Rotational Errors in IGS Orbit & ERP Products

- Systematic rotations are a leading IGS error
  - they affect all core products except probably clocks
- Sources include defects in:
  - IERS model for 12h + 24h tidal ERP variations
  - intra-AC product self-consistency & use of over-constraints
  - AC realizations of ITRF
  - models for GNSS orbit dynamics (SRP, gravity field variations)
- Examine evidence in IGS products
- Finals appear rotationally less stable than Rapids !

Jim Ray, Jake Griffiths	NOAA/NGS
P. Rebischung	IGN/LAREG
J. Kouba	NRCanada
W. Chen	Shanghai Astronomical Obs

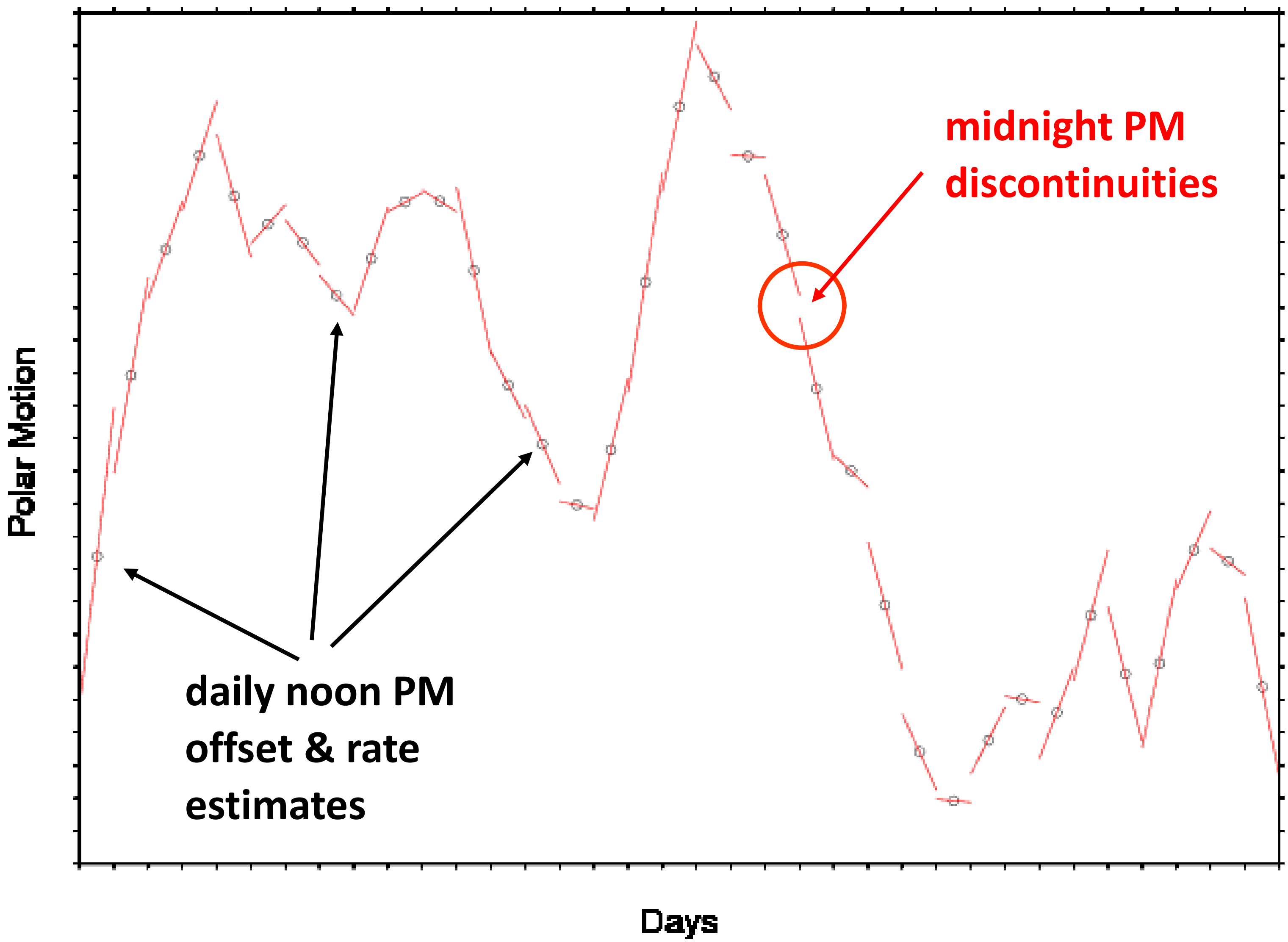
IGS Workshop 2012, Orbit Modeling Session, Olsztyn, Poland, 26 July 2012

1. Subdaily ERP Tidal Variations

- Ocean tides drive ERP variations near 12 & 24 hr periods
  - amplitudes reach ~1 mas level = ~13 cm shift @ GPS altitude
  - small atmosphere tides also exist at S1 & S2 periods (not modeled)
  - 1st IERS model issued in 1996 for 8 main tides (R. Ray et al., 1994)
  - most IGS ACs implemented IERS model in 1996
  - 2003 model extended to 71 tide terms via admittances (R. Eanes, 2000)
  - also added small prograde diurnal polar motion libration in 2003
  - UT1 libration added in 2010
  - but ocean tide model still that of R. Ray et al. (1994)

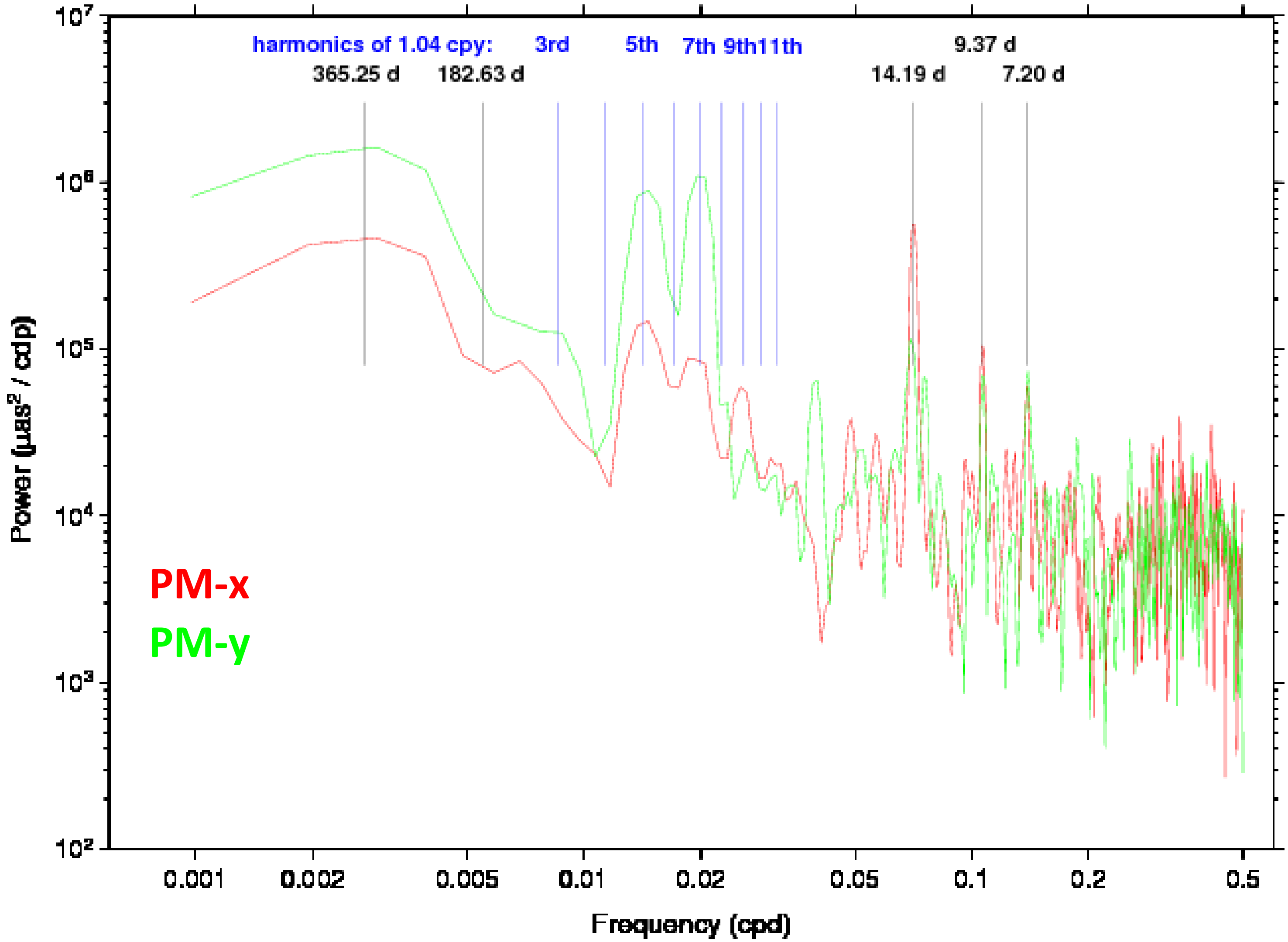
- Significant errors in IERS model definitely exist
  - 10 to 20% differences using modern ocean tide models (R. Ray)
  - IGS polar motion rate discontinuities show alias signatures (J. Kouba)
  - direct tide model fits to GPS & VLBI data (various groups)
  - but empirical ERP tide models are subject to technique errors
  - would be very interesting to see empirical fit to SLR data too !
  - GNSS orbits esp sensitive to ERP tide errors due to orbital resonance

Compute Polar Motion Discontinuities



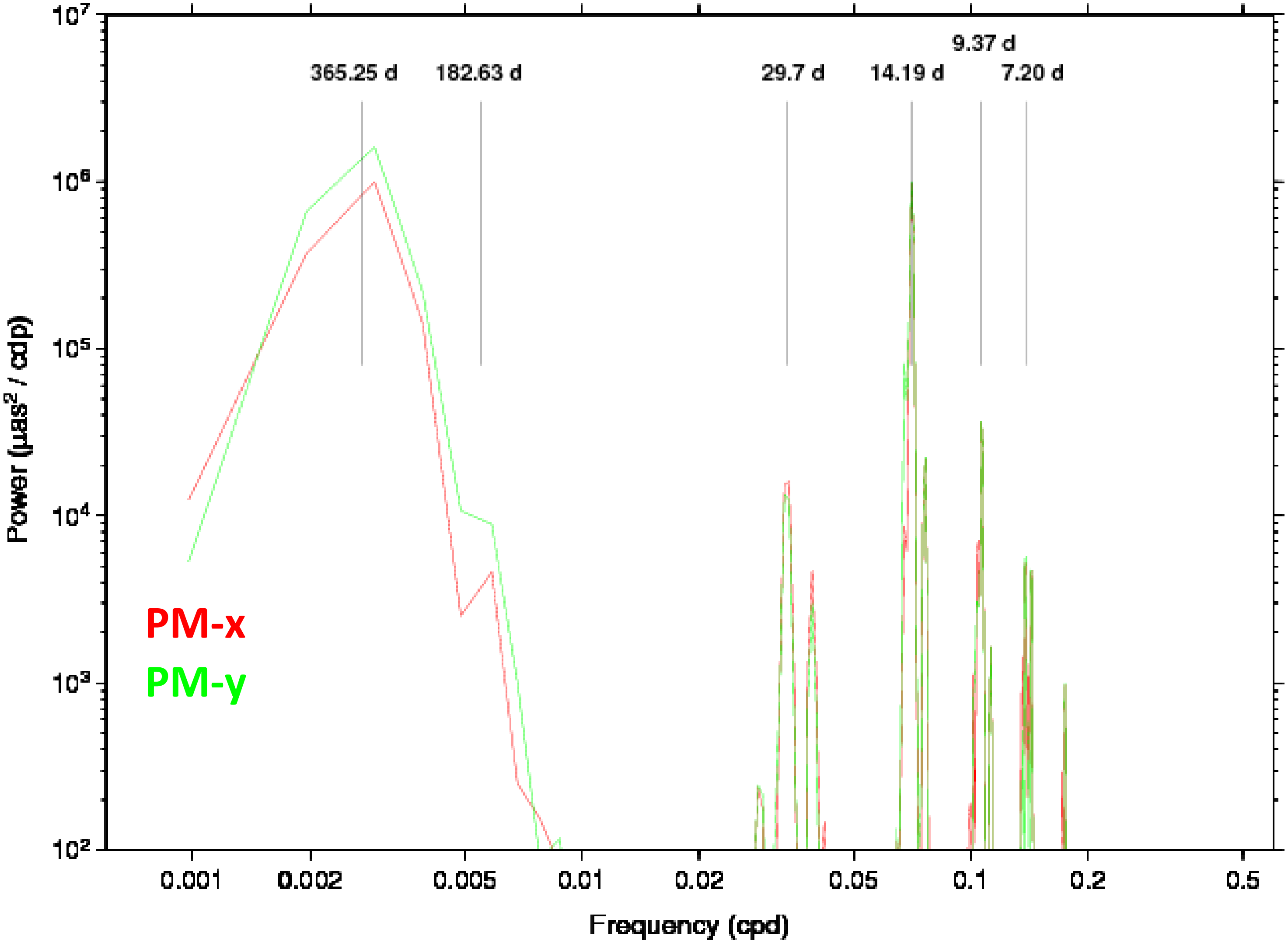
- Examine PM day-boundary discontinuities for IGS time series
  - NOTE: PM-rate segments are not continuous & should not be constrained !

Power Spectra of IGS PM Discontinuities



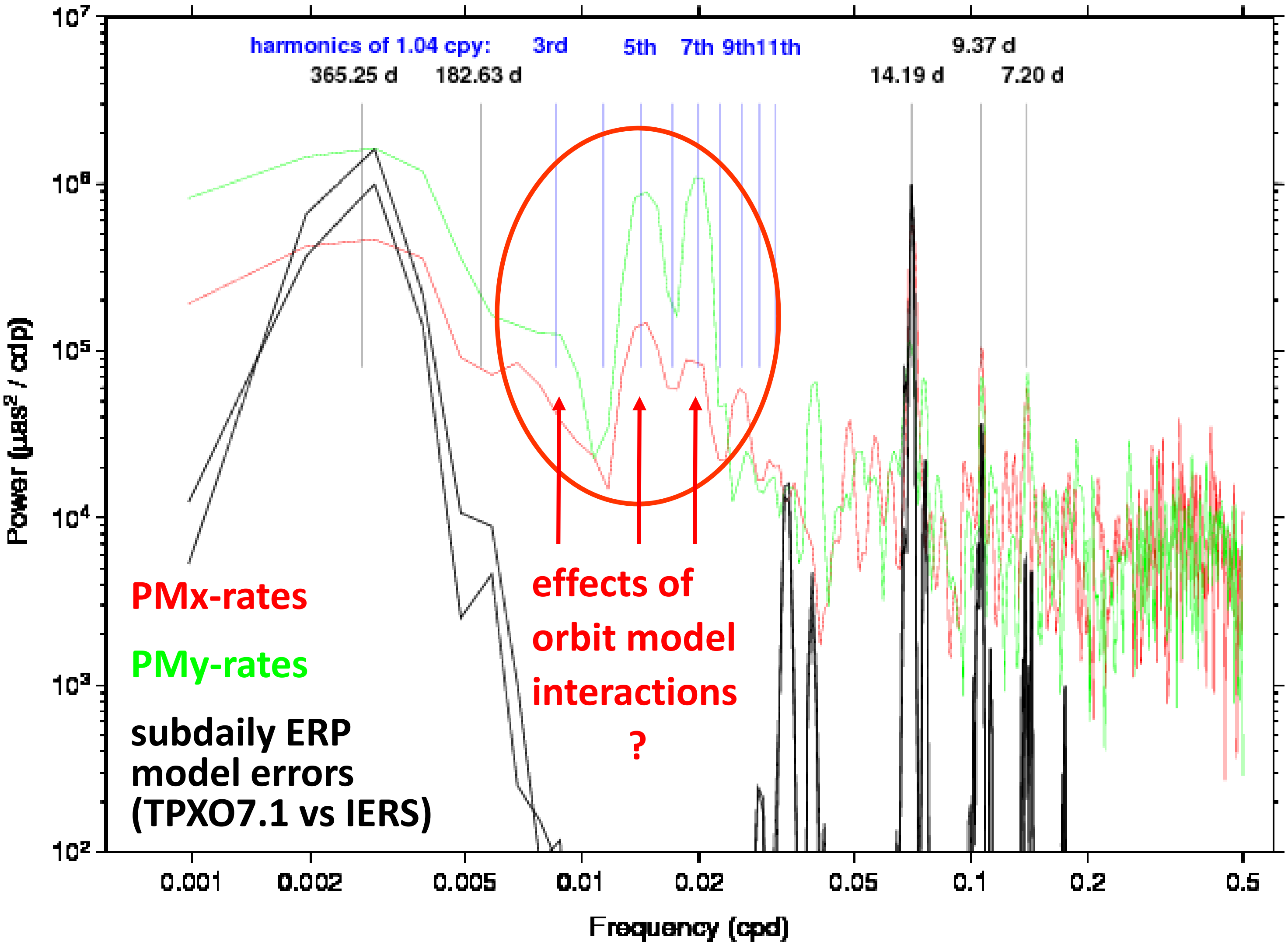
- Common peaks seen in most AC spectra are:
  - annual + 5th & 7th harmonics of GPS year (351 d or 1.040 cpy)
  - aliased errors of subdaily ERP tide model

Spectra of Subdaily ERP Tide Model Differences



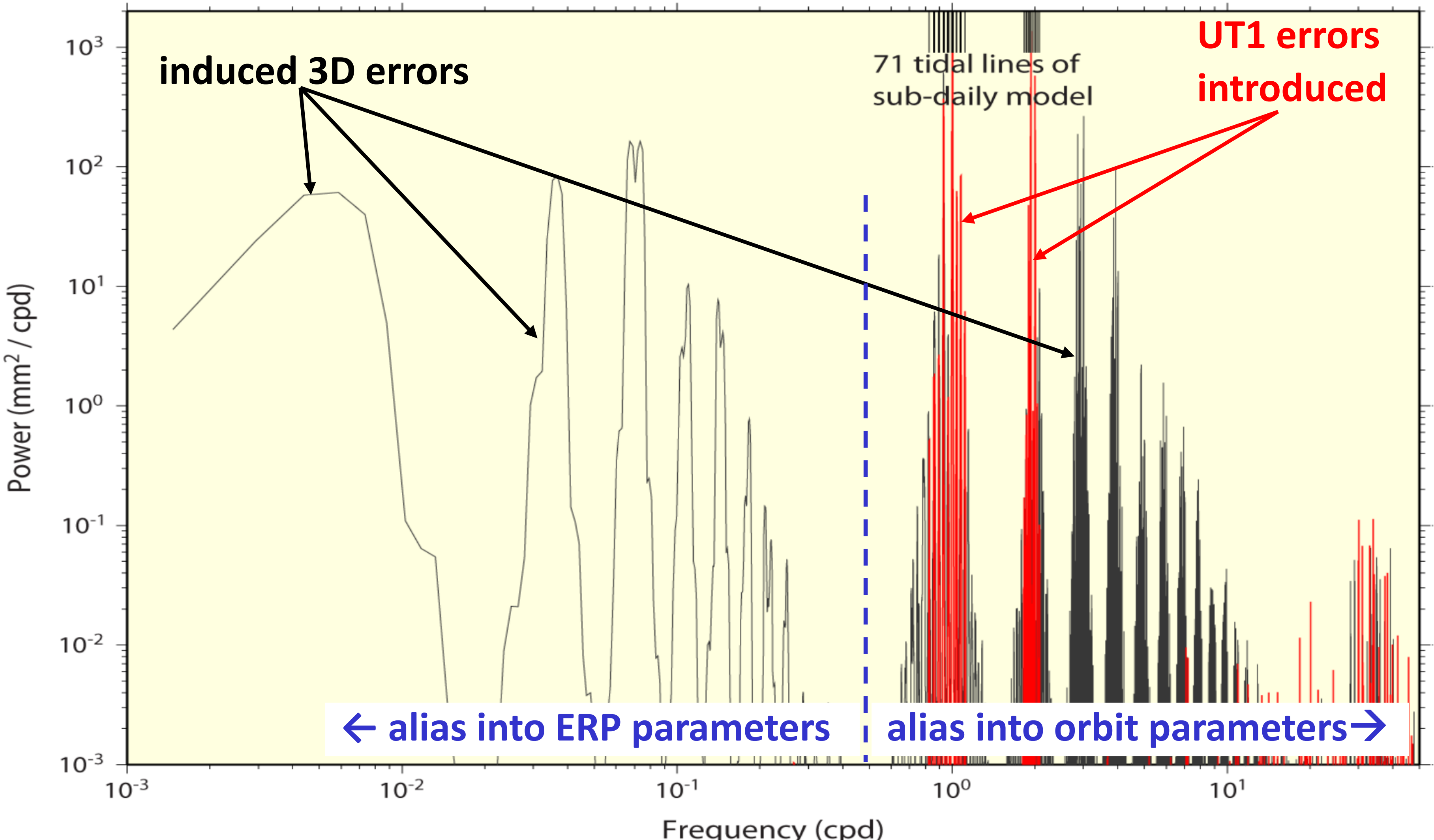
- Compare TPXO7.1 & IERS ERP models
  - TPXO7.1 & GOT4.7 test models kindly provided by Richard Ray
  - assume subdaily ERP model differences expressed fully in IGS PM results

Spectra of PM Discontinuities & Subdaily ERP Errors



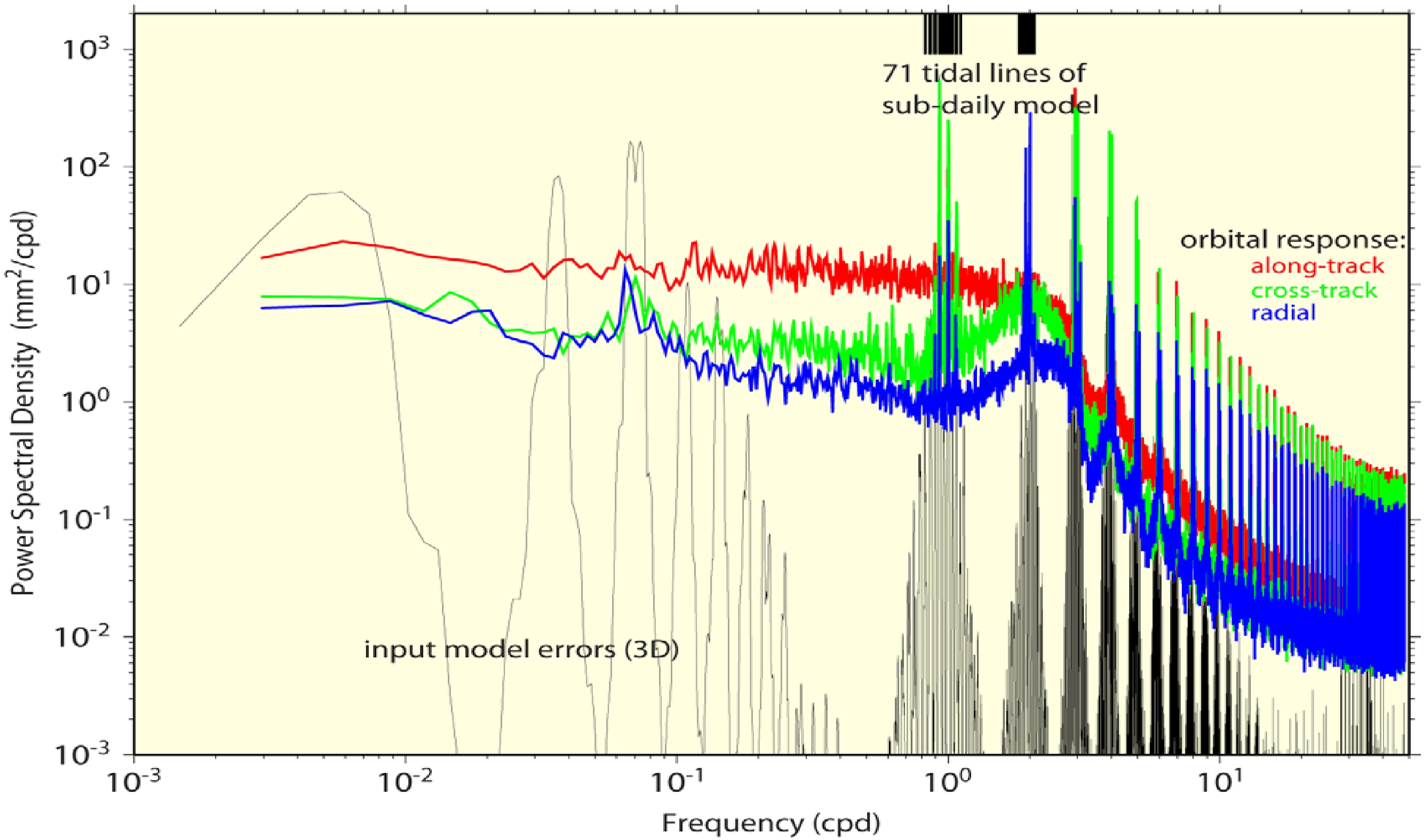
- **Aliasing of subdaily ERP tide model errors explains most peaks:**
  - **annual (K1, P1, T2), 14.2 d (O1), 9.4 d (Q1, N2), & 7.2 d (σ1, 2Q1, 2N2, μ2)**
- **Orbit interactions responsible for odd 1.04 cpy harmonics**

Simulated IERS ERP Tide Model Errors



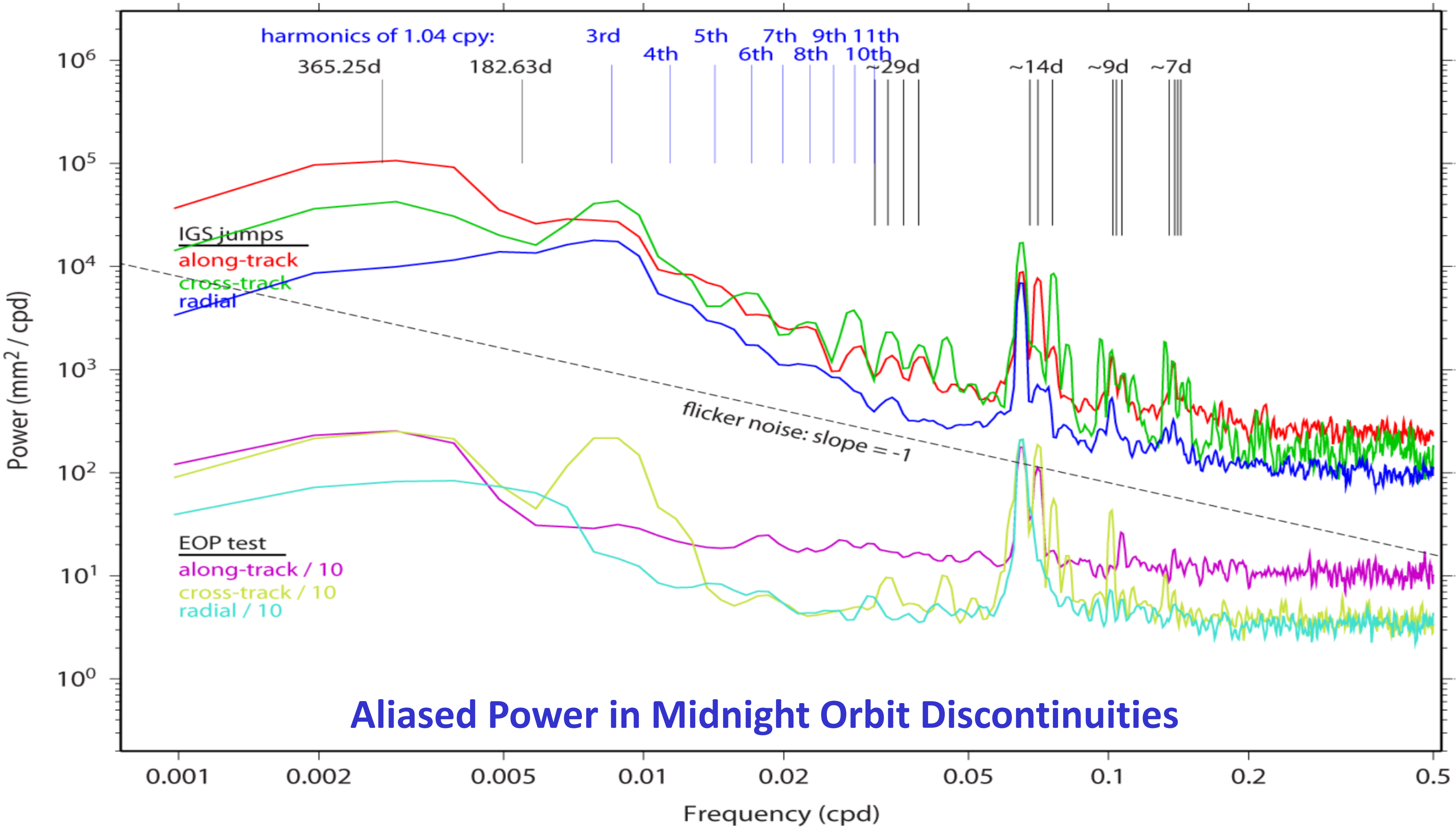
- **Introduce admittance errors to IERS model at 10 to 20% level**
  - simulated errors similar in magnitude to true model errors
  - 71 terms at 12h + 24h periods in each 1D component
  - in 3D, tidal errors beat to higher & lower frequencies

Impact of Simulated ERP Model Errors on Orbits



- **Subdaily ERP tidal errors alias into comb of ~1 cpd harmonics**
  - **power in model error transfers very efficiently into orbits**

Simulated ERP Errors vs Actual Orbit Discontinuities



- **Main features of IGS orbits (top lines) matched by ERP simulation**
  - **annual + 3rd harmonic of GPS year (351 d or 1.040 cpy)**
  - **~14d, ~9d, & ~7d subdaily ERP aliases**
  - **overall peak magnitudes alike but actual model errors could differ**

2. AC TRF, Orbit, & ERP Self-Consistency

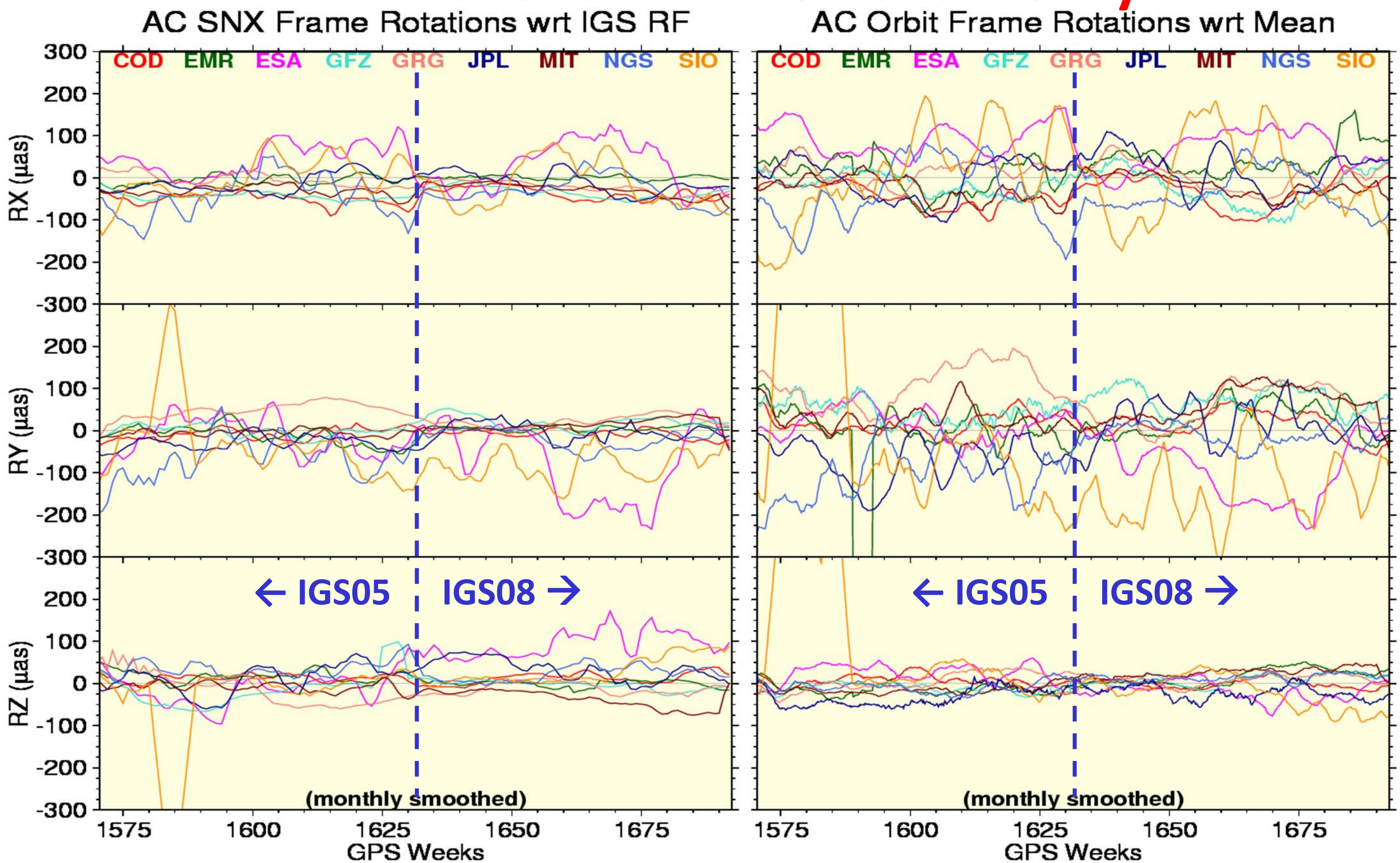
- A constant rotational shift of AC TRF realization should offset orbit frame & polar motion (PM) equally
  - expect: TRF RX = orbit RX = ΔPMy & TRF RY = orbit RY = ΔPMx
  - AC's processing should preserve these physical relationships
  - this is basis for IGS Final product "quasi-rigorous" combination method (J. Kouba et al., 1998)

- But, 12h + 24h ERP errors can alias mostly into empirical once-per-rev (12h) orbit parameters
  - e.g., due to errors in apriori IERS subdaily ERP tide model
  - does not equal any net rotation of TRF or ERPs

- Likewise, any net diurnal sinusoidal wobble of satellite orbits will alias purely into a ERP bias
  - e.g., due to systematic orbit model defect
  - does not equal any net rotation of TRF or orbit frame

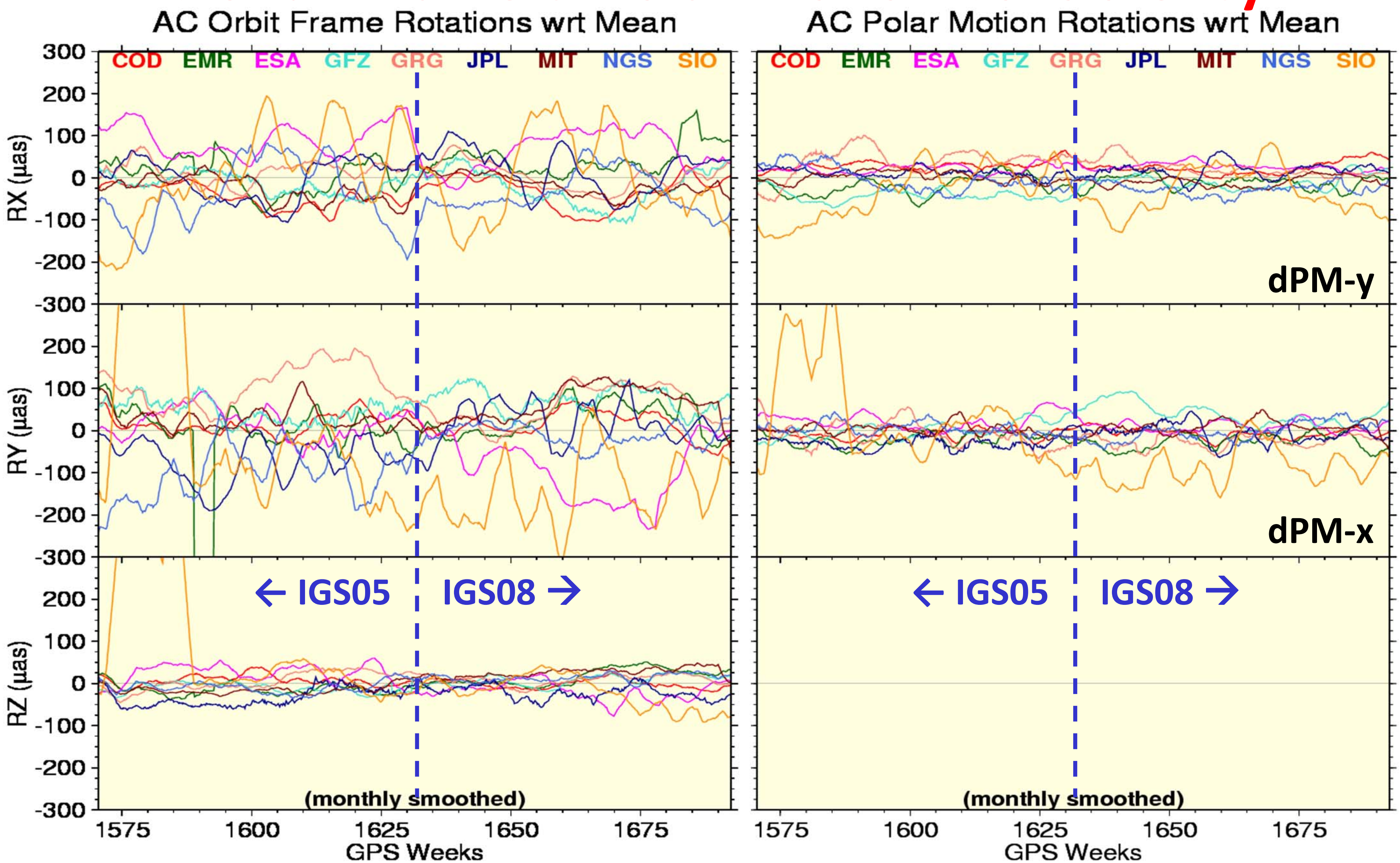
- So, check of AC rotational consistency can provide insights into analysis weaknesses
  - but most ACs apply some over-constraints on orbit and/or PM variations !

AC TRF & Orbit Frame Consistency



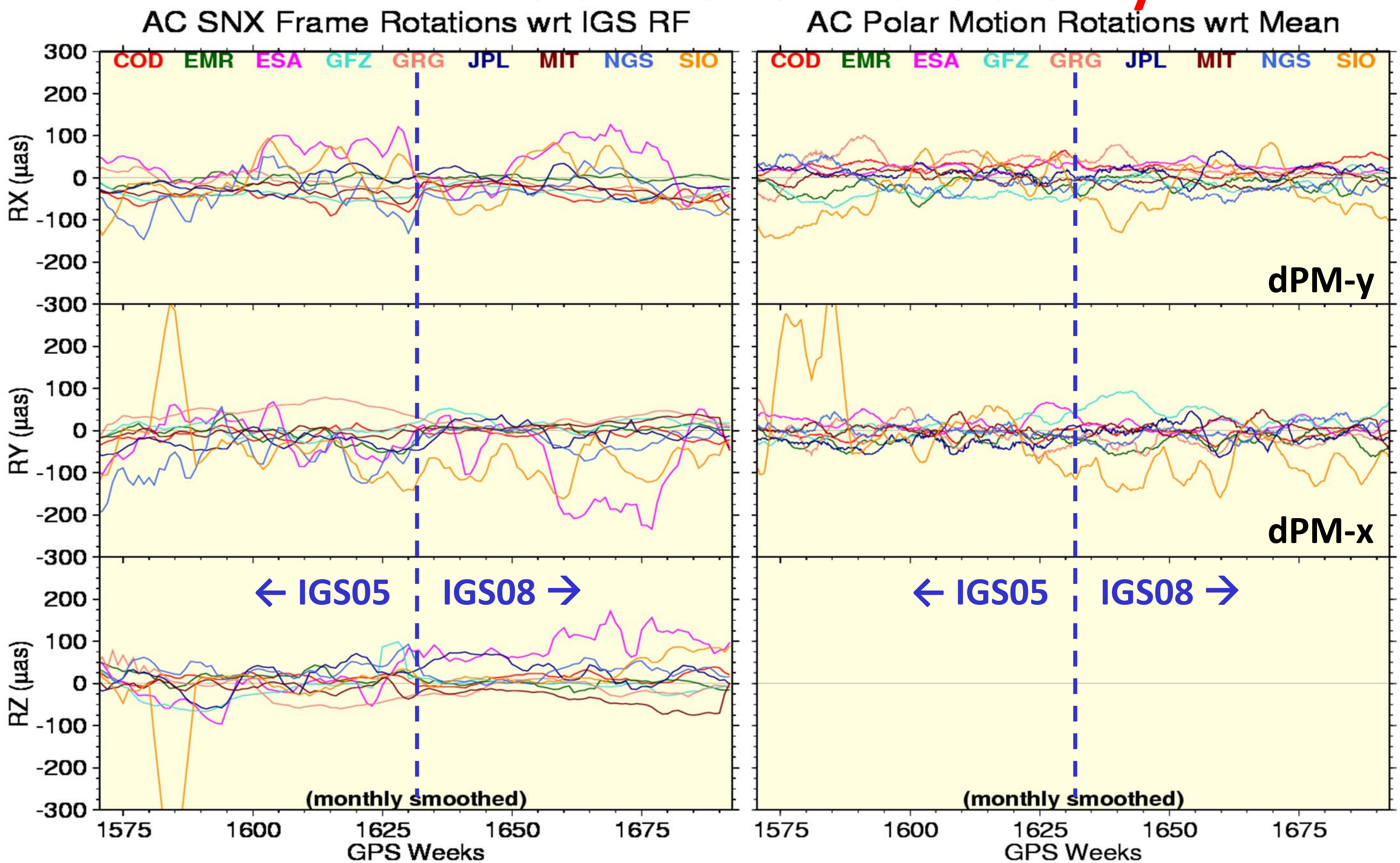
- **Poor rotational self-consistency by most ACs for RX & RY**
  - **apparently mostly due to AC orbit analysis effects, not RF realizations**

AC Orbit Frame & Polar Motion Consistency



- **Similarly poor RX & RY consistencies between AC orbits & PM**
  - **change from IGS05 to IGS08 RF had minimal impact**

AC TRF & Polar Motion Consistency



- **AC TRF & polar motions mostly much more consistent**
  - **except for a few ACs**

3. Inter-compare IGS Orbit Series

- Expect differences due to TRF realizations
  - TRF tightly constrained to IGSxx for IGU/IGR
  - TRF only rotationally aligned to IGSxx for IGS
- Expect differences due to overall product quality
  - normally think IGS is best due to 9 ACs & quasi-rigorous combination methodology
  - IGS also uses more processing time (up to ~10 d) & more stations
  - also has benefit of prior IGR & IGU results
  - IGR has 8 ACs & uses <16 hr processing time
  - IGU has only 5 usable ACs & uses <3 hr processing time
- But most analysis modeling effects should be similar
  - generally similar orbit modeling approaches
  - common softwares, conventions, data reduction models, etc
- Examine direct pairwise orbit differences
  - also check PPP & long-arc fit performances

Pairwise IGS Orbit Differences

Ultra Observed Differences wrt Rapids (mm @ GPS altitude)										
	dX	dY	dZ	RX	RY	RZ	SCL	RMS	wRMS	Medi
2008	1.2	0.6	0.5	-3.0	1.0	0.4	-3.0	12.4	11.2	10.4
±	1.1	1.2	1.7	4.4	4.2	15.6	1.6	2.8	1.9	1.7
2009	1.2	0.3	0.1	-0.2	0.9	2.6	-1.2	9.0	8.0	7.2
±	0.8	0.9	1.3	3.4	3.4	12.7	1.5	1.6	1.3	1.2
2010	1.3	0.8	-0.7	0.7	-0.9	0.7	-1.7	9.4	8.3	7.5
±	1.0	0.9	1.3	3.8	3.8	10.9	1.6	1.9	1.4	1.3
2011	0.9	0.6	-1.2	0.9	-1.0	3.0	-0.4	7.8	7.1	6.4
±	1.0	0.8	1.3	3.3	3.7	8.8	1.1	1.3	1.1	1.0
Rapid Differences wrt Finals (mm @ GPS altitude)										
2008	0.1	0.1	-0.3	0.6	-5.1	-2.5	1.3	6.9	6.6	6.2
±	0.8	0.9	1.5	3.3	4.4	3.8	1.2	1.0	1.1	1.0
2009	-0.3	0.3	0.1	0.5	-5.4	-4.6	1.2	5.8	5.6	5.1
±	0.7	0.8	1.3	4.7	3.6	4.6	1.0	0.7	0.7	0.7
2010	-0.5	-0.1	-0.1	4.0	-1.9	0.8	-0.4	5.7	5.5	5.0
±	0.7	0.8	1.3	5.8	5.2	3.8	1.2	0.7	0.6	0.6
2011	-0.1	-0.2	-0.6	0.2	-2.8	-2.8	-1.8	5.6	5.4	4.9
±	0.6	0.6	1.7	4.4	4.6	3.8	1.2	0.6	0.6	0.6
* rotations are equatorial @ GPS altitude										

Pairwise IGS Orbit Differences

RX/RY rotations more similar for IGU & IGR

RZ & WRMS/MEDI worse for IGU

Ultra Observed Differences wrt Rapids (mm @ GPS altitude)										
	dX	dY	dZ	RX	RY	RZ	SCL	RMS	wRMS	Medi
2008	1.2	0.6	0.5	-3.0	1.0	0.4	-3.0	12.4	11.2	10.4
±	1.1	1.2	1.7	4.4	4.2	15.6	1.6	2.8	1.9	1.7
2009	1.2	0.3	0.1	-0.2	0.9	2.6	-1.2	9.0	8.0	7.2
±	0.8	0.9	1.3	3.4	3.4	12.7	1.5	1.6	1.3	1.2
2010	1.3	0.8	-0.7	0.7	-0.9	0.7	-1.7	9.4	8.3	7.5
±	1.0	0.9	1.3	3.8	3.8	10.9	1.6	1.9	1.4	1.3
2011	0.9	0.6	-1.2	0.9	-1.0	3.0	-0.4	7.8	7.1	6.4
±	1.0	0.8	1.3	3.3	3.7	8.8	1.1	1.3	1.1	1.0
Rapid Differences wrt Finals (mm @ GPS altitude)										
2008	0.1	0.1	-0.3	0.6	-5.1	-2.5	1.3	6.9	6.6	6.2
±	0.8	0.9	1.5	3.3	4.4	3.8	1.2	1.0	1.1	1.0
2009	-0.3	0.3	0.1	0.5	-5.4	-4.6	1.2	5.8	5.6	5.1
±	0.7	0.8	1.3	4.7	3.6	4.6	1.0	0.7	0.7	0.7
2010	-0.5	-0.1	-0.1	4.0	-1.9	0.8	-0.4	5.7	5.5	5.0
±	0.7	0.8	1.3	5.8	5.2	3.8	1.2	0.7	0.6	0.6
2011	-0.1	-0.2	-0.6	0.2	-2.8	-2.8	-1.8	5.6	5.4	4.9
±	0.6	0.6	1.7	4.4	4.6	3.8	1.2	0.6	0.6	0.6

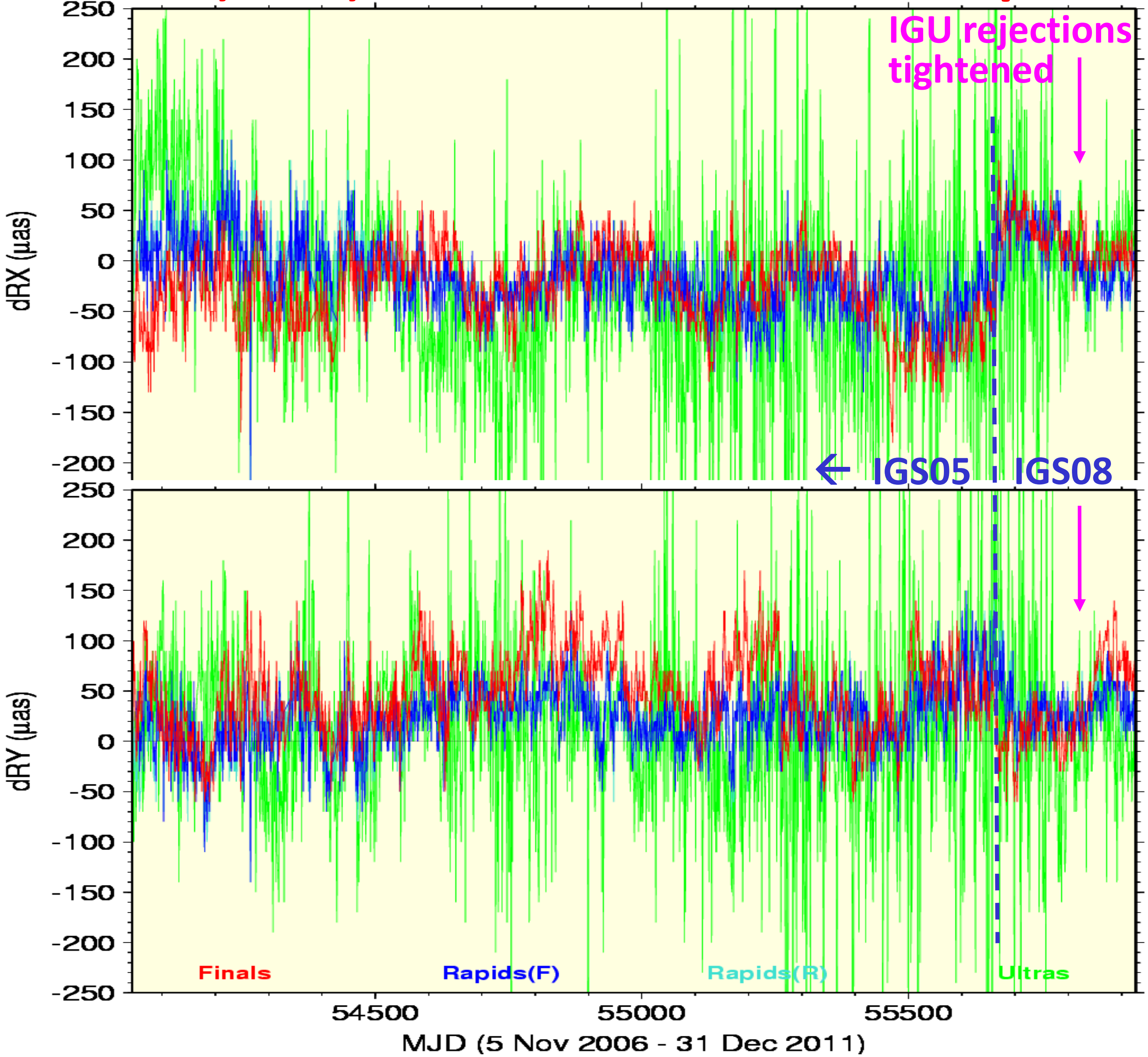
* rotations are equatorial @ GPS altitude

Compare IGR & IGS PPP Network Solutions

- Compute daily PPP solutions for global network of RF stations
  - align daily frame solutions to IGS long-term RF
- IGR RX & RY stabilities much better than for IGS
  - RZ performance similar for IGR & IGS
  - 3D station position WRMS much lower for IGS, probably due to better IGS clocks
- PPP results consistent with better RX/RY rotations for Rapids

PPP Global Soln Mean ± Std Dev	RX (µas)		RY (µas)		RZ (µas)		3D WRMS (mm)	
(wrt IGS RF)	IGR	IGS	IGR	IGS	IGR	IGS	IGR	IGS
2008	-23.1 ± 24.4	-14.8 ± 30.7	29.9 ± 26.8	61.0 ± 40.1	-36.2 ± 47.7	-38.0 ± 46.1	8.24 ± 1.09	7.67 ± 1.09
2009	-21.5 ± 28.4	-14.2 ± 36.4	23.8 ± 29.2	66.3 ± 34.6	-40.6 ± 47.6	-34.3 ± 47.4	8.74 ± 0.91	7.92 ± 1.05
2010	-38.4 ± 31.4	-38.8 ± 44.2	24.4 ± 30.2	41.5 ± 42.8	-8.1 ± 44.1	-19.3 ± 28.7	8.76 ± 0.90	7.57 ± 0.76
2011	-4.8 ± 37.3	-4.1 ± 46.8	41.1 ± 31.6	37.8 ± 39.6	-9.3 ± 32.2	0.1 ± 30.7	8.55 ± 0.92	7.73 ± 0.72

IGU, IGR, & IGS PPP Network RX/RY Rotations



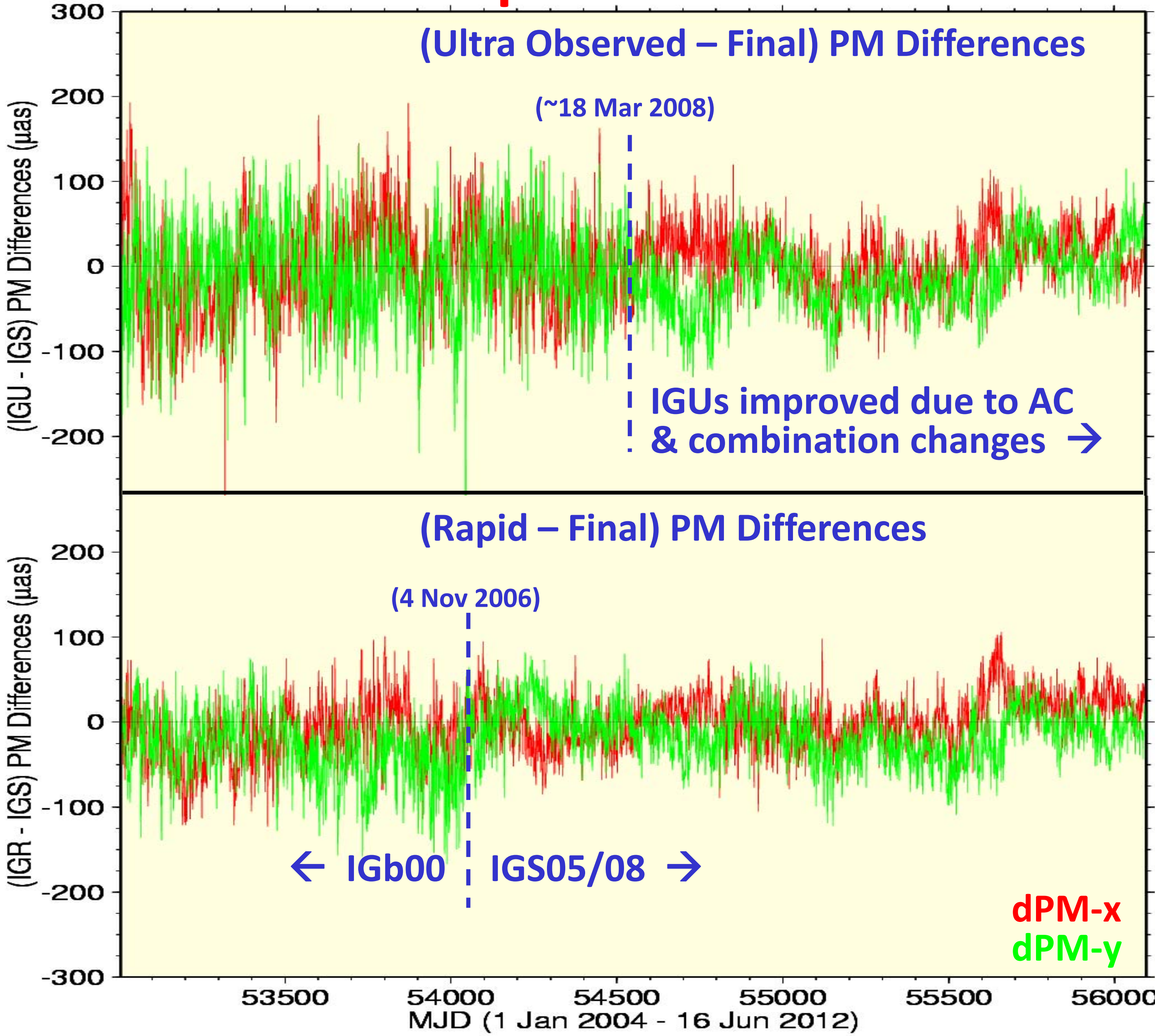
- RX/RY variations clearly greater for Finals than Rapids
- change from IGS05 to IGS08 RFs had no obvious affect
- IGU rotations much larger
- IGU stability improved when reject threshold tightened from 1.0 to 0.5 mas on 2011-09-15 (MJD 55819)

Compare IGR & IGS Long-Arc Orbit Fits

- Compute orbit fits over weekly intervals (long-arc)
  - use the CODE Extended model (6 + 9)
- Performance differences are quite small
  - Finals slightly better by all long-arc metrics over 2008-2011
- But long-period rotations have minimal impact on 7-d long-arc fits
  - IGR & IGS orbit quality probably very similar over daily to weekly periods

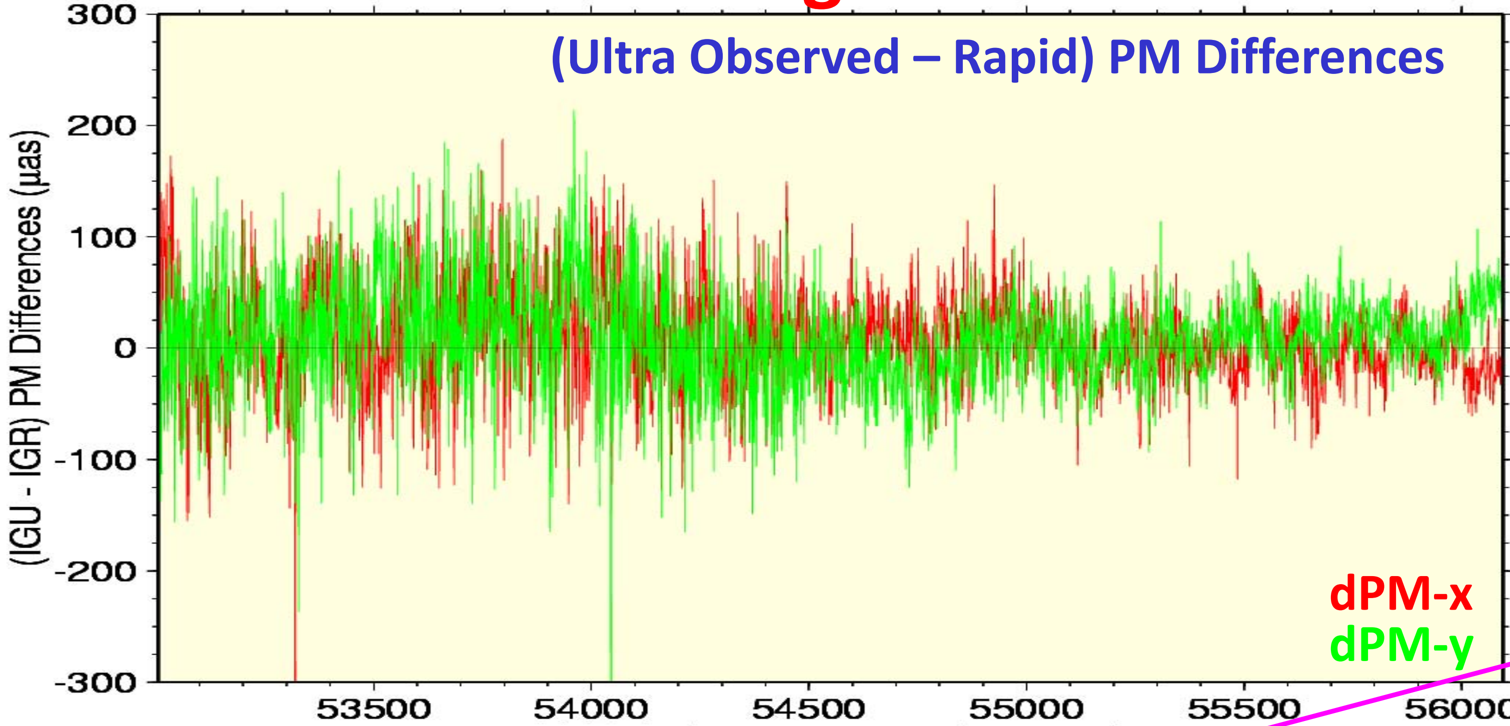
Long-Arc Orbit Residuals	Total WRMS (all SVs, mm)		Non-Eclipse WRMS (mm)		Median RMS (mm)	
	IGR	IGS	IGR	IGS	IGR	IGS
2008	24.6 ± 6.4	24.2 ± 4.0	21.0 ± 5.5	20.4 ± 3.4	20.5 ± 4.8	19.9 ± 2.6
2009	24.5 ± 4.6	23.6 ± 4.1	20.9 ± 4.2	19.9 ± 3.2	19.8 ± 2.9	19.5 ± 2.9
2010	25.3 ± 5.4	23.4 ± 4.5	22.1 ± 6.0	19.8 ± 2.9	19.5 ± 2.5	19.2 ± 2.5
2011	25.8 ± 5.4	24.4 ± 4.4	22.2 ± 5.6	21.0 ± 4.2	20.3 ± 3.0	20.2 ± 2.9

4. Inter-compare IGS Polar Motion Series

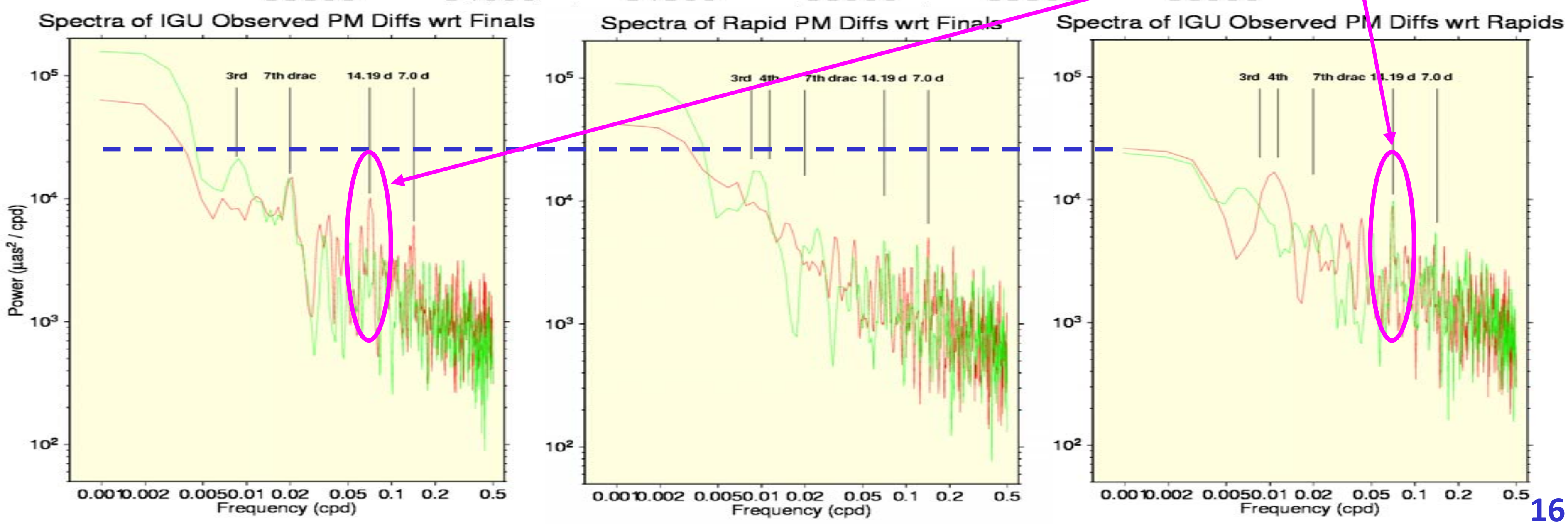


- since ~2008, IGU & IGR agree better with each other than with IGS Finals
- IGS Finals PM series shows low-frequency systematic components
- but more IGU high-frequency noise & some dPM-y deviations in 2012

Differences Among IGS Polar Motion Series



- IGU & IGR more similar to each other than to Finals
- subdaily ERP alias peaks imply not all ACs use IERS model (esp in IGUs) !



3 Cornered Hat Decomposition of ERP Errors

- 3 cornered hat method is sensitive to uncorrelated, random errors
  - for time series {i, j, k} form time series of differences (i-j), (j-k), (i-k)
  - then Var(i-j) = Var (i) + Var(j) (assuming $R_{ij} = 0$ for $i \neq j$)
  - and Var(i) = [Var(i-j) + Var(i-k) – Var(j-k)] / 2
  - but true errors also include common-mode effects removed in differencing

- Apply to IGS Ultra (observed), Rapid, & Final PM & dLOD
  - consider recent 1461 d from 1 Jan 2008 to 31 Dec 2011

- <u>Surprising results</u>:
  - apparently, Rapids give best polar motion & Ultras give best dLOD
  - Ultras give similar quality polar motion as Finals
  - perhaps Finals affected by weaknesses in AC quasi-rigorous procedures ?

IGS Product Series	σ(PM-x) (μas)	σ(PM-y) (μas)	σ(dLOD) (μs)
Ultra (Obs)	25.8	27.6	4.99
Rapid	16.0	15.4	5.69
Final	25.3	31.3	9.19

3 Cornered Hat PM Results with High-Pass Filtering

- Apply Vondrak high-pass filter before 3 cornered hat for PM
  - try 4 cutoff frequencies: pass all, >0.5 cpy, >1 cpy, >2 cpy
- IGU & IGR PM errors nearly insensitive to frequency filtering
- IGS Final PM appears to improve when high-pass filtered
  - implies low-frequency errors are in IGS Finals or common to IGU & IGR
  - AAM+OAM excitations not accurate enough to distinguish IGS series
  - ERPs from other techniques are much less accurate also
  - so must use other internal IGS metrics to study low-frequency rotational stability of Rapid & Final products

more low frequencies removed →

Freq Cutoff:	none		0.5 cpy		1 cpy		2 cpy	
	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
Ultra (Obs) (µas)	25.8	27.6	24.2	25.5	24.1	23.7	23.7	22.5
Rapid (µas)	16.0	15.4	16.2	14.6	15.6	16.1	15.2	16.8
Final (µas)	25.3	31.3	20.2	23.1	19.4	19.7	18.5	17.3

Conclusions

- **Defects in IERS subdaily ERP model are major IGS error source**
  - probably main source of pervasive draconitic signals in all products
  - little prospect for significant improvements in near future
  - ILRS should be strongly urged to estimate empirical model from SLR data, for comparison with GPS & VLBI results
  - not all ACs (e.g., IGUs) appear to use correct IERS model

- **Over ~annual scales, Final products appear rotationally less stable than Rapids**
  - appears to affect IGS polar motion
  - also seems to affect RX/RY stability of IGS orbit & PPP results
  - probably due to inadequate intra-AC self-consistency in Finals
  - situation might improve (inadvertently) when Finals move from weekly to daily TRF integrations
  - quasi-rigorous method should be re-examined

- **Further study of long-term dynamical stability of IGS products will be limited till these issues are resolved**

Backup Slides

AC PM Results from SNX & Orbit Combinations