A Prediction of How TAI and TT Will Be Computed in 2020

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My 1999 *Prediction* for 21st Century

State-of-the-Clock-Art, 2010

- UTC will be computed hourly using:
  - Masers for hours to weeks
  - Trapped-ion for days to months
  - Fountains for days to years
- Exciting clocks, just becoming operational, will include
  - Optical Frequency Standards
  - Space-based trapped-ion and beam clocks

The ideas presented here borrow heavily from the works of:

- Felicitas Arias (BIPM)
- John Davis (NPL)
- Chuck Greenhall (JPL)
- Niko Kalouptsides (U. Athens)
- Paul Koppang (USNO)
- Gianna Panfilo (BIPM)
- Gerard Petit (BIPM)
- Ken Senior (NRL)
- Jim Skinner (USNO)
- Patricia Travella (INRIM)

Current System

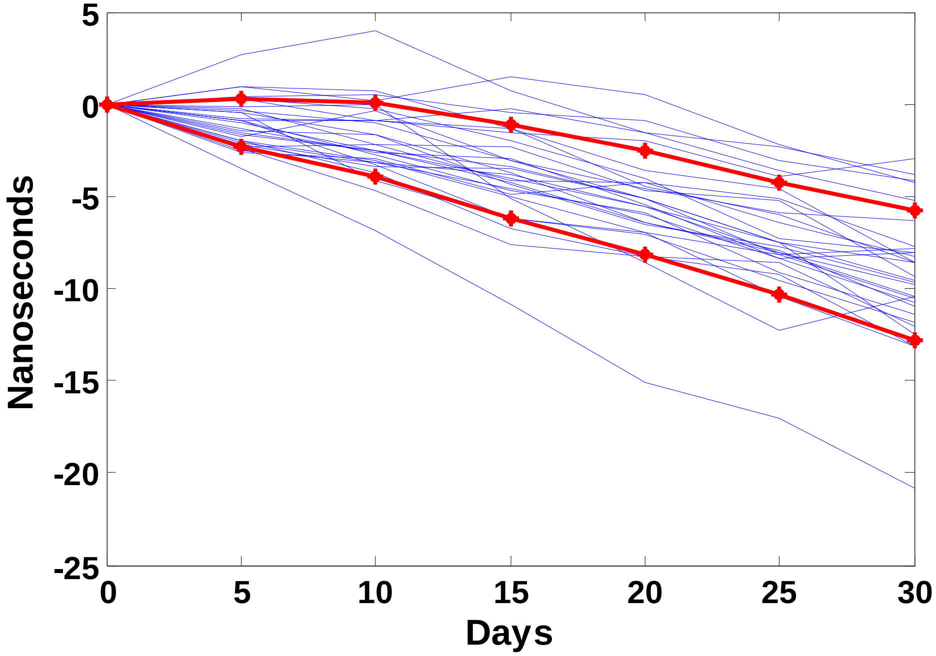
- EAL = Free-running average of secondary standards
  - Weighted by monthly frequency stability
    - Very democratic
    - Maximum weight ensures robustness
      - See Petit, Metrologia, 2003, 40 No3 252-256
  - Simple, robust clock model
    - Optimal for driftless clocks, white phase noise
    - Being modified for high-drift clocks (masers)
  - Algorithm has steady record of incremental improvements
- TAI = EAL frequency-steered to primaries
- Terrestrial Time (TT) = Post-processed TAI

Relative Precision of USNO Masers and Cesiums (σ_y)

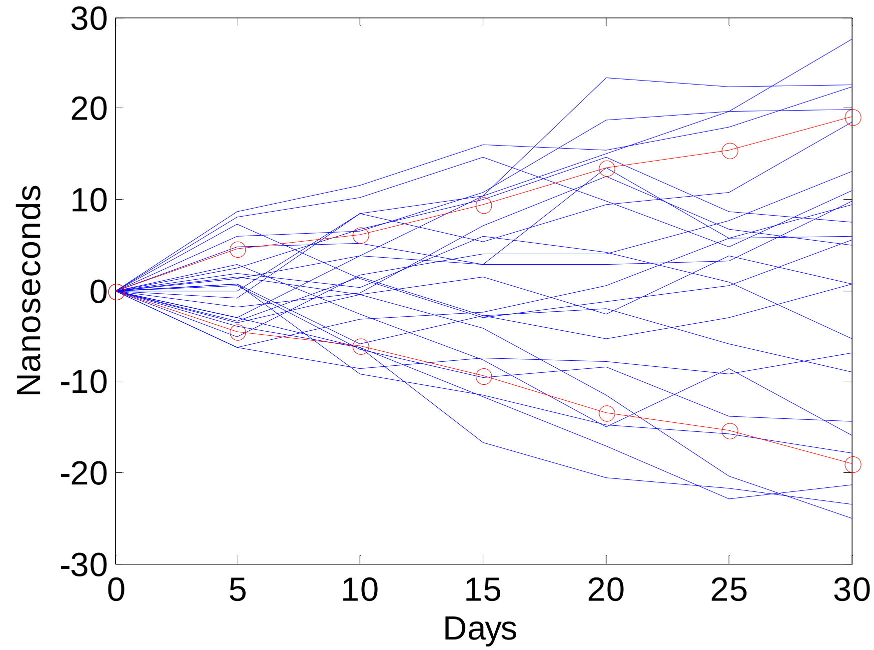
- @80days (vs. EAL or USNO Maser Mean)
  - Maser slightly better than cesium
- @40 days (vs. EAL or USNO Maser Mean)
  - Maser ~3 times better than cesium
- Daily at USNO
  - Maser ~20 times better than cesium
- Hourly at USNO
  - Maser ~40 times better than cesium
  - Limited by operational measurement system

Masers and Cesiums as Phase-Linear EAL Predictors

(Displaying maser frequency drift, 2006-2008)



Maser deviations after fit period



Cesium deviations after fit period

Viewgraph and Analysis from Panfilo and Arias, EFTF-09

Time Transfer Noise’s Bleak Future

- Less and less uncertainty
  - GPS carrier-phase time-transfer precision
    - 20 ps @ 5 minutes; 100-ps level issues at 24 hours
    - Software in use at BIPM
    - Calibration issues addressable
  - GPS =>GNSS
    - Improved robustness and precision
    - Enhanced multipath reduction in some planned signals
    - Paper by Uhrich and Tuckey, this session
  - Steadily falling component price => redundant systems
- Real-time Carrier-Phase GPS Networks Operational
  - Latency measured in seconds
- Possibility to optimize around short-term stability of masers
  - Rubidium Fountains too

The Full Kalman Approach

- Kalman Filter
  1. Cesium-only scale
     - Can be daily points
     - Incorporates primary standards as frequency measurement
  2. Maser frequencies referenced to cesium scale's frequency
     - Where the noise is whitest
     - Two-state characterization (frequency and frequency drift)
  3. Maser phases corrected for frequency and drift
  4. Corrected maser phases steered to cesium scale
  5. Global maser average gives TAI/UTC

- Terrestrial Time (TT)
  - TT is average of forward and backwards filters

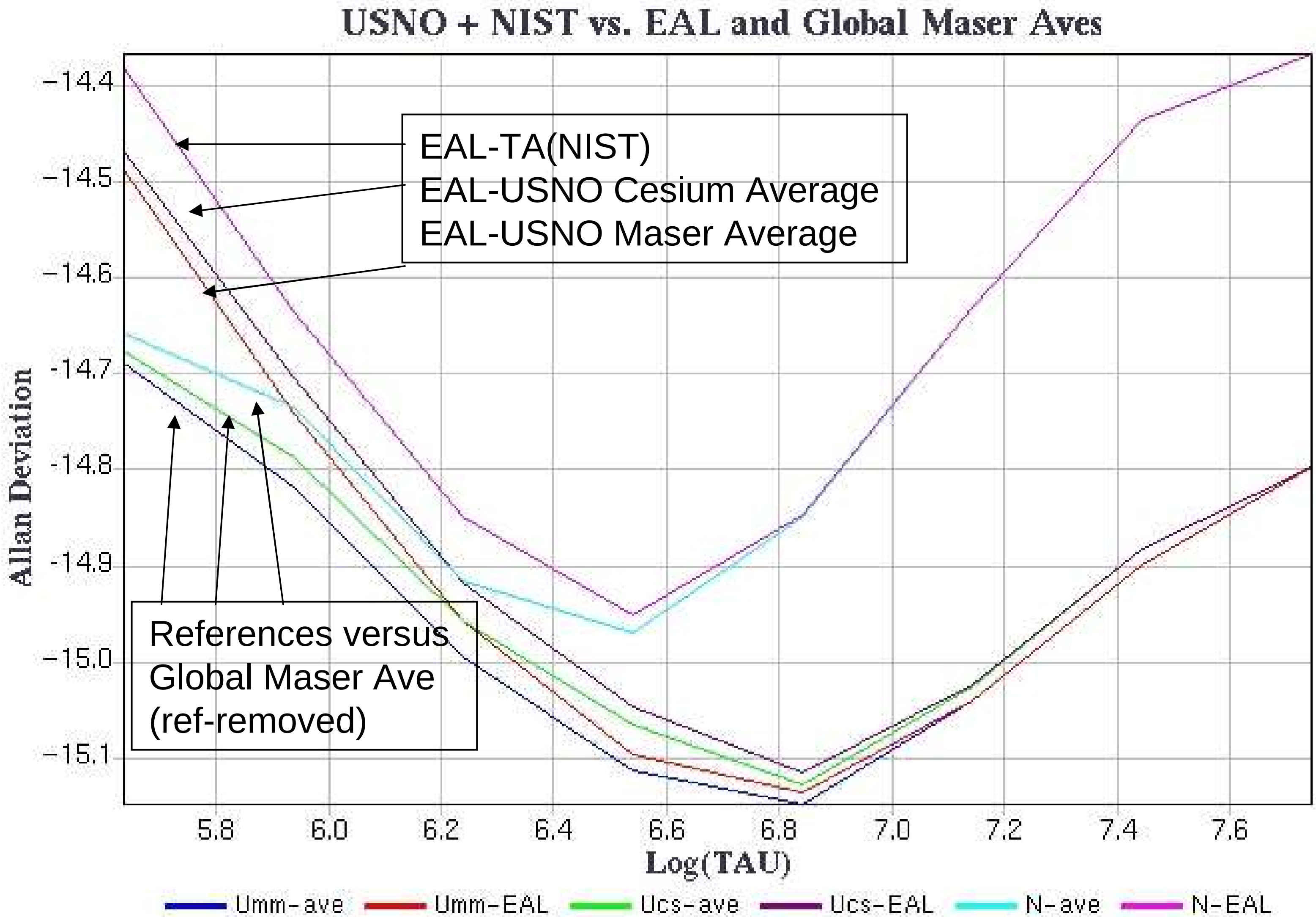
Pros and Cons of Kalman Basis

- Parameter tuning and selection requires care
  - But non-WFM noise can also be modeled
    - Davis et al, Metrologia 42, 1-10
- Measurement error correlations
  - Off-diagonal terms
  - Time-transfer noise correlations between links
  - Redundant time-transfer systems
- Process Noise
  - Can model clocks sharing common environment
  - Raising a Q helps alleviate modeling errors
    - Although a high Q is itself a modelling error
  - Minimum Q ⇔ Maximum Weight
    - Helps protect against Narcissus Effect

Will it really work?

- Download BIPM's 5-day data via anonymous ftp
  - None of it is by carrier phase
- Use Kalman Filter to generate EAL-maser
  - Use EAL as reference, for now
  - Outlier removal via standard Kalman techniques
- Create "Global Maser Average"
  - Global average of all masers reporting to BIPM
    - Remove frequencies and frequency drift
    - Integrate back to phase, steer phase @ 60 day time constant
  - Weighting by performance in any of several ways
- Compare with independent references
  - USNO Cesium and Maser Means, and TA(NIST)
    - Do not include reference's masers in the Global Maser Average
  - For short τ, Global Maser Average agrees as better with the references than EAL does
  - For large τ, Global Maser Average of course agrees with EAL

USNO and NIST Internal Means referenced to EAL and Global Maser Ave (which does not include reference's clocks)



Conclusion: My Predictions for 2020

- There will be >2 fully interoperable GNSS systems operating
  - They will want an improved short-term UTC
- Time Transfer noise >1 ns on any scale will be considered an embarrassment
- TAI algorithms will utilize full precision of masers and fountains over $\tau \ll 1$ month

Backups

USNO Algorithms

- Cesium-only average
  - Characterization in frequency-space
- Masers characterized/steered to cesium average
  - Rubidium fountains under evaluation
- All averages have copies steered to UTC
  - Equations allow for coupling of the averages
- UTC(USNO) steered to steered maser average
- Human oversight required
- Not yet fully operational

A Similar Approach For UTC

- Benefit from large number of cesiums on monthly scales
- Utilize full power of masers on short periods
  - Example: IGS Time Scale
  - Continuously-contributing fountains
- Optimally incorporate scattered primary frequency standard data

Issues That Can Be Addressed In Several Ways

- All masers are not equivalent
- Clock noise is not white FM and TT noise is not white PM
  - Particularly over long scales
- Noise is correlated
  - Even on subdaily scales

Kalman Parameters

- Rate and drift for all clock types
- Process Noise (Q)
  - Provides for stochastic change in frequency/drift over time
  - Published formulas relate noise to math
  - Gauss-Markov approximation possible for red noise
- Maximum weight limit ⇔ Minimum Q
  - ~ Petit, Metrologia, 2003, 40 No3 252-256
  - Raising a Q helps alleviate modeling errors in Kalman Filters