Synchronising Software Clocks on the Internet

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Collaboration with

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Motivation

Everyone needs a *Software Clock* :

- Physical support (e.g. timer chip)
- Synchronisation (absolute, and rate)
- Timestamping

And wants performance :

- Inexpensive (off the shelf hardware)
- Inexpensive, convenient synchronisation (off a network)
- Accurate and Robust

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Widely used SW-NTP solution in PC's not good enough

- Varies rate to drive offset to 0 – but rate essential for $\triangle(t)$ measurement!
- Not robust! jumps can occur, ms to seconds or worse

So Why Can We Do Better?

Advances in hardware have changed the status quo,

From

Local clock is very unreliable, must ask (and trust) the expert

To

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But new perspective: local centric & rate centric

- inspires new filtering philosophy $\longrightarrow$ greater accuracy and robustness
- defines separate difference and absolute clocks
- we deliver both rate **and** offset estimates

The CPU Oscillator as a Clock

TSC (or CCC) register counts CPU cycles, 1 cycle per p [sec].

Two simple ideas, based on *Simple Skew Model* (pure frequency):

Difference Clock: $\Delta(t) = \Delta(\text{TSC register value}) \times p$

Absolute Clock: $t = \theta_0 + (\text{TSC register value}) \times p$

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Features/Advantages

- CPU oscillator and TSC Register stable features of PC architecture
- Hardware updating
- Ultra fast raw timestamping (read register): ($<$ 50 ns)
- Nanosecond resolution

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The Catch:

– must estimate the cycle period p and offset θ_0 without special hardware.

Hardware Performance

Study of Oscillator Stability (variability) over different timescales shows:

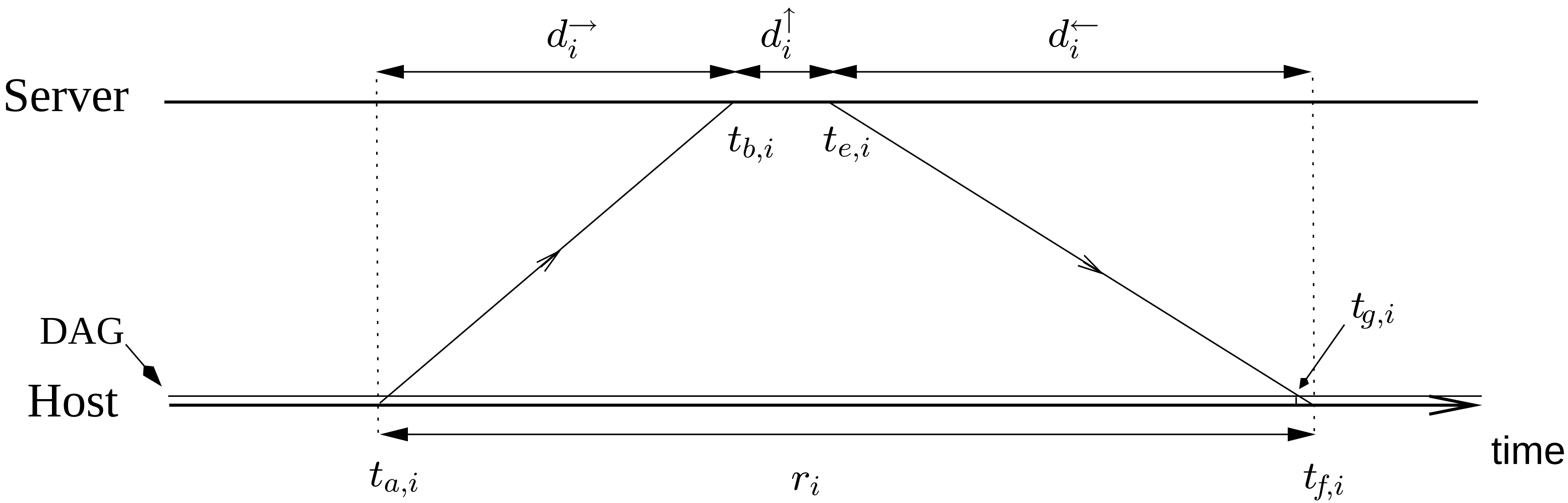
- Simple Skew Model: holds strictly for $\tau^* = 1000$ [sec]
- Average rate error never more than 10^{-7} no matter the scale

x

Very smooth constant rate: must take advantage!

Measured using reference: GPS synchronised DAG3.2E card (100ns)

A Supply of NTP Packets



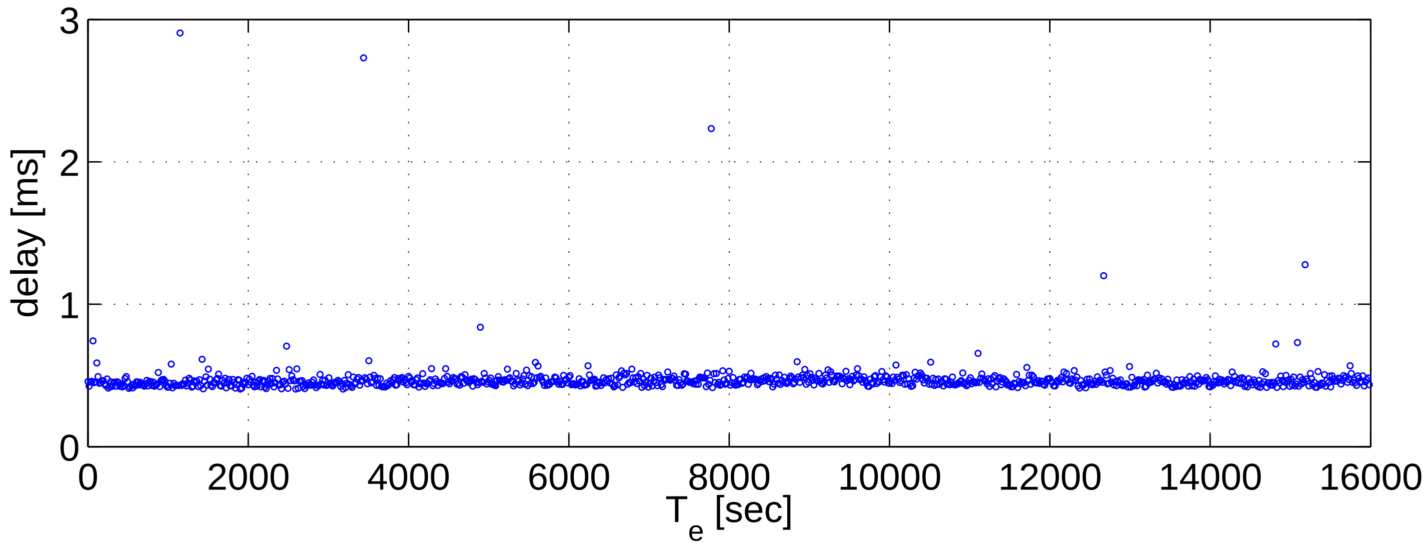
Timestamps $\{T_{a,i}, T_{b,i}, T_{e,i}, T_{f,i}\}$ are the raw data from the i-th NTP packet.

- $\{T_{a,i}, T_{f,i}\}$: host timestamps in TSC counter units
- $\{T_{b,i}, T_{e,i}\}$: server timestamps in seconds

Filtering Network and Server Delay

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

Round–Trip Times r_i of packet i



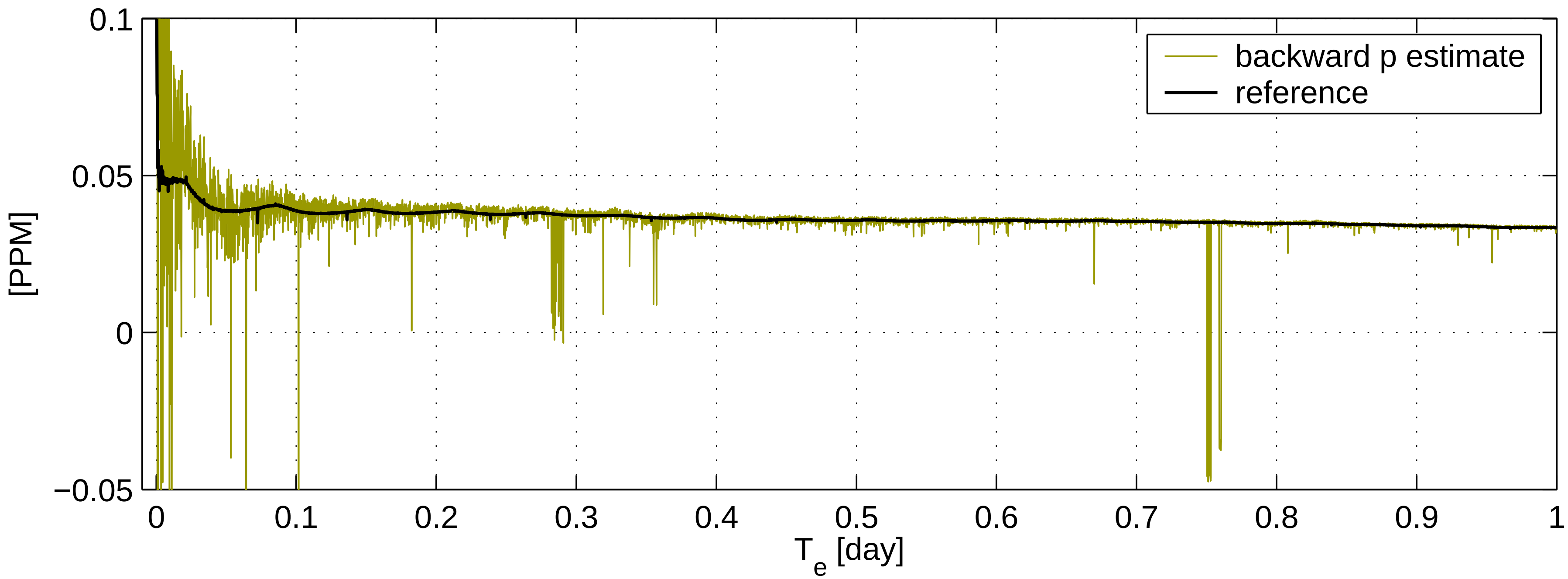
Model for RTT: $r_i = r + \text{positive random noise}$

Filter using point error: excess over minimum RTT

Naive Rate Synchronisation

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

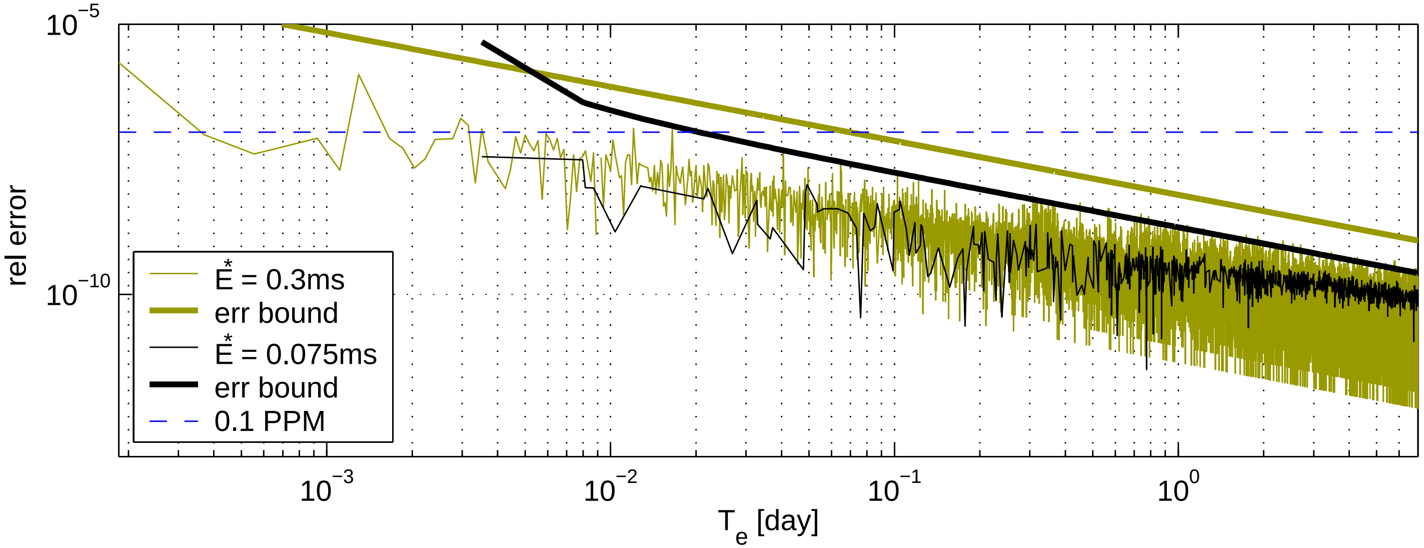
Simple naive estimate based on widely separated packets:



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

Rate Synchronisation Algorithm

Use selected naive estimates based on point errors



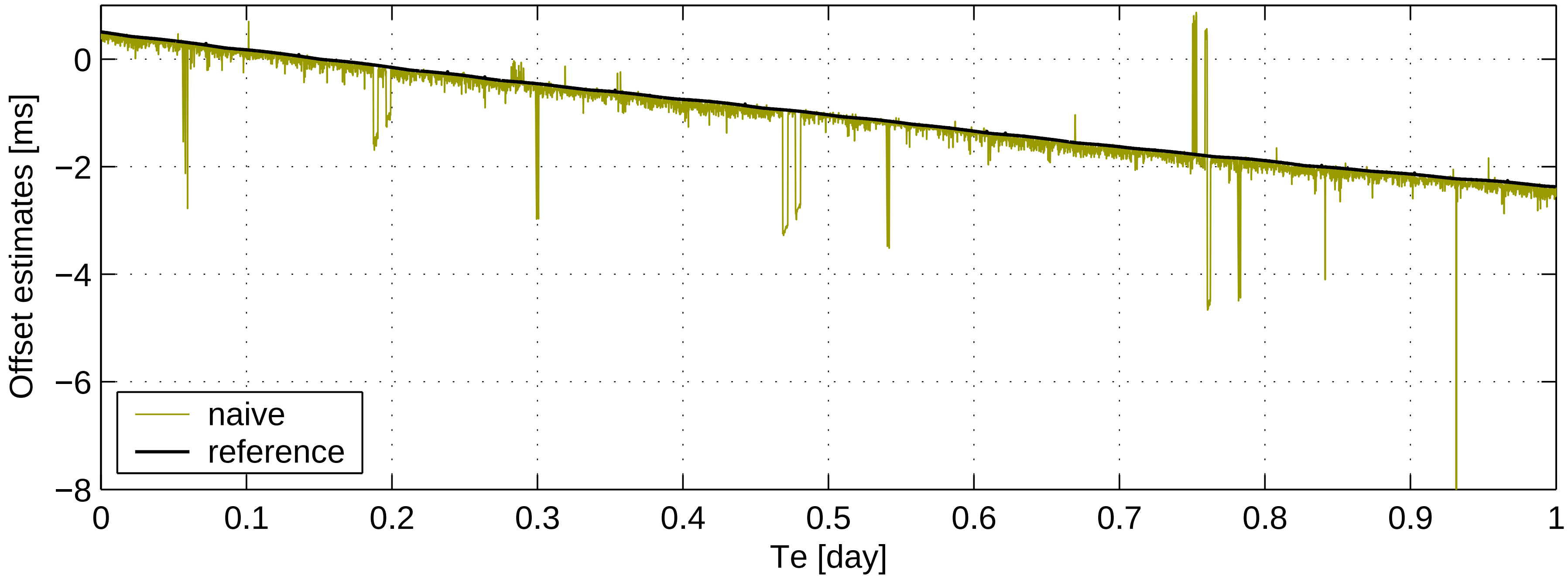
Key Features

- Error quickly $< 10^{-7}$, In 10mins, better than GPS for most active probing!
- Error reduction (in timestamping, latency, queueing) guaranteed by increasing $\triangle(t)$
- Inherently robust to packet loss, congestion, loss of server..
- Simple algorithm, no need for local estimates

Naive Offset Synchronisation

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

Naive estimate again ignores network congestion:



Offset Synchronisation Algorithm

Must track, so use all naive estimates, but be very fussy

Algorithm for $\widehat{\theta}(t)$

- For packets in SKM window τ' wide before t, define strict weight
- Form weighted estimate over window (If quality very bad, repeat previous packet)
- Sanity check: if behaviour impossible, repeat previous estimate.

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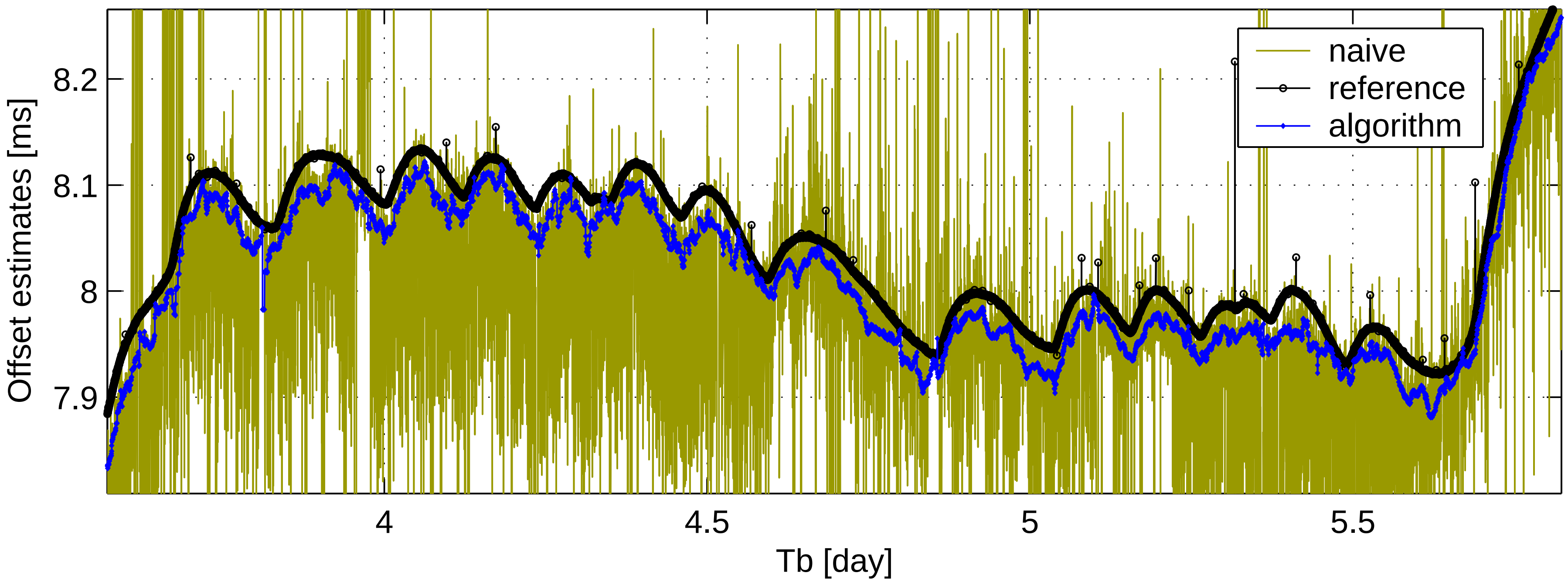


The Path Asymmetry Δ

Fundamental ambiguity:

Asymmetry $\Delta \equiv d^{\rightarrow} - d^{\leftarrow}$ and error in offset indistinguishable up to a constant.

Δ unknown: forced to assume $\Delta = 0$

But, error bounded by RTT: $\Delta \in (-r, r)$

Server Characteristics: RTT and Δ

Server	Reference	Distance	RTT	Hops	Δ
ServerLoc	GPS	3 m	0.38 ms	2	$\approx$ 0.05 ms
ServerInt	GPS	300 m	0.89 ms	5	$\approx$ 0.05 ms
ServerExt	Atomic	1000 km	14.2 ms	$\approx$10	$\approx$ 0.5 ms

For *ServerInt*: $\Delta \approx 50\mu$s

Theoretical best offset error is: $\Delta/2 \approx 25\mu$s

Measured median offset error only: 28μs

Choice of server is crucial:

- Close server has small RTT
- Close server more likely to have symmetric path: $\Delta \ll r$
- Aim: find a stratum–1 NTP server, with small $r \sim 1$ ms, and known, symmetric path.

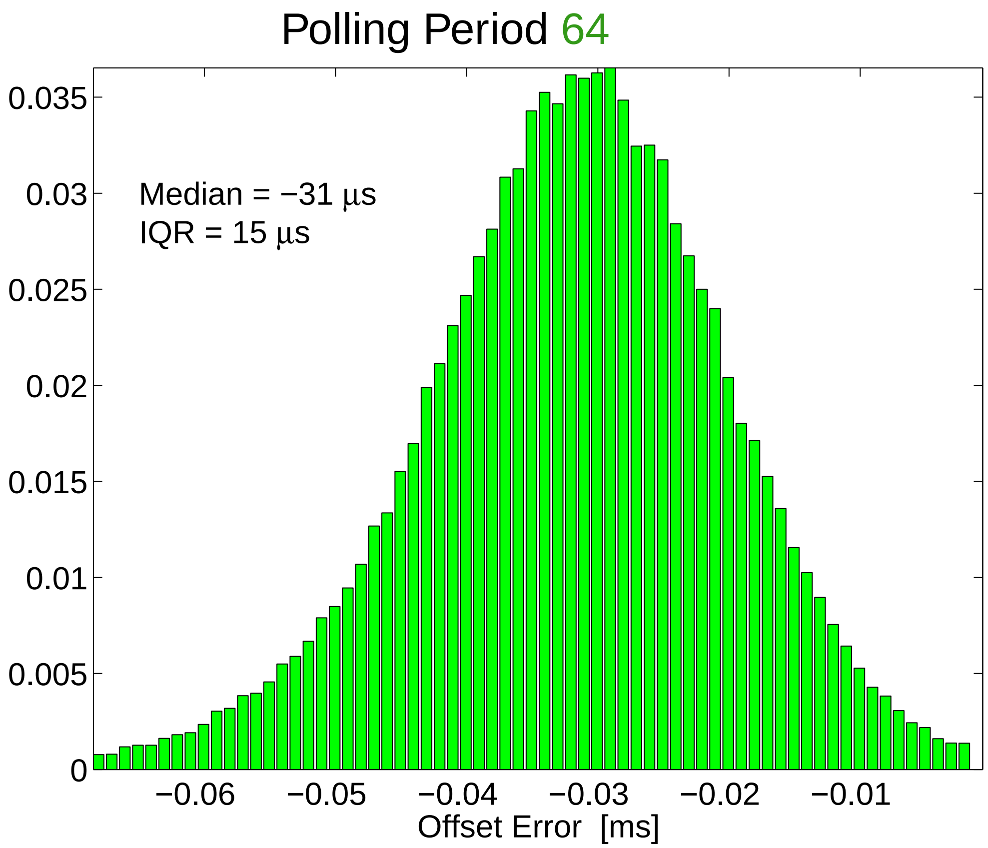
A Robust Working System

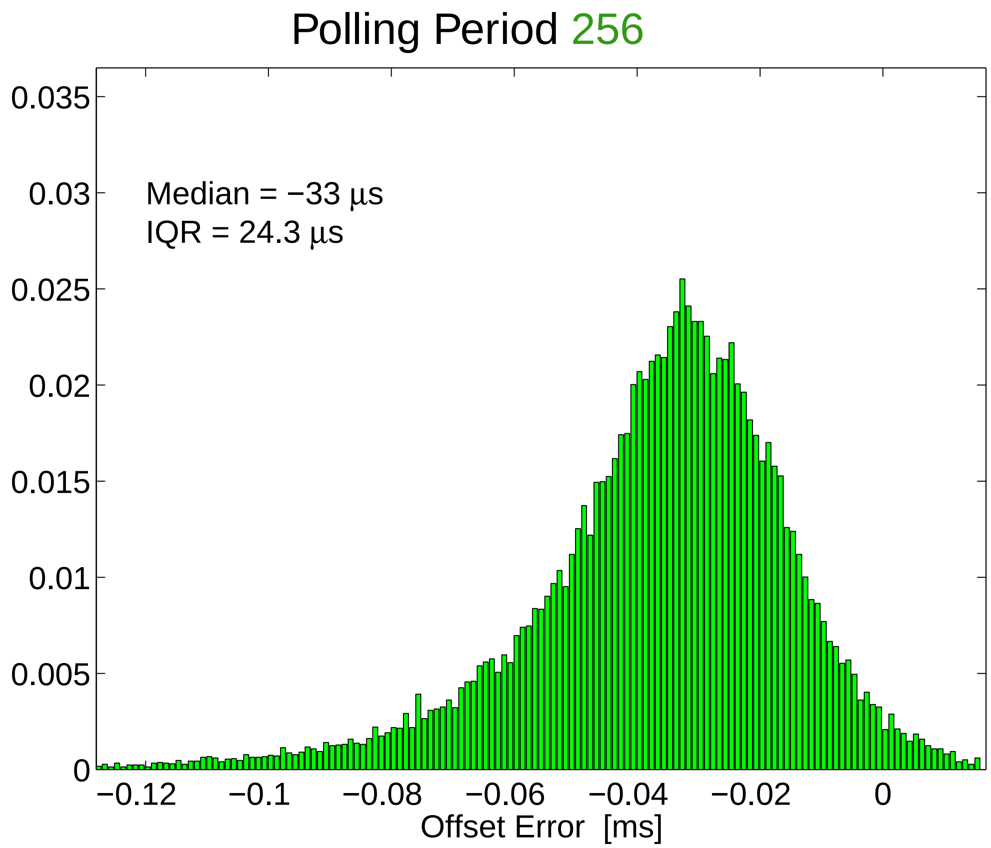
Build in Robustness to Diverse Factors

- Changes in environment/oscillator
- Changes in temperature
- Packet Loss (loss of connectivity..)
- Network congestion
- Timestamping errors (scheduling)
- Server errors
- Route/Server changes – Level shifts in RTT

  Possible to handle level shifts reliably with almost no dedicated code

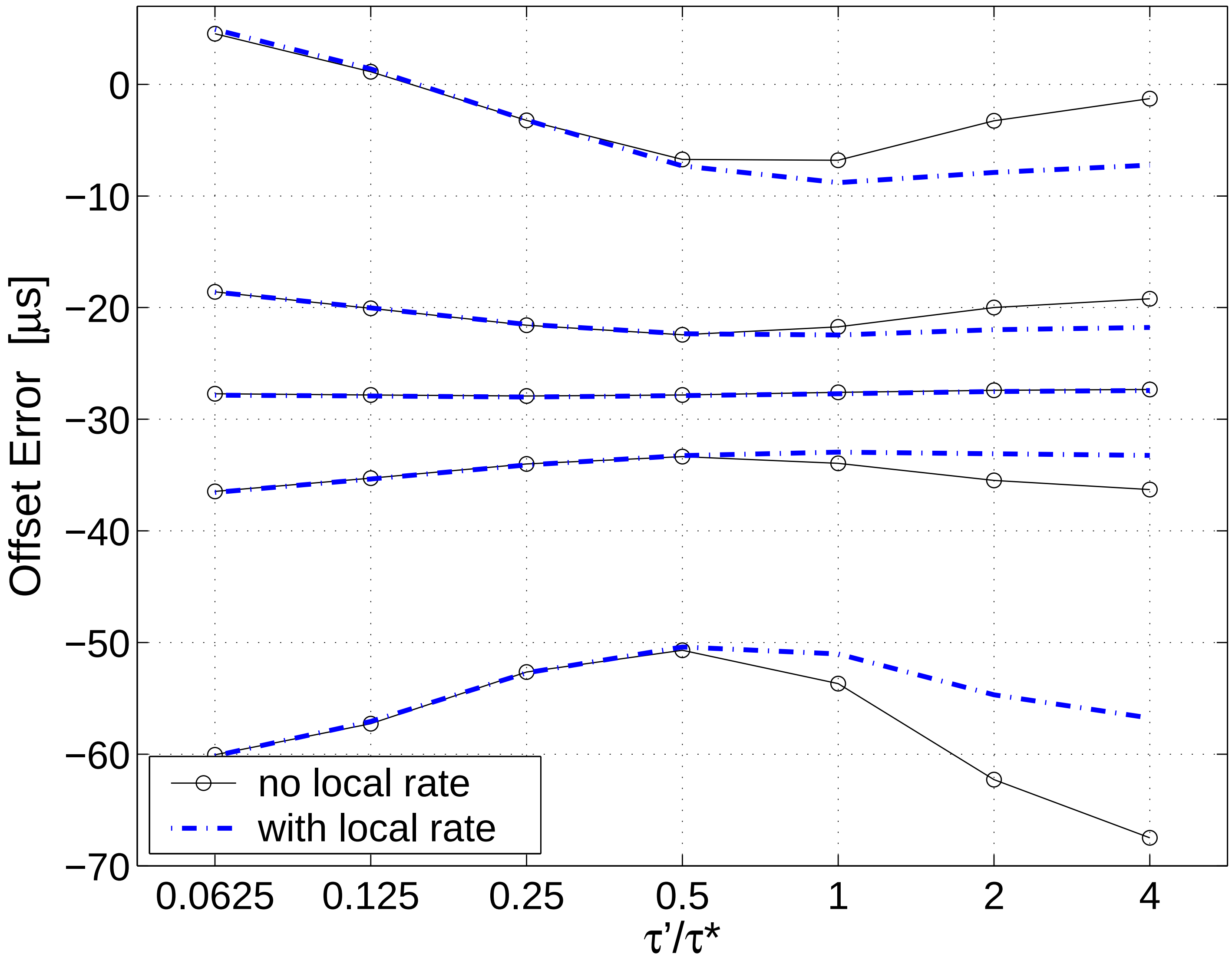
Full C Version, 3 months of Data with *ServerInt* – Machine-Room





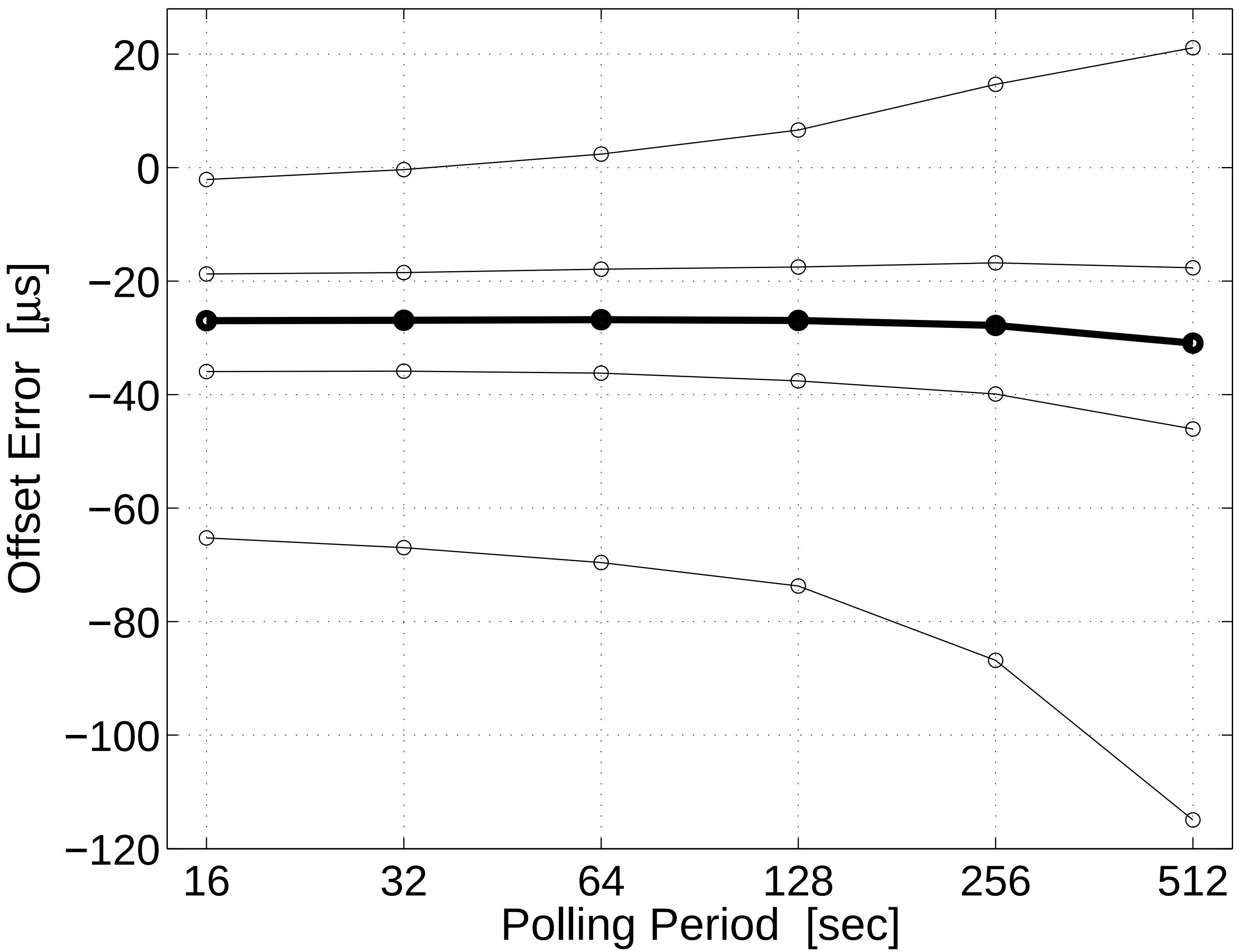
Histograms show 99% of all values, $\tau' = 2\tau^*$

Performance as Function of Window Size τ'



ServerInt, Machine-Room, $E = 4\delta$

Performance as Function of Polling Period



ServerInt, Machine-Room, $\tau' = \tau^*$, $E = 4\delta$

Conclusions

- Defined CPU oscillator based software clock for devices with TSC registers
- Absolute Clock:
  - more accurate than *SW–NTP*
  - far more robust
- Difference Clock:
  - not available under *SW–NTP*
  - more accurate than *SW–GPS* for many applications
- Low computational requirements
- Suited to network measurement, or as generic replacement for *SW–NTP*

Web Resources

- Publications (including preprint):
  http://www.cubinlab.ee.mu.oz.au/probing/articles.shtml
- Software and documentation (Linux) for TSC clock and early p calibration:
  http://www.cubinlab.ee.mu.oz.au/probing/software.shtml
- Software for new algorithms: BSD implementation coming
  http://www.cubinlab.ee.mu.oz.au/probing/software.shtml
- TSC based sender/receiver (Linux, LinuxTSC, RT-Linux) for active probing:
  http://www.cubinlab.ee.mu.oz.au/probing/software.shtml