Clock Modeling & Algorithms for Timescale Formation

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Outline:

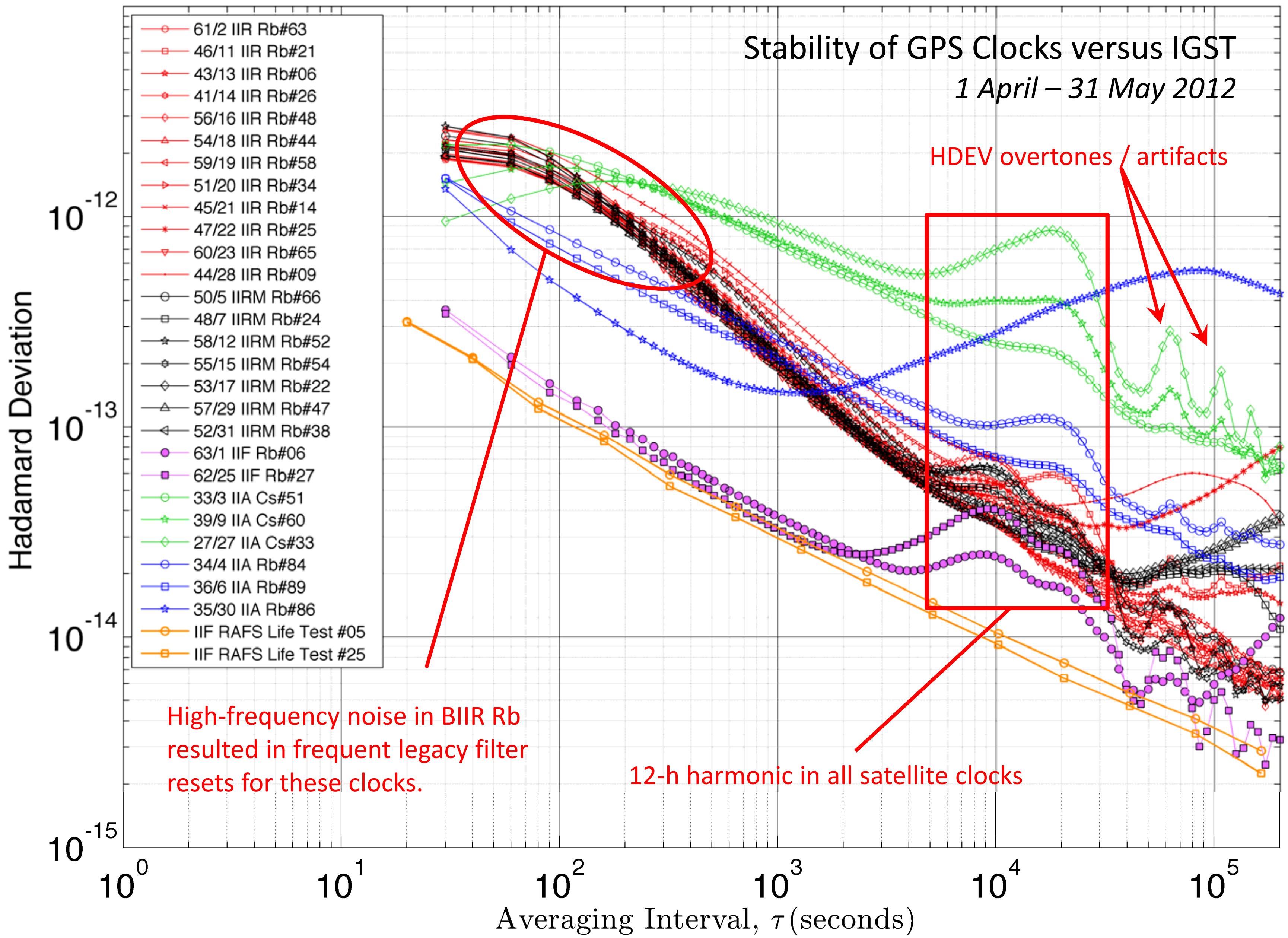
- **Motivation / history**
- **Timescale clock model**
- **Algorithm considerations**
- **Current Status / Results**

Motivation

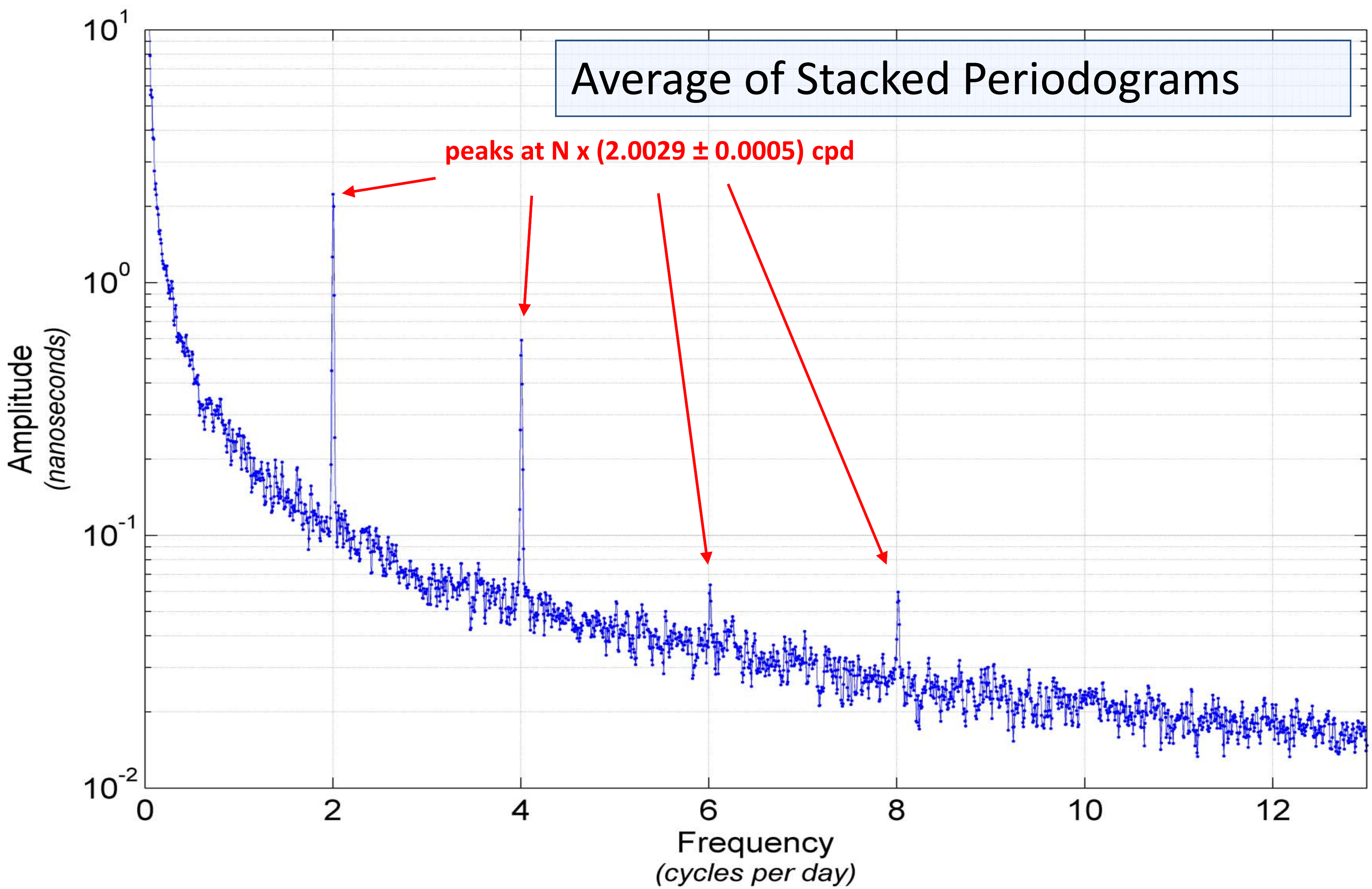
***GOAL**: Provide stable & robust reference timescales for IGS clock products (Rapid/Final) to enable improved station/satellite clock monitoring & access to the UTC timescale; timescale re-alignment should not affect use of IGS products in PPP.*

- IGS v1.0 (legacy) timescale algorithm
  - Rapid (IGRT) & Final (IGST) products aligned via v1.0 in 2003
  - 1 d instability < 1E-15
  - provides global autonomous GPS PPP access to UTC < 50 ns
  - stability suffers > 1d partly because of UTC alignment strategy (steering to UTC via GPS Time)
- IGS v2.0 (new) timescale algorithm
  - Rapid & Final products aligned via v2.0 beginning Spring 2011
  - developed to improve longer term stability
  - *improved clock modeling (e.g., to utilize better GPS clocks)*
  - *improved tie to UTC*
  - *improved clock ensemble weighting*

Motivation (*continued*). - GPS Clock Frequency Instabilities

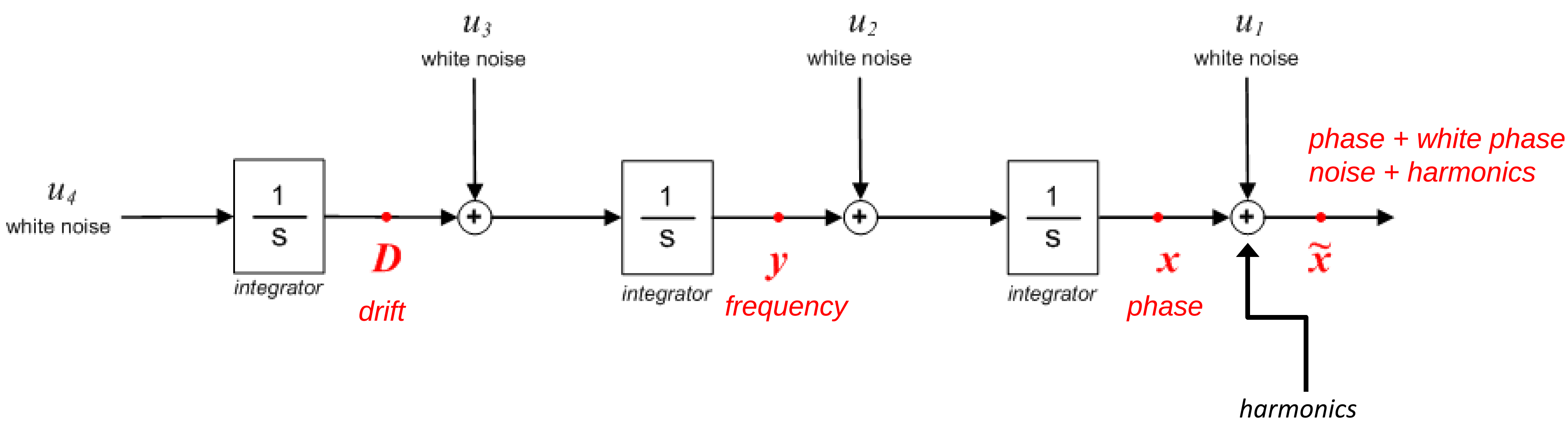


Harmonics in GPS Satellite Clocks



IGS v2.0 Clock Model

Basic 4 state model for all clocks:



Base model: a deterministic phase, derivative of phase (frequency), and second derivative of phase (drift) each with an independent random walk component; an additional phase state is included to model a pure white phase noise and to couple to any harmonic states

$$\mathbf{x} = [\tilde{x} \quad x \quad y \quad D \quad a_{\omega_1} \quad b_{\omega_1} \quad a_{\omega_2} \quad b_{\omega_2}]^T$$

plus additional optional (per clock) states to model up to two harmonics (e.g., 12- & 6-hour)

Timescale Constraints

Observability problem

- Only clock (phase) ***differences*** are measured
- 4 independent random excitations per clock require 4 constraints to prevent unbounded covariance growth

(3 are sufficient since white phase noise cannot be distinguished from phase measurement noise)

Multiple Weights per Clock

Weights a, b, c, and d, are specified as the inverse of the levels of WHPH, RWPH, RWFR, & RWDR, respectively

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

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

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

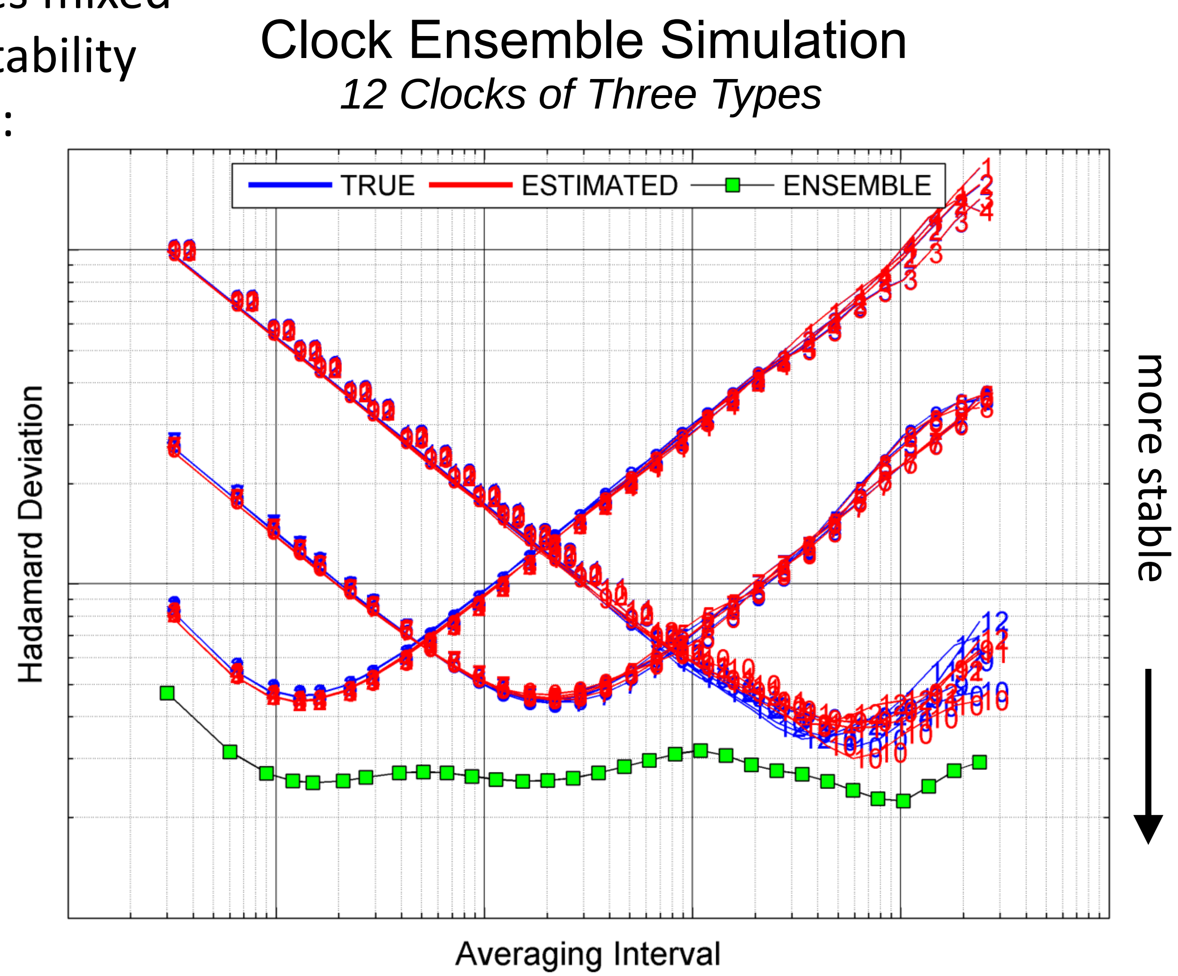
$$\sum_{i=1}^{N} d^{(i)} \left(x_D^{(i)}(t+\delta \,|\, t) - x_D^{(i)}(t+\delta) \right) = 0$$

These additional constraints address the observability problem

Clock Multi-Weighting

Multiple weights per clock admits a timescale that optimally utilizes mixed clock types and can improve stability over a wider 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*

IGS v2.0 Timescale – *General Characteristics*

- Fully automated
- U-D Kalman filter implementation
- Up to 8 (at least 4) states estimated per clock
- Timescale constraints
- Adaptive clock parameter estimation
- LQG steering algorithm for external UTC alignment
  - "gentle" acceleration applied to ensemble to align to UTC
  - v2.0 utilizes weighted ensemble of UTC(*k*) realizations in addition to GPS Time as steering references

IGS v2.0 algorithm now being used as the basis for development of the next generation GPS system time, GPS Time

Practical Considerations

- New clocks are added to filter using a quadratic fit to data and corresponding covariance adjustment
  - Prevents transitioning covariance from near-infinite values to relatively small ones
  - New clocks initially carry all zero weights (estimate only)
  - Nominal weighting engaged automatically when states are well-determined or held zero whenever bad behavior is detected
- Ensemble timescale not affected by clocks entering/leaving filter
  - Clocks may enter/leave at any epoch (e.g., new clocks, missing data, etc.) with minimal impact to timescale
- Upper limit of weights imposed
  - Upper limit chosen is $2.5/N$
  - Prevents single clocks from ultimately taking over the ensemble

Practical Considerations – *(cont.)*

- Per-epoch (pivot) reference clock
  - The reference clock of the measurements cannot be down-weighted in the filter
  - Therefore, a well-behaved choice of a pivot reference is made at every epoch using a robust selection procedure (*median of data-predictions*)
  - Re-reference all data to new pivot clock
  - All other clocks may then be analyzed for down-weighting
- Measurement Down-weighting
  - Clock difference measurement innovations [data – prediction] are analyzed for bad data or ill-behaving clocks

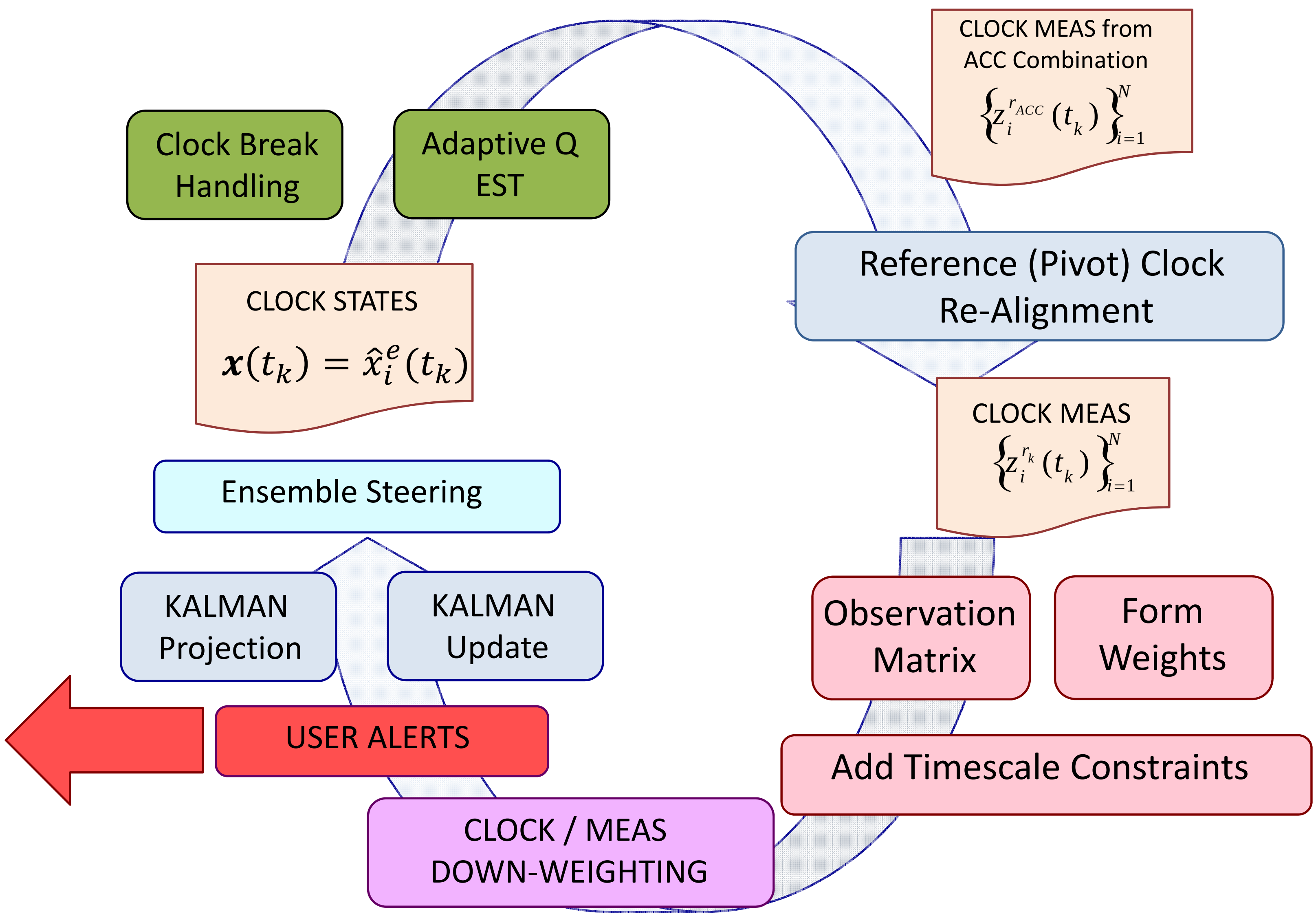
$$\vartheta_i(t_k) \triangleq z_i^r(t_k) - [\tilde{x}_i(t_k|t_{k-1}) - \tilde{x}_r(t_k|t_{k-1})]$$

  - Ill-performing clocks/meas. are gracefully (linearly) down-weighted beginning at 3 σ; at 5 σ the clock/meas. is not used at all
  - Down-weighting trumps all other weighting
  - Promotes timescale stability

Practical Considerations – *(cont.)*

- Repeated failures of the innovation test results in a hierarchy of filter responses
  - outlier rejection *(response immediate)*
  - phase break detection/handling *(response immediate)*
  - frequency break detection/handling *(response day to days)*
  - full clock states reset *(response many days)*
  - clock Qs reset *(last resort; response weeks)*

Timescale Filter Loop

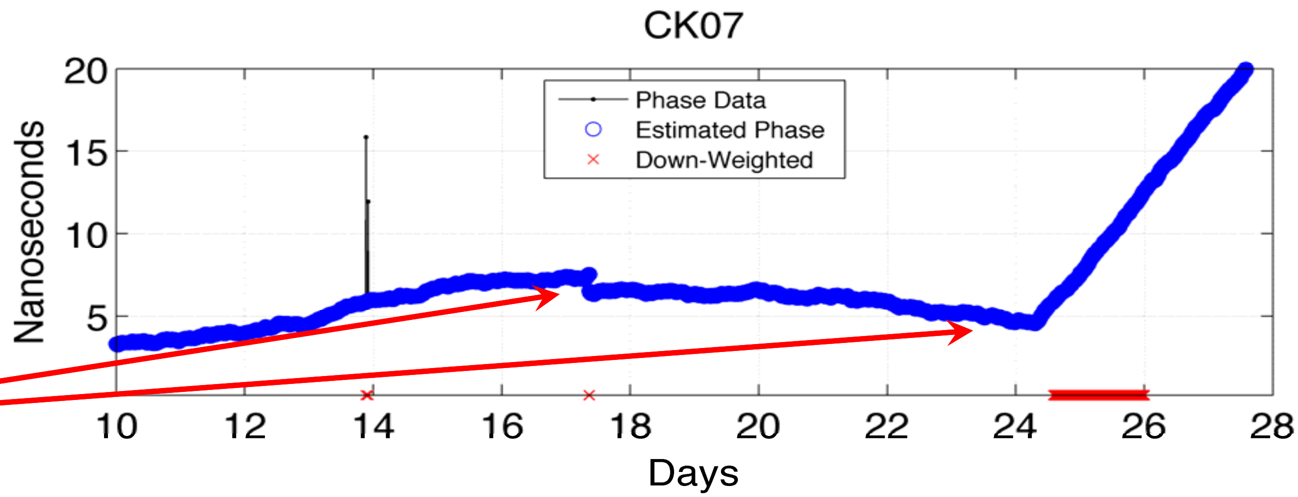


Clock Break Detection - example

10 Clock Simulation

- bad data injected for several clocks
- phase + frequency breaks also imposed

Breaks are automatically repaired

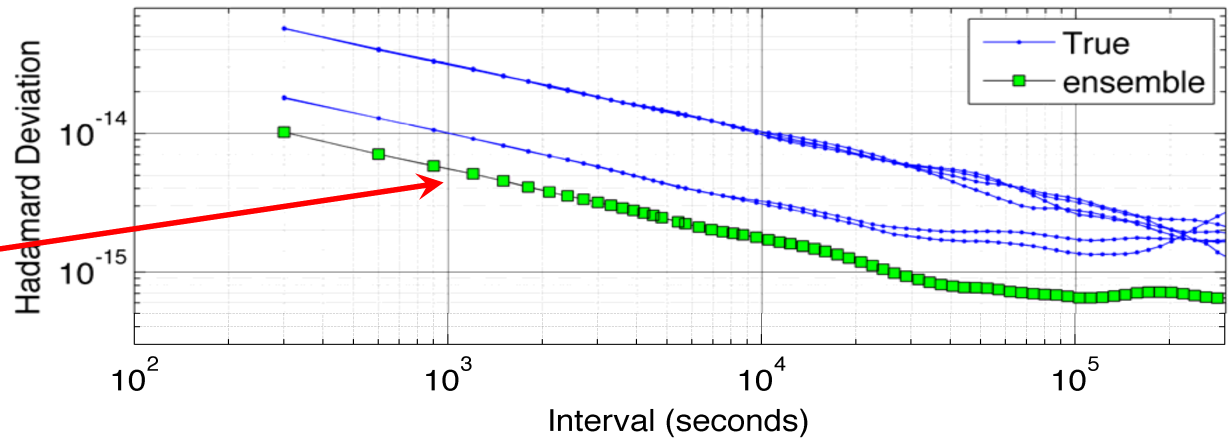


Logging Alerts

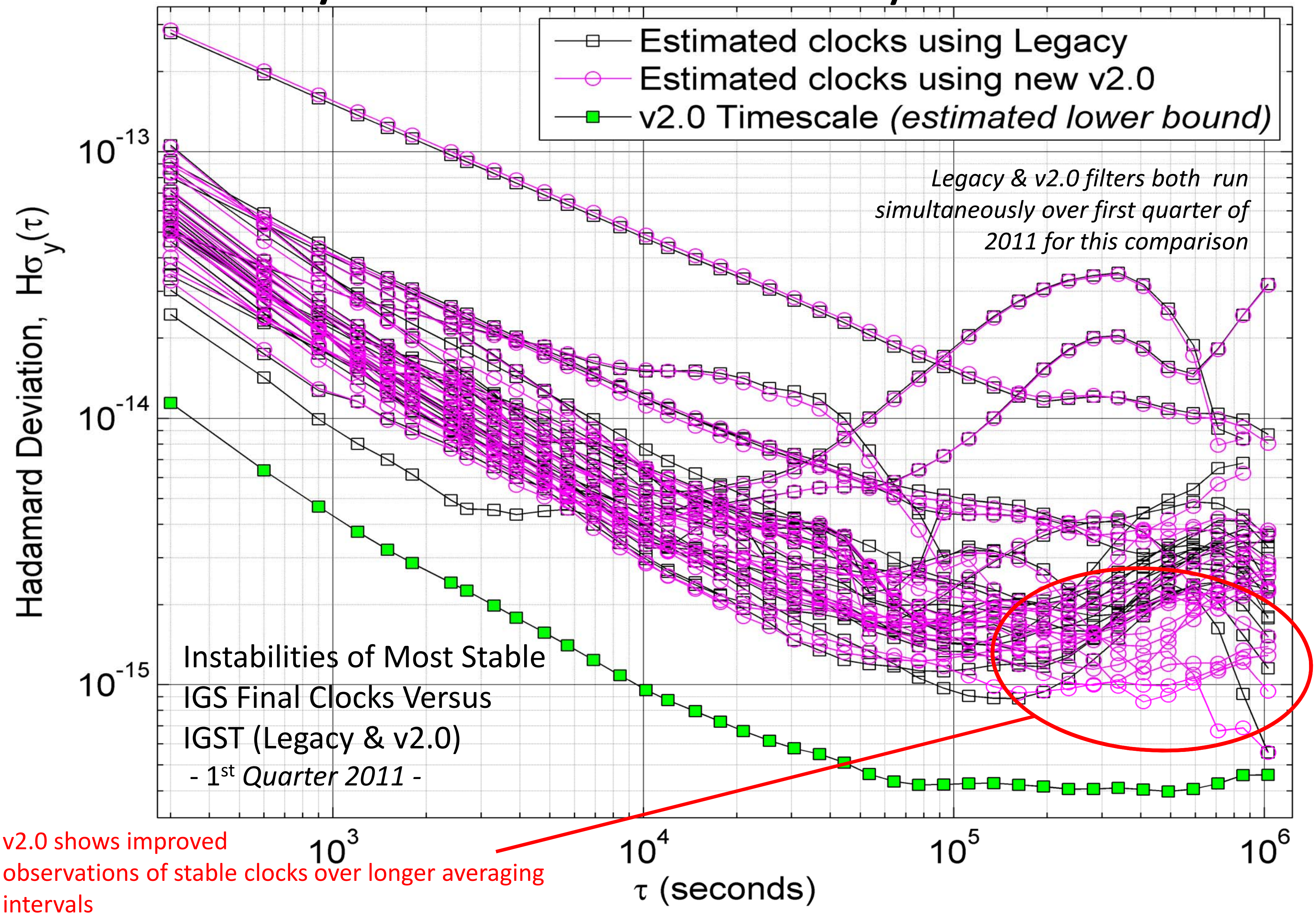
```
(m=1,k=5002,MJD=54117.364583) 17-Jan-2007 08:45:00 ---- Phase break of 1.003 ns removed for clock : CK07

(m=2,k=7081,MJD=54124.583333) 24-Jan-2007 14:00:00 iiii Frequency break detected for clock : CK07
(m=1,k=7081,MJD=54124.583333) 24-Jan-2007 14:00:00 ---- RWFM (150.3097 ns^2/day^3) noise injected for clock: CK07
```

Neither bad data nor phase / frequency breaks unduly affect the ensemble

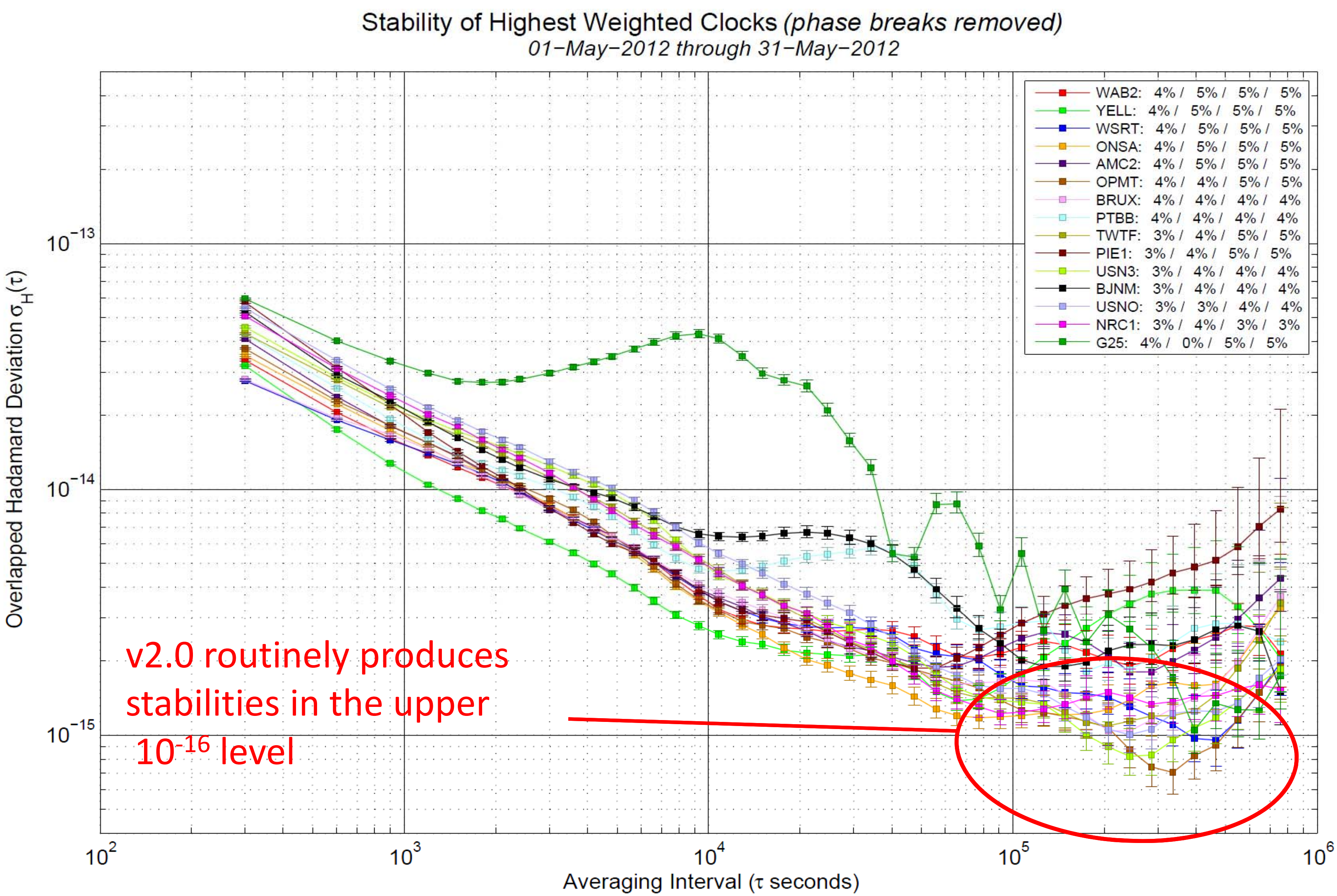


Results 1/5 – Timescale Stability v1.0 vs v2.0



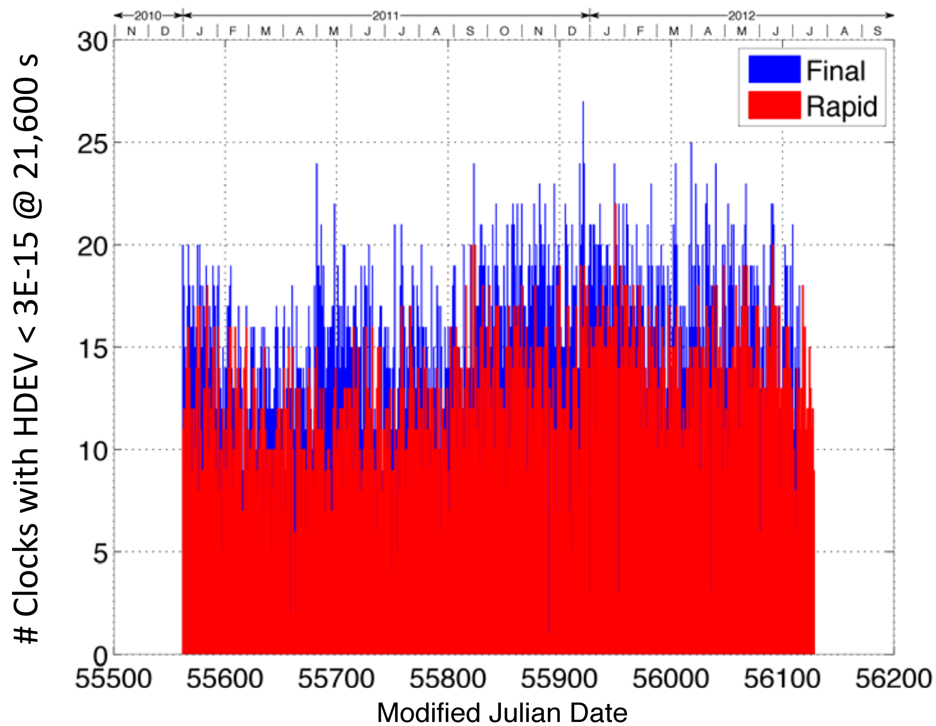
v2.0 shows improved observations of stable clocks over longer averaging intervals

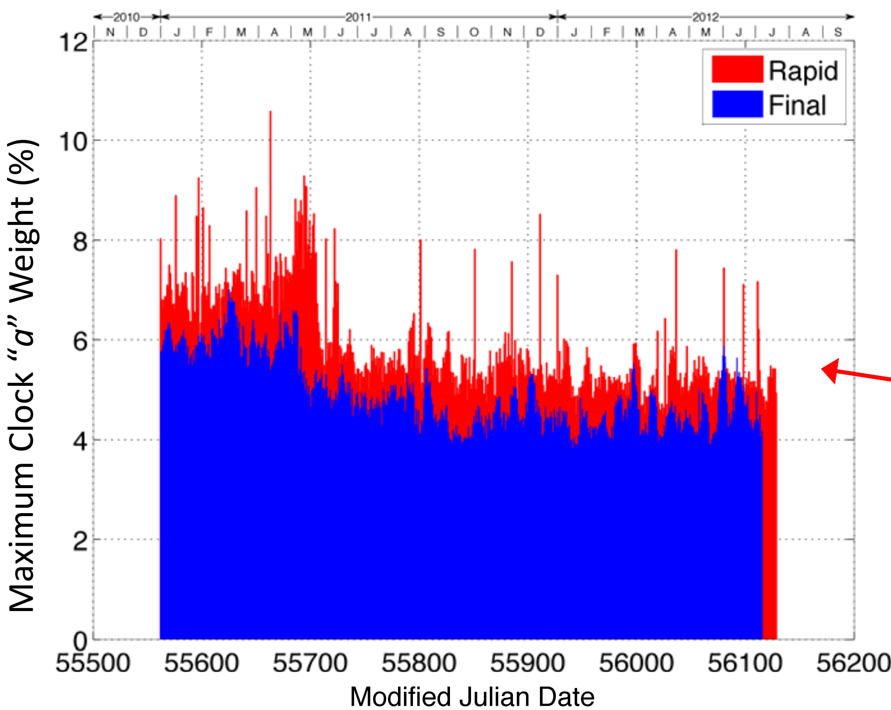
Results 2/5 – Timescale Stability #2



Results 3/5 – Stability Consistency over Time

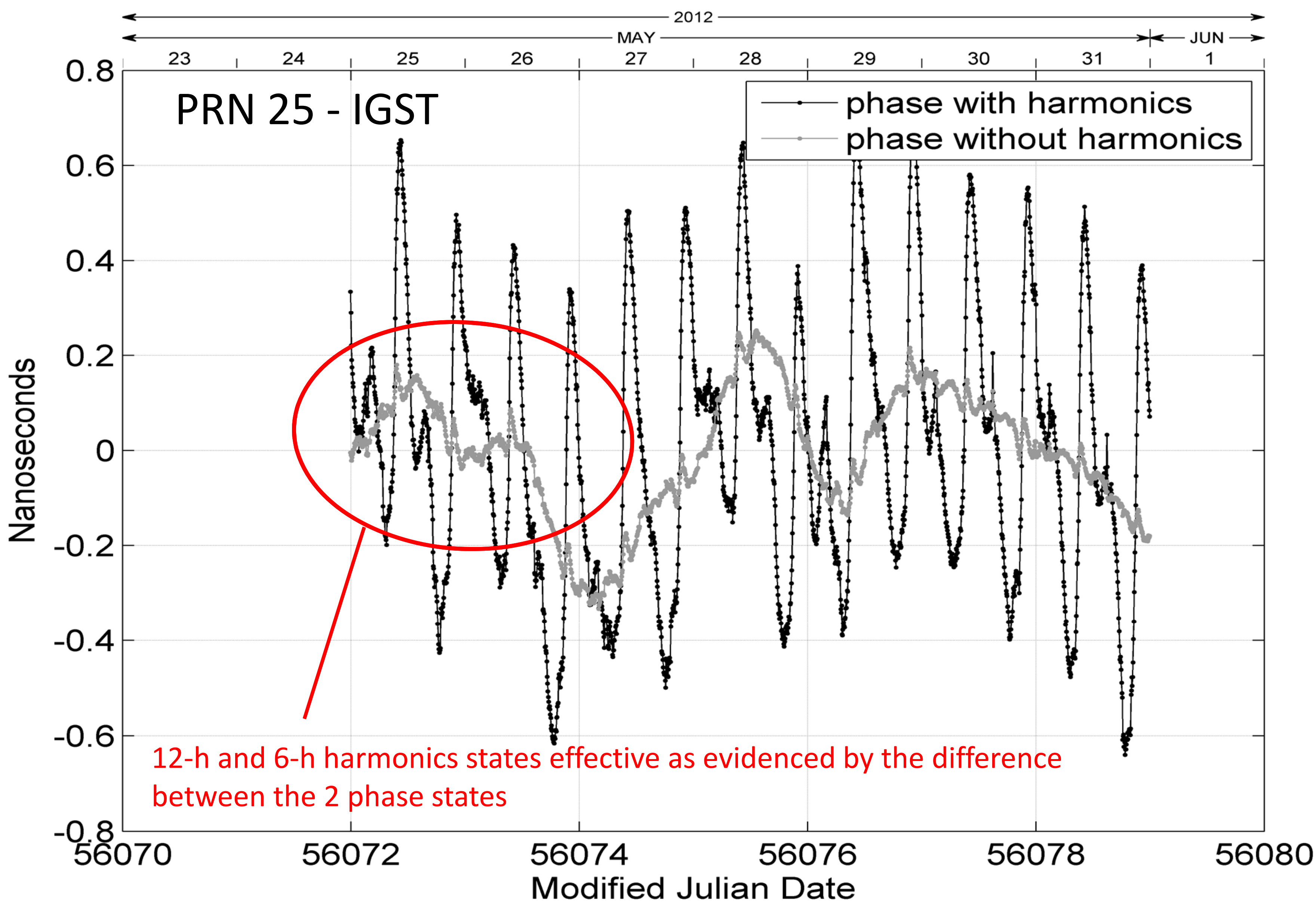
v2.0 shows consistency over time of improved clock stabilities



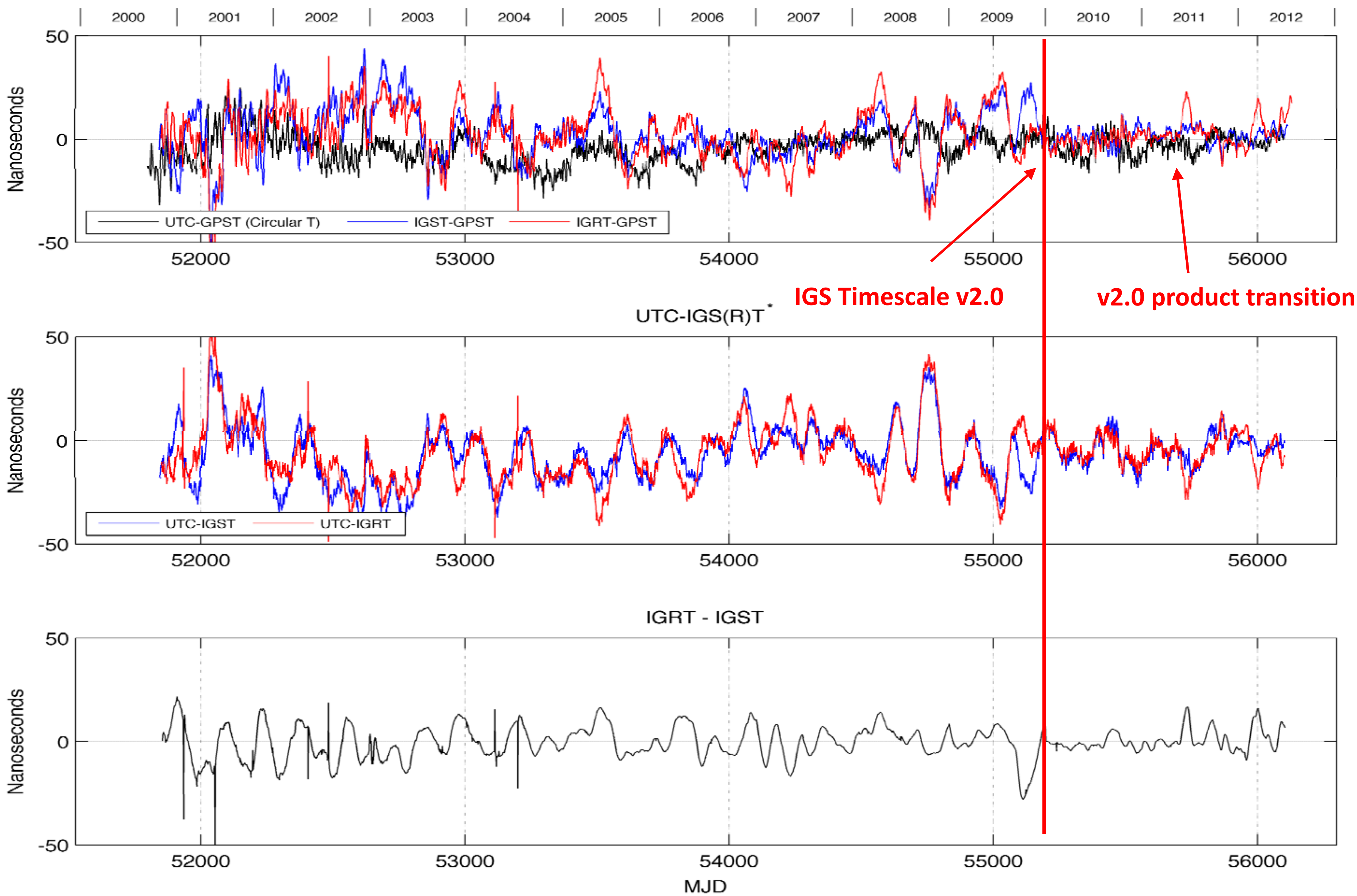


v2.0 maximum "*a*" weights also shows consistency over time; rapids occasionally suffer

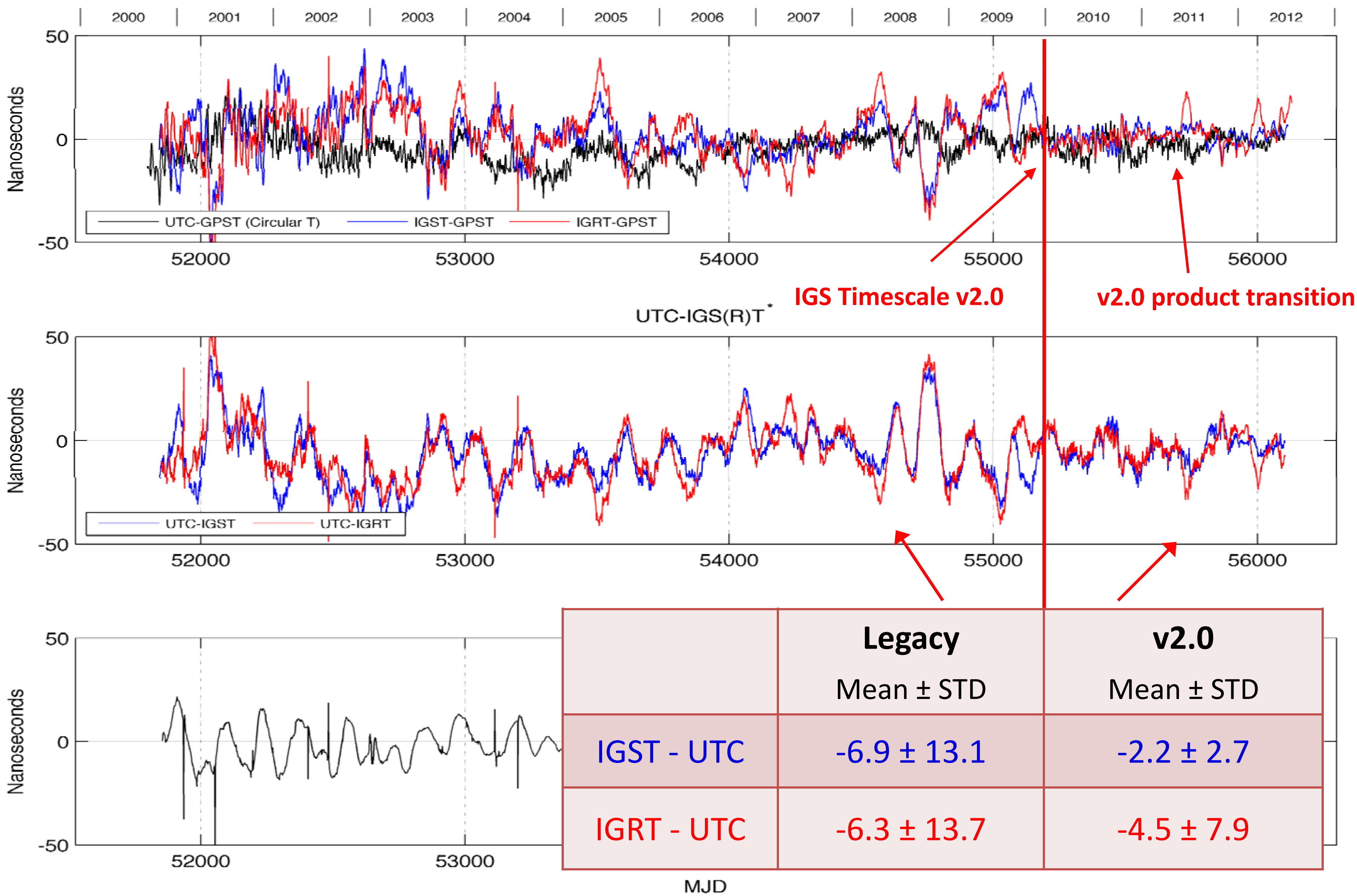
Results 4/5 - GPS Harmonic Estimation



Results 5/5 – Tie to UTC



Results 5/5 – Tie to UTC



	Legacy Mean ± STD	v2.0 Mean ± STD
IGST - UTC	-6.9 ± 13.1	-2.2 ± 2.7
IGRT - UTC	-6.3 ± 13.7	-4.5 ± 7.9

Conclusions

- New v2.0 algorithm transitioned to Rapid/Final products in 2011
- Additional harmonic states effective for utilization of GPS satellites
- Timescale stabilities better than 1E-15 for averaging intervals from 1d now to many days; often in upper 1E-16 level
- UTC alignment now routinely < 5-10 ns

Thank You!