Development and test of a low-cost ground terminal ~~for ACES-MWL~~

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Outline

Objective 1: Make at least 1 G/T operational

- Revival of the old Computer Infrastructure
- Re-Evaluate Earlier Measurements
- Activities with the G/T RF EGSE
- Improved T&F Infrastructure
  - Short- and long-term performance

Objective 2: Modernise G/T hardware

- 2-way: Current state-of-the-art, where to go?
- Cost Reduction…
  - Digital Implementation, SATRE TWSTFT
  - Breadboarding

Outlook

Revival of the old Computer Infrastructure, VMware

TIMETECH

- EM-Server
  - DataCollector-ACES-7.19 use for EM_migrated
  - DataRecorder-ACES-21-4 use for EM_migrated
  - Free_MWL_EM_123.99 use for EM_migrated
  - SLES11.1-64-ACES-2 GT-42
  - X2-VM-123.73 ACES GT-3 controller use for EM_migra
  - X2-VM-123.93 GT-2 Controller use for EM_migrated
  - X2-VM-73clone ACES GT Controller-2
  - X3-VM-74-i3 ACES EM use for EM_migrated
  - X4-VM-75 MWL EGSE controller use for EM_migrated
  - X5-VM76-i3 EGSE Controller use for EM_migrated
- FM Blue Box

Veeam-Server: 22-10-19 14:24:23

- FM Blue Box
  - FS-DataCollector-ACES-19_restored
  - FS-FeeNAS-99_restored
  - FS-SLES12SP2-DR-MWL-21
  - SLES11.1-64-ACES-1 FS-43
  - X3-FS-Analyser-74_restored
  - X3-VM-74clone-FS
  - X4-FS-Power control-75_restored
  - X4-VM-75clone-FS (do not use, use EM instead)
  - X5-FS-RF-EGSE Control-76 allways off_restored

Veeam-Server: 22-10-19 14:25:46

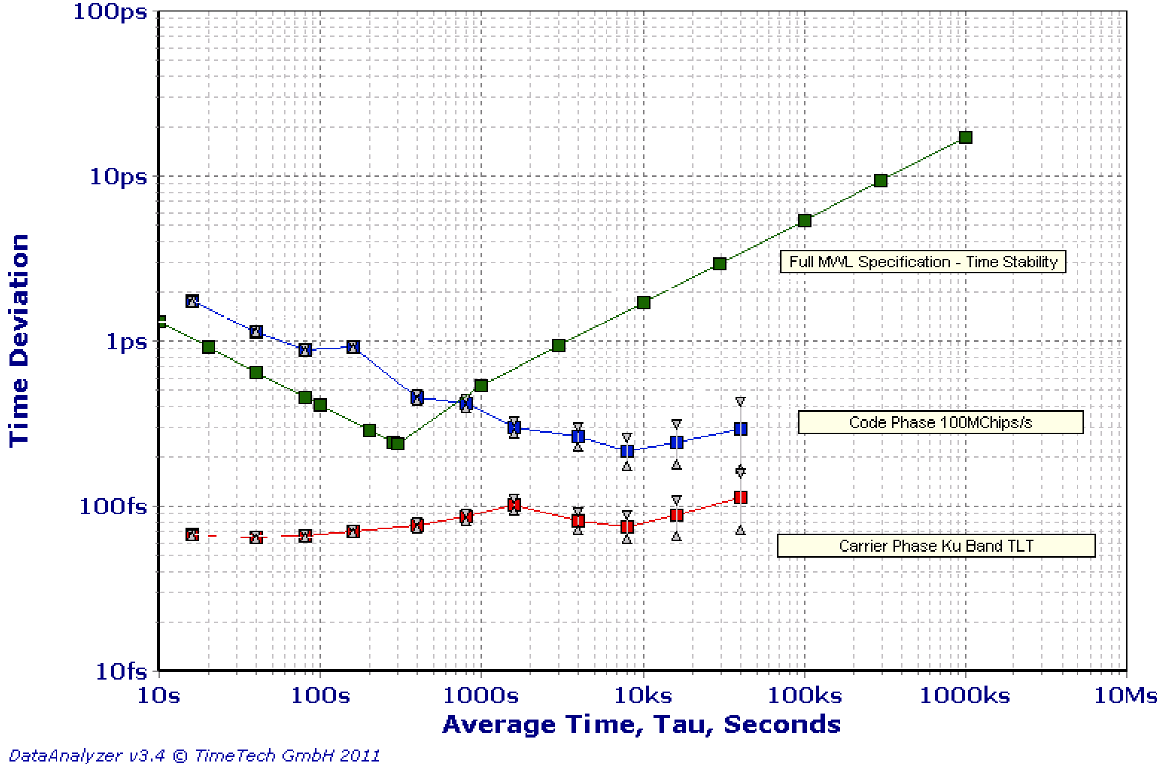
EM Server: 10 virtual machines running, incl G/T controller

FM Blue Box (part of EGSE)
8 virtual machines running

The full set of M&C computers has been restored from backup, is again available in virtualised environment (VMware)

Re-Evaluate Earlier Measurements (read from database) top: Code Phase, bottom: Carrier Phase

TIMETECH



Time Deviation vs. Tau
Time Deviation vs. Tau

2019/01/18 19:00 - 01/21 11:59
Data Source A: GT-GTCA1.Ins
Data Source B: GT-GTCO1.Abs
No Averaging

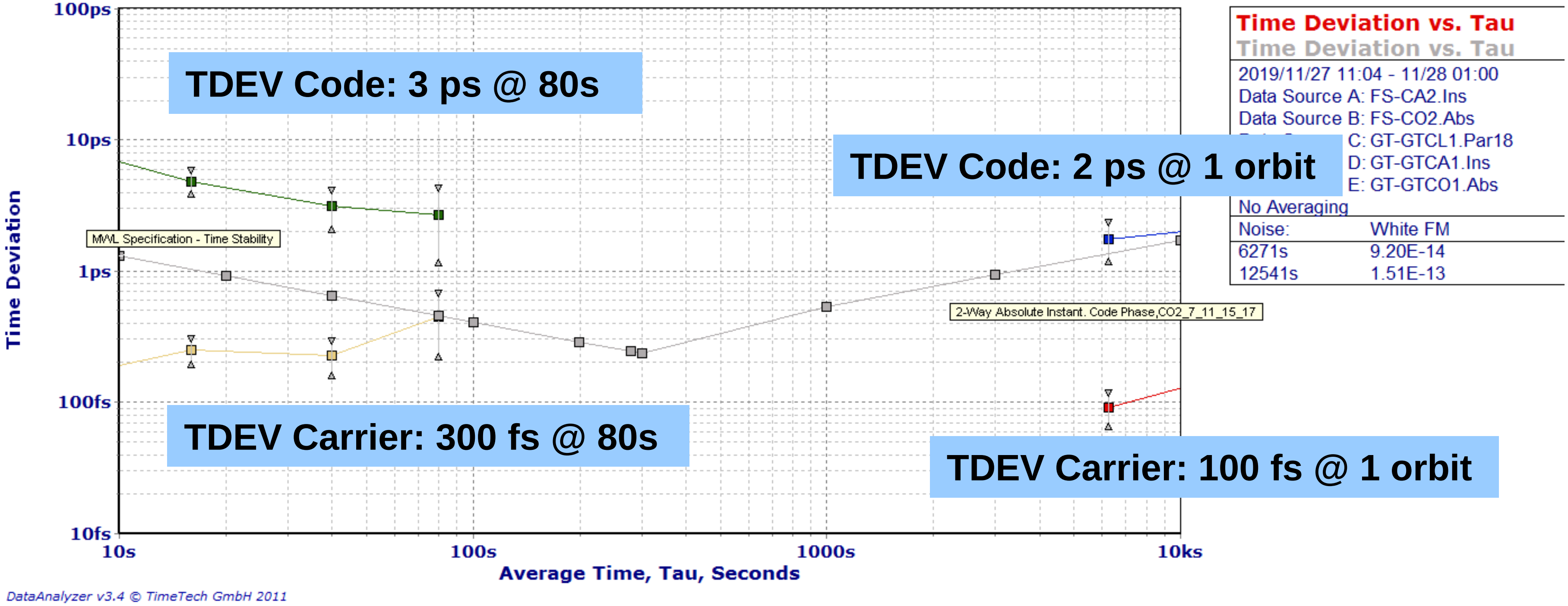
Noise:	White PM
2s	1.39E-13
4s	9.53E-14
8s	7.67E-14
16s	6.69E-14
40s	6.45E-14
80s	6.59E-14
160s	7.00E-14
400s	7.71E-14
800s	8.60E-14
1600s	1.03E-13
4000s	8.21E-14
8000s	7.52E-14
16000s	8.79E-14
40000s	1.14E-13

G/T with continuous Test-Loop Translator, carrier phase stays at 100 fs for 3 days

Database and data-analysis fully functional

TIMETECH

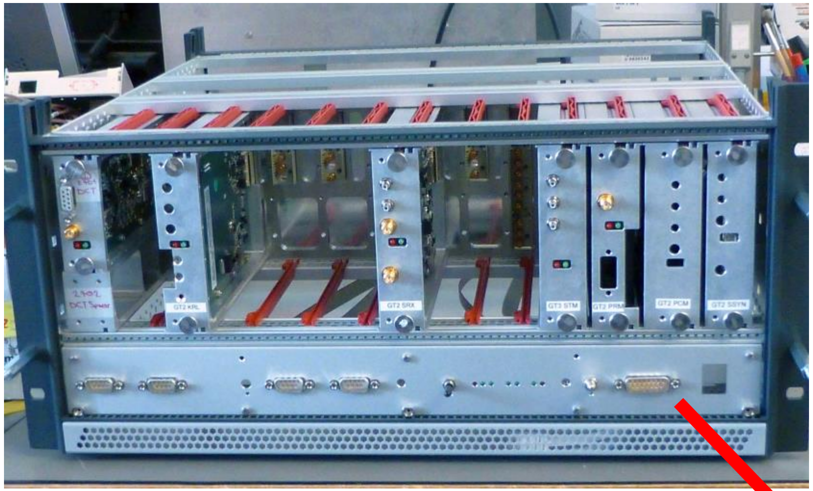
Re-Evaluate Earlier Measurements (2), End-to-End Test



- Lambda config, FS & G/T with realistic orbits, incl. Doppler
- Right data: 1 point / orbit
- Reproducible, estimate carrier cycle / orbit
- TDEV carrier phase: 100 fs in the long run

TIMETECH

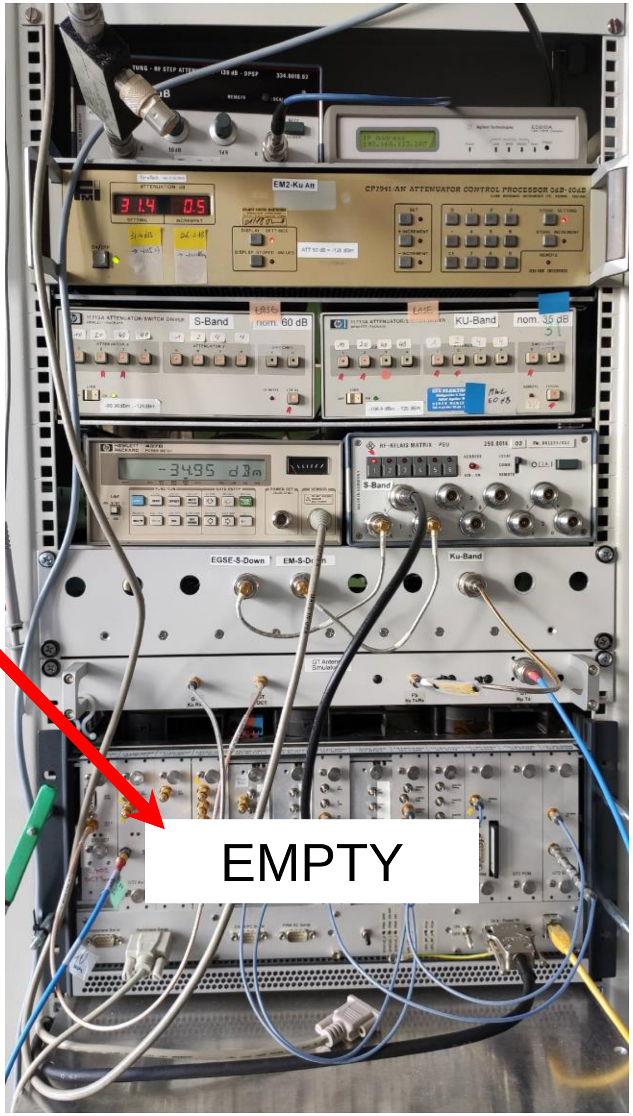
Activities with the G/T RF EGSE: ready to accept test items



The right picture is from my last presentation 2019, holding GT #2

Today, the G/T drawer (above) is mostly empty, awaiting modules to be tested.

Otherwise, the G/T RF EGSE is unchanged



EM S-Band level

EM Ku-Band level

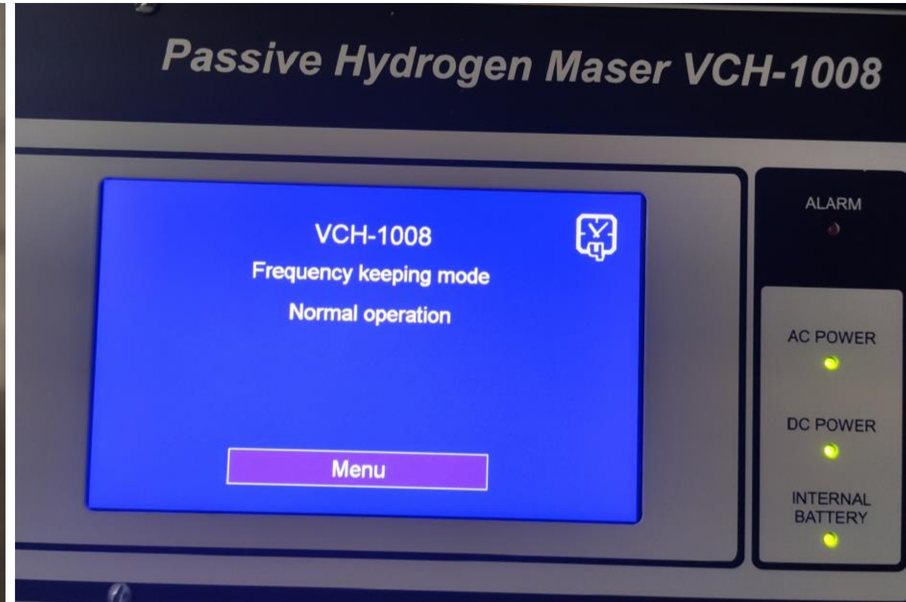
EGSE level S&Ku

GT vs EGSE S-selection

Ku-RF combiner Antenna simulator Test-Loop

GT #2, fully assembled

Improved T&F Infrastructure, Hardware



Operational 2-way link using
SATRE Modem

RAKON USO: 4E-14@ 1s, locked to PHM
Steered to UTC(PTB) via 2-way,
time constant 1 day

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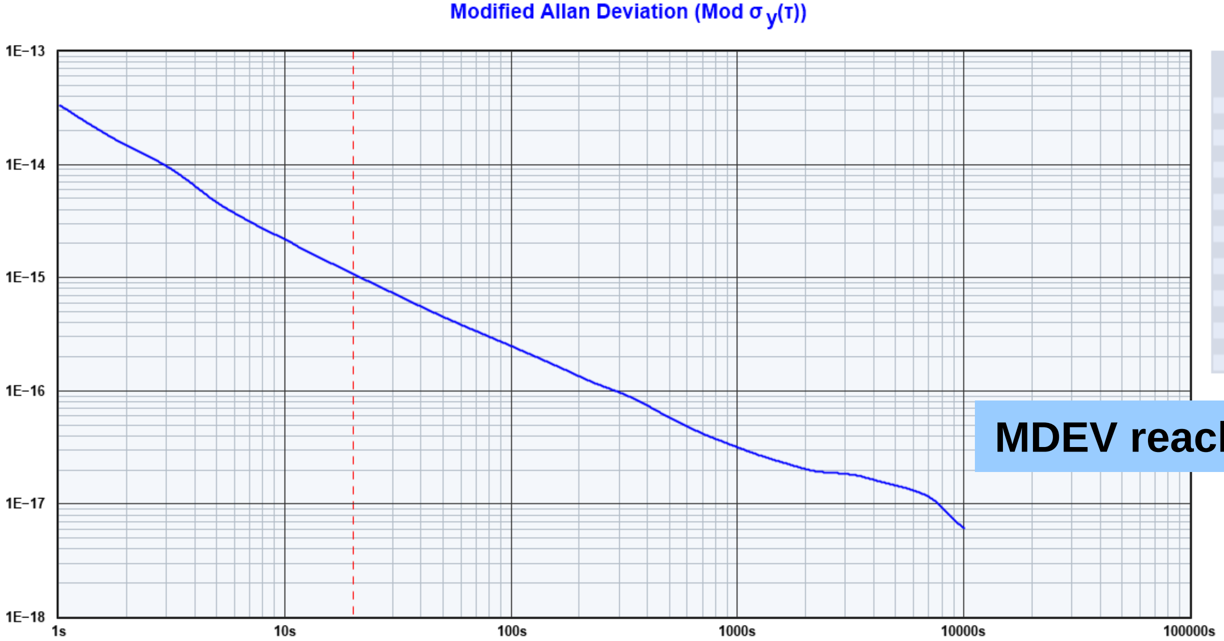
Improved T&F Infrastructure, 100 MHz Phase Noise

PN of 100 MHz signal approx 10 dB better than best Swiss Maser
Test equipment: R&S FSWP

Improved T&F Infrastructure, Phase Measurements

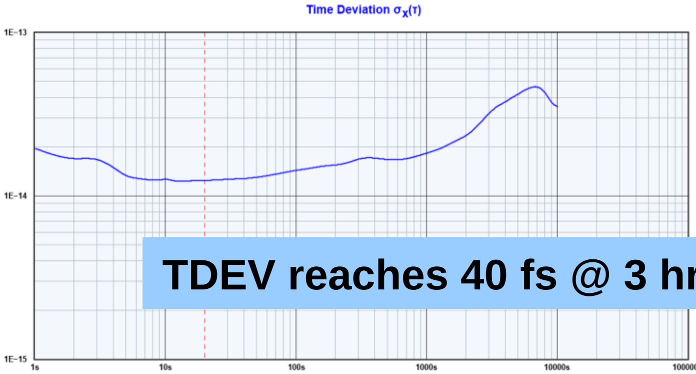


Tau	Sigma(Tau)
1s	3.40E−14
2s	1.47E−14
4s	6.46E−15
8s	2.72E−15
10s	2.20E−15
20s	1.08E−15
40s	5.56E−16
80s	3.02E−16
100s	2.50E−16
200s	1.35E−16
400s	7.42E−17
800s	3.78E−17
1000s	3.19E−17
2000s	2.05E−17
4000s	1.65E−17
8000s	9.31E−18
10000s	6.15E−18

MDEV reaches 1E-17 @ 3 hrs

Trace	Notes	DUT Freq	MDEV at 20s	RMS Jitter (1 Hz-100 kHz)	Duration	Acquired	Time/Date
AHMPLL 3.6, #1 vs #3, 2*47k, with ground (Unsaved)	REF TIM 5 MHz, Pin 9.6 dBm, unit vs unit	100.0 MHz	1.08E−15	2.7E−14 s	15 h	51848 pts	18.10.2022 19:15:23

Comparison between two 100 MHz generators 15 hrs



Tau	Sigma(Tau)
1s	1.96E−14
2s	1.70E−14
4s	1.49E−14
8s	1.26E−14
10s	1.27E−14
20s	1.25E−14
40s	1.28E−14
80s	1.40E−14
100s	1.44E−14
200s	1.56E−14
400s	1.71E−14
800s	1.75E−14
1000s	1.84E−14
2000s	2.37E−14
4000s	3.81E−14
8000s	4.28E−14
10000s	3.52E−14

TDEV reaches 40 fs @ 3 hrs

Trace	Notes	DUT Freq	TDEV at 20s	RMS Jitter (1 Hz-100 kHz)	Duration	Acquired	Time/Date
AHMPLL 3.6, #1 vs #3, 2*47k, with ground (Unsaved)	REF TIM 5 MHz, Pin 9.6 dBm, unit vs unit	100.0 MHz	1.25E−14	2.7E−14 s	15 h	51779 pts	18.10.2022 19:15:23

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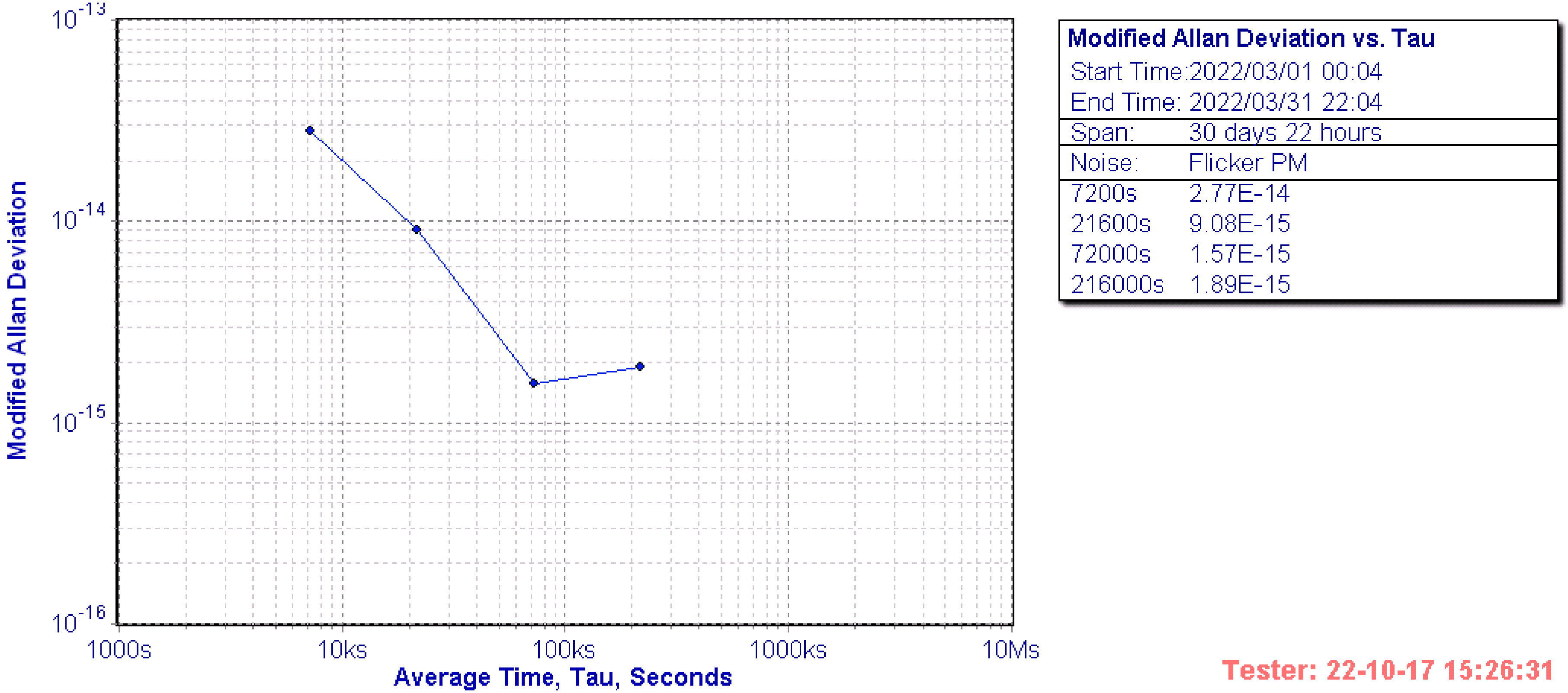
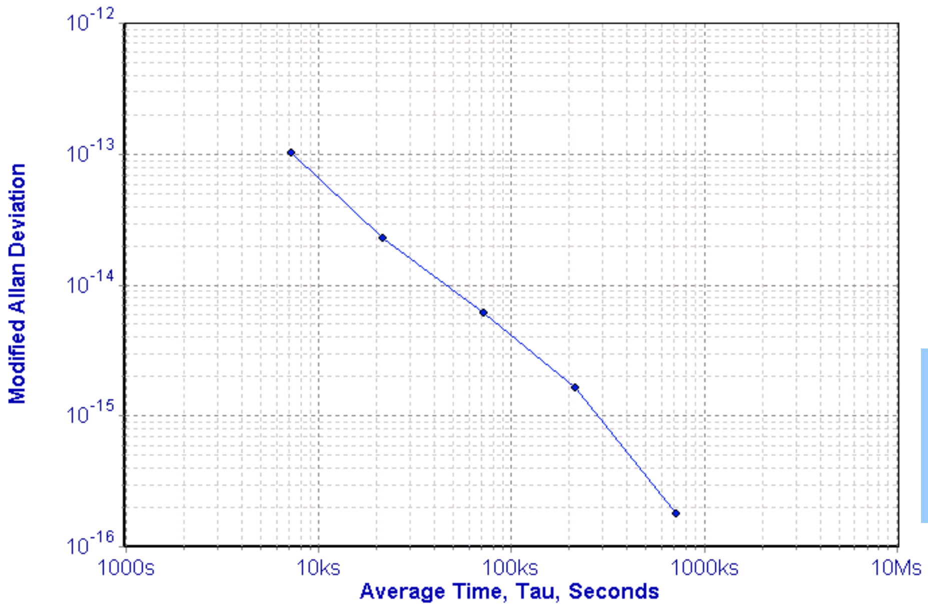
T&F Infrastructure, PHM long-term performance



Free-running PHM VCH-1008, compared to UTC(PTB), March 2022
Approx 1.5E-15 @ 1 day

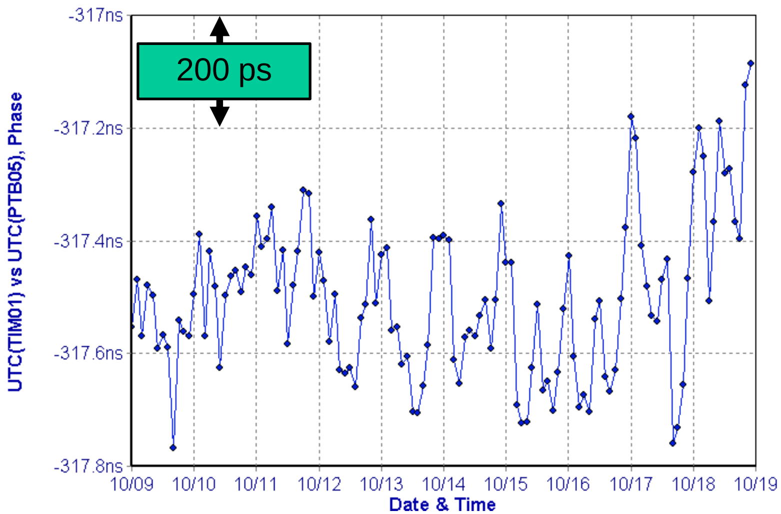
TIMETECH

T&F Infrastructure, PHM locked to UTC(PTB), time constant 1 day, in-loop performance, ITU-files



Modified Allan Deviation vs. Tau	
Start Time:	2022/08/16 00:04
End Time:	2022/10/18 22:04
Span:	63 days 22 hours
Noise:	White PM
7200s	1.02E-13
21600s	2.27E-14
72000s	6.12E-15
216000s	1.62E-15
720000s	1.78E-16

MDEV 1.8E-16 @ 8 days during 64 days In-loop

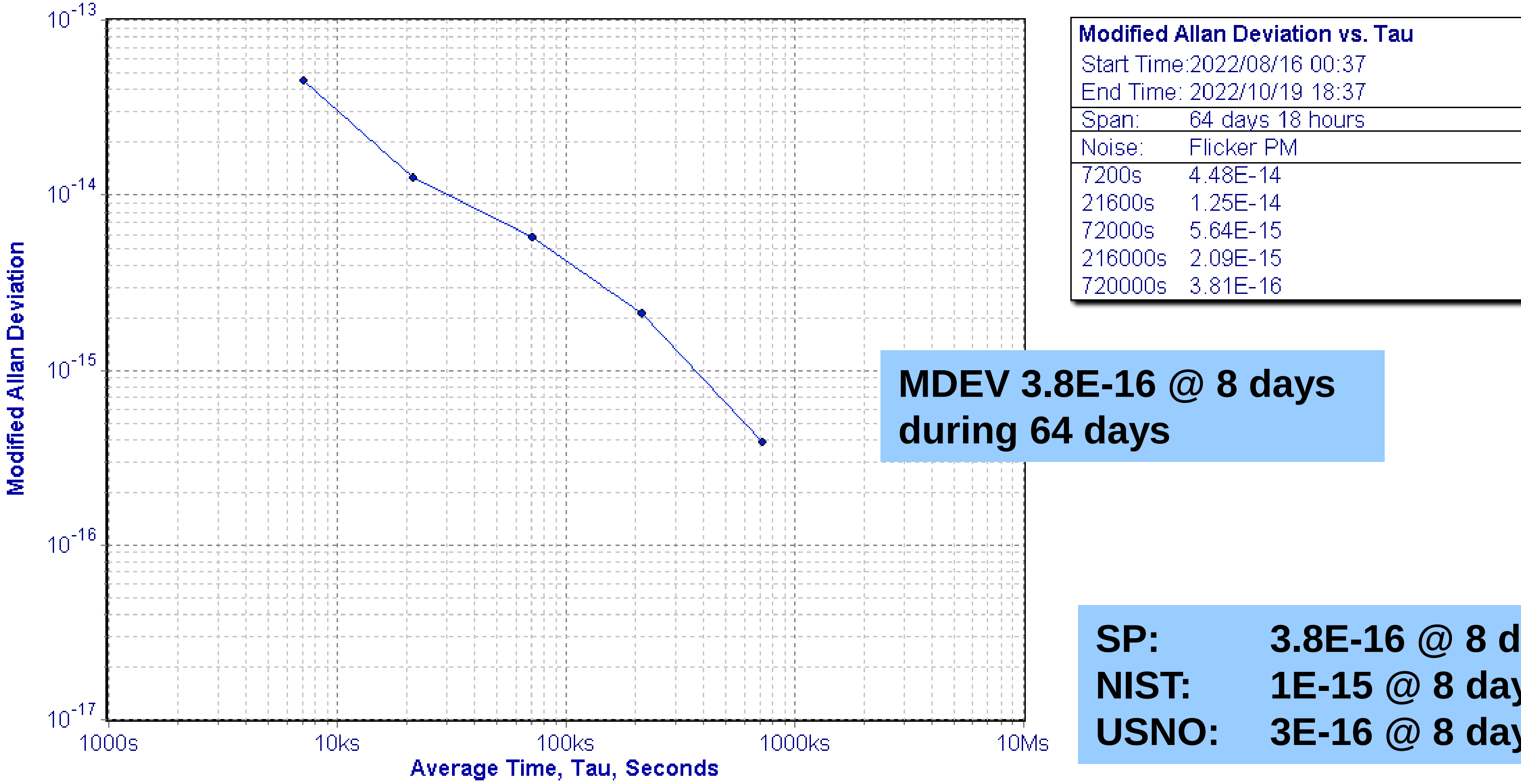


UTC(TIM01) vs UTC(PTB05)	
Start Time:	2022/10/09 00:04
End Time:	2022/10/18 22:04
Span:	9 days 22 hours
Sample Interval:	7200 s
Min:	-317768.500 ps
Max:	-317086.000 ps
Mean:	-317502.992 ps
PP:	682.500 ps
DRMS:	129.421 ps
Std.Dev:	138.809 ps
Drift / Second:	1.011E-16
Scale:	200 ps/div
Normalized by:	none

StDEV 140 ps during 10 days

WS: 22-10-19 22:58:08

T&F Infrastructure, PHM locked to UTC(PTB), compared to Sweden (SP), using ITU-files



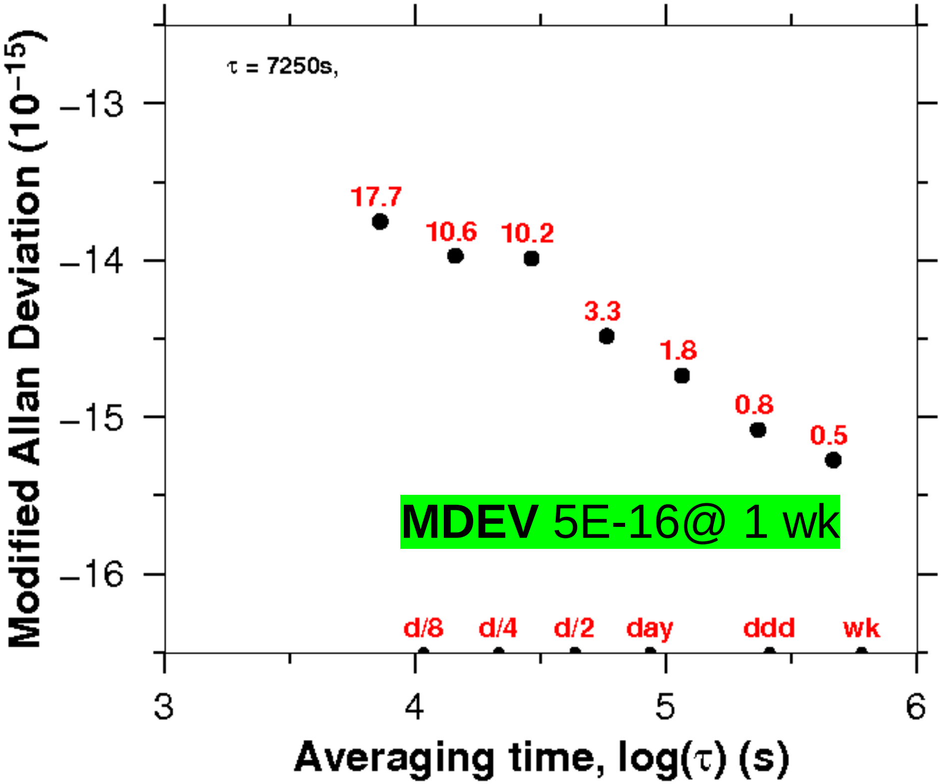
MDEV 3.8E-16 @ 8 days during 64 days

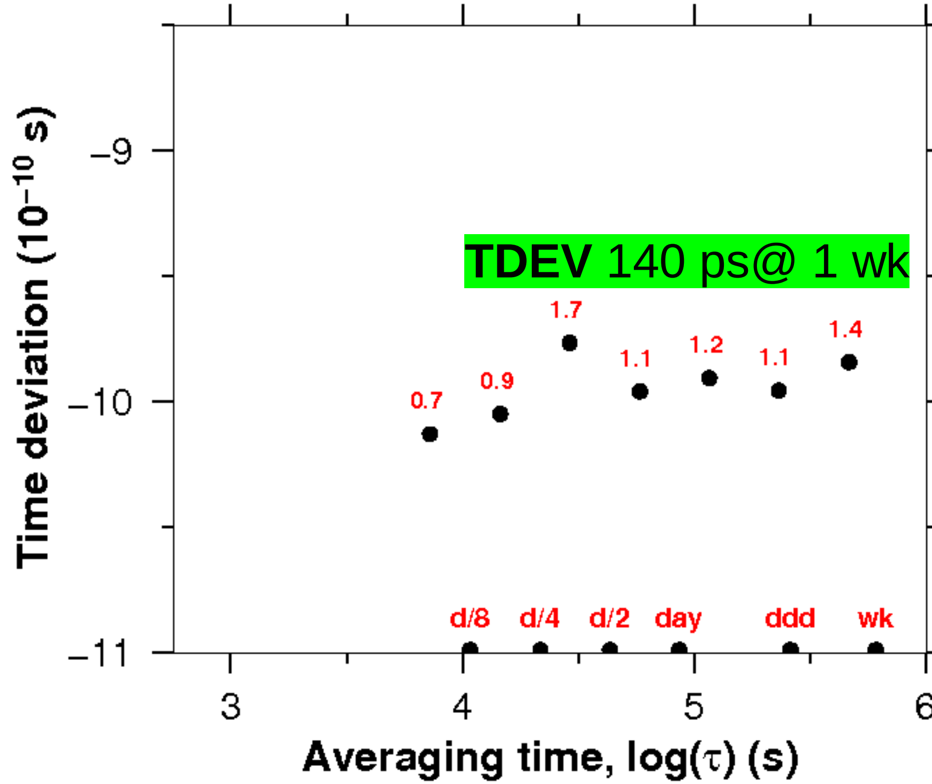
SP:	**3.8E-16 @ 8 days**
NIST:	**1E-15 @ 8 days**
USNO:	**3E-16 @ 8 day**

Proof: compare to other, independent time scales

2-way: Current state-of-the-art: where to go?

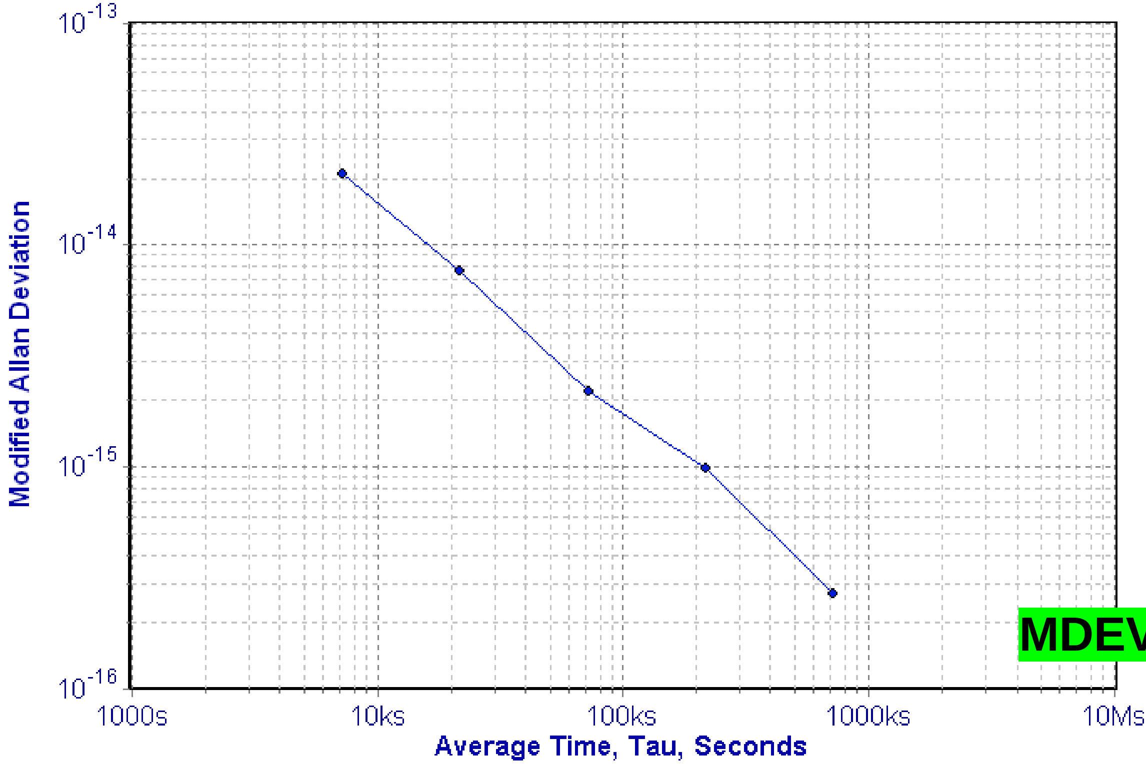
From the BIPM web server: PTB vs USNO (best Ua 200 ps)





https://webtai.bipm.org/ftp/pub/tai/timelinks/lkc/2207/usnoptb/lnk/usnoptb.t3b3_.gif

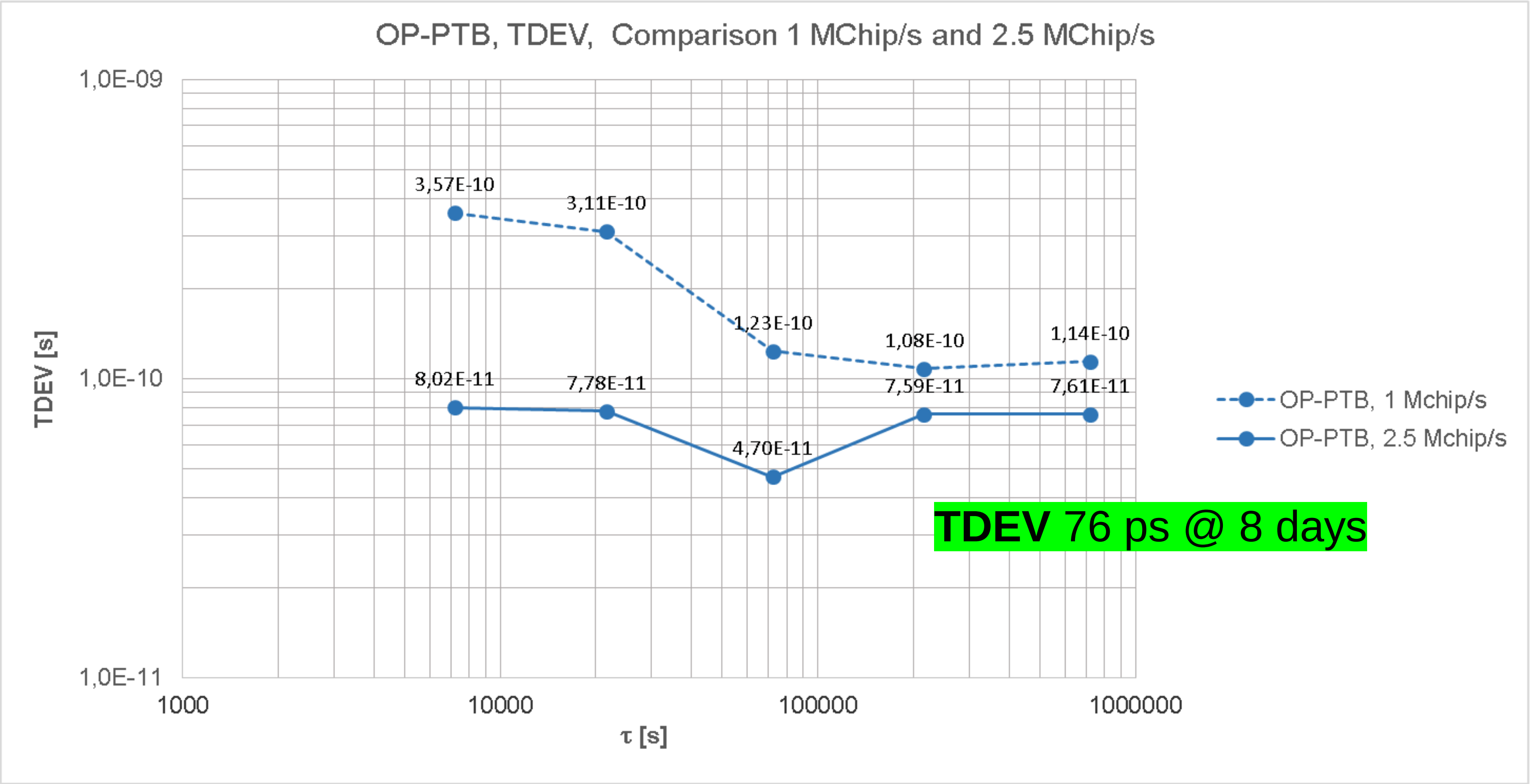
USNO – PTB, 2022, 2.5 MChip/s, duration: 54 days



Modified Allan Deviation vs. Tau	
Start Time:	2022/08/26 00:46
End Time:	2022/10/18 22:46
Span:	53 days 22 hours
Noise:	Flicker PM
7200s	2.08E-14
21600s	7.65E-15
72000s	2.19E-15
216000s	9.82E-16
720000s	2.66E-16

MDEV 2.7E-16@ 8 days

OP - PTB, 2021-2022, 1 MChip/s vs 2.5 MChip/s, 54 days



Expected improvement by increasing the chip rate, 1 .. 2.5 MChip/s

Current systems fall short in the view of science and clock developments, like ACES: 1E-17 and far away from 1E-18 goals, which are around

TIMETECH

Cost Reduction: Digital Implementation

Red Pitaya 250MSa/s,
1 pps input

Compatible with MWL signal structure, code and carrier

Activity started

Zynq 7020: 125 MSa/s,
SATRE: 20 MCh/s and higher

Digital implementation of SATRE
Full set of features, ongoing

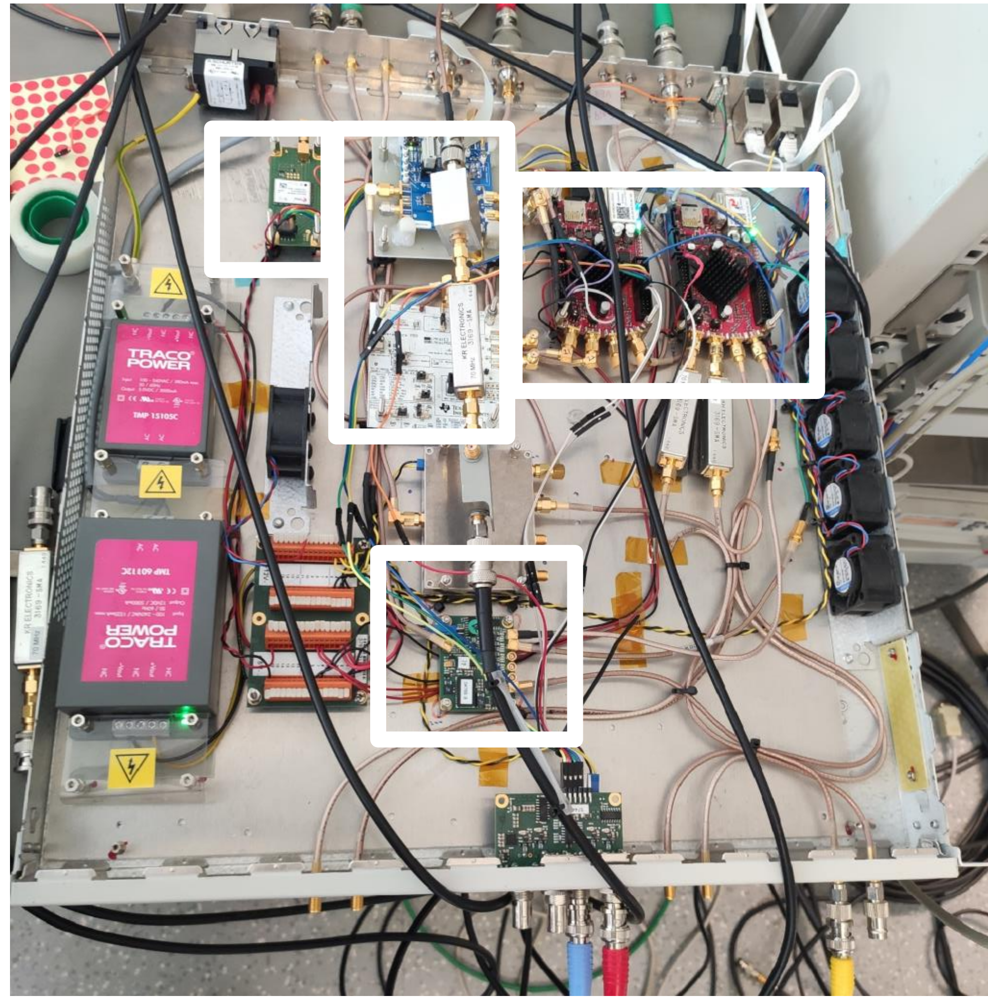
Breadboarding:
Digital SATRE: Tx and Rx, direct sampling receiver

GPS

Synthesiser
18 GHz

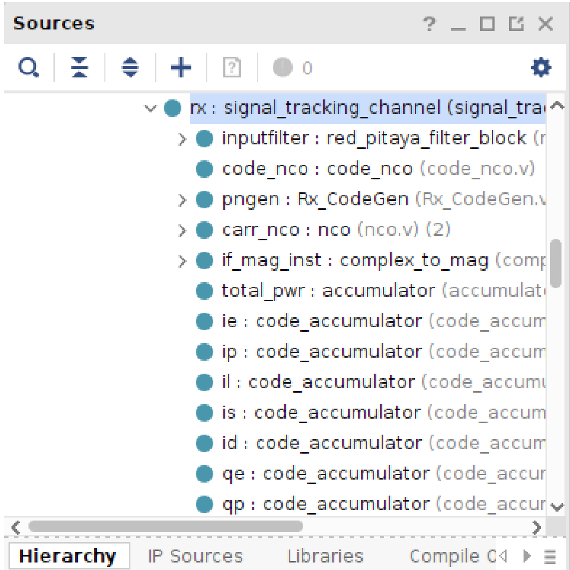
2 * Z7020

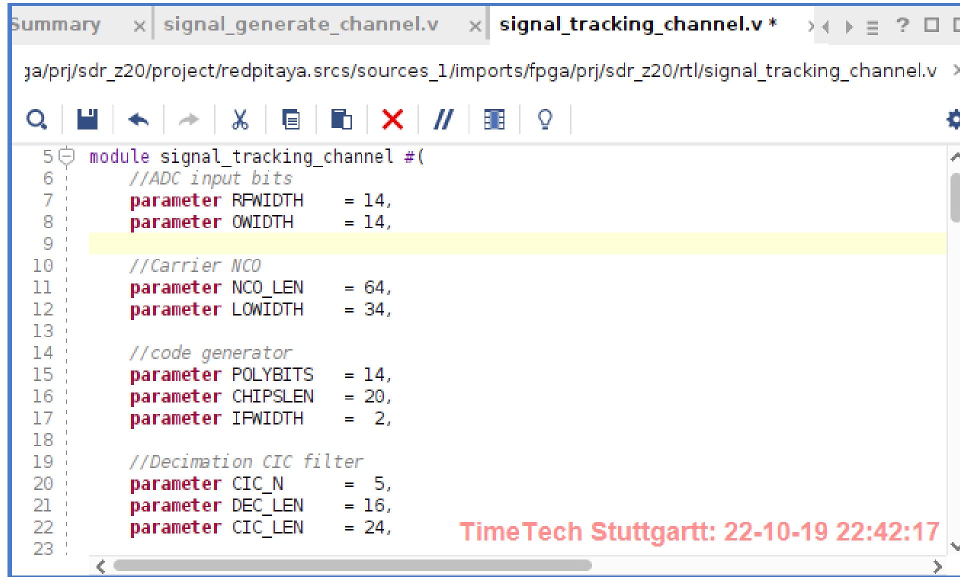
1 pps
Distribution



Breadoarding: Development Chain

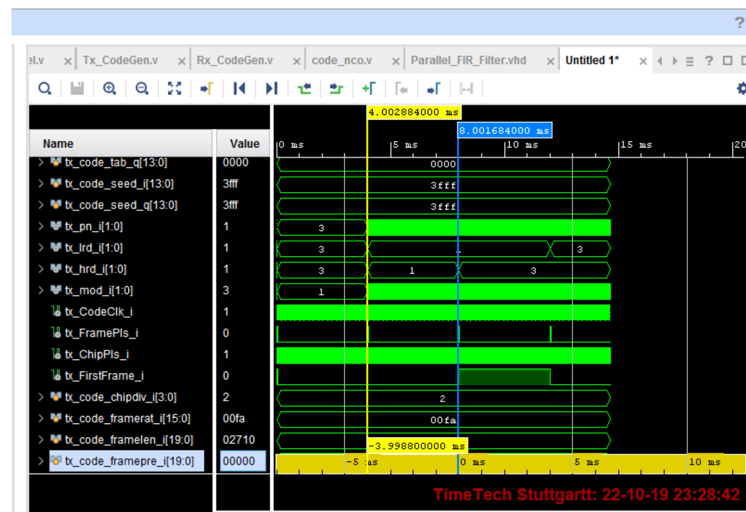
TIMETECH



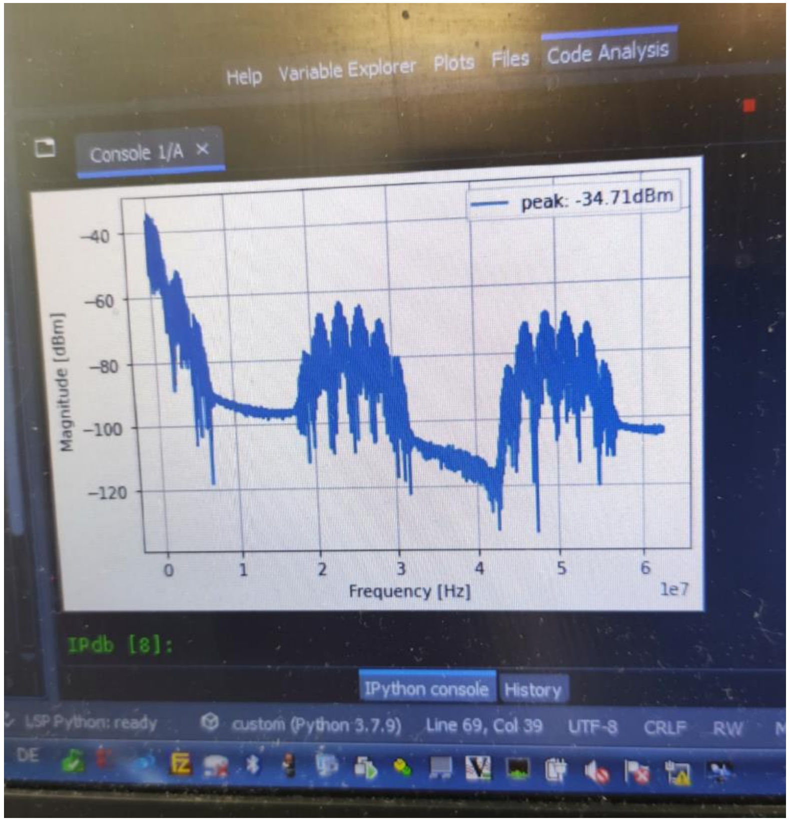


Development Chain, incl.

- All-VHDL implementation
- No copyrighted libraries
- Bitwise Simulation



Beardboarding: Development and Verification



Digital Signal Analysis
Internal Test Points, DAC output to Scope

- **1 pps**
- **PN Sequency**
- **Modulated RF**

Numerical Signal analysis, incl FFT

Zero IF, showing data modulation

SDR Major elements and progress

- Major elements realised in FPGA

  > **40x FPGA cores** developed / verified by test bench incl.

  different DDS appoarches, look-up table & CORDIC,

  PID controller, modulation, demodulation, saturation, complex multiplier, decimator etc.
- **Major C code elements** incl. FPGA DDR interface, data streaming, FFT etc, running on embedded ARM cores in ZYNQ SoC
- **Code re-use from SATRE,** but complied in high level language

Conclusion: „Low-Cost MWL“ ground terminal

- Low-cost MWL G/T is not commercially feasible, reproduction of G/T impossible due to obsolescense
- Chip-shortage prohibits any fast solution
- „Market research“: Investment **too high** for a short mission like ACES
- ACES MWL: Lets optimise, what is available
- Maximise operational outputs

Conclusion, Outlook signal reception

- Aim for highest possible chip rates
- Direct Sampling is complex for BW above few 100 MHz, although this is definitely the future
- Allows for multi-channel operation
- But: Not ready „now“

- **MWL-Rx mixed signal architecture** can be scaled to 1 GSa/s and above, ground and space,
But single channel reception only

- **In the near term, ACES-MWL architecture is most promising**

Conclusion, Outlook: Satellite and transponder selection

TIMETECH

- Traditional bent-pipe transponders have limited capabilities, even at very high BW (500 MHz and up)
- Better use on-board signal regeneration, multiple channel operation, all links like ACES-MWL
- Downlink the translation oscillator as separate signal
- Transmit coherent carrier and modulation, cycle identification
- 32, 48 GHz and up

Plan for dedicated, optimised transponder(s) in GEO orbit, optimise footprint