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 Workshop 2010, Newcastle Upon Tyne, 28 June 2010

IGS Core Product Lines (2010)

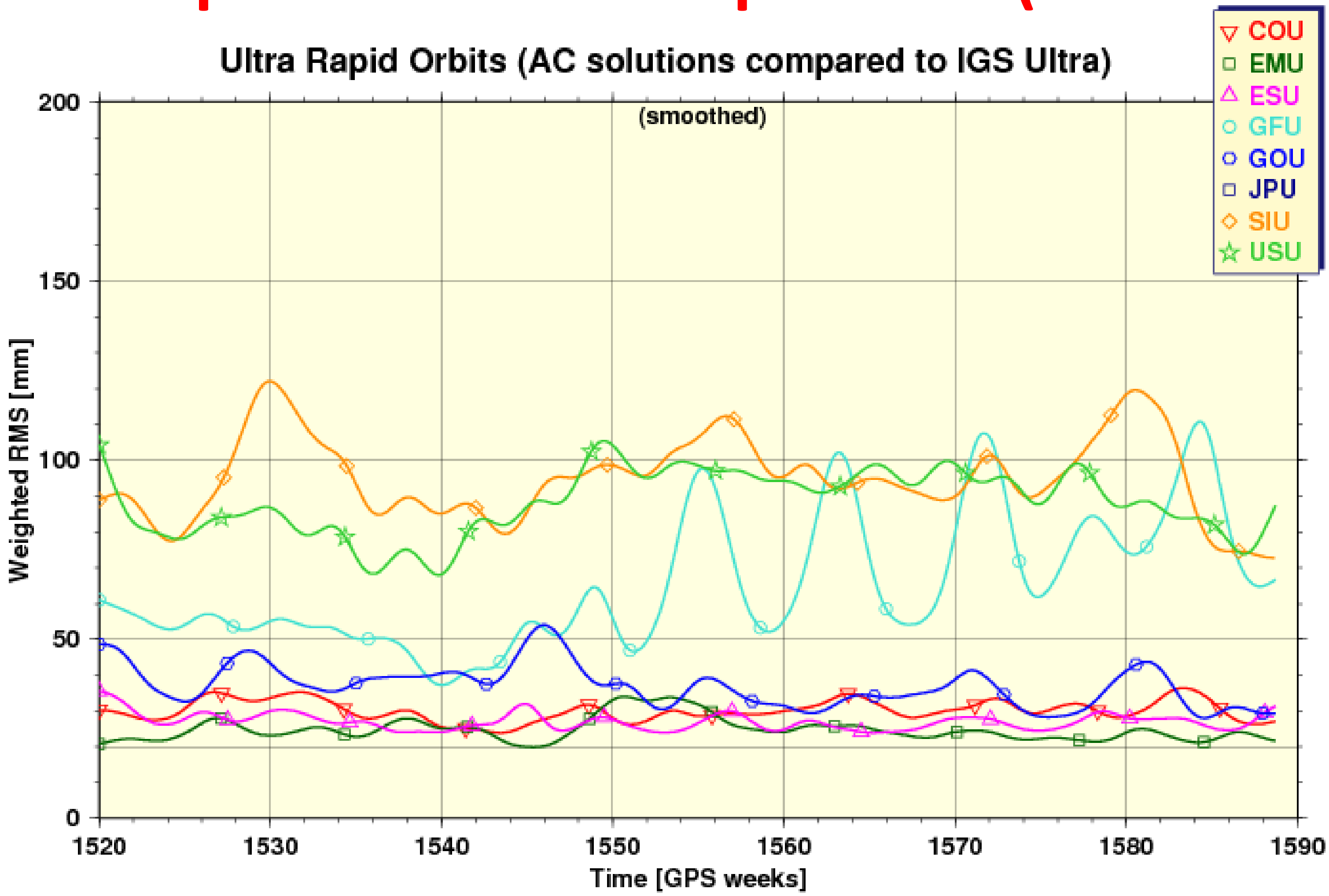
Series	ID code	Latency	Issue times (UTC)	Data spans (UTC)	Remarks
Ultra-Rapid (predicted half)	IGU	real-time	@ 03:00, 09:00, 15:00, 21:00	+24 hr @ 00:00, 06:00, 12:00, 18:00	• for real-time apps • GPS only • issued with prior IGA
Ultra-Rapid (observed half)	IGA	3 - 9 hr	@ 03:00, 09:00, 15:00, 21:00	-24 hr @ 00:00, 06:00, 12:00, 18:00	• for near real-time apps • GPS only • issued with following IGU
Rapid	IGR	17 - 41 hr	@ 17:00 daily	±12 hr @ 12:00	• for near-definitive, rapid apps • GPS only
Final	IGS	11 - 17 d	weekly each Thursday	±12 hr @ 12:00 for 7 d	• for definitive apps • GPS & GLONASS

IGS Product Types & ACs (June 2010)

Series	Product types	# of contributing ACs Submit	Reject	Used	Output sample interval
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
		5	1	4	30 s
	• **station clocks**	7	1	6	5 min
	• **GLO orbits**	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

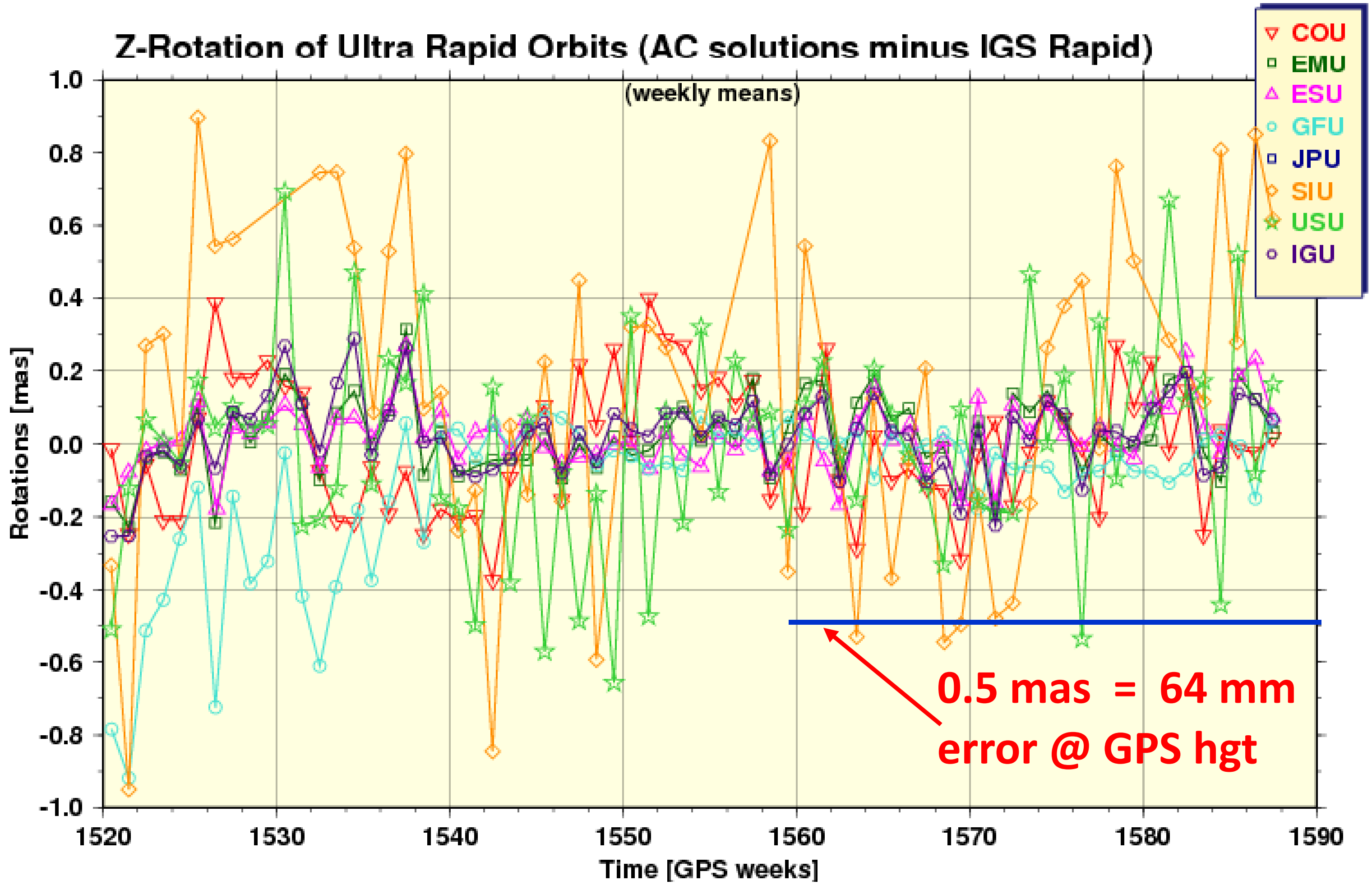
Ultra-Rapid Products

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
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std dev	0.8	0.9	1.3	3.4	3.4	**12.7**	1.5	1.6	1.3	1.2	

Z rotation errors are largest RT error – from UT1 prediction errors

- **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:											
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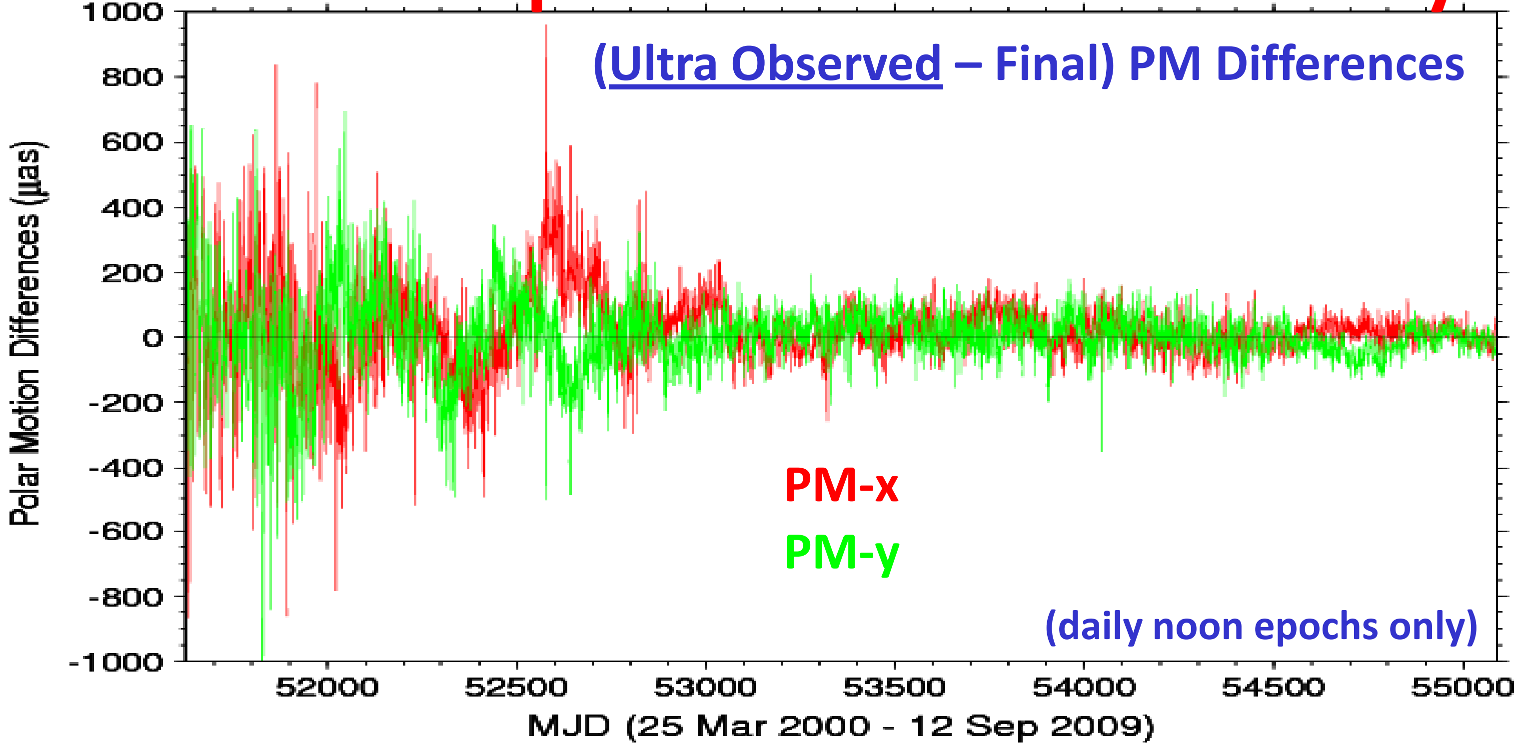
std dev	0.8	0.9	1.3	3.4	3.4	**12.7**	1.5	1.6	1.3	1.2	

due to modelling of orbit dynamics

large X, Y rotation errors – from PM prediction errors

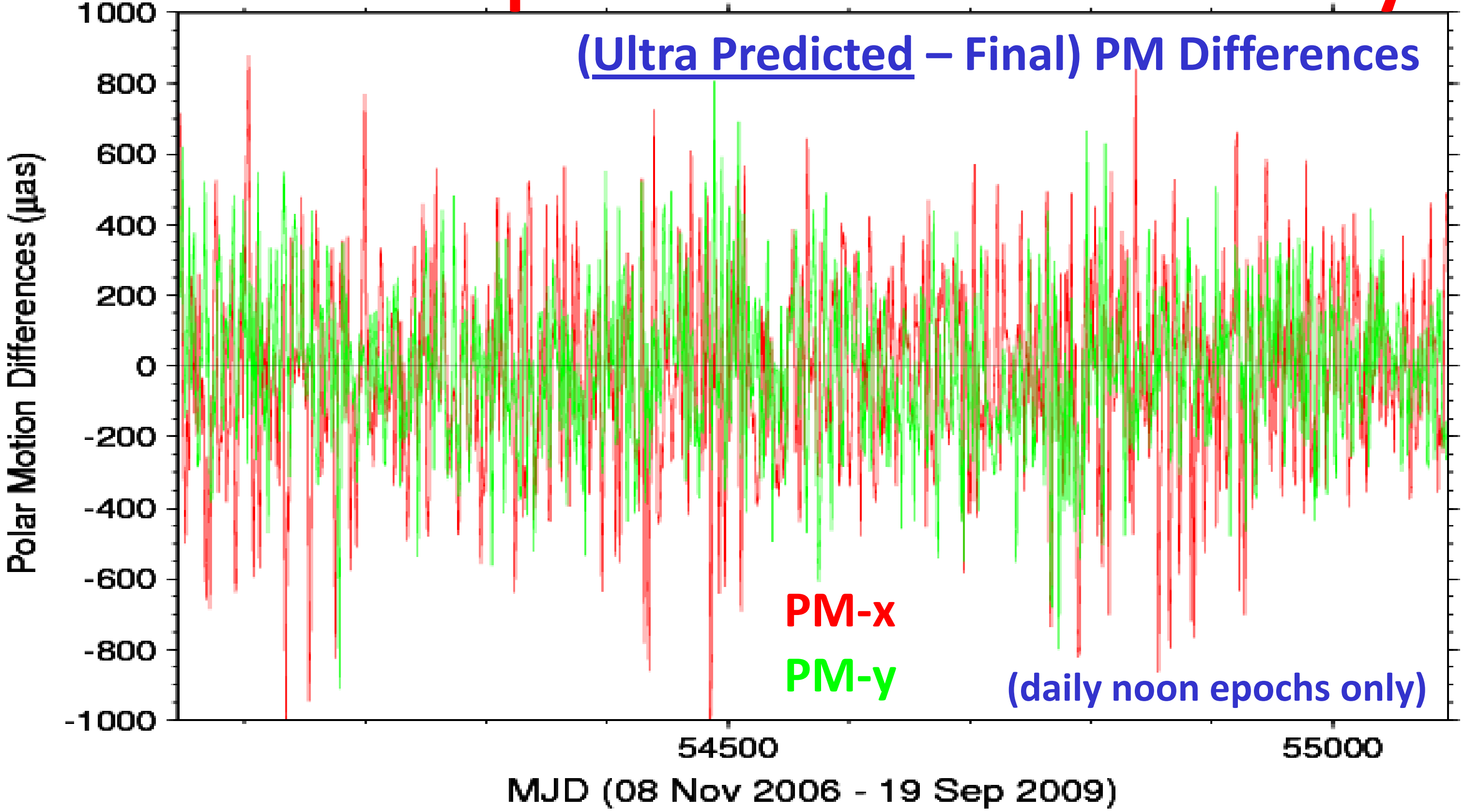
- **Next largest RT limits from orbit modelling & PM prediction errors**

IGS Ultra-Rapid Polar Motion Accuracy



Years (units = µas)	**Ultra-Rapid**		**Final**		**Δ(Ultra-Final)**	
	<σ$_x$>	**<σ$_y$>**	**<σ$_x$>**	**<σ$_y$>**	**<Δx> ± SDev**	**<Δy> ± 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 ± **33.6**	-18.5 ± **41.1**

IGS Ultra-Rapid Polar Motion Accuracy



Years (units = µas)	Ultra-Rapid		Final		Δ(Ultra-Final)	
	$\langle\sigma_x\rangle$	$\langle\sigma_y\rangle$	$\langle\sigma_x\rangle$	$\langle\sigma_y\rangle$	$\langle\Delta x\rangle \pm$ SDev	$\langle\Delta y\rangle \pm$ 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 ± **266.6**	12.7 ± **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 μas (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: ~250 μas (7.7 mm)
  - reported formal errors are too optimistic by a factor of 3 to 4

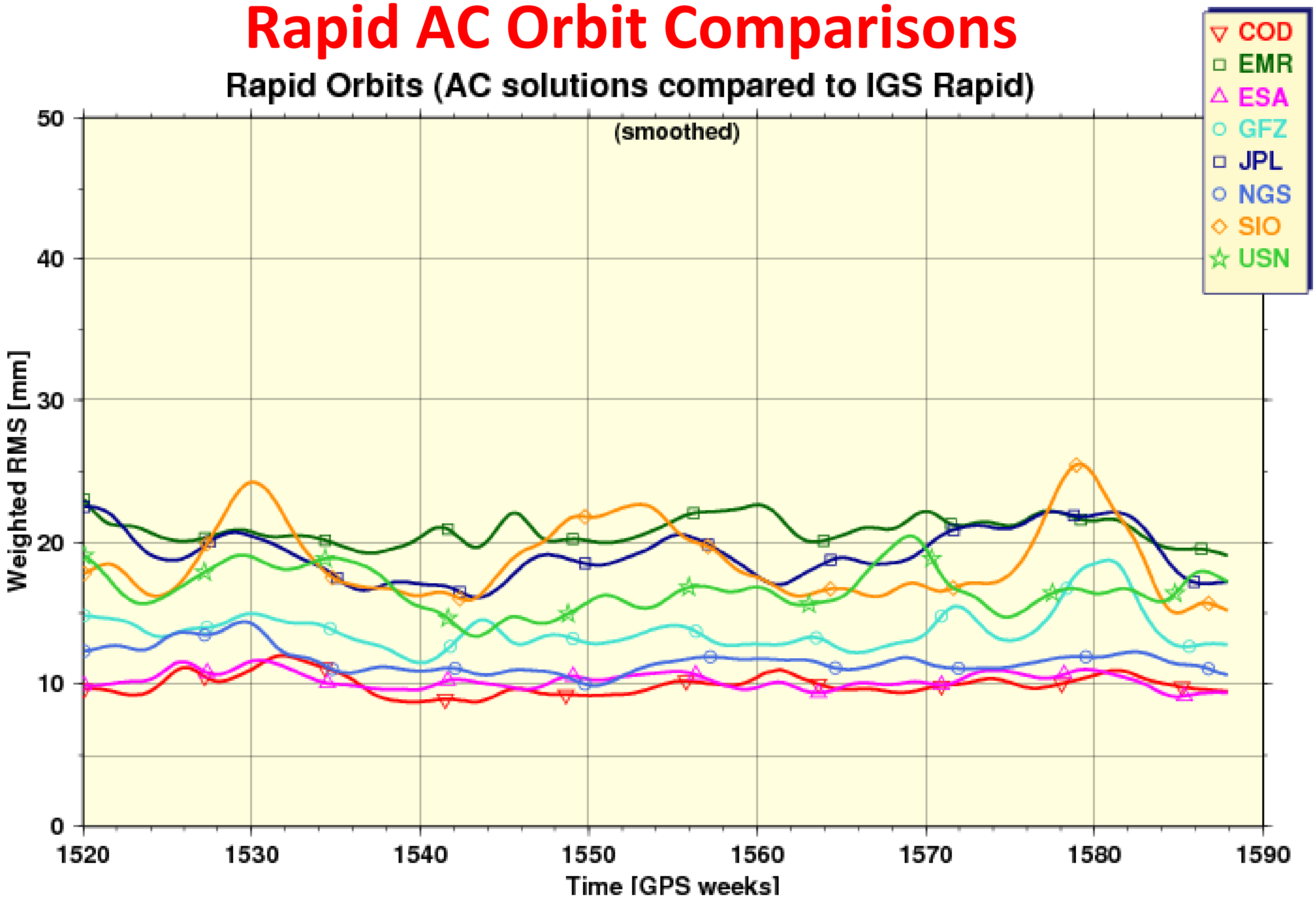
- ACs should predict EOPs internally rather than use IERS
  - or use JPL service, esp for UT1
  - AC's near-term EOP predictions usually better than values from IERS (due to availability of most recent IGA observations)

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



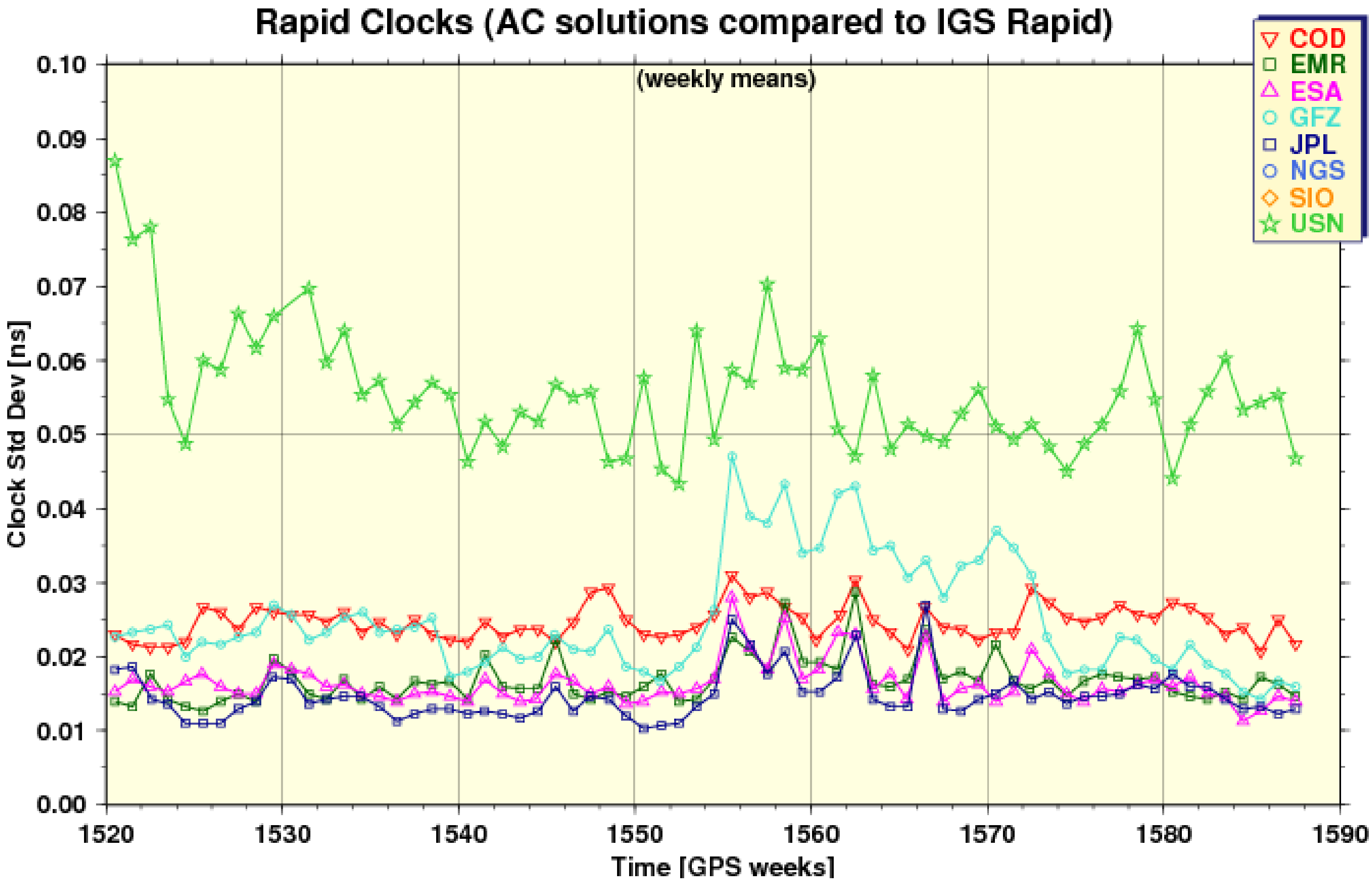
- **Performance dispersion among ACs is reasonable**
  - **best & worst differ by only factor of ~2**

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**

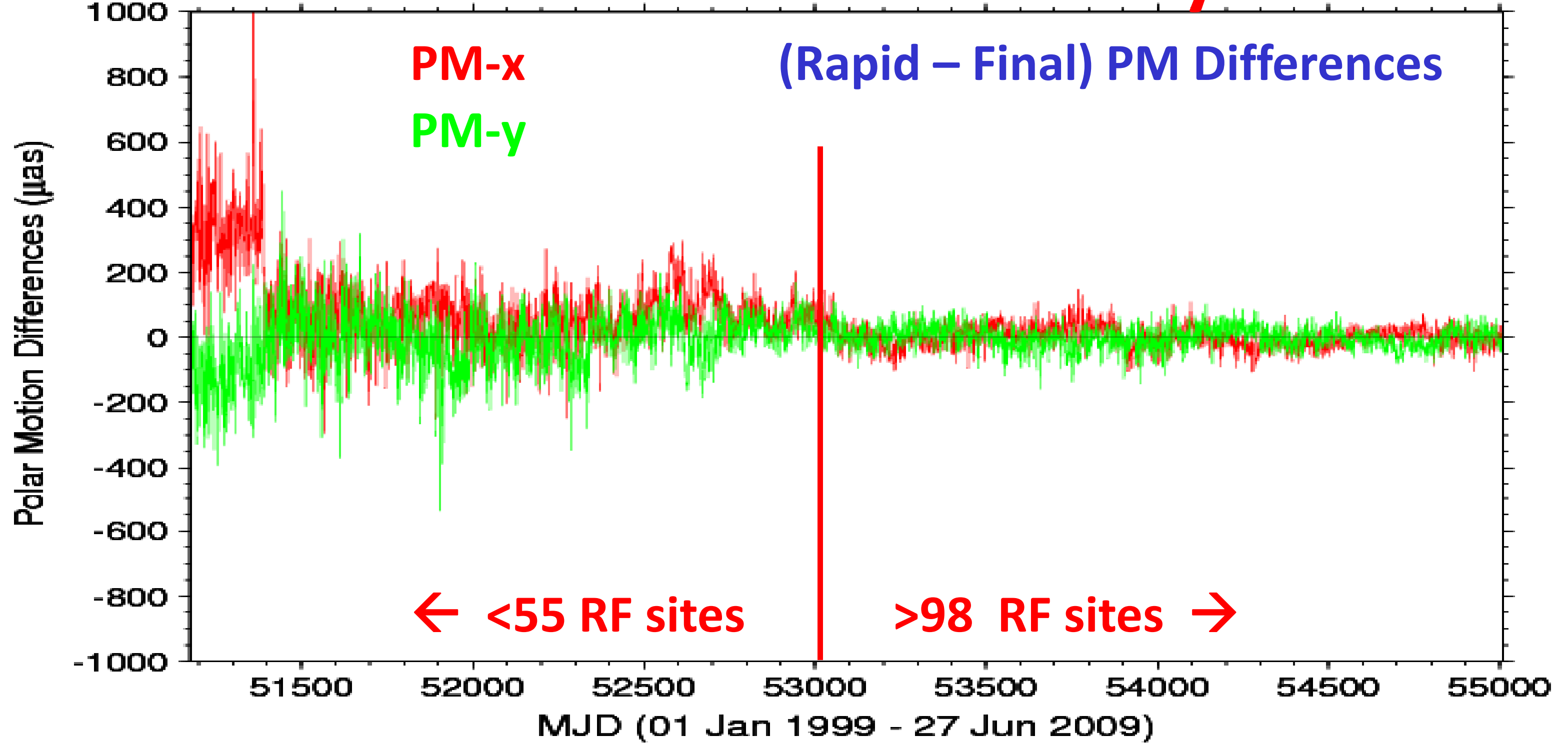
- **Possible common mode IGR/IGS errors not visible here**
  - **especially long-period errors (>1 d)**
  - **e.g., due to Reference Frame or form of empirical orbit model**

Rapid AC Clock Comparisons



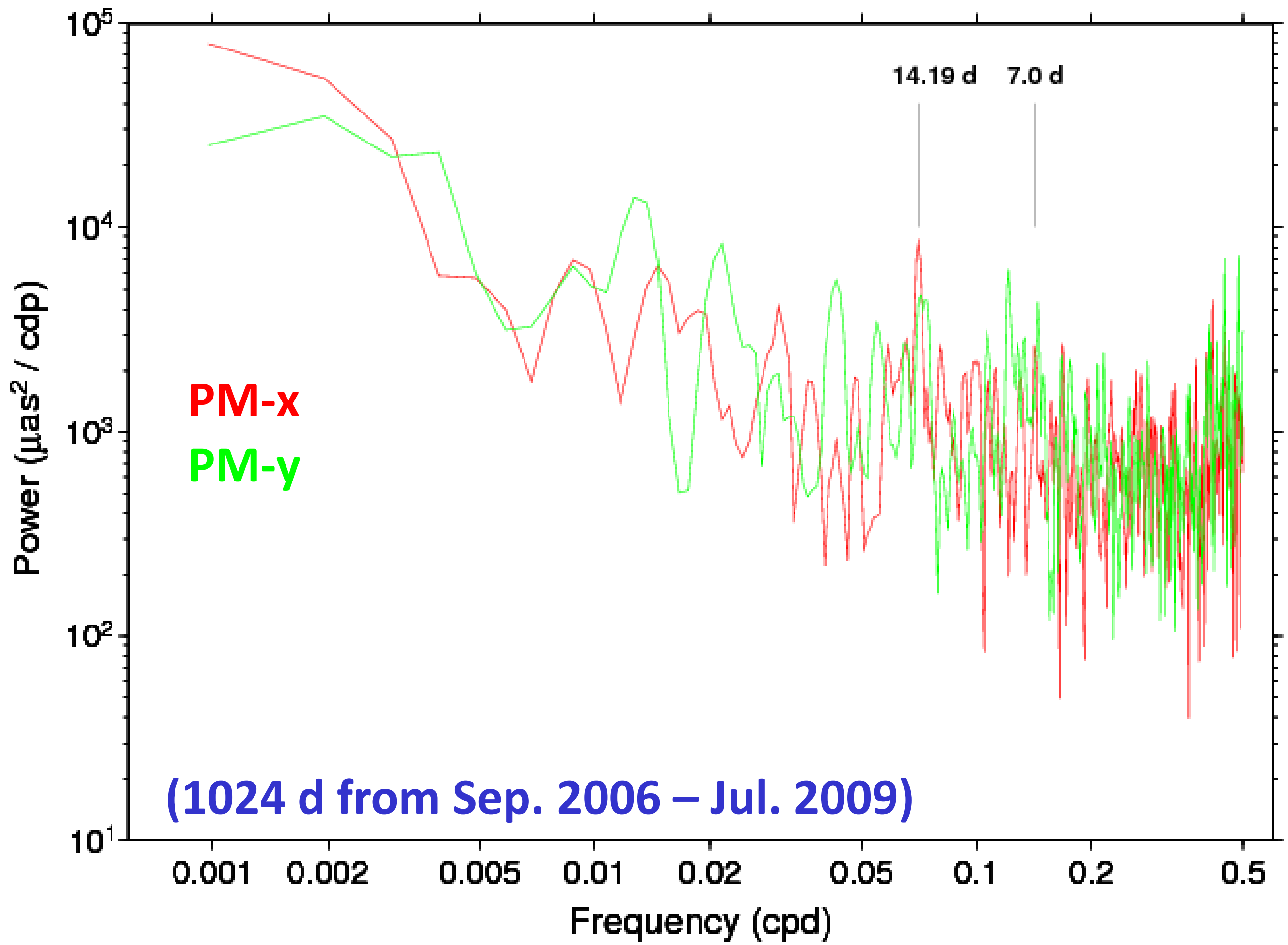
- **Normally, high-quality – but only 5 usable Rapid clock ACs**
  - **causes product weakness if 1 or more ACs miss**

IGS Polar Motion Accuracy



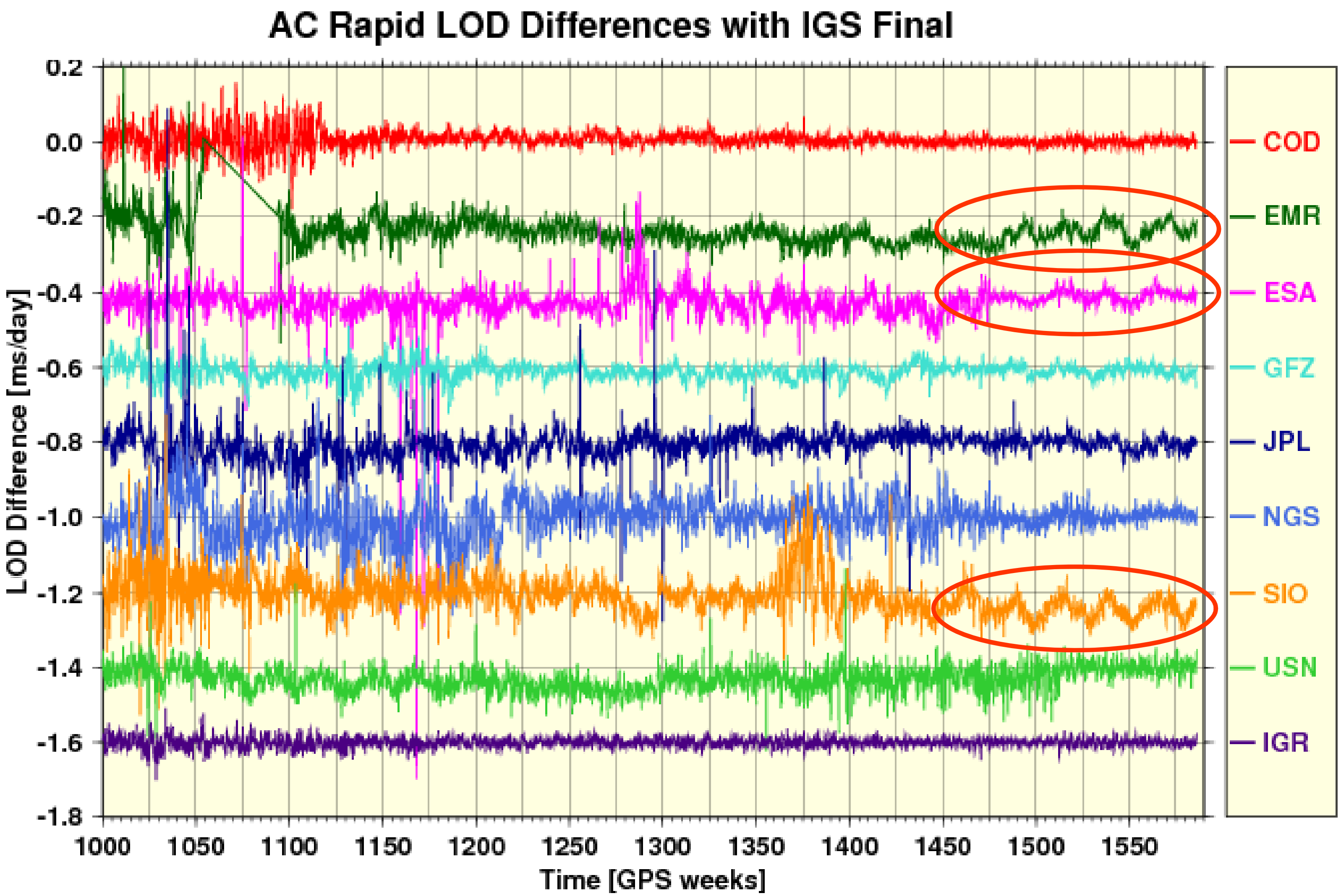
Years (units = µas)	**Rapid**		**Final**		**Δ(Rapid-Final)**	
	$\langle\sigma_x\rangle$	**$\langle\sigma_y\rangle$**	**$\langle\sigma_x\rangle$**	**$\langle\sigma_y\rangle$**	**$\langle\Delta x\rangle \pm$ SDev**	**$\langle\Delta y\rangle \pm$ SDev**
1999-2001.5	77.3	85.9	44.1	44.4	119.9 ± 153.2	-29.7 ± 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 ± **28.9**	-1.4 ± **31.1**

Spectra of (Rapid-Final) PM Differences



- **High-frequency noise consistent with ~30 µas accuracy recently**
  - **but longer period errors are most significant**
  - **fortnightly feature near 14.2 d may signify tide model errors**

Rapid AC LOD Comparisons



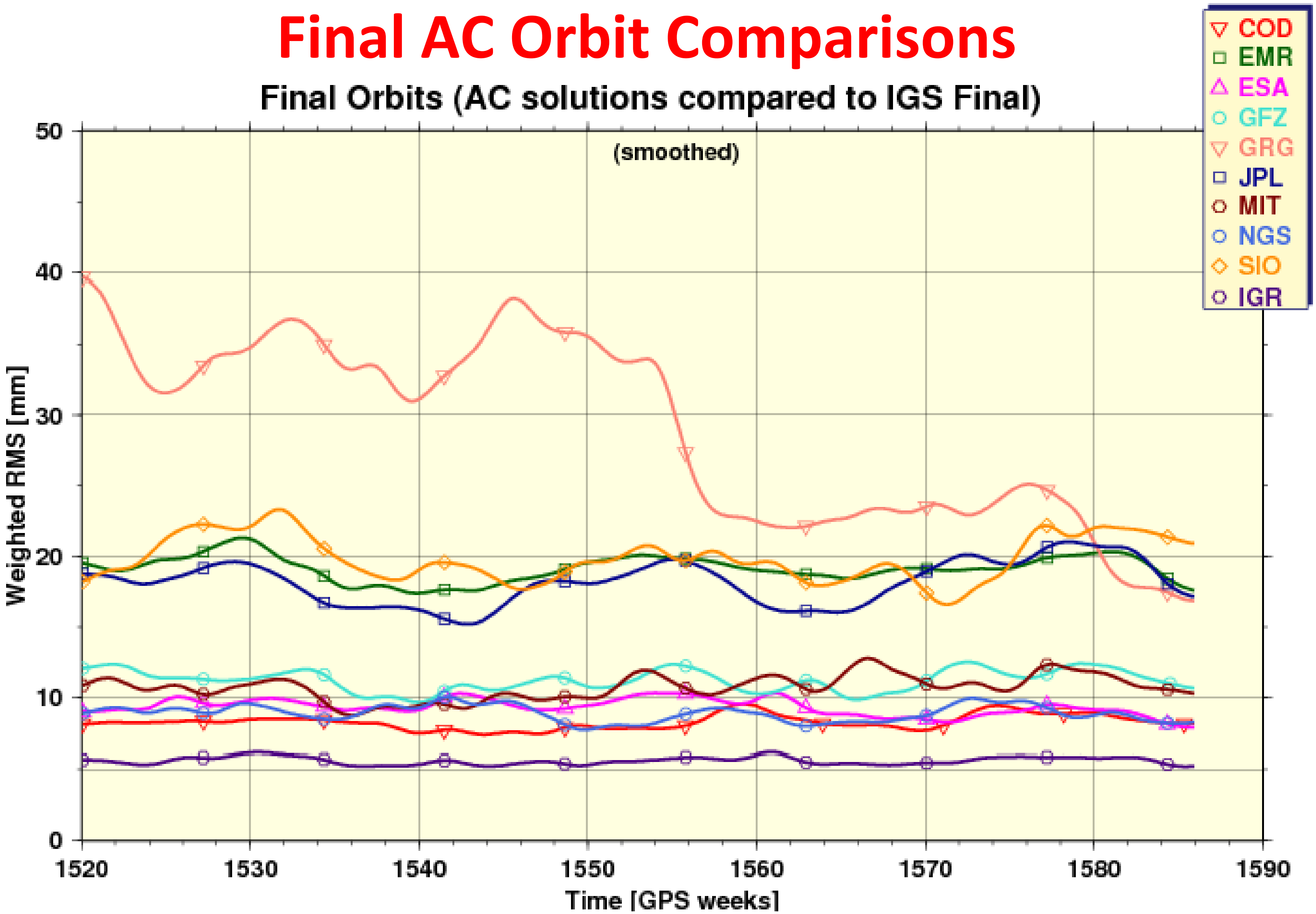
- EMR, ESA, & SIO show annual LOD variations
  - also strong LOD biases for EMR & SIO
  - similar features in Final LODs

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 → ≤ 12:00, if IGU latency reduced to 2 hr
  - AC deliveries from 16:00 → ≤ 11:00, if IGU latency reduced to 1 hr

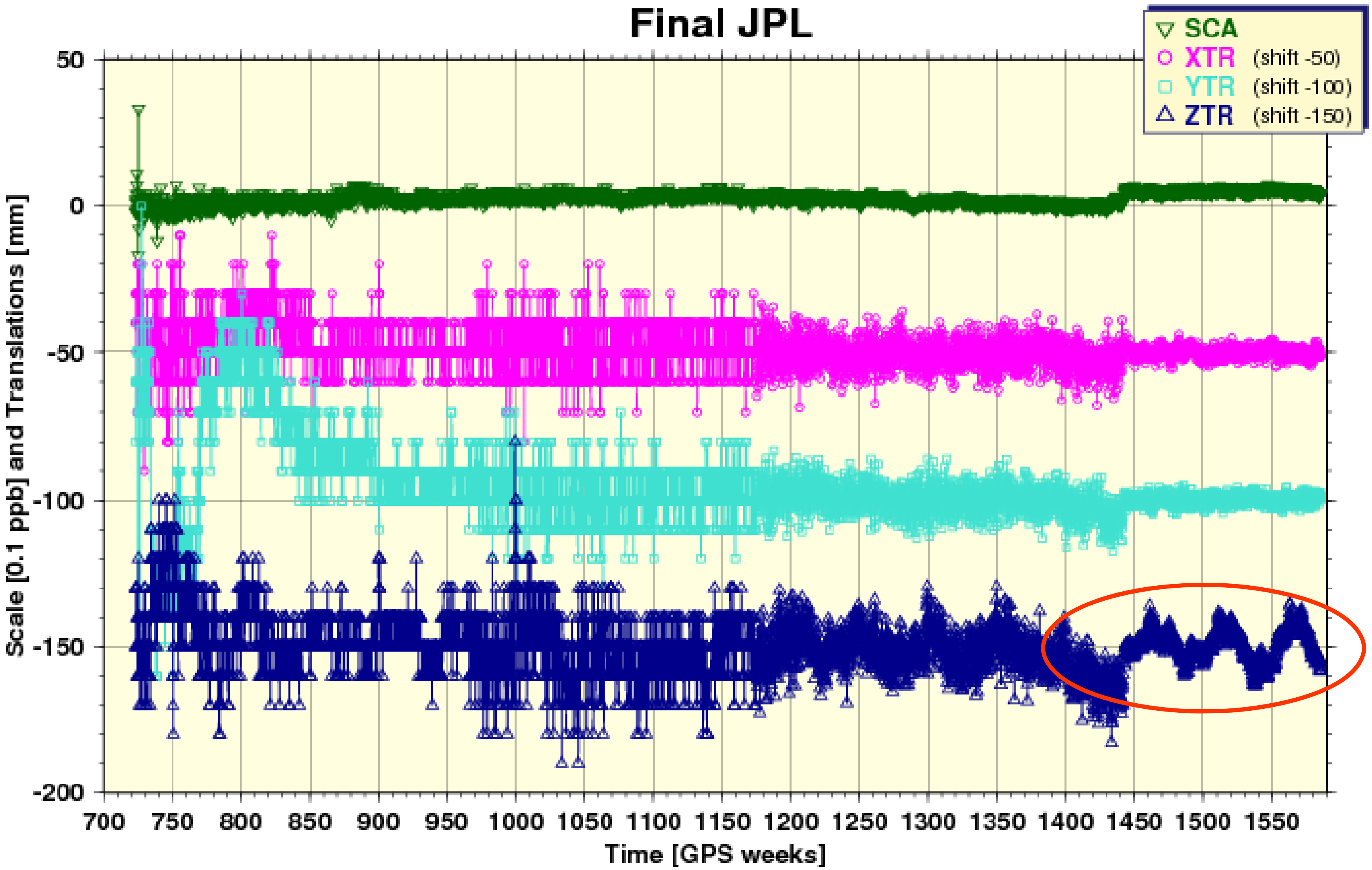
Final Products

Final AC Orbit Comparisons



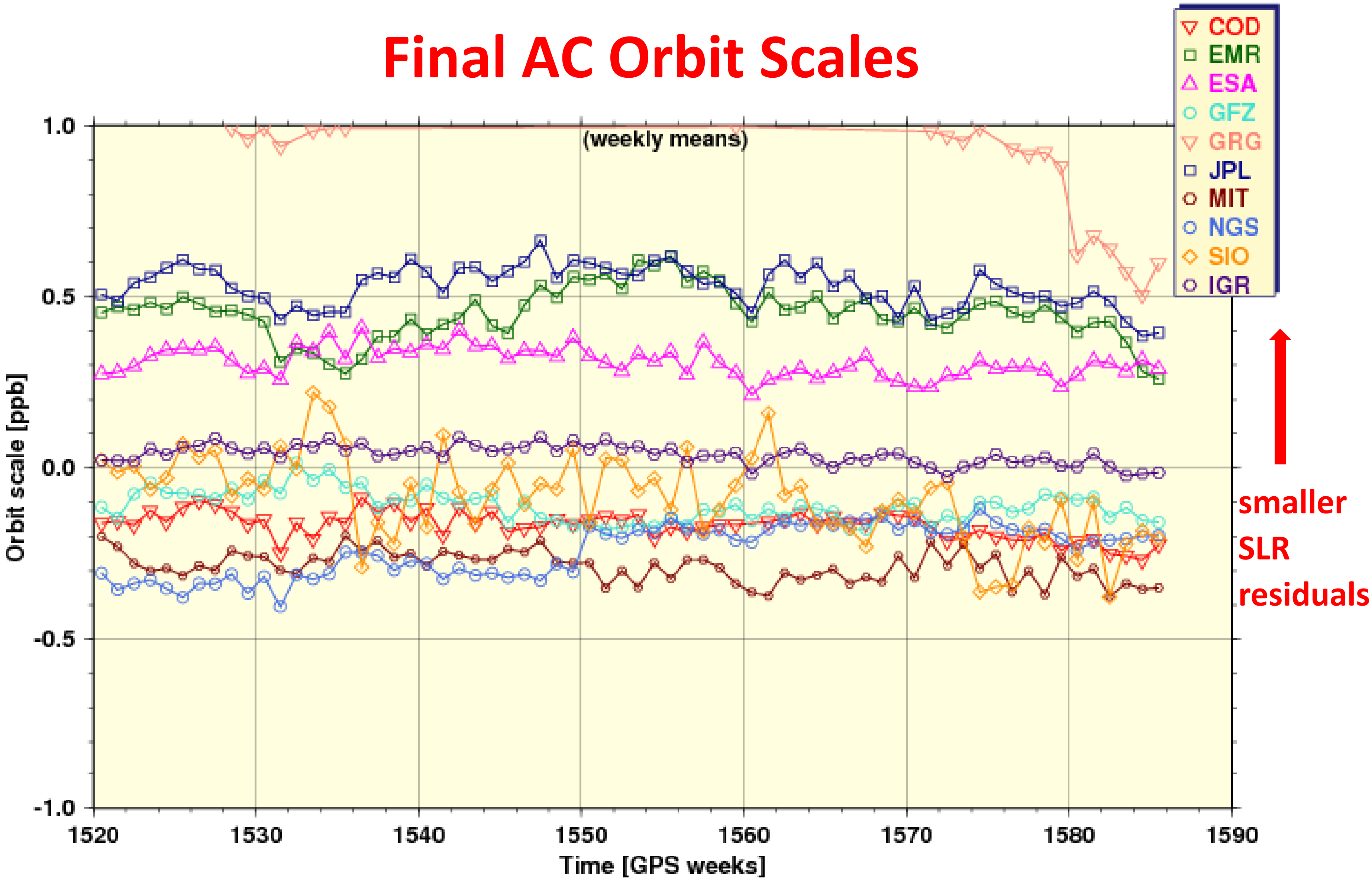
- AC performances cluster in two bands, but dispersion is OK
  - IGR orbits are consistently & significantly better than any single AC Final

Final Orbit Z Translations



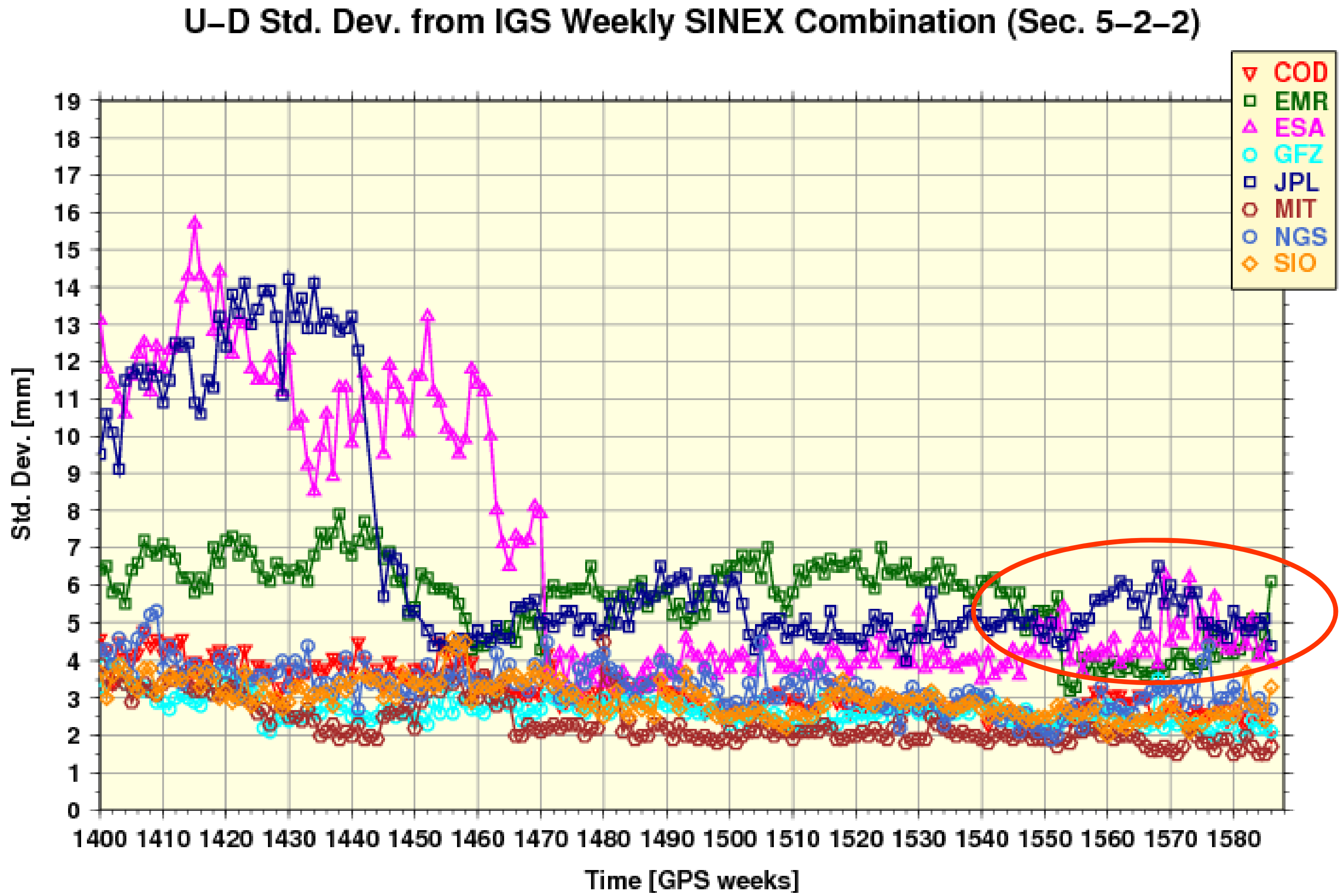
- Similar annual TZ variations seen for EMR, ESA, GFZ, JPL, & SIO (?)
  - source of effect is unknown

Final AC Orbit Scales



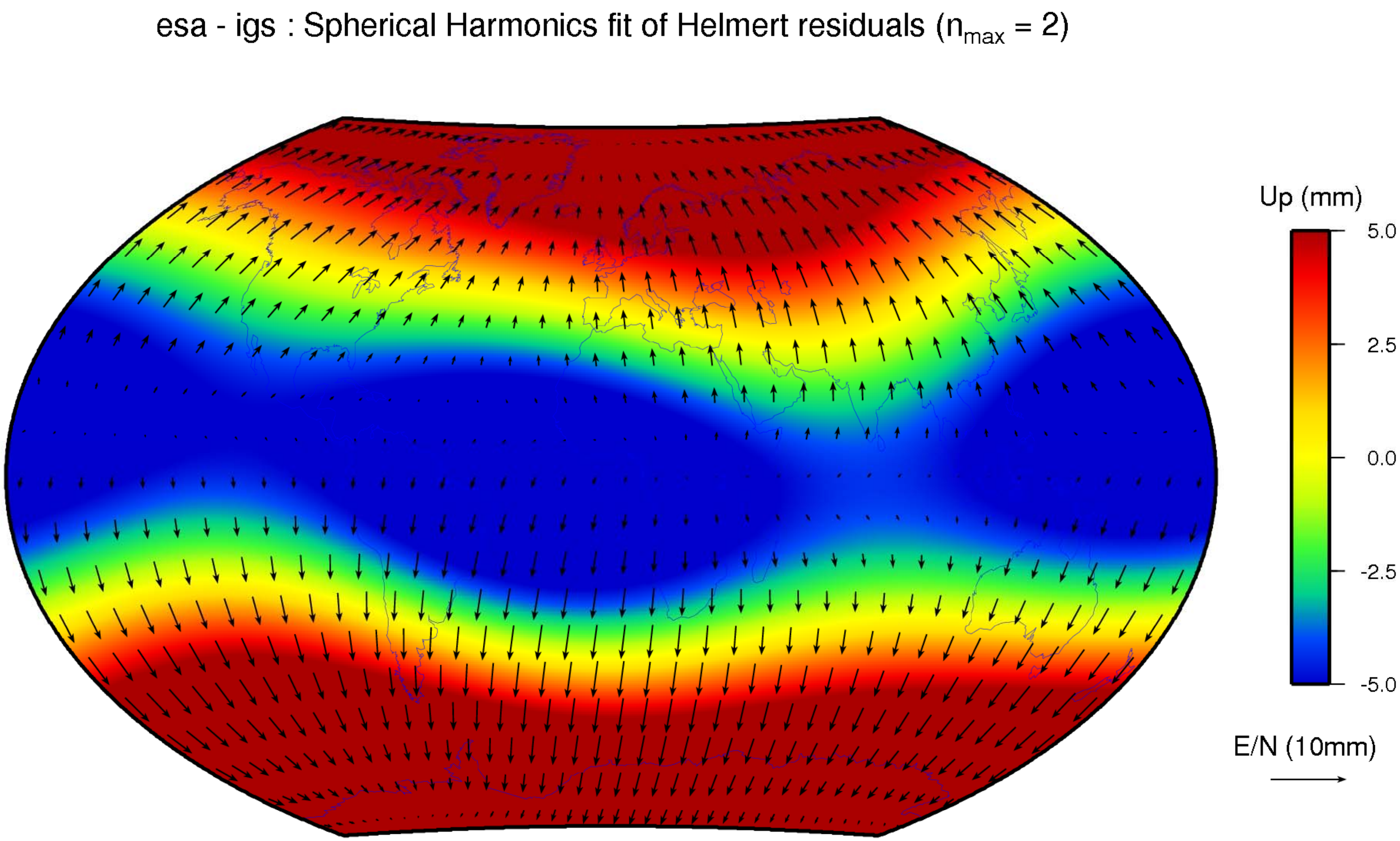
- **Bimodal distribution of AC orbit scales**
  - ESA, JPL, & GRG apply albedo models & have scales closer to SLR ranges
  - EMR does *not* apply albedo model

TRF Differences: Albedo Model Effect ?



- 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” ?

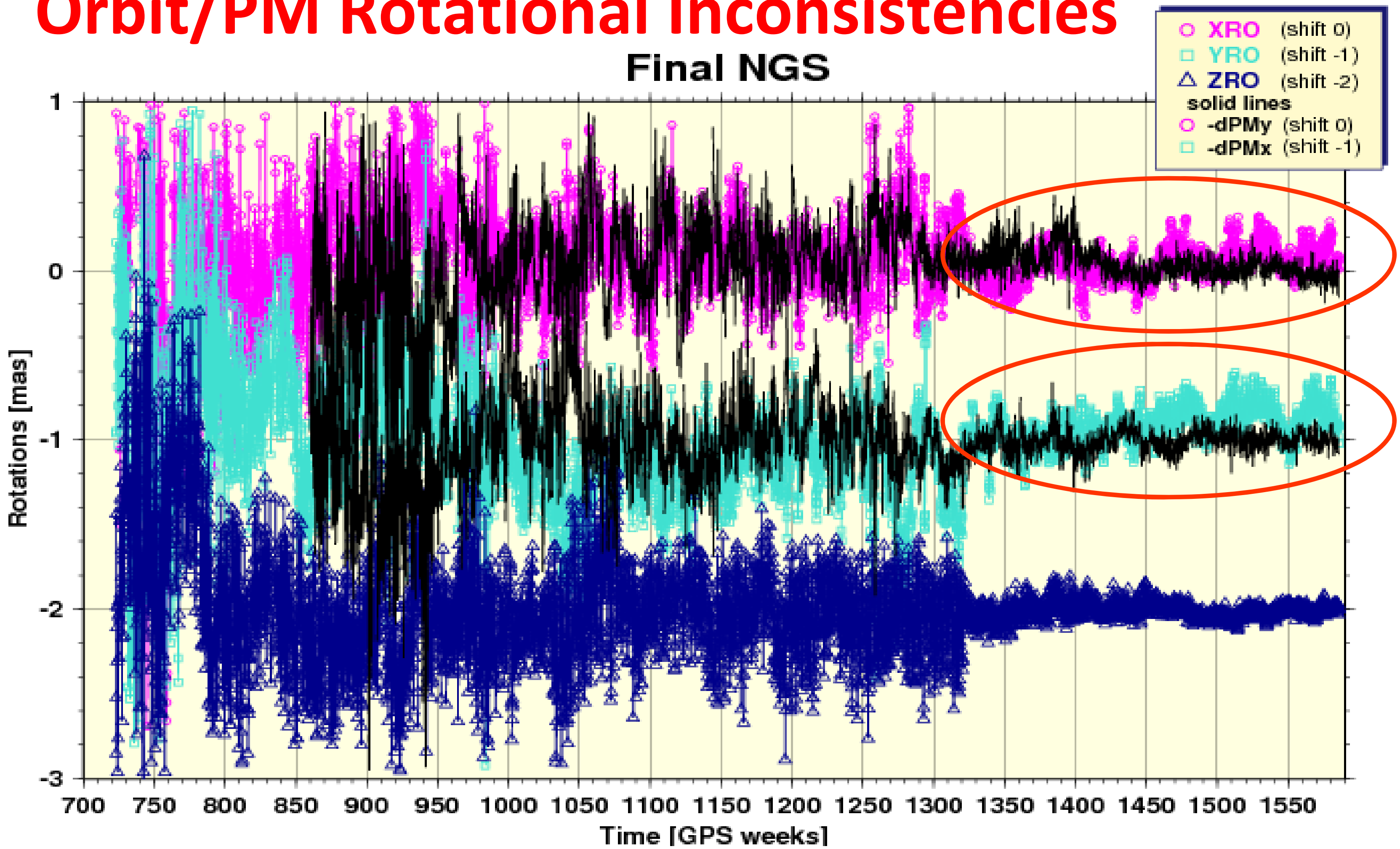
TRF Differences: Albedo Model Effect ?



(courtesy of Paul Rebischung)

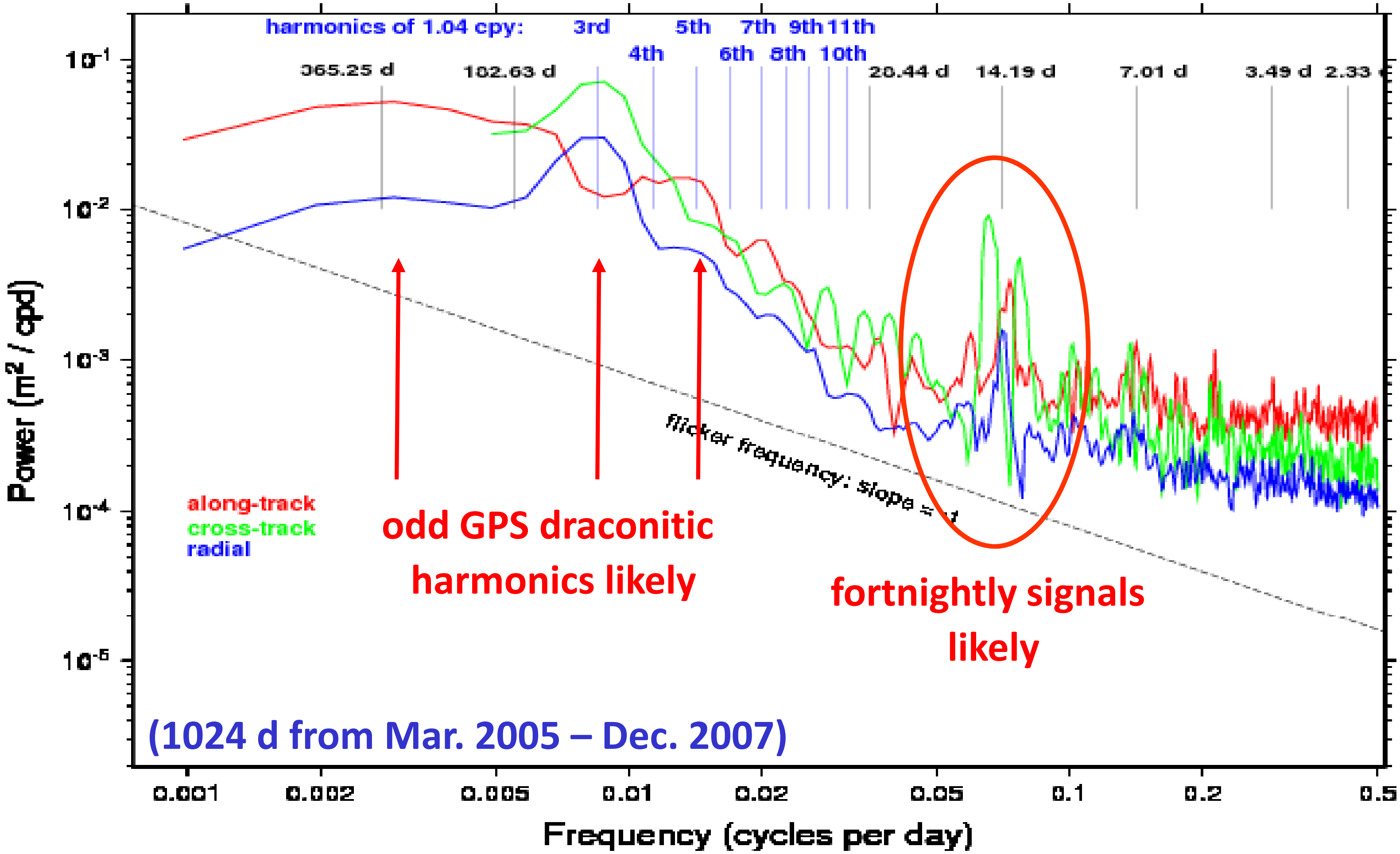
- Example of ESA frame differences for week 1573
  - character is systematic & roughly zonal in Up & North for this week
  - but pattern is not stable over time
- Question: How to know which frame is less deformed ?

Orbit/PM Rotational Inconsistencies



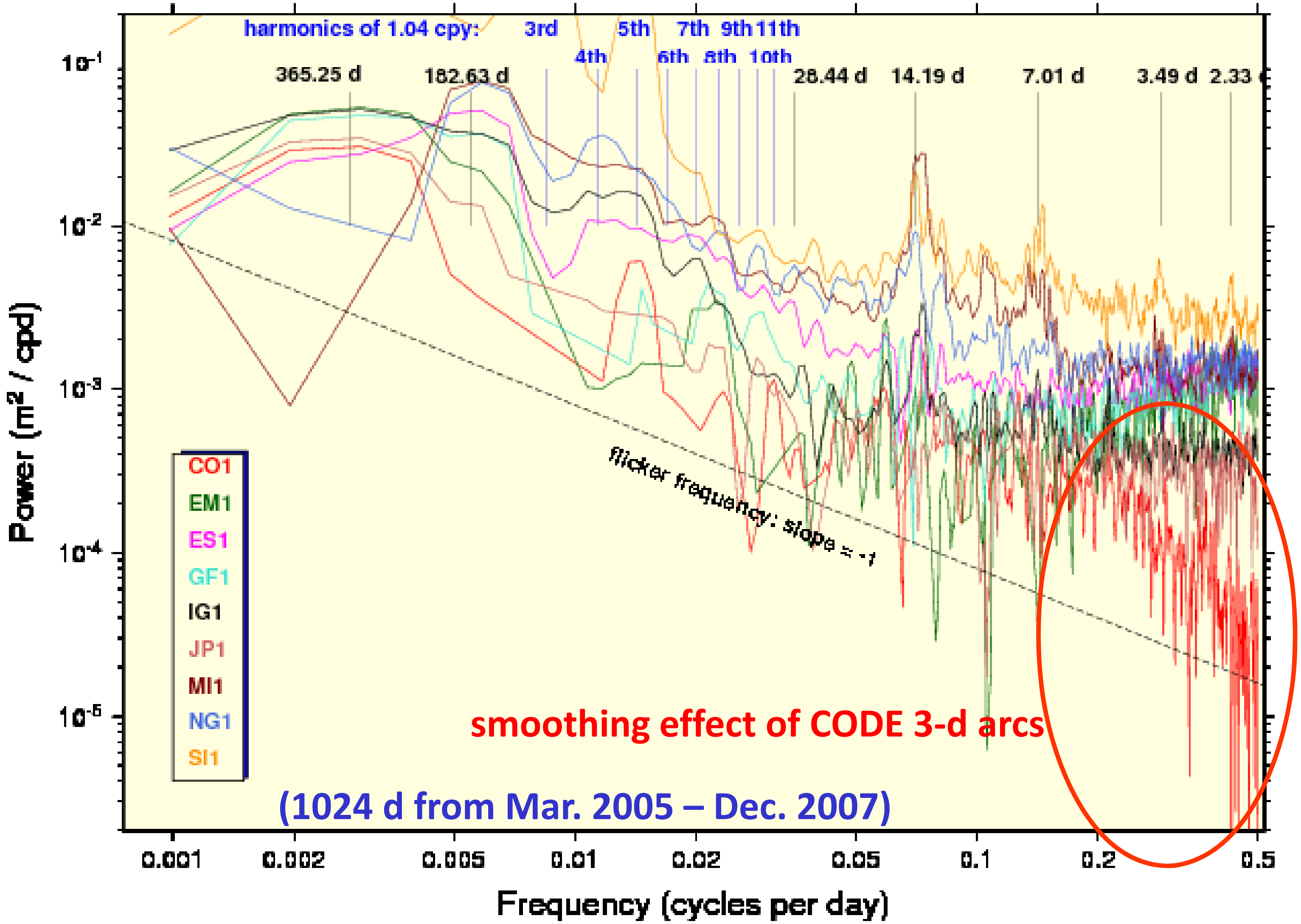
- **AC orbit & PM rotational offsets should be self-consistent**
  - **but orbit rotations show larger dispersion for all ACs**
  - **smallest inconsistencies seen for recent CODE, JPL, MIT, & IGR**
- **Orbit accuracy probably limited by such rotational effects**

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



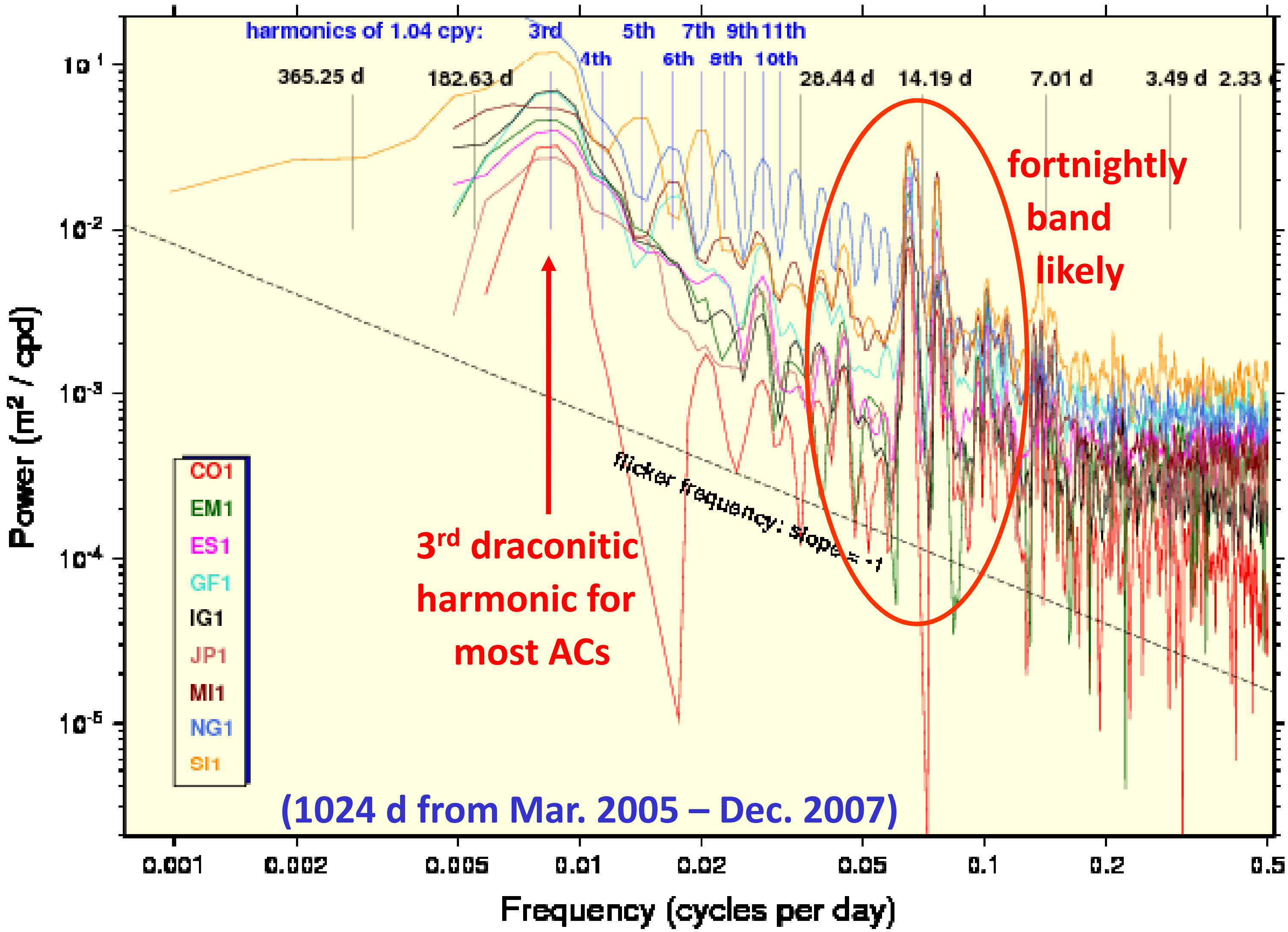
- Jumps computed from Berne-model fit to adjacent orbit days
  - stacked over all SVs & lightly smoothed
  - "calibrated" for errors due to (fit + extrapolation) method
- Background errors follow ~flicker noise on seasonal time scales
  - transition to whiter noise for <14 d

Along-track Spectra of AC Orbit Day-Jumps



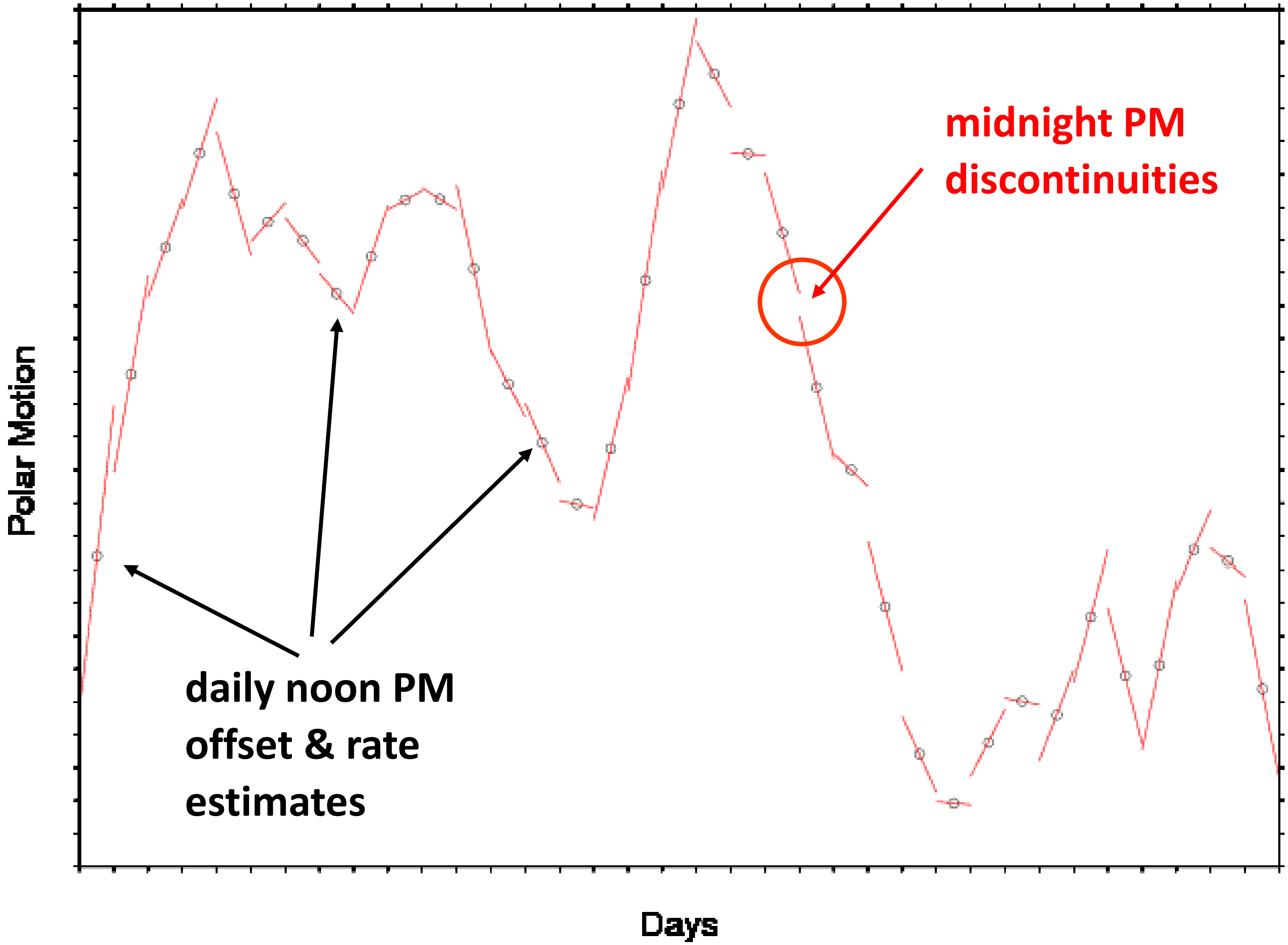
- AC along-track spectra show mostly flicker + white noise
- Some AC peaks but good agreement only for fortnightly

Cross-track Spectra of AC Orbit Day-Jumps



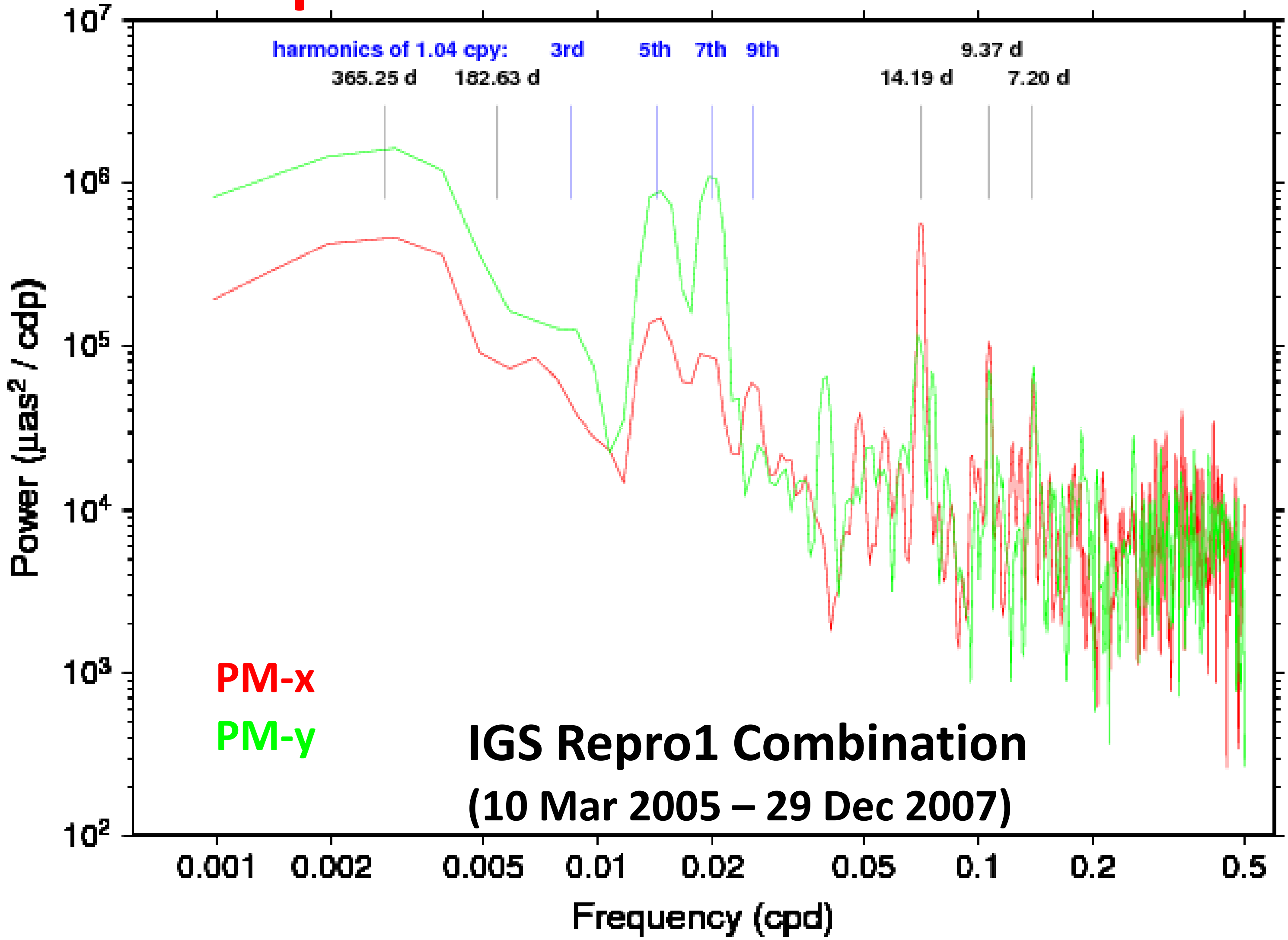
- AC cross-track spectra show 3rd draconitic & fortnightly bands
- Some spurious AC peaks & lower white noise floor

Compute Polar Motion Discontinuities



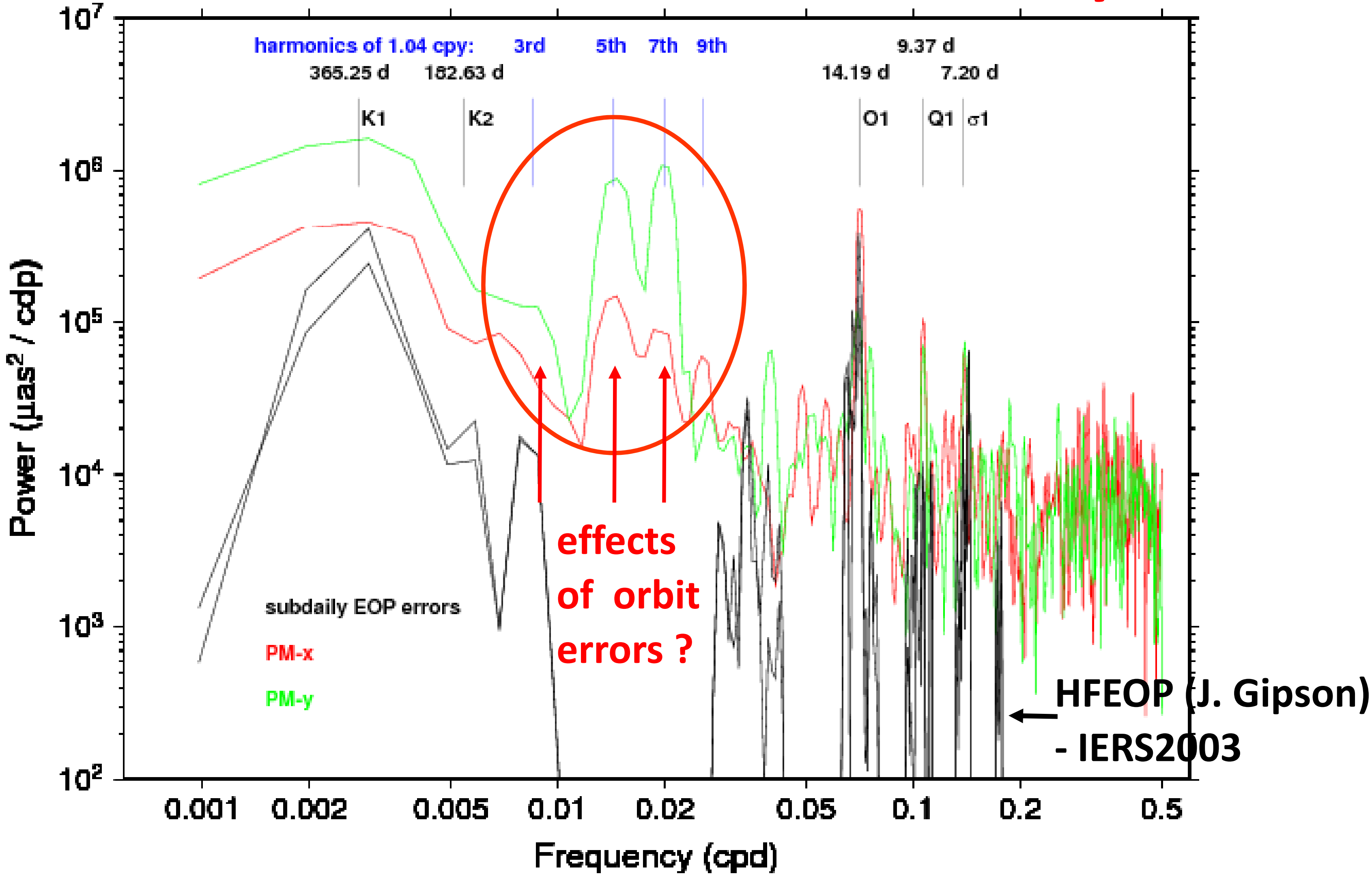
- **Examine PM day-boundary discontinuities for IGS time series**
  - **should be non-zero due to PM excitation & measurement errors**

Power Spectra of IGS PM Discontinuities



- Common peaks seen in most AC spectra are:
  - annual + 5^{th} & 7^{th} 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 (σ1, 2Q1, 2N2, µ2)
- Orbit errors presumably responsible for odd 1.04 cpy harmonics

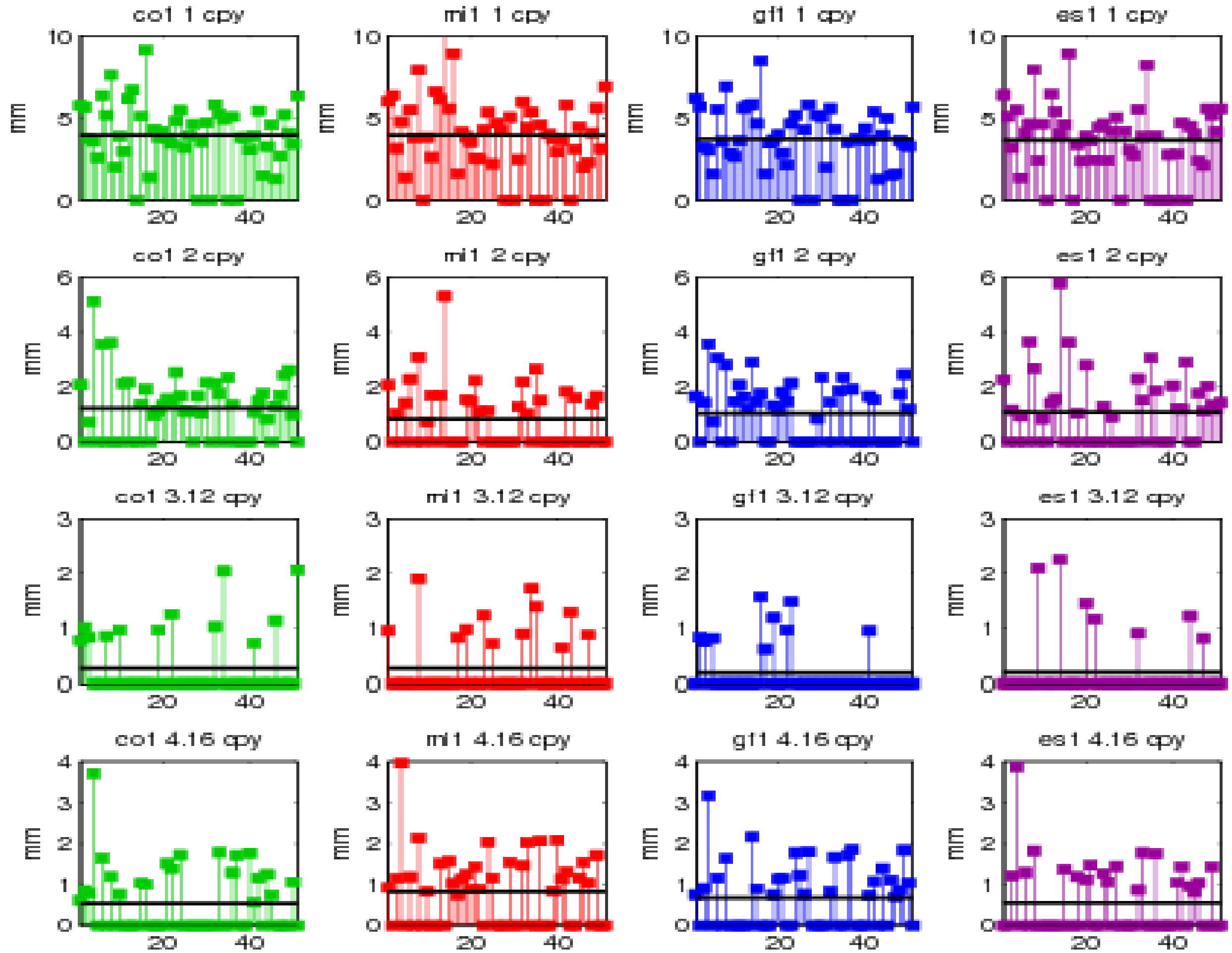
Station Position Harmonics Persist in Repro1

1 cpy:

2 cpy:

3.12 cpy:

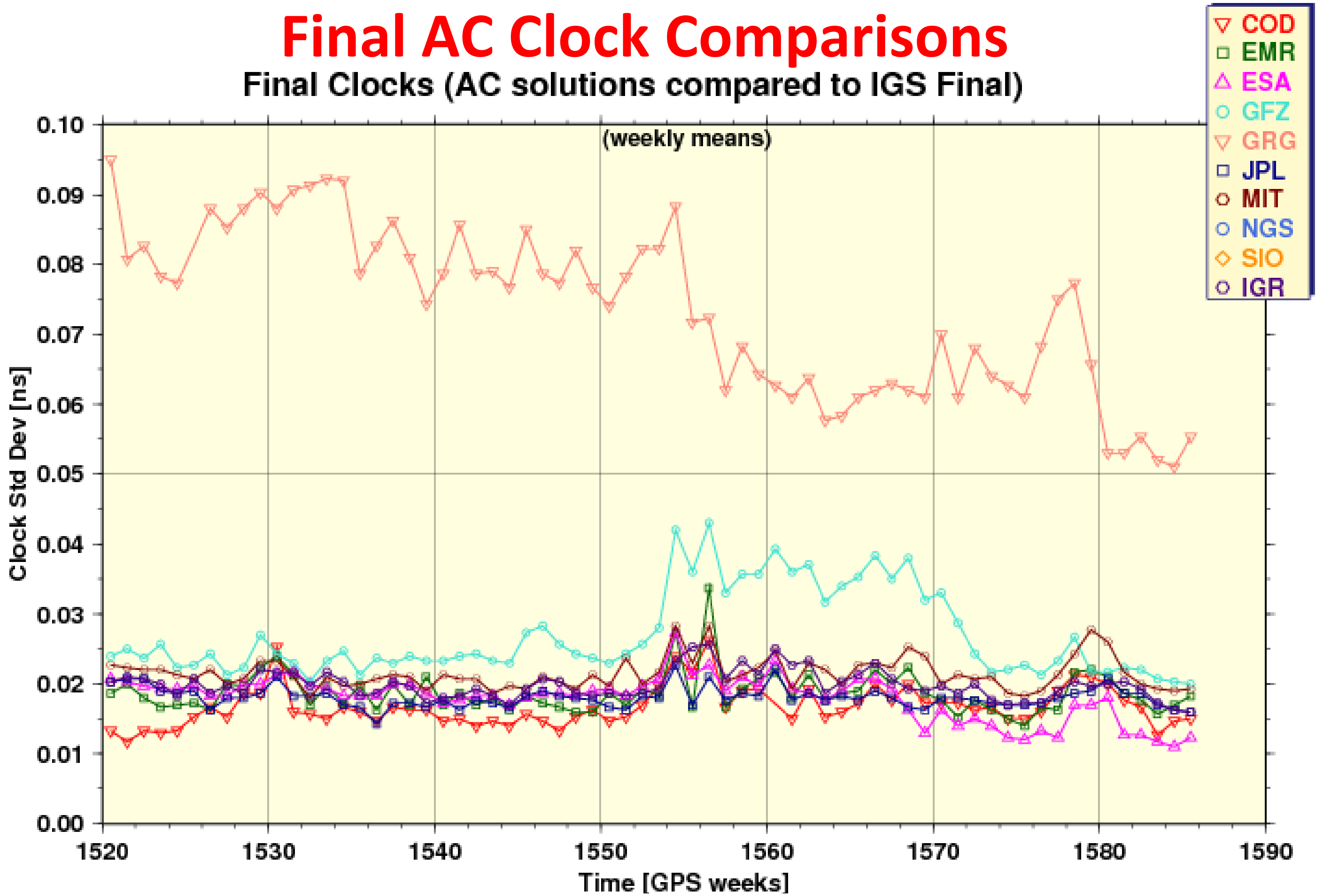
4.16 cpy:



(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 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 !

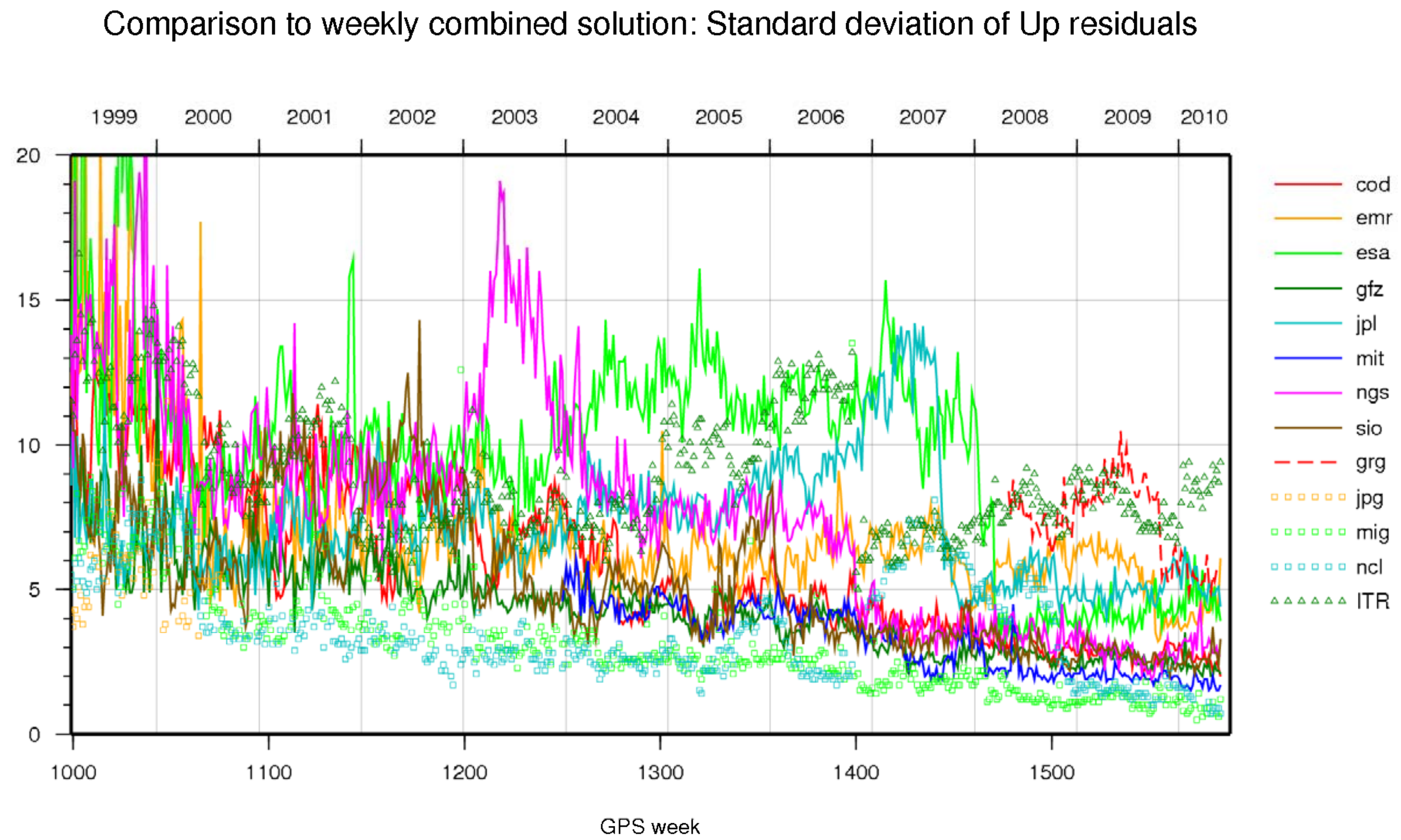
- IERS2003 subdaily EOP model errors alias into daily rate estimates, esp PM-rates, & probably 12 hr orbit parameters

- 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 – <u>but only if TRF impact is understood</u>
  - 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 ?

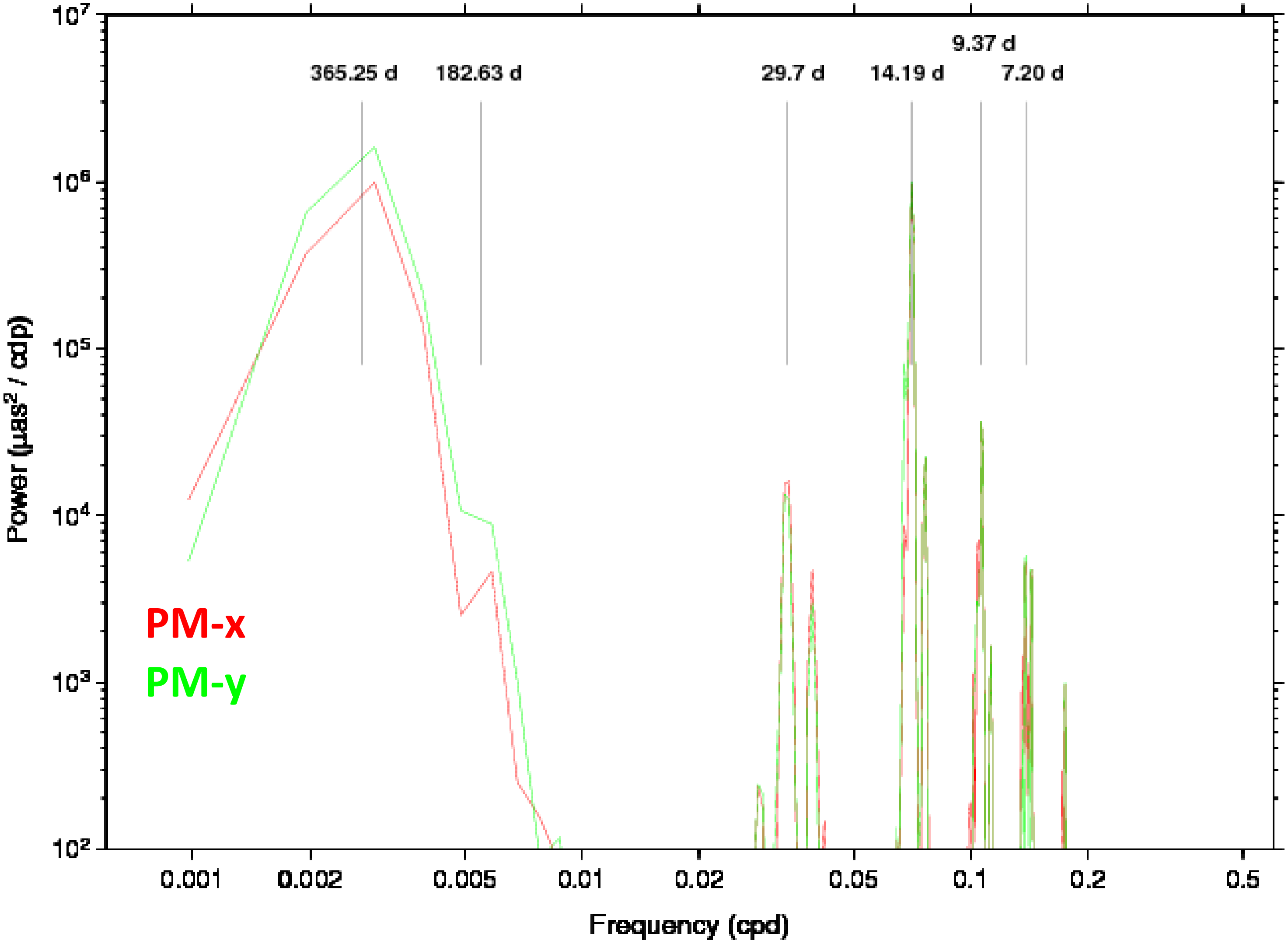
TRF Differences: Albedo Model Effect ?



- **ACs using albedo models (+ EMR) show largest Up residuals**
  - **possibly related to internal frame differences for these ACs**
  - **if so, differences are not stationary in time**

- **Questions: Is albedo model the cause & which frame is “correct” ?**

Spectra of Subdaily EOP Tide Model Differences



- Compare TPXO7.1 & IERS2003 (used by IGS) EOP models
  - TPXO7.1 & GOT4.7 test models kindly provided by Richard Ray
  - assume subdaily EOP model differences expressed fully in IGS PM results

Recent Final PM-Rate Accuracy

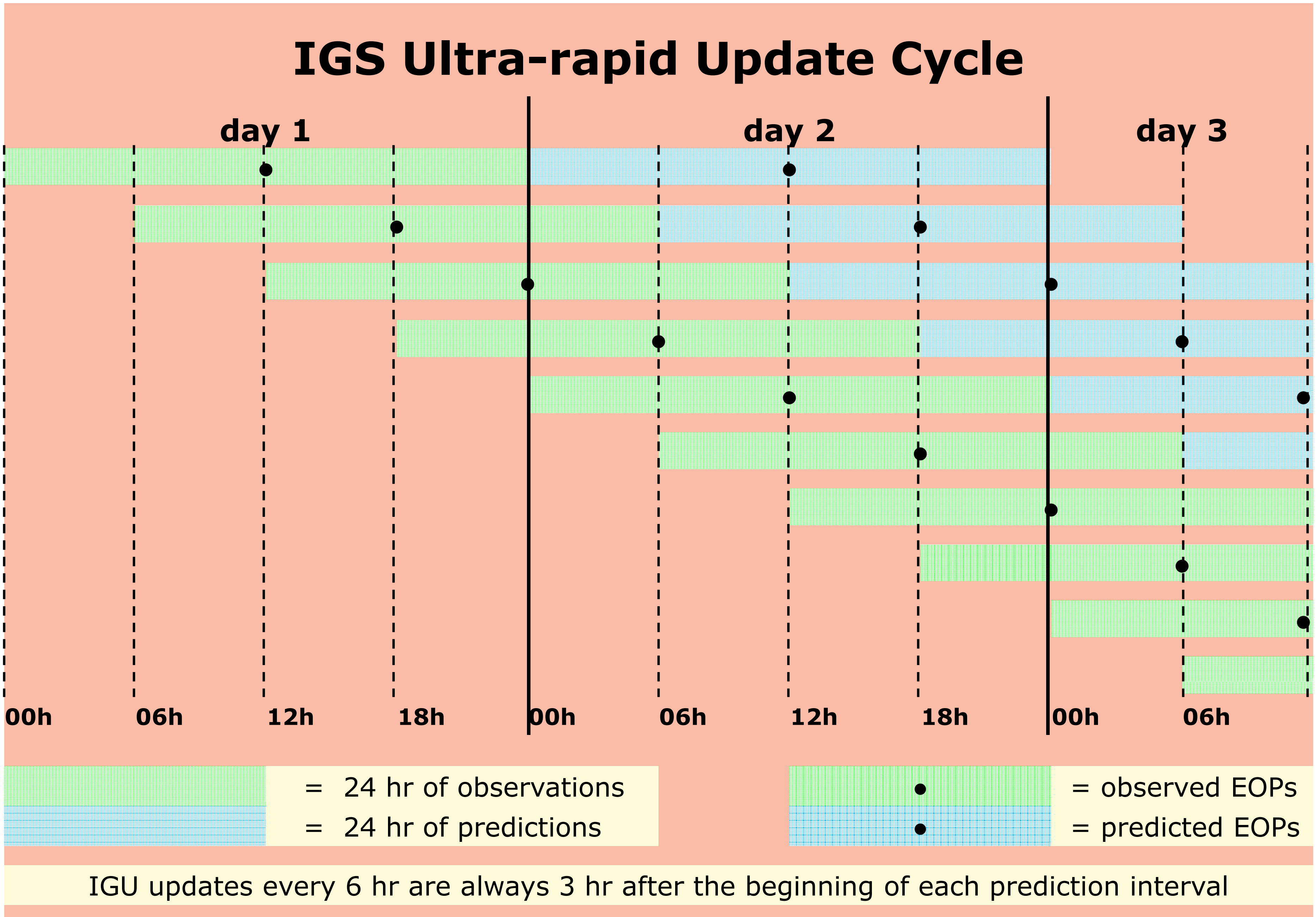
- ITRF2005 multi-technique combination experience
  - scaled formal errors ~90 µas/d for PM-xrate & PM-yrate
  - but these estimates are optimistic

- IGS GPS also dominates PM-rate combinations

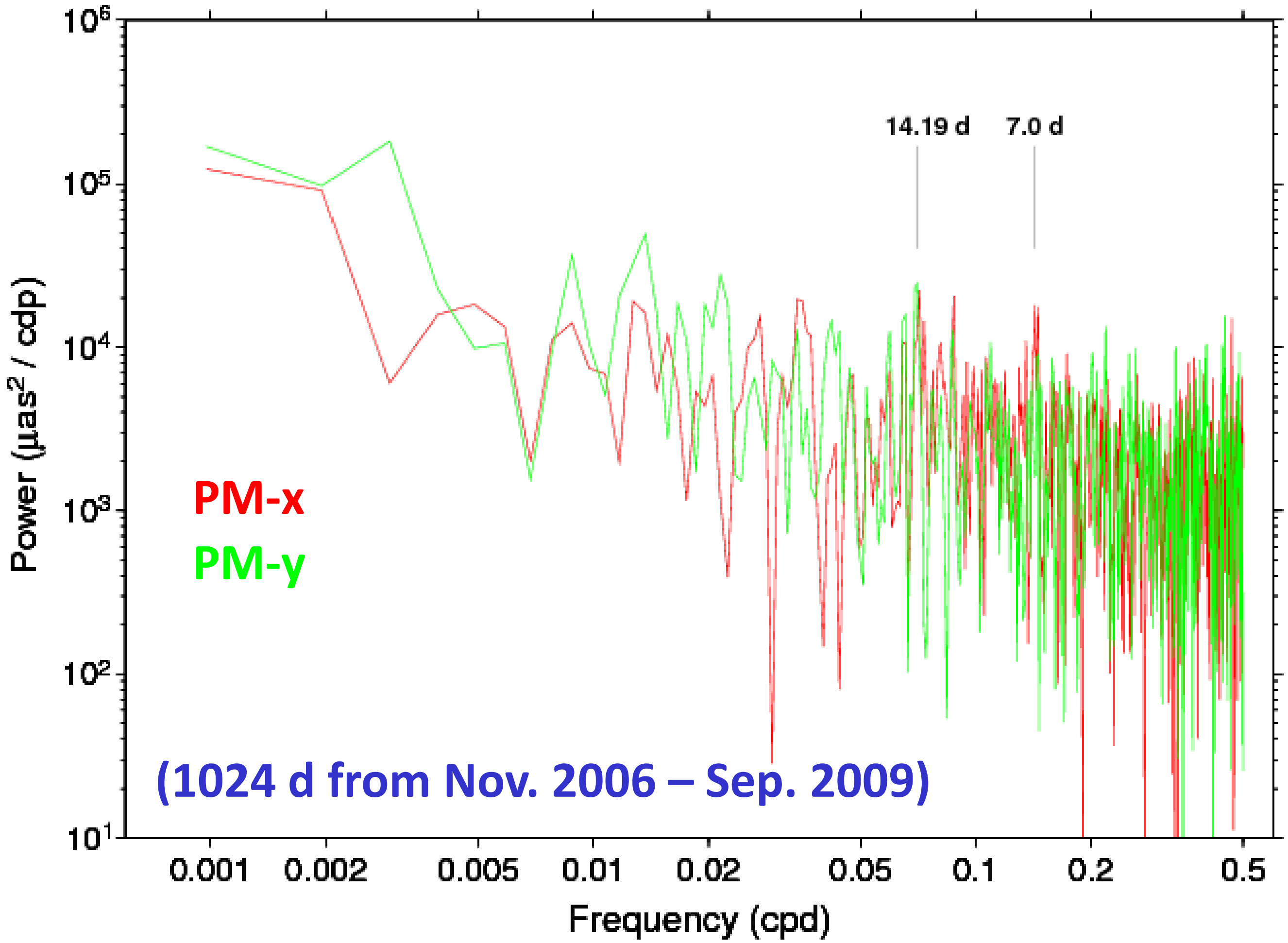
- GPS PM-rate errors can be assessed by examining day-boundary discontinuities

- PM-rates very sensitive to subdaily EOP tide model errors
  - imply IERS2003 errors for K1, O1, Q1/N2, & probably other lines
  - odd numbered harmonics of 1.04 cpy point to orbit errors
  - estimated IGS PM-rate errors: ~140 µas/d for xrate; ~180 µas/d for yrate
  - PM-yrate errors larger due to greater 1.04 cpy orbit harmonics

- For excitation studies, probably best to use PM time differences, not directly observed PM-rates


IGS Ultra-rapid Update Cycle
day 1
day 2
day 3
00h
06h
12h
18h
00h
06h
12h
18h
00h
06h
= 24 hr of observations
= 24 hr of predictions
= observed EOPs
= predicted EOPs
IGU updates every 6 hr are always 3 hr after the beginning of each prediction interval

Spectra of (Ultra Observed-Final) PM Differences



- **High-frequency noise consistent with ~50 µas accuracy**
  - not much coherent long-period errors
  - possible minor features near 7 d & 14.2 d

EOP Error Sources

σ_{EOP} =

Station-related measurements:

- thermal noise
- instrumentation
- propagation delays
- multipath, etc

$\sigma_{Station} \approx 1/\sqrt{N_{Station}}$

\+

Geophysical & parameter models:

- esp near S1, K1, K2 tidal periods

\+

Source-related errors:

- orbit dynamics (GPS, SLR, DORIS)
- quasar structures (VLBI)

$\sigma_{Source} \approx 1/\sqrt{N_{Source}}$

Possible improvements:

- more robust SLR, VLBI networks ?
- more stable site installations ?
- near asymptotic limit for GPS already

- new subdaily EOP tide model ?
- better handling of parameter constraints ?
- modern theory of Earth rotation ?

- new GNSS constellations
- better GNSS orbit models ?
- quasar structure models (VLBI) ?

→ Multi-technique EOP combinations mostly sub-optimal ! ←

Conclusions

- **Since 2004.0 IGS Final polar motion accuracy <~30 µas**
  - robust global network is prime factor
  - Rapid PM is only slightly poorer, <~40 µas
- **GPS PM nearing asymptotic limit for random errors (~20 µas)**
  - smaller systematic errors possible with new GNSSs, better orbit modeling, & better handling of solution constraints
  - better PM-rates require new subdaily EOP tide model & reduced orbit effects – prospects currently unclear
- **IGS Ultra-rapid observed PM accuracy currently <50 µas**
  - updated 4 times daily with 15 hr latency
  - should be used by EOP prediction services !
- **IGS Ultra-rapid orbit predictions (real-time use) are limited by EOP prediction errors (esp UT1)**
  - IERS predictions are not adequate
  - IGS ACs generate better near-term EOP predictions internally

Backup Slides

Recent UT1 Accuracy

- ITRF2005 multi-technique combination experience
  - mean scaled formal errors ~8.0 µs since 2002.0 (at irregular epochs)
  - equivalent to net equatorial rotation errors of ~3.7 mm

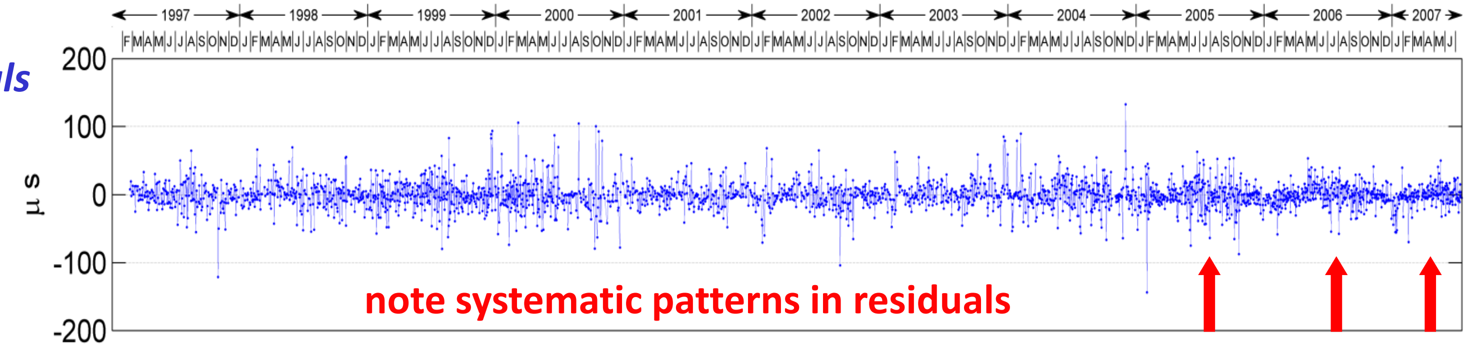
- UT1-UTC only measured by VLBI, but irregular quality & epochs

- For VLBI data since 2002:
  - 24-hr EOP sessions give UT1 formal errors of 2.2 to 2.8 µs (twice weekly)
  - accuracy is about twice formal errors: ~5 µs (= 2.3 mm rotation)
  - other 24-hr sessions have estimated mean accuracy ~20 µs (irregular)
  - 1-hr Intensive sessions have mean formal errors ~13 µs (nearly daily)
  - but Intensives show clear systematic effects that are difficult to handle

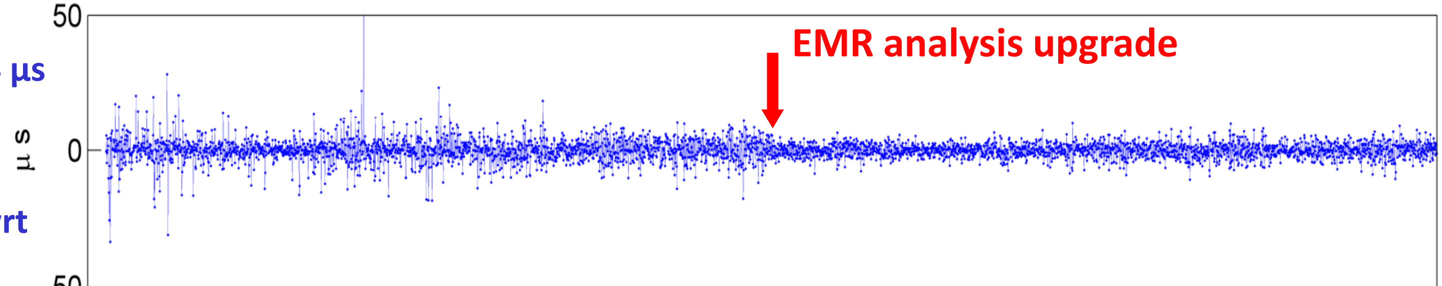
- Daily GPS LOD (= -UT1-rate) generally not used optimally
  - must model time-correlated biases – easy in Kalman filter, difficult otherwise
  - LOD residuals from such a Kalman filter are ~4 µs
  - combinations with VLBI UT1 yield best UT1/LOD time series

Some Kalman Filter Combination Outputs

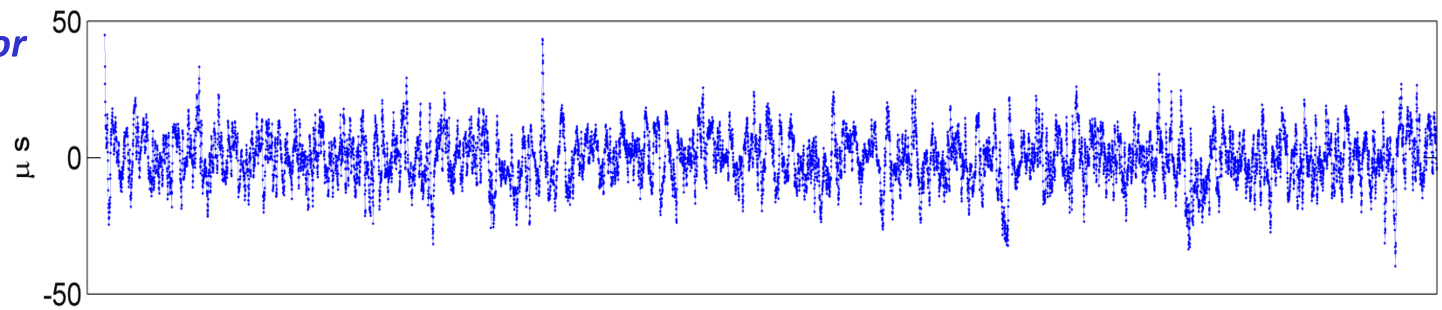
- ***VLBI 1-hr UT1 residuals***
  - show systematic patterns
  - RMS = 20 µs



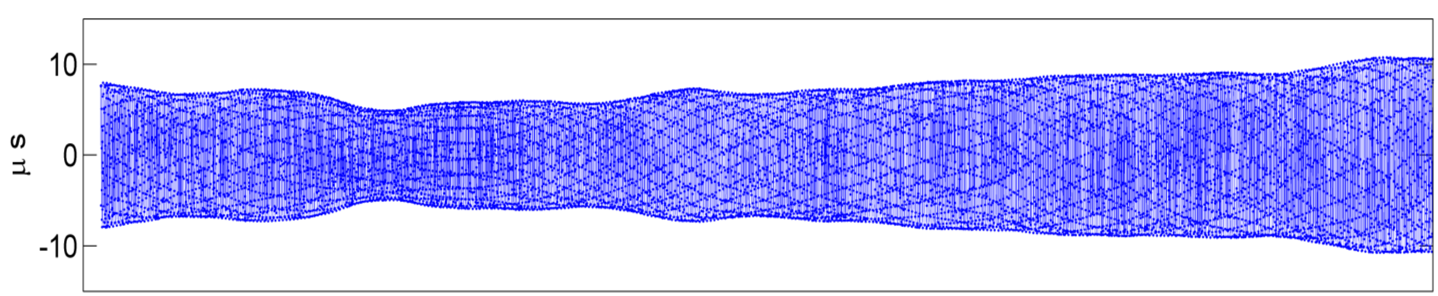
- ***GPS LOD residuals***
  - approx. white, RMS = 4 µs
  - small peak at 13.7 d
  - possible difference in *a priori* tidal models wrt VLBI



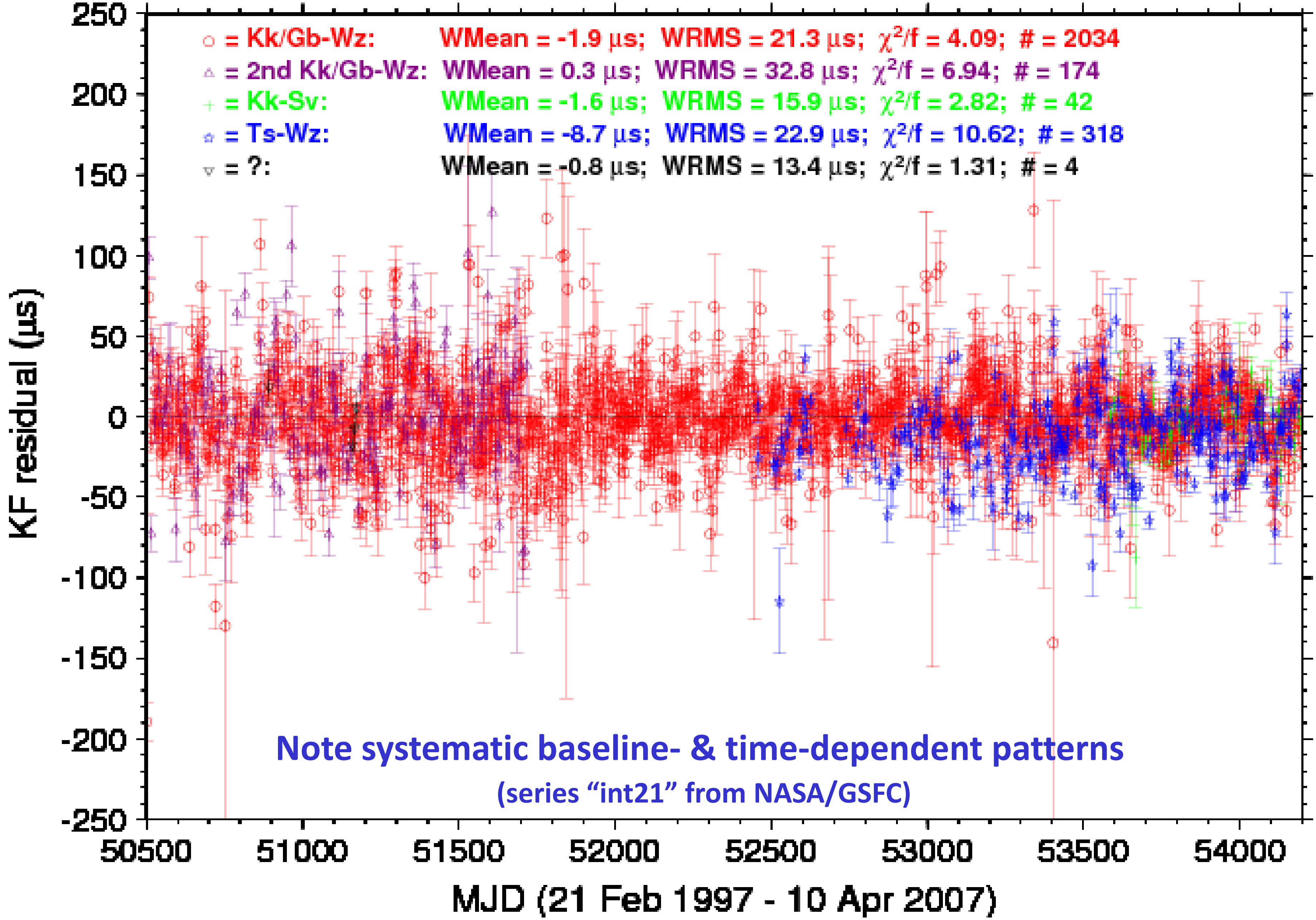
- ***Gauss-Markov values for GPS LOD biases***
  - peak-to-peak range = ± 40 µs
  - RMS = 9 µs



- ***14.19-d periodic***
  - treated as GPS artifact
  - amplitude varies between 5 & 11 µs
  - phase & period vary linearly w/ time



UT1 KF Residuals for VLBI 1-hr Intensives



Position Harmonics Linked to GPS Year

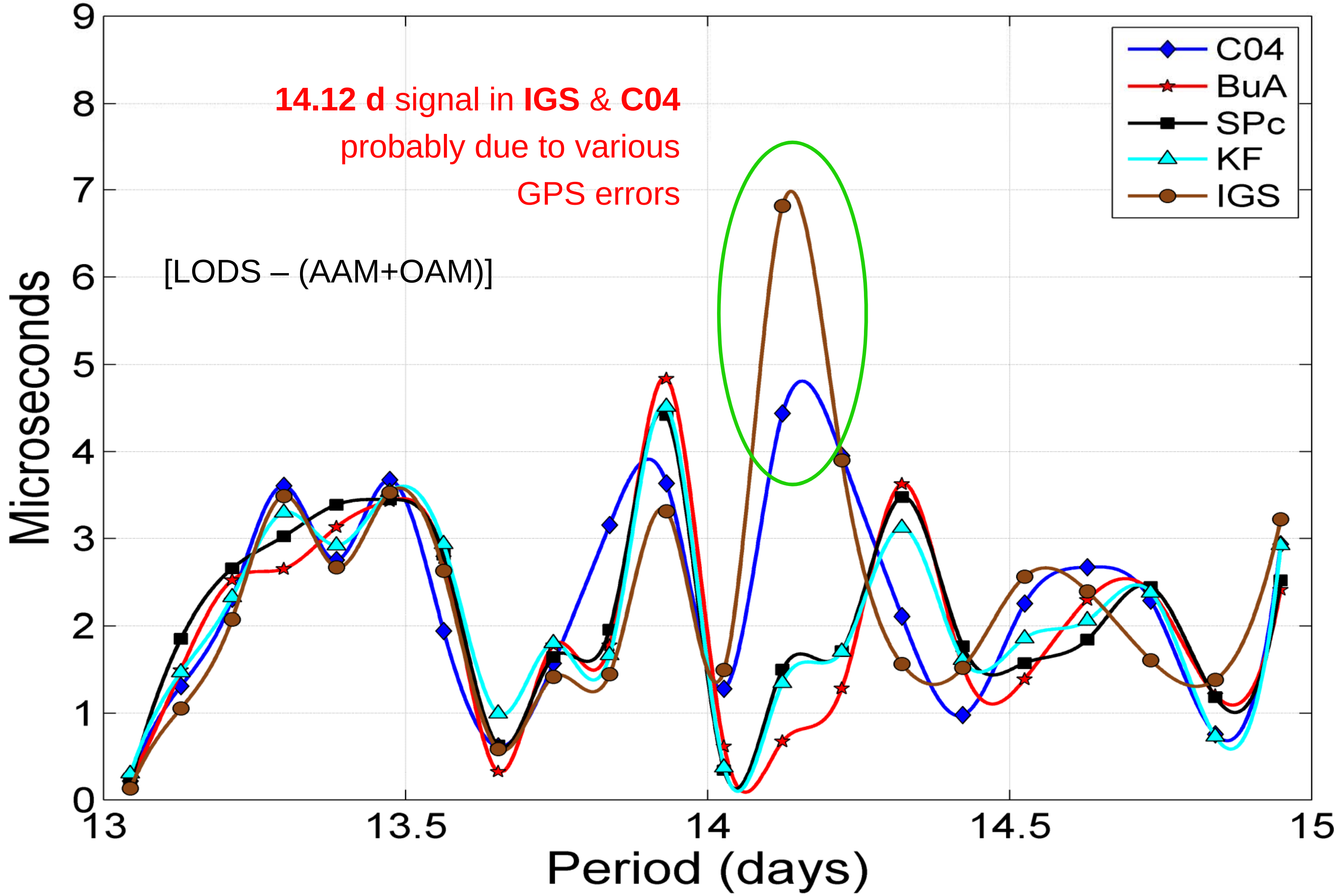
- **1.040 ± 0.008 cpy fundamental does not match any expected alias or geophysical frequency**
  - also not seen in VLBI, SLR, or fluid load spectra

- **Closely matches GPS "draconitic" year**
  - rotation period of Sun w.r.t. GPS nodes (viewed from Earth)
  - GPS nodal drift is -14.16° per year (due to Earth's oblateness)
  - period = 351.4 day or frequency = 1.039 cpy

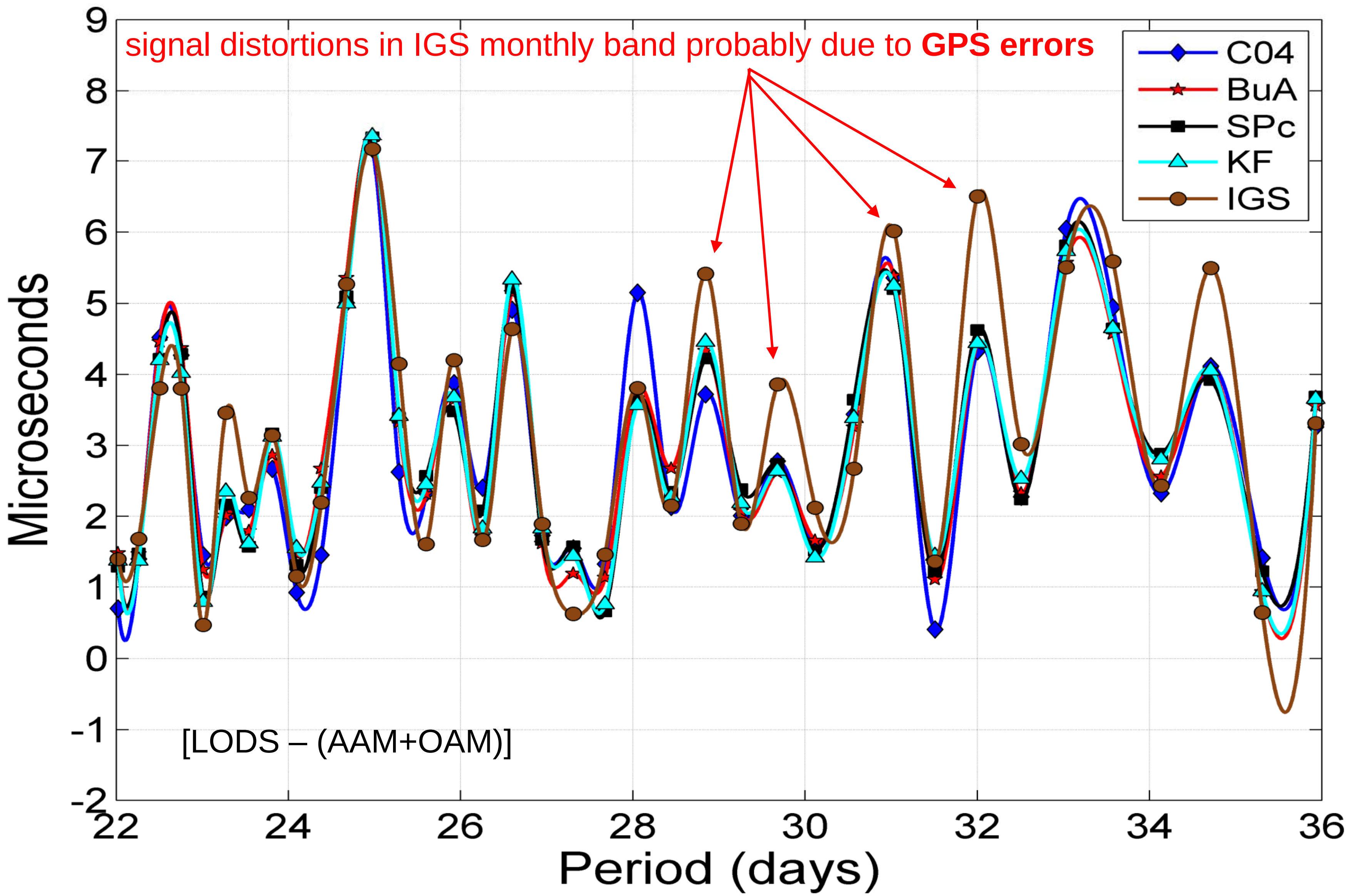
- **Two possible coupling mechanisms suggested:**
  1) direct orbit modeling errors (e.g., related to eclipse periods & planes)
  2) alias of site position biases (e.g., near-field phase multipath) due to beating of 24-hr processing arc against 23.93-hr GPS repeat period

  - useful distinguishing tests not yet made

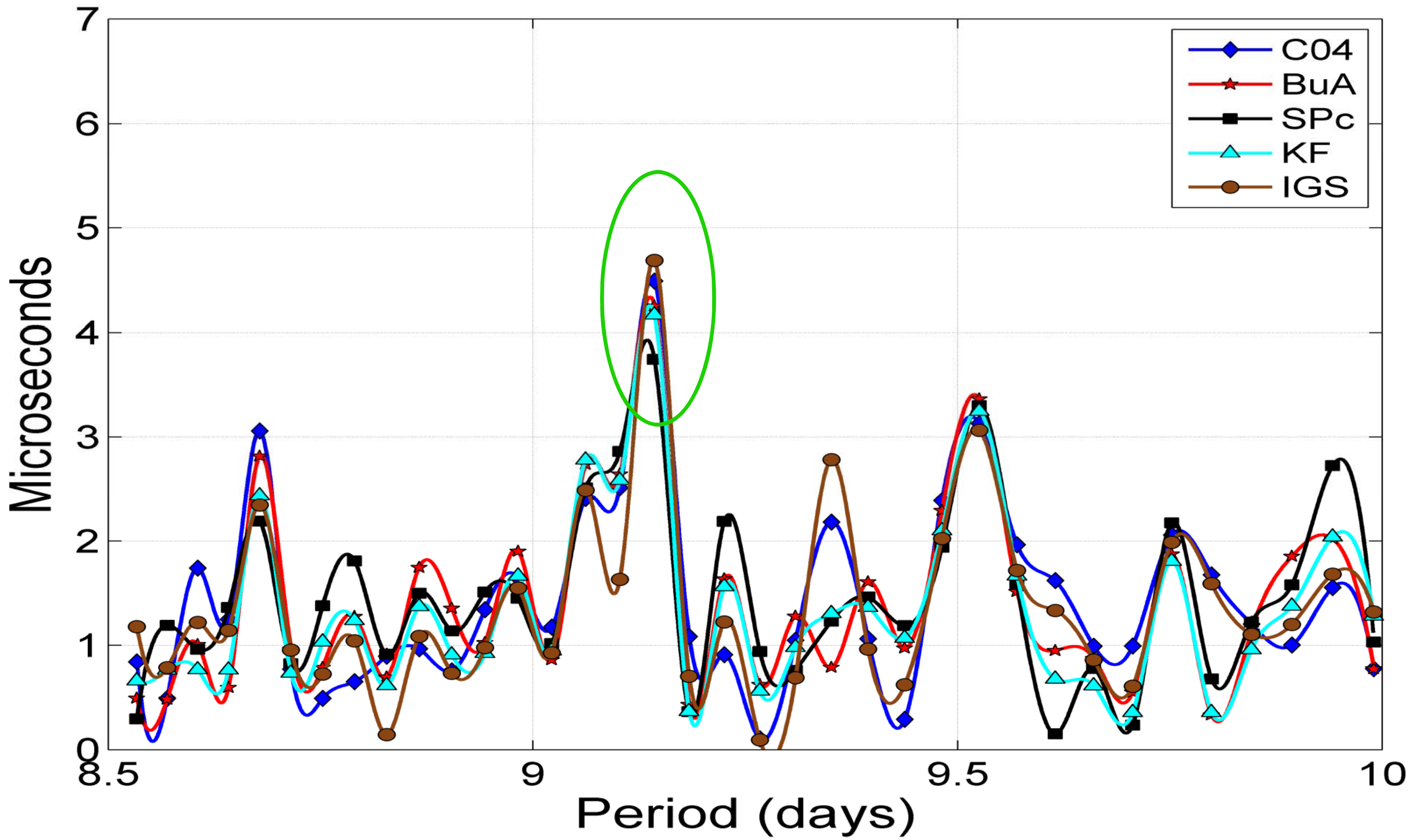
Fortnightly Band – Spurious IGS LOD Peak



Monthly Band – Probable GPS Errors



9-d Band – Unmodeled Geophysical Effect?



- 9.14 d peak seen in all LODS series – probably geophysical
- needs further investigation – could be included in [LODS-(AAM+OAM)] fit