OVERVIEW OF IGS PRODUCTS & ANALYSIS CENTER MODELING

- Status of core products
  - focus on Ultra-rapid predicted orbits
  - issues with current products
- Comparisons of AC analysis strategies
  - evidence for systematic errors, esp. fortnightly harmonics
- Recommendations

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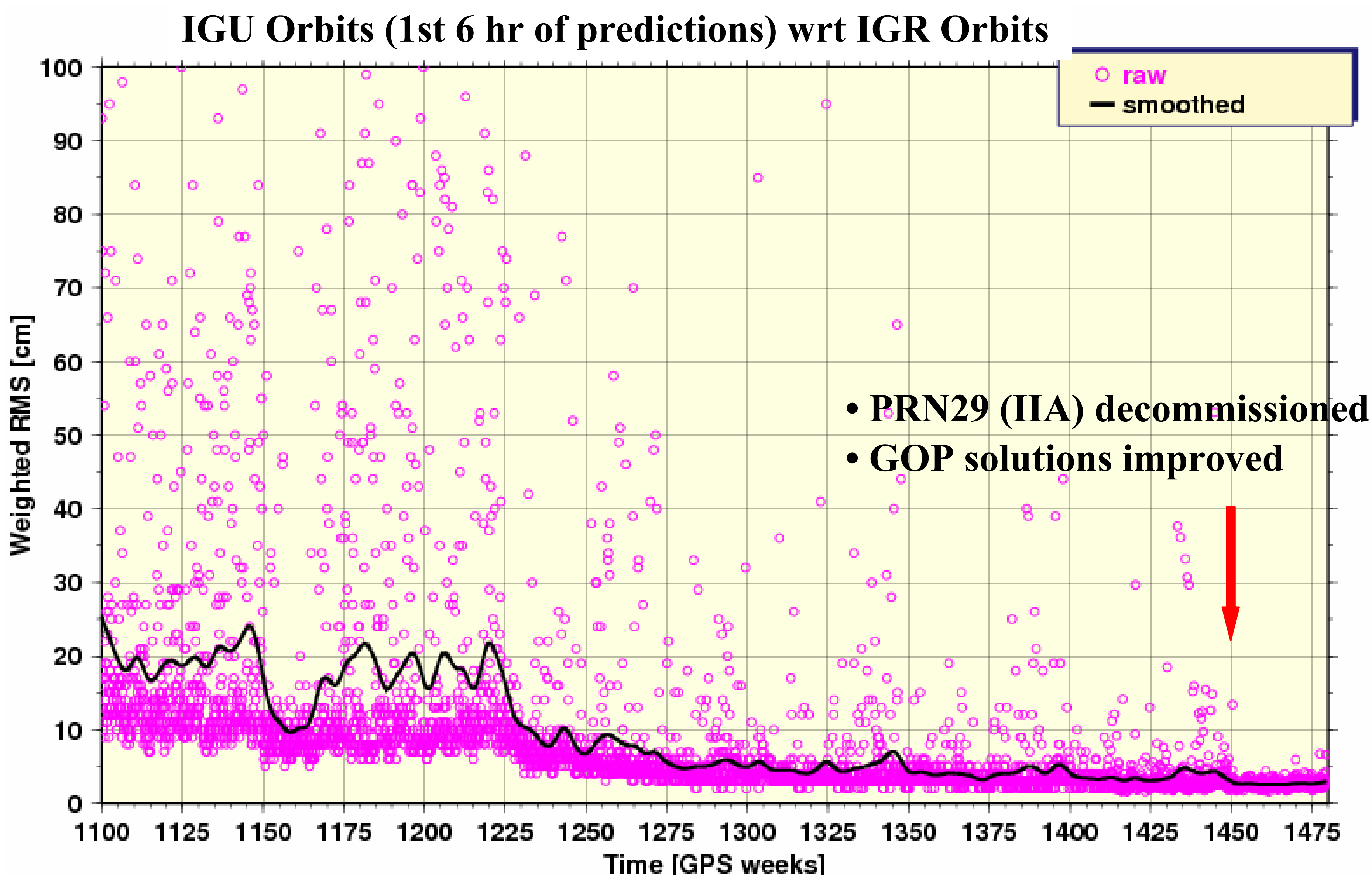
IGS 2008 Workshop, Miami Beach, 2 June 2008

SUMMARY OF IGS CORE PRODUCTS

PRODUCT SUITES	# ACs	CURRENT PRECISION	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	< ~15 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

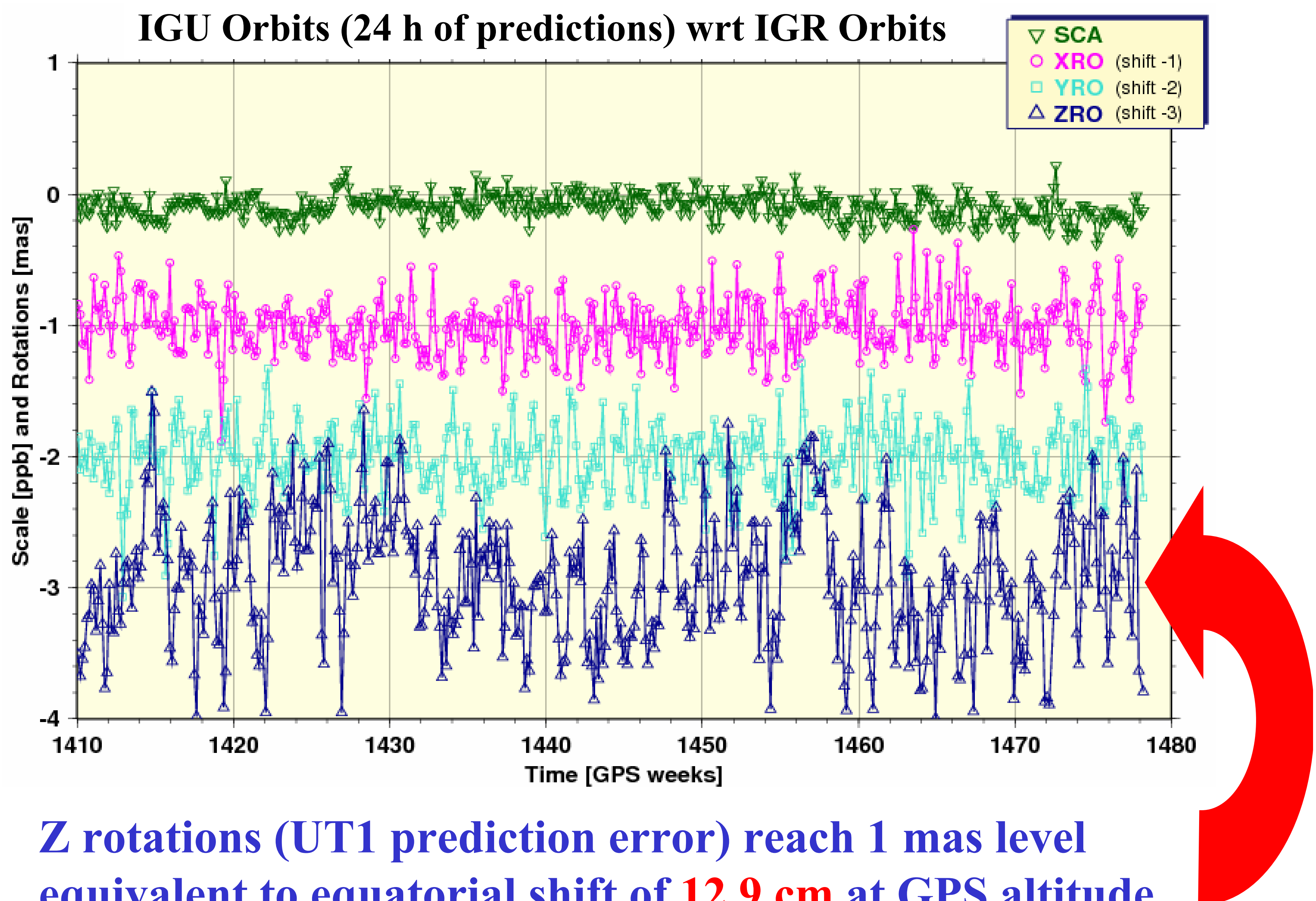
* indicates AC contributions that are weaker than others

Predicted IGU Orbit WRMS



- WRMS of IGU orbit predictions have improved to <5 cm RMS

Scale & Rotations of Predicted IGU Orbits



- Z rotations (UT1 prediction error) reach 1 mas level
- equivalent to equatorial shift of 12.9 cm at GPS altitude

Issues with Current Products

- IGU orbit combination only marginally robust
  - sometimes AC predictions are better than combo

Ultra-Rapid IGS Orbit Comparison for 1478_6_06 (10 May 2008 06h)

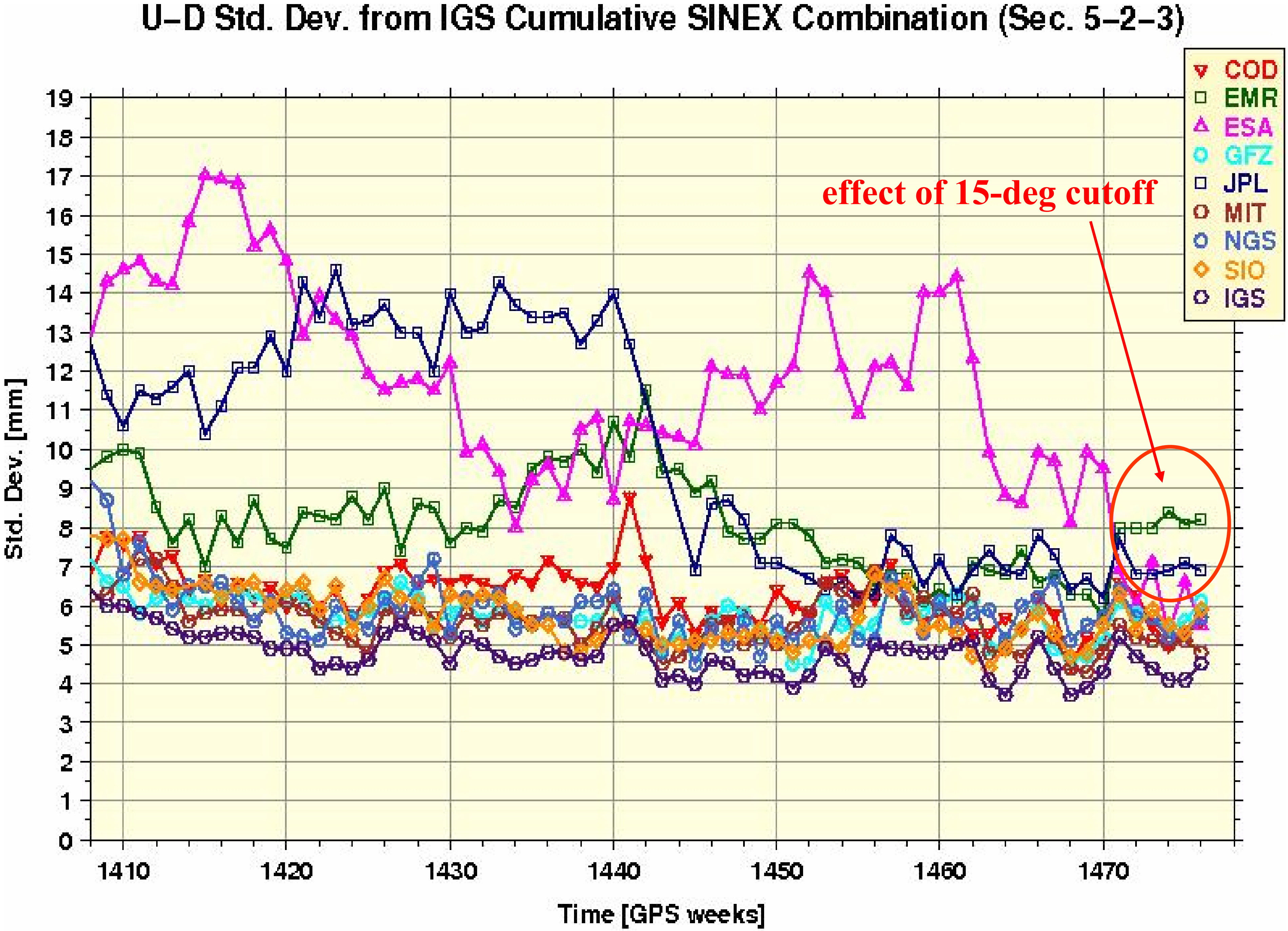
CENT	STA	DX [mm]	DY [mm]	DZ [mm]	RX [uas]	RY [uas]	RZ [uas]	SCL [ppb]	RMS [mm]	WRMS [mm]	MEDI [mm]
cou	73	11	-1	-4	536	-389	254	-.29	64	34	33
emu	49	7	0	0	486	38	-60	.03	84	44	21
esu	95	4	5	-2	-396	687	-72	.13	77	77	29
gfu	65	1	-2	-2	302	-21	127	-.34	77	78	29
gou	82	-5	-4	-1	260	334	48	-.35	89	78	31
siu	62	0	17	-33	-221	1068	730	.02	130	131	71
usu	33	19	9	0	297	-394	-20	.14	123	111	56
igu	n/a	5	0	-5	283	103	45	-.08	74	79	18

  - would benefit from more high-quality ACs
  - accuracy now limited by ERP predictions, mostly
    - may also apply to IGR orbits (but less severe)

- IGU combined clocks are very poor
  - clock predictions no better than BRDC
  - not enough clock ACs
    - even IGR clocks sometimes weak when some ACs miss

COMPARISON OF AC DATA USAGE

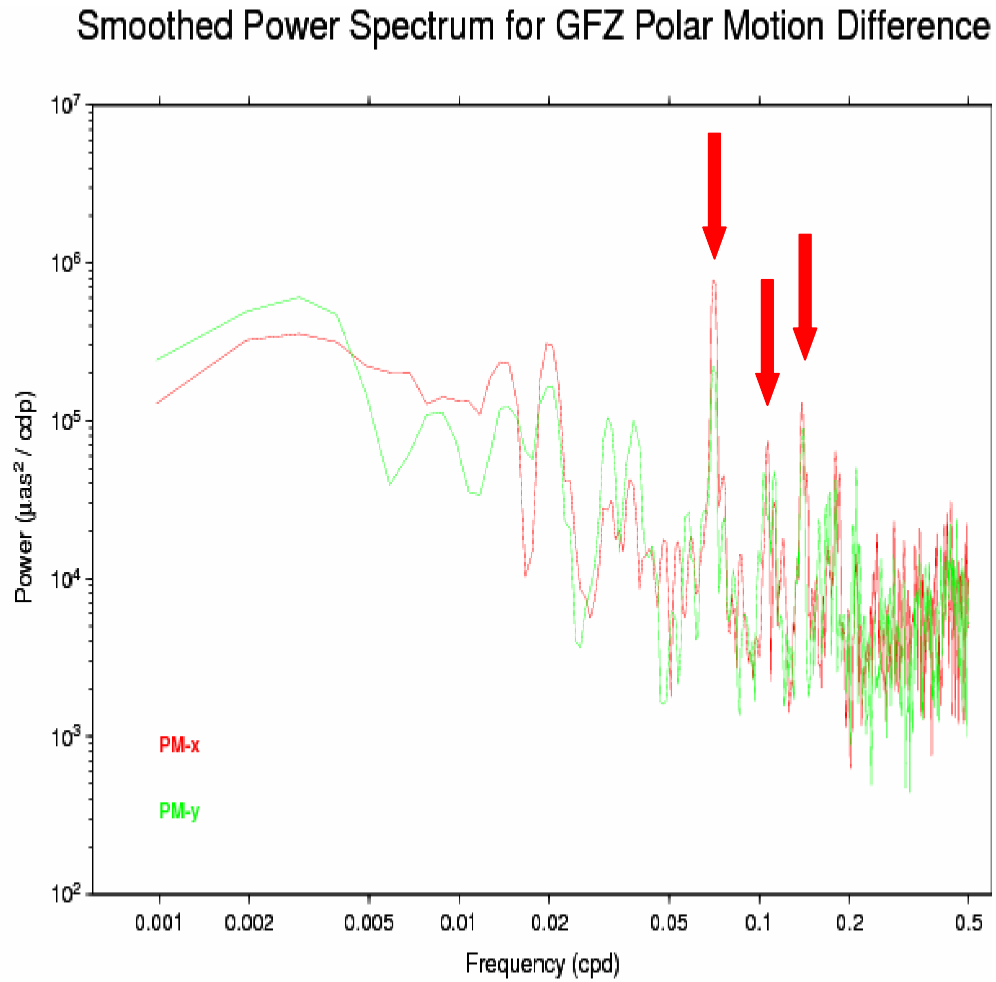
ANALYSIS CENTER	OBS TYPE	ORBIT DATA ARC LENGTH	DATA RATE	ELEVATION CUTOFF	ELEVATION INVERSE WGTS
CODE	DbDiff (redundant)	24 + 24 + 24 h	3 min	3 deg	$1/\cos^2(z)$
EMR	UnDiff	24 h	5 min	15 deg	none
ESA	UnDiff	24 h	5 min	10 deg	$1/\sin^2(e)$
GFZ	UnDiff	n x 24 h n = 3 (Rapid = 2)	5 min	7 deg	1/2sin(e) for e < 30 deg
GRGS (new)	UnDiff	48 h	15 min	10 deg	$1/\cos^2(z)$
JPL	UnDiff	3 + 24 + 3 h	5 min	15 deg → 7 deg	none
MIT	DbDiff (independent)	24 h (SRPs over 9d)	2 min	10 deg	$a^2 + (b^2/\sin^2(e))$ a,b from site residuals
NGS	DbDiff (redundant)	24 h	30 s	10 deg	$[5 + (2/\sin(e))\ \mathrm{cm}]^2$
PDR (Repro)	DbDiff (redundant)	24 + 24 + 24 h	3 min	3 deg	$1/\cos^2(z)$
SIO	DbDiff (independent)	24 h	2 min	10 deg	$a^2 + (b^2/\sin^2(e))$ a,b from site residuals


U-D Std. Dev. from IGS Cumulative SINEX Combination (Sec. 5-2-3)
COD
EMR
ESA
GFZ
JPL
MIT
NGS
SIO
IGS
effect of 15-deg cutoff
Std. Dev. [mm]
Time [GPS weeks]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
1410
1420
1430
1440
1450
1460
1470

COMPARISON OF AC TIDAL MODELS

ANALYSIS CENTER	SOLID EARTH	EARTH POLE	OCEAN LOAD	OCEAN POLE	OCEAN CMC	SUBDAILY EOPs
CODE	IERS 2003; dehanttideinel.f	eqn 23a/b mean pole	FES2004; hardisp.f	none	sites & SP3	IERS 2003; subd nutation
EMR	IERS 2003	eqn 23a/b mean pole	FES2004; gipsy	none	sites & SP3	IERS 1996; no subd nutation
ESA	IERS 2003; dehanttideinel.f	eqn 23a/b mean pole	FES2004; hardisp.f	none	sites & SP3	IERS 2003 & PMsdnut.for
GFZ	IERS 1992	eqn 23a/b mean pole	FES2004; hardisp.f	none	sites & SP3	IERS 2003; subd nutation
GRGS (new)	IERS 2003	nominal mean PM	FES2002	none	none	IERS 2003 & PMsdnut.for
JPL	IERS 2003	eqn 23a/b mean pole	FES2002; gipsy	none	none → sites & SP3	IERS 1996 → IERS 2003
MIT	IERS 2003	eqn 23a/b mean pole	FES2004	none	sites & SP3	IERS 2003 & PMsdnut.for
NGS	IERS 2003; dehanttideinel.f	eqn 23a/b mean pole	FES2004; hardisp.f	none	sites & SP3	IERS 2003 & PMsdnut.for
PDR (Repro)	IERS 2003; dehanttideinel.f	fixed mean pole	GOT00.2 w/ 11 terms	none	none	IERS 2003; no subd nutation
SIO	IERS 2003	eqn 23a/b mean pole	FES2004	none	sites & SP3	IERS 2003 & PMsdnut.for

Aliased Tidal Peaks in PM Discontinuities



Peaks in PM Differences

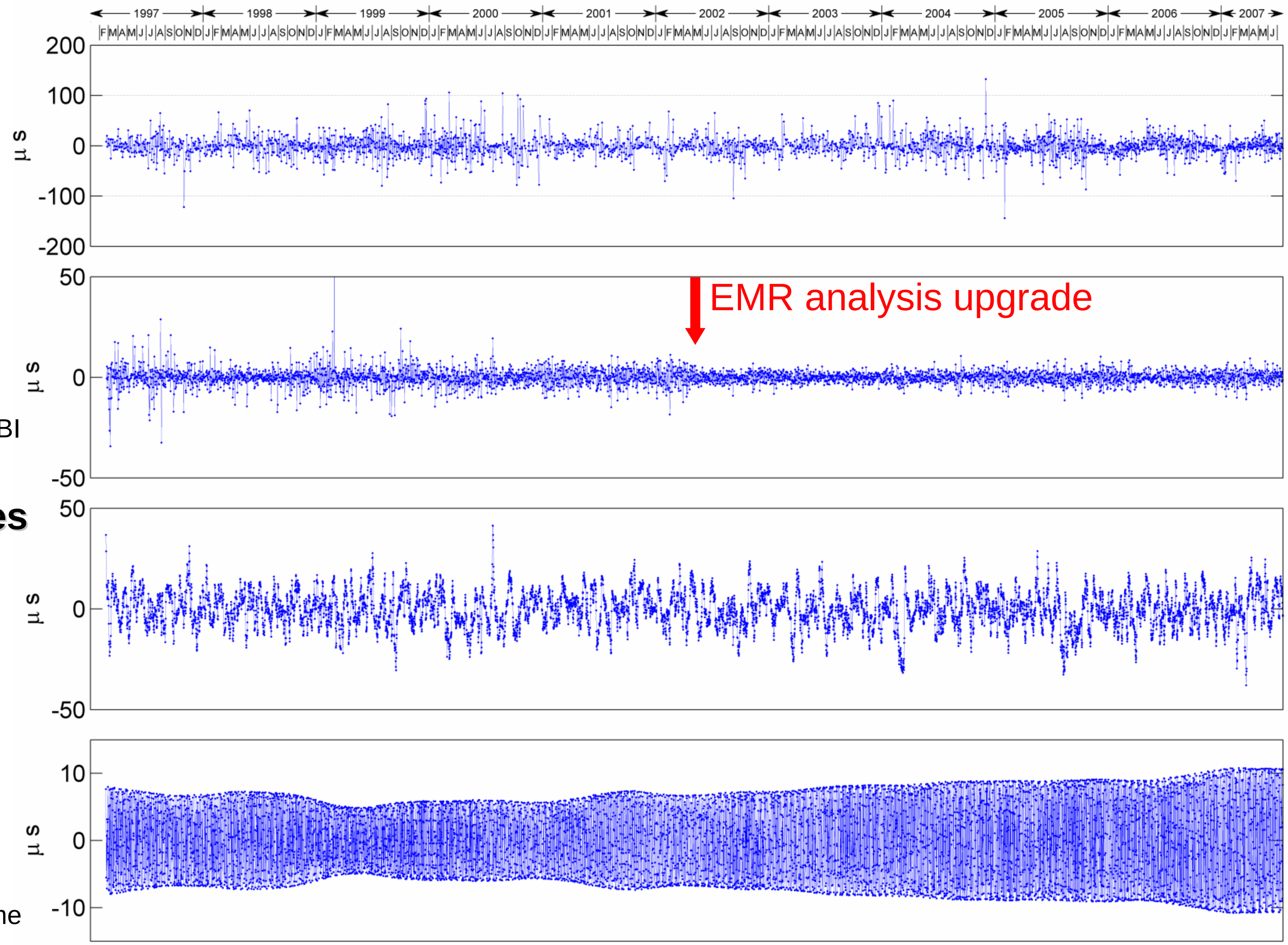
AC	14 d	9 d	7 d
EMR PM-x	14.2	9.35	7.18
±	0.2	0.09	0.05
EMR PM-y	14.1	9.6 & 9.0	7.16
±	0.2	0.1	0.05
GFZ PM-x	14.2	9.4	7.21
±	0.2	0.1	0.05
GFZ PM-y	14.2	9.6 & 8.9	7.14
±	0.2	0.1	0.05
JPL PM-x	14.2	9.4	7.23
±	0.2	0.1	0.05
JPL PM-y	14.2	9.2	7.26
±	0.2	0.1	0.05

- **Spectra of polar motion day-boundary discontinuities show signatures of aliased O1, Q1, & N2 tides + unknown 7.2 d line**

Kalman Filter of VLBI UT1 + GPS LOD

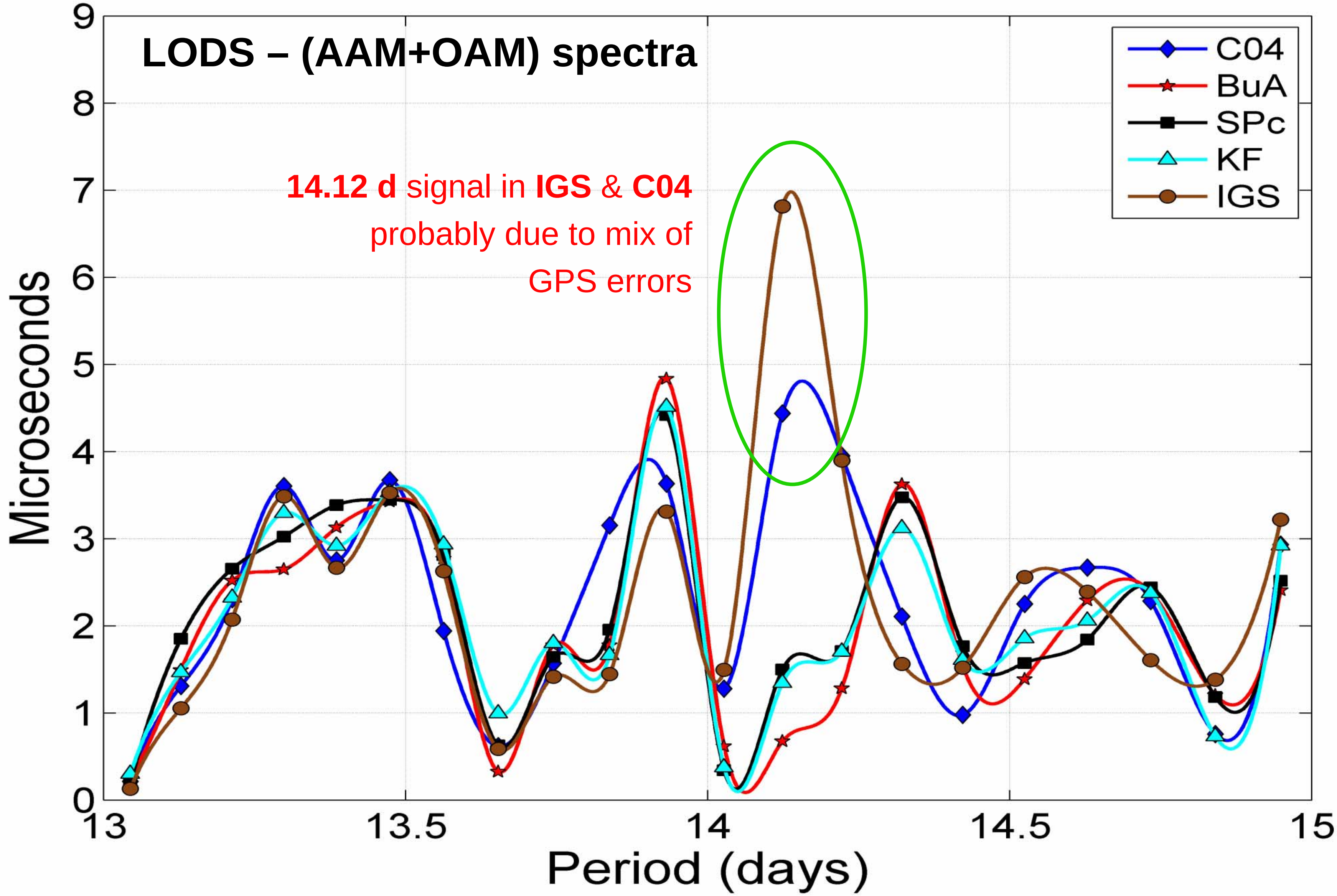
(Senior, Kouba, Ray – EGU 2008)

- **VLBI (1-hr) UT1 residuals**
  - white over full frequency range
- **GPS LOD residuals**
  - approximately white
  - with 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 varies linearly w/ time due to changing period

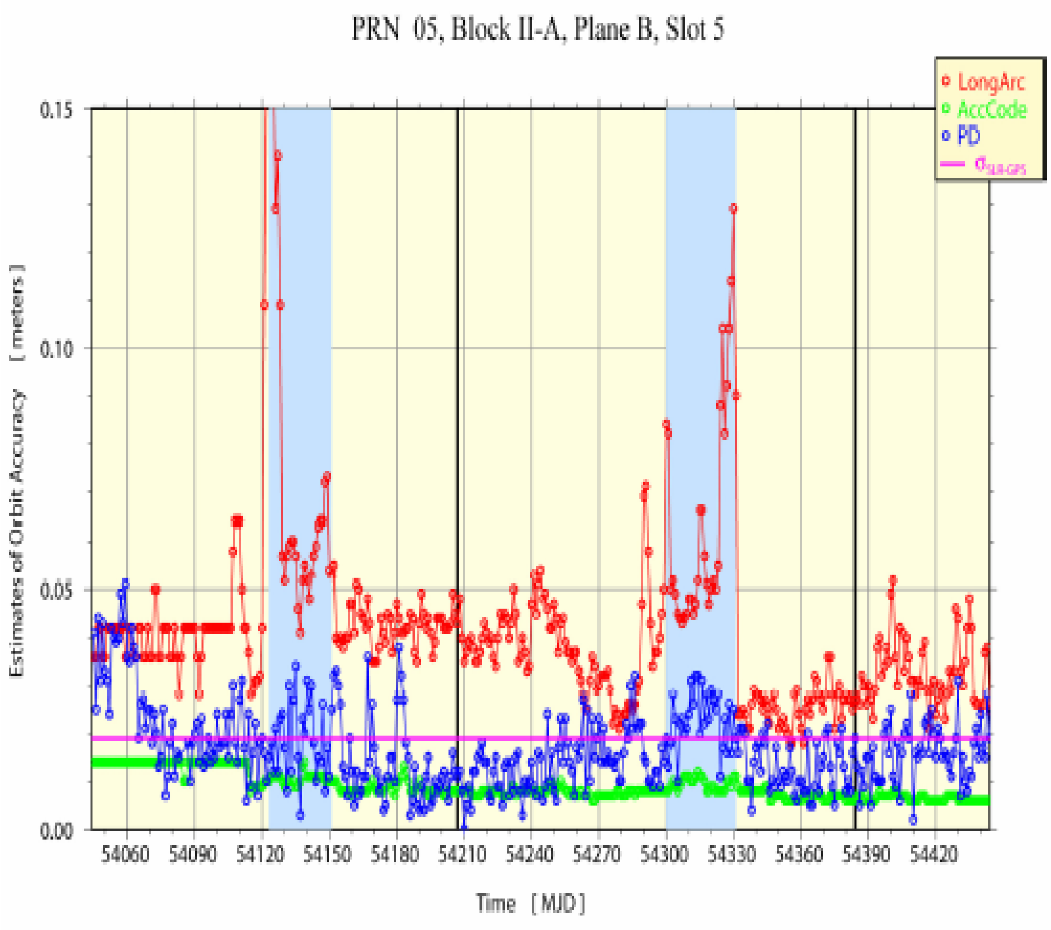


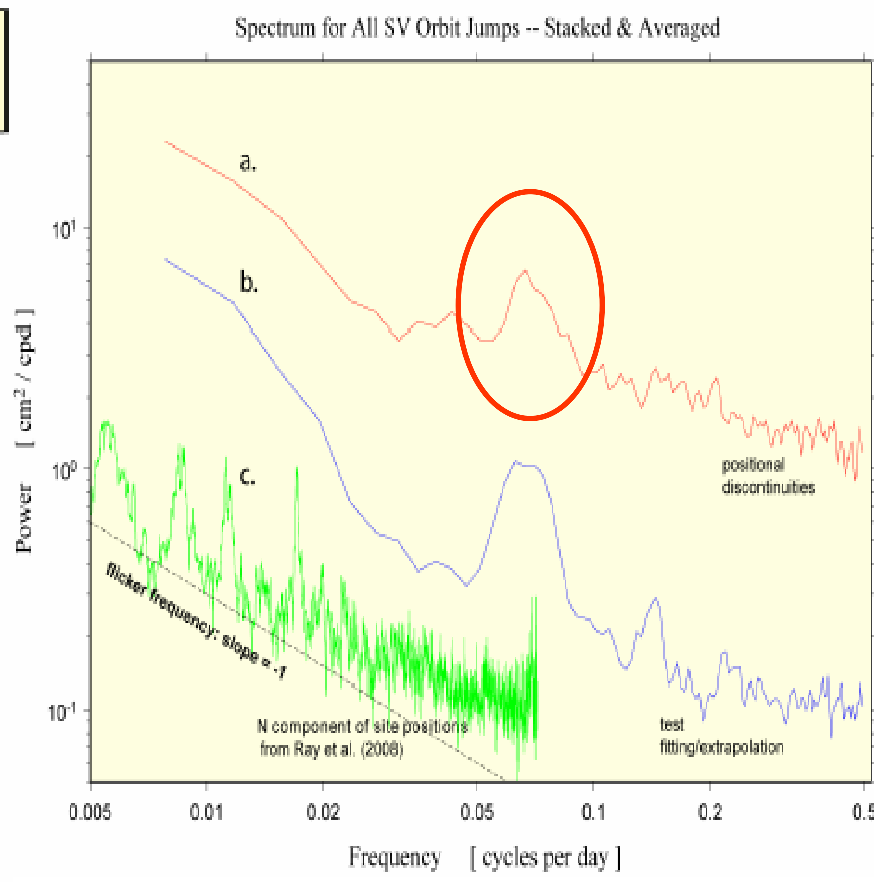
Fortnightly Band – Spurious IGS LOD

(Senior, Kouba, Ray – EGU 2008)



Day-boundary Orbit Discontinuities





- **Orbit discontinuities between days show temporally correlated errors & broad fortnightly spectral peak**
- **From Griffiths & Ray (AGU 2007)**

COMPARISON OF AC GRAVITY FORCE MODELS

ANALYSIS CENTER	GRAVITY FIELD	EARTH TIDES	EARTH POLE	OCEAN TIDES	OCEAN POLE	RELATIVITY EFFECTS
CODE	JGM3; C21/S21 due to PM	IERS 2003	IERS 2003	CSR 3.0	none	dynamic corr & bending applied
EMR	JGM3; C21/S21 due to PM	freq-depend. Love #	IERS 2003	CSR	none	no dynamic corr; bending applied
ESA	EIGEN; C21/S21 due to PM	IERS 2003	IERS 2003	IERS 2003	none	dynamic corr & bending applied
GFZ	JGM2; C21/S21 due to PM	Wahr Love #	GFZ model	GEM-T1	none	dynamic corr & bending applied
GRGS (new)	EIGEN; C21/S21 due to PM	IERS 2003	IERS 2003	FES 2004	none	dynamic corr applied; no bending
JPL	JGM3; C21/S21 due to PM	IERS 2003	IERS 2003	CSR → FES2004	none	dynamic corr & bending applied
MIT	EGM96; C21/S21 due to PM	IERS 1992; Eanes Love #	none	none	none	no dynamic corr; bending applied
NGS	GEM-T3; C21/S21 due to PM	IERS 1992; Eanes Love #	none	none	none	no dynamic corr; bending applied
PDR (Repro)	JGM3; constant C21/S21	IERS 2003 except step 2	IERS96; fixed pole	CSR 3.0	none	dynamic corr & bending applied
SIO	EGM96; C21/S21 due to PM	IERS 1992; Eanes Love #	none	none	none	no dynamic corr; bending applied

COMPARISON OF AC SATELLITE DYNAMICS

ANALYSIS CENTER	NUTATION & EOPs	SRP PARAMS	VELOCITY BRKs	ATTITUDE	SHADOW ZONES	EARTH ALBEDO
CODE	IAU 2000; BuA ERPs	D,Y,B scales; B 1/rev	every 12 hr + constraints	none	E+M: umbra & penumbra	none
EMR	IAU 1980; extrap. past 3d	X,Y,Z scales stochastic	none	yaw rates estimated	E: umbra & penumbra	none
ESA	IAU 2000; BuA ERPs	D,Y,B scales; B 1/rev	none; Along, Along 1/rev accelerations	none	E+M: umbra & penumbra	applied + IR
GFZ	IAU 2000; GFZ ERPs	D,Y scales	@ 12:00 + constraints	yaw rates estimated	E: umbra & penumbra	none
GRGS (new)	IAU 2000; C04 + BuA ERPs	D,Y,B scales; D,B 1/rev	none	none	E+M: umbra & penumbra	applied + IR
JPL	IAU 1980; BuB ERPs → BuA	X,Y,Z scales stochastic	none	nominal yaw rates used	E+M: umbra & penumbra	applied
MIT	IAU 2000; BuA ERPs	D,Y,B scales; B(D,Y) 1/rev	none; 1/rev constraints	nominal yaw rates used	E+M: umbra & penumbra	none
NGS	IAU 2000; IGS PM; BuA UT1	D,Y,B scales; B 1/rev	@ 12:00 + constraints	none; delete eclipse data	E+M: umbra & penumbra	none
PDR (Repro)	IAU 2000; BuA ERPs	D,Y,B scales; B 1/rev	every 12 hr + constraints	none	E+M: umbra & penumbra	none
SIO	IAU 2000; BuA ERPs	D,Y,B scales; D,Y,B 1/rev	none; 1/rev constraints	nominal yaw rates used	E+M: umbra & penumbra	none

COMPARISON OF AC TROPOSPHERE MODELS

ANALYSIS CENTER	METEO DATA	ZENITH DELAY	MAPPING FNCT	GRAD MODEL	ZENITH PARAMS	GRAD PARAMS
CODE	GPT	Saastamoinen dry	GMF dry	none	2-hr contin. w/ GMF wet	24-hr NS + EW continuous
EMR	ECMWF 6-hr grids	ECMWF dry + wet	NMF dry + wet	none	5-min stochastic ZTD	5-min stochastic
ESA	GPT	Saastamoinen dry	GMF dry	none	2-hr contin. w/ GMF wet	none
GFZ	GPT	Saastamoinen dry + wet?	GMF dry + wet ?	none	1-hr constants w/ GMF ?	24-hr NS + EW constants
GRGS (new)	ECMWF 6-hr grids	ECMWF dry + wet	Guo dry + wet	none	2.4-hr contin. w/ Guo dry	none
JPL	none → GPT	dry=hgt scale wet=0.1 m	NMF → GMF	none	5-min stochastic ZTD	5-min stochastic
MIT	GPT	Saastamoinen dry + wet	GMF dry + wet	none	2-hr contin. w/ GMF wet	NS + EW vary linearly
NGS	GPT	Saastamoinen dry + wet	GMF dry + wet	none	1-hr constants w/ GMF wet	NS + EW vary linearly
PDR (Repro)	Berg (1948)	Saastamoinen dry	IMF dry w/ ECMWF z200	none	2-hr contin. w/ NMF wet	24-hr NS + EW continuous
SIO	GPT	Saastamoinen dry + wet	GMF dry + wet	none	2-hr contin. w/ GMF wet	NS +EW vary linearly

Conclusions

- **Despite huge progress by IGS since 1994, numerous small systematic errors remain in products**
  - **see EGU 2008 presentation by J. Ray**

    http://www.ngs.noaa.gov/IGSWorkshop2008/docs/igs-errs_egu08.pdf

- **Applications to cutting-edge science are currently limited**
  - **need to focus on identifying, understanding, & mitigating errors**
  - **should avoid rush to premature science conclusions**
  - **must renew basic GNSS research efforts, not just in geophysical applications**
  - ***requires accurate knowledge of AC processing strategies***

- **Improvements will probably require better station installations (to reduce near-field multipath biases) & analysis upgrades**
  - **more research into field configuration effects badly needed**
  - **need better leadership to popularize lessons learned**
  - **need better cooperation & coordination between analysts & network**

Recommendations

- **For more robust products:**
  - **recruit new or improved IGU ACs & more IGR clock ACs**
  - **investigate improved near-RT & predicted ERPs**
  - **should IGS start (UT1 + LOD) service ?   (à la Senior et al., EGU08)**
- **Reject GGOS UAW actions for:**
  - **SINEX parameter & naming extensions**
  - **piecewise, continuous segment parameterization as SINEX standard**
- **Reject rigidly standardized AC procedures & parameterizations**
  - **would lead to stagnation & end of progress**
  - **would eliminate basis for multi-solution product combinations**
  - ***but ACs must agree on conventional choices & use of modern models***
- **Instead, set up inter-service SINEX & combinations WG**
  - **investigate technique-specific systematic errors**
  - **maintain SINEX format**

Recommendations (cont'd)

- **Updated AC summaries are required:**
  - **EMR** **23 Jan 2002**
  - **GFZ** **27 Feb 2003**
  - **JPL** **13 Apr 2004**
  - **SIO** **31 Oct 2005**
  - (USNO 12 Sep 2006)

- **Suggest suspending ACs with no updates by 30 Sep 2008**
  - **if processing summary is older than 2 years**
  - **submissions would be rejected from IGS products after Sep 2008**

- **Rescind AC status if no updates by 31 Dec 2008**
  - **would need to formally rejoin IGS ACs after Dec 2008**

- **Or ask above ACs for *effective* alternative proposal**