TSCclock: A low cost, robust, accurate software clock for networked computers

Darryl Veitch
d.veitch@ee.unimelb.edu.au
http://www.cubinlab.ee.unimelb.edu.au/∼darryl
Collaboration with **Julien Ridoux**

CUBIN, Department of Electrical & Electronic Engineering
The University of Melbourne

Google Tech Talk, Googleplex CA, July 23, 2007

We Need Clocks

The Obvious

- Clocks used everywhere in networking and computing
- Network measurement (active and passive)
- Real-time services

The Future

- Tighter server integration
- Coordination of simultaneous multiple connections
- Latency a fundamental constraint in distributed services/computing
  Example: Virtual world realism in distributed games

We Need Clocks

The Obvious

- Clocks used everywhere in networking and computing
- Network measurement (active and passive)
- Real-time services

The Future

- Tighter server integration
- Coordination of simultaneous multiple connections
- Latency a fundamental constraint in distributed services/computing
  Example: Virtual world realism in distributed games

And Want Good Clocks

Reliability/Robustness

- Can't build tight systems unless have bounds
- Status quo (*ntpd*) can be 'good' (1ms), bad (20ms), outrageous (100's ms)
- Measurement community pushed to GPS synchronized capture cards

Accuracy

- Greater accuracy → wider range of applications
- Status quo (*ntpd*) limited to 1ms, if all is well..
- Constant error versus 'jitter', absolute time versus time differences

Affordability

- Use existing hardware (oscillator(s) in PCs)
- Network based synchronization cheap and convenient
- But GPS also cheap, right?

And Want Good Clocks

Reliability/Robustness

- Can't build tight systems unless have bounds
- Status quo (*ntpd*) can be 'good' (1ms), bad (20ms), outrageous (100's ms)
- Measurement community pushed to GPS synchronized capture cards

Accuracy

- Greater accuracy → wider range of applications
- Status quo (*ntpd*) limited to 1ms, if all is well..
- Constant error versus 'jitter', absolute time versus time differences

Affordability

- Use existing hardware (oscillator(s) in PCs)
- Network based synchronization cheap and convenient
- But GPS also cheap, right?

And Want Good Clocks

Reliability/Robustness

- Can't build tight systems unless have bounds
- Status quo (*ntpd*) can be 'good' (1ms), bad (20ms), outrageous (100's ms)
- Measurement community pushed to GPS synchronized capture cards

Accuracy

- Greater accuracy → wider range of applications
- Status quo (*ntpd*) limited to 1ms, if all is well..
- Constant error versus 'jitter', absolute time versus time differences

Affordability

- Use existing hardware (oscillator(s) in PCs)
- Network based synchronization cheap and convenient
- But GPS also cheap, right?

And Want Good Clocks

Reliability/Robustness

- Can't build tight systems unless have bounds
- Status quo (*ntpd*) can be 'good' (1ms), bad (20ms), outrageous (100's ms)
- Measurement community pushed to GPS synchronized capture cards

Accuracy

- Greater accuracy → wider range of applications
- Status quo (*ntpd*) limited to 1ms, if all is well..
- Constant error versus 'jitter', absolute time versus time differences

Affordability

- Use existing hardware (oscillator(s) in PCs)
- Network based synchronization cheap and convenient
- But GPS also cheap, WRONG!
  Can cost 12 months and $10,000 to instrument a machine room

The TSCclock

Design

- Re-engineered from scratch
- Built on
  - time-scale aware abstraction of oscillator performance
  - separate and decoupled treatment of rate and absolute time
  - RTT based delay filtering
  - feedforward not feedback
- Use oscillator driving CPU, accessible via TSC register
  (commonly available, high resolution, hardware updating, fast read)

Provides

- Very high robustness
- Accuracy an order of magnitude higher than *ntpd* (or more)
- Separate Absolute and Difference clocks

The TSCclock

Design

- Re-engineered from scratch
- Built on
  - time-scale aware abstraction of oscillator performance
  - separate and decoupled treatment of rate and absolute time
  - RTT based delay filtering
  - feedforward not feedback
- Use oscillator driving CPU, accessible via TSC register (commonly available, high resolution, hardware updating, fast read)

Provides

- Very high robustness
- Accuracy an order of magnitude higher than *ntpd* (or more)
- Separate Absolute and Difference clocks

The TSCclock

Design

- Re-engineered from scratch NOT just the fact that TSC is used!
- Built on
  - time-scale aware abstraction of oscillator performance
  - separate and decoupled treatment of rate and absolute time
  - RTT based delay filtering
  - feedforward not feedback
- Use oscillator driving CPU, accessible via TSC register (commonly available, high resolution, hardware updating, fast read)

Provides

- Very high robustness
- Accuracy an order of magnitude higher than *ntpd* (or more)
- Separate Absolute and Difference clocks

The TSCclock

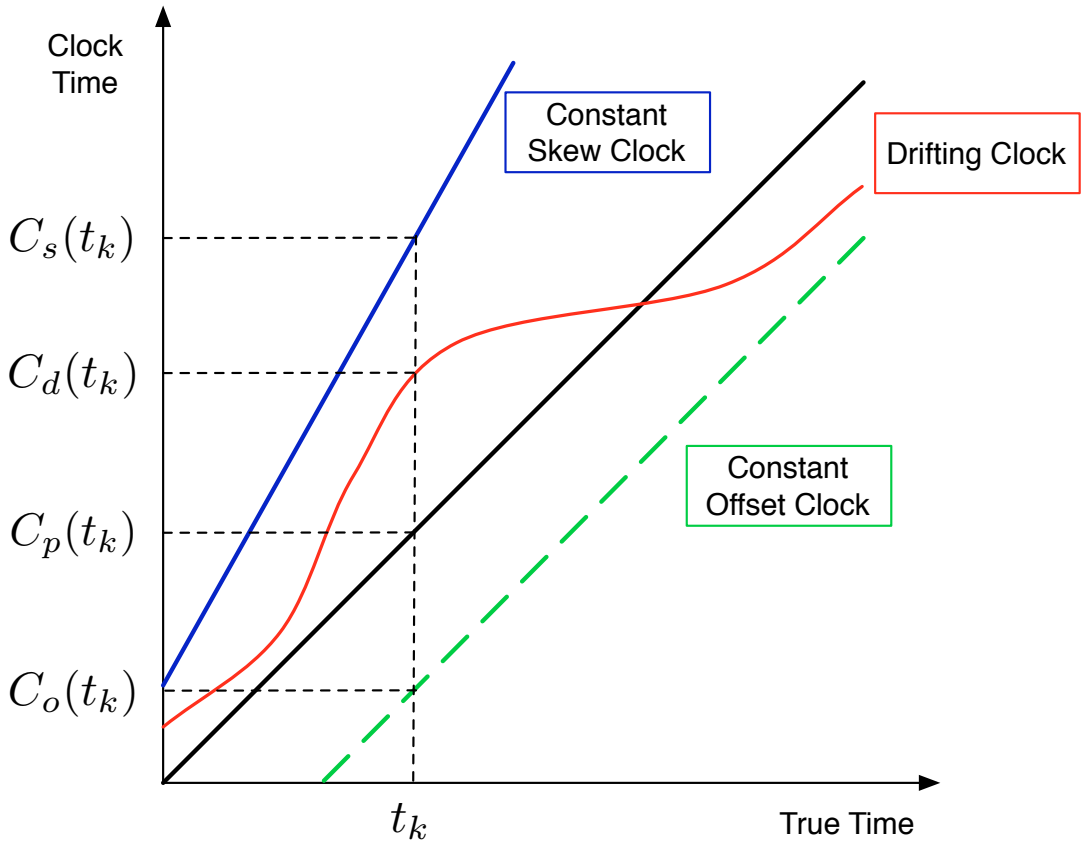
Design

- Re-engineered from scratch NOT just the fact that TSC is used!
- Built on
  - time-scale aware abstraction of oscillator performance
  - separate and decoupled treatment of rate and absolute time
  - RTT based delay filtering
  - feedforward not feedback
- Use oscillator driving CPU, accessible via TSC register (commonly available, high resolution, hardware updating, fast read)

Provides

- Very high robustness
- Accuracy an order of magnitude higher than *ntpd* (or more)
- Separate Absolute and Difference clocks

Offset, Skew and Drift

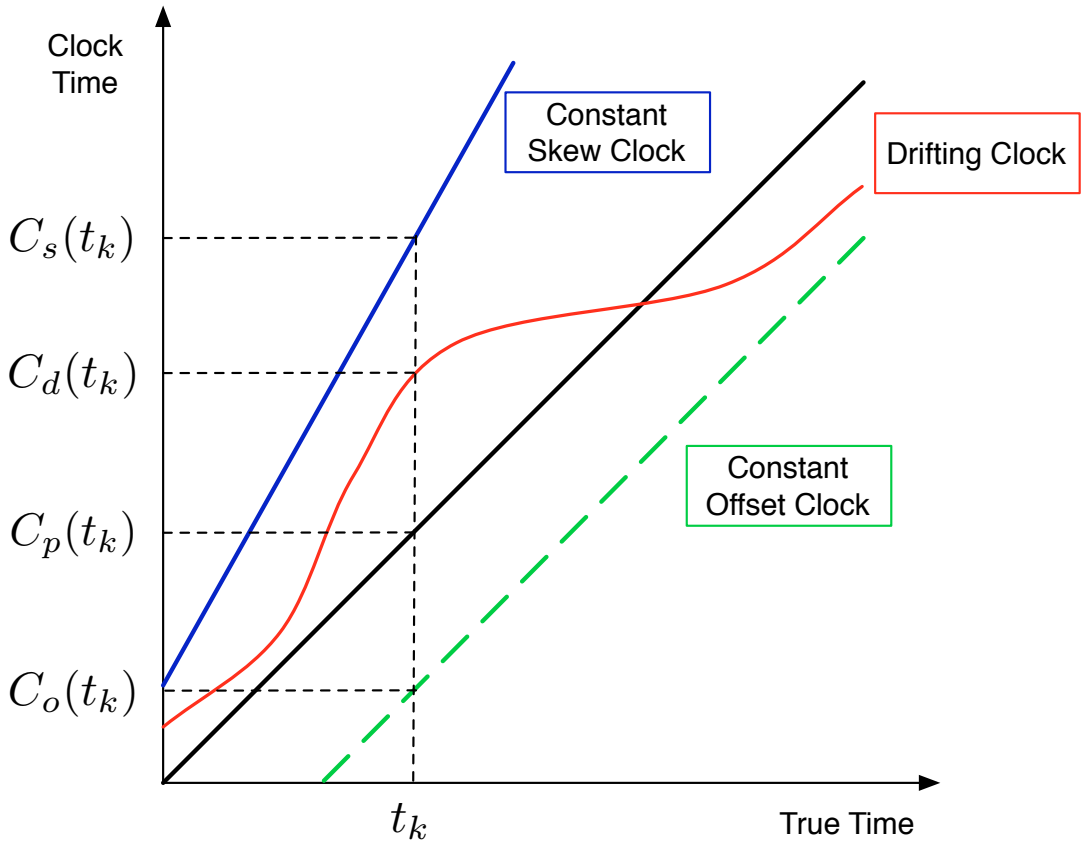


Offset: error $\theta(t) = C(t) - t$ of clock $C(t)$ at time t

Skew: error in rate. E.g.: $\theta(t) = C + \gamma t$ (*Simple Skew Model* (SKM))

Drift: non-linear evolution of $\theta(t)$

Offset, Skew and Drift



Offset: error $\theta(t) = C(t) - t$ of clock $C(t)$ at time t

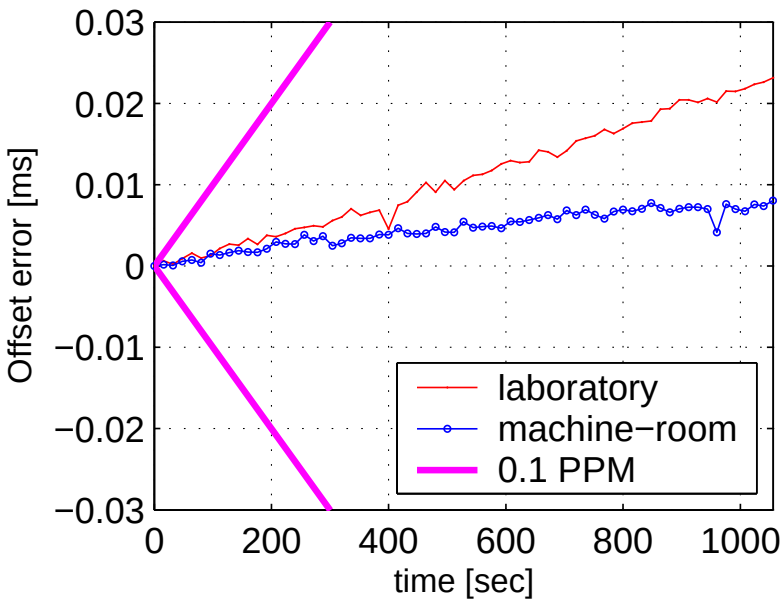
Skew: error in rate. E.g.: $\theta(t) = C + \gamma t$ (*Simple Skew Model* (SKM))

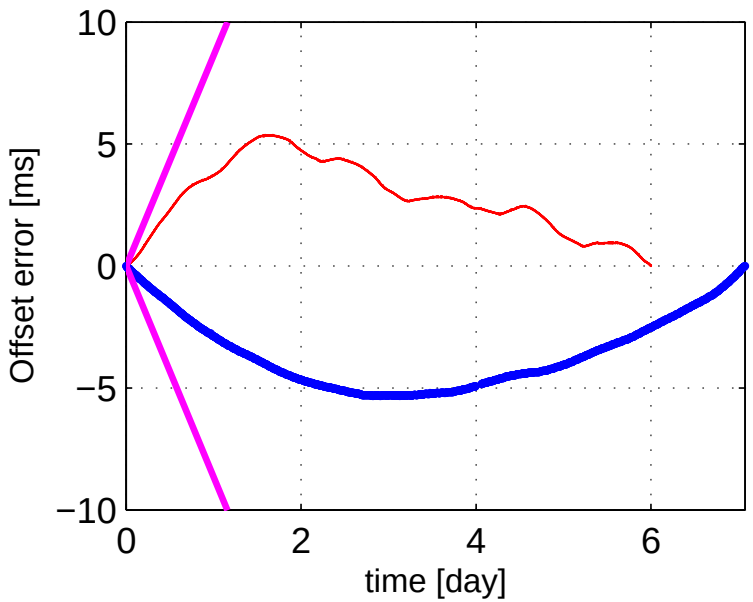
Drift: non-linear evolution of $\theta(t)$

The Role of Time Scale

Laboratory: $\bar{p} = 1.8226381 2 * 10^{-9}$ (548.65527 Mhz)

Machine Room: $\bar{p} = 1.8226383 2 * 10^{-9}$ (548.65521 Mhz)





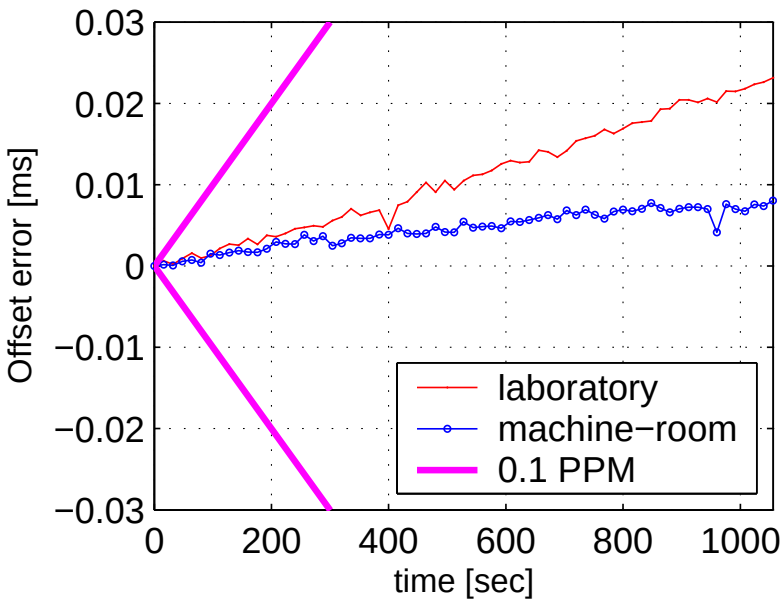
Short timescales: Simple Skew Model applies

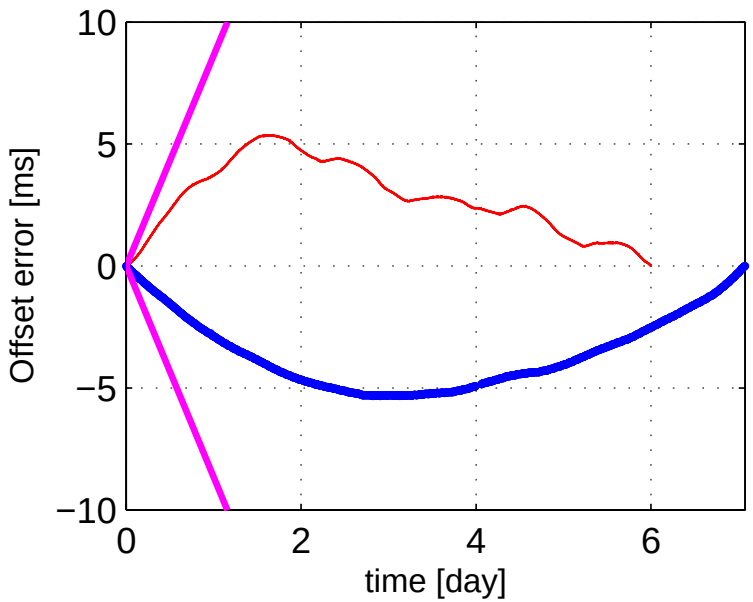
Large timescales: unpredictable drift must be tracked

The Role of Time Scale

Laboratory: $\bar{p} = 1.8226381{2} * 10^{-9}$ (548.6552{7} Mhz)

Machine Room: $\bar{p} = 1.8226383{2} * 10^{-9}$ (548.6552{1} Mhz)



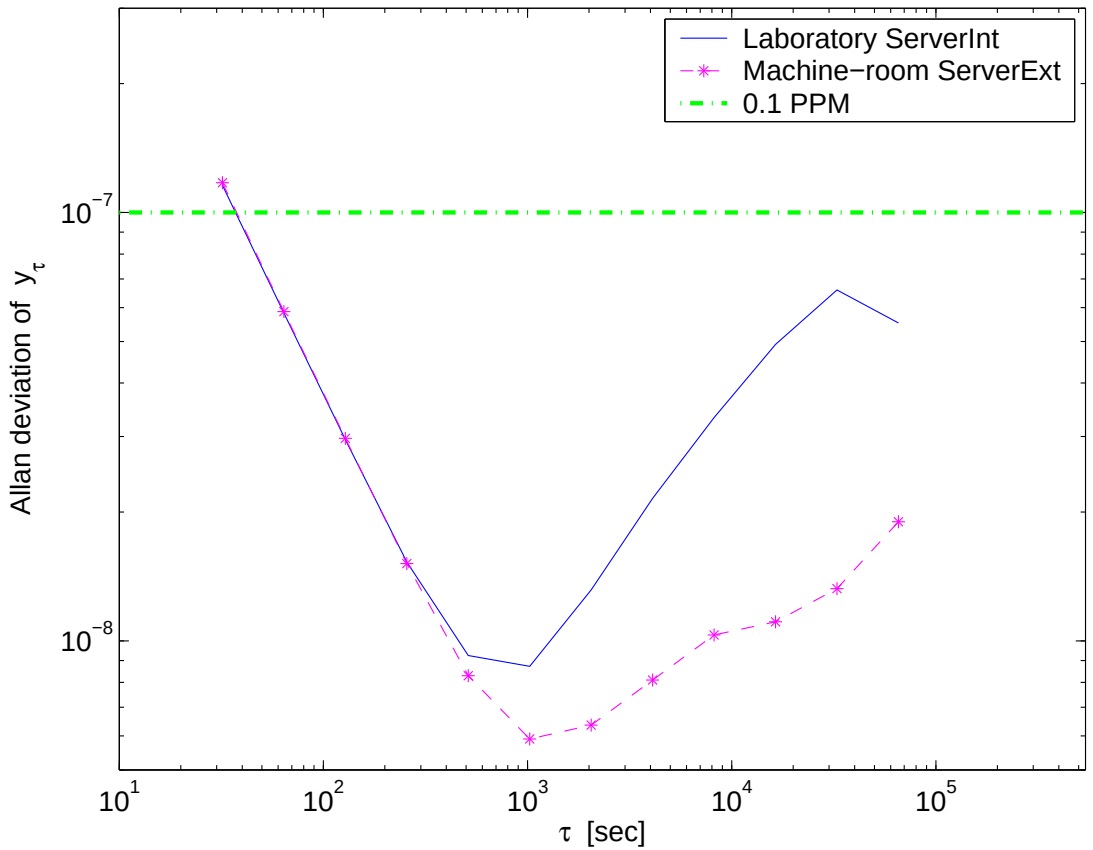


Short timescales: Simple Skew Model applies

Large timescales: unpredictable drift must be tracked

Oscillator Stability

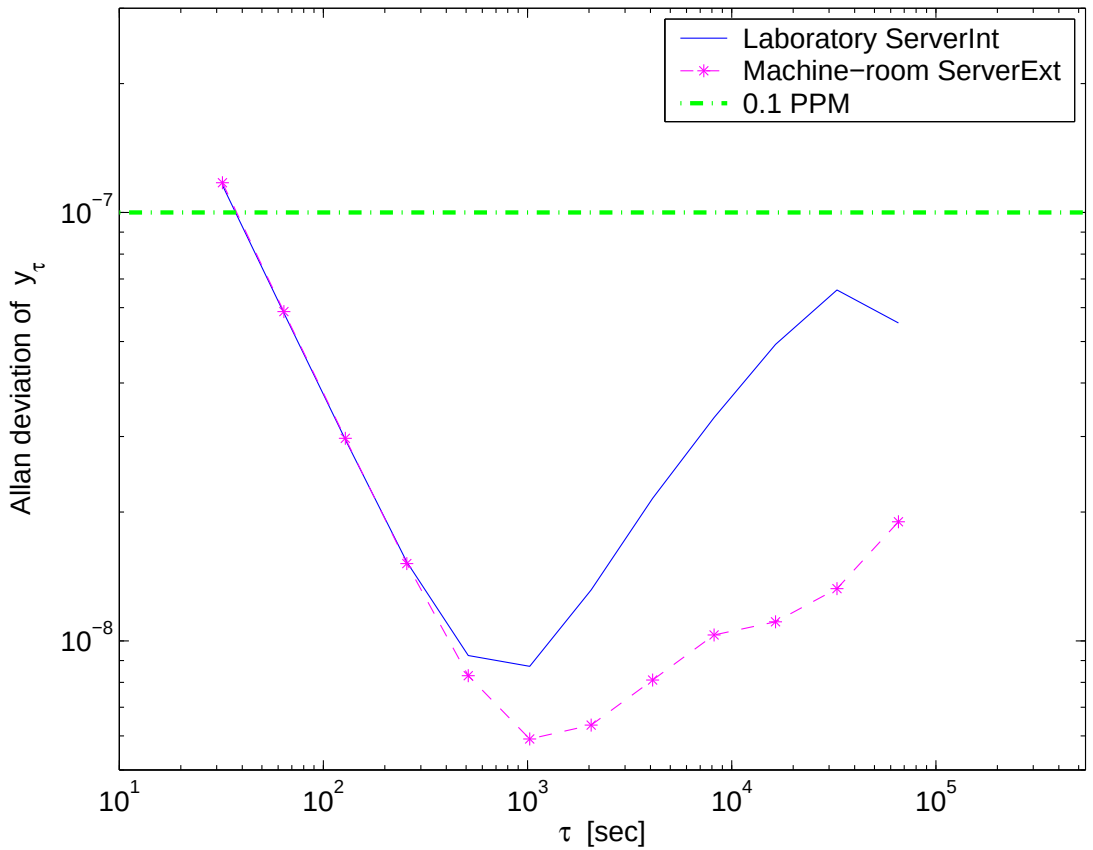
Allan deviation: scale dependent rate errors: $y_\tau(t) = \dfrac{\theta(t+\tau) - \theta(t)}{\tau}$



- SKM holds for $\tau^* = 1000$ [sec], (here TSC period p meaningful)
- Average rate error upper bounded by 0.1 PPM no matter the scale

Oscillator Stability

Allan deviation: scale dependent rate errors: $y_\tau(t) = \dfrac{\theta(t+\tau) - \theta(t)}{\tau}$



- SKM holds for $\tau^* = 1000$ [sec], (here TSC period p meaningful)
- Average rate error upper bounded by 0.1 PPM no matter the scale

The Need for Difference Clocks

Stable rate (p good to 10^{-7}) implies accurate $\Delta(t)$ measurement:

Example: error in RTT of 100ms just 10ns

However an absolute clock $C_a(t)$ requires constant correction to negate drift:

- To synchronize $C_a(t)$, could
  - continuously modulate rate (*ntpd* uses $\pm$500 PPM band)
  - regularly add corrective jumps
- Either way, rate is disturbed
- Effect large! since drift estimation inherently difficult

Result: high native stability degraded by unbounded amount!

The Need for Difference Clocks

Stable rate (p good to 10^{-7}) implies accurate $\Delta(t)$ measurement:
Example: error in RTT of 100ms just 10ns

However an absolute clock $C_a(t)$ requires constant correction to negate drift:

- To synchronize $C_a(t)$, could
  - continuously modulate rate (*ntpd* uses $\pm$500 PPM band)
  - regularly add corrective jumps
- Either way, rate is disturbed
- Effect large! since drift estimation inherently difficult

Result: high native stability degraded by unbounded amount!

The Need for Difference Clocks

Stable rate (p good to 10^{-7}) implies accurate $\Delta(t)$ measurement:
Example: error in RTT of 100ms just 10ns

However an absolute clock $C_a(t)$ requires constant correction to negate drift:

- To synchronize $C_a(t)$, could
  - continuously modulate rate (*ntpd* uses $\pm$500 PPM band)
  - regularly add corrective jumps
- Either way, rate is disturbed
- Effect large! since drift estimation inherently difficult

Result: high native stability degraded by unbounded amount!

A Dual Clock Architecture

Foundation is the *uncorrected clock*: $C_u(t) = \bar{p} \cdot \mathrm{TSC}(t) + K$

Difference Clock

- Used for time differences below $\tau^* \sim 1000$ sec
- $C_d(t) = C_u(t)$ Example: $C_d(t_2) - C_d(t_1) = \bar{p} \cdot (\mathrm{TSC}(t_2) - \mathrm{TSC}(t_1))$
- Immune from errors in drift correction
- Use: RTTs, delay jitter, execution time, local event ordering ..

Absolute Clock

- Absolute timestamps (and time differences above τ^*)
- $C_a(t) = C_u(t) - \hat{\theta}(t)$
- Drift correction estimate $\hat{\theta}(t)$ only applied when clock read
- Use: latency, global event ordering and scheduling ..

Require robust, accurate algorithms for $\bar{p}$ and $\hat{\theta}$

A Dual Clock Architecture

Foundation is the *uncorrected clock*: $C_u(t) = \bar{p} \cdot \mathrm{TSC}(t) + K$

Difference Clock

- Used for time differences below $\tau^* \sim 1000$ sec
- $C_d(t) = C_u(t)$ Example: $C_d(t_2) - C_d(t_1) = \bar{p} \cdot (\mathrm{TSC}(t_2) - \mathrm{TSC}(t_1))$
- Immune from errors in drift correction
- Use: RTTs, delay jitter, execution time, local event ordering ..

Absolute Clock

- Absolute timestamps (and time differences above τ^*)
- $C_a(t) = C_u(t) - \hat{\theta}(t)$
- Drift correction estimate $\hat{\theta}(t)$ only applied when clock read
- Use: latency, global event ordering and scheduling ..

Require robust, accurate algorithms for $\bar{p}$ and $\hat{\theta}$

A Dual Clock Architecture

Foundation is the *uncorrected clock*: $C_u(t) = \bar{p} \cdot \mathrm{TSC}(t) + K$

Difference Clock

- Used for time differences below $\tau^* \sim 1000$ sec
- $C_d(t) = C_u(t)$ Example: $C_d(t_2) - C_d(t_1) = \bar{p} \cdot (\mathrm{TSC}(t_2) - \mathrm{TSC}(t_1))$
- Immune from errors in drift correction
- Use: RTTs, delay jitter, execution time, local event ordering ..

Absolute Clock

- Absolute timestamps (and time differences above τ^*)
- $C_a(t) = C_u(t) - \hat{\theta}(t)$
- Drift correction estimate $\hat{\theta}(t)$ only applied when clock read
- Use: latency, global event ordering and scheduling ..

Require robust, accurate algorithms for $\bar{p}$ and $\hat{\theta}$

A Dual Clock Architecture

Foundation is the *uncorrected clock*: $C_u(t) = \bar{p} \cdot \mathrm{TSC}(t) + K$

Difference Clock

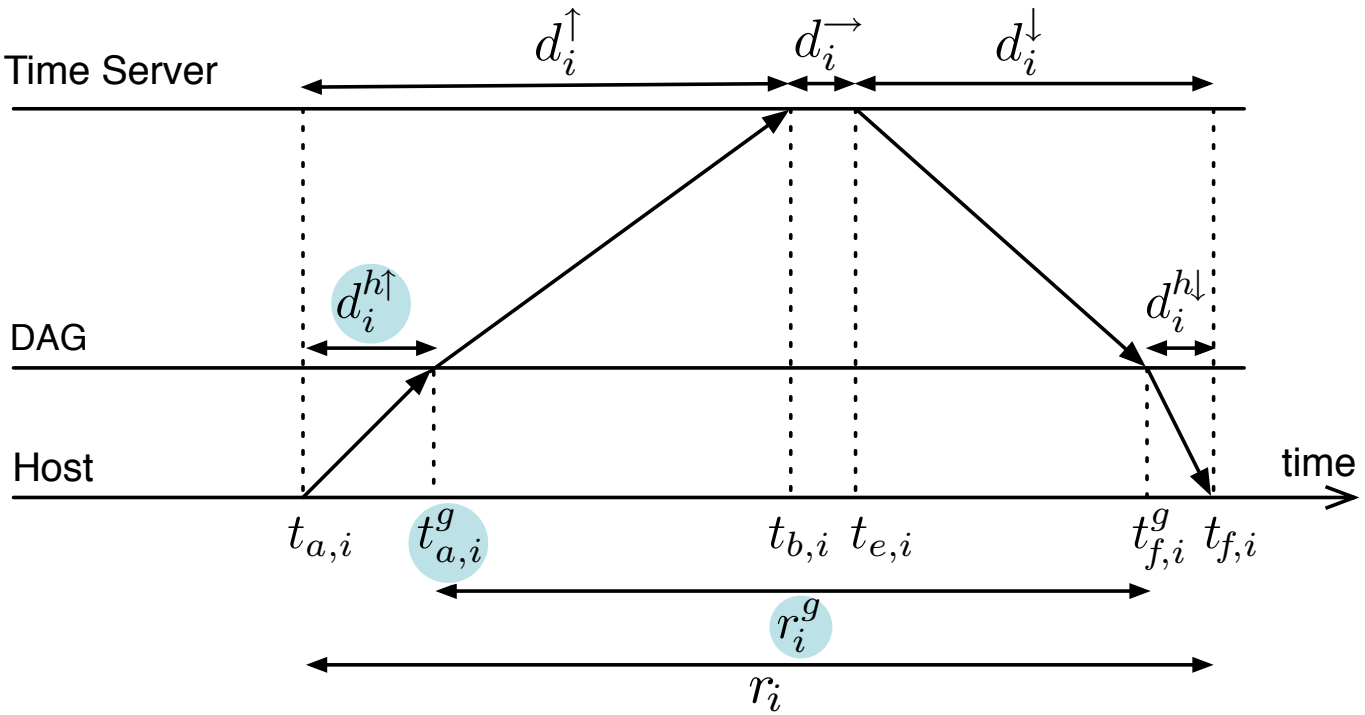
- Used for time differences below $\tau^* \sim 1000$ sec
- $C_d(t) = C_u(t)$ Example: $C_d(t_2) - C_d(t_1) = \bar{p} \cdot (\mathrm{TSC}(t_2) - \mathrm{TSC}(t_1))$
- Immune from errors in drift correction
- Use: RTTs, delay jitter, execution time, local event ordering ..

Absolute Clock

- Absolute timestamps (and time differences above τ^*)
- $C_a(t) = C_u(t) - \hat{\theta}(t)$
- Drift correction estimate $\hat{\theta}(t)$ only applied when clock read
- Use: latency, global event ordering and scheduling ..

Require robust, accurate algorithms for $\bar{p}$ and $\hat{\theta}$

A Client-Server Paradigm



Obtain timestamps $\{T_{a,i}, T_{b,i}, T_{e,i}, T_{f,i}\}$ from i-th exchange

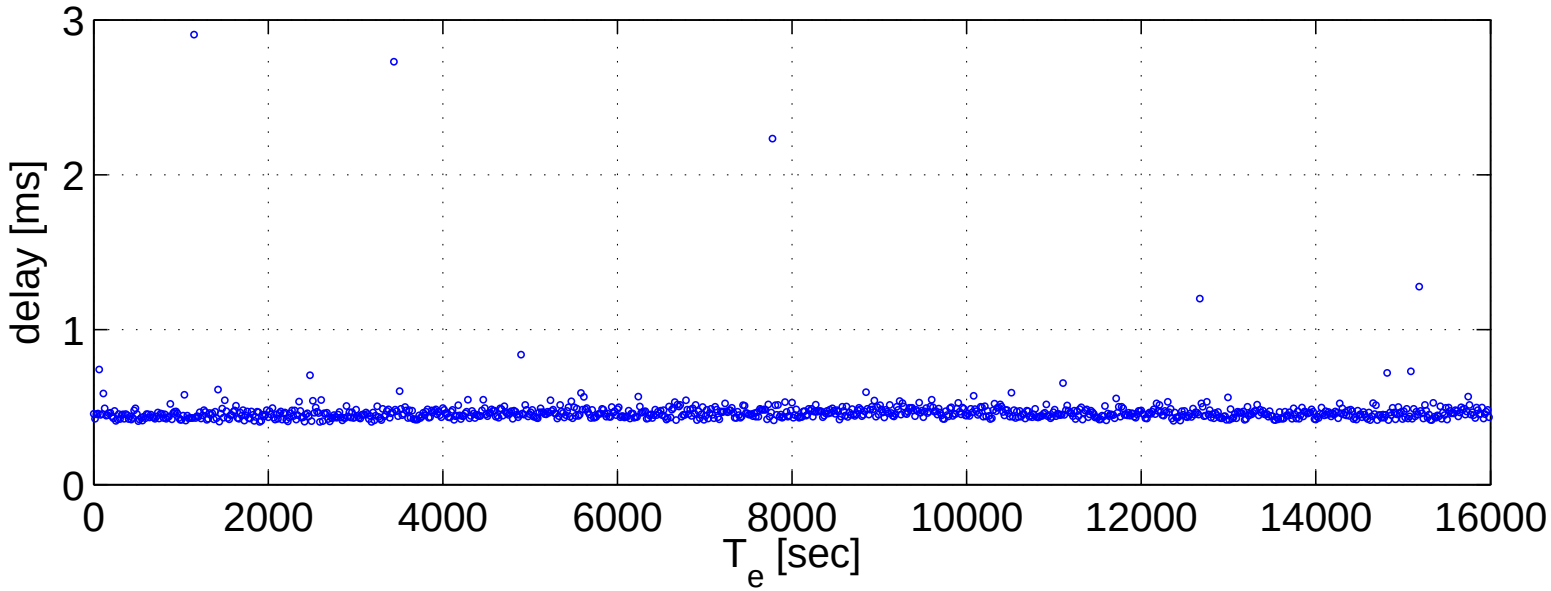
$\{T_{a,i}, T_{f,i}\}$: host timestamps in TSC counter units

$\{T_{b,i}, T_{e,i}\}$: server timestamps in seconds

Filtering Network Delays

Choose RTT based filtering, not one-way (using same clock good!)

Round–Trip Times r_i of packet i



Model for RTT: $r_i = r +$ positive random noise

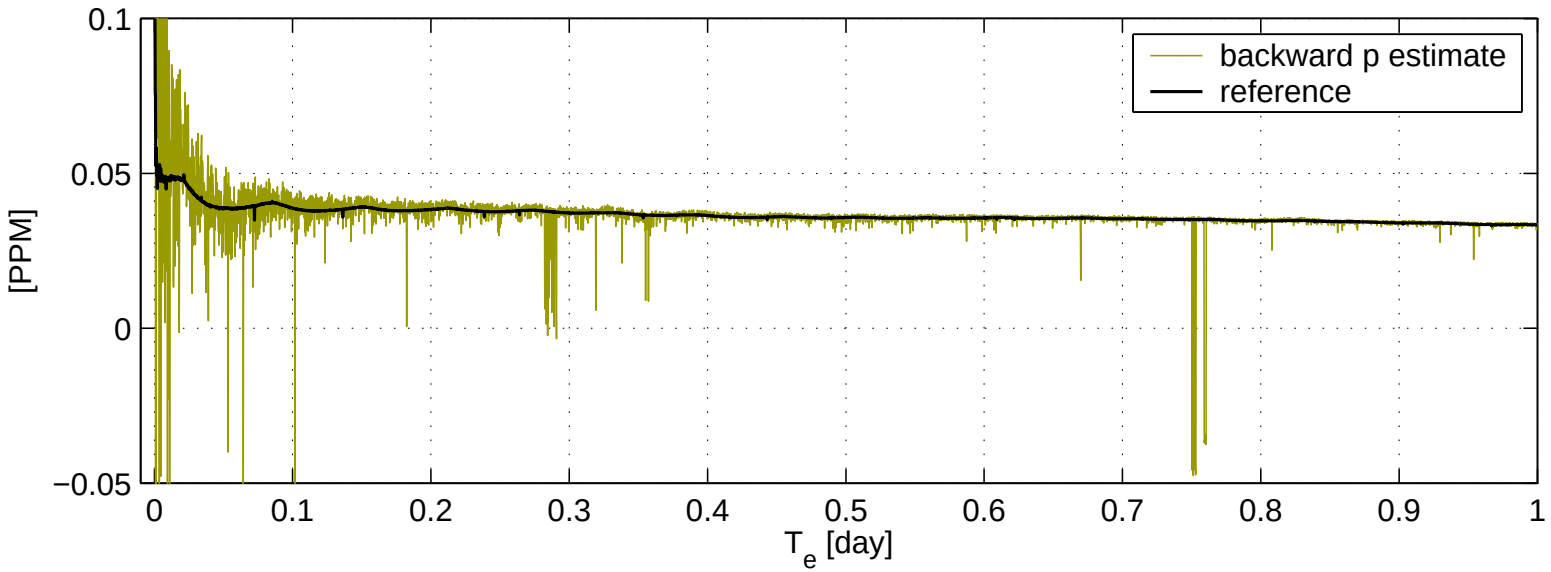
Filter using point error: excess over minimum RTT

NAIVE RATE SYNCHRONIZATION

Wish to exploit the relation $\Delta(t) = \Delta(\text{TSC}) * \bar{p}$

Naive estimate based on widely separated packets $j$and i:

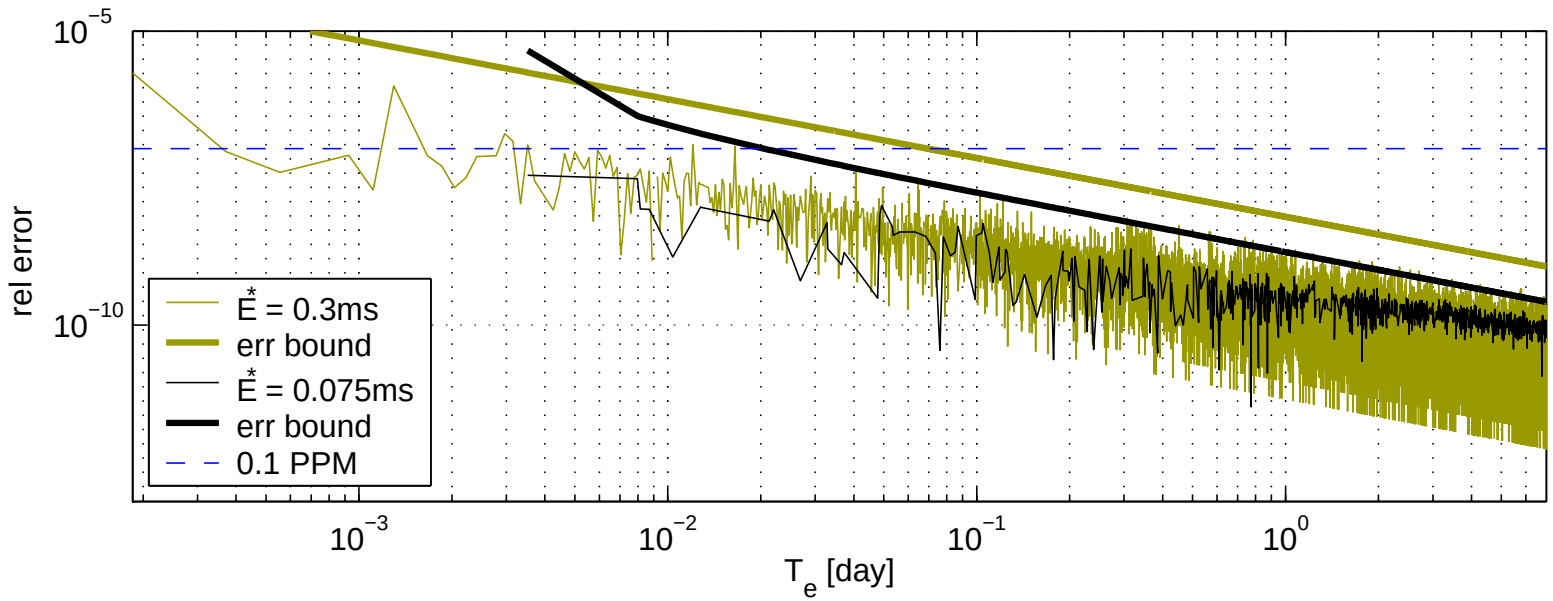
$$\hat{p}^{\uparrow}_{i,j} \equiv \frac{T_{b,i} - T_{b,j}}{T_{a,i} - T_{a,j}}$$



Network delay and timestamping noise $\sim \frac{1}{\Delta(\text{TSC})}$, but errors not bounded.

RATE SYNCHRONIZATION ALGORITHM

Use selected naive estimates based on point error threshold

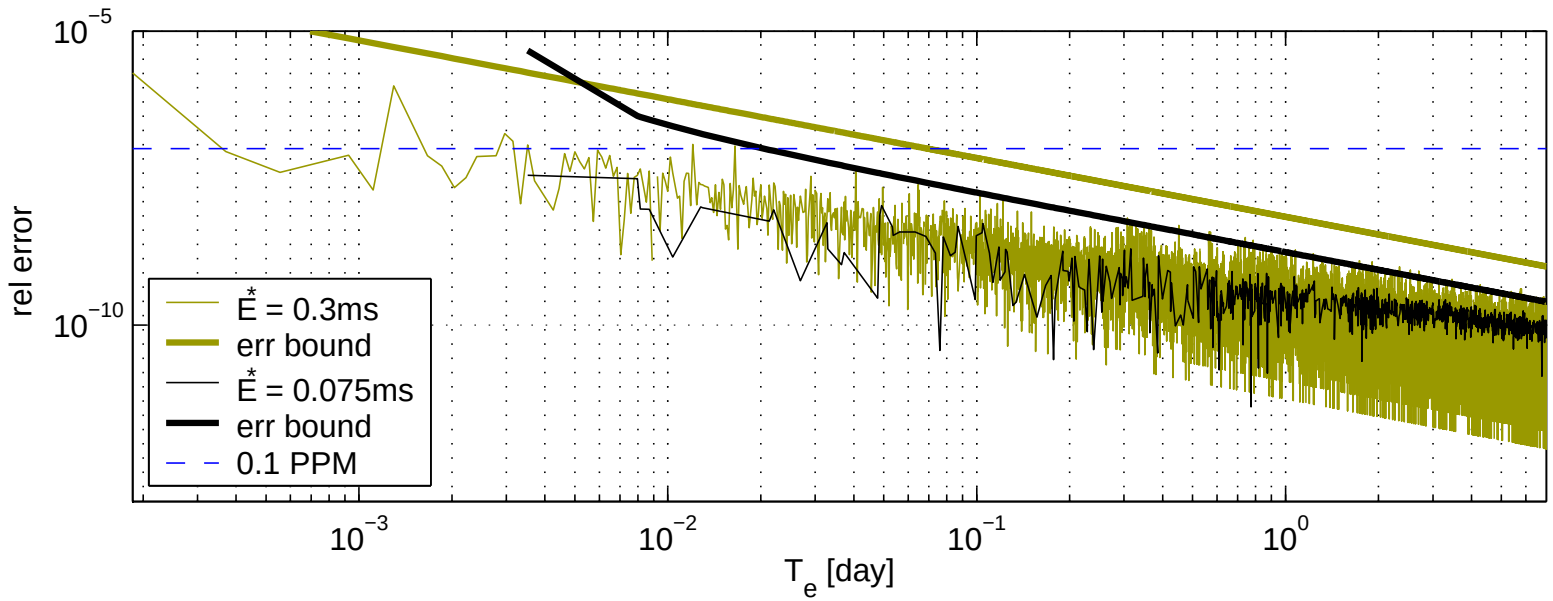


PROPERTIES

- Error quickly < 0.1 PPM, In 10mins, better than GPS!
- Error reduction (in timestamping, latency) guaranteed by $\Delta(t)$
- Inherently robust to packet loss, congestion, loss of server..
- Based on $\bar{p}$, no local rate estimates

RATE SYNCHRONIZATION ALGORITHM

Use selected naive estimates based on point error threshold



PROPERTIES

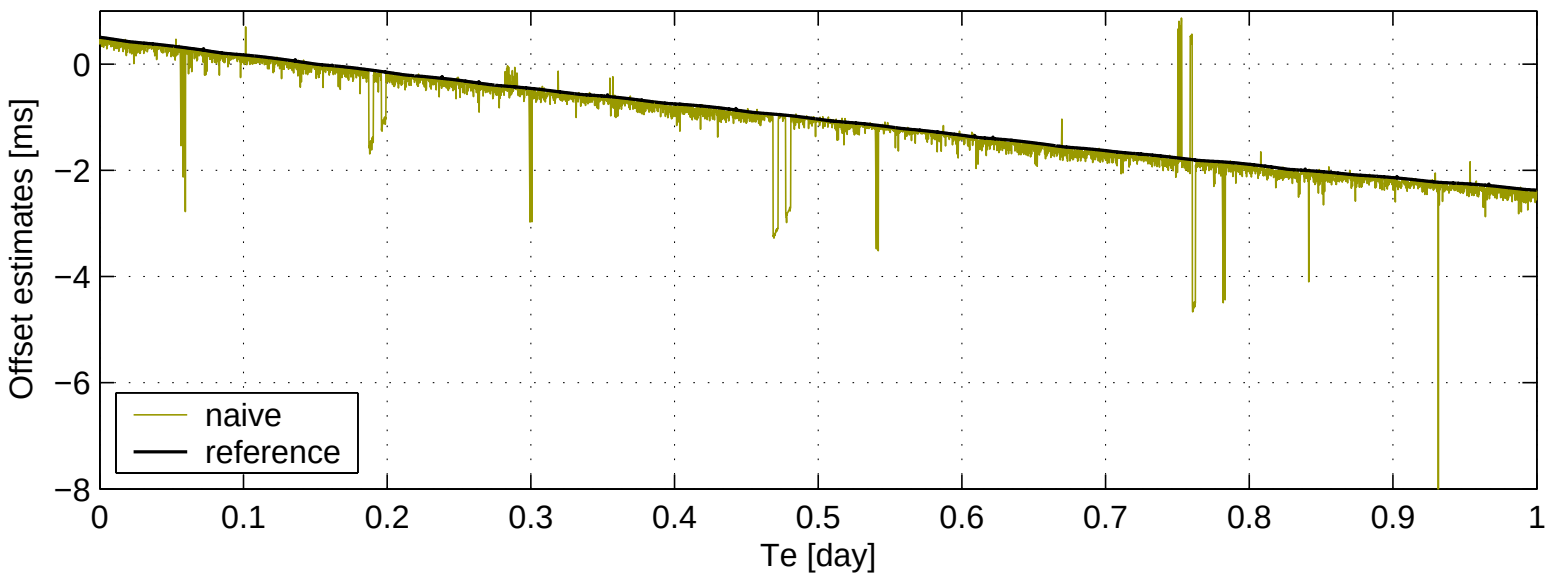
- Error quickly < 0.1 PPM, In 10mins, better than GPS!
- Error reduction (in timestamping, latency) guaranteed by $\Delta(t)$
- Inherently robust to packet loss, congestion, loss of server..
- Based on $\bar{p}$, no local rate estimates

NAIVE ABSOLUTE SYNCHRONIZATION

Wish to exploit SKM over small scales to measure $\theta(t)$

Naive estimate again ignores network congestion, exploits steady rate over RTT

$$\hat{\theta}_i = \frac{1}{2}(C(t_{a,i}) + C(t_{f,i})) - \frac{1}{2}(T_{b,i} + T_{e,i})$$

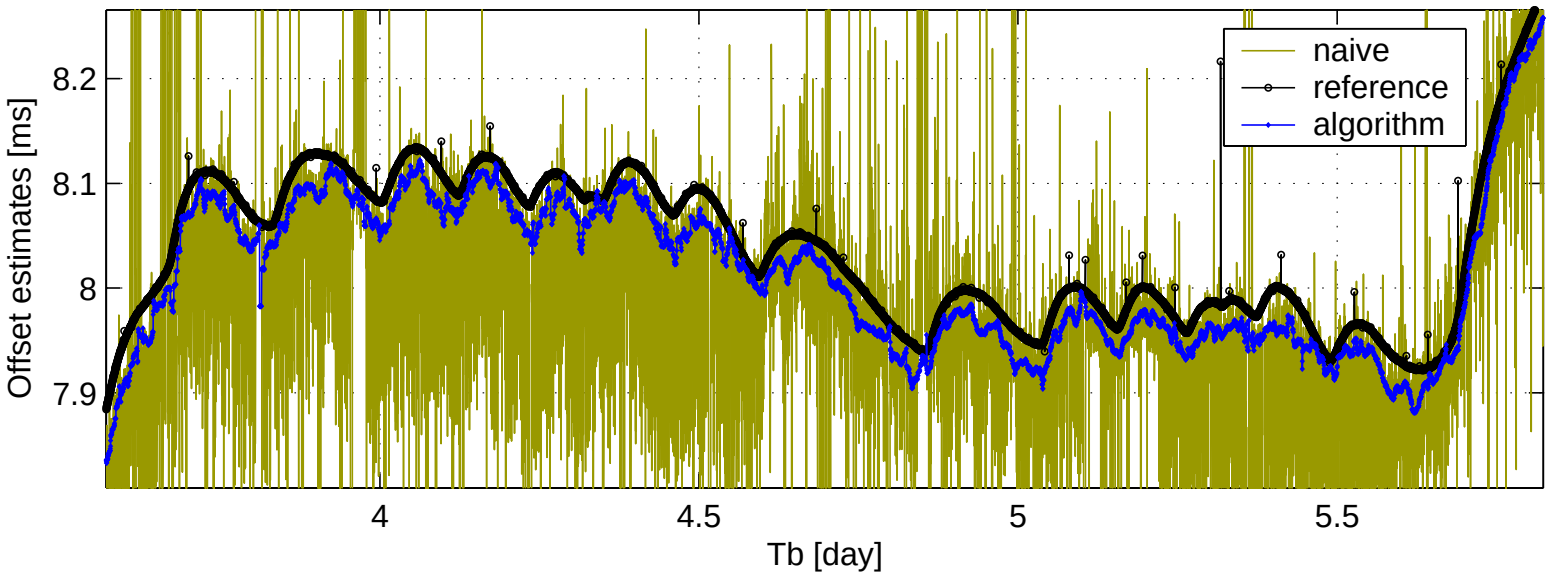


ABSOLUTE SYNCHRONIZATION ALGORITHM

Must track, so use all naive estimates, but carefully

ALGORITHM FOR $\hat{\theta}(t)$

- Weighted estimate of naive θ_i's over SKM window
- Weights very strict, based on RTT quality (if quality very bad, freeze)
- Meaningful sanity check: ignore if hardware rate bound exceeded



The Path Asymmetry

Fundamental Ambiguity

Asymmetry $A \equiv d^{\uparrow} - d^{\downarrow}$ and $2\theta(t)$ non-unique up to a constant.

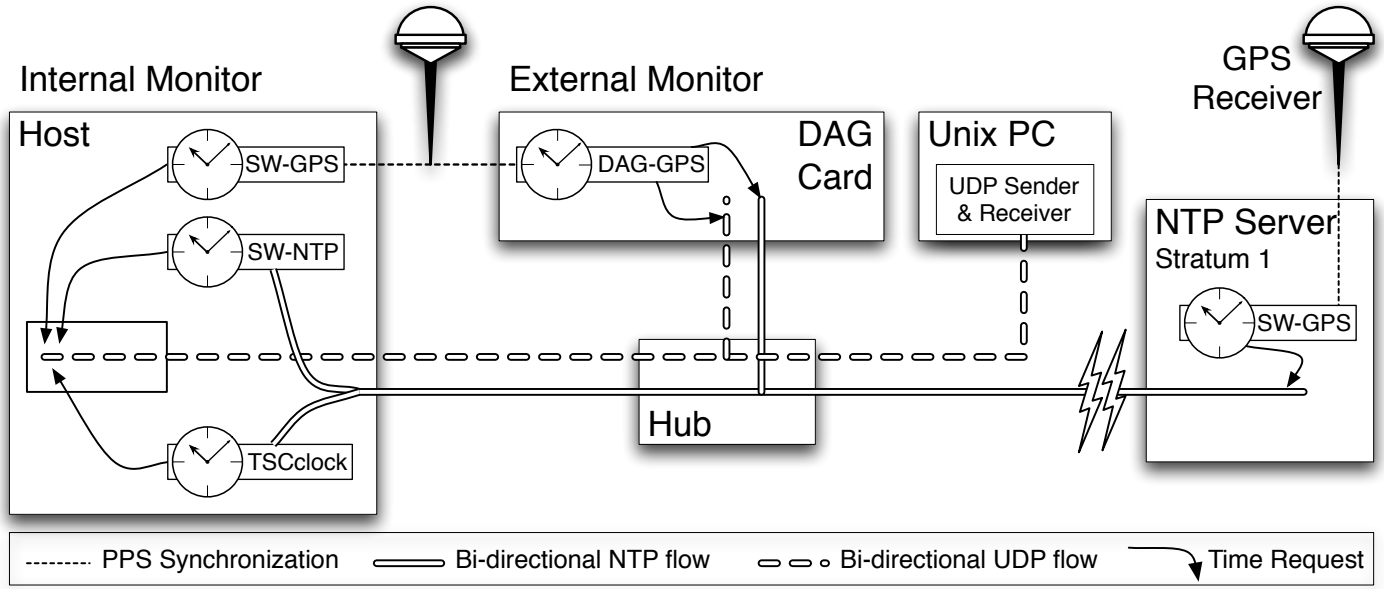
Impact on Absolute Clock

- A unknown: generally forced to assume $A = 0$
- However, bounded by minimum RTT: $A \in (-r, r)$
- Create constant errors from 5μs to 100's ms
- Causes jumps when server changed
- $\rightarrow$ Important to use a single, close, server.

Impact on Difference Clock

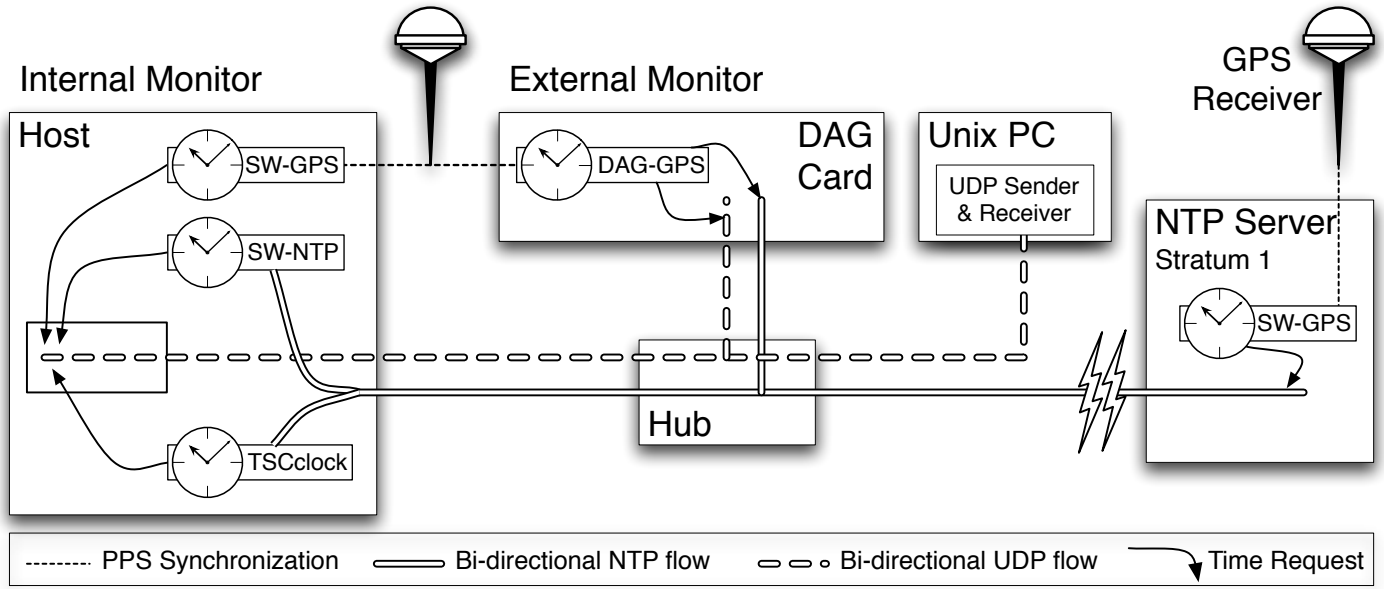
- None
- Difference clock can be used to measure r

TESTBED



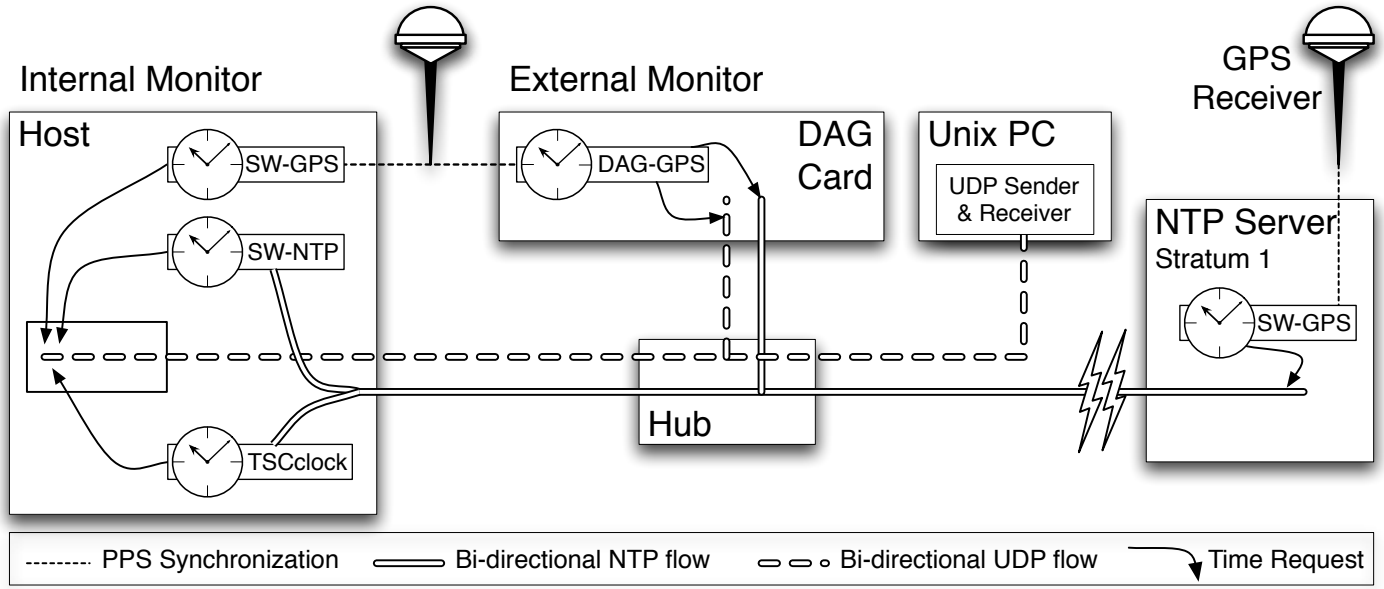
- GPS synchronized DAG card for *external* validation
- GPS synchronized SW and modified kernels for *internal* validation

TESTBED



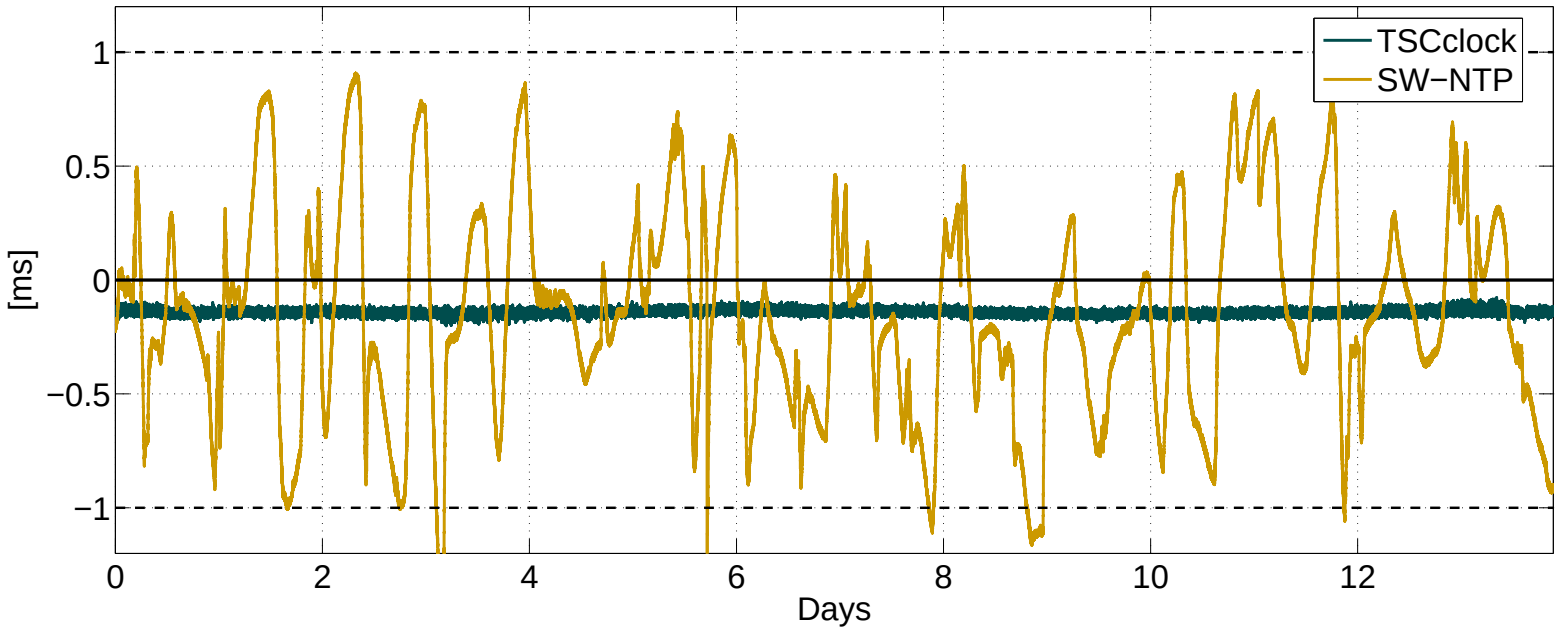
- GPS synchronized DAG card for *external* validation
  - timestamps accurate to 100ns, but
  - comparison polluted by 'system noise'
  - splits asymmetry: $A = A_n + A_h$
  - allows network component A_n to be measured
  - host component A_h can only be bounded, can be >200μs!
- GPS synchronized SW and modified kernels for *internal* validation

TESTBED



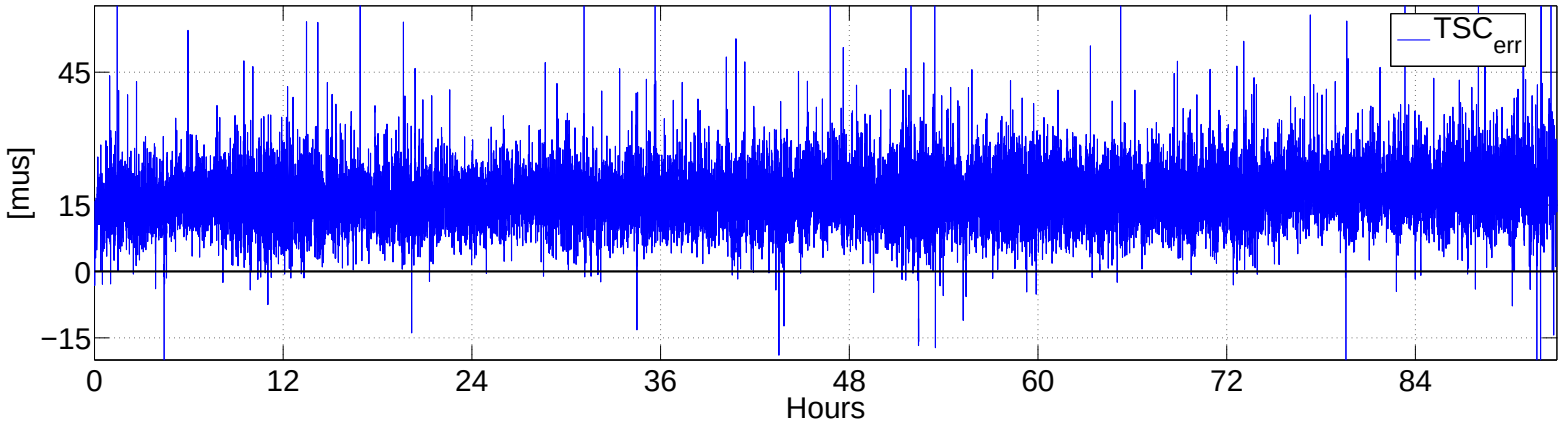
- GPS synchronized DAG card for *external* validation
- GPS synchronized SW and modified kernels for *internal* validation
  - side by side timestamps cancels noise, but
  - only relative performance measurable, not absolute

A Quick Comparison with *ntpd*

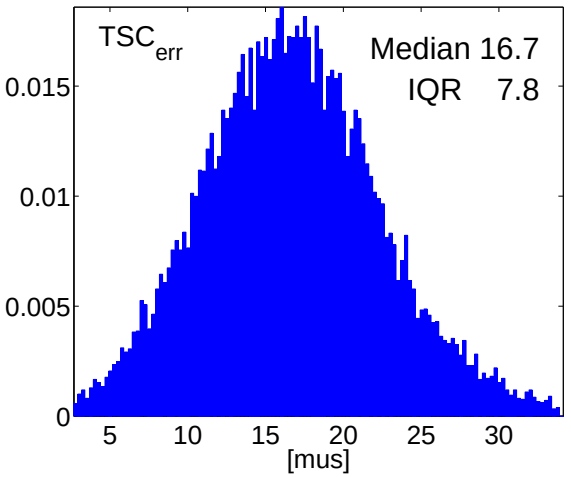


ntpd: sync'd to stratum-1 NTP server on LAN (broadcast mode)
TSCclock: sync'd to stratum-1 NTP server outside LAN

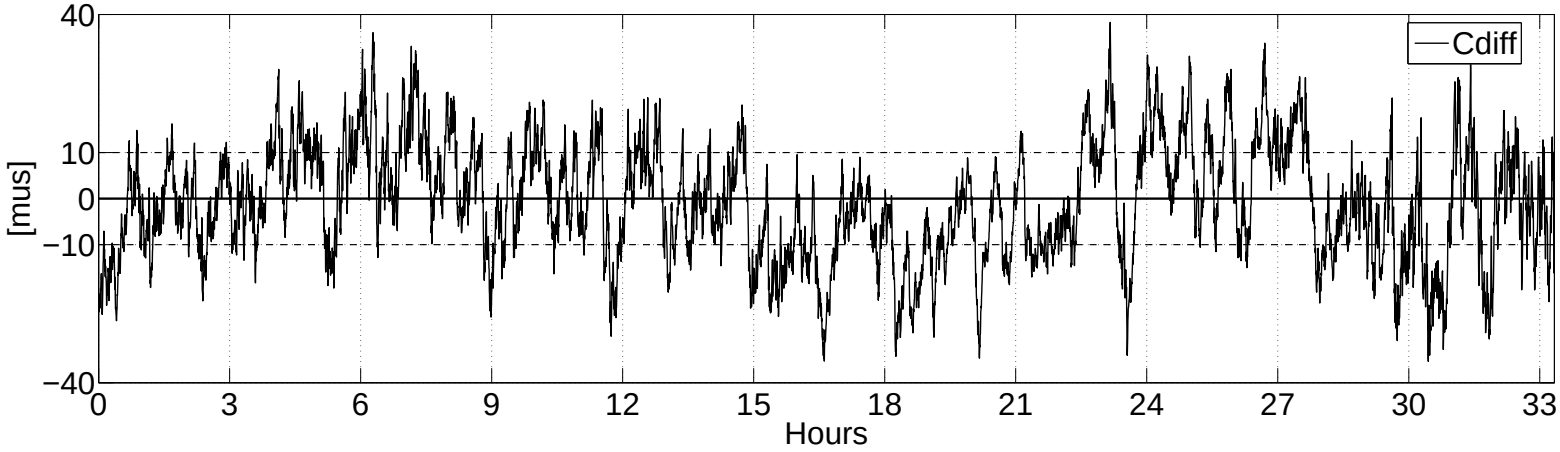
External Validation: TSCclock vs DAG



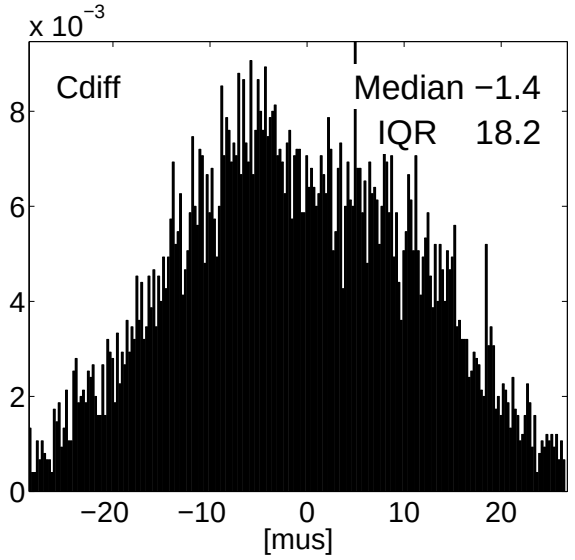
Server: Stratum-1 NTP on LAN
Polling Period: 256 sec
System Noise: $\sim 20\mu s$
Asymmetry: Measured at $36\mu s$ and removed



INTERNAL VALIDATION: TSCCLOCK VS SW-GPS

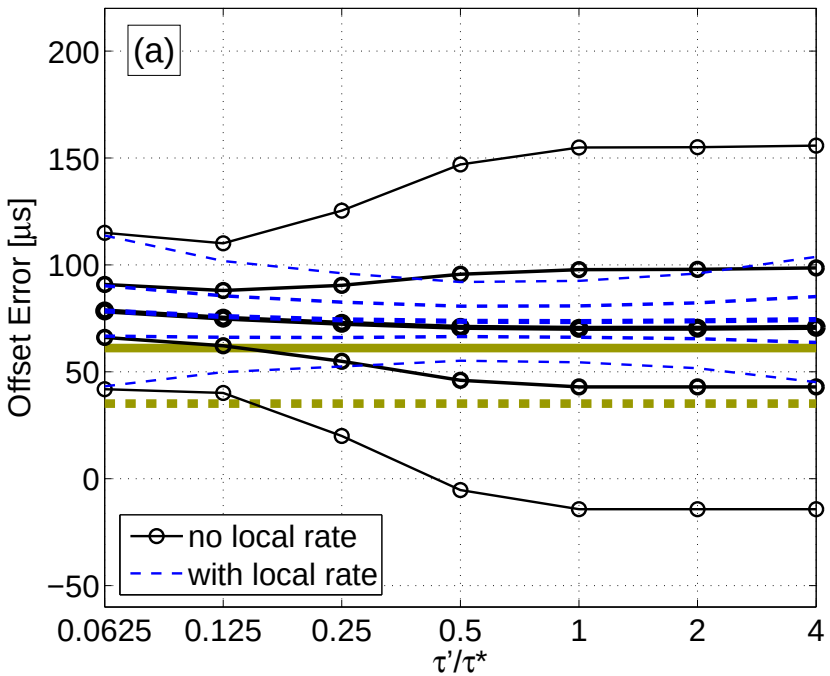


Server: Stratum-1 outside LAN
Polling Period: 16 sec
System Noise: $\ll 1\mu$s
Asymmetry: As before for TSCclock, but SW-GPS component?

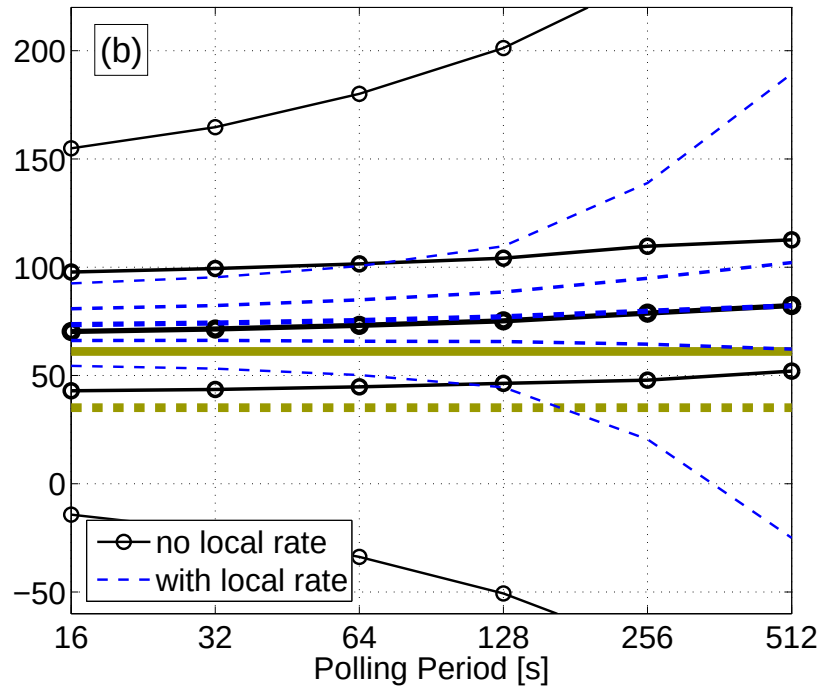


Parameter Dependence

window width



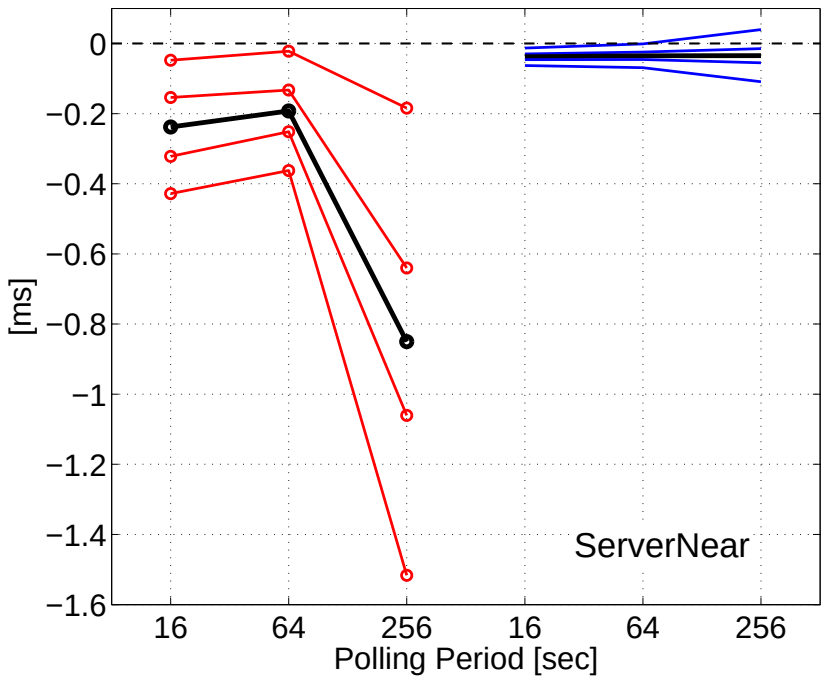
polling period



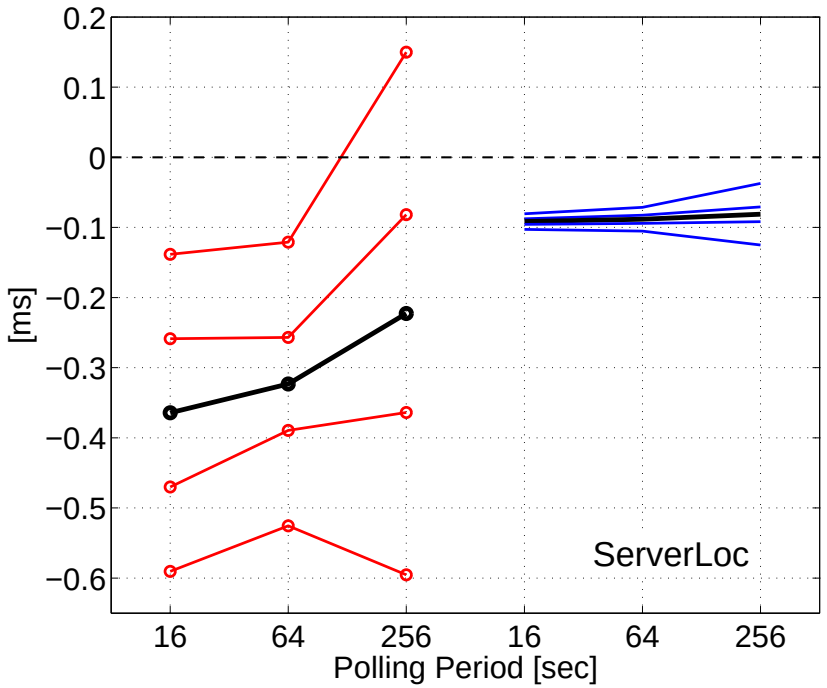
Duration: 32 days
Server: Stratum-1 NTP, 5 hops away, $r = 0.61$ ms
Poll Period: 16 sec
Asymmetry: $A_n = 70\ \mu$s
Median IQR: 12μs (corrected for A)
IQR: 15μs (including external validation noise)

COMPARISON WITH *nptd*

Server on LAN

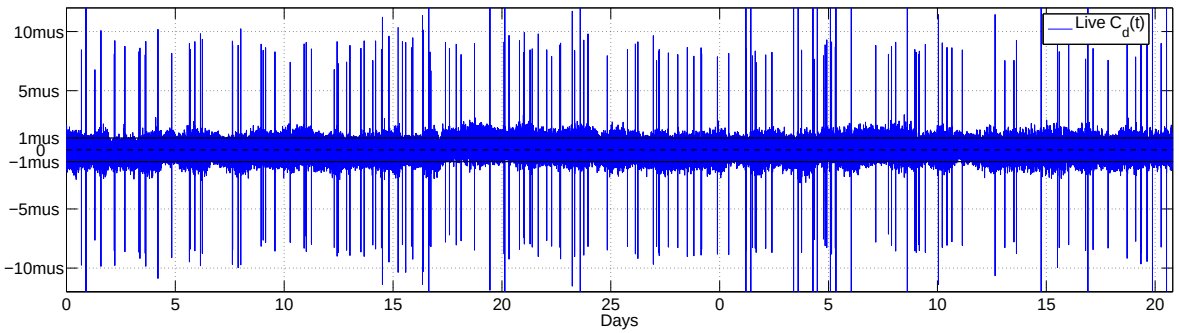


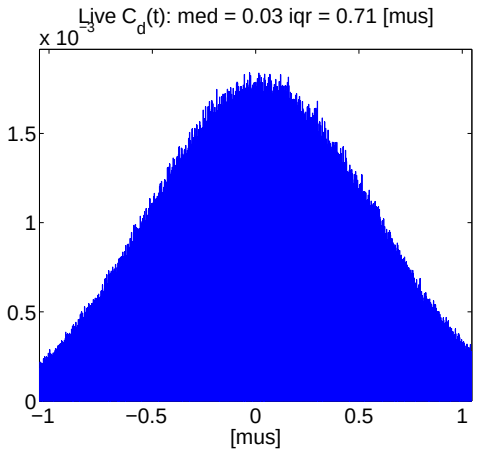
Server outside LAN



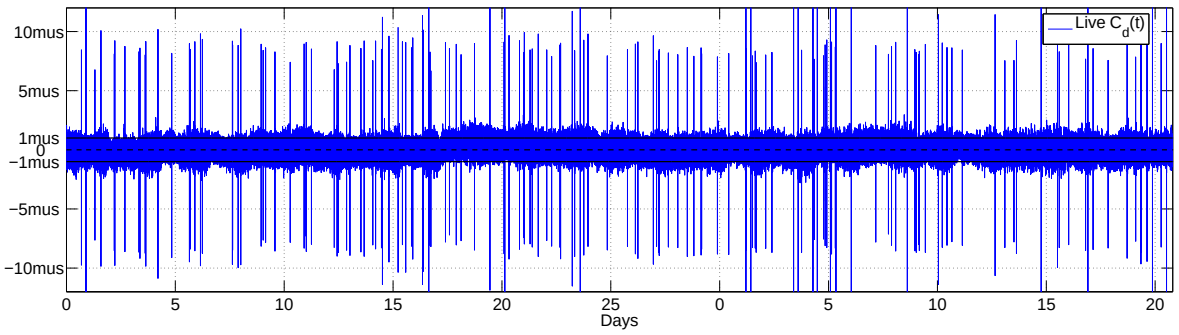
Asymmetry: Same for each clock

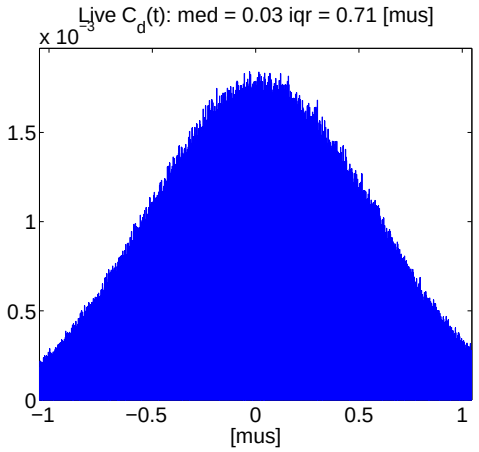
DIFFERENCE CLOCK VERSUS GPS





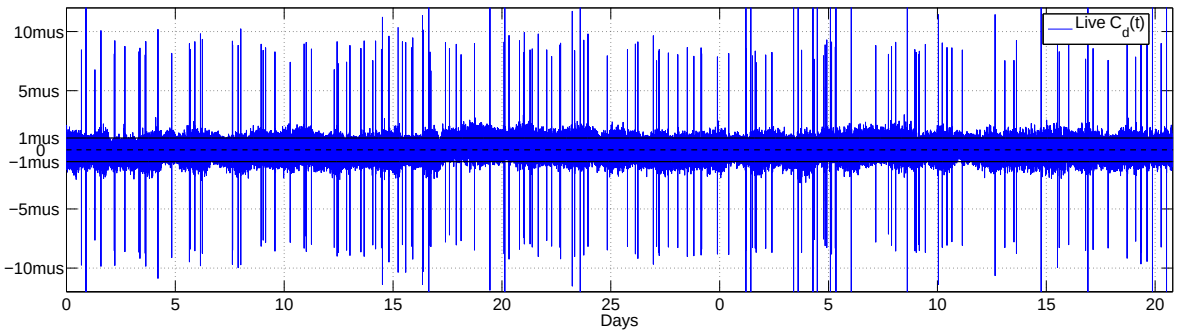
DIFFERENCE CLOCK VERSUS GPS

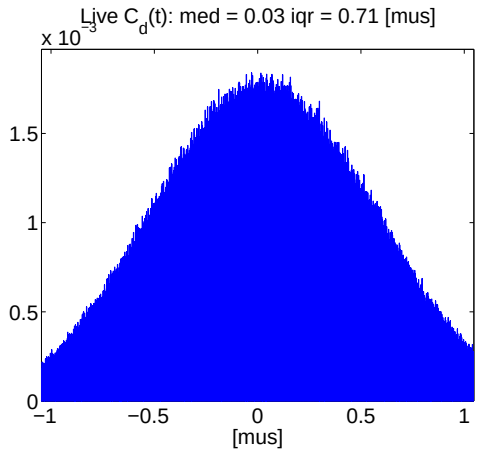


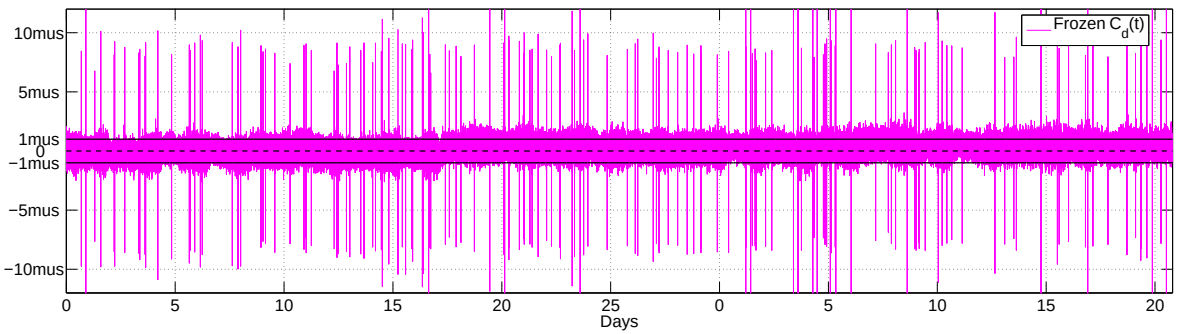


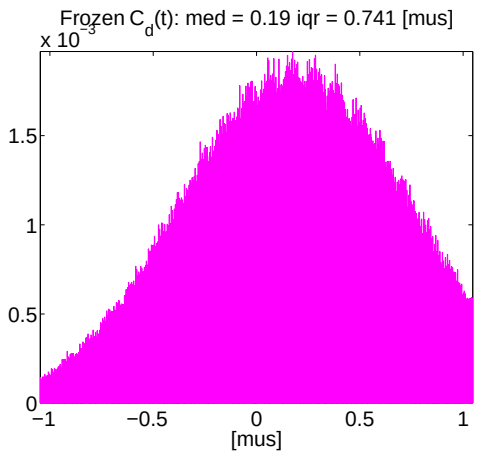
Now compare if *no connectivity* with server

DIFFERENCE CLOCK VERSUS GPS









The System

- API
  - absolute and difference clock reading
  - mode setting/reading
  - diagnostics
- Timestamping solution
  - better with kernel support
- Synchronization algorithm:
  - runs as daemon or on command line
  - can store and replay log files
- Server
  - no server side solution, yet
  - client compatible with existing NTP servers
  - designed (and recommended) for use with a single server

TIMESTAMPING

KERNEL

USER

TIMESTAMPING

KERNEL

- Packet timestamping:
  - Normal mode: TSCclock works in parallel with SW
  - TSCclock mode: SW also returns $C_a(t)$ transparently
- Other timestamping:
  - TSCclock works in parallel with SW

USER

TIMESTAMPING

KERNEL

- Packet timestamping:
  - Normal mode: TSCclock works in parallel with SW
  - TSCclock mode: SW also returns $C_a(t)$ transparently
- Other timestamping:
  - TSCclock works in parallel with SW

USER

- Packet timestamping:
  - Kernel packet timestamps inferred from userland
  - TSCclock works in parallel with SW

PACKAGING

- Ubuntu 6.10 (Edgy)
- Ubuntu 7.04 (Feisty)
- Debian 4.0 (Etch)
- Fedora Core 6
- and soon Fedora Core 7 ...

CONCLUSIONS

- TSCclock: for synchronization over networks
- Currently based on CPU oscillator accessible via TSC register
- Absolute Clock:
  - far more robust than *ntpd*
  - order of magnitude more accurate
- Difference Clock:
  - exceptionally robust
  - not available under *ntpd*
  - more accurate than standard GPS solution for small time intervals
- Kernel and userland packet timestamping solutions
- Low computational requirements
- Runs as daemon in parallel with *ntpd*
- Works with existing NTP server network
- Packages written for BSD and popular Linux distributions

CONCLUSIONS

- TSCclock: for synchronization over networks
- Currently based on CPU oscillator accessible via TSC register
- Absolute Clock:
  - far more robust than *ntpd*
  - order of magnitude more accurate
- Difference Clock:
  - exceptionally robust
  - not available under *ntpd*
  - more accurate than standard GPS solution for small time intervals
- Kernel and userland packet timestamping solutions
- Low computational requirements
- Runs as daemon in parallel with *ntpd*
- Works with existing NTP server network
- Packages written for BSD and popular Linux distributions

CONCLUSIONS

- TSCclock: for synchronization over networks
- Currently based on CPU oscillator accessible via TSC register
- Absolute Clock:
  - far more robust than *ntpd*
  - order of magnitude more accurate
- Difference Clock:
  - exceptionally robust
  - not available under *ntpd*
  - more accurate than standard GPS solution for small time intervals
- Kernel and userland packet timestamping solutions
- Low computational requirements
- Runs as daemon in parallel with *ntpd*
- Works with existing NTP server network
- Packages written for BSD and popular Linux distributions

LINKS

- Publications:
  http://www.cubinlab.ee.unimelb.edu.au/articles
- TSCclock page:
  http://www.cubinlab.ee.unimelb.edu.au/tscclock