Alternative schemes for array-wide clock generation/distribution

FPI/ELEC parallel session
CTA general meeting Toulouse, 17.05.11

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Motivation

- For synchronising events from different telescopes within CTA, a common timing system is required.
- Usually, a tree-like structure is used to distribute a single clock/timing source to all receivers (telescopes).
- Depending on technology used, this can be rather expensive (singlemode optical fiber).

- Introduce two different schemes for clock/timing distribution for CTA:
  - GPS-synchronized clock source located at each individual telescope (GPSDO, Uni Zürich)
  - Use existing Ethernet cabling (*White Rabbit*, CERN/GSI)

GPS disciplined Oscillator (GPSDO)

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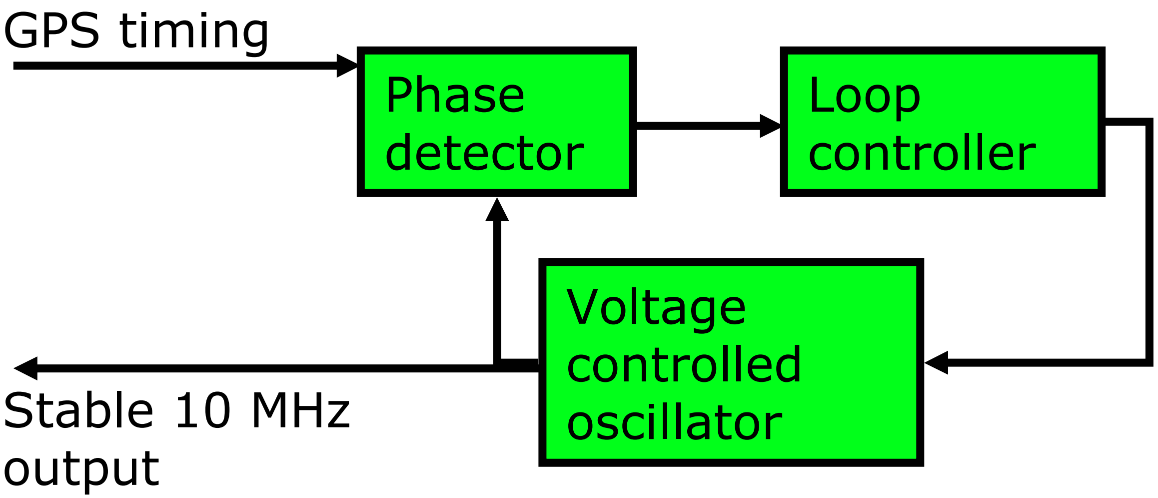
- GPSDOs have been around for years (GSM base stations) but with limited timing accuracies (typ. 1 usec)
- Idea: use GPS’s 4th coordinate (time!) instead of x/y/z as reference input for phase locked loop -> frequency control of 10 MHz crystal oscillator



- Recent advances in GPS receivers allow time tags of <5ns.

Why not using GPS directly?

- GPS receiver only delivers 1 PPS (pulse per second) signal
- dedicated GPS timing receivers use *position hold* mode to overdetermine time → better 1 PPS timing
- 1 PPS ouput jitter ca. 2ns rms
- very high compared to (short-term) oscillator jitter (typ. 1 ps pk-pk and better)
- Oscillators are good on short time-scales, GPS is best (absolute) on long timescales
  → use PLL to lock the oscillator to 1 PPS!
- How to choose PLL loop time constant?

Stability: Allan Deviation

- Definition of Allan Deviation $\sigma_y(\tau)$:

$$\sigma_y^2(\tau) = \frac{1}{2}\left\langle \left(\bar{y}_{n+1} - \bar{y}_n\right)^2 \right\rangle = \frac{1}{2\tau^2}\left\langle \left(x_{n+2} - 2x_{n+1} + x_n\right)^2 \right\rangle$$

- τ is the observation period, $\bar{y}_n$ is the *n*-th fractional frequency average over the observation time τ. x_n is the *n*-th phase error with the sampling time τ.
- NB: constant frequency offsets (linear phase drifts) are not visible.

Maximum Time Interval Error (MTIE)

- Time interval error: phase difference between the signal being measured and the reference clock
- MTIE: is the largest Peak-to-Peak TIE in any observation interval (sliding window) of length τ

- For any oscillator with residual drift, MTIE $\rightarrow \infty$ for $\tau \rightarrow \infty$
- For any reference-locked oscillator, MTIE $\rightarrow$ const. for $\tau \rightarrow \infty$

- If we want phase-stable relation between individual clock sources, we have to
  - Lock local master clock to common reference (GPS)
  - Minimize MTIE to reduce error between any two local clocks

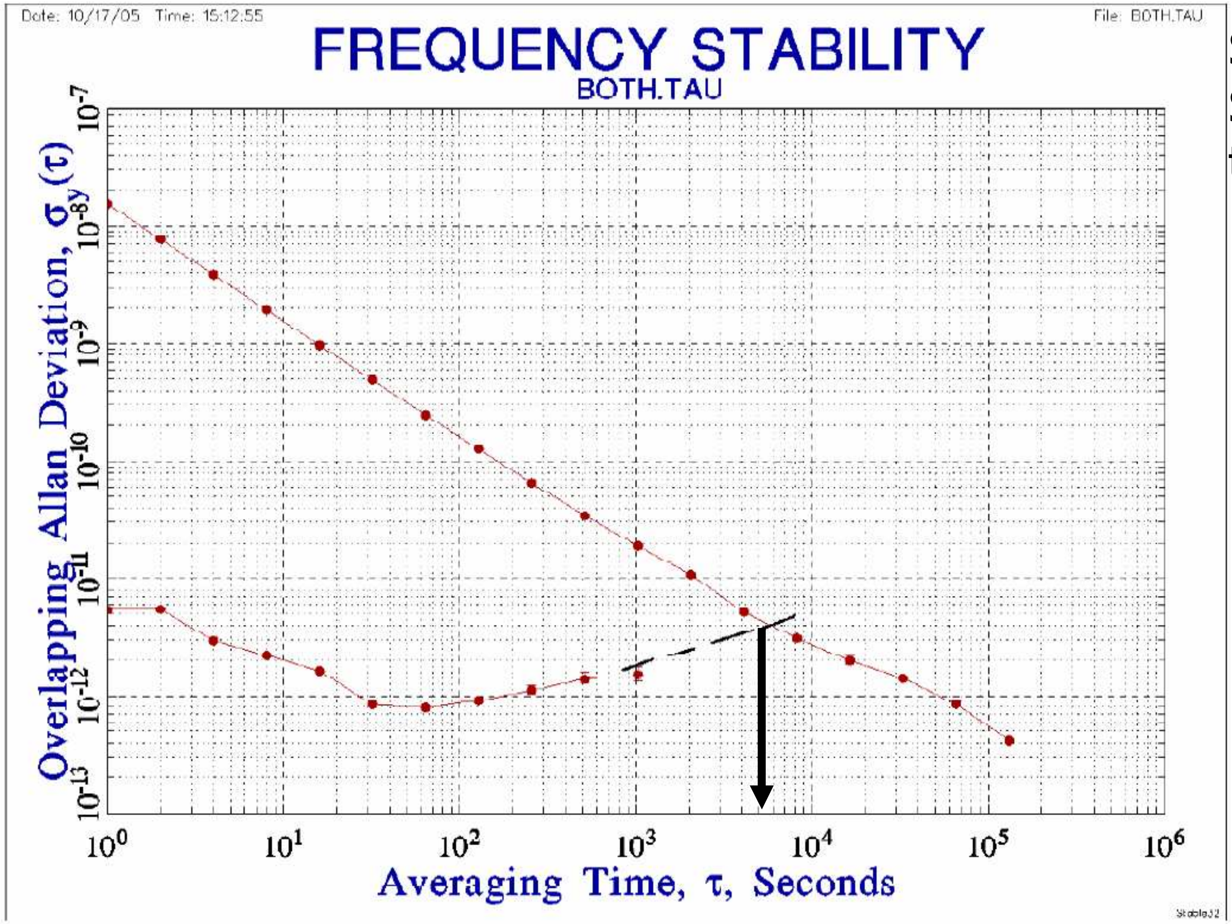
Oscillator Stability

- The statement "This 10 MHz oscillator is stable to 1 ppb." alone is worthless, the time span of the measurement is missing:
  - osc #1 varies by 1 ppb during 1 sec
  - osc #2 varies by 1 ppb during 1000 sec
    → #2 is more stable than #1

- Stability needs to be quantified for varying time spans:
  - Measure phase deviation for each second
  - Calculate stability for τ= 1 sec
  - Decimate every second value
  - Calculate stability for τ= 2 sec
  - Decimate every second value
  - …
    → Sigma-Tau diagram

How to lock 10 MHz to GPS?

- Million-dollar question for PLL: loop bandwidth (or time constant)
- compare GPS-receiver with oscillator in one diagram



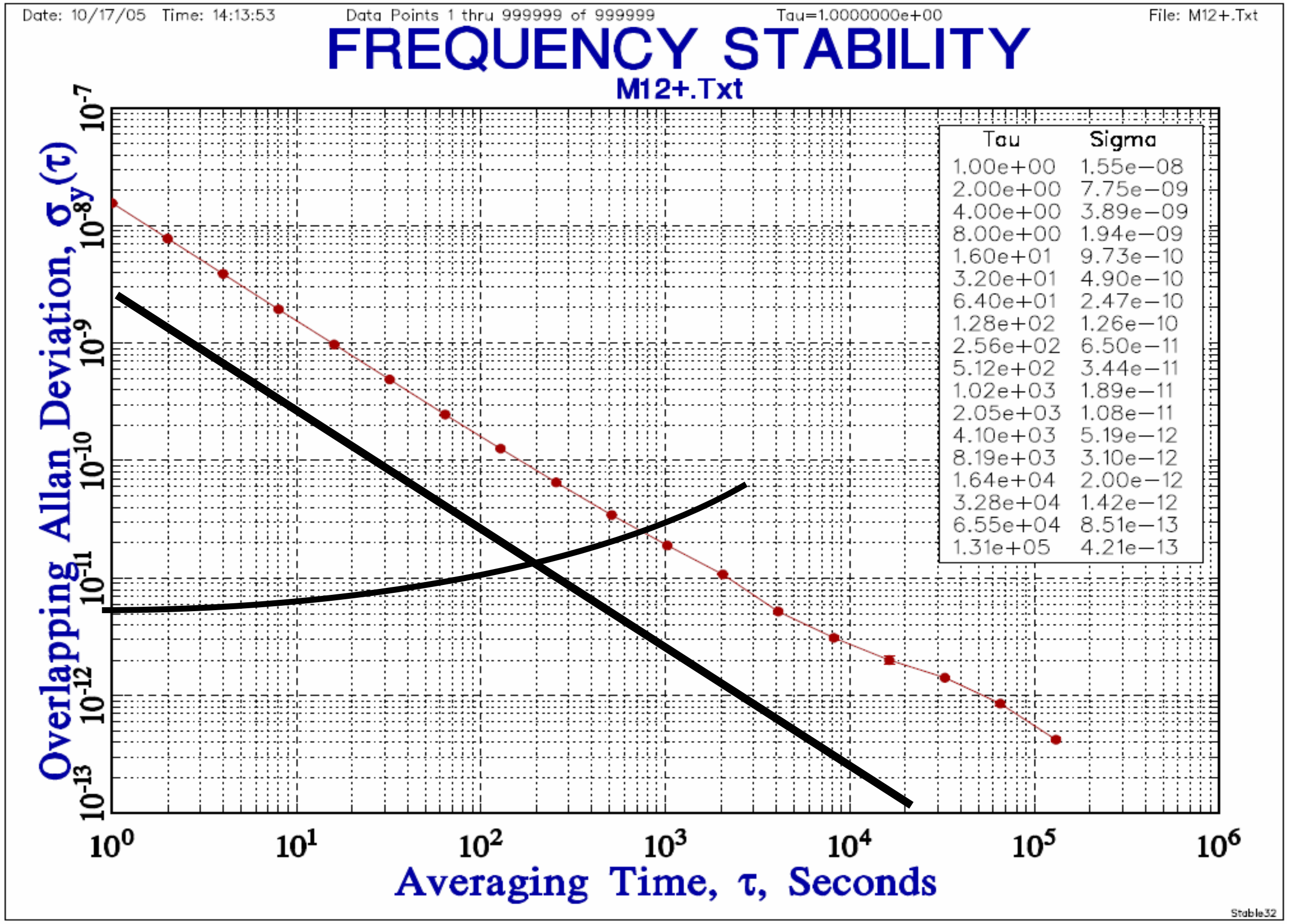
Straight slope:
Stability plot for GPS timing reeciver

Banana graph:
Very good oven-stabilised (OCXO) SC-cut crystal (too expensive)

a time constant of <u>5000 seconds</u> should be fine

Used components

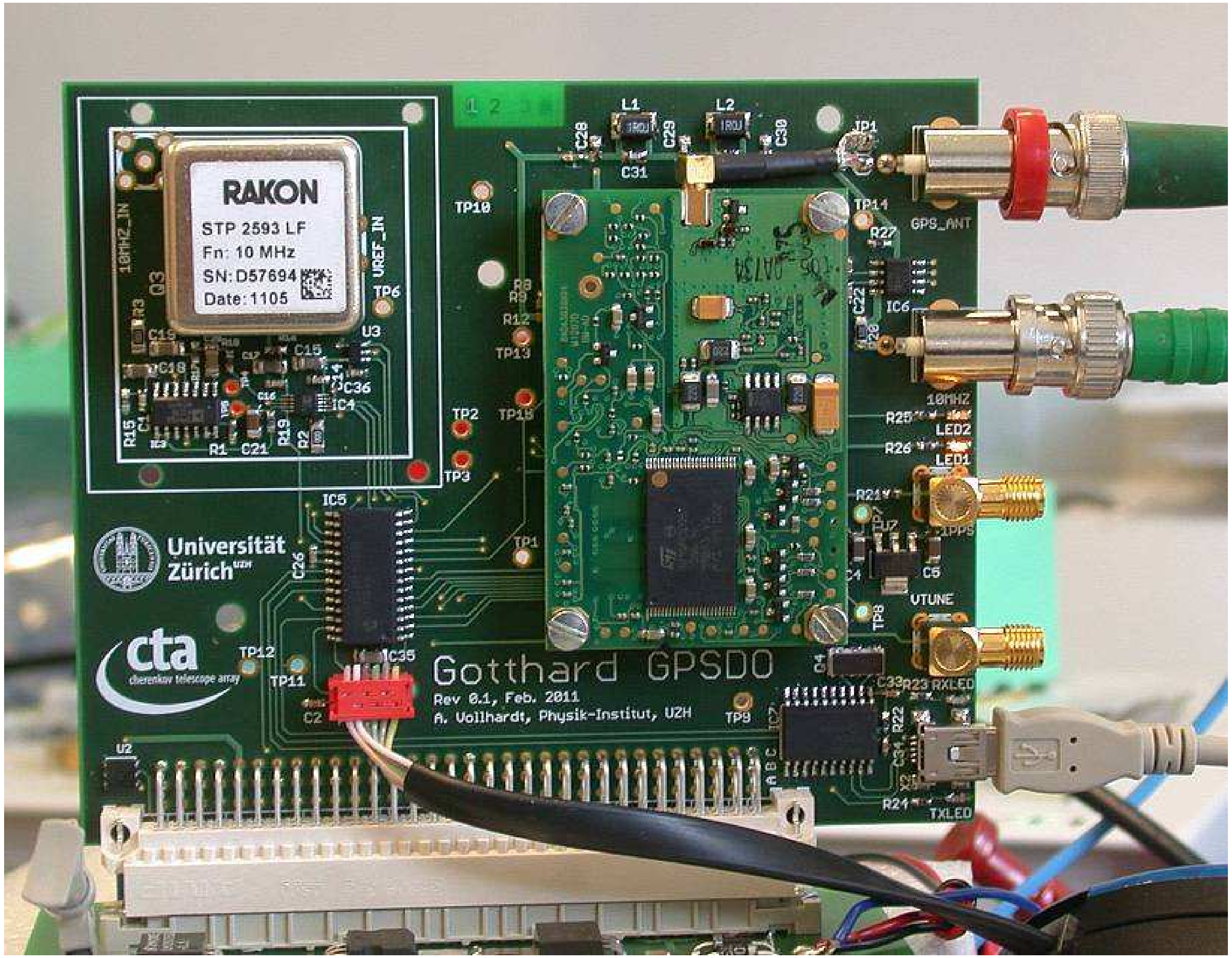
- Use state-of-the art GPS timing receiver with sawtooth correction
- Use cheapest possible OCXO to meet requirements



Simulations show that for
τ= 200 seconds MTIE
< 10 ns
is possible

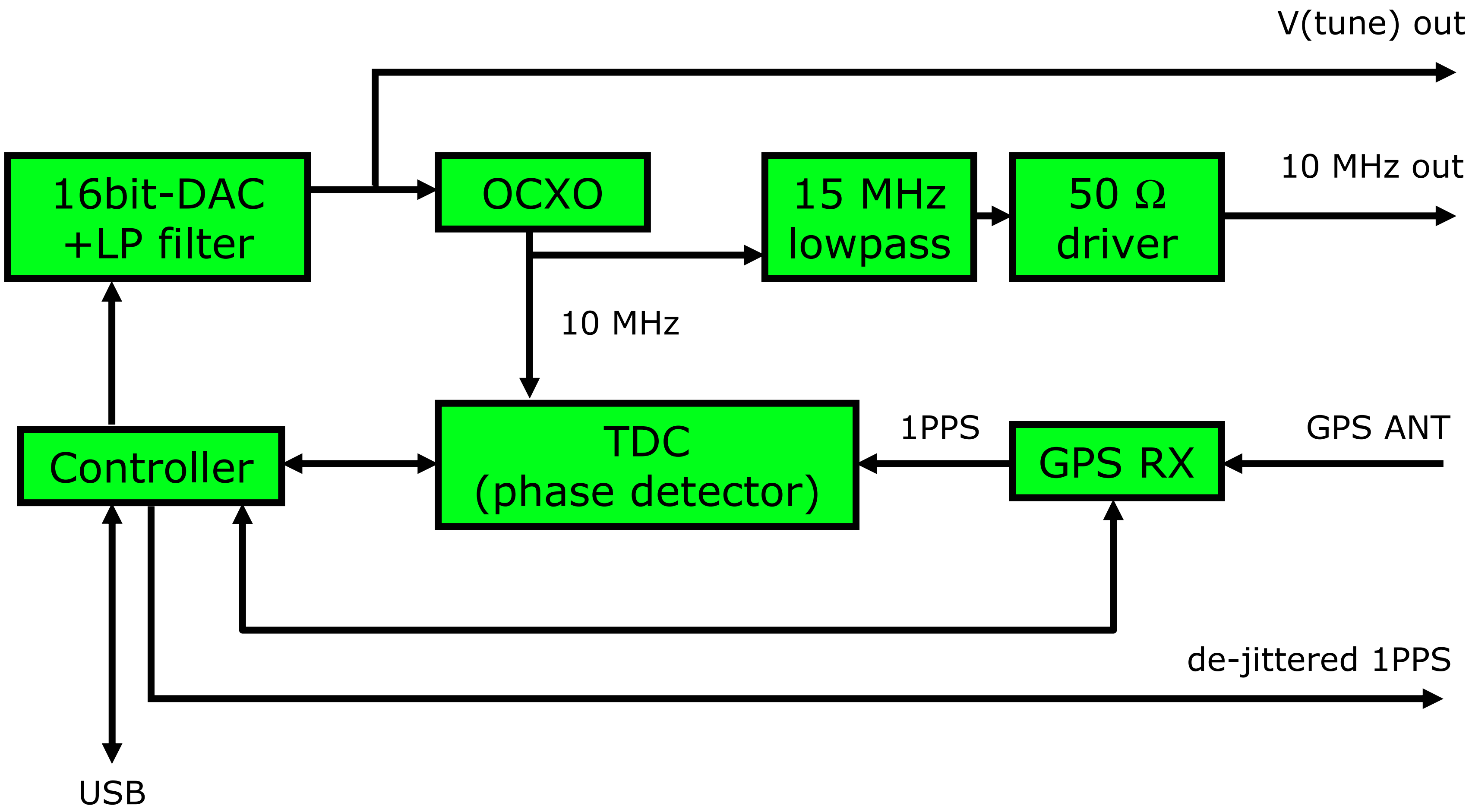
Requirement for OCXO:
<1E-11 @ 100 sec

Complete GPSDO unit



- 120mm x 100mm
- GPS in, 10 MHz out (BNC)
- Filtered 1PPS + tuning voltage (SMA)
- USB interface for monitoring
- 5V/250mA + 3.3V/100mA

Block diagram



GPSDO performance results

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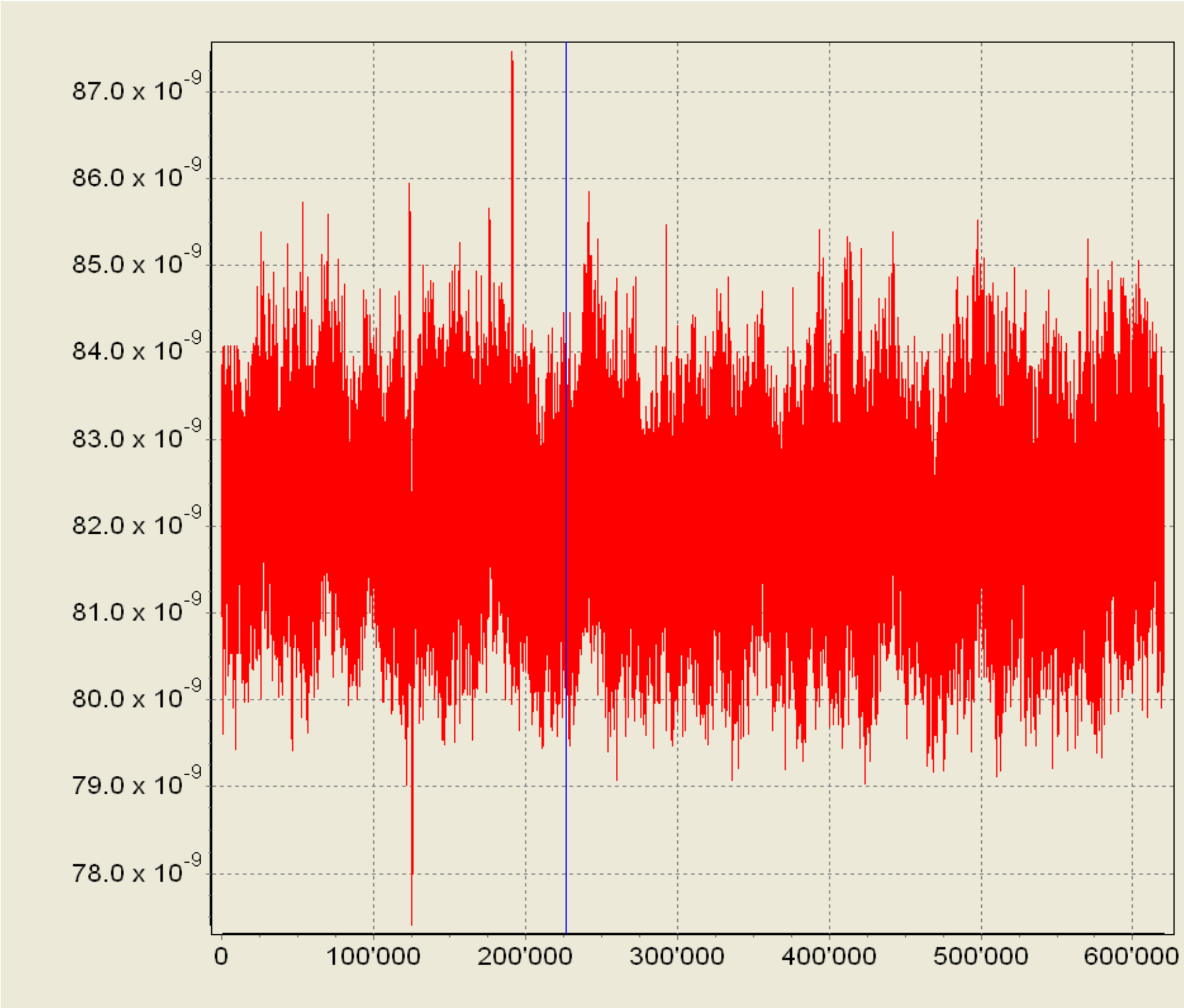
- rms noise < 1 ns
- MTIE ca. 10 ns

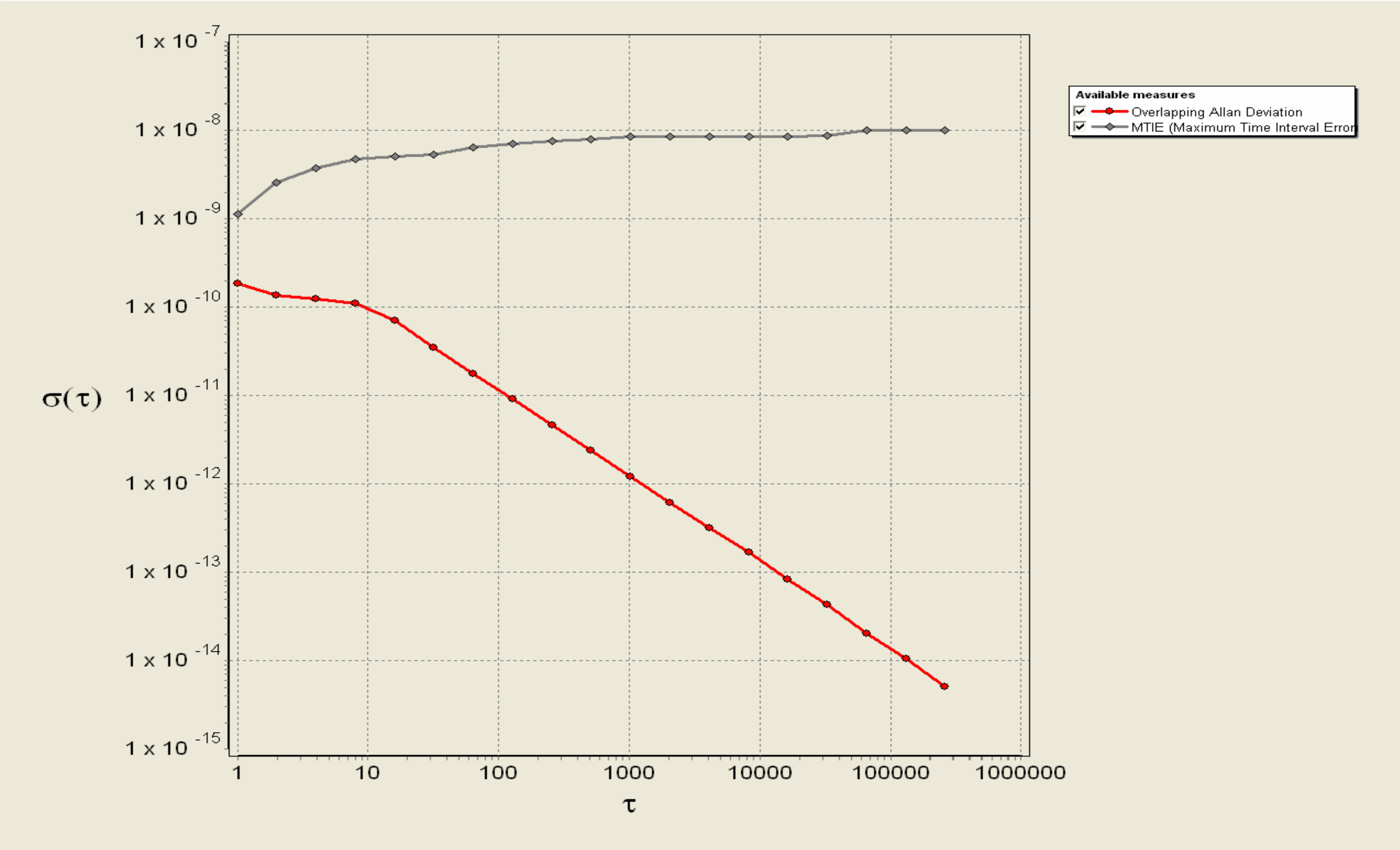
- Time difference measured with two independent GPSDOs + 50ps resolution TDC
- Use more aggressive loop time constant (ca. 16 sec) for tighter phase control
- Temperature variations (opening lab window, $\Delta T=5K$ in 10 mins) completely compensated

t(RX1)-t(RX2) [s] vs. time [s]

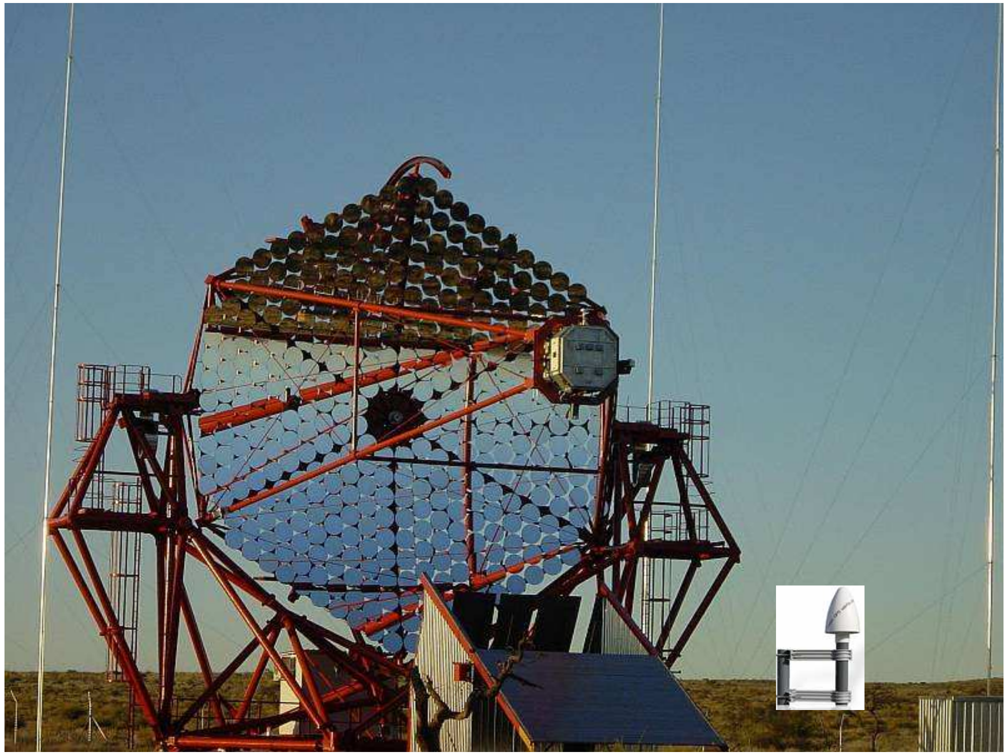


- 7 days of data
- 1 sample/sec
- 82 ns arbitrary offset
- rms 0.78 ns
- pk-pk 10.1 ns
- 1 day (1 siderial day?) period visible
- phase measurement glitches (ca. 1/day) deteriorate pk-pk data
  → to be improved in next version, 6-7 ns pk-pk in reach

Sigma-Tau/MTIE diagram



Required hardware + cost



- Clock source system @ camera (< 19”, 2HE)
- GPS antenna at ground shelter (requires FIXED position)
- Full sky coverage not needed (multipath effects filtered in receiver firmware)
- Coax cable connecting the two (currently using 60m with excellent signal strength)
- Target price for full system <500 EUR (quantities of 100)

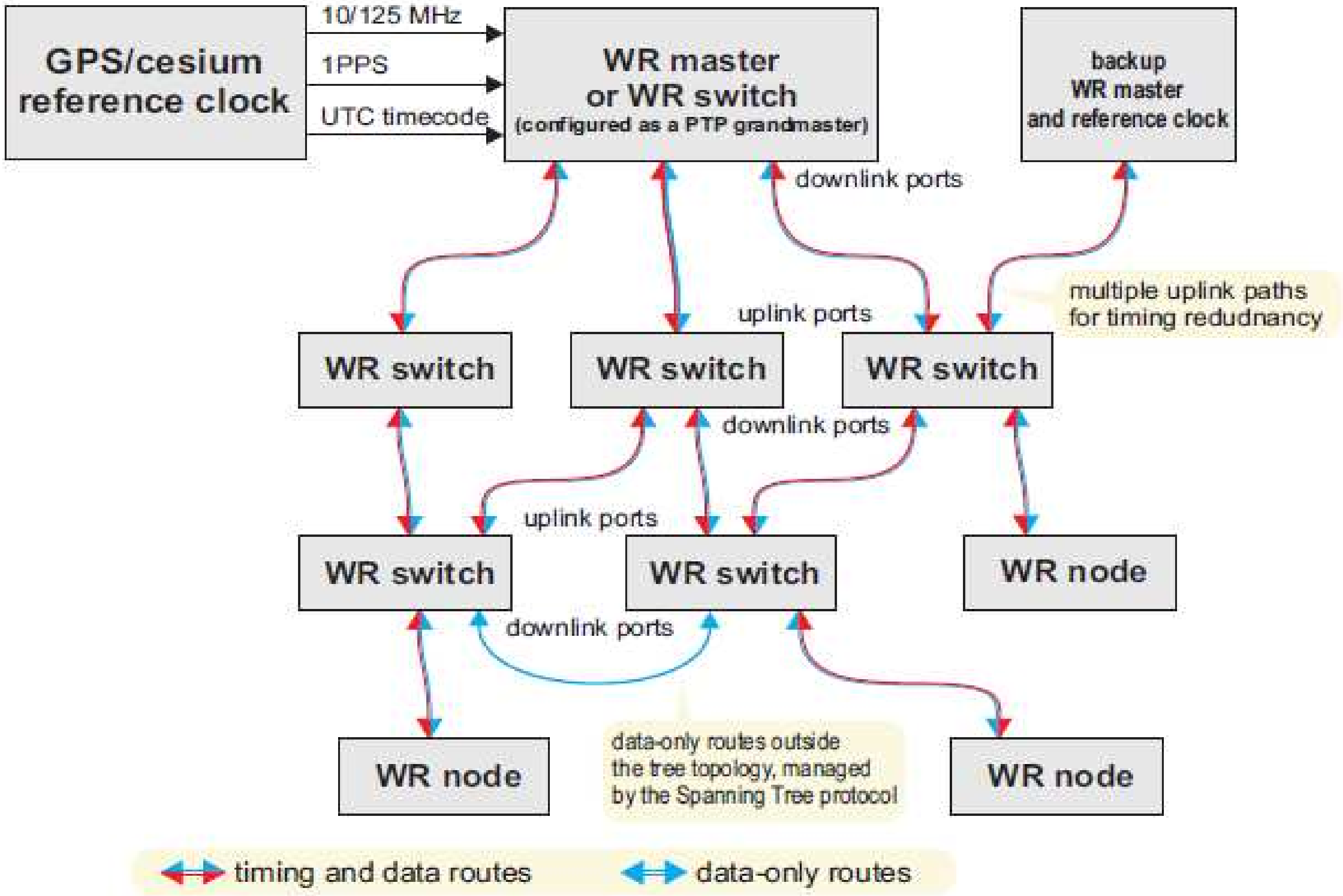
Yet another idea: using Ethernet

- Ethernet cabling will be present for data transmission between telescopes and a central control site.
- Distributing timing information over Ethernet done via NTP protocol since the 1980s
- Accuracy around 100 usec in fast LANs

- *White Rabbit* taking it to the next level:
  - Scalable up to 2000 nodes
  - 1 ns time synchronisation accuracy, 20 ps jitter
  - Based on Synchronous Ethernet + PTP (IEEE 1588)
  - Completely transparent for standard TCP/IP traffic

- Common development of CERN/GSI/industry using open hardware repository.
- See http://www.ohwr.org/projects/white-rabbit

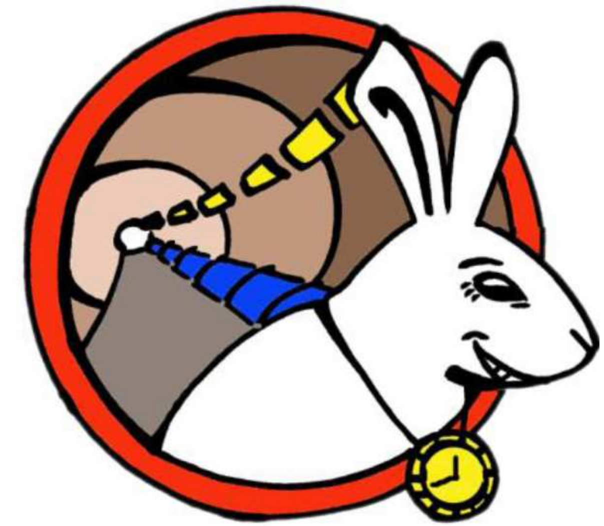
WR network topology



Courtesy T. Włostowski (CERN)

White Rabbit status

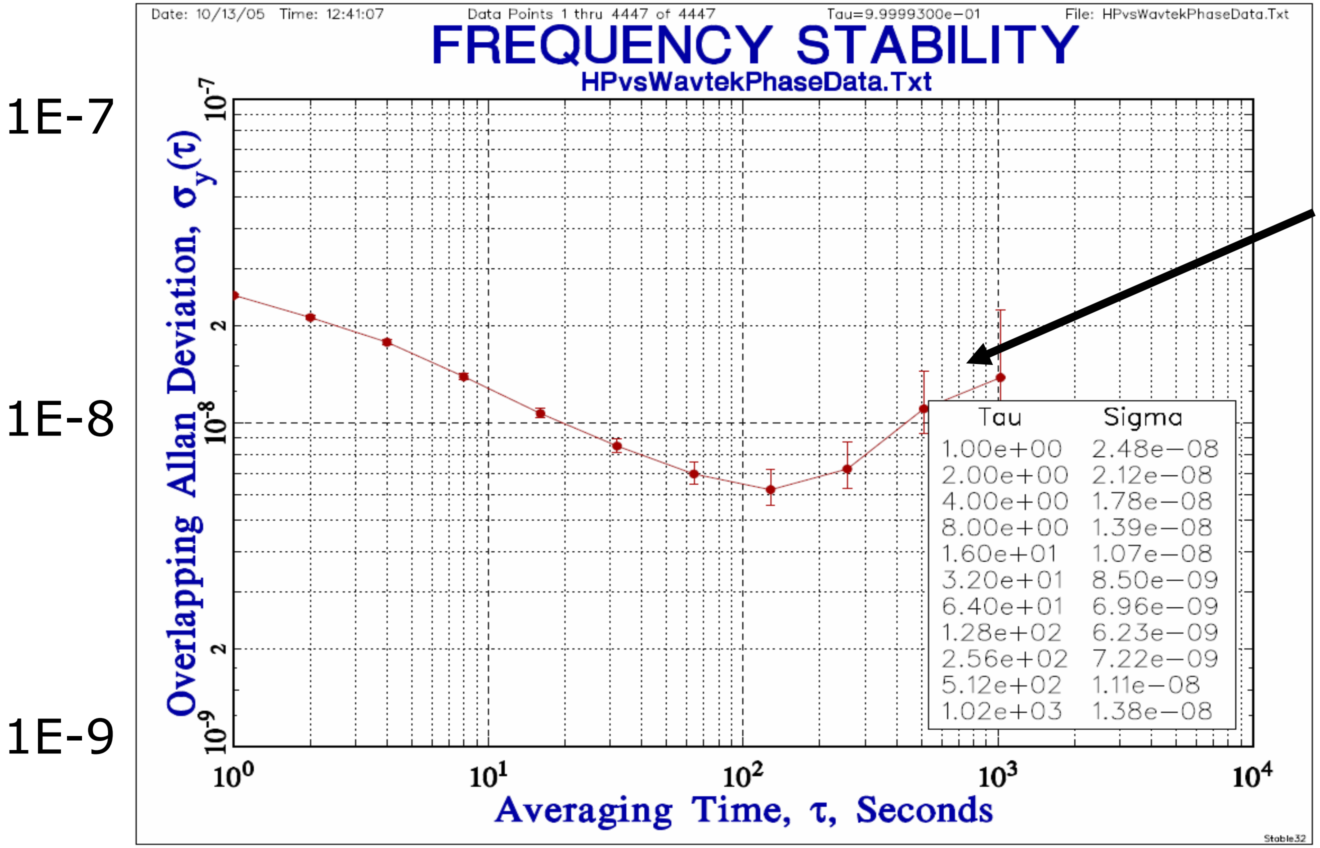
- Fourth White Rabbit Workshop held in April 2011 (ca. 30 participants)
- working timing prototype (stabilized link) shown in 2009, ethernet switching shown in 2010
- v3 switches expected for summer 2011



BACKUP SLIDES

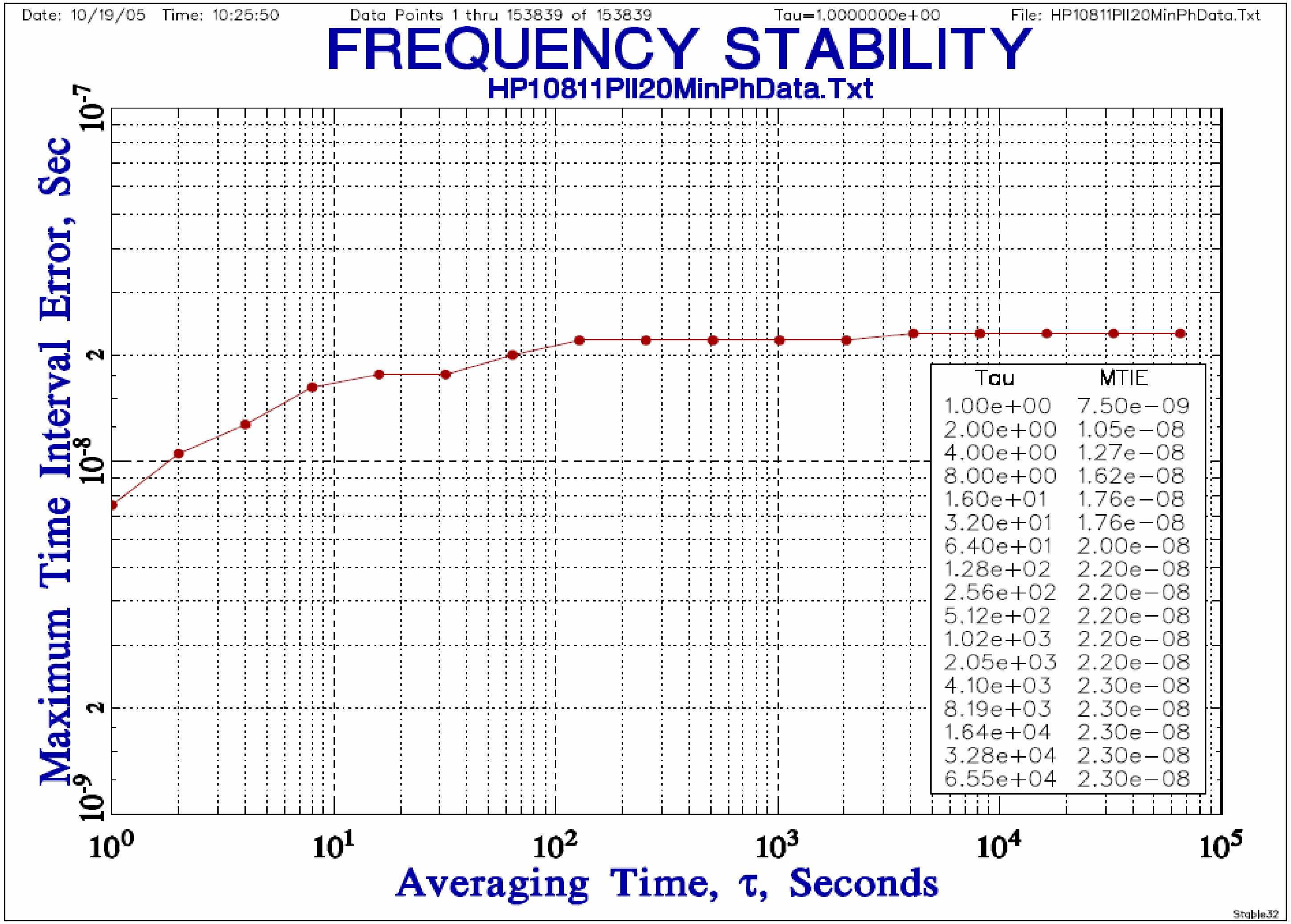
Sigma-Tau diagram

- Log-log plot: allan deviation (ADEV) vs. tau
- Typical shape (example: ordinary crystal oscillator)



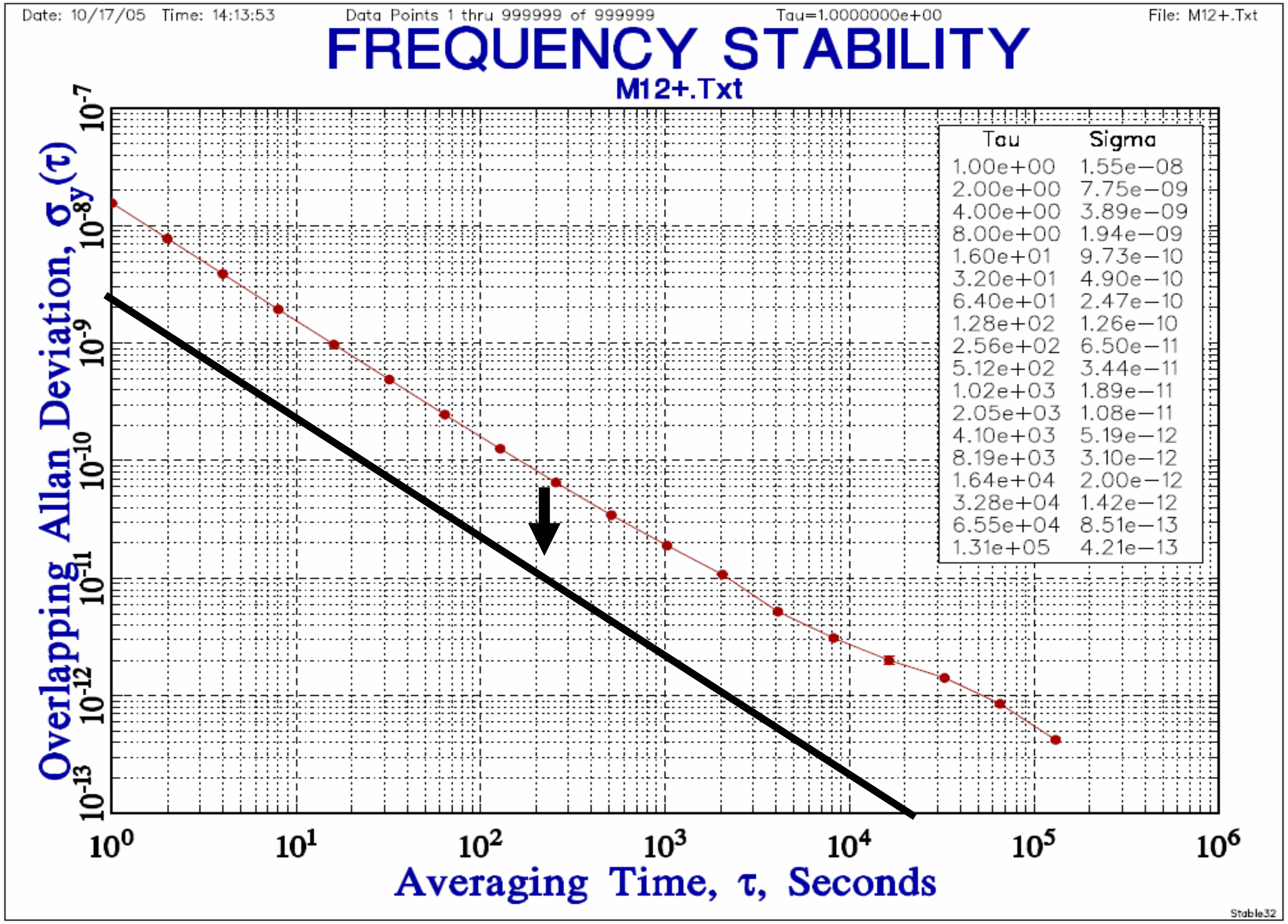
Plot rising due to aging, external effects → random walk

Maximum Time Interval Error (MTIE)



23 nsec

Sigma-Tau for GPS receiver



Tau	Sigma
1.00e+00	1.55e−08
2.00e+00	7.75e−09
4.00e+00	3.89e−09
8.00e+00	1.94e−09
1.60e+01	9.73e−10
3.20e+01	4.90e−10
6.40e+01	2.47e−10
1.28e+02	1.26e−10
2.56e+02	6.50e−11
5.12e+02	3.44e−11
1.02e+03	1.89e−11
2.05e+03	1.08e−11
4.10e+03	5.19e−12
8.19e+03	3.10e−12
1.64e+04	2.00e−12
3.28e+04	1.42e−12
6.55e+04	8.51e−13
1.31e+05	4.21e−13

Slope: -1
(white noise)

Shift down by one decade by using sawtooth correction on 1PPS-signal

How to lock 10 MHz to GPS?

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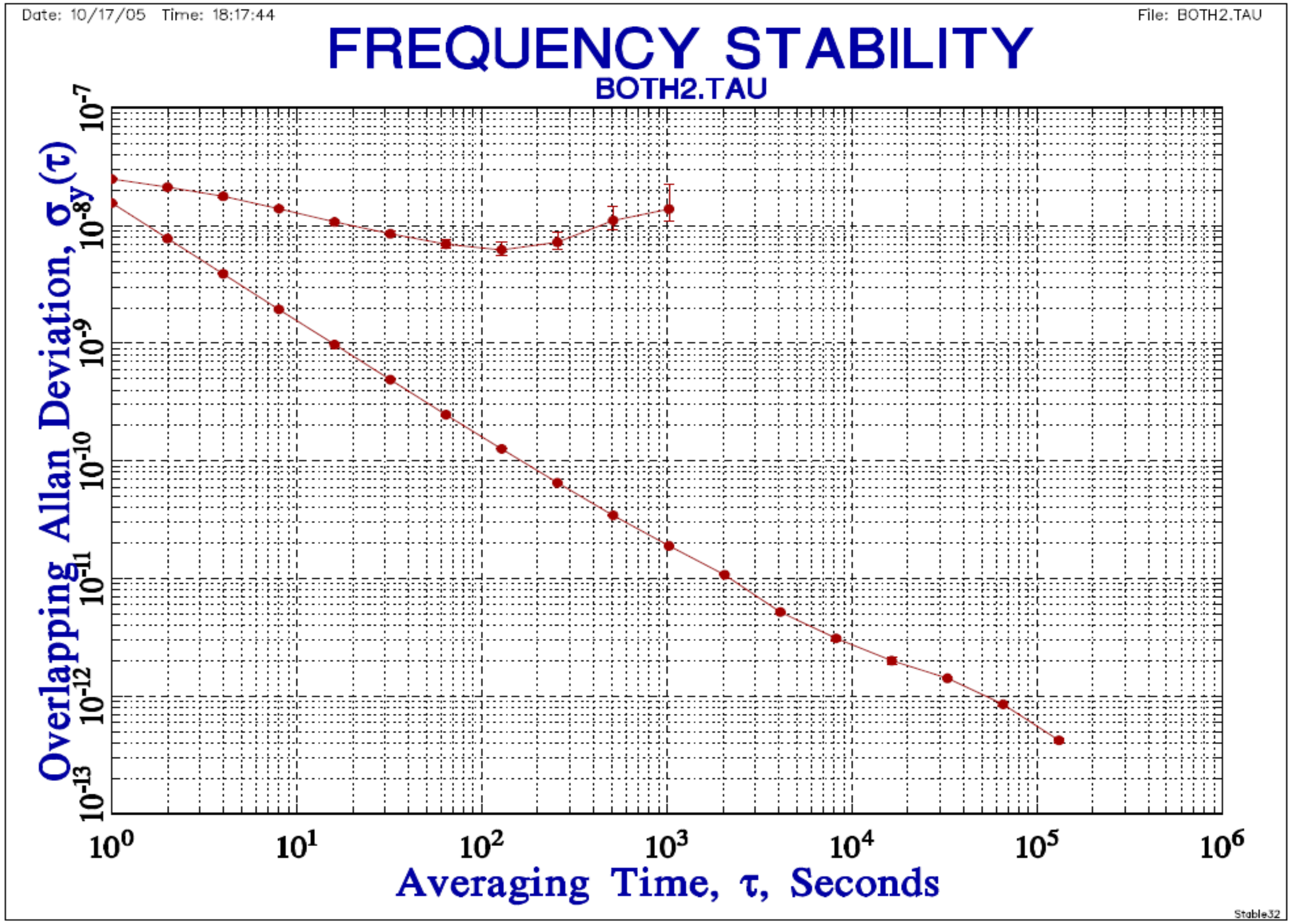

simple XO is not stable enough