STATUS & PROSPECTS FOR IGS POLAR MOTION MEASUREMENTS

- Why does the IGS care about EOPs?
  - observations, predictions, & IGS product table
- Recent pole & pole-rate accuracies & error sources
  - Rapid & Final products
  - Ultra-rapid products
- Improvements possible from better networks, new GNSSs, reduced systematic errors

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IERS Workshop on EOP Combination & Prediction, Warsaw, 19 October 2009 – session 1.1

Why Does the IGS Care About EOPs?

- post-processed EOP observations
  - needed to relate GNSS orbits (in ITRF in SP3 files) to quasi-inertial frame
  - pole very useful to tie GNSS frame to other technique frames
  - valuable for geoscience & EOP monitoring services due to high accuracy

- EOP predictions
  - required for Ultra-rapid GNSS orbit predictions

IGU Orbit Prediction Differences wrt IGS Rapids (units = mm)										
	dX	dY	dZ	RX	RY	RZ	SCL	RMS	wRMS	Medi
mean	3.1	0.7	0.8	-8.0	-0.5	0.5	-0.7	31.4	23.9	17.9
±	4.7	4.0	3.3	20.8	24.3	34.7	0.7	14.0	6.2	3.0
* for first 6 hr of each prediction during 2008.5-2009; rotations are equatorial @ GPS altitude										

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  - RZ rotation errors (= UT1 predictions) are largest real-time error source
  - RX, RY (= polar motion predictions) & wRMS scatters next largest
  - RZ rotation errors 50% larger than PM systematic or wRMS random errors

IGS EOP Product Table (2009)

Series	EOP Comp.	Estimated Accuracy	Latency	Updates	Sample Interval
Ultra-Rapid (predicted half)	PM PM rate LOD	250 µas ~500 µas/d ~50 µs	real time	@ 03, 09, 15, 21 UTC	±12 hr integrations @ 00, 06, 12, 18 UTC
Ultra-Rapid (observed half)	PM PM rate LOD	<50 µas 250 µas/d ~10 µs	3 - 9 hr	@ 03, 09, 15, 21 UTC	±12 hr integrations @ 00, 06, 12, 18 UTC
Rapid	PM PM rate LOD	<40 µas 200 µas/d ~10 µs	17 - 41 hr	@ 17 UTC daily	±12 hr integrations @ 12 UTC
Final	PM PM rate LOD	<30 µas 150 µas/d ~10 µs	11 - 17 d	each Wednesday	±12 hr integrations @ 12 UTC

* 100 µas = 3.1 mm of equatorial rotation; 10 µs = 4.6 mm of equatorial rotation
* IGS uses IERS Bulletin A to partly calibrate for LOD biases over 21-d windows, but residual LOD errors remain

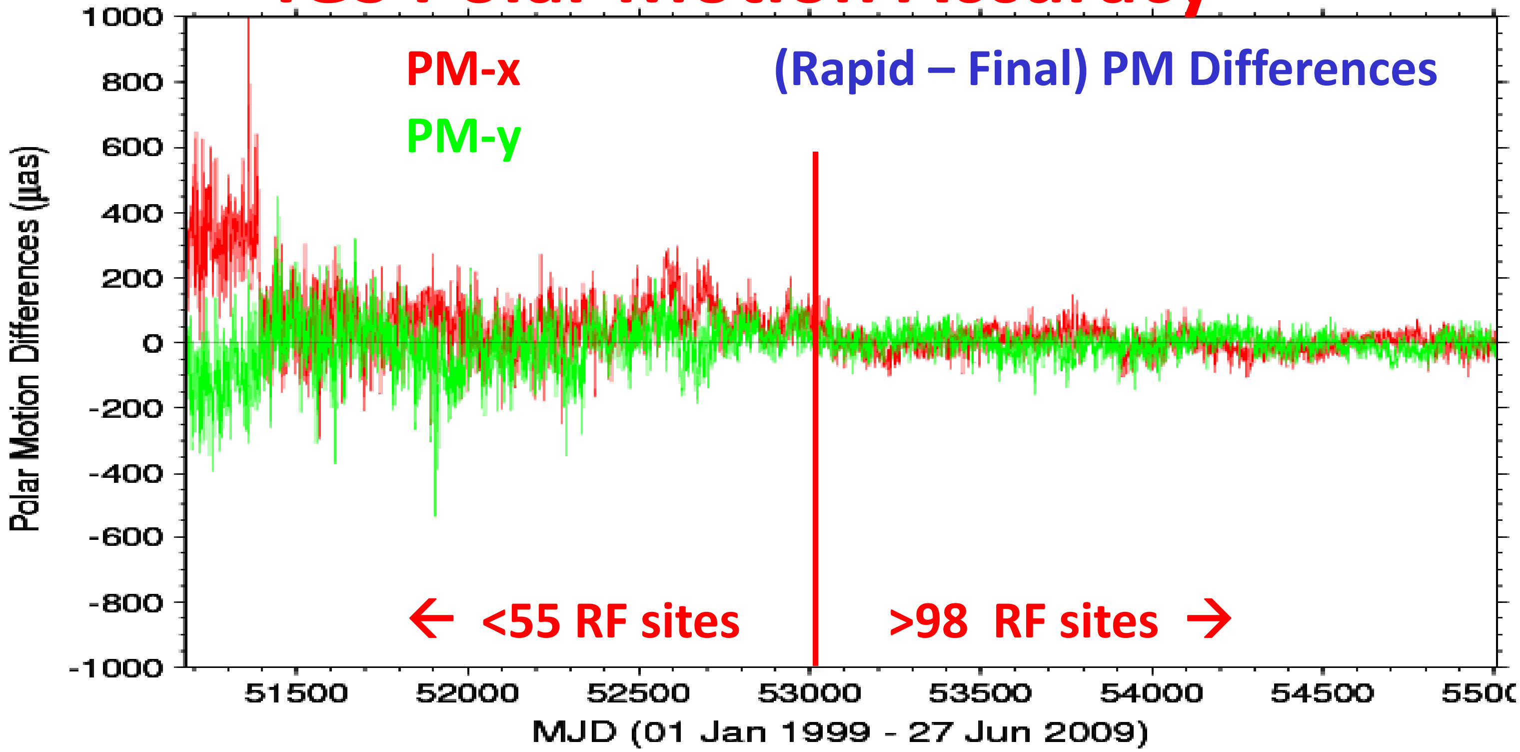
Recent Rapid & Final Polar Motion Accuracy

- **ITRF2005 multi-technique combination experience**
  - scaled formal errors ~30 µas for daily PM-x & PM-y
  - equivalent to net equatorial rotation errors of ~1 mm

- **IGS GPS heavily dominates multi-technique combinations**
  - due to robust global network & continuous, high-accuracy data
  - SLR & VLBI networks are sparse, non-uniform, & irregularly observed
  - SLR & VLBI PM contribute to rotational frame alignments, less for EOPs
  - DORIS PM noisy due to limited satellite constellation

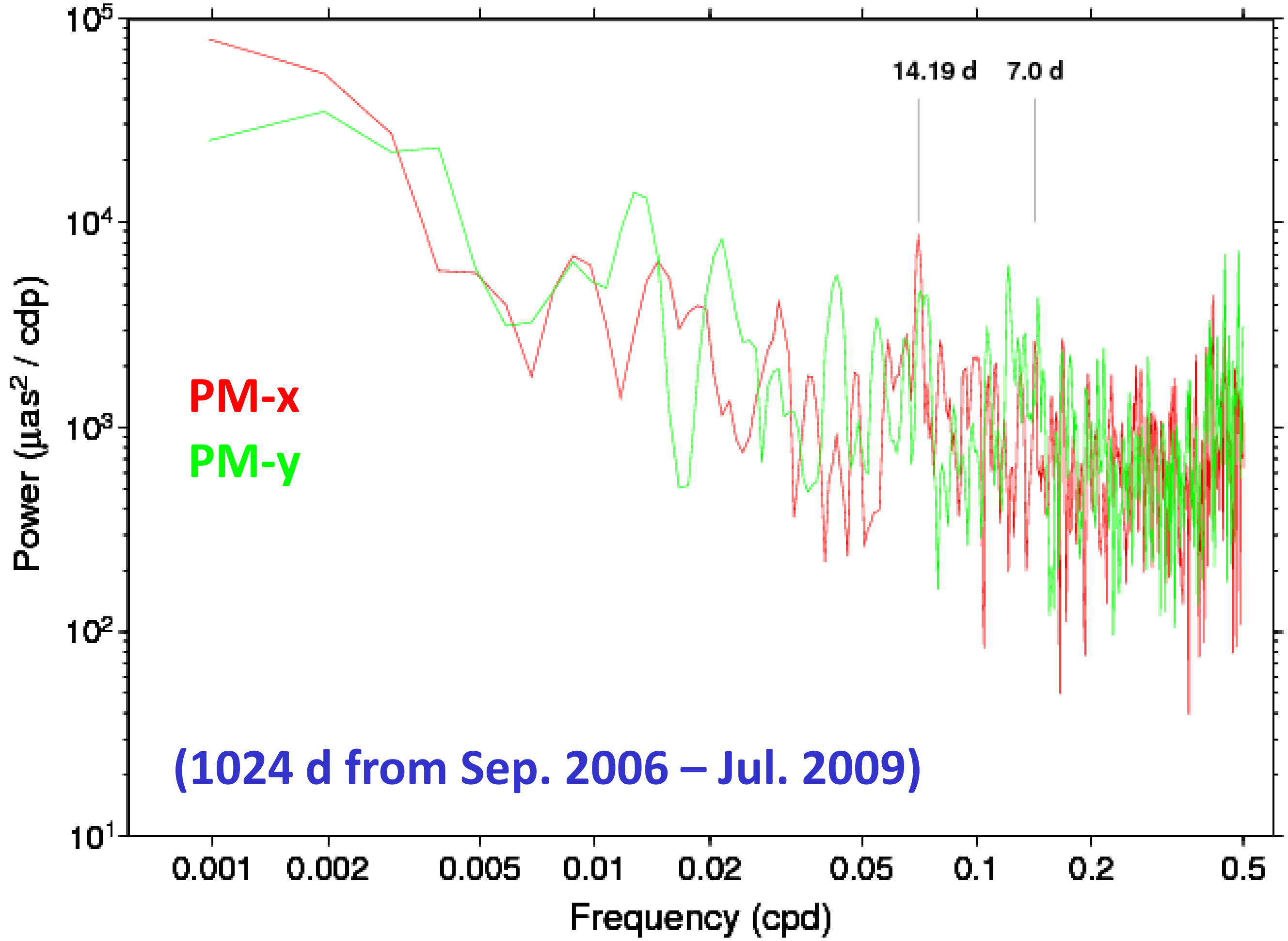
- **GPS PM errors probably nearing asymptotic limit (~20 µas)**
  - since increase in IGS RF to 99+ sites (Jan. 2004), PM errors <~30 µas
  - PM accuracy limited by: orbit mismodeling, subdaily EOP tide model errors, & AC solution constraints
  - IGS Rapid EOPs about 25 to 50% poorer than Finals
  - evidence for fortnightly & longer-period errors
  - IGS reprocessing campaign will improve old PM results (back to ~1995)

IGS Polar Motion Accuracy



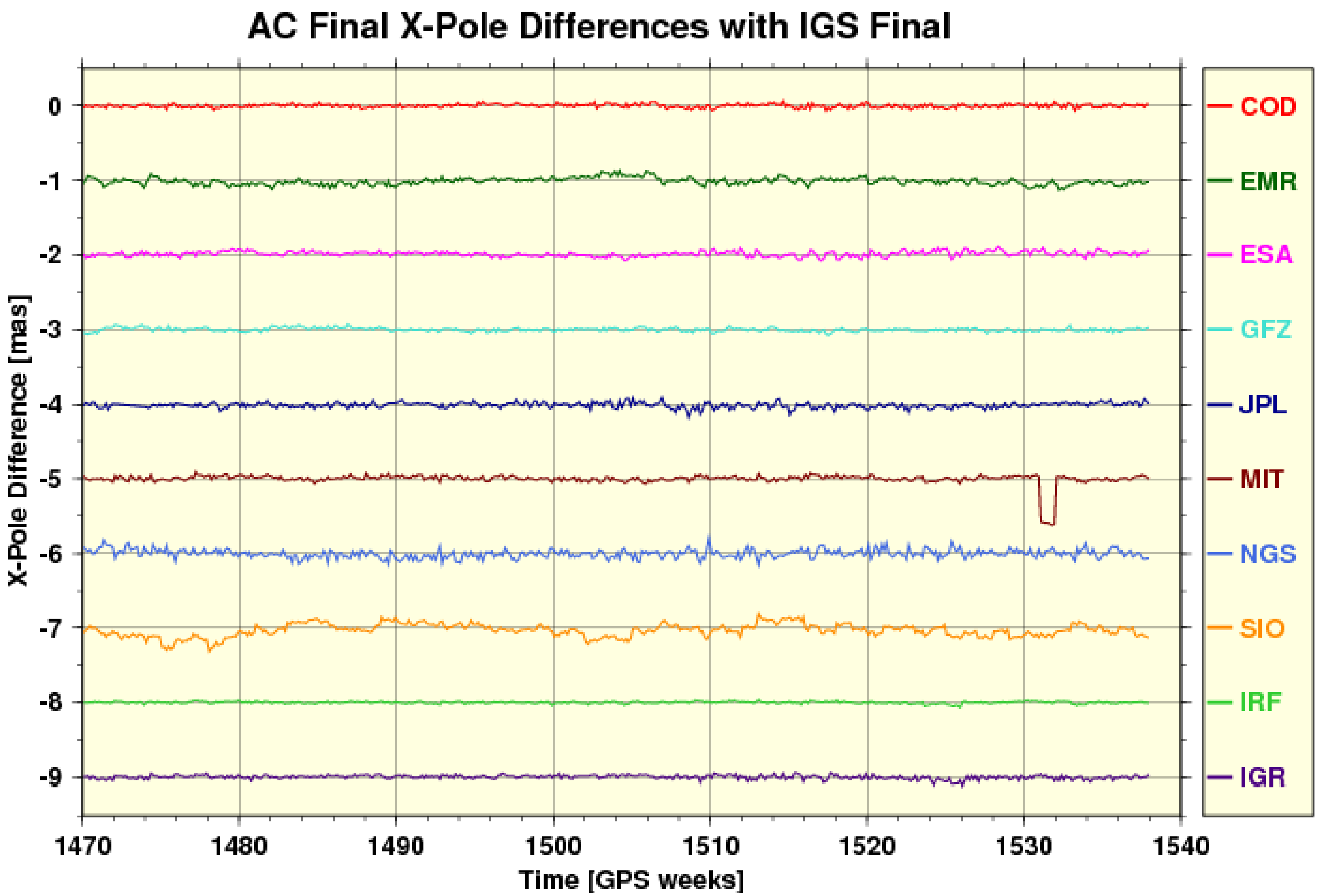
Years (units = µas)	Rapid		Final		Δ(Rapid-Final)	
	$<\sigma_x>$	$<\sigma_y>$	$<\sigma_x>$	$<\sigma_y>$	<Δx> ± SDev	<Δy> ± SDev
1999-2001.5	77.3	85.9	44.1	44.4	119.9 ± 153.2	-29.7 ± 113.8
2001.5-2003	47.5	47.3	33.3	35.0	65.4 ± 73.9	6.3 ± 70.0
2004-2006	34.0	39.5	25.6	27.2	7.2 ± 38.7	-1.7 ± 38.8
2007-2009.5	**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**
  - but longer period errors might be significant
  - fortnightly feature near 14.2 d may signify tide model errors

PM Differences among IGS ACs



- Differences among ACs reflect mostly analysis variations
  - networks, geophysical models, & parameterizations quite similar
  - main analysis differences relate to orbit dynamics & solution constraints

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

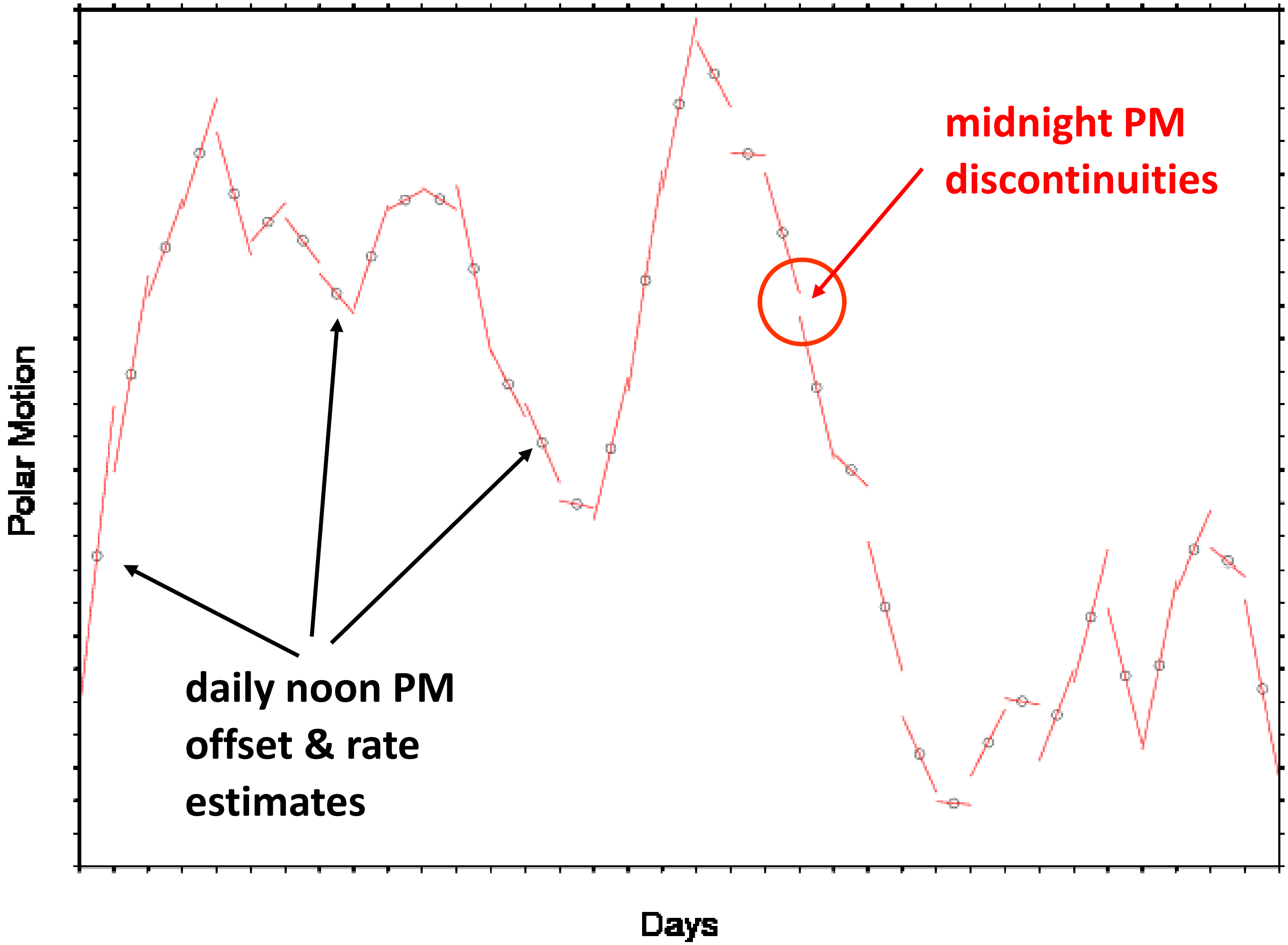
- **IGS GPS also dominates PM-rate combinations**

- **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

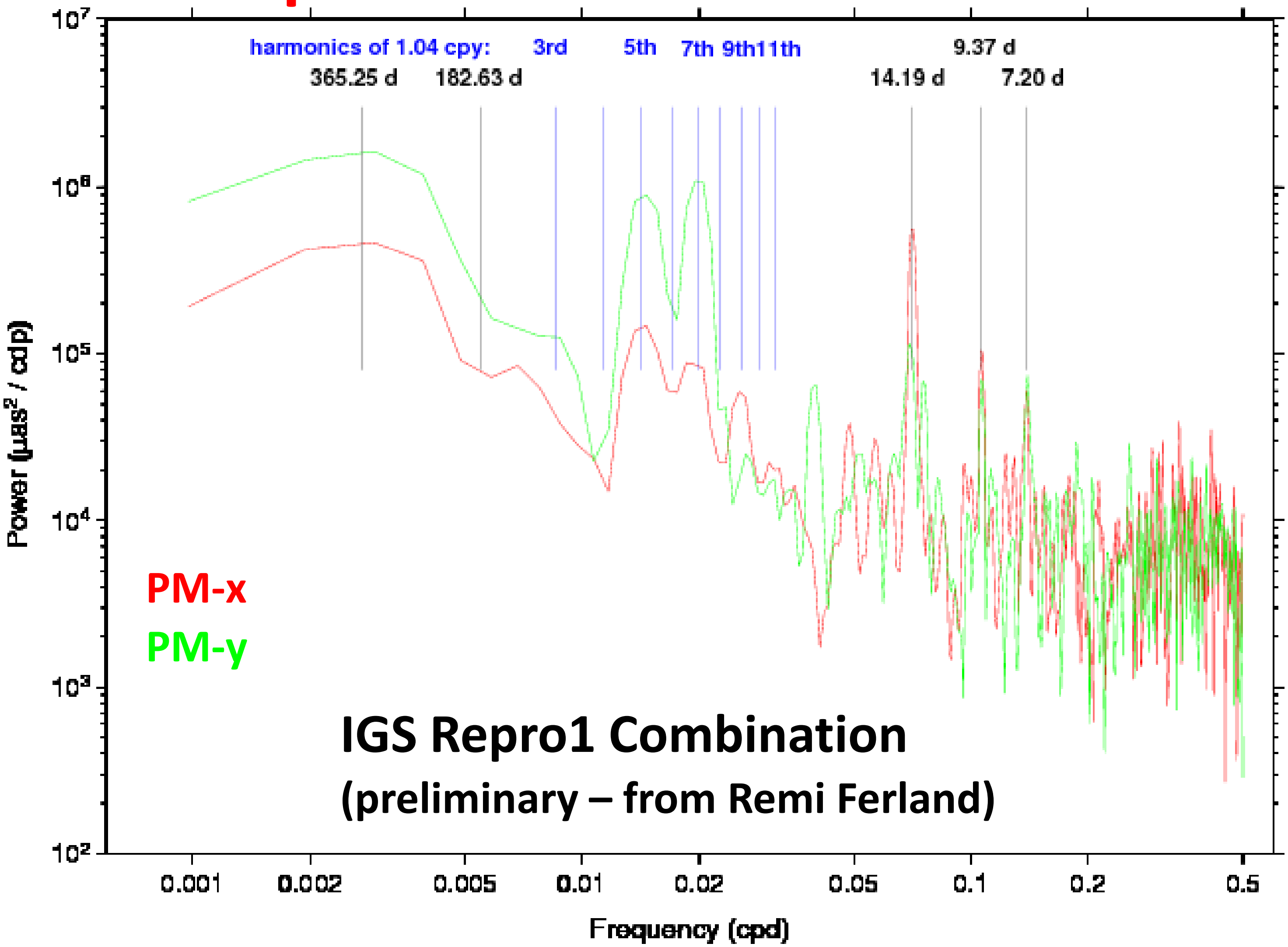
- **For excitation studies, probably best to use PM time differences, not directly observed PM-rates**

Compute Polar Motion Discontinuities



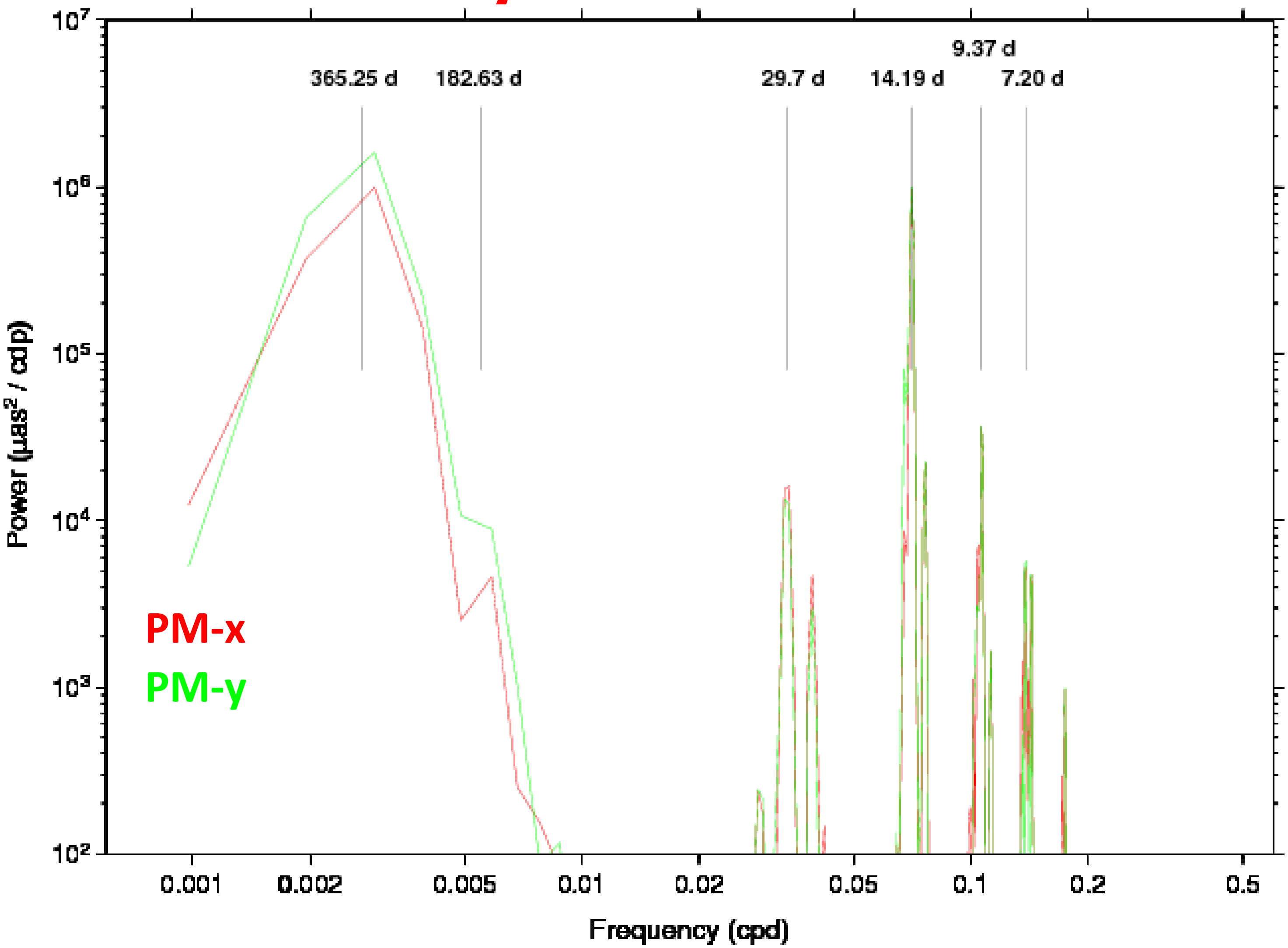
- **Examine PM day-boundary discontinuities for IGS time series**
  - should be non-zero due to PM excitation & measurement errors

Power Spectra of IGS PM Discontinuities



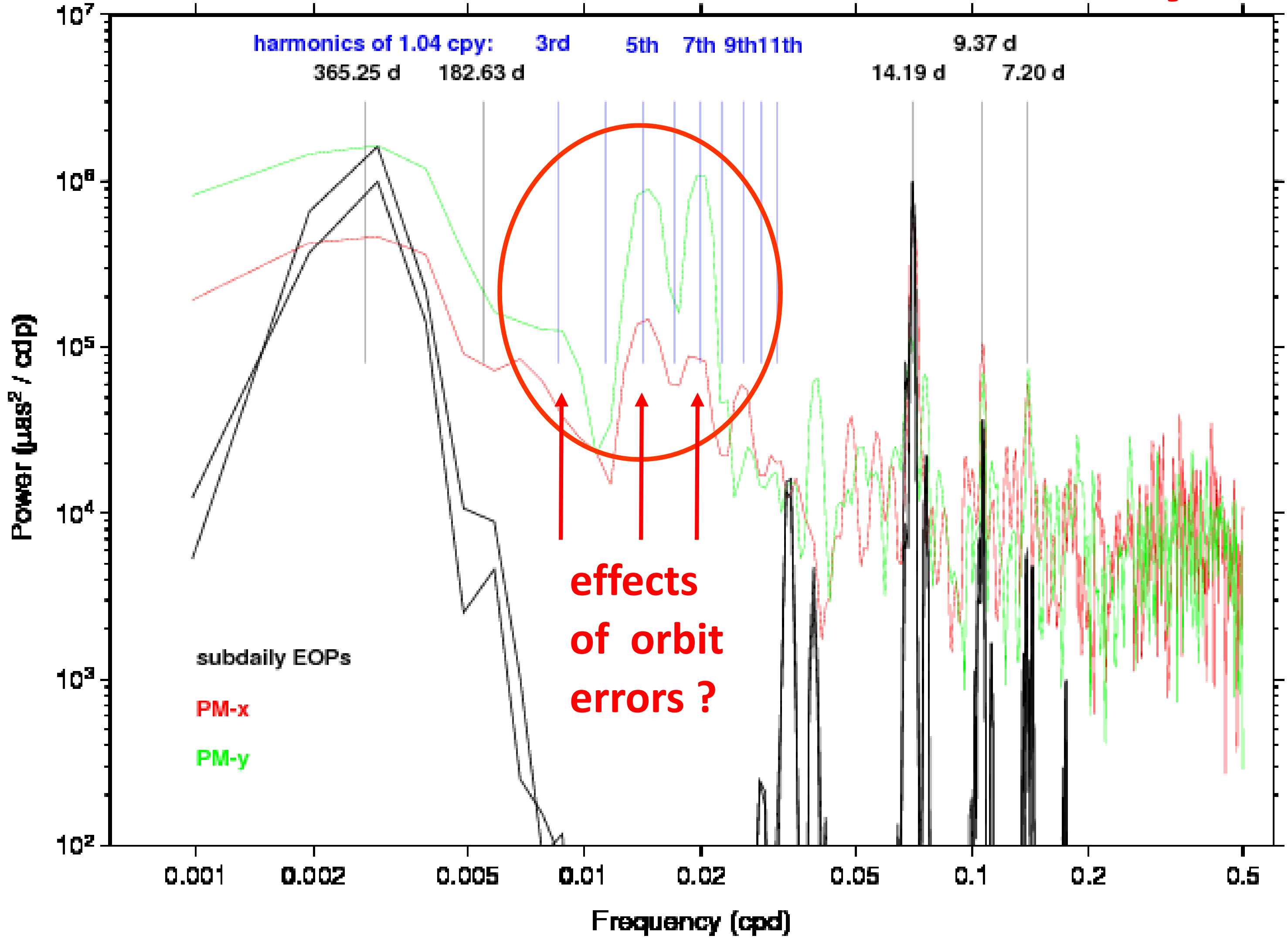
- **Common peaks seen in most AC spectra are:**
  - annual + 5th & 7th harmonics of GPS year (351 d or 1.040 cpy)
  - probably aliased errors of subdaily EOP tide model (IERS2003)

Spectra of 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

Spectra of PM Discontinuities & Subdaily EOPs



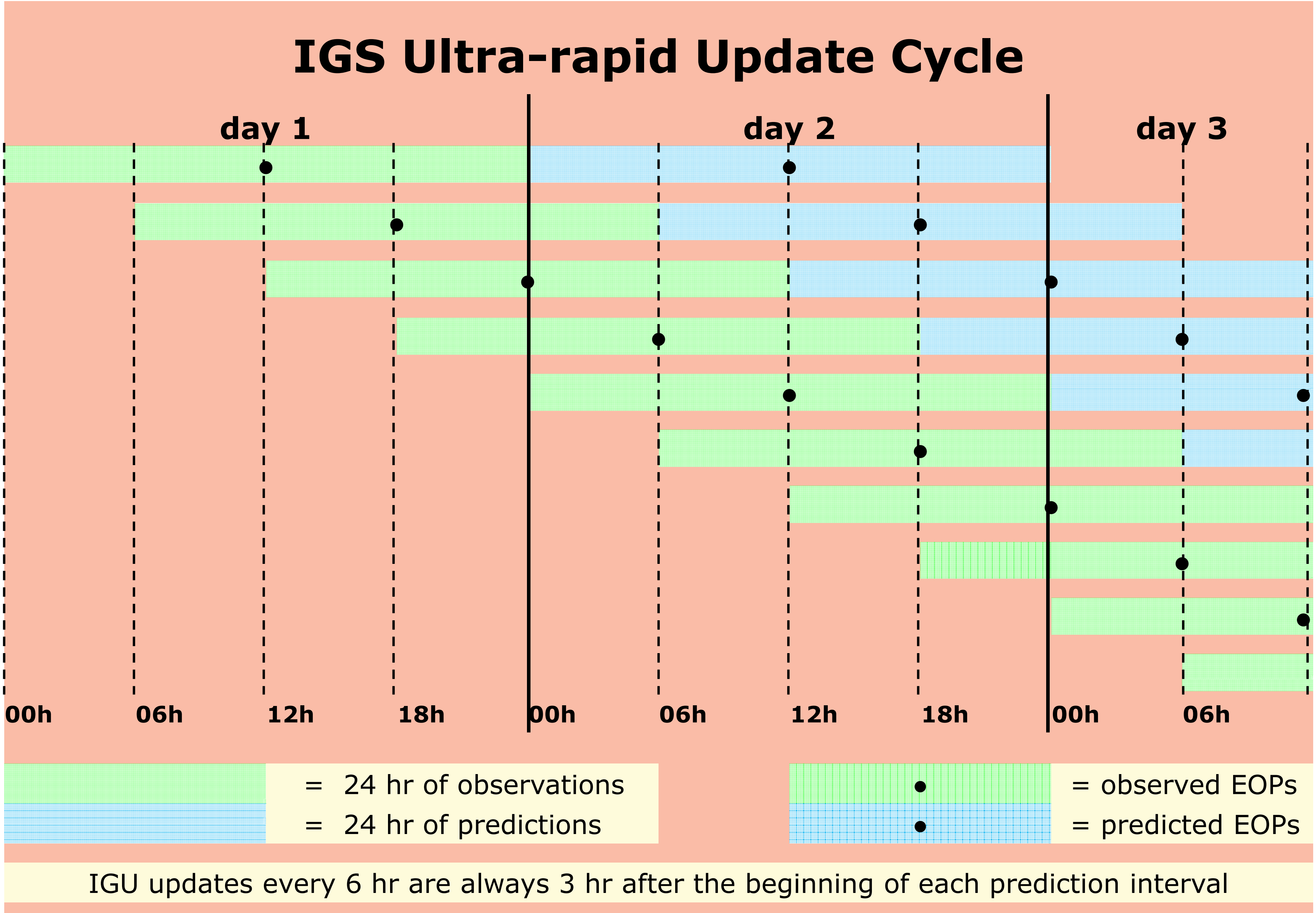
- **Aliasing of subdaily EOP tide model errors probably explains:**
  - **annual (K1, P1, T2), 14.2 d (O1), 9.4 d (Q1, N2), & 7.2 d (σ1, 2Q1, 2N2, μ2)**
- **Orbit errors presumably responsible for odd 1.04 cpy harmonics**

Recent Ultra-rapid Polar Motion Accuracy

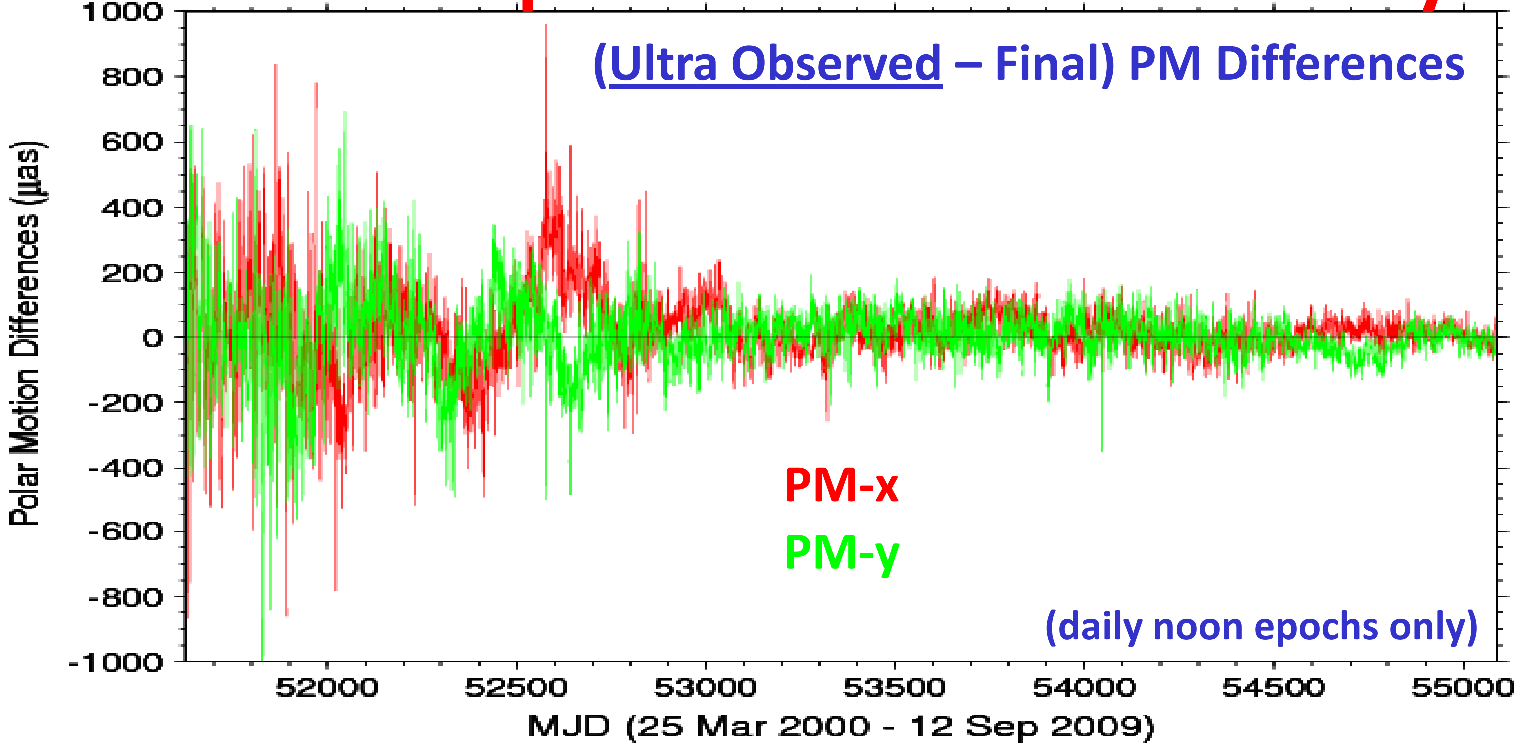
- IGU <u>observed</u> EOPs updated every 6 hr
  - latency is 15 hr for each update
  - each EOP value is integrated over 24 hr
  - polar motion accuracy recently: **<50 μas (1.5 mm)**
  - reported formal errors are generally reliable

- IGU <u>predicted</u> 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 ~4

  - most ACs now generate their own EOP predictions internally rather than use IERS predictions
  - IGS near-term EOP predictions usually better than values from IERS (due to use of most recent IGU observations)

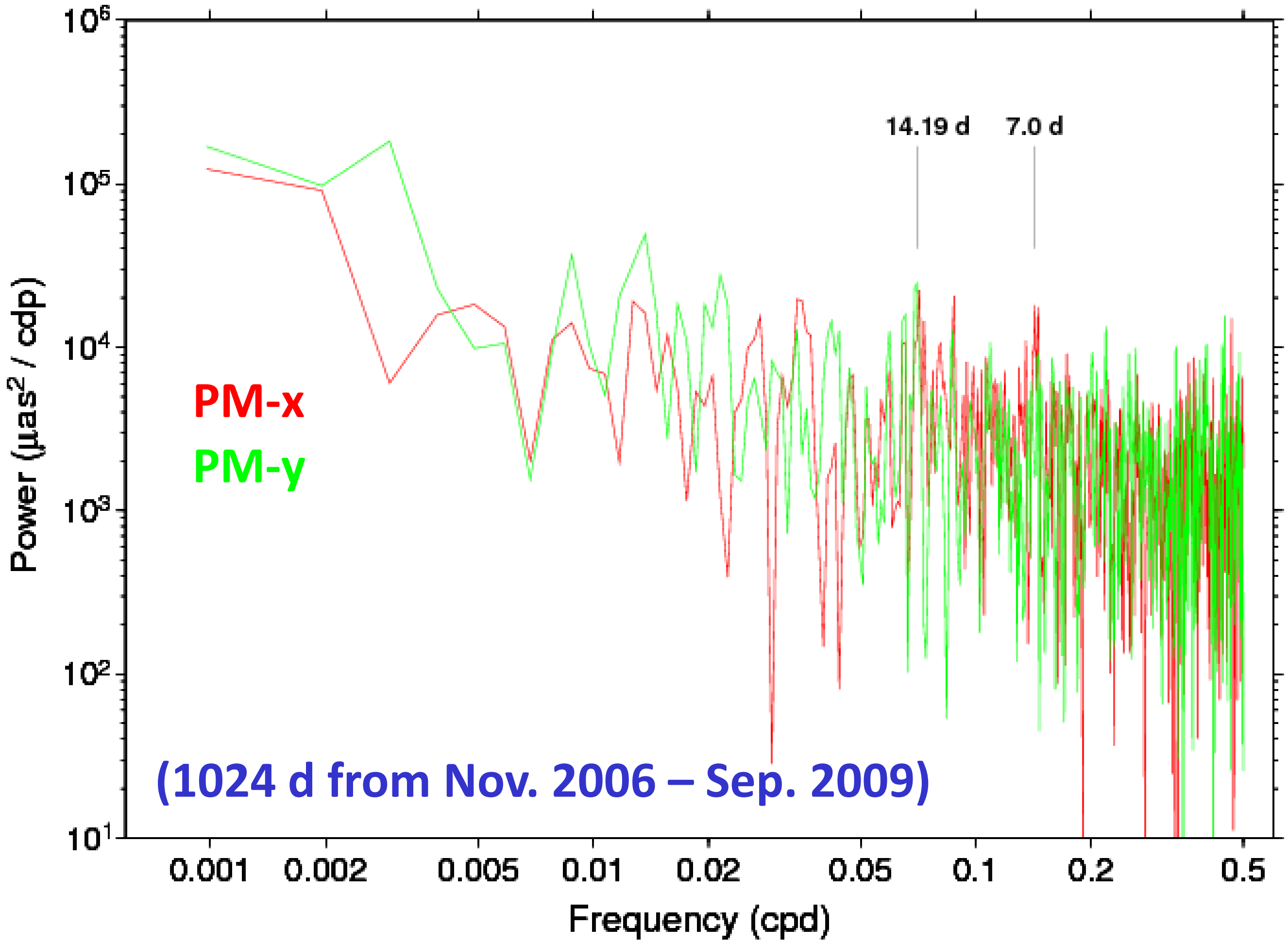

IGS Ultra-rapid Update Cycle
day 1
day 2
day 3
00h
06h
12h
18h
00h
06h
12h
18h
00h
06h
= 24 hr of observations
= 24 hr of predictions
= observed EOPs
= predicted EOPs
IGU updates every 6 hr are always 3 hr after the beginning of each prediction interval

IGS Ultra-rapid Polar Motion Accuracy



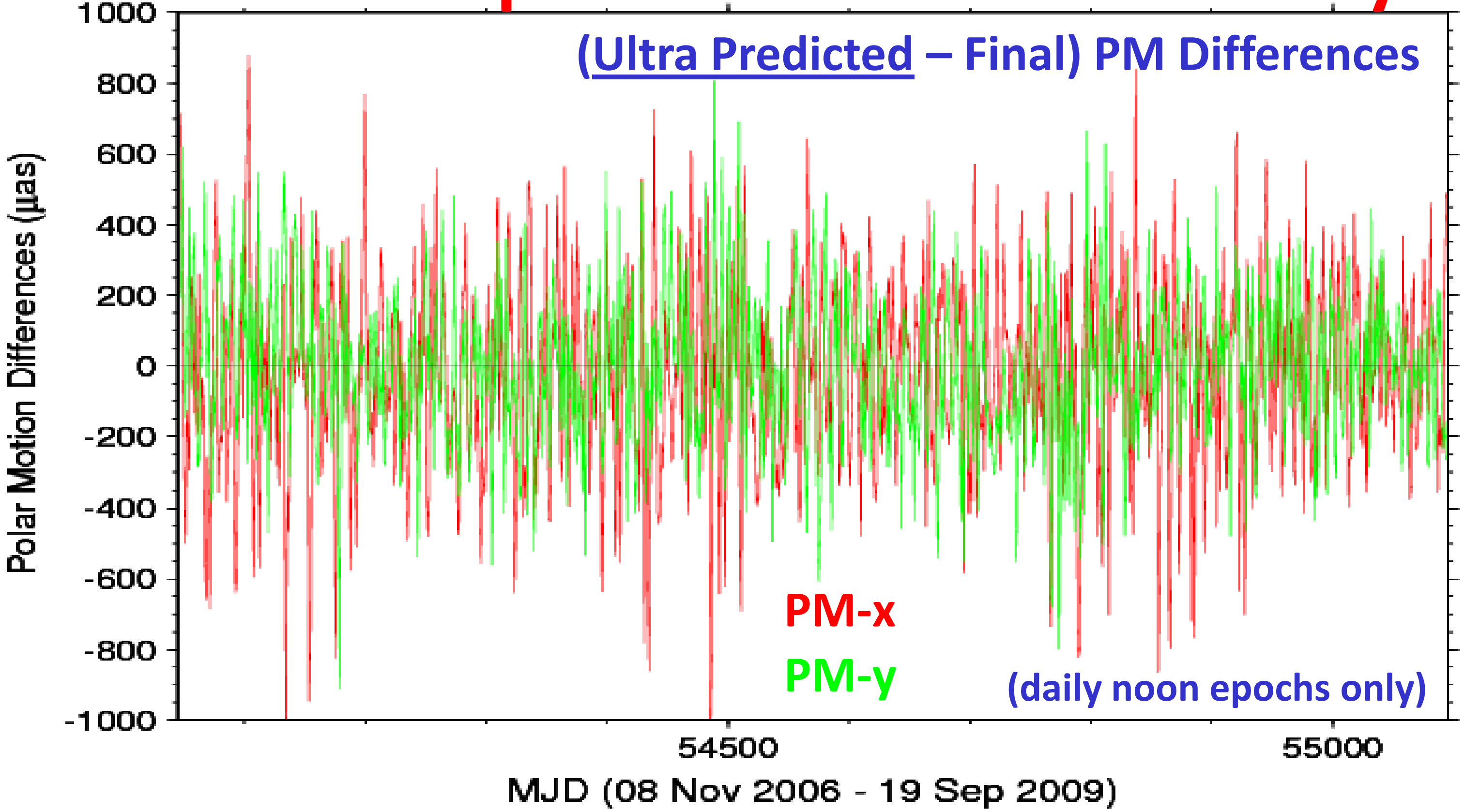
Years (units = µas)	**Ultra-rapid**		**Final**		**Δ(Ultra-Final)**	
	<σ_x>	**<σ_y>**	**<σ_x>**	**<σ_y>**	**<Δx> ± SDev**	**<Δy> ± SDev**
2000.2-2002	136.2	135.7	38.2	40.4	20.5 ± 213.8	2.9 ± 192.6
2003-2005.5	73.8	74.2	27.2	28.7	37.0 ± 93.5	7.0 ± 81.0
2005.5-2007	51.9	63.6	23.8	25.1	17.1 ± 59.9	10.8 ± 59.9
2008-2009.7	**31.7**	**32.6**	**18.8**	**18.2**	12.7 ± **33.6**	-18.5 ± **41.1**

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

IGS Ultra-rapid Polar Motion Accuracy



Years (units = µas)	Ultra-rapid		Final		Δ(Ultra-Final)	
	$<\sigma_x>$	$<\sigma_y>$	$<\sigma_x>$	$<\sigma_y>$	$<\Delta x> \pm$ SDev	$<\Delta y> \pm$ 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**

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