Algorithms and Features of the New GPS System Timescale

Civil GPS Service Interface Committee
Timing Sub-Committee Meeting
Convened Remotely w/ ION GNSS+
Monday 21 September 2020

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GPS Atomic Clock Components

2 Vehicles (IIF)
broadcast
Cs AFS Clock

29 Vehicles
broadcast
Rb AFS Clock

H Maser at
USNO and AMC

Commercial
Cesiums at 15
Monitor Stations

Clock Synchronization

- Receiver solves for position $\mathbf{p}_r$ and time t_r on its local clock using at least four satellites:

Three unknowns

$$\rho_i = c\delta t = |\mathbf{p}_r - \mathbf{p}_i| + c(t_r - t_i) + \cdots$$

Signal Transit Time

- The clock offset is one unknown, if $t_j = t_k$ for all satellites j,k.
- The common reference time for the system allows the system clocks to become effectively synchronized.

$$\rho_i = c\delta t = |\mathbf{p}_r - \mathbf{p}_i| + c(t_r - t_s) + c(t_s - t_i) + \cdots$$

- Errors in $t_s - t_i$ translate into user range error.

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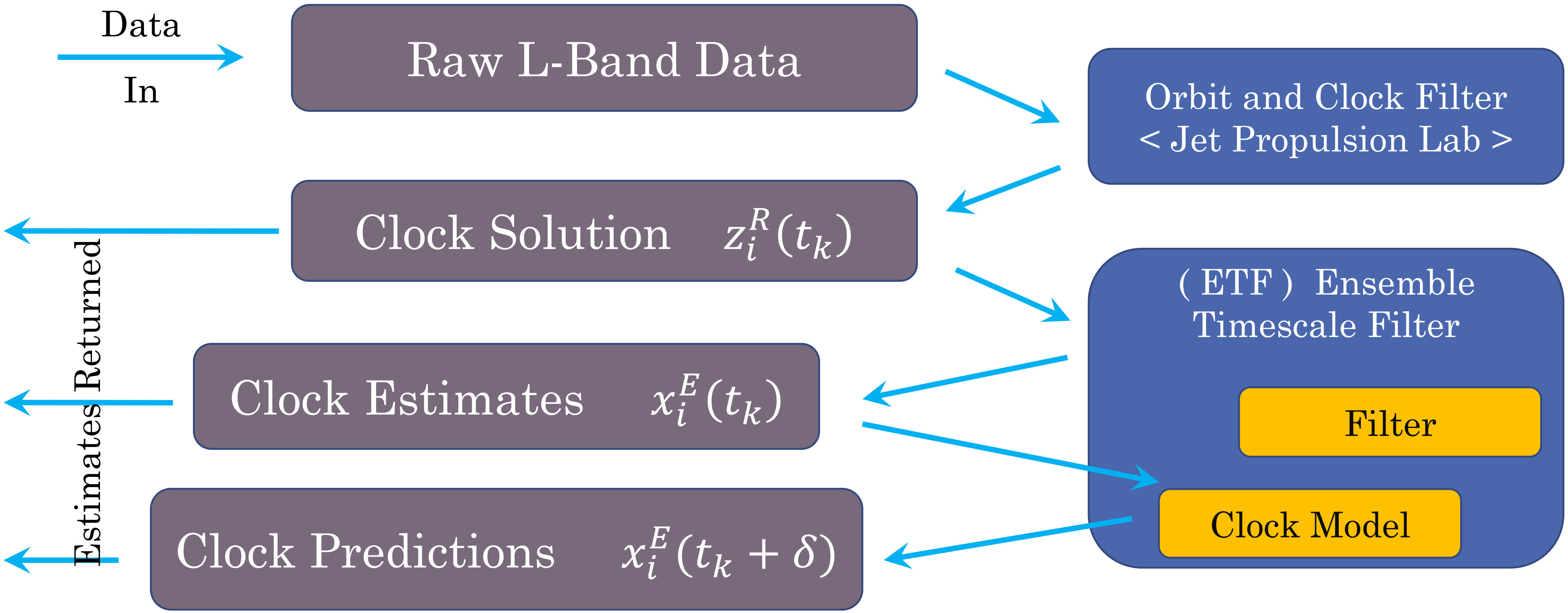
Ground Control Segment

Raytheon

NASA JPL Jet Propulsion Laboratory California Institute of Technology

NAVAL CENTER FOR SPACE TECHNOLOGY ★NCST★

L3HARRIS™ FAST. FORWARD.



Solves for all system clocks with respect to reference clock R.

Calculates reference time E and returns clock estimates with respect to E.

Ensemble Timescale Filter

Requirements

- Estimate phase, frequency and drift of each constellation member in real time.
- Generate an ensemble reference independent of any particular master clock.
- Be able to observe and steer to external solutions and timing references– USNO, in particular.
- Respond to clock anomalies.

Highlights

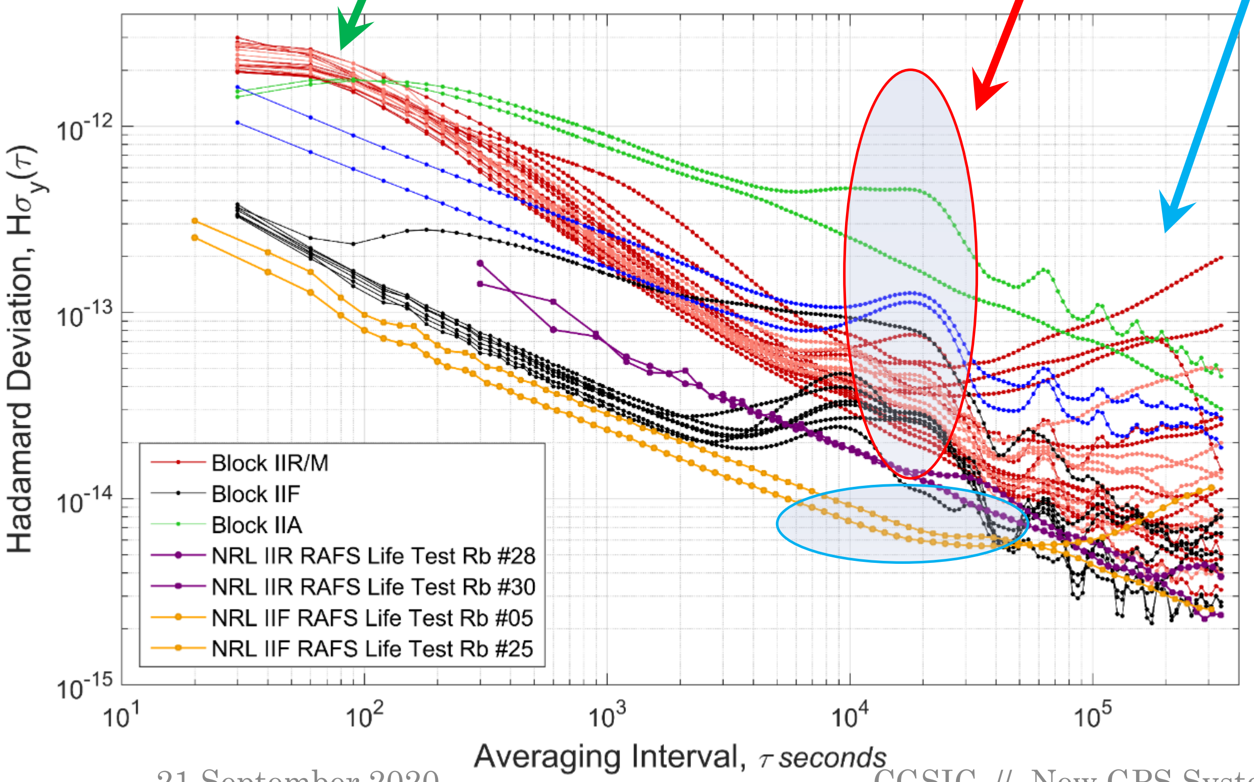
- NRL's timescale refined and completely re-coded in C++ with extensive testing.
- Standard Kalman Filter for real time implementation.
- Covariance factorized by $\mathbf{P} = \mathbf{U}\mathbf{D}\mathbf{U}^T$
- Clock weighting algorithm partitioned to four states.
- Independent measurement weight reduces impact of outliers or excessive noise on measurements.

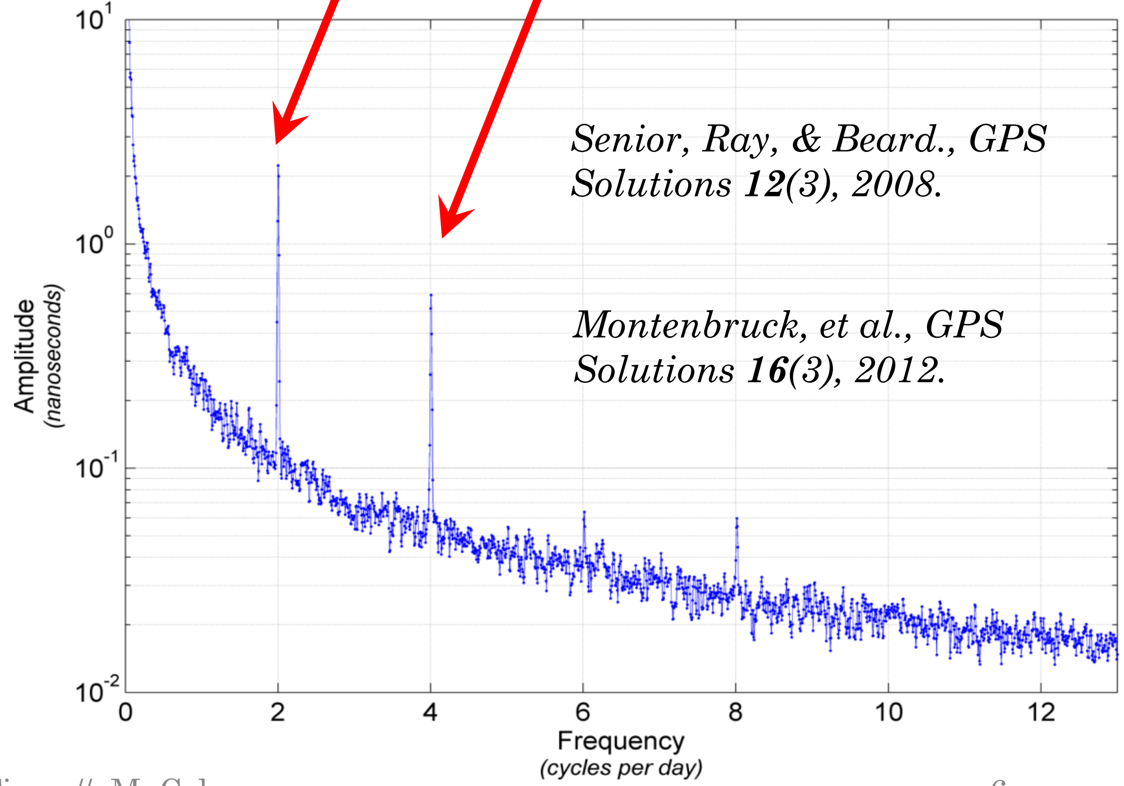
Environmental Harmonics

High frequency TKS noise in Block IIR / IIRM satellites.

Periodics detected in clock phase at 1/rev and 2/rev.

Not observed in the lab.





*Senior, Ray, & Beard., GPS Solutions **12**(3), 2008.*

*Montenbruck, et al., GPS Solutions **16**(3), 2012.*

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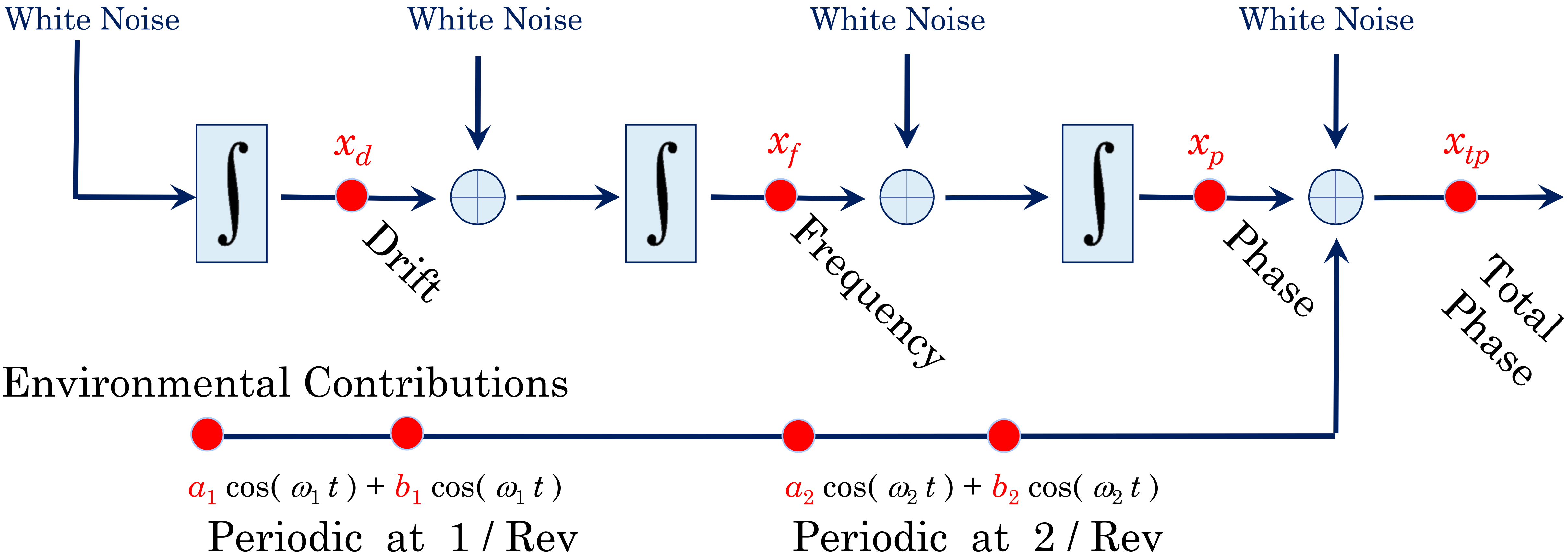
Clock Model Basis



A small random walk process is modeled for each environmental state allowing sufficient flexibility in the filter for the states to converge to each clocks' periodic components.

Observations

Final clock estimates are calculated with Kalman Gain **K** and observation $z_i^R(t_k)$ by

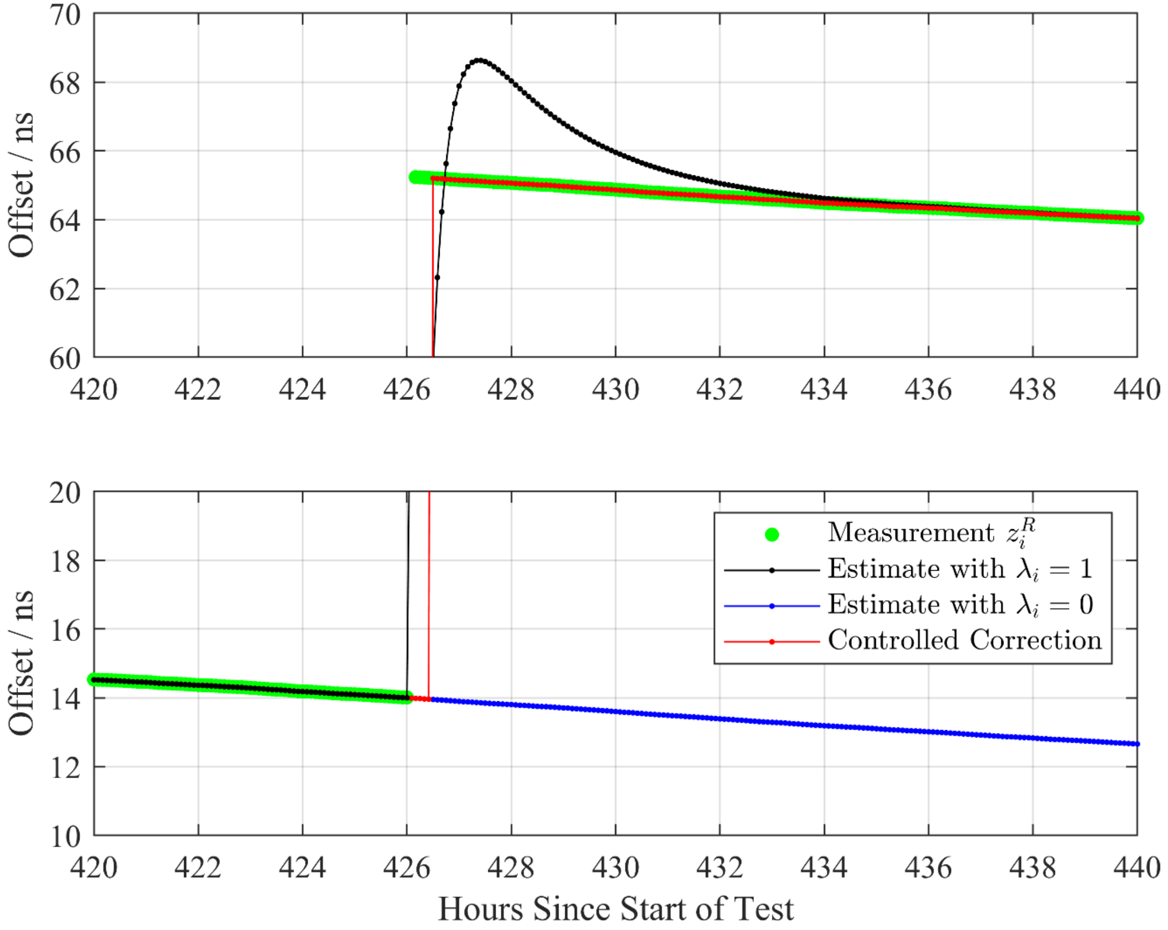
$$\hat{\mathbf{x}}_i(t_k) = \hat{\mathbf{x}}_i(t_k^-) + \lambda_i \, \mathbf{K} \left(z_i^R(t_k) - \hat{x}_{pi}^R(t_k^-) \right)$$

- Bad measurements can ruin the clock estimates $\hat{\mathbf{x}}_i(t_k)$.
- Reduce impact on the estimation with independent measurement weight, λ_i.

$$0 < \lambda_i < 1$$

- If $|\, z_i^R(t_k) - \hat{x}_{pi}^R(t_k^-) \,|$ is small, then $\lambda_i = 1$.
- When this difference is larger than 5σ, then we reduce λ_i to 0.

Response of Clock Estimates to Phase Break Anomaly with Different Parameter Values



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Automatic Responses

If a break in the clock measurement has been identified, the break handling algorithm attempts to adjust the clock state and covariance to match.

Phase Break

Following a break in phase, an impulse can be added immediately:

$$\mathbf{x}(t_k) = \Phi\, \mathbf{x}(t_{k-1}) + \delta\mathbf{x}$$

- Typically the filter estimates converge to the new phase value quickly (within one epoch).
- Clock can participate as ensemble member immediately after the impulse.

Frequency Break

After a frequency break, one can add to the process noise parameter to inflate the covariance:

$$\mathbf{Q} = \int_{t_j}^{t_k} \Phi\,(\mathbf{S} + \delta\mathbf{S})\,\Phi^T\, dt$$

- Gives flexibility for the filter to converge on a new frequency value.
- Clock must lose ensemble membership until state error covariance reduces.

Even if a particular break is not corrected quickly, the ensemble's stability is protected throughout.

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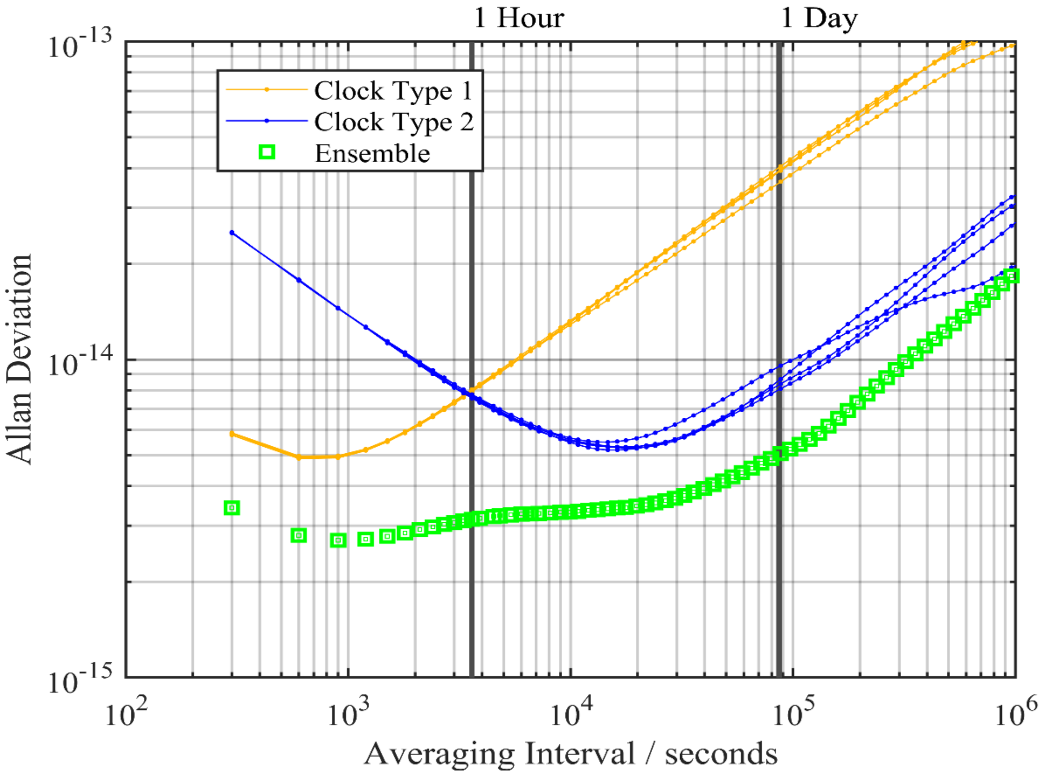
Clock Multi-weighting

The ensemble algorithm has a dynamic clock weighting routine that updates the weights from one epoch to the next depending on: clock noise spectral densities, clock state error covariance, and recent clock anomalies.

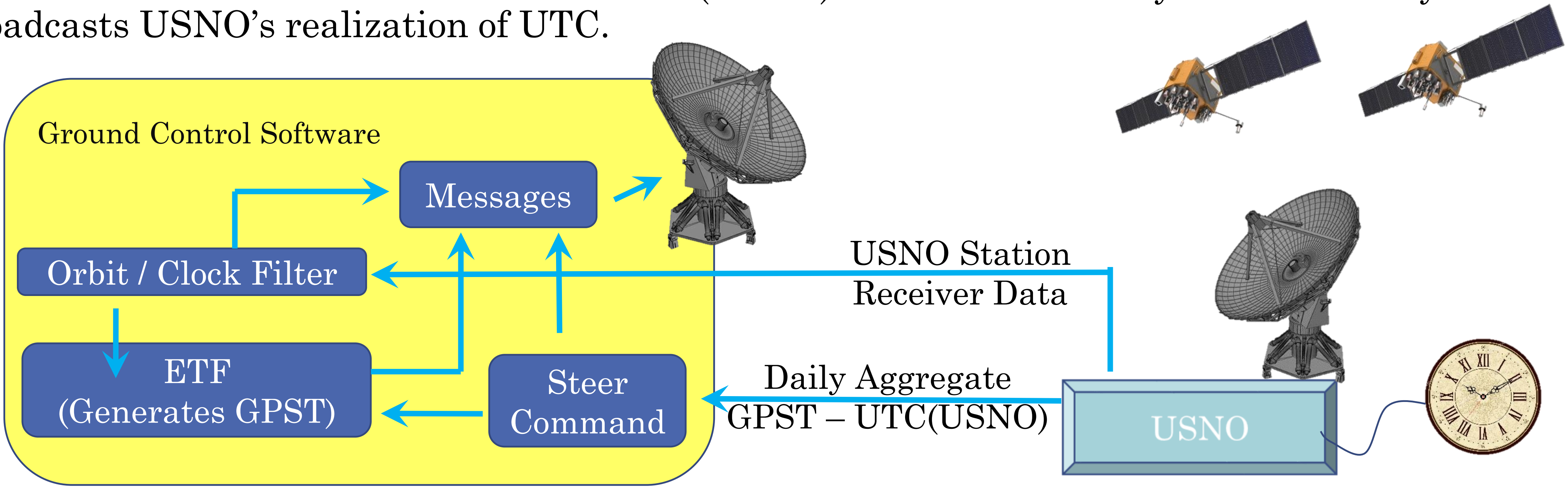


- Utilize multi–weighting to gain the most stable components of the various clocks.
- Allows the ensemble to achieve better stability for a wider range of averaging intervals.
- One set of weights exists for each noise process. For example, the constrain on the phase state random walk is:

$$\sum_{i=1}^{N} w_{pi}\left[\hat{x}_p(t_k) - \hat{x}_p(t_k^-)\right] = 0$$

UTC Reference

- Ensemble maintains a low offset from UTC(USNO) using Linear Quadratic Gaussian steering.
- System continues to broadcast GPST – UTC(USNO) offset so that the system effectively broadcasts USNO's realization of UTC.

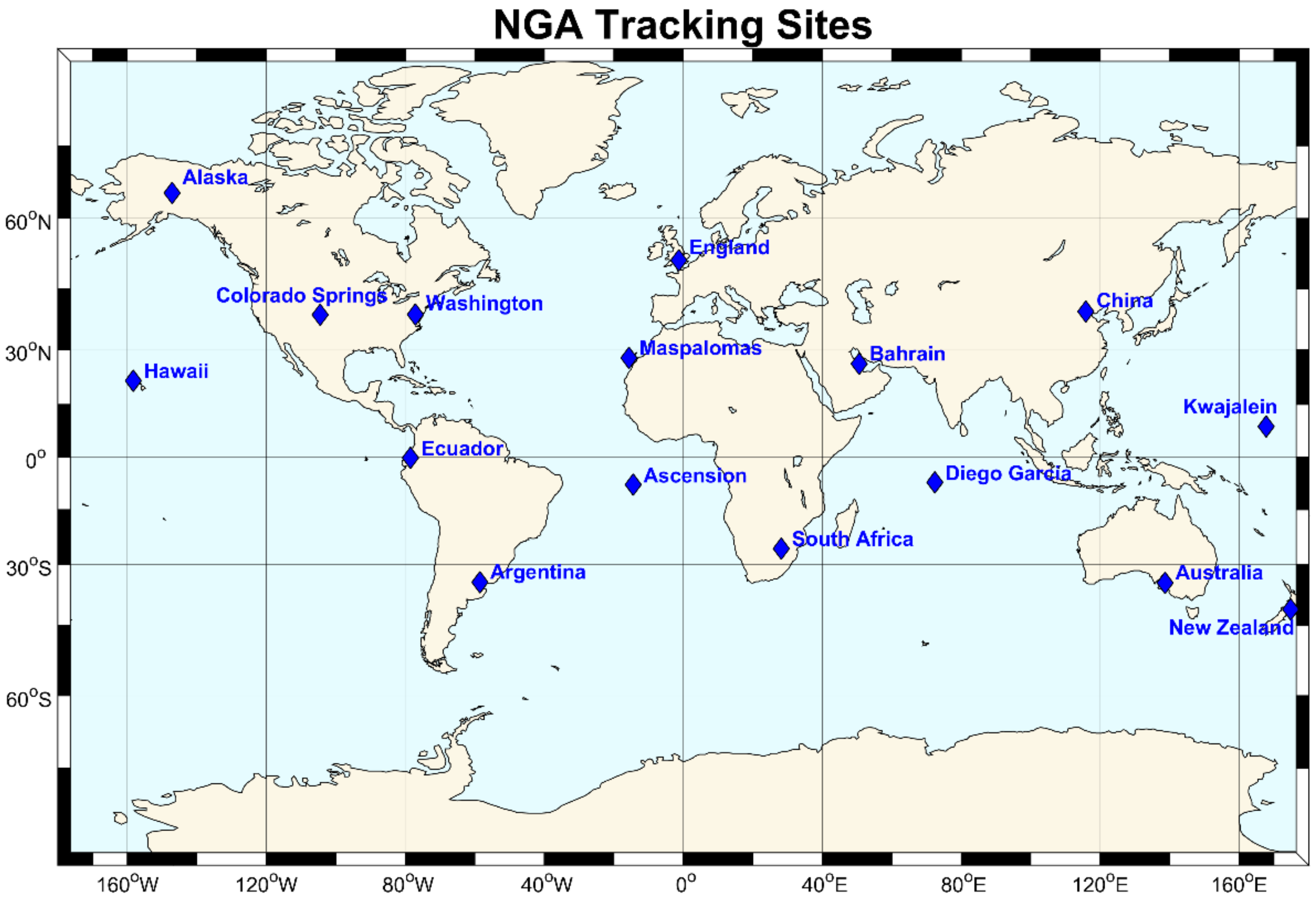


Data Set

Data Set & ETF Configurations:

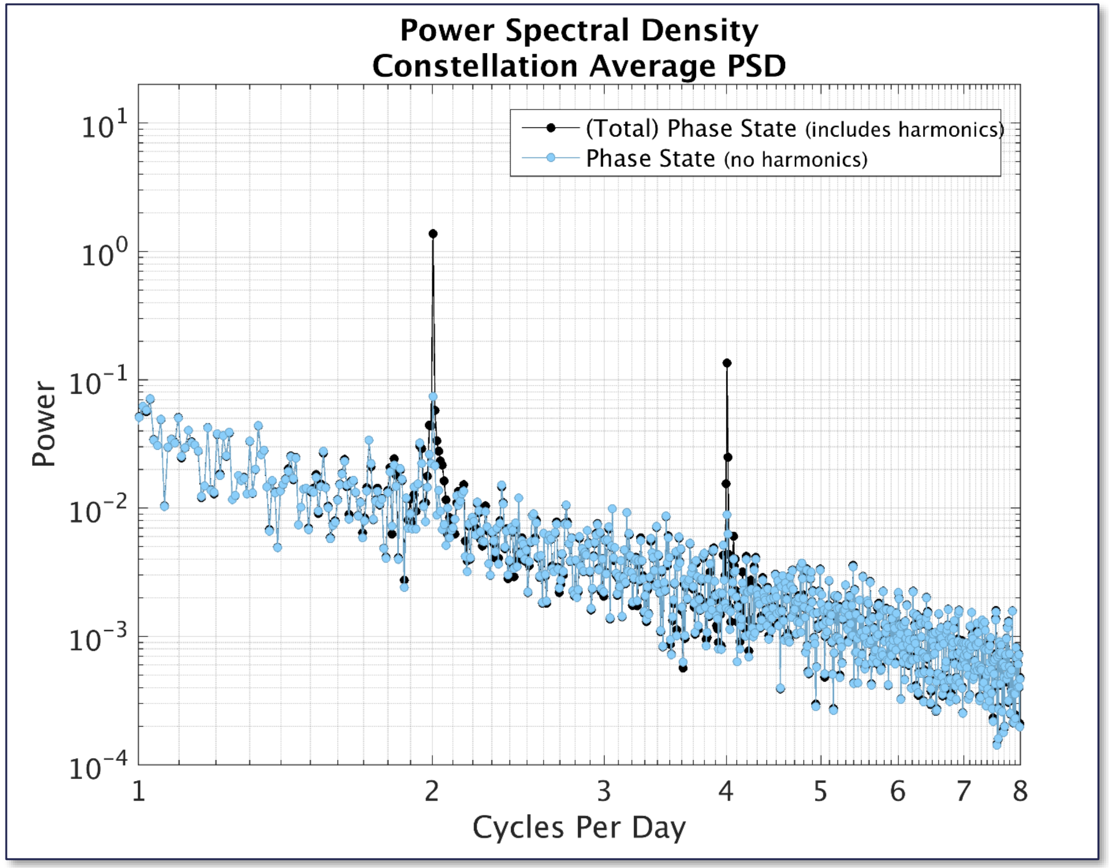
- 110 day period; 5-minute data
- Clock data ingested are the clock solutions of JPL's RTGx.
- Ground Clocks
  - High performance cesiums
  - UTC(USNO)

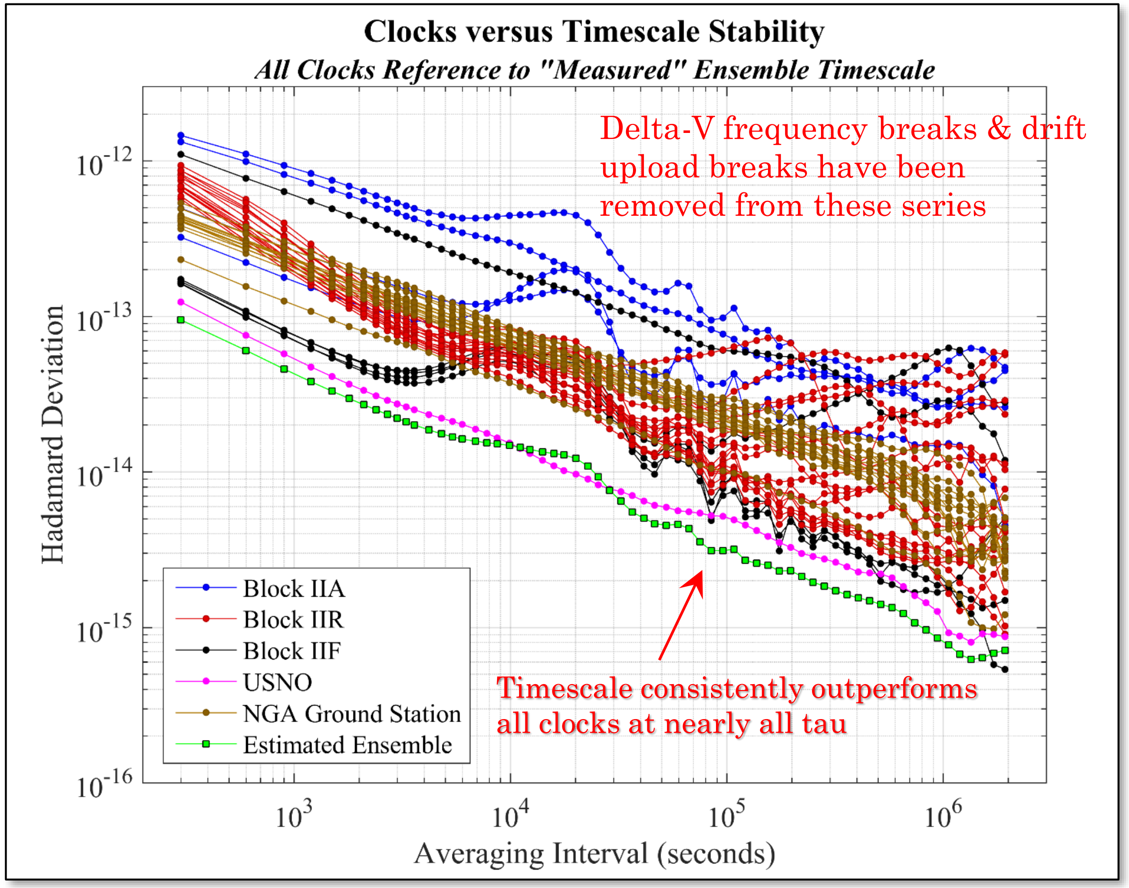
  Satellite Clocks
  - 3 Block IIA Rb // 2 Block IIA Cs
  - 12 Block IIR Rb // 7 Block IIR M Rb
  - 7 BIIF Rb / 1 BIIF Cs
- Upper limit of weights: 2.5/N
- Measurement noise assumed white at 300 ps
- 6 Frequency Breaks owing to Delta-V removed using ETF manual break facility
- 3 Drift Upload Drift Breaks also removed
- Clock model parameters determined using same data and Hadamard deviation profiles
- Periodic state estimation turned ON for all satellites at frequencies of 2.003 and 4.006 cycles/day.



Results

- Total phase state absorbs the environmental periodics thereby protecting the ensemble.





- No common mode timescale effects seen even after tens of days.
- Upper limit of timescale weights imposed is 6.5%

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Acknowledgments

Key References

- Richard H. Jones and Peter V. Tryon. Estimating time from atomic clocks. Journal of Research of the National Bureau of Standards, 88(1):17{24, January{February 1983.
- Ken Senior, Jim Ray, and Ronald L. Beard. Characterization of periodic variations in the GPS satellite clocks. GPS Solutions, DOI:10.1007/s10291-008-0089-9:211–225, February 2008.
- Robert G. Brown and Patrick Y.C. Hwang. Introduction to Random Signals and Applied Kalman Filtering. John Wiley and Sons, New York, 3rd edition, 1997.
- Steven T. Hutsell. Relating the hadamard variance to MCS kalman lter clock estimation. In Proceedings of the 27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pages 291–302, San Diego, CA, 29 November { 1 December 1995.
- Samuel R. Stein. Kalman lter analysis of precision clocks with real{time parameter estimation. In Proceedings of the 43rd Annual Symposium on Frequency Control, pages 232–236, Denver, CO, 31 May–2 June 1989.
- Paul Koppang and Robert Leland. Steering of frequency standards by the use of linear quadratic Gaussian control theory. In Proceedings of the 27th Annual Precise Time and Time Interval Applications and Planning Meeting, pages 257{267, San Diego, CA, 29 November – 1 December 1995.

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