	0.8	0.9	1.3	3.4	3.4	12.7	1.5	1.6	1.3	1.2	

- Largest RT orbit prediction error comes from UT1 predictions
- IGA accuracy also limited by RZ rotations

Ultra-Rapid Orbit Diffs (mm) wrt IGR (2009)

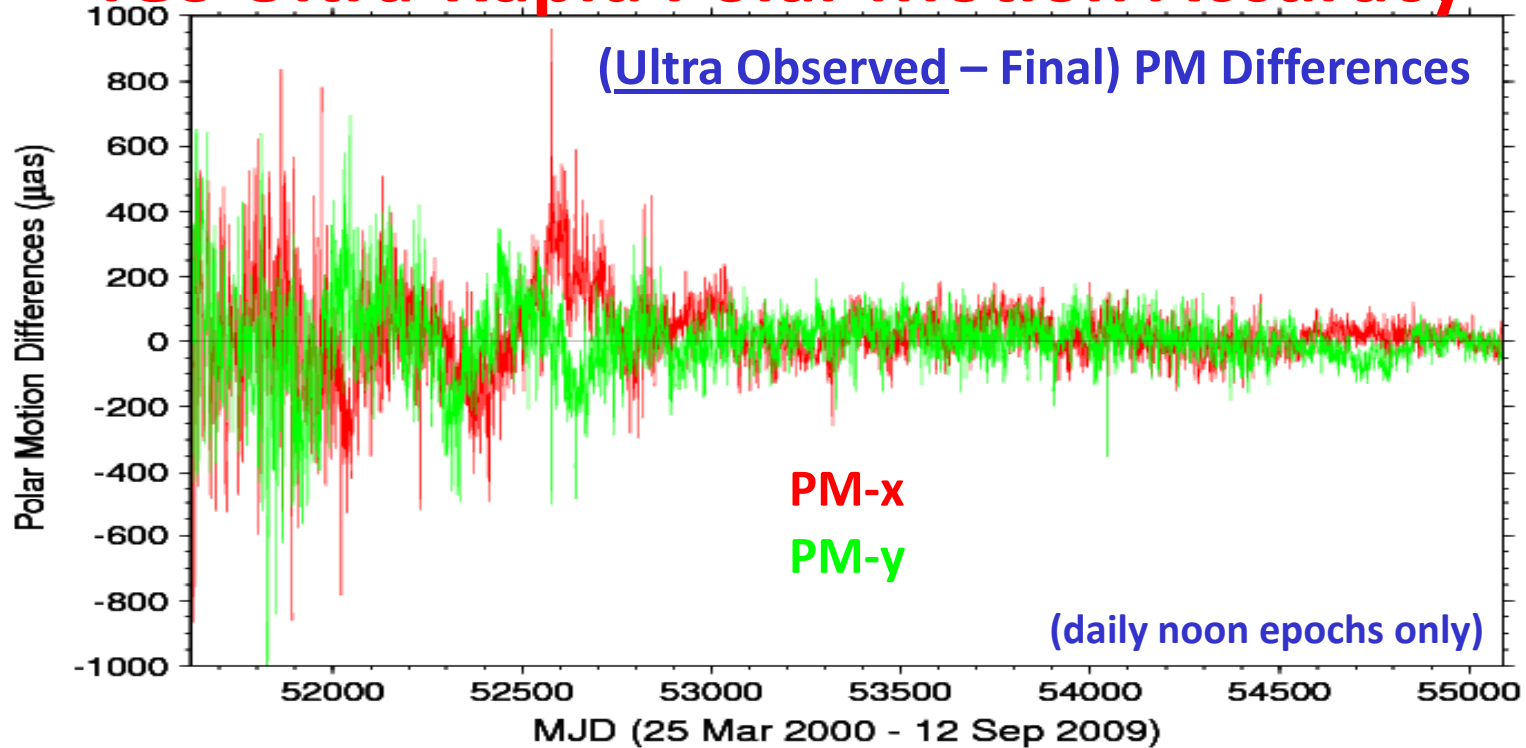
	DX	DY	DZ	RX	RY	RZ	SCL	RMS	WRMS	MEDI	TOTAL ERR
IGU 6-hr predictions:											
mean	3.5	-0.6	0.3	0.3	0.8	3.1	-0.7	28.9	21.3	15.6	41.7
std dev	4.7	4.9	3.4	13.8	16.3	27.2	2.6	19.7	8.0	2.6	
IGU 24-hr predictions:											
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std dev	1.8	2.0	3.8	21.9	31.2	52.0	1.9	33.3	16.3	6.0	
IGA observations:											
mean	1.2	0.3	0.1	-0.2	0.9	2.6	-1.2	9.0	8.0	7.2	16.3
std dev	0.8	0.9	1.3	3.4	3.4	12.7	1.5	1.6	1.3	1.2	

due to modelling of orbit dynamics

large X, Y rotation errors – from PM prediction errors

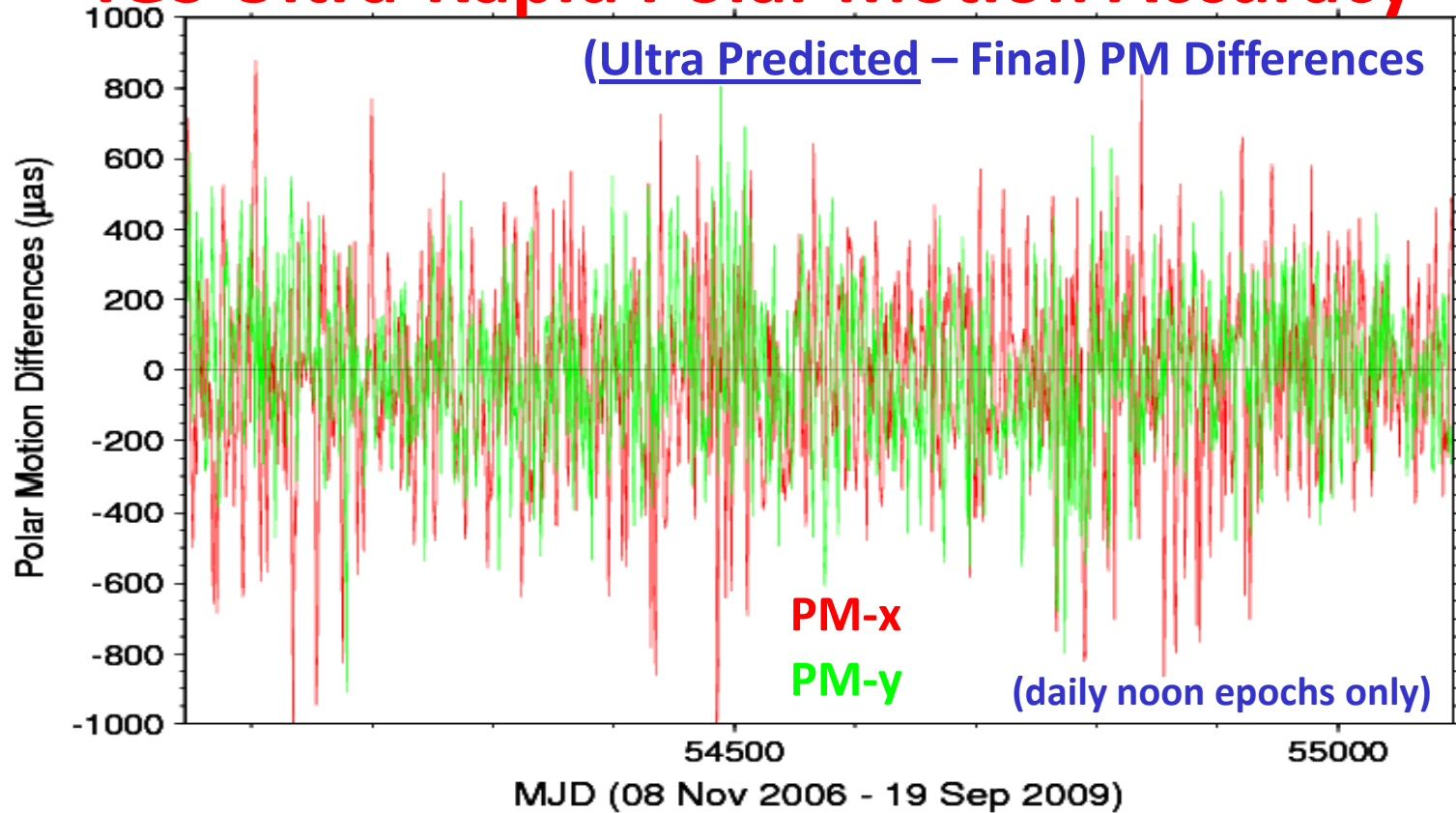
- Next largest RT limits from orbit modelling & PM prediction errors

IGS Ultra-Rapid Polar Motion Accuracy



Years (units = μas)	Ultra-Rapid		Final		$\Delta(\text{Ultra-Final})$	
	$\langle\sigma_x\rangle$	$\langle\sigma_y\rangle$	$\langle\sigma_x\rangle$	$\langle\sigma_y\rangle$	$\langle\Delta x\rangle \pm \text{SDev}$	$\langle\Delta y\rangle \pm \text{SDev}$
2000.2-2002	136.2	135.7	38.2	40.4	20.5 ± 213.8	2.9 ± 192.6
2003-2005.5	73.8	74.2	27.2	28.7	37.0 ± 93.5	7.0 ± 81.0
2005.5-2007	51.9	63.6	23.8	25.1	17.1 ± 59.9	10.8 ± 59.9
2008-2009.7	31.7	32.6	18.8	18.2	$12.7 \pm \mathbf{33.6}$	$-18.5 \pm \mathbf{41.1}$

IGS Ultra-Rapid Polar Motion Accuracy



Years (units = μas)	Ultra-Rapid		Final		$\Delta(\text{Ultra-Final})$	
	$\langle\sigma_x\rangle$	$\langle\sigma_y\rangle$	$\langle\sigma_x\rangle$	$\langle\sigma_y\rangle$	$\langle\Delta x\rangle \pm \text{SDev}$	$\langle\Delta y\rangle \pm \text{SDev}$
2006.9-2007	119.0	109.7	21.7	22.7	-39.3 ± 288.0	9.7 ± 221.2
2008	80.1	75.0	18.8	18.3	-13.2 ± 271.8	-37.3 ± 239.1
2009-2009.7	65.9	59.0	18.9	18.2	$-6.9 \pm \mathbf{266.6}$	$12.7 \pm \mathbf{184.3}$

Recent Ultra-Rapid Polar Motion Accuracy

- IGA observed EOPs updated every 6 hr
 - latency is 15 hr for each update
 - each EOP value is integrated over 24 hr
 - polar motion accuracy recently: **<50 μ as (1.5 mm)**
 - reported formal errors are generally reliable
- IGU predicted EOPs updated every 6 hr
 - for real-time applications
 - issued 9 hr before EOP epoch
 - polar motion prediction accuracy recently: **\sim 250 μ as (7.7 mm)**
 - reported formal errors are too optimistic by a factor of 3 to 4
- ACs should predict EOPs internally rather than use IERS
 - or use JPL service, esp for UT1
 - AC's near-term EOP predictions usually better than values from IERS (due to availability of most recent IGA observations)

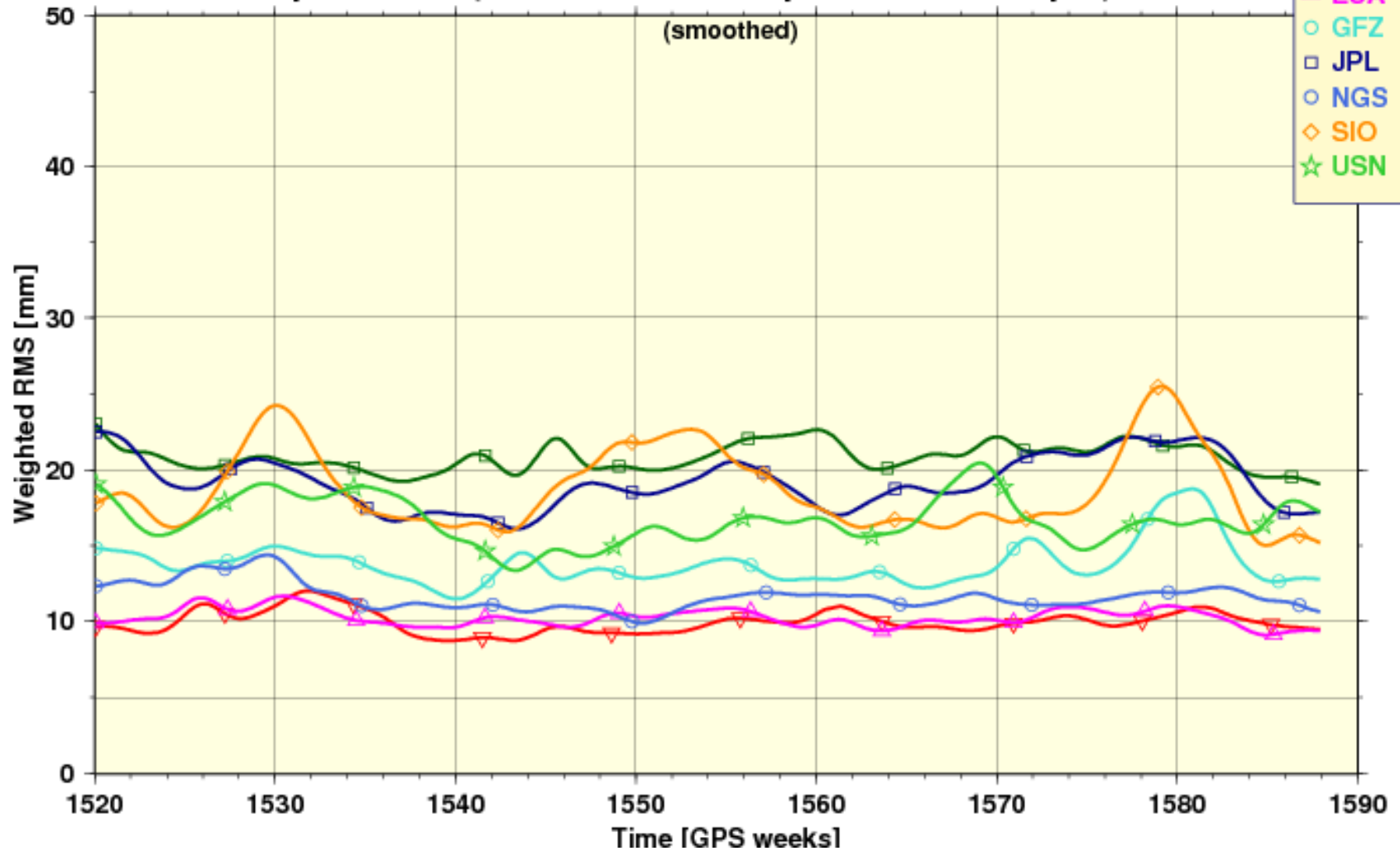
Summary of Ultra-Rapid Issues

- Generally, IGA/IGU orbits & ERPs are of very high quality
 - but only GPS included now
- But too few usable IGU ACs
 - combination is only marginally robust
 - need new IGU ACs or improvements by some current ACs
 - esp need more clock ACs (unless RTPP clocks will supercede)
- Rotations are leading orbit error
 - due to UT1 & PM prediction errors for IGU orbits
 - due to near-RT UT1 errors (?) for IGA orbits
- But what is future role for IGU products in IGS RT context ?
 - will IGU/IGA products still be needed ?
 - or do RT products depend on IGU/IGA products ?
- Is latency reduction feasible, from 3 hr → 1 or 2 hr ?

Rapid Products

Rapid AC Orbit Comparisons

Rapid Orbits (AC solutions compared to IGS Rapid)



- Performance dispersion among ACs is reasonable
 - best & worst differ by only factor of ~2

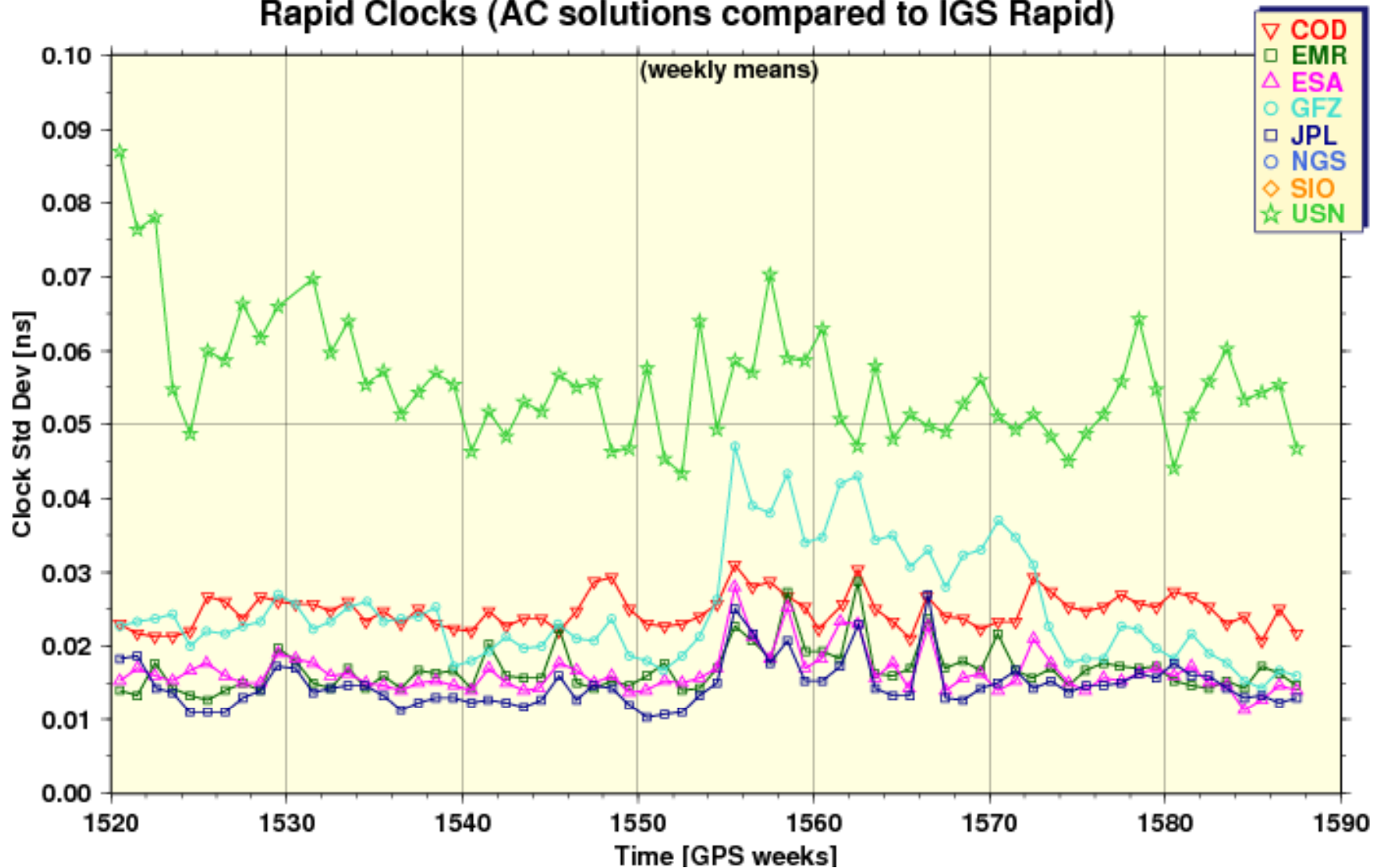
Rapid Orbit Diffs (mm) wrt IGS (2009)

	DX	DY	DZ	RX	RY	RZ	SCL	RMS	WRMS	MEDI	TOTAL ERR
mean	-0.3	0.3	0.2	0.5	-5.3	-4.6	1.2	5.8	5.6	5.1	11.9
std dev	0.7	0.8	1.2	4.7	3.6	4.6	1.0	0.7	0.7	0.7	

- **Rotations are also leading orbit error for Rapids**
 - but must come more from modelling of dynamics rather than EOPs
 - **RY & RZ biases support link between rotation errors & orbit modelling**
- **Possible common mode IGR/IGS errors not visible here**
 - especially long-period errors (>1 d)
 - e.g., due to Reference Frame or form of empirical orbit model

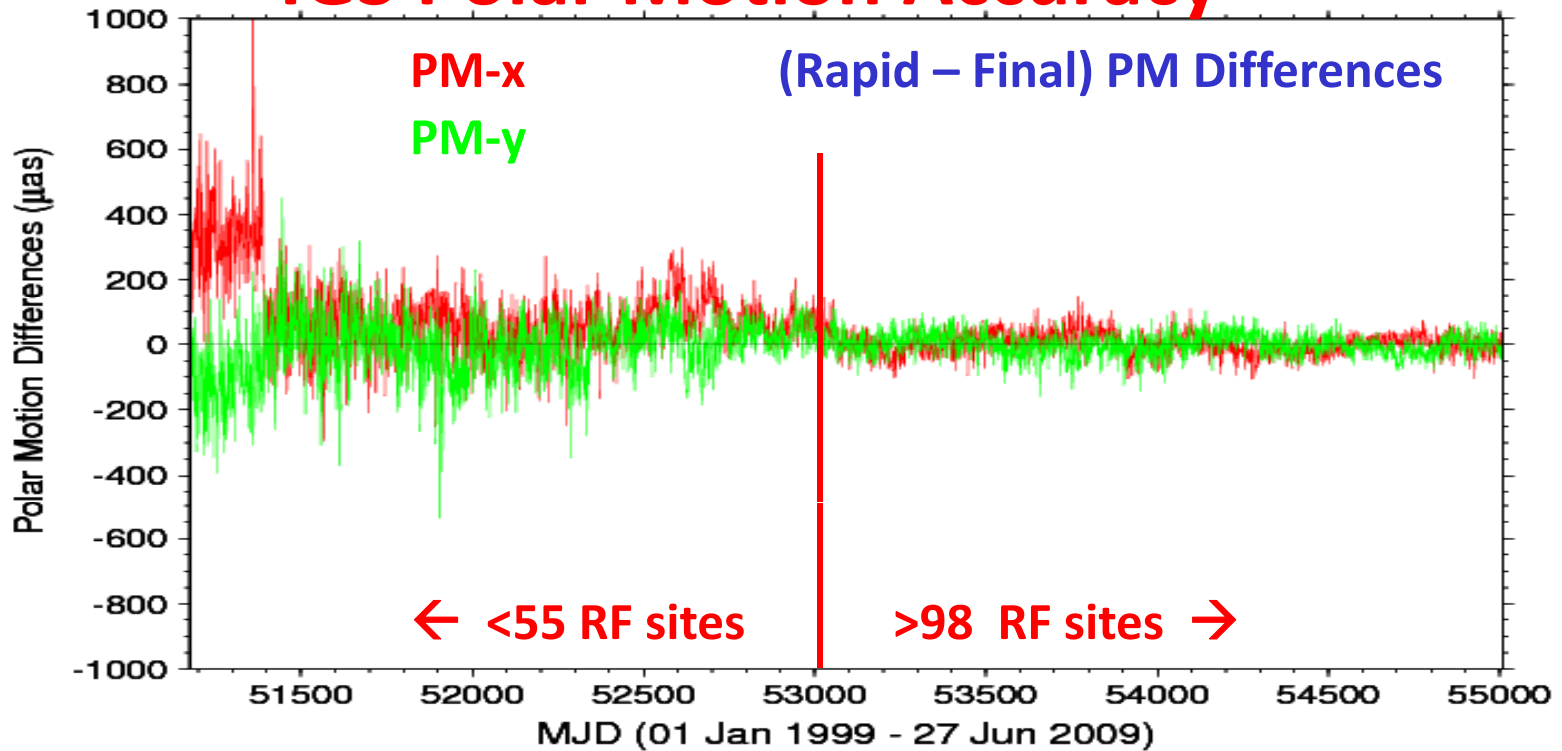
Rapid AC Clock Comparisons

Rapid Clocks (AC solutions compared to IGS Rapid)



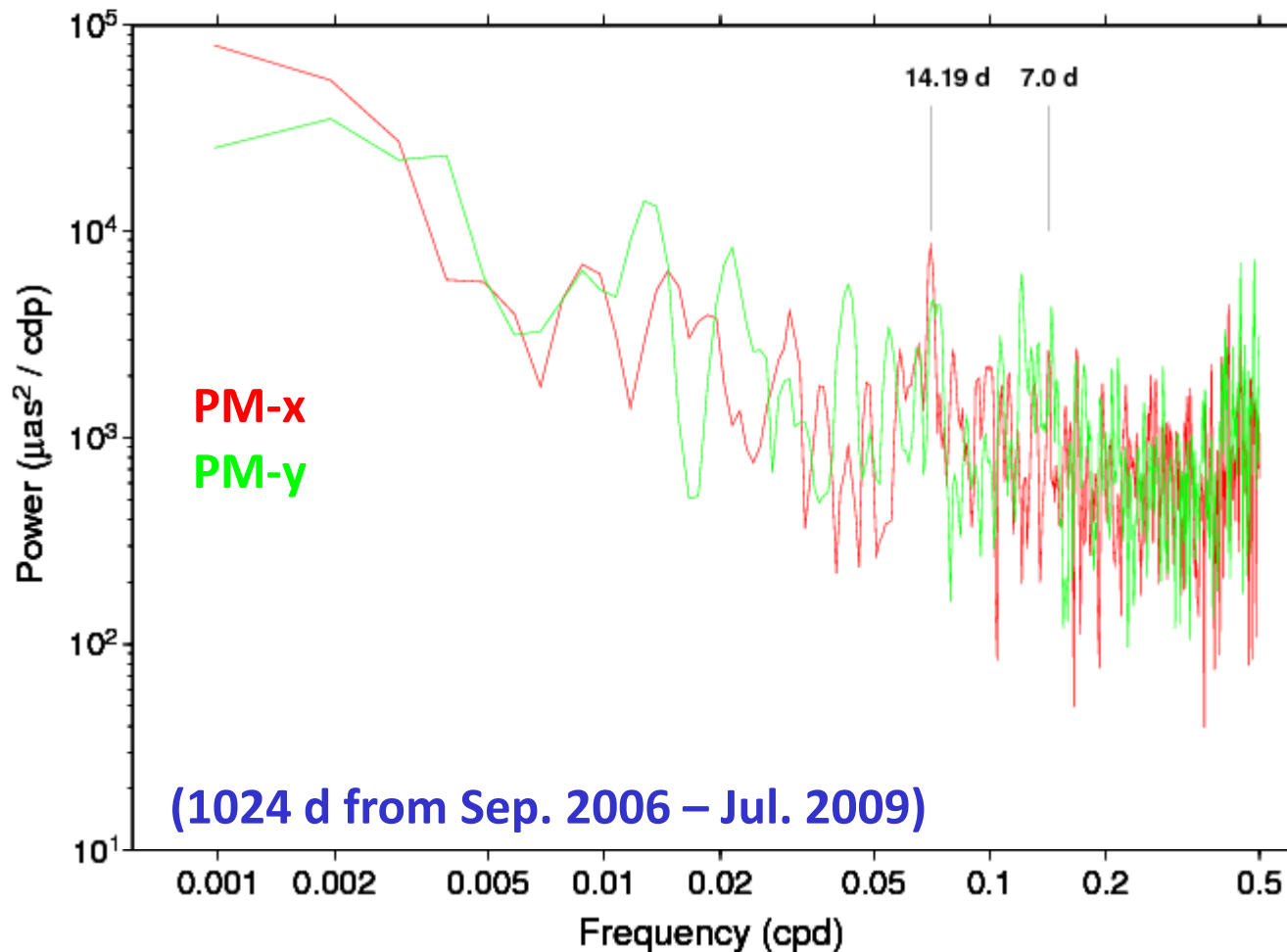
- Normally, high-quality – but only 5 usable Rapid clock ACs
 - causes product weakness if 1 or more ACs miss

IGS Polar Motion Accuracy



Years (units = μas)	Rapid		Final		Δ (Rapid-Final)	
	$\langle\sigma_x\rangle$	$\langle\sigma_y\rangle$	$\langle\sigma_x\rangle$	$\langle\sigma_y\rangle$	$\langle\Delta x\rangle \pm \text{SDev}$	$\langle\Delta y\rangle \pm \text{SDev}$
1999-2001.5	77.3	85.9	44.1	44.4	119.9 ± 153.2	-29.7 ± 113.8
2001.5-2003	47.5	47.3	33.3	35.0	65.4 ± 73.9	6.3 ± 70.0
2004-2006	34.0	39.5	25.6	27.2	7.2 ± 38.7	-1.7 ± 38.8
2007-2009.5	24.3	27.7	20.1	20.1	$-4.8 \pm \mathbf{28.9}$	$-1.4 \pm \mathbf{31.1}$

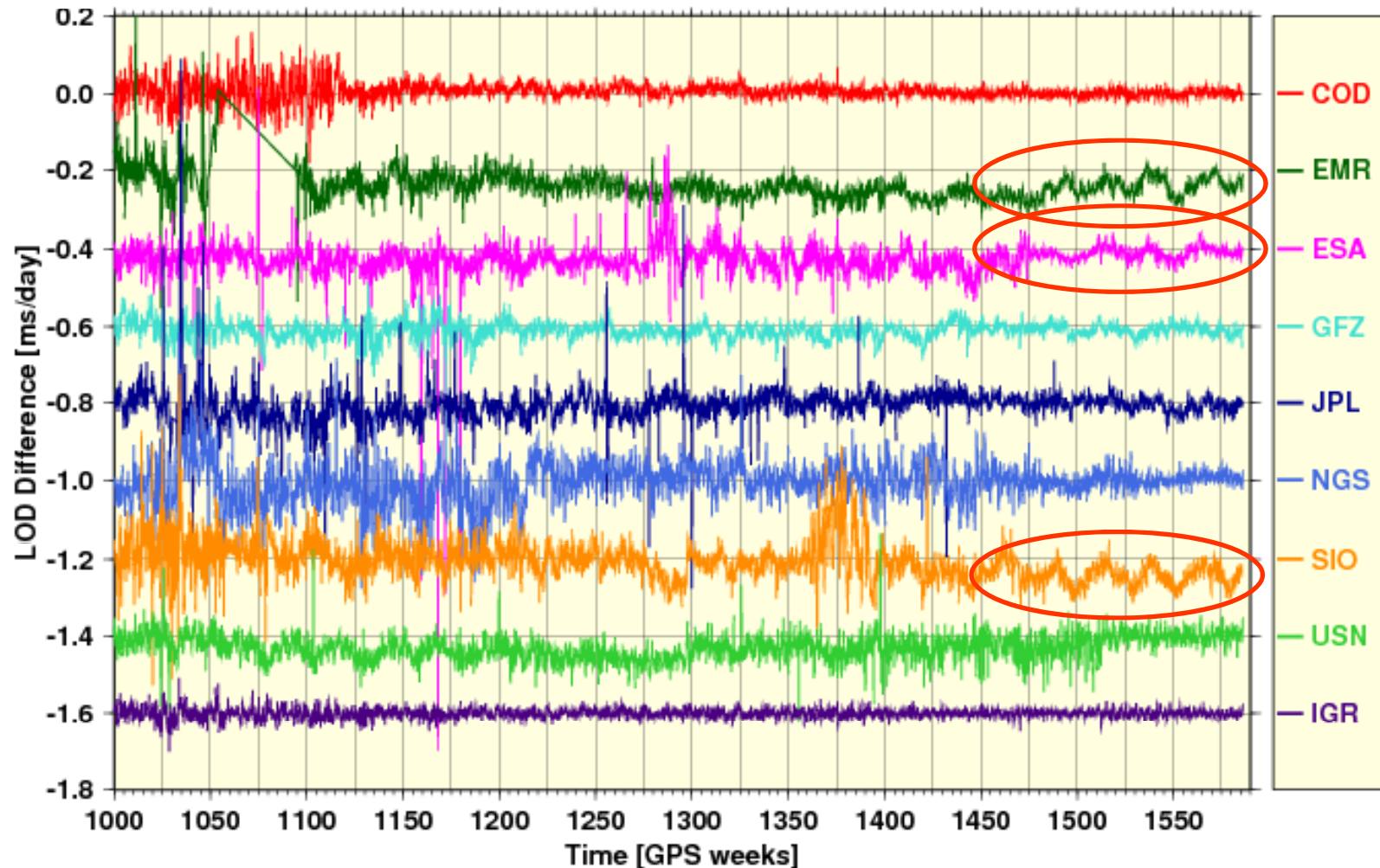
Spectra of (Rapid-Final) PM Differences



- High-frequency noise consistent with $\sim 30 \mu\text{as}$ accuracy recently
 - but longer period errors are most significant
 - fortnightly feature near 14.2 d may signify tide model errors

Rapid AC LOD Comparisons

AC Rapid LOD Differences with IGS Final



- EMR, ESA, & SIO show annual LOD variations
 - also strong LOD biases for EMR & SIO
 - similar features in Final LODs

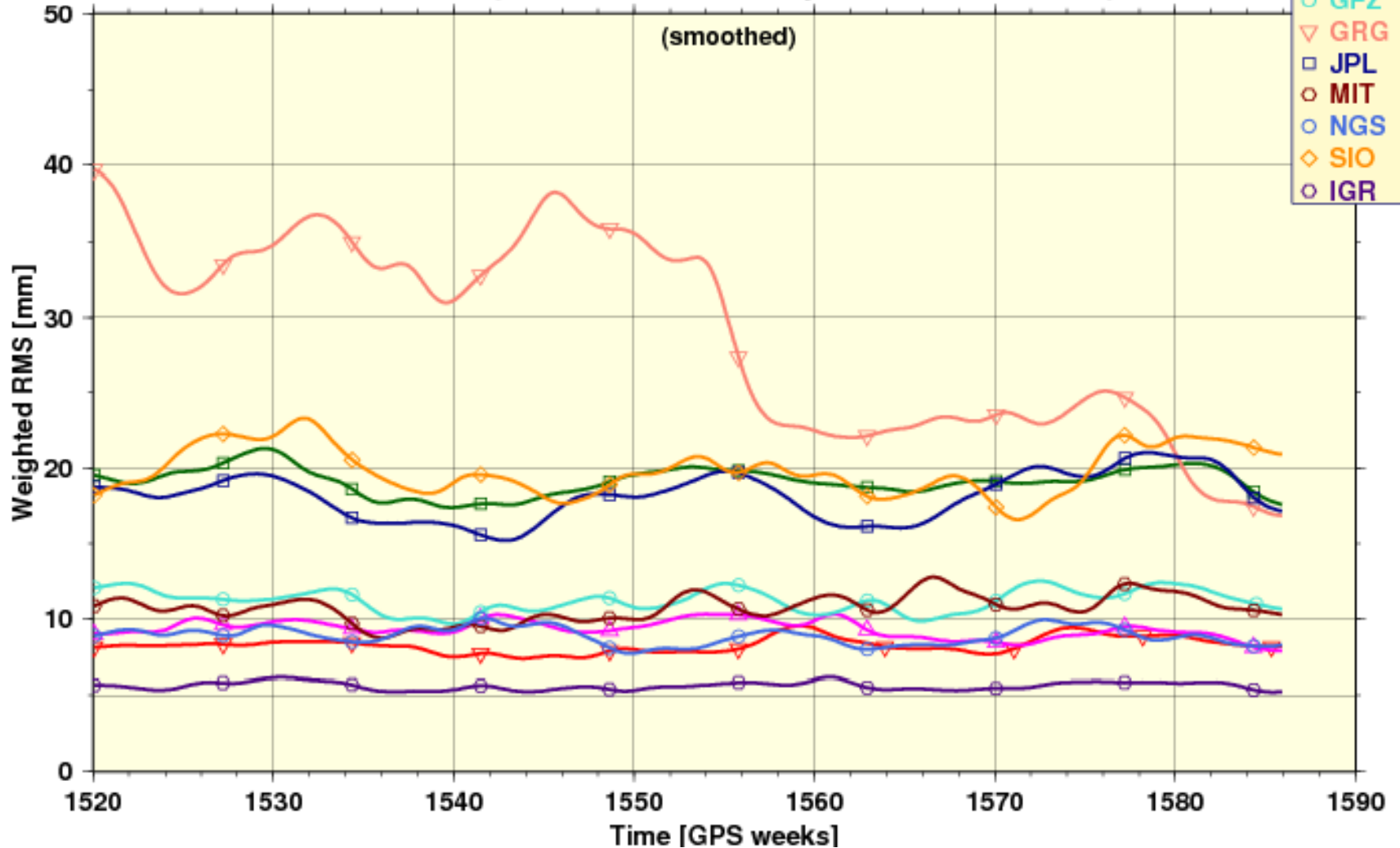
Summary of Rapid Product Issues

- **Generally, IGR orbits, clocks, & ERPs are of excellent quality**
 - but only GPS included now
- **More Rapid clock ACs would improve robustness**
- **Rotations are leading orbit error**
 - most likely related to orbit modelling
 - probably impact long-period ERPs too
- **Some ACs need to mitigate spurious LOD annual signals**
- **Is latency reduction feasible ?**
 - want to avoid overlap of IGUs & IGRs
 - AC deliveries from 16:00 \rightarrow \leq 12:00, if IGU latency reduced to 2 hr
 - AC deliveries from 16:00 \rightarrow \leq 11:00, if IGU latency reduced to 1 hr

Final Products

Final AC Orbit Comparisons

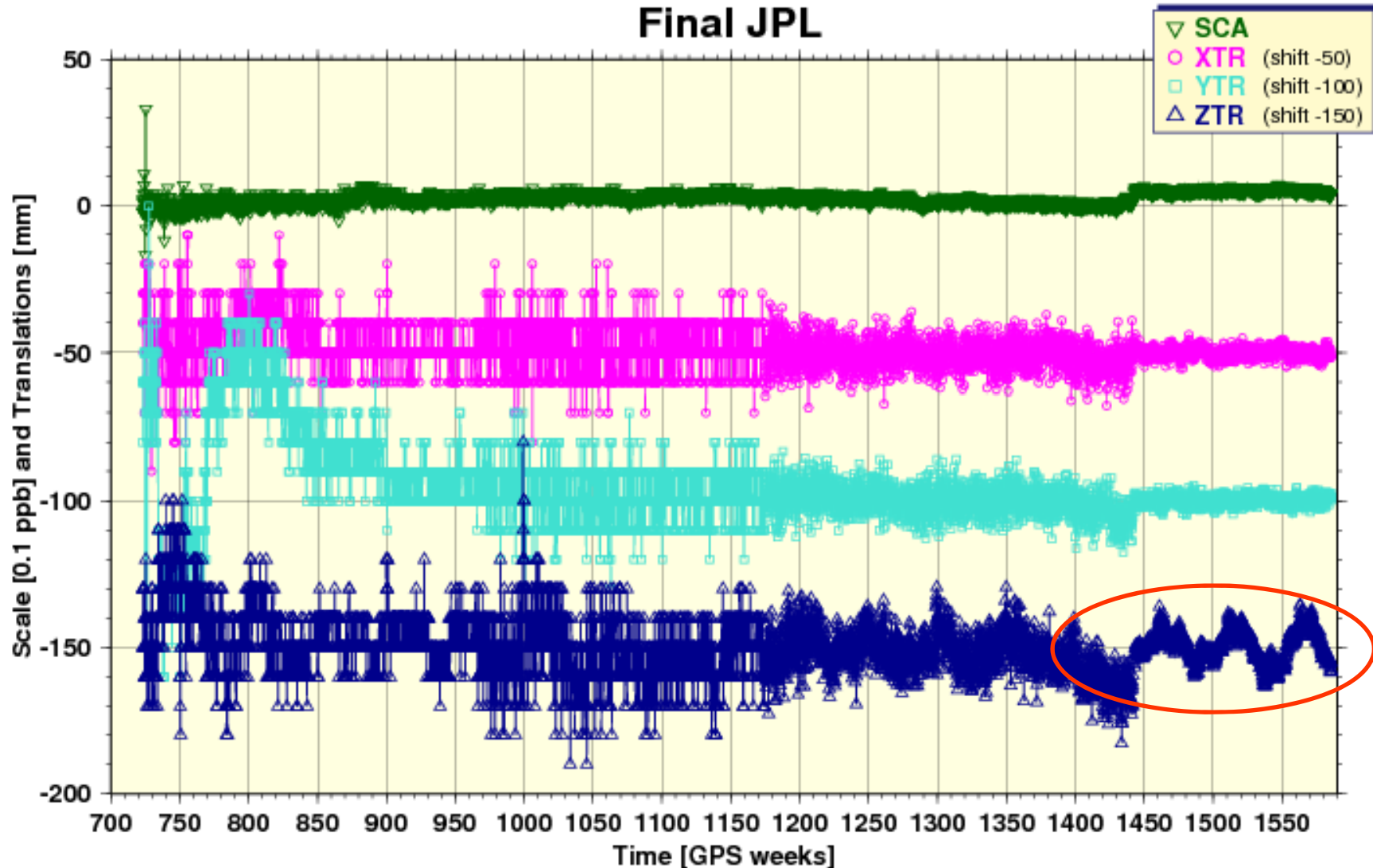
Final Orbits (AC solutions compared to IGS Final)



- AC performances cluster in two bands, but dispersion is OK
 - IGR orbits are consistently & significantly better than any single AC Final

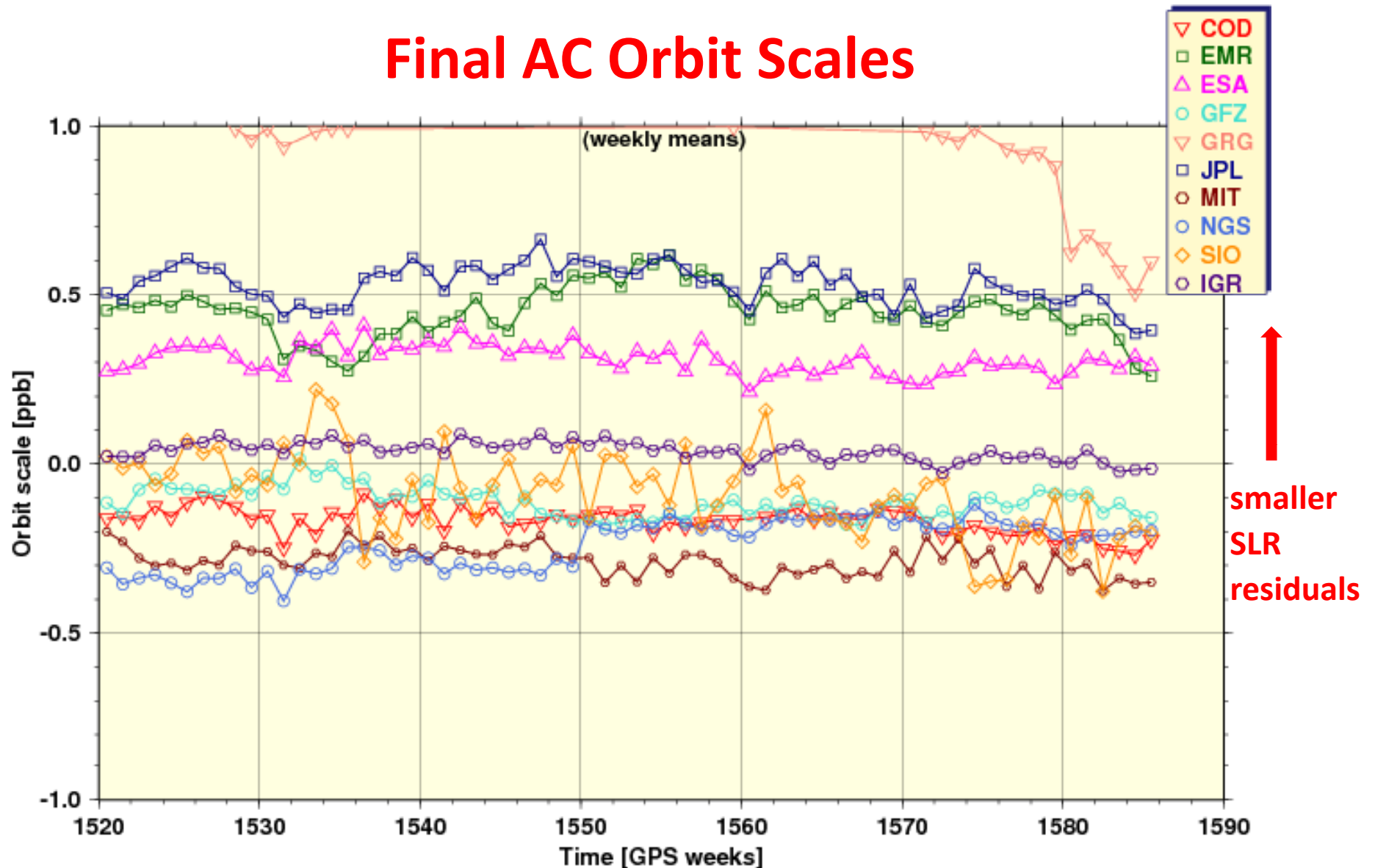
Final Orbit Z Translations

Final JPL



- Similar annual TZ variations seen for EMR, ESA, GFZ, JPL, & SIO (?)
 - source of effect is unknown

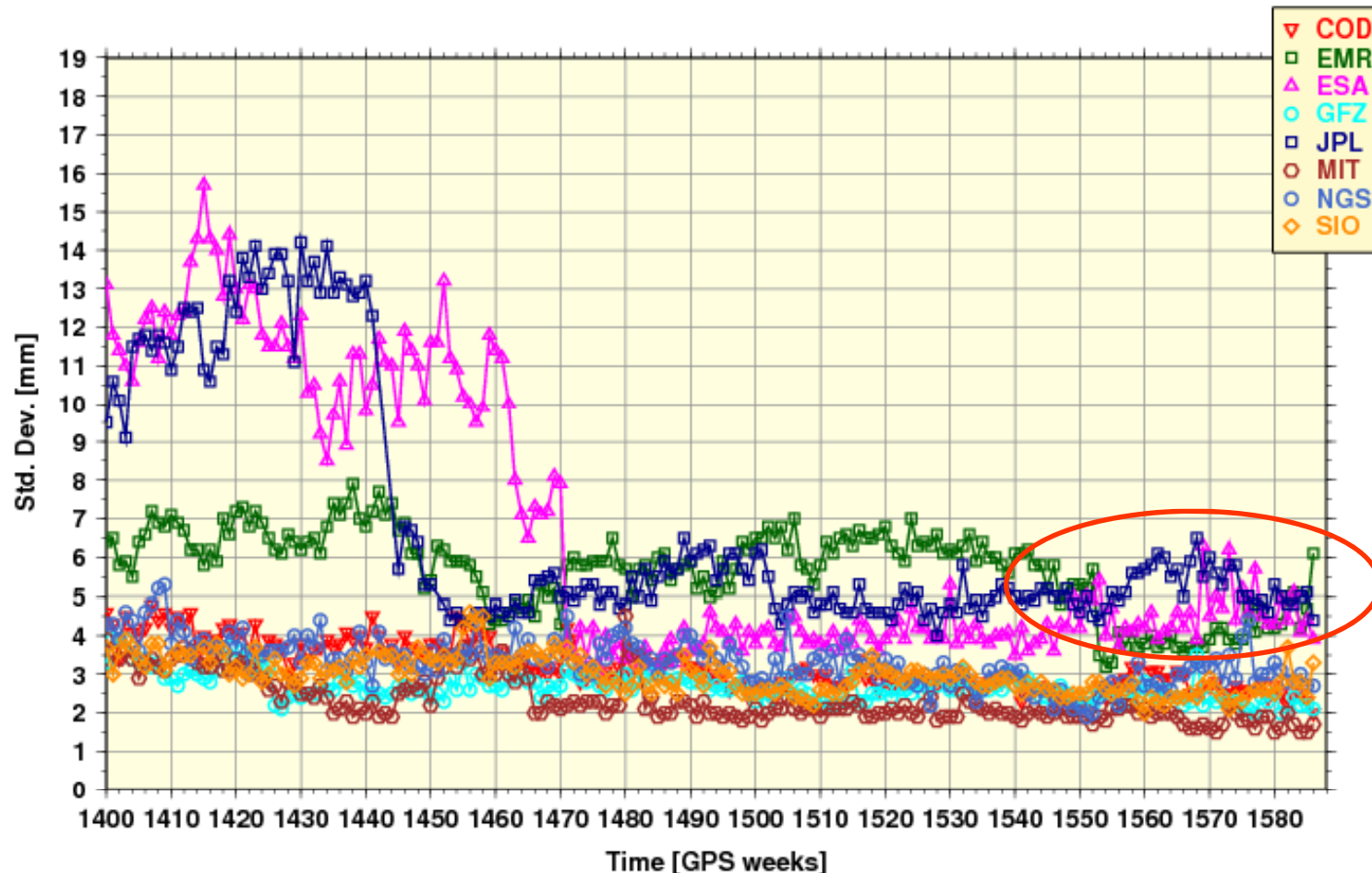
Final AC Orbit Scales



- Bimodal distribution of AC orbit scales
 - ESA, JPL, & GRG apply albedo models & have scales closer to SLR ranges
 - EMR does *not* apply albedo model

TRF Differences: Albedo Model Effect ?

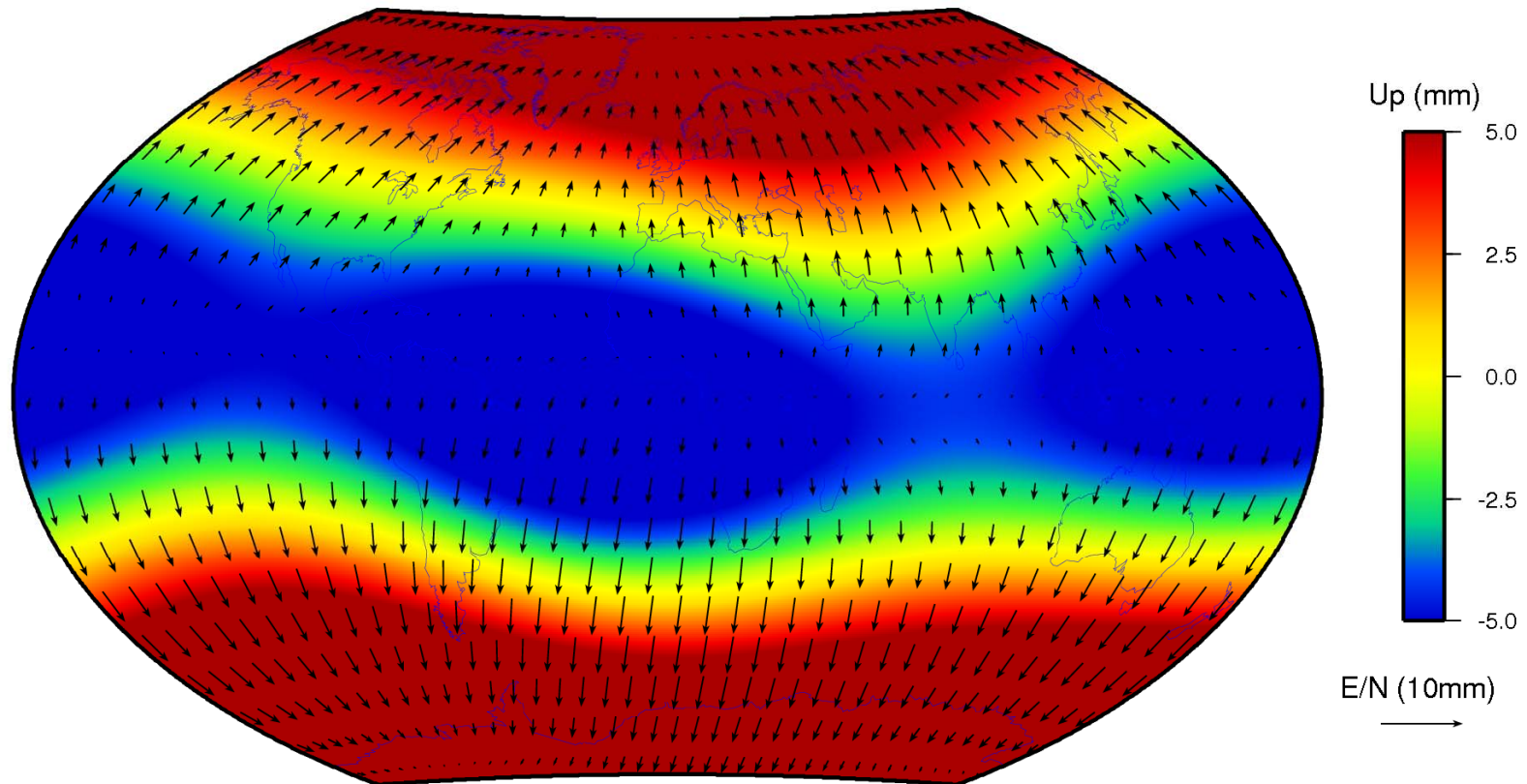
U-D Std. Dev. from IGS Weekly SINEX Combination (Sec. 5-2-2)



- ACs using albedo models (+ EMR) show largest Up residuals
 - related to internal frame differences for these ACs wrt IGS weekly SINEX
 - but those frame differences are not stationary in time
- Questions: Is albedo model the cause & which frame is “correct” ?

TRF Differences: Albedo Model Effect ?

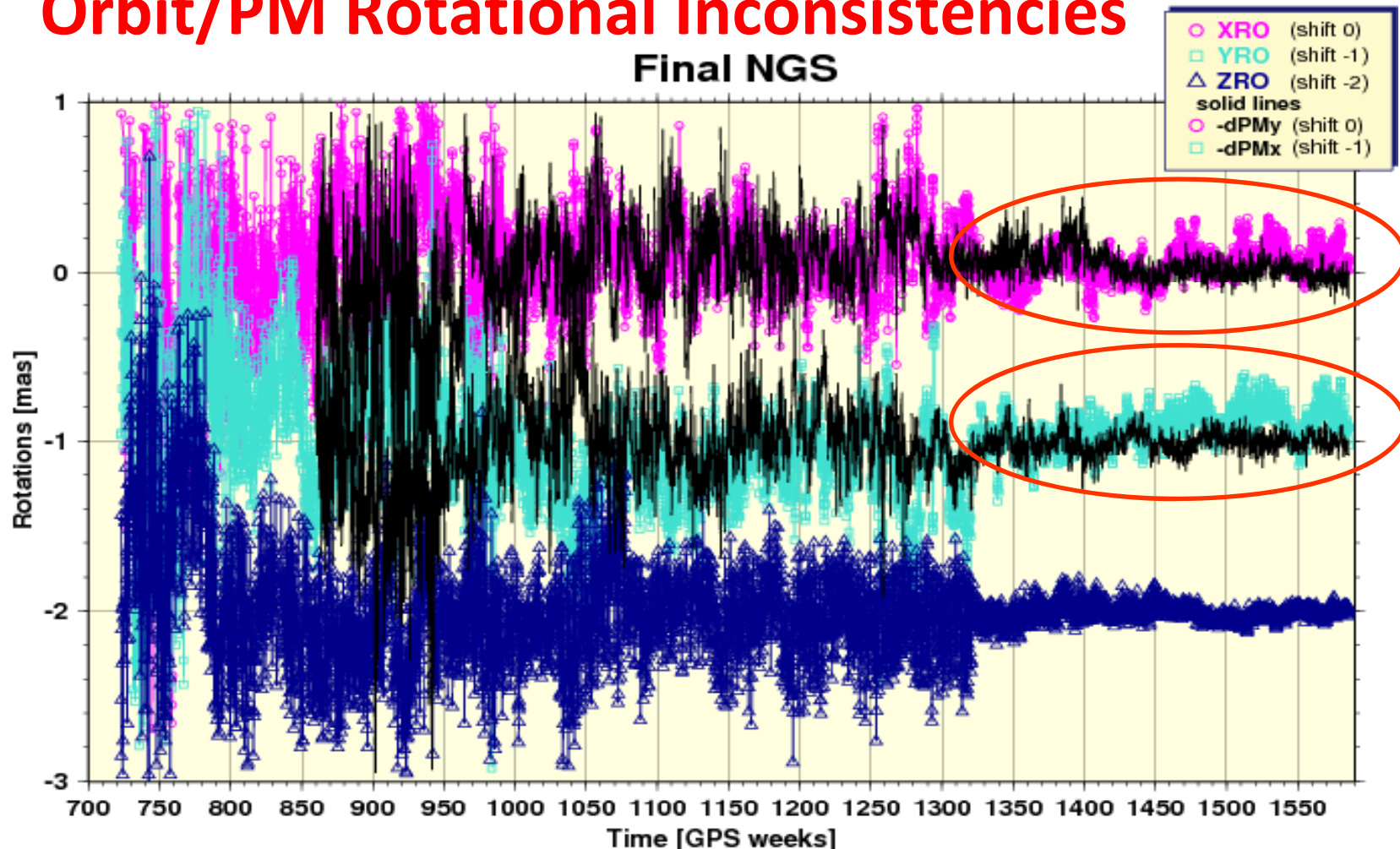
esa - igs : Spherical Harmonics fit of Helmert residuals ($n_{\max} = 2$)



(courtesy of Paul Rebischung)

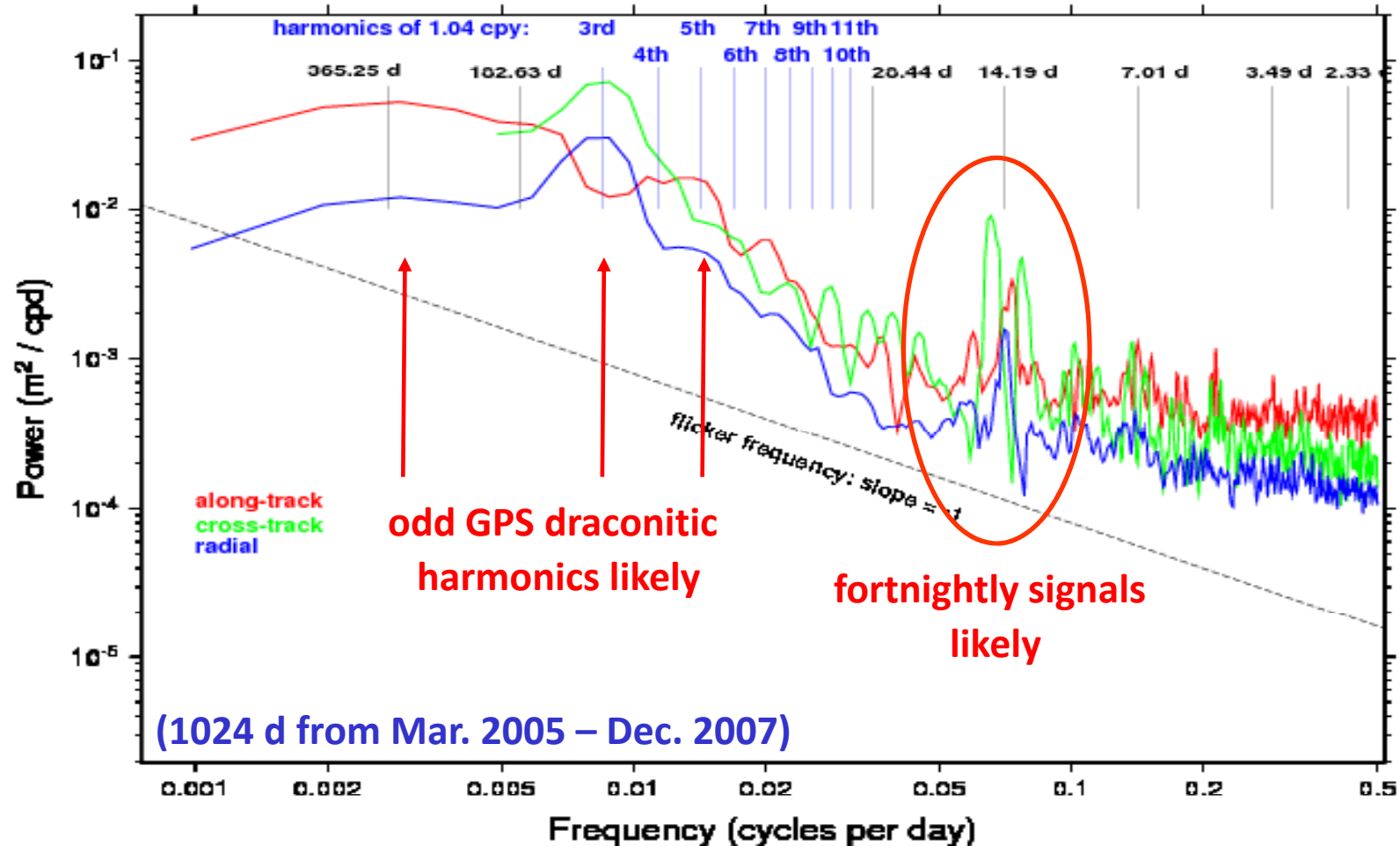
- Example of ESA frame differences for week 1573
 - character is systematic & roughly zonal in Up & North for this week
 - but pattern is not stable over time
- Question: How to know which frame is less deformed ?

Orbit/PM Rotational Inconsistencies



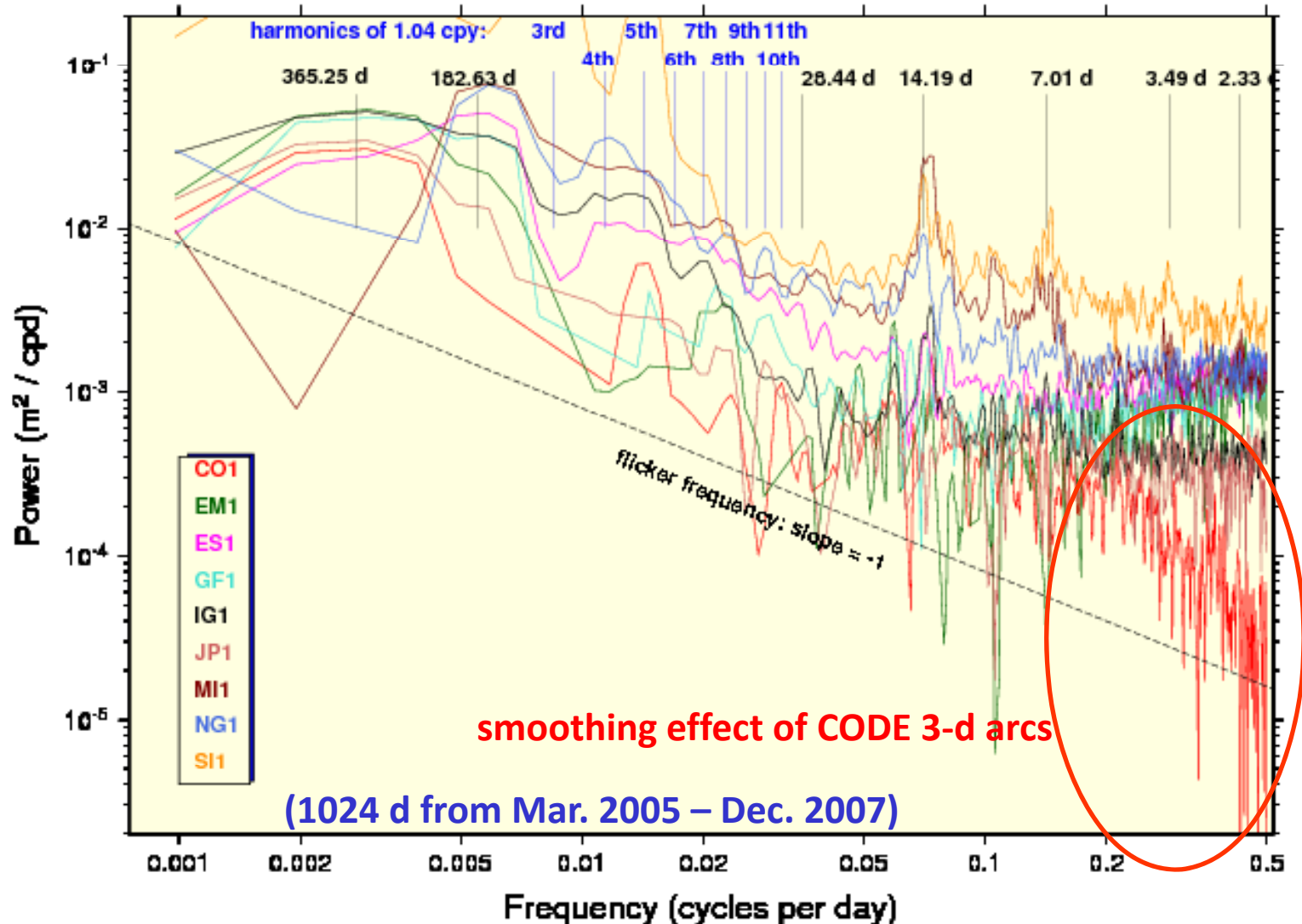
- AC orbit & PM rotational offsets should be self-consistent
 - but orbit rotations show larger dispersion for all ACs
 - smallest inconsistencies seen for recent CODE, JPL, MIT, & IGR
- Orbit accuracy probably limited by such rotational effects

A,C,R Spectra of IG1 Orbit Day-Jumps



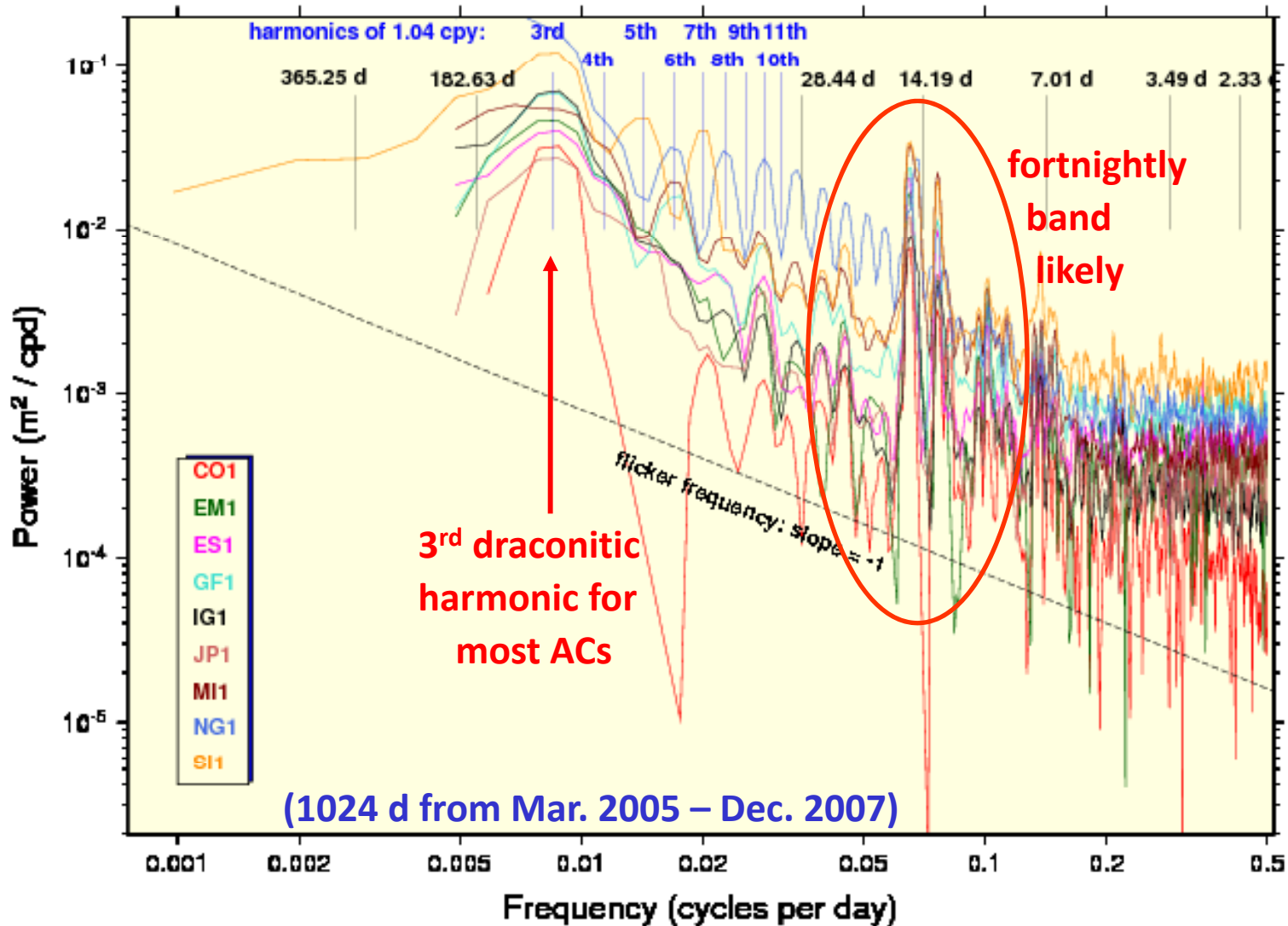
- Jumps computed from Berne-model fit to adjacent orbit days
 - stacked over all SVs & lightly smoothed
 - “calibrated” for errors due to (fit + extrapolation) method
- Background errors follow ~flicker noise on seasonal time scales
 - transition to whiter noise for <14 d

Along-track Spectra of AC Orbit Day-Jumps



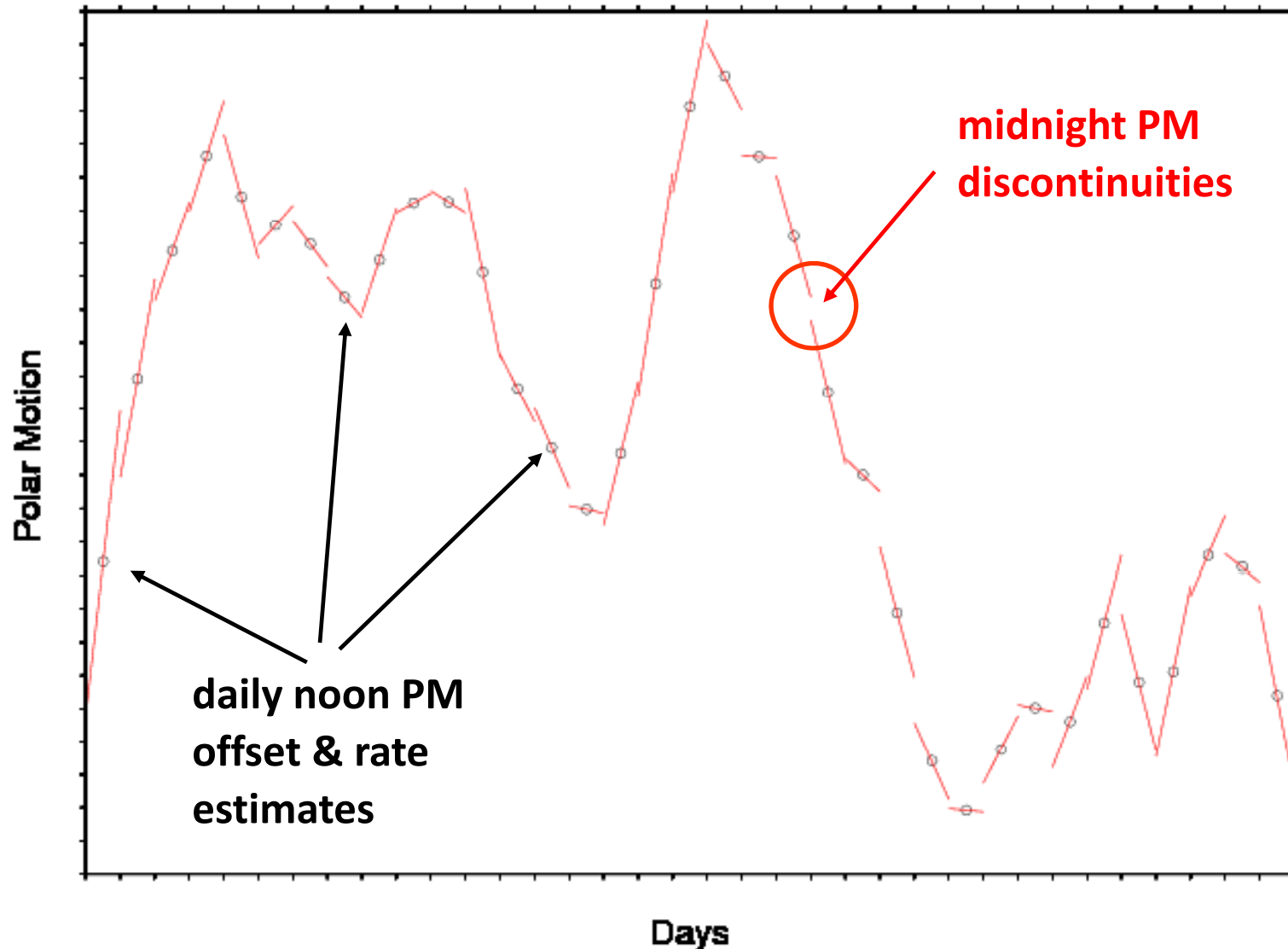
- AC along-track spectra show mostly flicker + white noise
- Some AC peaks but good agreement only for fortnightly

Cross-track Spectra of AC Orbit Day-Jumps



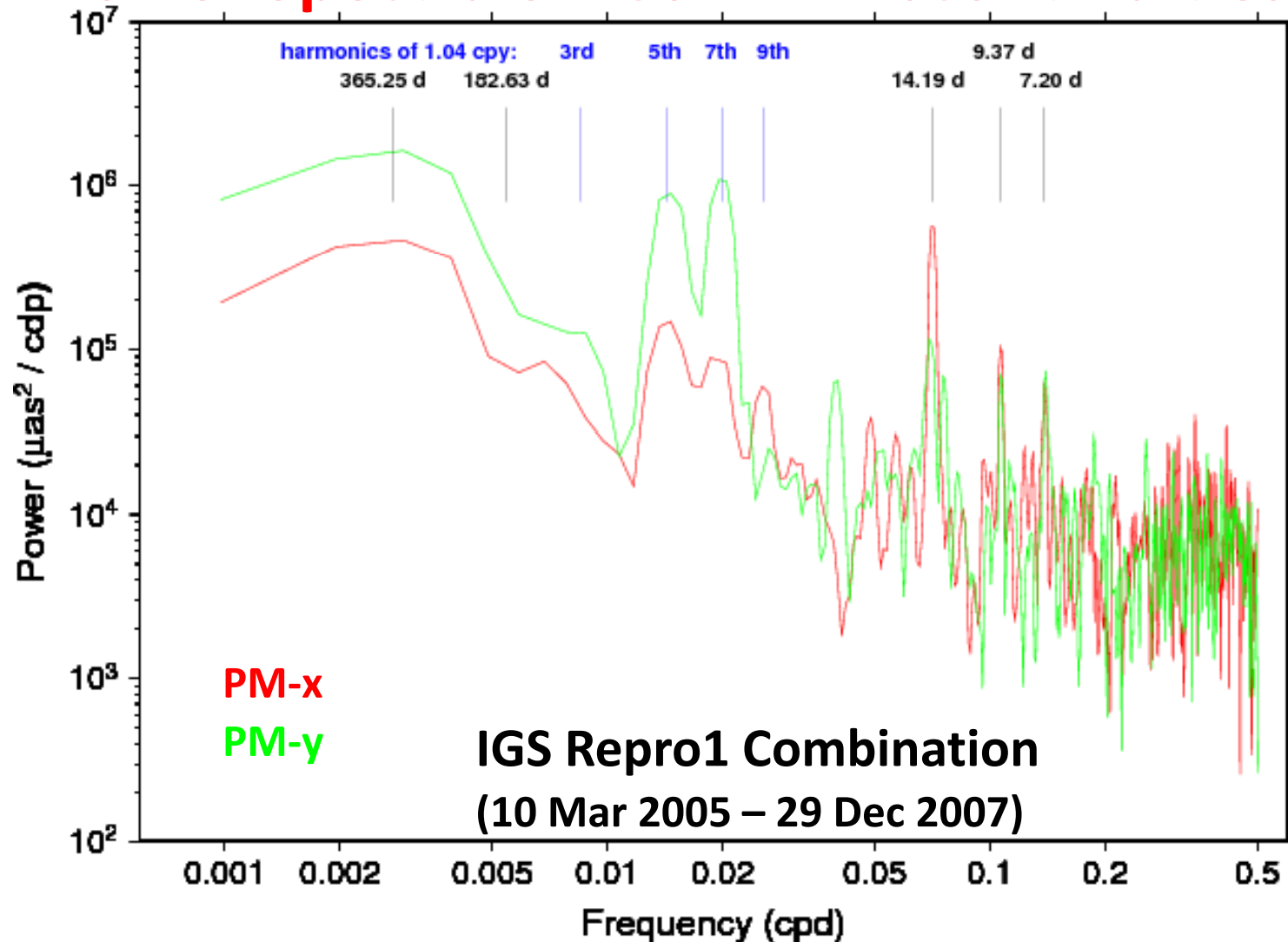
- AC cross-track spectra show 3rd draconitic & fortnightly bands
- Some spurious AC peaks & lower white noise floor

Compute Polar Motion Discontinuities



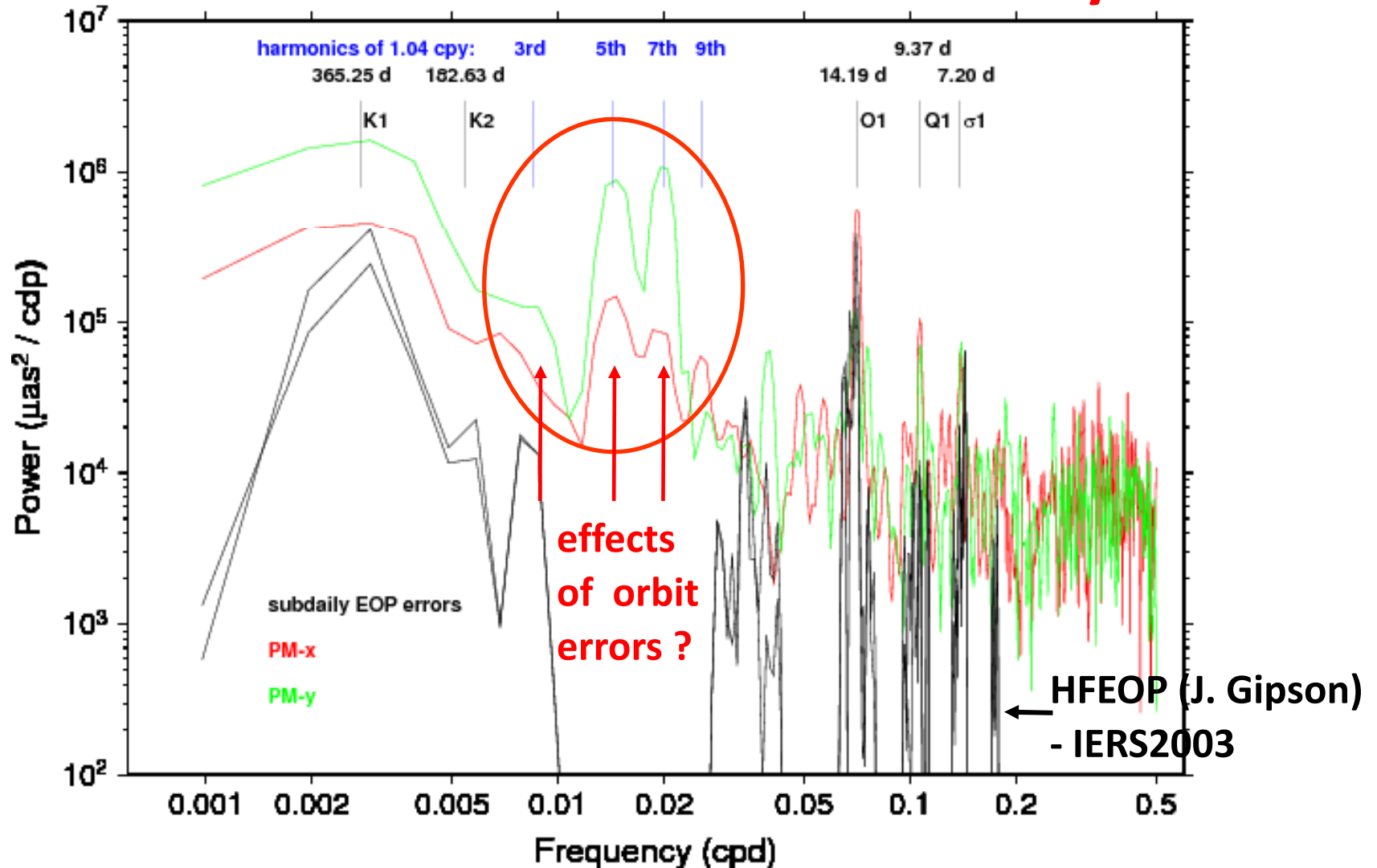
- Examine PM day-boundary discontinuities for IGS time series
 - should be non-zero due to PM excitation & measurement errors

Power Spectra of IGS PM Discontinuities



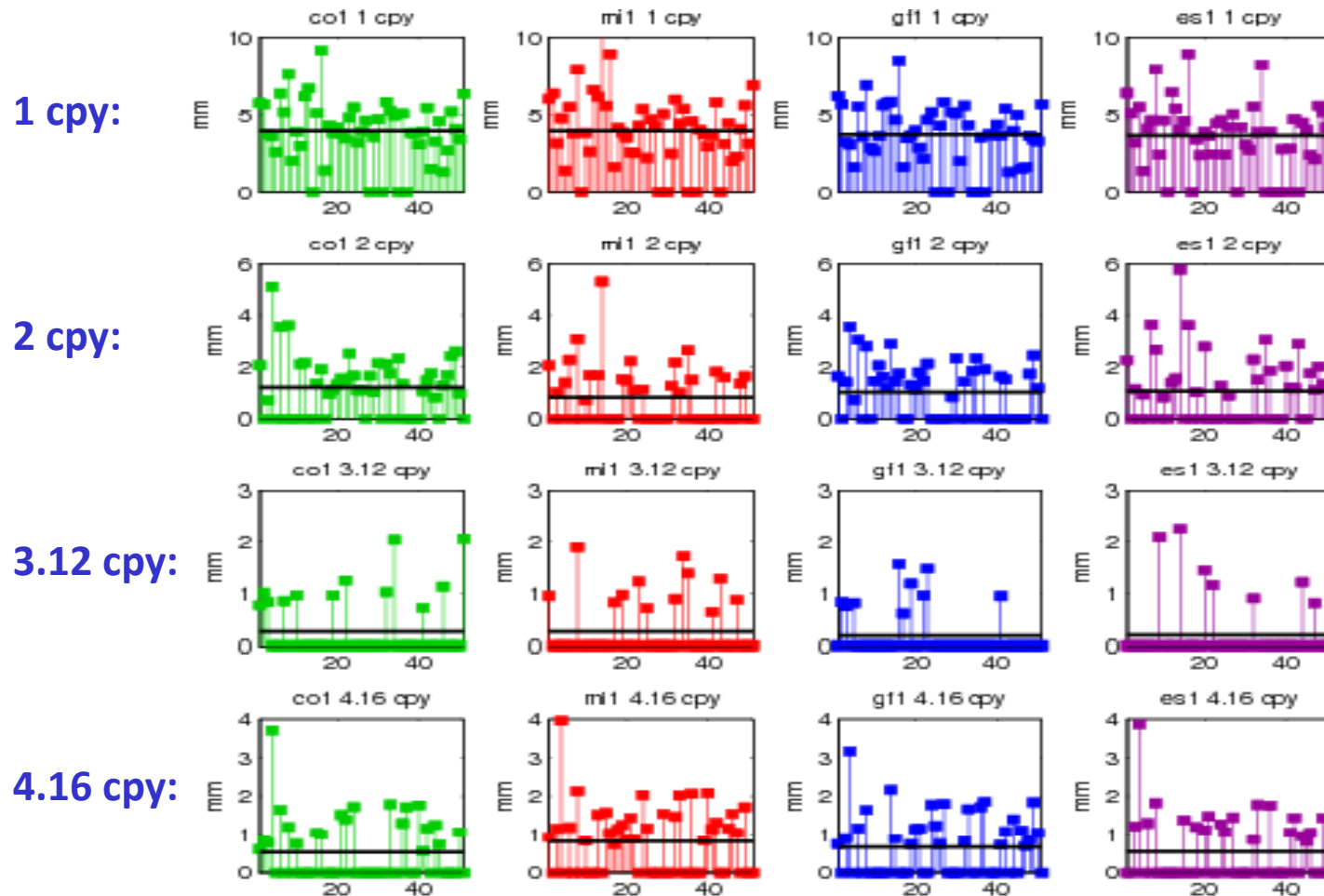
- Common peaks seen in most AC spectra are:
 - annual + 5th & 7th harmonics of GPS year (351 d or 1.040 cpy)
 - probably aliased errors of subdaily EOP tide model (IERS2003)

Spectra of PM Discontinuities & Subdaily EOPs



- Aliasing of subdaily EOP tide model errors probably explains:
 - annual (K1, P1, T2), 14.2 d (O1), 9.4 d (Q1, N2), & 7.2 d ($\sigma 1$, 2Q1, 2N2, $\mu 2$)
- Orbit errors presumably responsible for odd 1.04 cpy harmonics

Station Position Harmonics Persist in Repro1

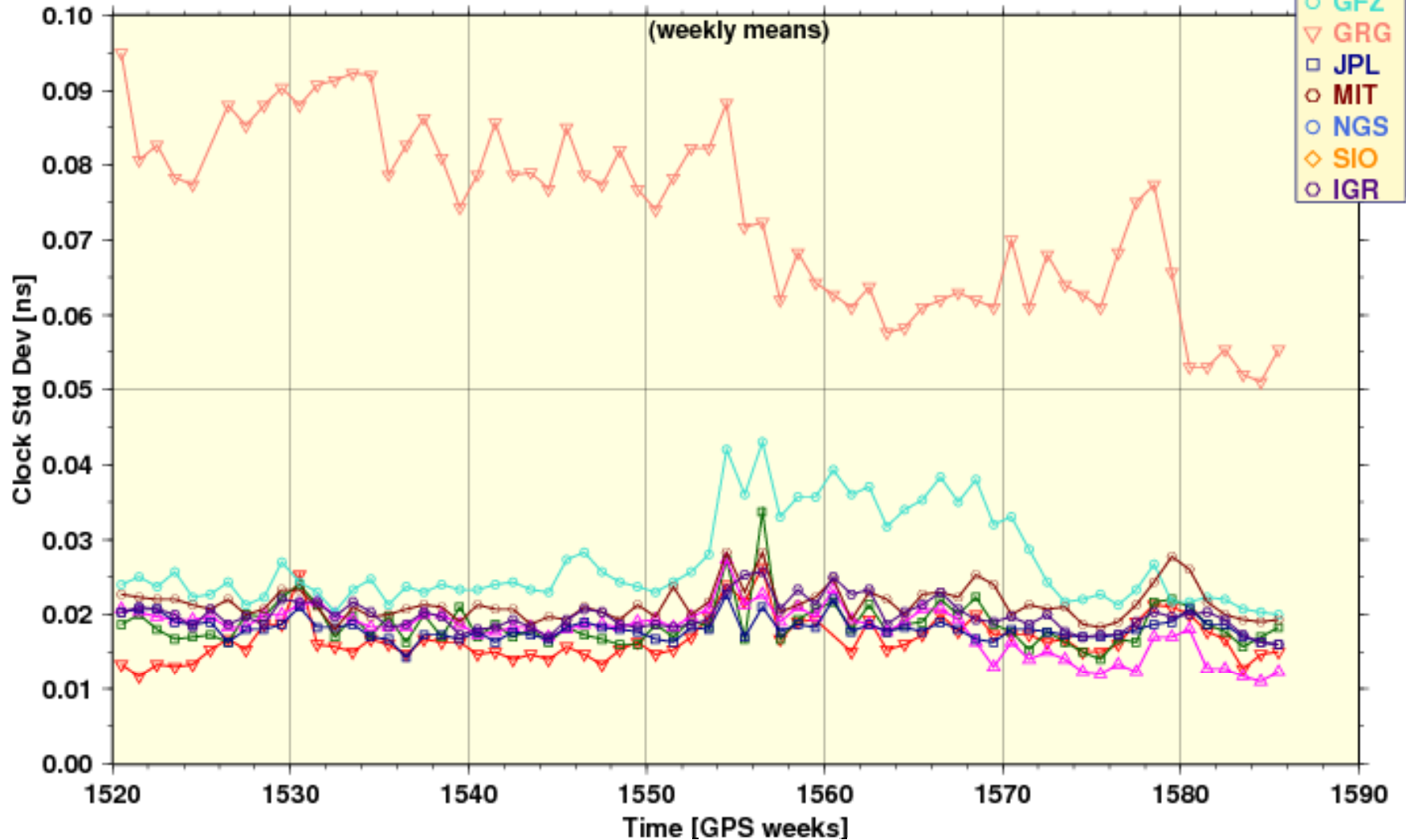


(courtesy of Xavier Collilieux)

- Significant Height harmonic amplitudes for 4 Repro1 ACs
 - similar behavior for North & East components
- Subtle variation among ACs implies possible analysis component
 - could suggest link to orbit modelling

Final AC Clock Comparisons

Final Clocks (AC solutions compared to IGS Final)



- Final clock combination is robust (6 ACs + 1 AC pending)
 - even 30s satellite clock products have 4 ACs now (+1 AC pending)

Summary of Final Product Issues

- Final GPS orbit accuracy ~2 cm in recent years
 - mostly long-period (odd draconitics) errors in C- & A-track directions
 - short-period precision ~8 mm
 - limiting errors due to rotations from orbit modelling
 - GLONASS orbit accuracy probably poorer by factor of 2 to 3
- Several AC-specific effects are significant
 - annual orbit oscillation in TZ for some ACs
 - orbit/PM rotational inconsistencies by most ACs – probably the main error source !
 - albedo model may cause zonal changes in TRFs – we must understand this !
- IERS2003 subdaily EOP model errors alias into daily rate estimates, esp PM-rates, & probably 12 hr orbit parameters
- Possible latency reduction but only by ~1 or 2 d

Goals for 2nd IGS Reprocessing Campaign

- Orbit model improvements
 - probably add an albedo + IR acceleration model – but only if TRF impact is understood
 - ensure attitude modelling by all ACs for full clock consistency
 - reduced AC rotational variations & inconsistencies
 - maybe linked with once-per-rev parameters & subdaily EOP model
 - add UT1-acceleration parameter ?
- Implement higher-order ionosphere corrections
- Any updates for obs bias corrections & conventions
- Reconsider all AC solution constraints, esp over-constraints
- Updated IERS Conventions (Fall 2010)
 - new mean pole & geopotential models
 - new S1/S2 atmosphere pressure loading model
 - model for thermal expansion of monuments & bedrock ?