STEERING UTC(k) TO UTC

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1. Introduction
2. Prediction
3. Steering Options

Omnipresence of Steering

TAI = EAL + frequency steers to primary frequency standards

(calibrated to meet definition of the second)

(EAL = ave of >200 clocks, including USNO's)

UTC = TAI + leap seconds

(crude steers, in phase, to Earth's rotation)

UTC(k) = TA(k) + steers to UTC = realization of UTC by laboratory k

(TA(k) = ave of Lab_k's clocks)

GPS* = Unsteered GPS clocks + steers to UTC(USNO) [in acceleration]

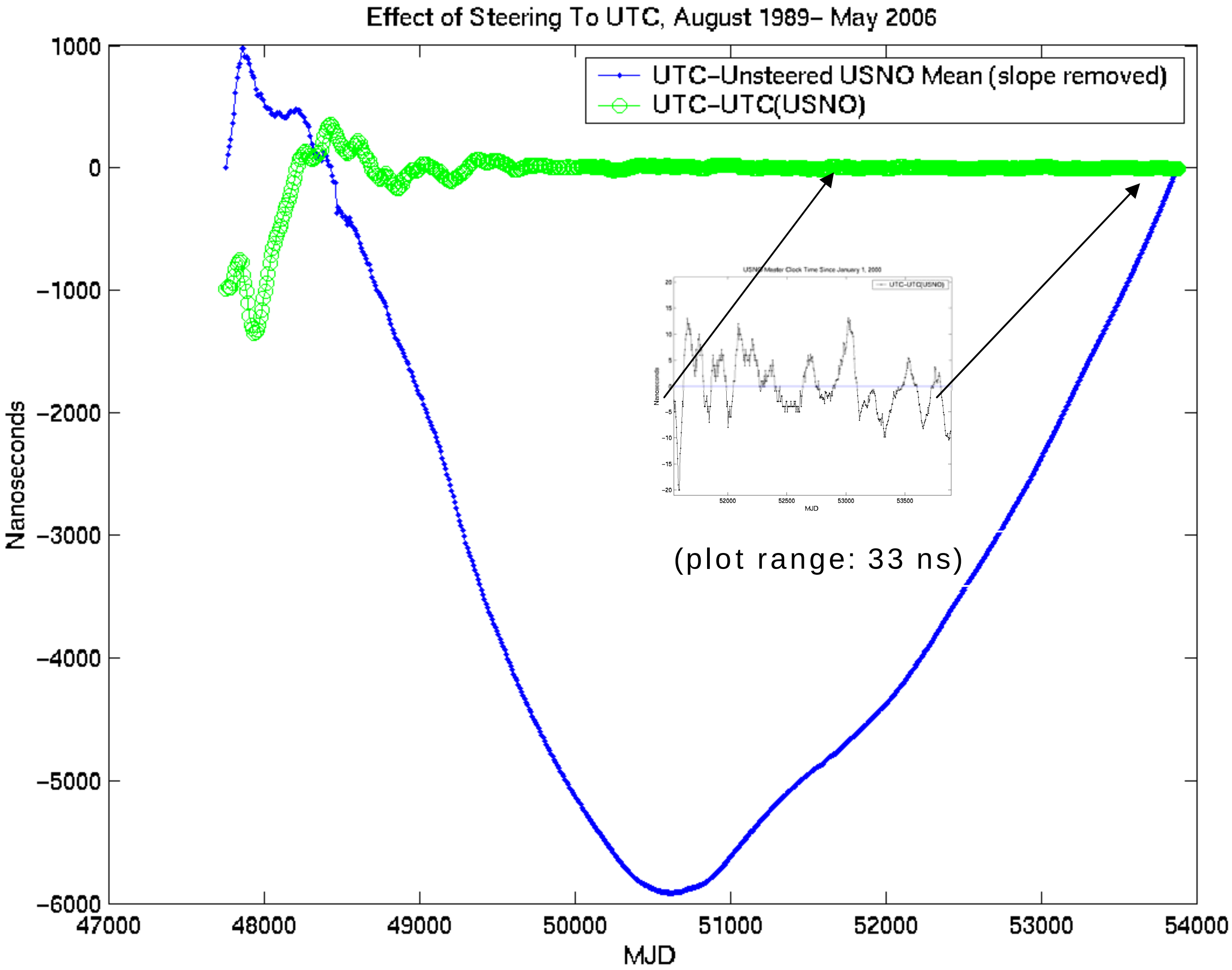
(Composite Clock= implicit average of steered satellite and monitor station clocks)

Cell Phone's Time = crystal + steers to UTC(k) or GPS*

Atomic Clock's time = clock's crystal + steers to atomic frequencies

(GPS* denotes GPS Time with leap seconds added)

Improvement Due to Steering



(plot range: 33 ns)

How Timing Labs Steer to UTC

- Some don’t steer at all
- Others wait until UTC-UTC(k) is “too large”
  - Step rate of UTC(k)
  - Step phase of UTC(k)
- Better method:
  - First estimate future UTC-UTC(k)
  - Then steer UTC(k) so as to reduce UTC-UTC(k)
    - Do not jump your phase
    - Do adjust your frequency
      - Adjust Master Clock’s voltage parameters
      - Or adjust microstepper/AOG/equivalent
      - Or software steer

Rest of This Talk

- Part II: State Estimation: model of UTC-UTC(k)

- Part III: Gains for Proportional Steering
  - Steer = g_X * Phase + g_Y * Freq + g_Z * Drift
  - Described by Gain Vector: (g_X, g_Y, g_Z)

- Separation Principle: Optimal control (gain) is independent of optimal state estimation

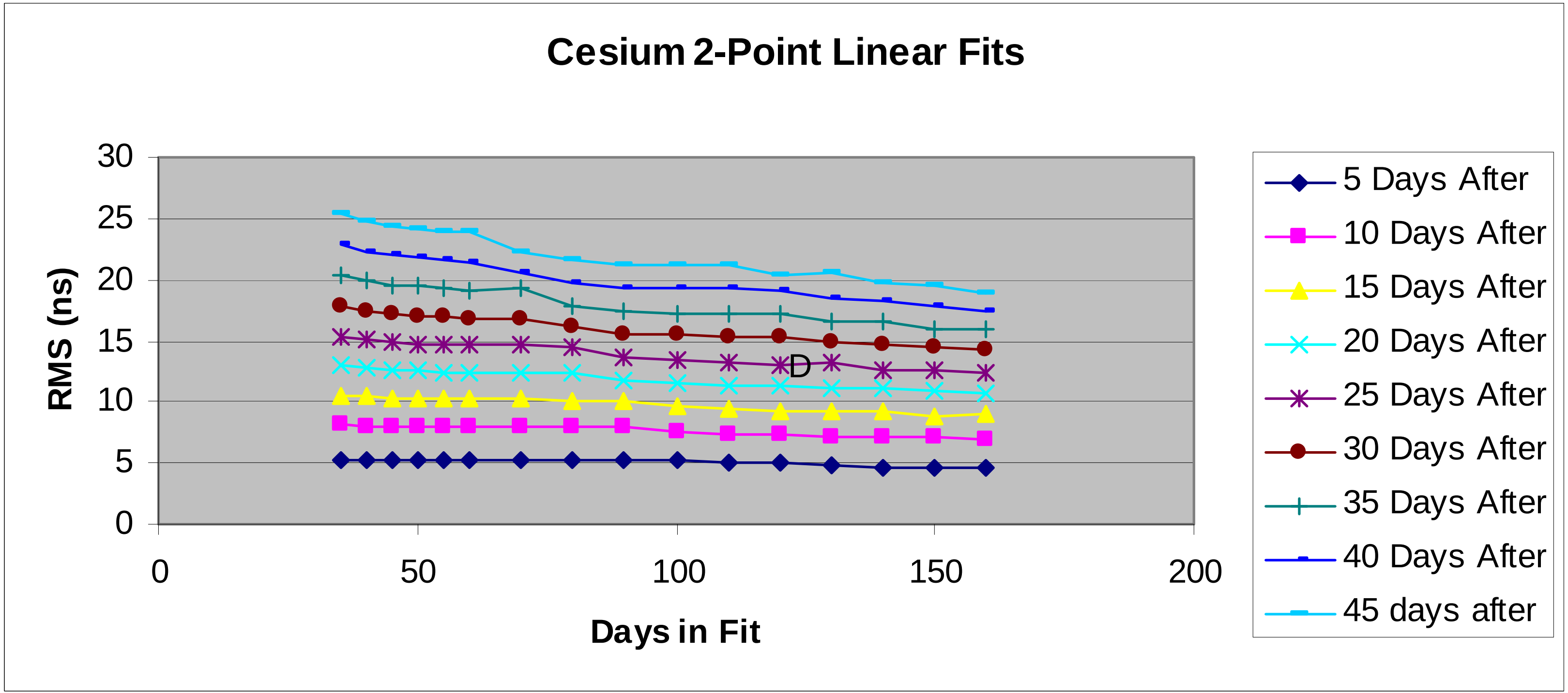
Part II: Estimate UTC-UTC(k)

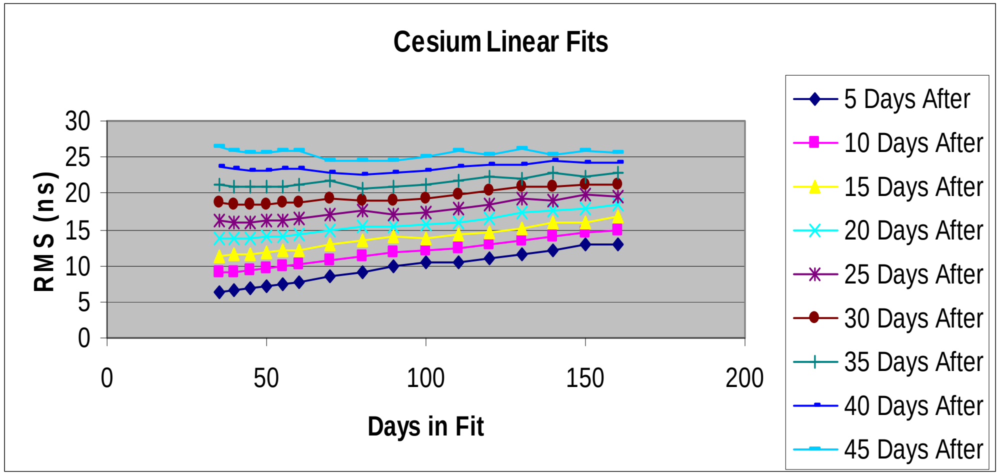
1. Start with published Circular T values of UTC-UTC(k)
2. Convert to EAL minus some unsteered real-time timescale
   - Timescale usually internal, could even be one cesium
   - Timescale could also be external real-time UTC realization
     - GPS makes UTC(USNO) easy to use, SIM makes UTC(NIST) easy too
3. Compute EAL-timescale
4. Extrapolate to future
5. Convert extrapolation to prediction of UTC-UTC(k)
   - Add back in the steers you took out in step 2
   - Future steers of EAL to generate UTC, from Circular T

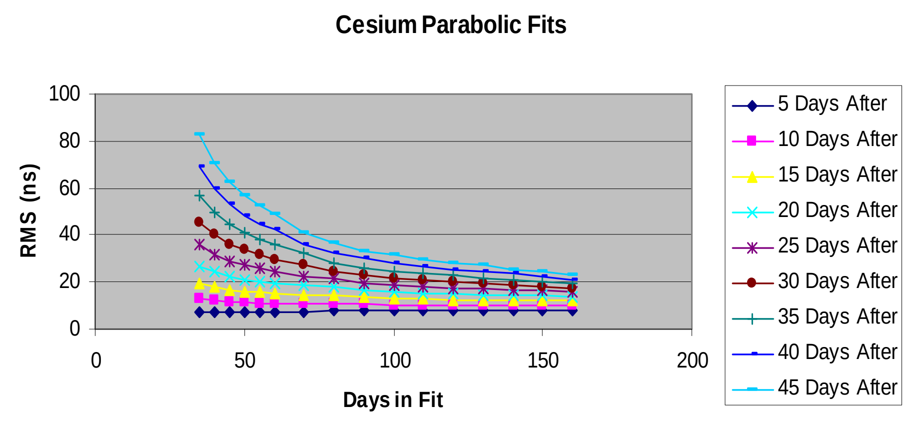
Extrapolating EAL-timescale

- Polynomial Fit
  - Fit Order: linear for Cesiums, quadratic for Masers
  - How far back in time to fit to? (recommend 60 days)
  - Fit in frequency domain, not phase
    - Because frequency noise is white
    - Simple method for cesiums:
      - Use only first and last phase points
      - Last point minus first point yields average frequency
- Other ways exist
  - Auto-Regressive Integrated Moving Average (ARIMA) and State Space Models
  - Kalman Filters are one form of estimator

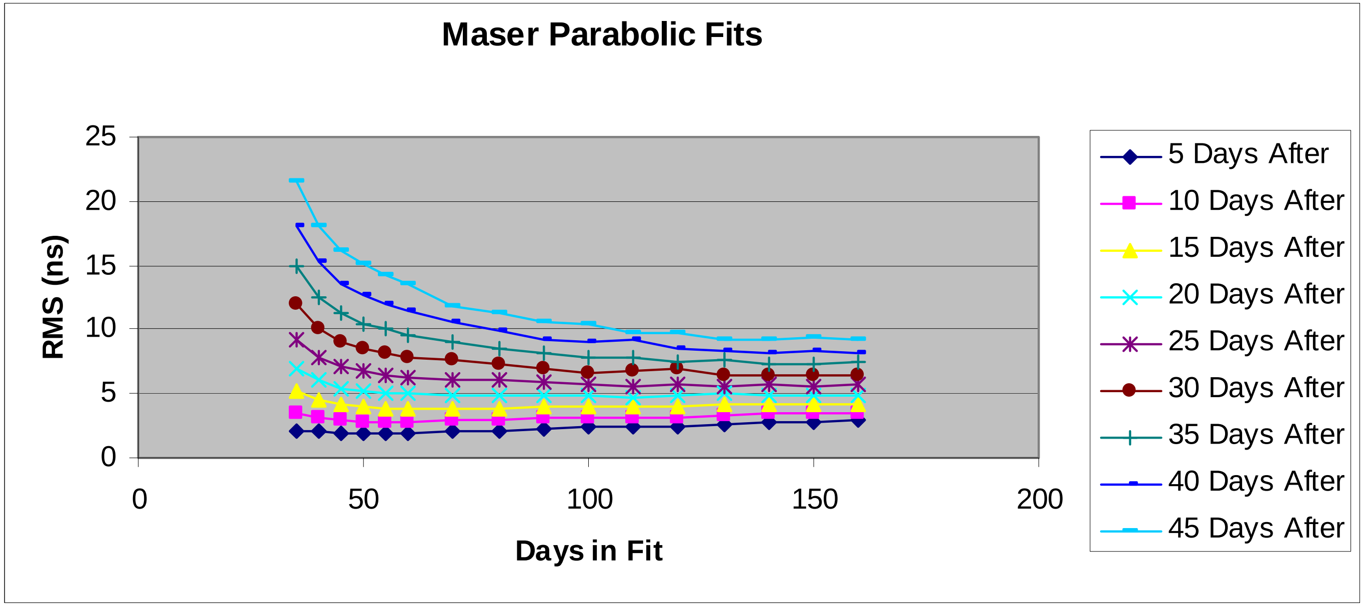
Extrapolating EAL-cesiums

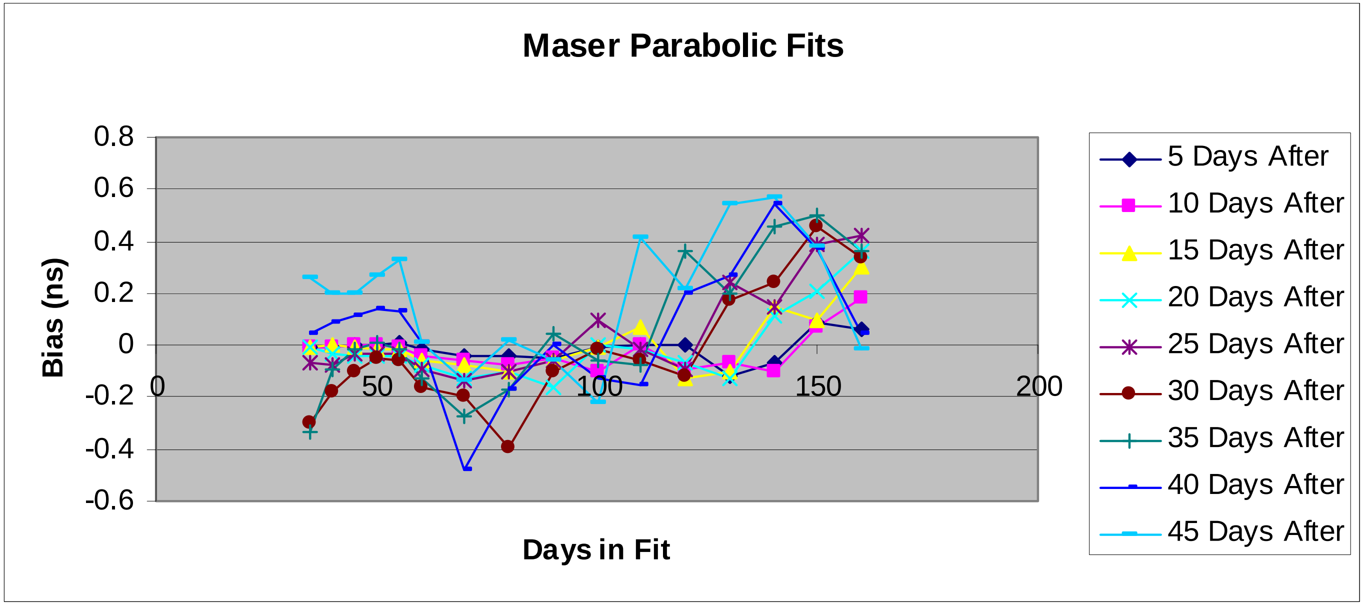






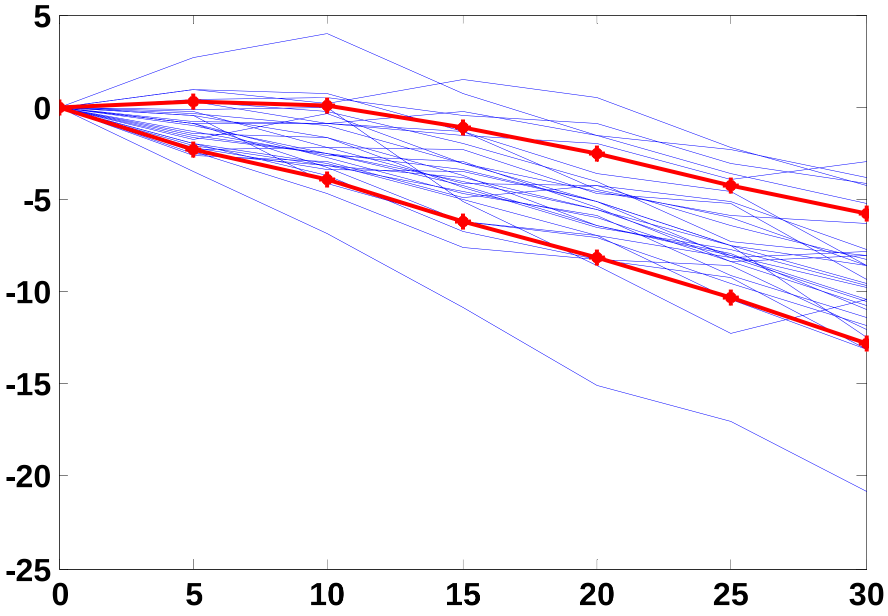
Extrapolating EAL-USNO masers



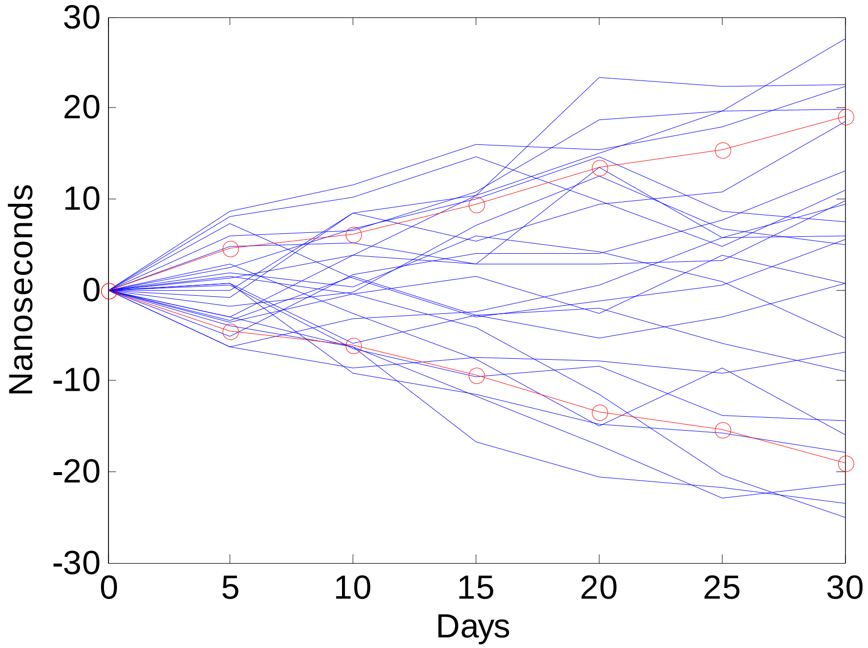


Masers and Cesiums as EAL Predictors

3-year test period (2006-2008)



Maser deviations after fit period



Cesium deviations after fit period

Viewgraph and Analysis from Panfilo and Arias, EFTF-09
See also: Matsakis et al., ION Annual Meeting, June 2000

Part III: Setting the Gain Vector

- Steer $= g_X * \text{Phase} + g_Y * \text{Freq} + g_Z * \text{Drift}$
- ALL steering involves a trade-off between:
    - frequency offset
    - time offset
    - control effort
        - Control perturbs local clock
- Linear Quadratic Gaussian (LQG) theory can compute the optimal gains for your goals.

See Koppang and Leland, 1999, IEEEE Trans. Ultrason. Ferroelect., Freq. Control 46, pp 517-522.

See also Appendix IV.

Some Ways to Set Gains

- LQG Theory
  - A compromise between goals
- Pole Placement
  - Set response times
- Gentle Steering
  - Minimum amount of steering to achieve desired phase and frequency shift

MILD Recommendation

- Estimate difference in UTC-UTC(k), 30 days into the future
  - When next Circular T comes
  - Assuming you did nothing
- Steer so that 30 days into the future you will have removed 50% of the predicted frequency difference and 50% of the phase difference
  - Ignore frequency drift for steering
- Make one steer every 6 days
  - Use formula on next slide (N=5) …

“Gentle Steering”

Change clock’s time by Δx and frequency by Δy

Use N steers of magnitude U_n spaced τ seconds apart

Minimum Amount of Control Effort (U)

Ideal for steering to Circular T

http://www.pttimeeting.org: Koppang and Matsakis, PTTI-00, pp. 277-284

$$U = -\frac{6}{N(N+1)} \begin{bmatrix} \frac{1}{\tau} & \frac{2N-1}{3} \\ \frac{1}{\tau}\left(1-\frac{2}{N-1}\right) & -1+\frac{2N-1}{3} \\ \vdots & \vdots \\ -\frac{1}{\tau} & -(N-1)+\frac{2N-1}{3} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}$$

Warning !

- Be careful what you ask for ...
- With control theory, you might get it.
- Therefore, simulate control performance