New IGS Timescale & New UT1/LOD Series

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OUTLINE:

- Current timescale algorithm
  - advantages/disadvantages
  - GPS clock issues
- New timescale algorithm
  - new clock model
  - filter description/considerations
  - Results
- New UT1/LOD series
  - comparisons with other series

Current Timescale

- 2-state clock model: frequency + drift
- Kalman filter with random walk models for each state
- steered to UTC via GPS Time
- simple weighting
  - one weight per clock
  - weight = inverse of sub-daily frequency noise variance
- driven almost totally by H-Masers

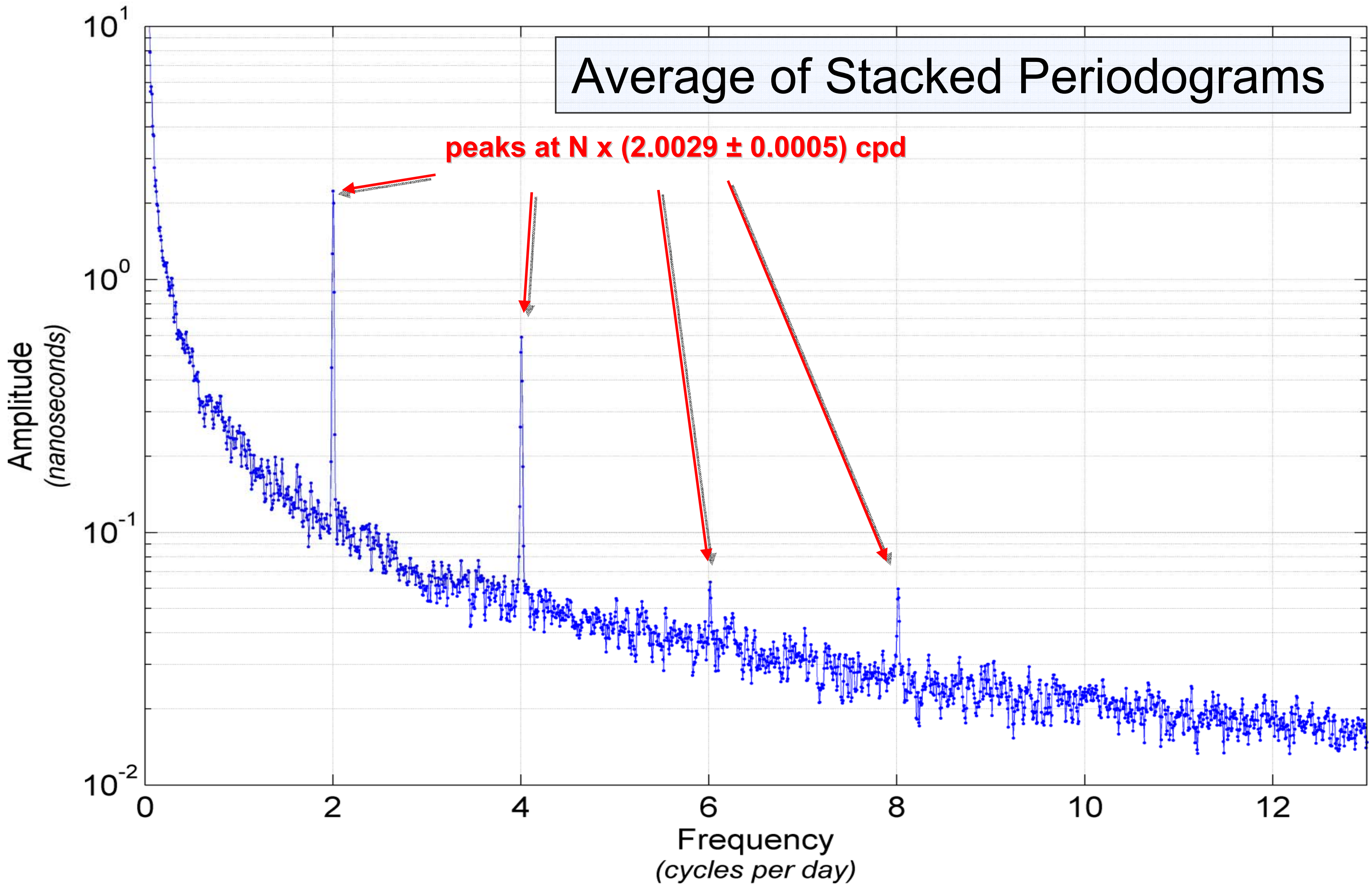
Advantages

- simple
- fully automated
- adaptive

Disadvantages

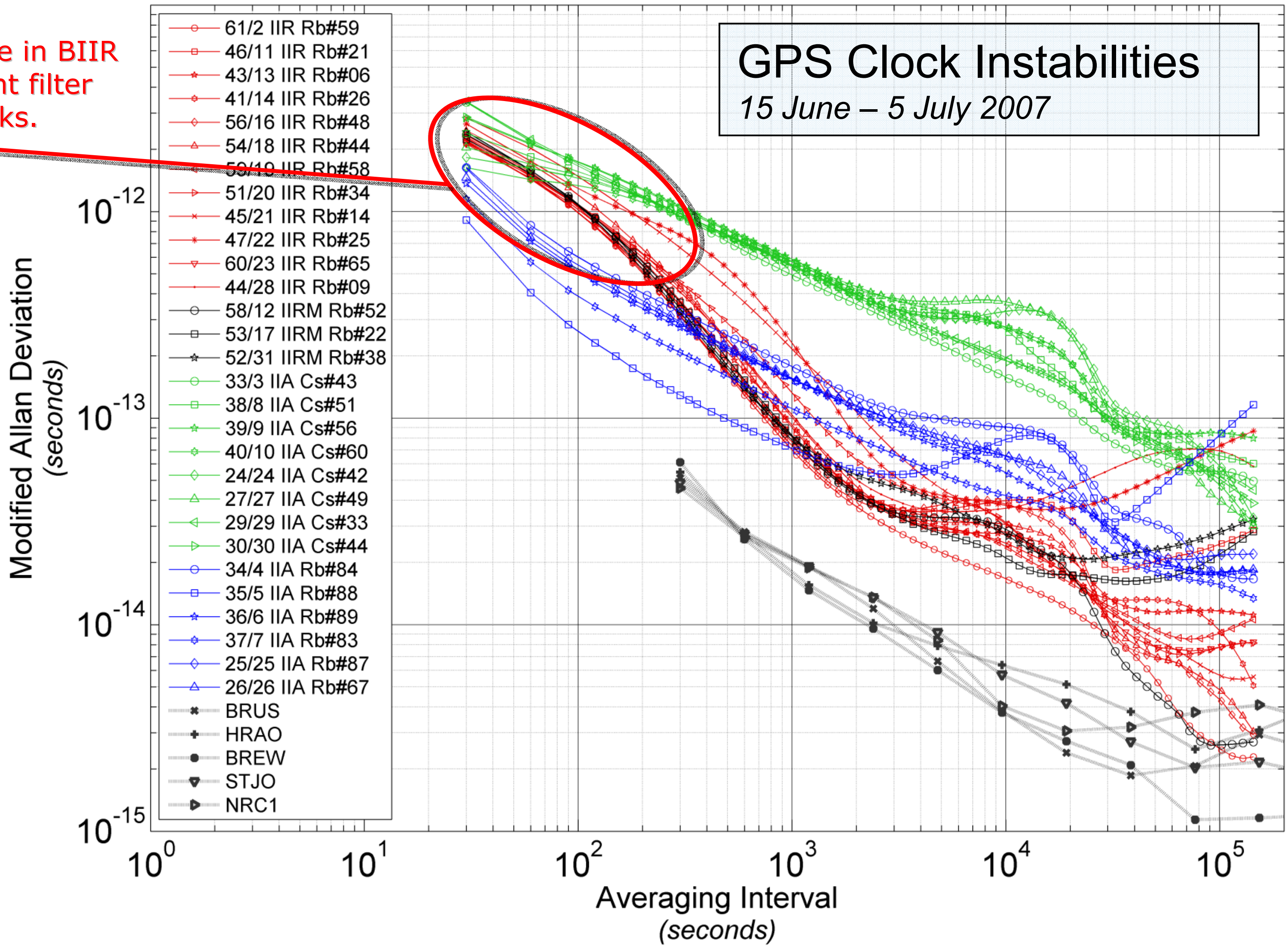
- long term stability not optimal
- could track UTC better
- Cesiums largely ignored
- GPS clocks under-utilized

Harmonics in GPS Satellite Clocks

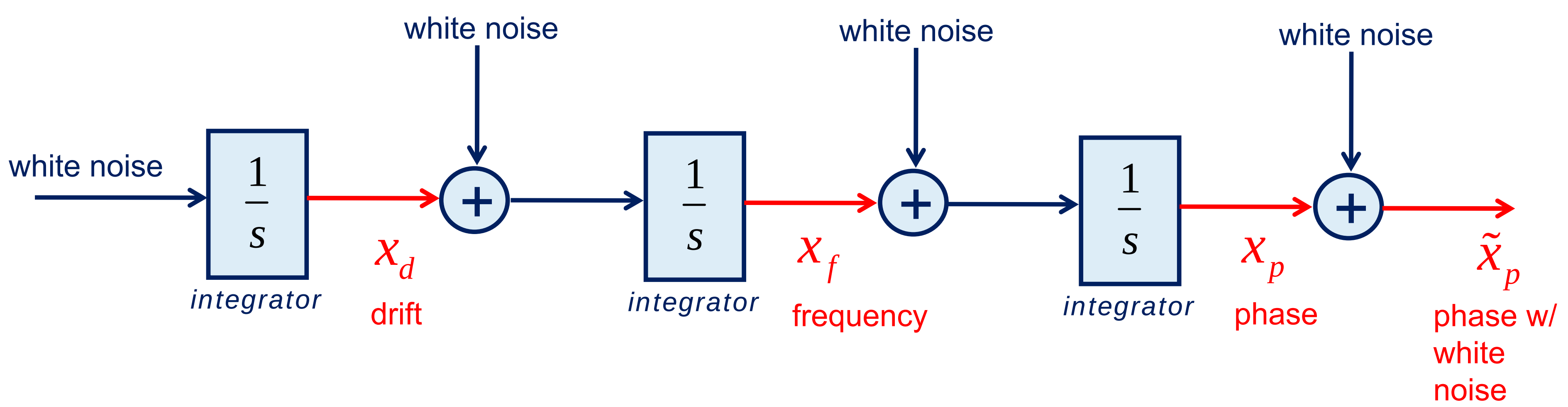


BIIR Rb High-Freq. Noise Problem

High-frequency noise in BIIR Rb results in frequent filter resets for these clocks.



New Clock Model – 8 states per clock



Process noise models:

- WH phase
- RW phase
- RW freq.
- RW drift

$$\mathbf{x} = \begin{bmatrix} \tilde{x}_p & x_p & x_f & x_d & a_{\omega_1} & b_{\omega_1} & a_{\omega_2} & b_{\omega_2} \end{bmatrix}^T$$

additional states to model two harmonics (e.g., 6- & 12-hour)

Timescale Constraints

- Observability problem
  - Only clock (phase) ***differences*** are measured.
  - 4 independent excitations per clock implies 4 new constraints necessary to isolate *individual* clock excitations:

multiple clock weights

$$\sum_{i=1}^{N} a_i \left(\tilde{x}_p^{(i)}(t+\delta \mid t) - \tilde{x}_p^{(i)}(t+\delta) \right) = 0$$

$$\sum_{i=1}^{N} b_i \left(x_p^{(i)}(t+\delta \mid t) - x_p^{(i)}(t+\delta) \right) = 0$$

$$\sum_{i=1}^{N} c_i \left(x_f^{(i)}(t+\delta \mid t) - x_f^{(i)}(t+\delta) \right) = 0$$

$$\sum_{i=1}^{N} d_i \left(x_d^{(i)}(t+\delta \mid t) - x_d^{(i)}(t+\delta) \right) = 0$$

These constraints solve the observability problem: the weighted sum of the phase, frequency, & drift excitations are zero.

Multiple Weighting

- New multiple weighting per clock allows a timescale which is optimized over a wide range of intervals:

  e.g., ~ 1 day,

  ~ 10 days, &

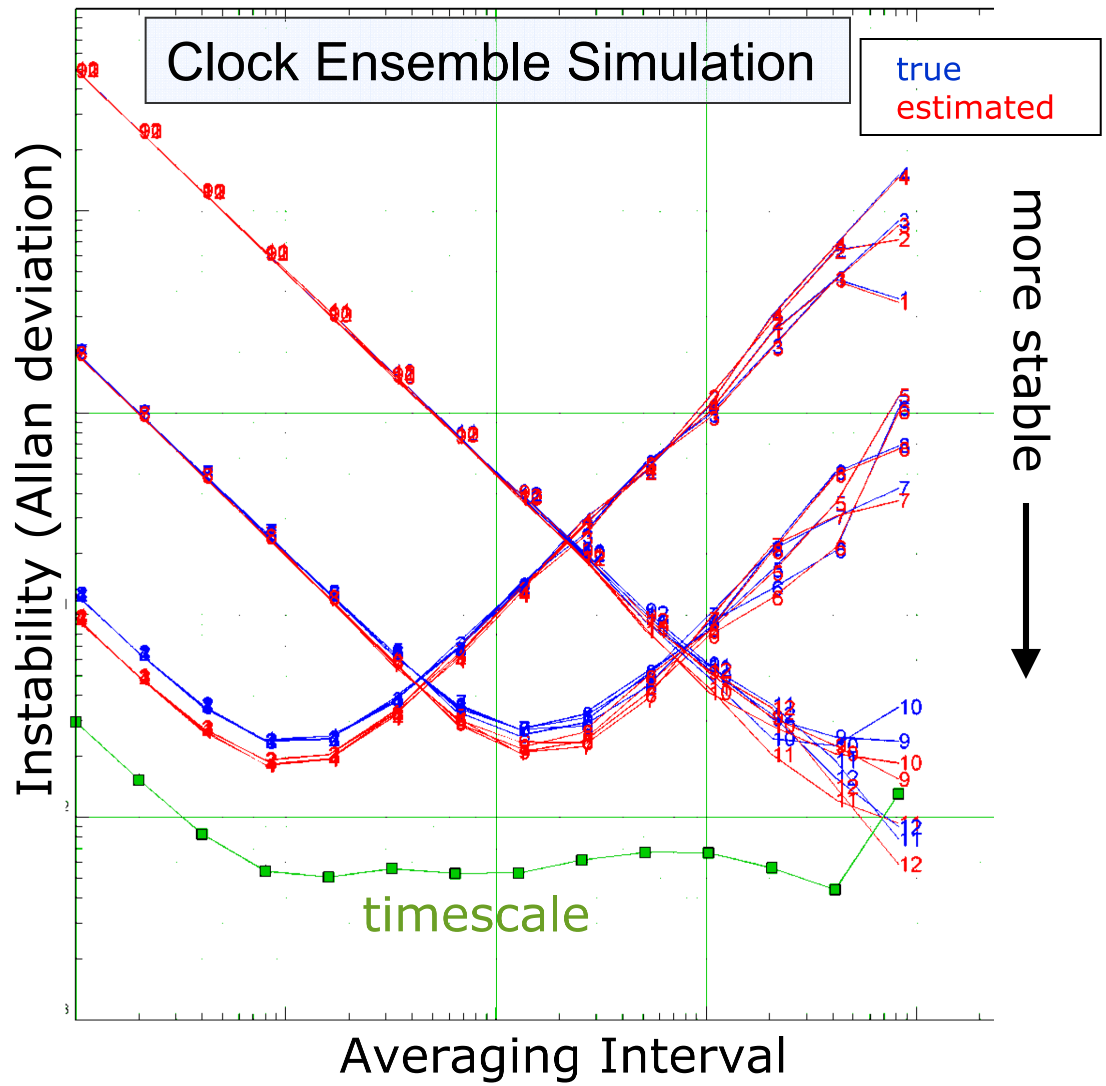
  ~ months)

a_i ~ inverse WH ph level for clock i

b_i ~ inverse RW ph level for clock i

c_i ~ inverse RW fr level for clock i

d_i ~ inverse RW dr level for clock i



Filter Bank – adaptive parameter estimation

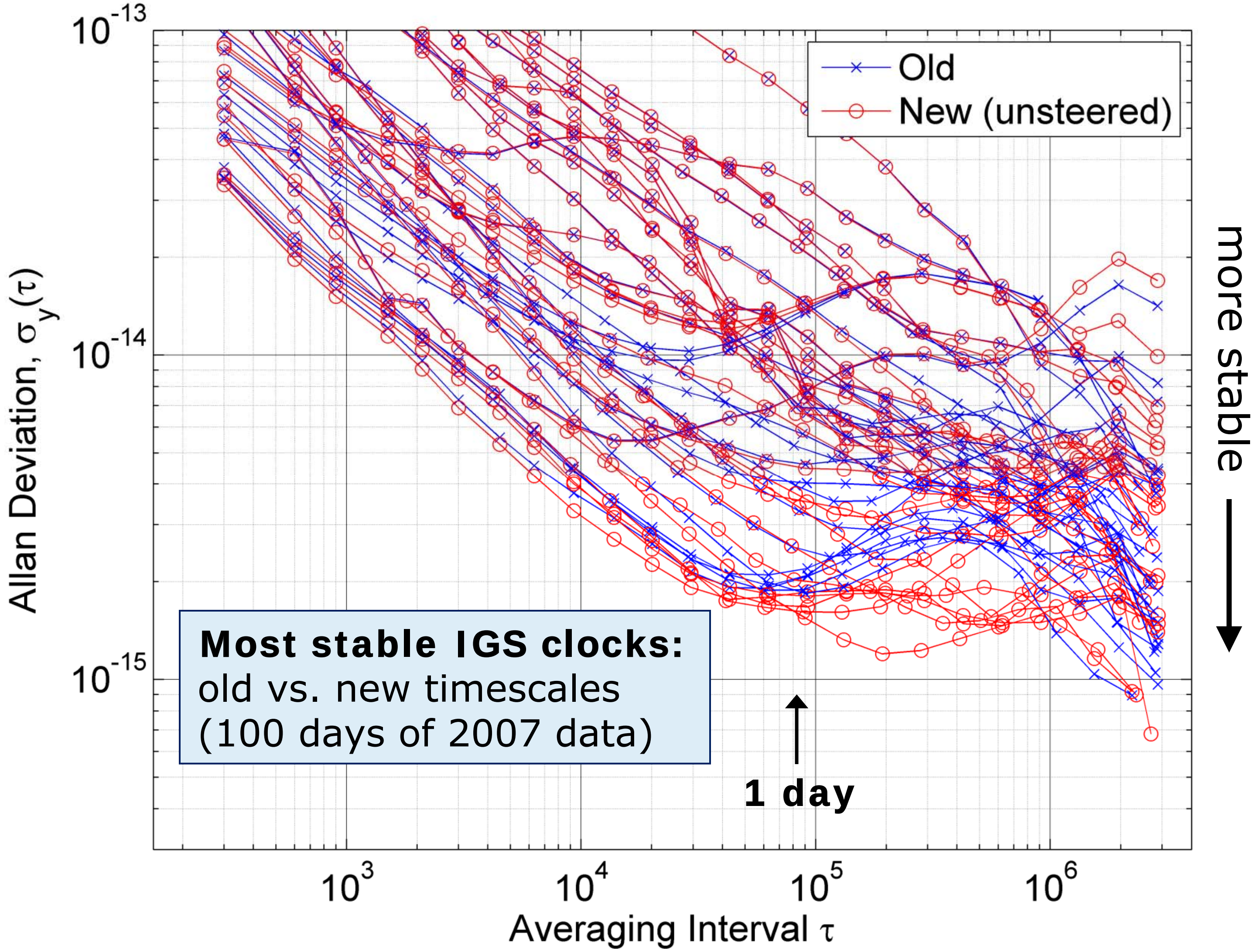
- Several filters run at nominally different intervals
  - 5-min, 1-hr, 3-hr, 1-day, 4-days, 16-days *(Stein, 94)*
  - each has a sensitivity to an individual type of excitation (RW phase, RW frequency, or RW drift excitations)
    - ***adaptive estimation*** of level of excitation for each type

> Each filter's individual clock innovation sequence will be dominated by a single noise type, depending on that filter's nominal interval

  - each has increasing sensitivity to small freq. breaks
    - short-interval filters detect large phase, freq. breaks
    - longer-interval filters detect smaller freq. breaks

New Timescale Results

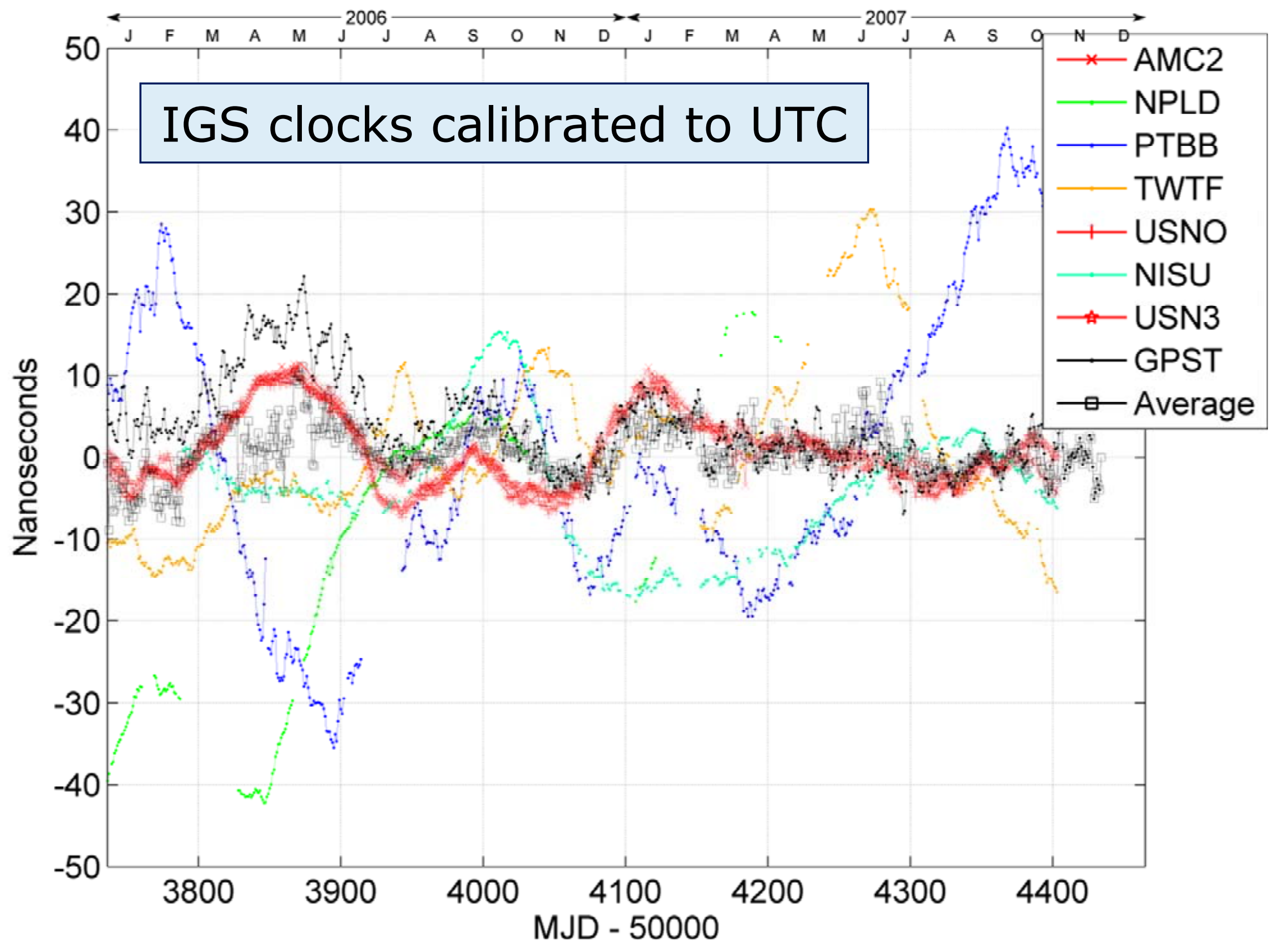
New version shows improved stability from 1 day to ~10 days.



Most stable IGS clocks:
old vs. new timescales
(100 days of 2007 data)

Tie to UTC

- Current version relies on GPS Time as sole reference to UTC
- Stations colocated at timing labs can provide a more robust link to UTC
- The average of these 8 calibrated (UTC) clocks reaches a stability of 1e-15 only after 70 days
- This implies that the new steering time-constant should probably be longer than 30 days



New Timescale Considerations

- Continued testing phase
  - Must complete several years of processing ~FY08
- Move to operational use ~FY09
- Plan to use new timescale in IGS reprocessing
  - *if enough clock ACs participate*

A Kalman Filter to Combine VLBI UT1 & GPS LOD Estimates

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UT1/LOD Context & Objectives

- Cannot easily assimilate full UT1 & LOD information in ITRF time series combination with station coordinates & other EOPs
  - UT1/LOD from 24-hr multi-baseline VLBI included OK
  - UT1 from 1-hr single-baseline VLBI ***not*** included
    - not available in SINEX format
    - can distort station positions due to limited observing geometry
  - LOD from satellite techniques also ***not*** included
    - time-varying biases are significant & not easily modeled
    - frame-related errors are not significant compared to orbit-related biases

- Previously proposed a multi-step ITRF & EOP combination process
  - ITRF2005-type TRF + EOP combination
  - Reduce 1-hr single-baseline VLBI sessions consistent with ITRF2005 for denser UT1 time series
  - Merge UT1 time series from ITRF & 1-hr VLBI steps
  - Assimilate GPS LOD into VLBI UT1 time series using Kalman filter

- Question: Can a Kalman filter provide a useful combination of VLBI UT1 and satellite LOD quasi-optimally?

Kalman Filter Combination Model

- UT1 is the (negative) integral of LOD + random walk
  - excitation variance using modern data found to agree with *Morabito et al. (1988)* value

$$-\frac{d^2}{dt^2}UT1R = \frac{1}{86400}\frac{d}{dt}LODR = w_L \qquad \sigma^2_{w_L} = 3600\ \mu s^2/\mathrm{day}^3$$

- Gauss-Markov process used to model GPS LOD biases
  - time-constant $= 1/\beta = 2.17$ days

$$\frac{d}{dt}B_M = -\beta B_M + w_M \qquad \sigma^2_{w_M} = 56.4\beta\ \mu s^2/\mathrm{day}^3$$

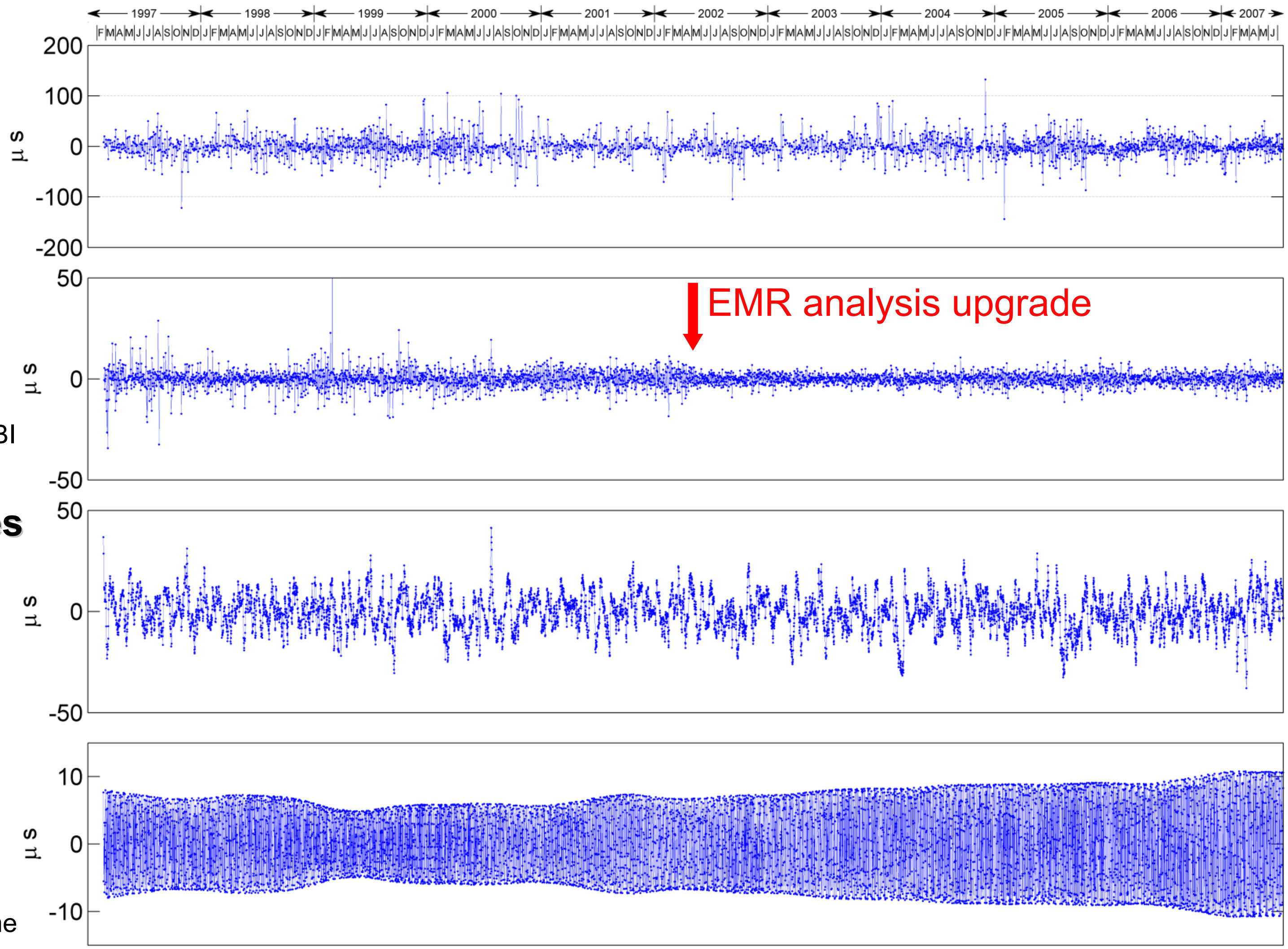
- Harmonic with period 14.19 d added to capture effect of mismodeled tides in GPS LOD biases *(Kouba, 2003)*

Input Data Sets

- UT1 from 24-hr multi-baseline VLBI sessions
  - series "2007c" from NASA/GSFC
  - from 21 Feb 1997 to 17 Jul 2007
  - at irregular epochs, about 2 to 3 per week
  - formal errors scaled by 2
- UT1 from 1-hr single-baseline VLBI sessions
  - series "int21" from NASA/GSFC
  - from 21 Feb 1997 to 18 Jul 2007
  - formal errors scaled by 2
  - at irregular epochs, about 5 per week
  - consistent with 24-hr sessions: mean differences = -0.7 ± 22.5 μs with N = 1244 & χ^2/dof = 2.58
- daily LOD from IGS combination
  - series "igs00p03.erp"
  - noon epochs from 23 Feb 1997 to 18 Jul 2007
  - formal errors scaled by 2
  - some bias corrections applied already by IGS using IERS Bulletin A
- corrections for zonal tides applied to all series before combination
- VLBI UT1 accuracy could be improved by adding GPS polar motion & global network in raw reduction *(Ray et al., 2005)* – not studied here

Some Characteristics of Kalman Filter Output

- **VLBI (1-hr) UT1 residuals**
  - white over full freq. 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



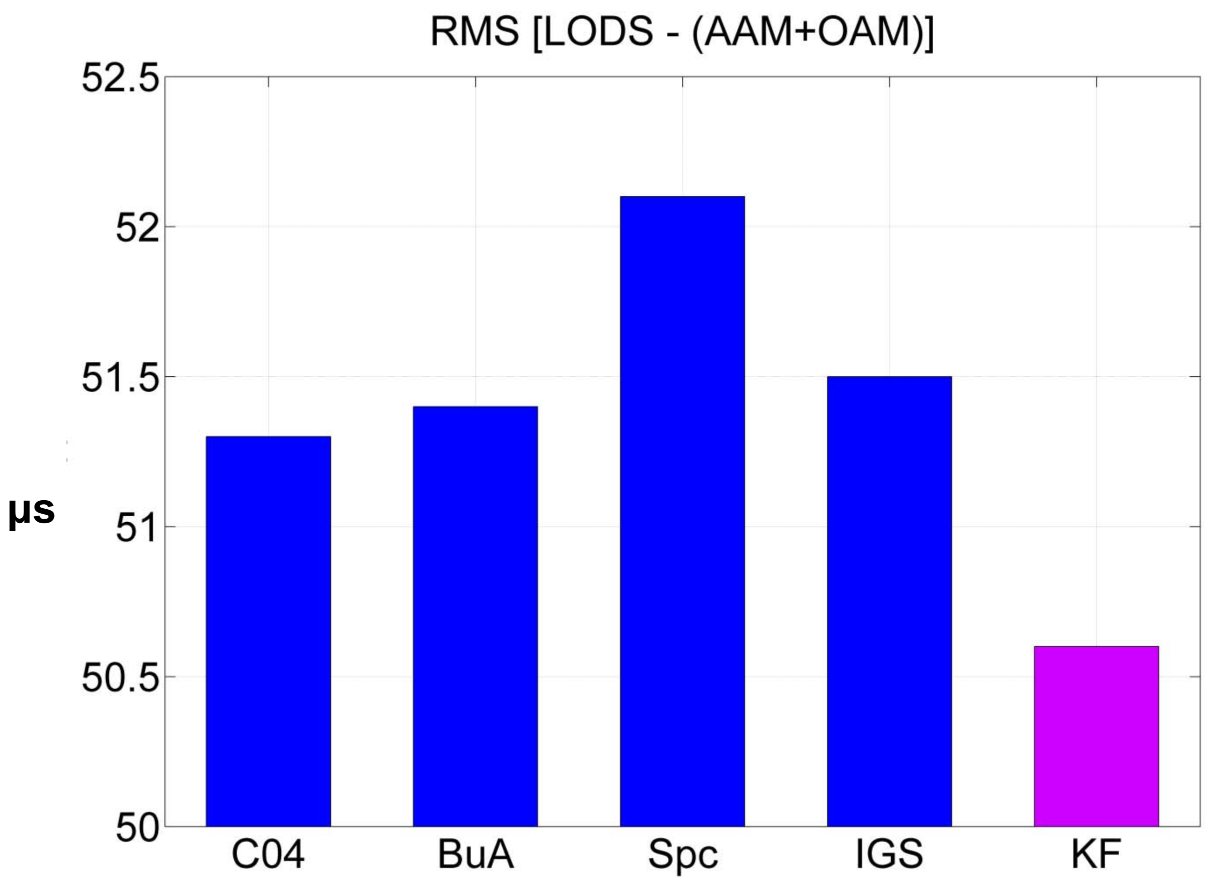
Compare w/ AAM+OAM Excitation

- our KF w/ other LOD combinations
  - corrected for zonal tides, LODS *(Yoder et al., 1981; Kantha et al., 1998)*
- Atmospheric Angular Momentum (AAM) from NCEP Reanalysis
  - 4 values daily, during Feb 1997 – Mar 2006
  - inverted barometer correction applied
  - averaged to daily values at 00:00 or 12:00 epochs to match respective LOD series epochs
- Oceanic Angular Momentum (OAM) from ECCO model *(Gross et al., '05)*
  - 4 values daily, during Feb 1997 – Mar 2006
  - averaged to daily values at 00:00 or 12:00 epochs to match respective LOD series epochs
- for each [LODS – (AAM+OAM)] time series, fit for imperfectly known geophysical & systematic effects *(Kouba & Vondrak, 2005)*
  - annual + semi-annual differences
  - monthly (27.56 d) oceanic tide correction
  - fortnightly (13.63/13.66 d) oceanic tide corrections
  - k/C core-mantle coupling constant
  - long-term drift differences
  - AAM transfer function scale factor
- compute residuals & compare
- compute LODS/[AAM+OAM] cross-correlations & compare

[LODS – (AAM+OAM)] RMS Residuals

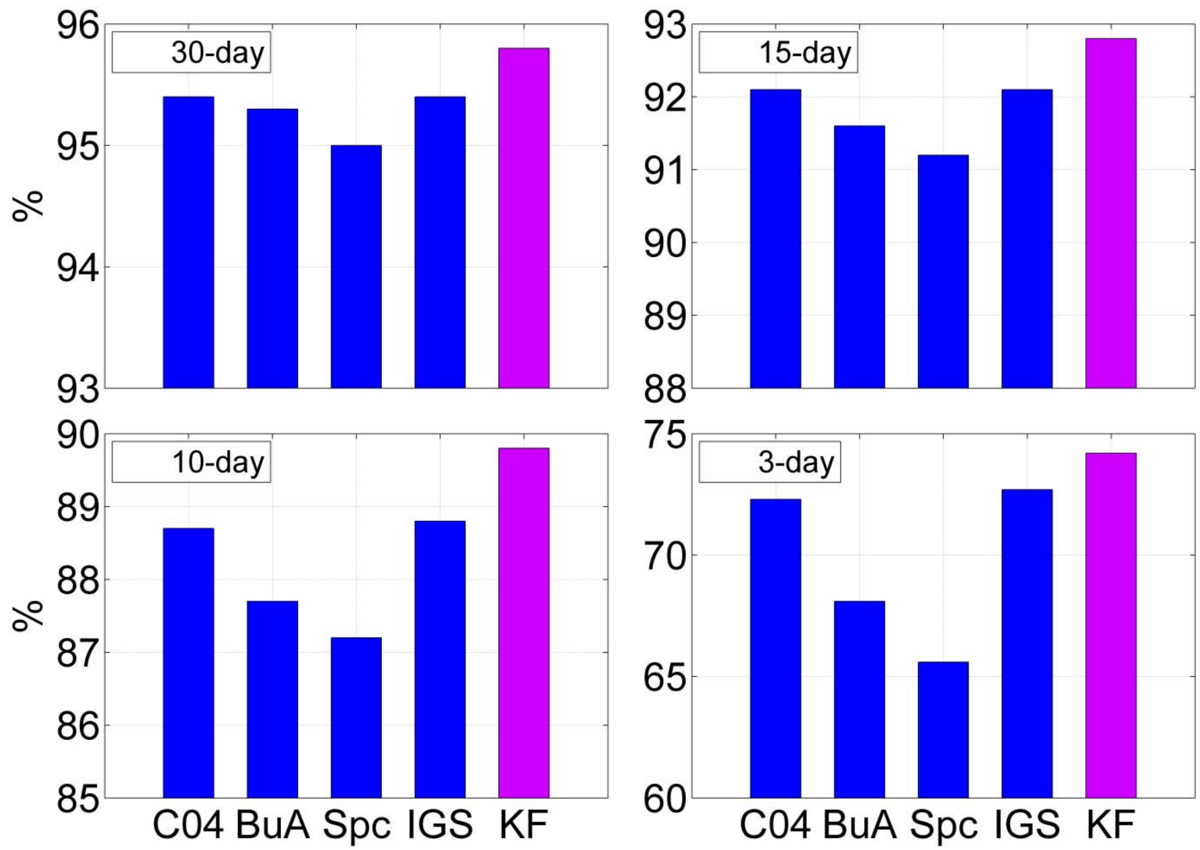
- LOD time series studied
  - IERS 05C04 (00:00)
  - IERS Bulletin A (00:00)
  - JPL's SPACE 2006 (12:00)
  - IGS (no UT1) (12:00)
  - our KF (12:00)

- our KF has smallest residual



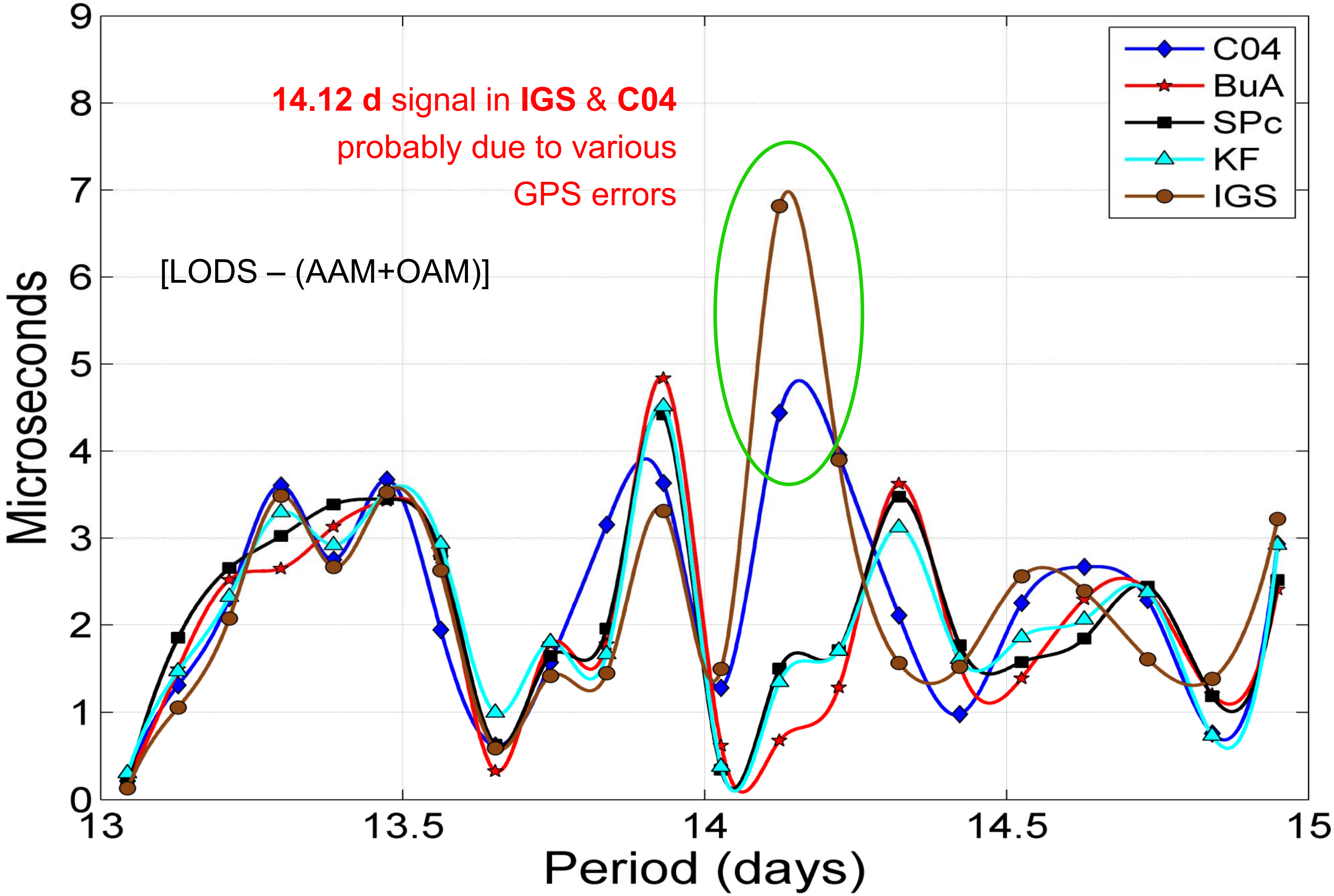
LODS/(AAM+OAM) Correlation Coeff.

- computed over sliding windows from 3 d to 5.6 yr
  - correlation over full range = 99.0% for BuA, C04, SPc, & IGS and 99.1% for KF

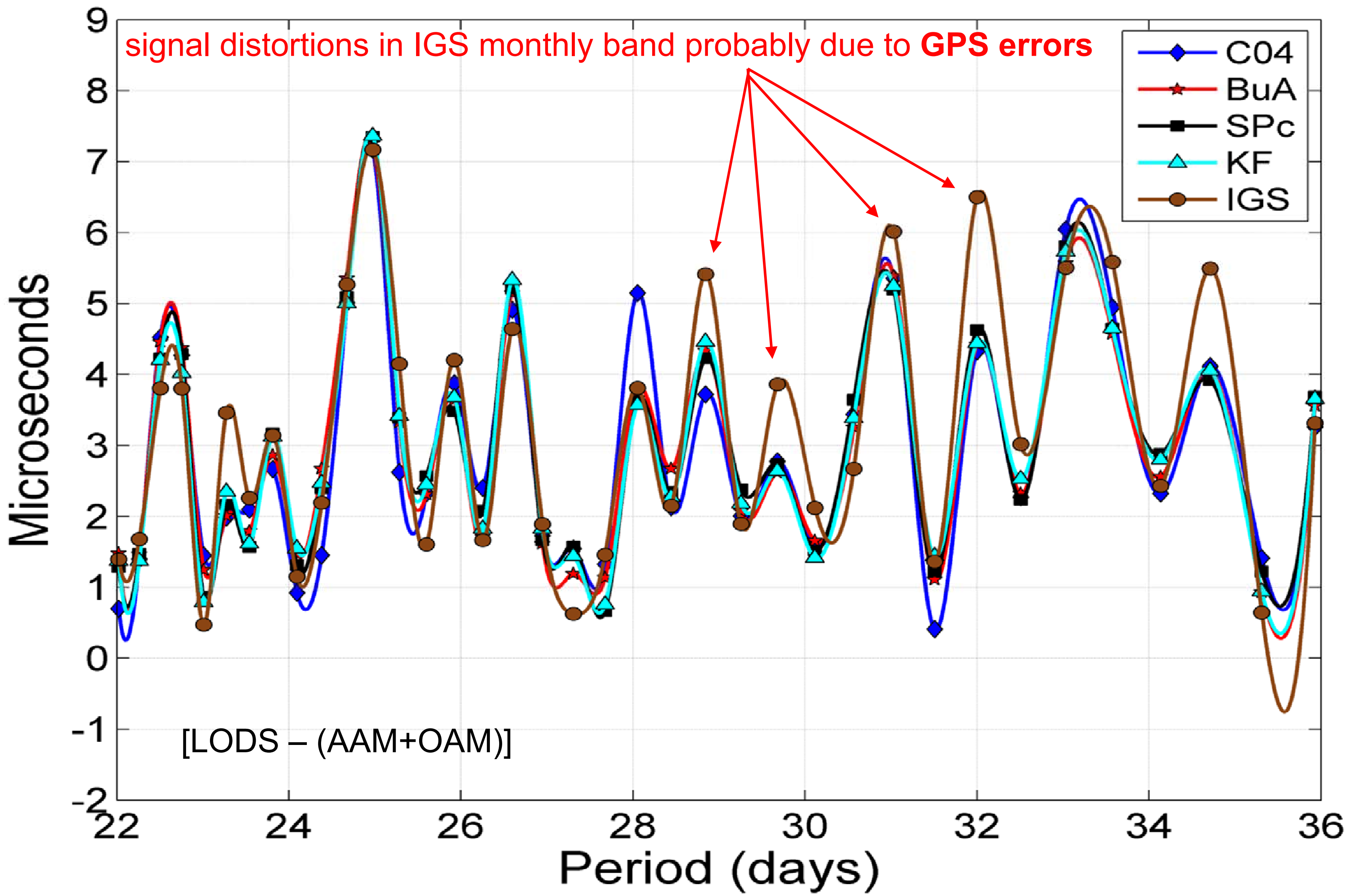


- KF has highest correlations w/ AAM+OAM over all intervals; SPACE 2006 has lowest

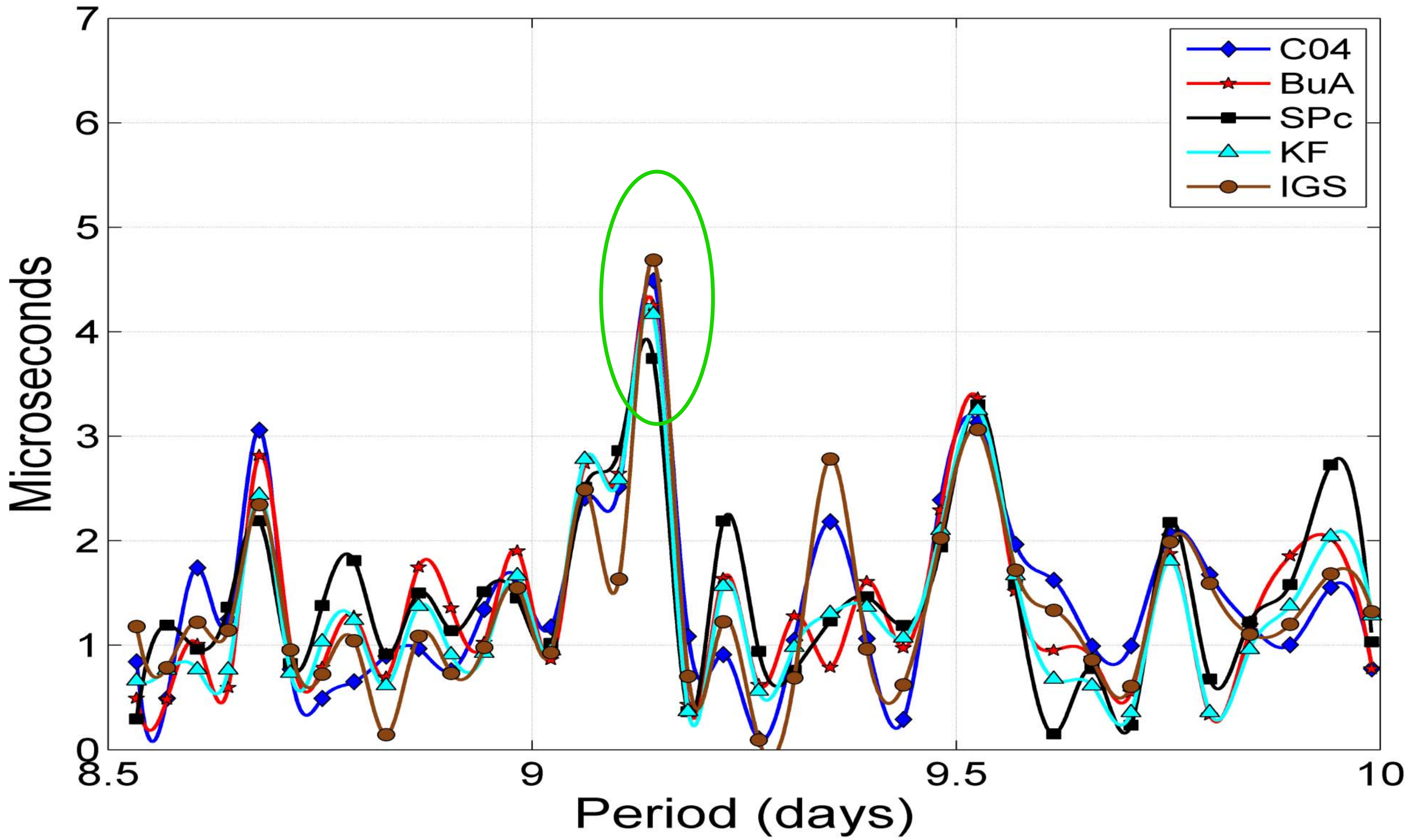
Fortnightly Band – Spurious IGS LOD Peak



Monthly Band – Probably GPS Errors



9-d Band – Unmodeled Geophysical Effect?

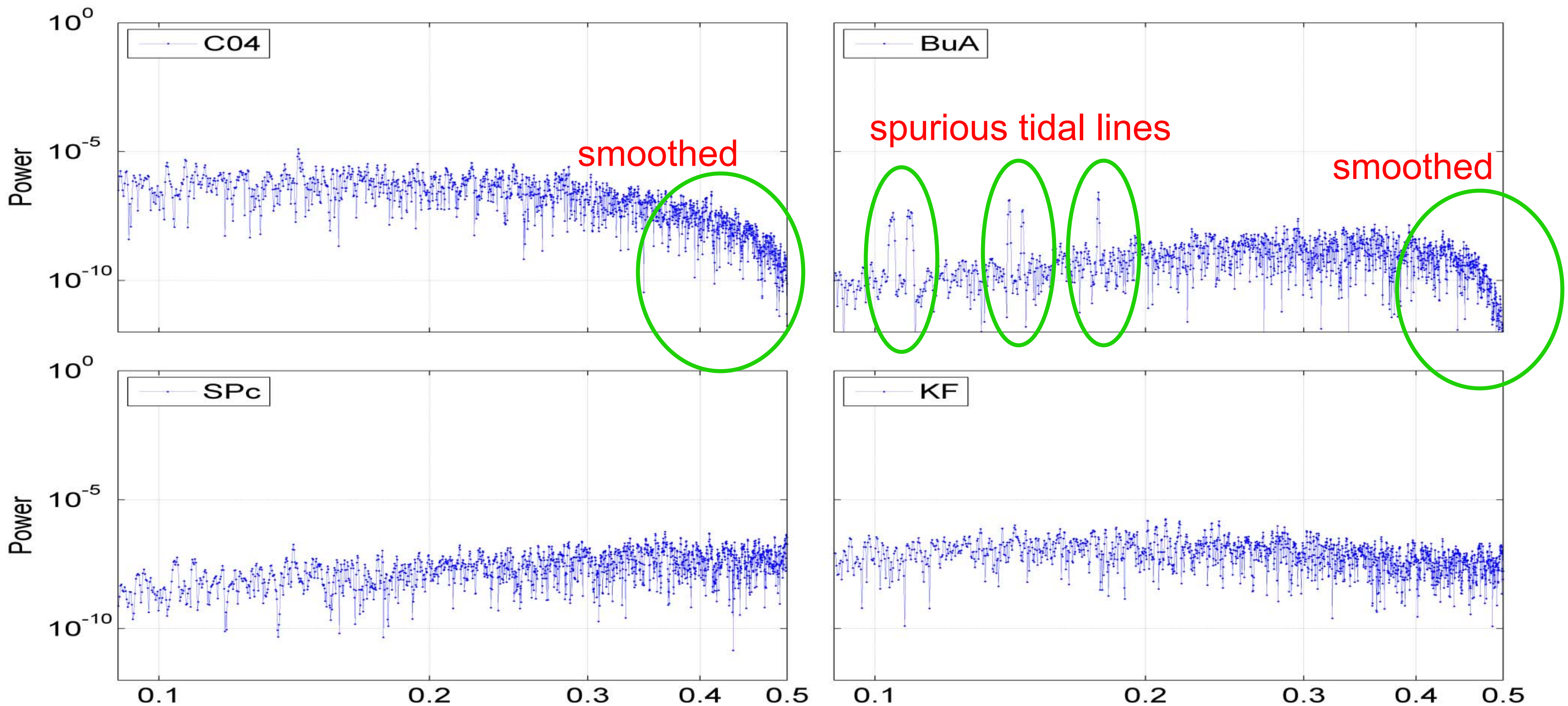


- 9.14 d peak seen in all LODS series – probably geophysical
- needs further investigation – could be included in [LODS-(AAM+OAM)] fit

Consistency of UT1/LOD Series

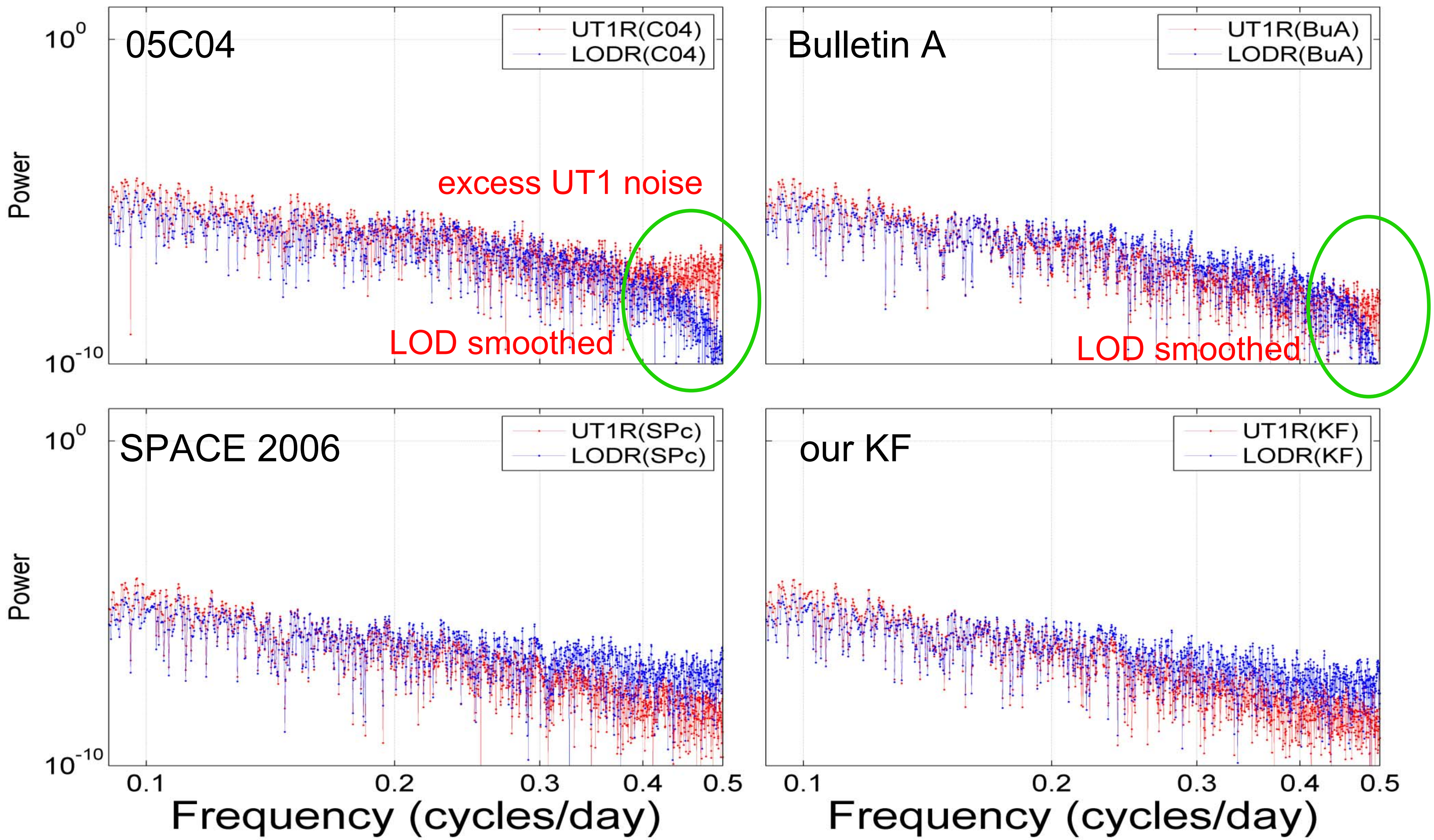
- comparisons w/ AAM excitation only test LOD correlation
- to verify UT1 consistency, compare –dUT1 & LOD values:
  - **05C04**: RMS = **21.2 μs** (**HIGH**)
  - **Bull A**: RMS = **1.9 μs** (**LOW**)
  - **SPC**: RMS = **6.7 μs**
  - **KF**: RMS = **10.5 μs**

expected difference due to –dUT1 interpolation = ~10 μs



UT1 & LOD Power Spectra

- seasonally detrended



UT1/LOD Conclusions

- our KF UT1/LOD combination performs best by all measures
  - further improvements possible, e.g., if VLBI UT1 analyses use IGS polar motion

- IGS LOD series adds critical high-frequency information
  - but care needed to handle correlated biases & spurious signals

- IERS 05C04 LODs correlate well with [AAM+OAM] – based on IGS LODs
  - LODs enjoy benefits & liabilities of IGS LODs; but should filter out spurious signals
  - however, UT1 & LOD values are not consistent
  - strong high-frequency smoothing for LODs; excess noise for UT1

- IERS Bulletin A LODs derived from UT1 values with strong tidal signals
  - LODs have excess high-frequency noise indicated by lower AAM correlations
  - sharp high-frequency smoothing for LODs due to derivation from UT1 values

- SPACE 2006 correlates worst with [AAM+OAM] over all intervals due to excess noise
  - badly hurt by not using GPS LODs

Discussion

- Any discussion of new timescale?
  - (Possible) Recommendation: Utilize new timescale algorithm to provide reference timescale for reprocessing, provided enough clock ACs contribute.

- Is a new IGS UT1/LOD series needed?
  - (Possible) Recommendation: Provide a new IGS UT1/LOD combination series (e.g., for scientific applications)