Design of the F&T subsystems for ESA's deep space stations

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Outline

- Some remarks about T&F Metrology
- Design Logic: Noise & thermal aspects
- Distribution Elements
  - Passive Elements: Cables
  - Active Elements: Amplifiers, Dividers
- Introduction to ESA‘s DSA
- Evolution of DAS F&T Systems
- Design of DSA3- Malargüe, Argentine
- Design drivers
- Reference clocks
- System architecture
- Frequency distribution system
- Timing system
- System verification
- Summary, Conclusions

Introduction

ESA's Deep Space Antennas:

- 2002: DSA1 in New Norcia, Australia
- 2005: DSA2 in Cebreros, Spain
- 2012: **DSA3 in Malargüe, Argentina**

DSA3 needed for global coverage.

DSA3 Applications

- Ka-band reception
- X-band transmission and reception
- Future possibles:
  - Ka-band transmission
  - K-band reception
- Operated for:
  - Telemetry and Telecommand functions
  - Satellite tracking and ranging
  - Radio Science research
  - Scientific missions: Gaia, BepiColombo,…
- High stability of frequency references and accurate time is required.

History and Evolution

- **DSA1, New Norcia, 2002**
  - "Commercialised" H-Maser (ON), unattended operation, two in hot redundant configuration, automatic failover
  - "Classical" 5 MHz distribution, Masers inside antenna building
- **DSA2: Cebreros, 2005**
  - 2 masers, T4Science, class 1E-13@1s) inside antenna building
  - Add 100 MHz low phase noise signal, using two "combined clean-up oscillators" to generate 100 MHz signal
  - Profit from signal combination
- **Kourou (Backup station, 15 m)**
  - "cost effective" 5 MHz distribution, 100 m distance
  - The 5 MHz "cable effect" (or cable disaster), introduce electronic length compensation
- **DSA3: Malargüe, 2013**
  - Have clocks in dedicated clock rooms, allow for expansion and advanced clocks, 100 m distance to antenna
  - Remove PLLs and cleanups for reliability, use maser signals directly,
  - Distribute 100 MHz, generate lower frequencies locally, dividers, filters
  - Add short term stable cryogenic sapphire oscillator (class 2E-15 @ 1s), locked to Maser for long-term stability (PLL again, but "experimental")
- All **masers free running, compared to GPS**, time adjustment to +/- 50 ns, frequency adjustment "as needed", i.e few/yr

Objectives of T&F systems in DSA

- Use „best“ short term stable clocks, generally there is no reference to be measured against (Act H-Maser)
- Ensure long-term frequency stability, with known time offset to UTC, by measurements to references (GPS)
- Generate signals 5, 10, 100 MHz (sharp, accurate) with „best“ phase noise, 1 Hz to 100 kHz offset from carrier
- Distribute signals with minimum performance loss to the station user, up- down converters, ranging equipment, signal samplers
- Rule-of-thumb:
  - degrade source frequency stability by no more than 10% (allow ADEV of 30%, RSS!), **„10%-rule“,** 0% is impossible
- Phase noise shall not be affected, same as source
- Cover any distance, in actual environment

Some remarks about T&F Metrology
Stability measures of Clocks, Specifications

- Clocks are characterisised by statistical measures, commonly
  - **ADEV** (Allan Deviation)
  - **MDEV** (Modified Allan Deviation)
  - **TDEV** (Time Deviation)
  - **Phase Noise** (density), 0.001 Hz<carrier offset<1 MHz
- Tell about "Fractional frequency stability", do not say anything about the actual frequency of a clock.
  - A clock running @ 10 MHz + 1 Hz can be as good as a clock @ 10.0 MHz, beware of offsets
- xDEV: Common characteristics: 2-sample variances, standard measurement bandwidth: 1 Hz
  - **ADEV:** two 1s-samples spaced τ [s], slope τ^{-1}
  - **MDEV:** Averages between samples, slope $\tau^{-1.5}$ (improves faster, "looks better")
  - **TDEV:** white phase noise: τ^{-1}, flicker of phase: constant
- **Abstain from ADEV!** It cannot be converted into other measures, but MDEV, TDEV and PN can.
- MDEV comes closer to reflect actual applications, which integrate signals
- TDEV does not tell anything about the time or phase-time stability of a system!
- **Drawbacks, twists:**
  - Statistical significance is achieved with large number of avarages only
  - Some customers require "**small error bars**", leading to excessive no of samples, test time
  - Most annoying for real-world applications: single events are "masked" by avaraging.
    - Consequence: Better error bars hide single events. (Good for industry).
  - Use "running" ADEV, TDEV, watch "stability" of stability, limit no of samles (i.e. 300 per τ)

Characterisation of Clocks and Systems

- Best means for system stability characterisation and modeling, as basis for any other measure
  - **(Single-sided) Phase Noise (density), "PN"**
- **Art of stability characterisation: "Understand the slopes"**
  - E. Rubiola: "Oscillator hacking" -> Understand internals by inspection of noise slopes
- Best means to characterise absolute frequency: do not use the term "accuracy"
- **Uncertainty concept, types uA and uB**
  - uA "stability, noise, jitter, precision"
  - uB "absolute uncertainty, systematics, calibration, reproducibility, scale errors"
- Even the si-unit [1s] has limited uncertainty
- Uncertainty concept **requires and allows** the definition, what is included, followed by an analysis of individual contribuions.
- Total uncertainty is calculated as: RMS of uA and uB, mostl often dominated by uB
- **Drawbacks, twists:**
  - Error sources are commonly considered statistically independent, using RMS
  - What to do with correlated (noise)-sources?
  - Rigorous analysis must consider correlation between sources,
  - **Often leads to surprises**
- **How Clocks and Distribution compare?**
  - Distribution cannot induce "infinite phase drift", unless "rubber-cables" are used, which eventually would break when stretched
  - Clock's phase can drift infinitely

Effects of Temperature

- On clocks: Frequency change
- On distribution: Phase change (delay)
- This chapter can be closed simply by:

  „keep the temperature constant“
- What is constant temperature?
  - JPL clock lab: air at 10 mK out of the false floor: „rather good“
  - Then look at the AC machines outside of the building!
- **How to improve Clocks** (Sylvère‘s talk)
  - Add thermal stabilisation (heater-cooler box)
  - Use and increase thermal capacity (air-conditioning can be fast)
  - Keep them in dedicated „clock rooms“ (maintenance)
  - Shield against the environment (Sylvère‘s talk)
  - Model the known components of instability (HDEV, Hadamard deviation)

Effects of Temperature on Distribution

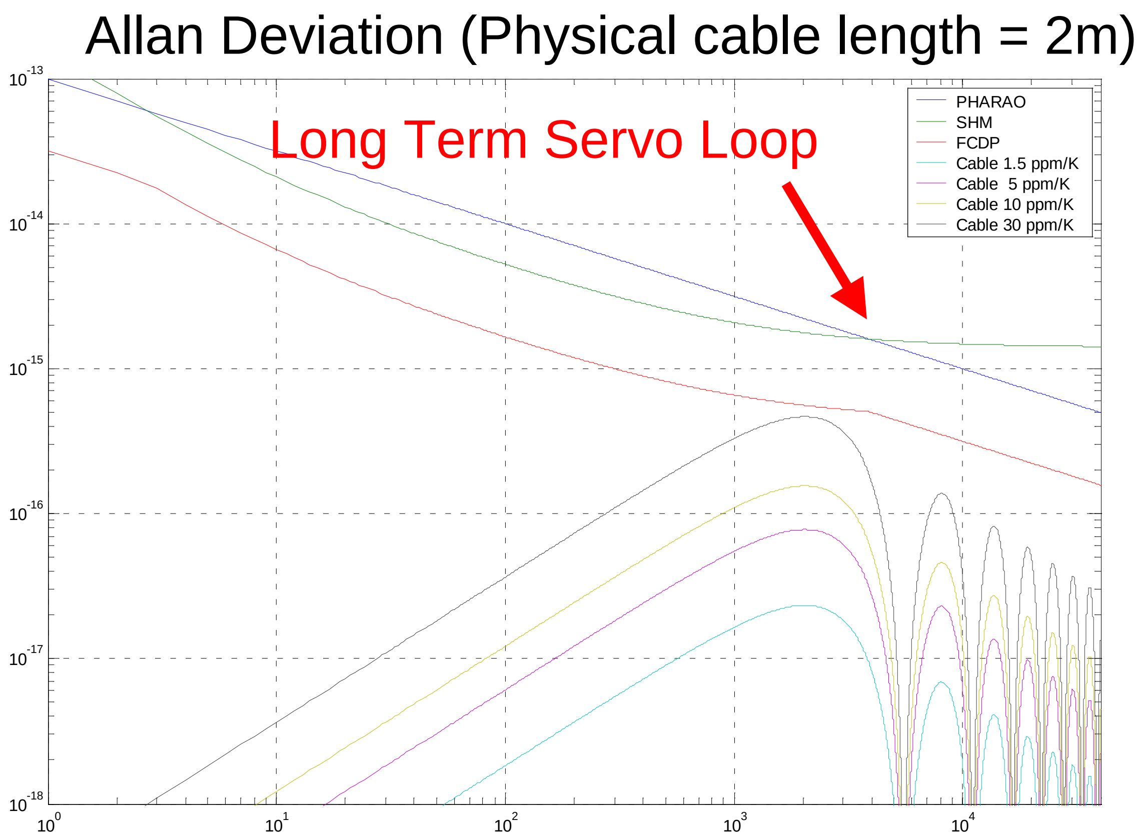
- **Thermal co-efficient of (group) delay.**
  - Specified as „ppm/K“ or „s/K“.
  - ppm/K needs the knowledge of absolute delay
  - ps/K (or fs/K) lead directly to phase-time variation, independent from frequency of operation and absolute delay.
  - Cables are mostly characterised by „ppm/K“
- Chapter can be closed easily by: **„keep the temperature constant“**
- **Something good and bad**
  - **Most TK are linear with temperature**, cables and active elements
  - Beware of the nonlinear „PTFE“ effect around room temperature (mainly solid PTFE), manufacturers „shift“ that tmperature out of practical range, foam and composite dielectrics)
  - Cables may show hysteresis (but only one found so far, type „A“)
  - Amplifiers and active elements can be considered linear, without hysteresis, if properly engineered
  - Known TKs can be modeled using thermal sensors
  - Beware of thermal slopes (AC), dynamic thermal environment, unequal thermal capacity of individual elements: requires complicated models
  - Cables have frequency-dependent TKs: measure at the frequency of operation!

My favorite error sources, stability measurements

1. **Constant TK with constant thermal slope:**
   - Linear phase slope, perfect xDEV, but finite frequency offset (do not measure until system burns), but might happen during a single observation, which is performed at wrong frequency
2. **Determine ADEV with frequency counter, have single phase jump**:
   – Perfect ADEV, single phase jump causes frequency outlayer, “averaged away”
   – Phase jump is detected with phase meter, frequency error reduces with observation time, but jump is detected from all samples.
3. **Fill data gaps by linear interpolation:**
   - Note: xDEV is undefined in presence of data gaps
   - “linear phase” has no noise, statistics improve magically and proportional to gap size (“best results with no data”)

Solution: Use phase meter instead of frequency counter, bridge gaps using time comparison, ensure phase continuity after gaps.

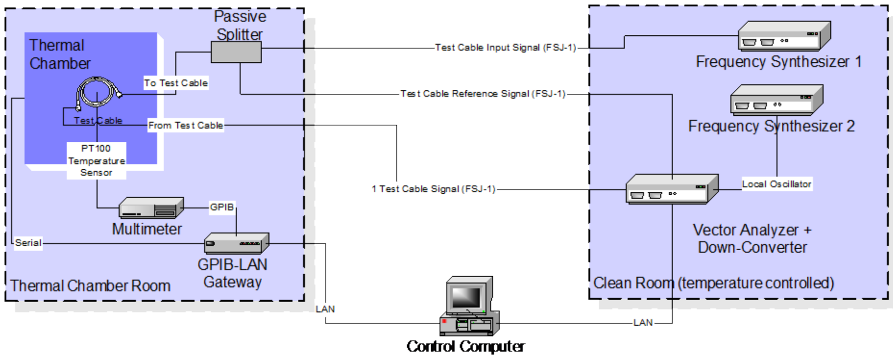
My favorite error sources: cables periodical temperature variations



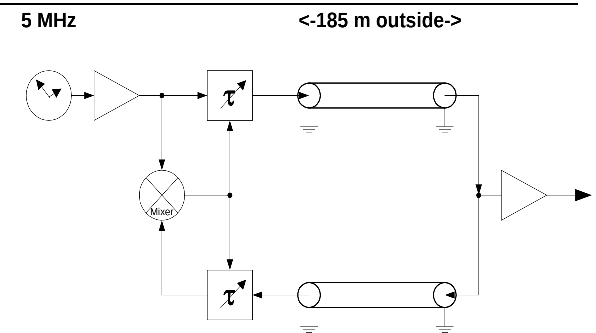
Theoretical effect on ACES-microwave- link ADEV due to cyclic (sinusoidal) thermal variation, for ACES-typic environment (orbit 90 minutes, 4Kpp), ADEV peak occurs at half obit time period, 3000 s)

Rule: Bump at half period and harmonics, **vanish at full period (!),** effect proportional to T

Cable selection

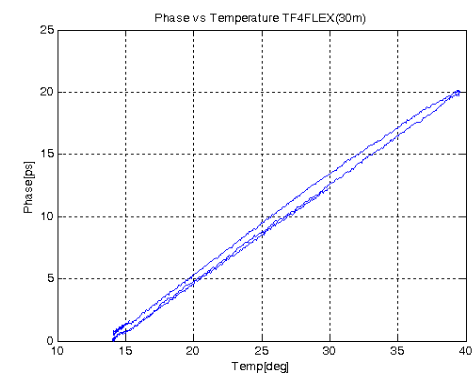


Test setup, DUT in thermal chamber, test equipment stabilised)



Active delay compensation, 185m FSJ-4, „Kourou“

Cable	TK at 5 MHz	TK at 10 MHz	TK at 100 MHz
Huber-Suhner Multiflex 141 10m	51.3ppm/K	-6.0ppm/K	-25.2ppm/K
RG-223 10m	-141.2ppm/K	-131.9ppm/K	-125.9ppm/K
Semiflex Cable 8.18m	6.6ppm/K	-11.5ppm/K	-28.6ppm/K
Huber-Suhner 10m	-6.9ppm/K	-8.6ppm/K	-11.1ppm/K
Times Microwave LMR-240 10m	17.1ppm/K	-3.4ppm/K	-24.0ppm/K
Times Microwave SFT-205 10m	15.4ppm/K	7.7ppm/K	-4.3ppm/K
Meggitt 2T693 SiO_2 7m		30.6ppm/K	4.3ppm/K
Andrew FSJ-1 12m	25.0ppm/K		7.1ppm/K
Andrew FSJ-4 20m	10.0ppm/K		1.3ppm/K
Andrew LDF-1P-50-42 10.6m	15.1ppm/K	2.8ppm/K	-10.4ppm/K
Andrew LDF4-50A 10.6m	7.2ppm/K	4.7ppm/K	0.6ppm/K
Times Microwave TF4FLEX 30m			6.4ppm/K
Phasetrack PT210 6m			2.0ppm/K



Cable with hysteresis

100 MHz: LDF4-50A, 0.6ppm/K @ 100 MHz, good for 1 pps

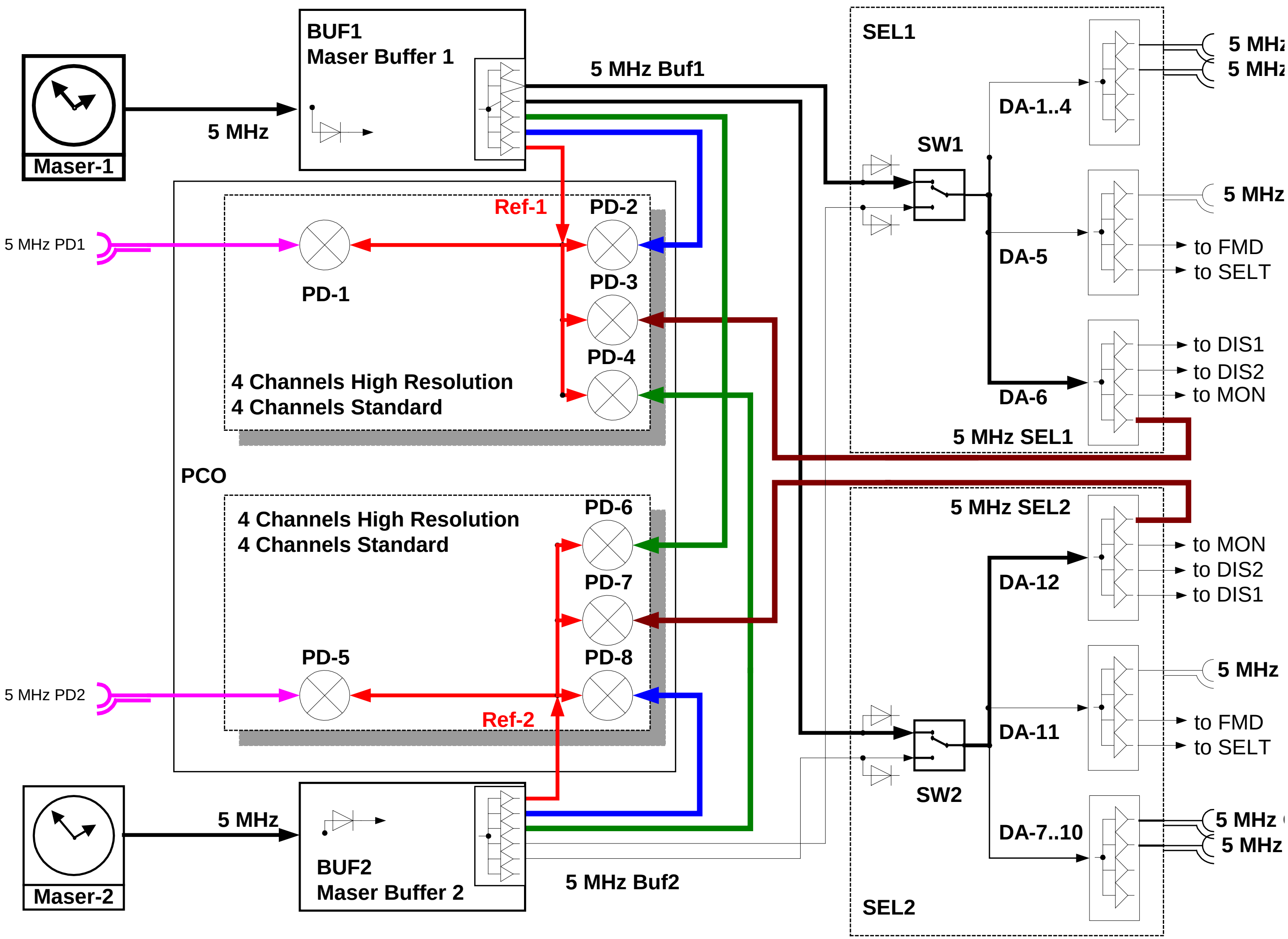
1 pps: ECOFLEX 10, TK better than fiber (< 20ppm/K) , to 200 m

My favorite error sources: measurement topology

- „Beat“ two sources, clocks, signal chains
  - Assumes two identical sources, bad one dominates, cannot determine, which!
  - Use 3rd source, 3-corner hat, results for all individual sources
  - 2 clocks + GPS
  - Phase noise with cross correlation. Agilent source analyser 5042B (super!) good down to 3 Hz off carrier
  - ADEV, TDEV with cross correlation: TimeTech phase comparator, best source 10 times better than average source, $\tau > 1$ s
  - “Timepod”: cost effective, to 30 MHz only

DSA1 designs and features

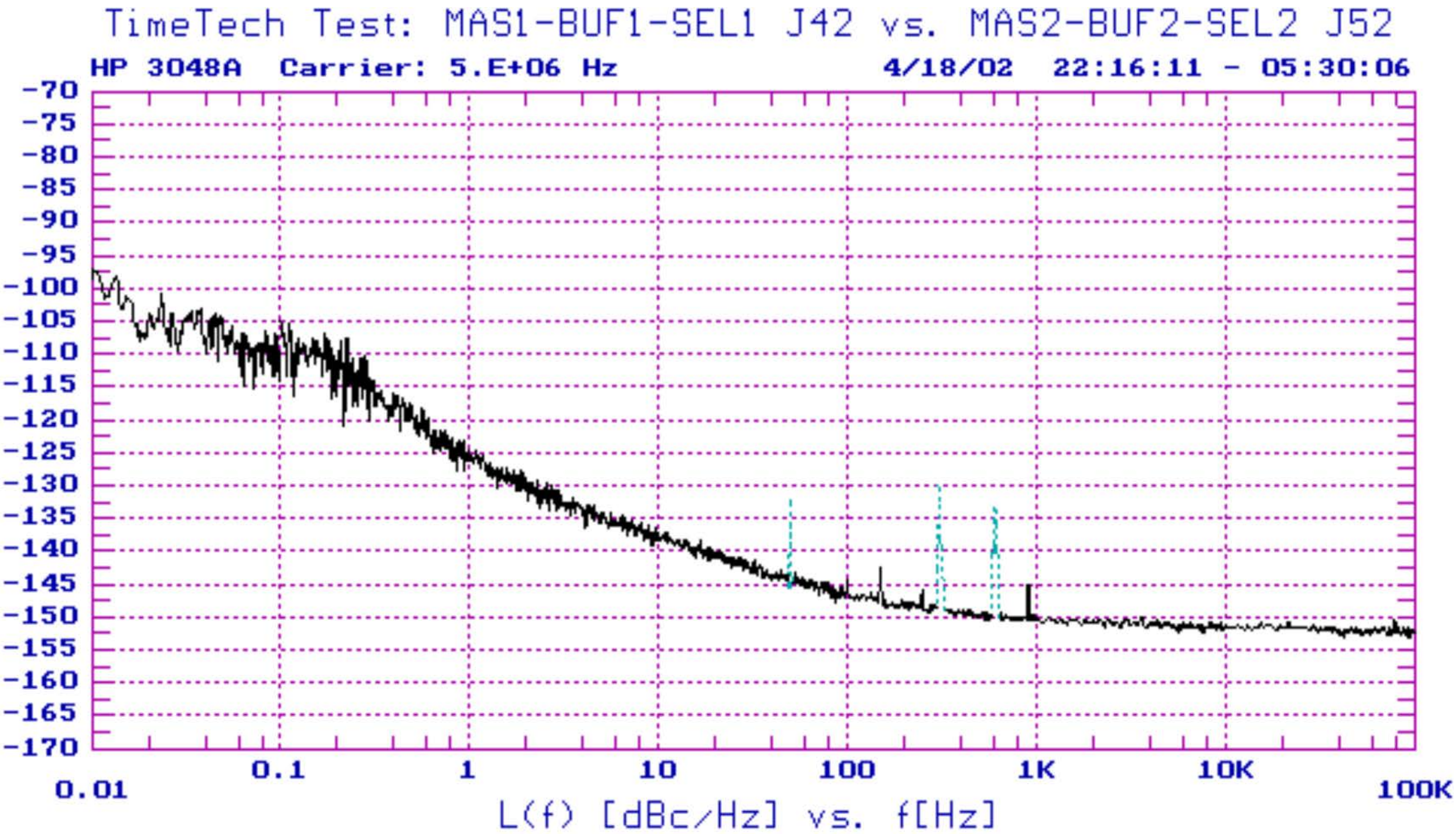
New Norcia, DAS 1



Masers in thermal boxes

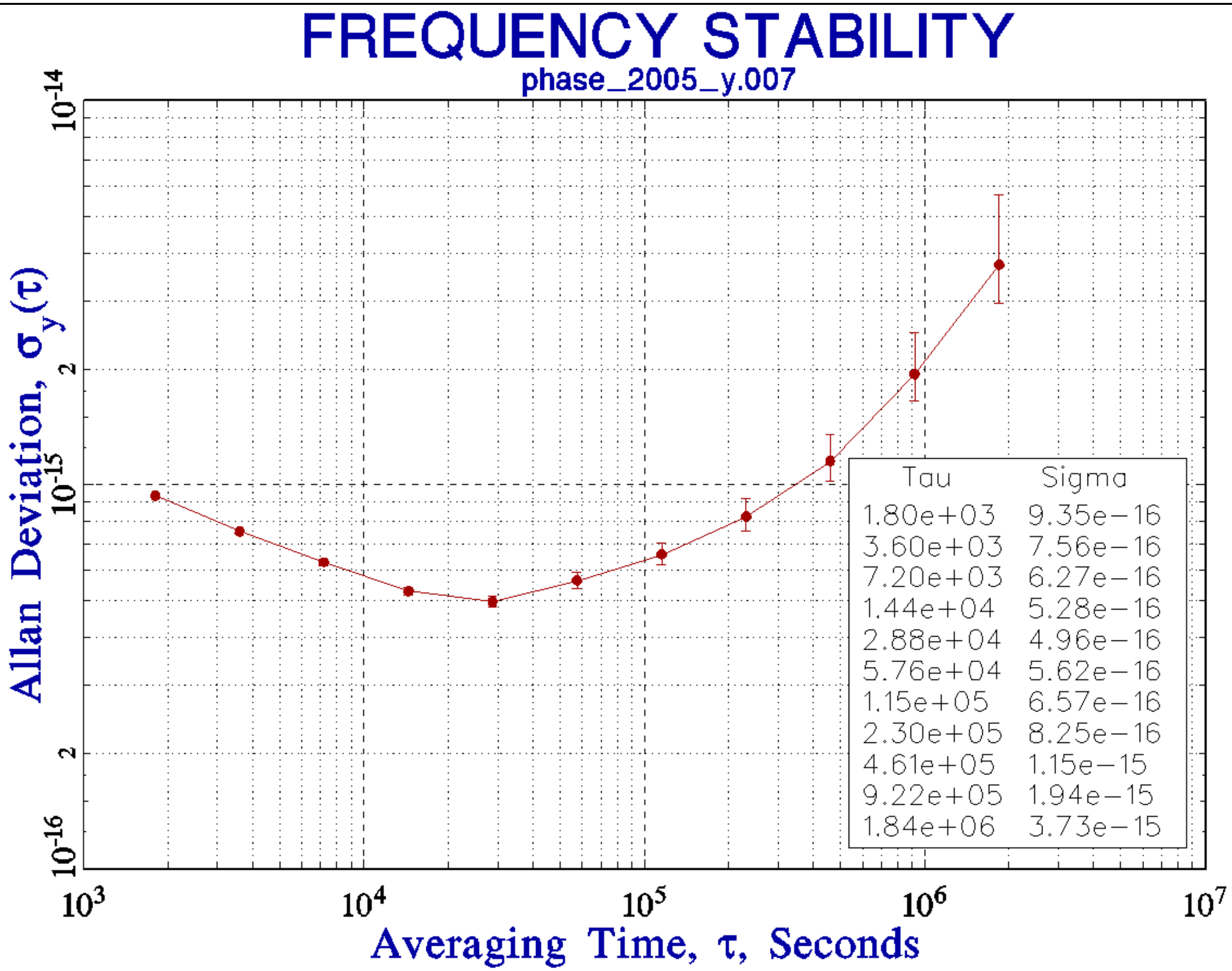
Masers too close, risk of synchronisation! Improve shielding

5 MHz phase noise,
2 sources, chain vs chain



Which one is better?

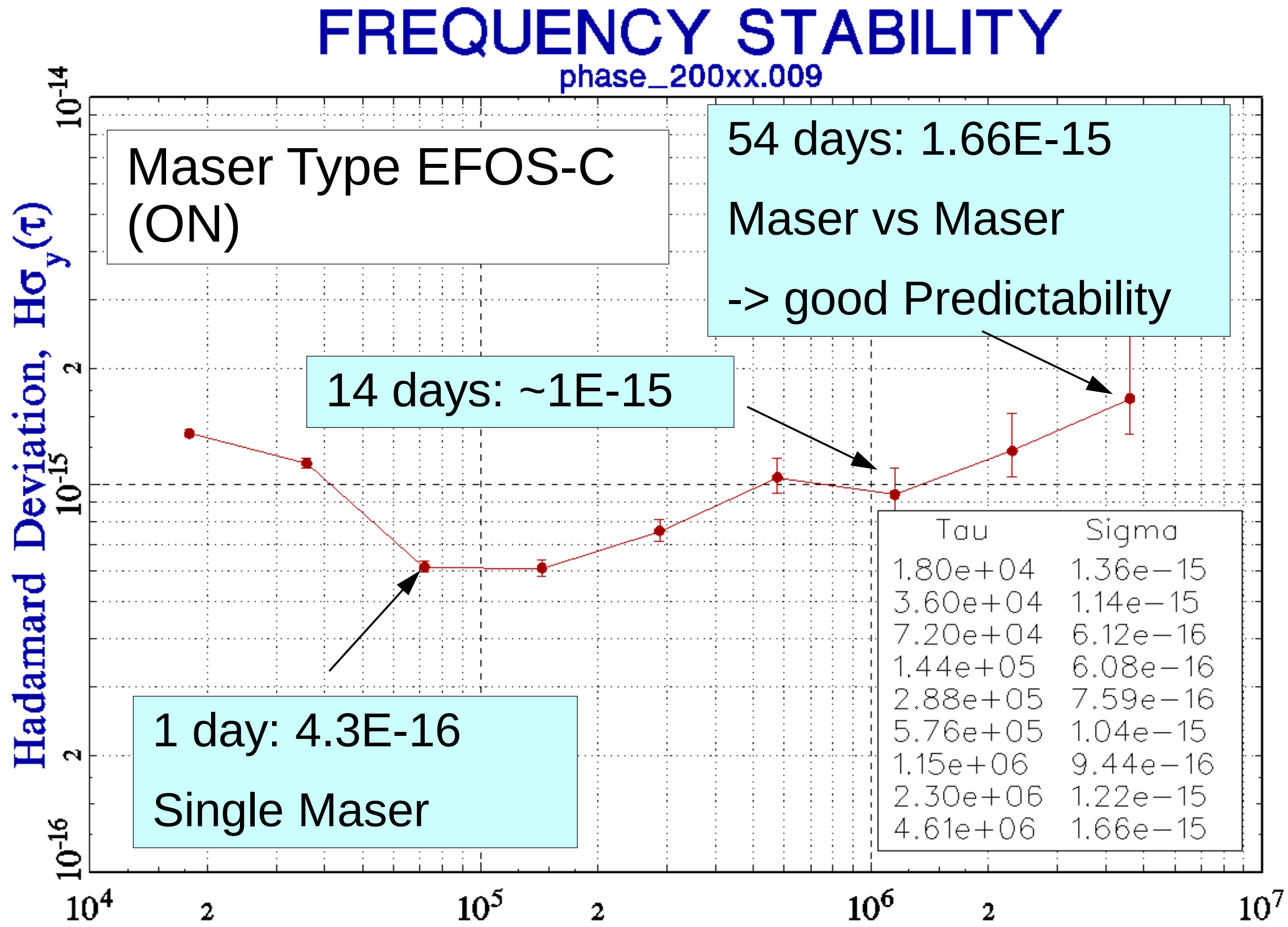
DSA1: Long-term ADEV Maser-1 vs Maser-2



Which one is better? Thermal environment is common mode!

New Norcia: HDEV Maser-1 vs Maser-2
“predictability of maser drift”

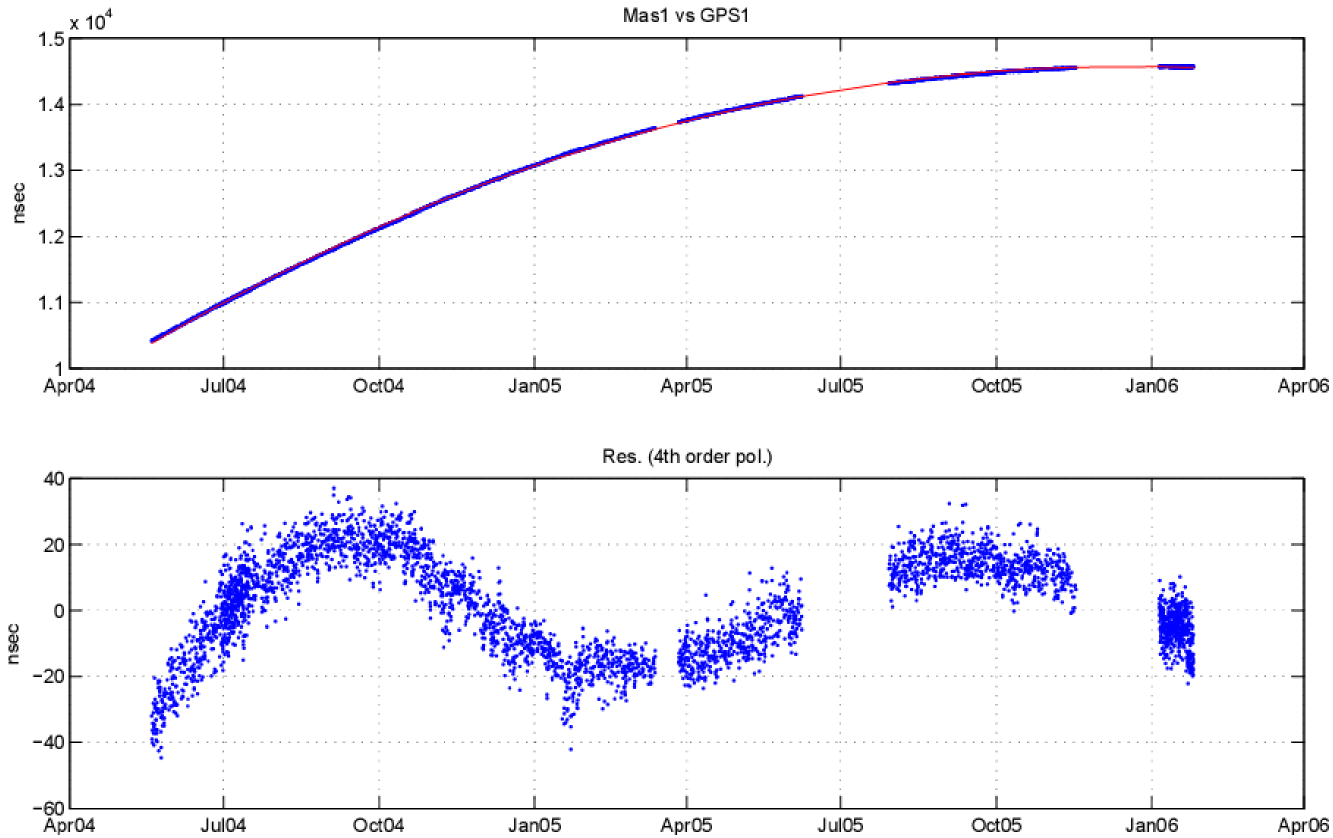
TIMETECH femto-st SCIENCES & TECHNOLOGIES T4Science iPRECISION MASER SOLUTIONS™



Which one is better?

HDEV: „Capability to improve by modeling or steering!

DSA1. MAS-1 vs GPS



Frequency Drift: **2.6E-16 / d @ 1.7 yr**

This is actually the best Maser EOC operates, ever!
GAPS are bridged by time comparison.

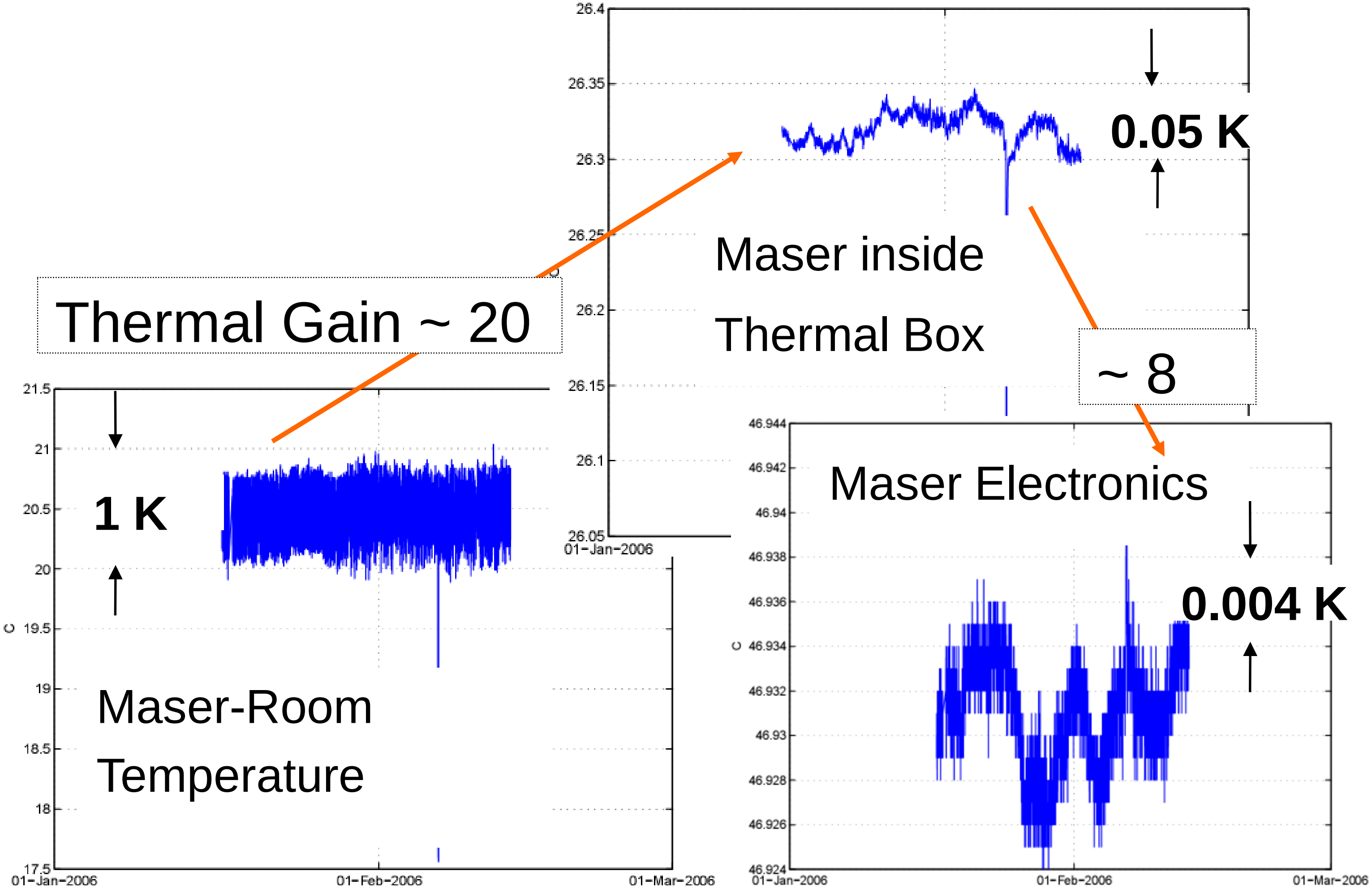
DSA2 Design and features

DSA2 signal specifications

Item	unit	100 MHz	5 MHz
Phase Noise @ 1 Hz	**dBc/Hz**	**- 102**	- 126
Phase Noise @ 100 Hz	**dBc/Hz**	**- 131**	- 145
Harmonics	dBc	< - 40	< - 53
Spurious	dBc	< - 90	< - 105
Isolation (I / O)	dB	80	80
Return Loss (I / O)	**dB**	**40**	35
Level	dBm	11.5	13

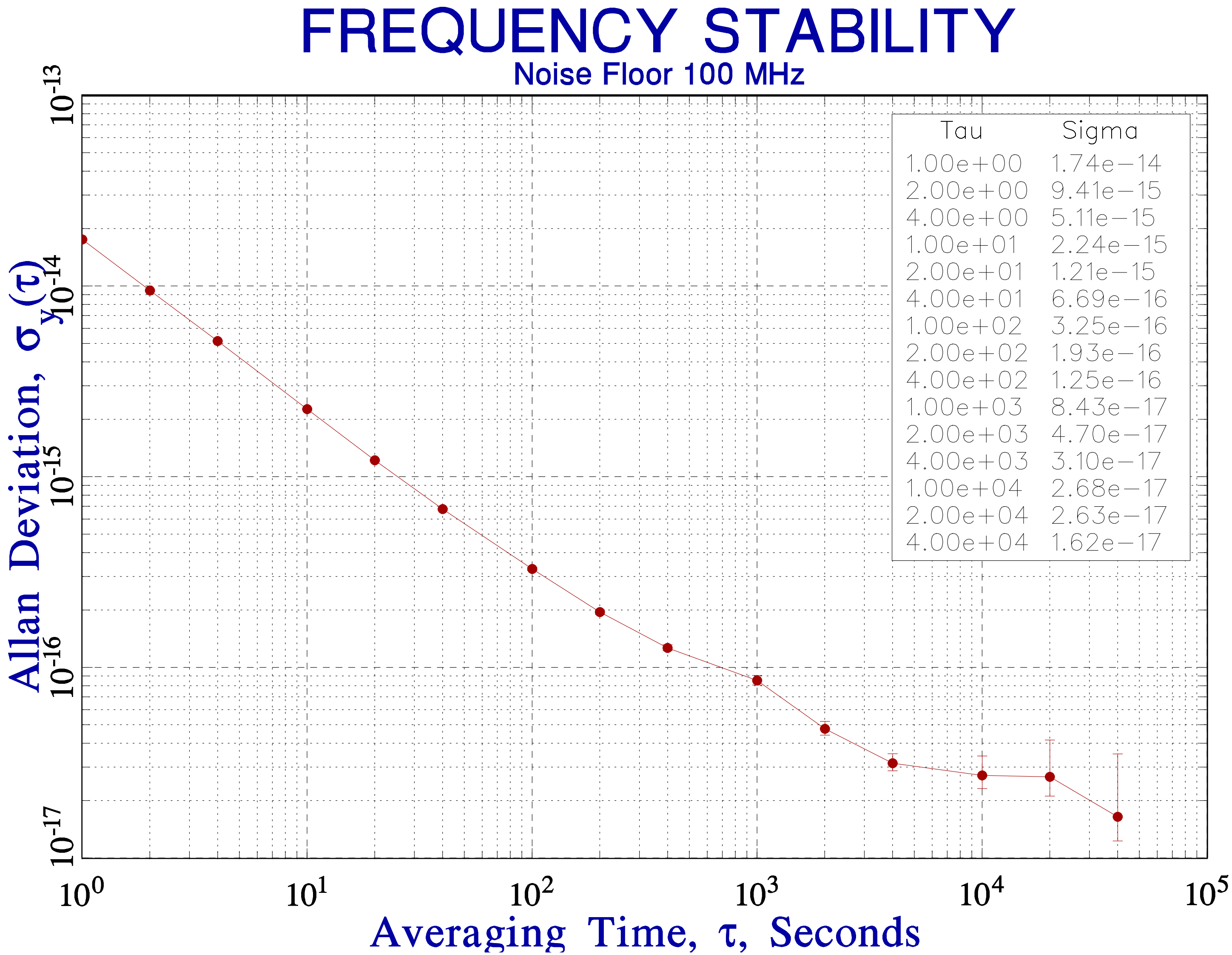
new

DSA2 Maser thermal effects

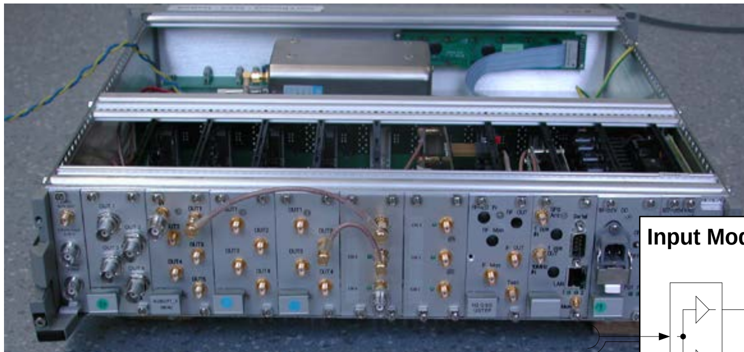


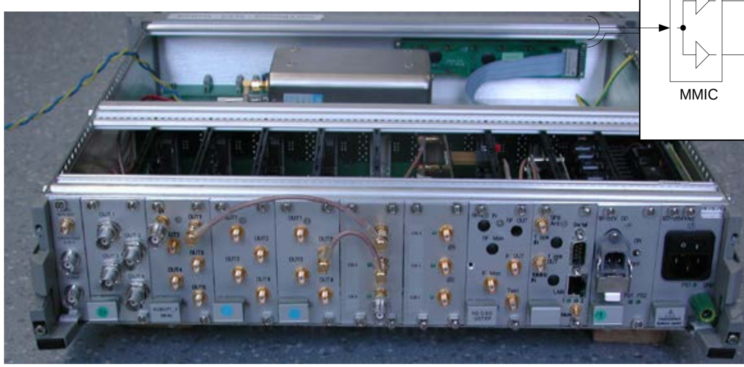
Total thermal gain: 80, room to electronics, Beware or air conditioning!

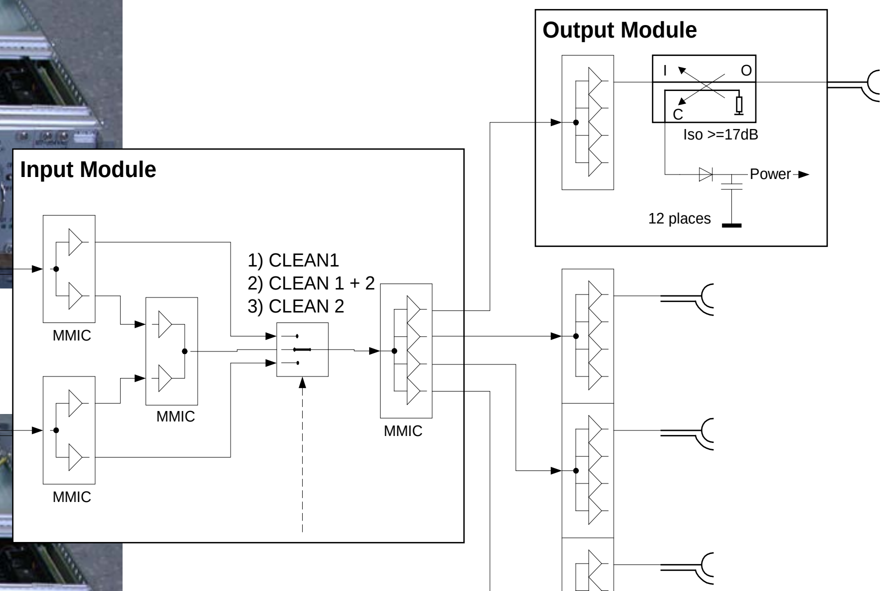
DSA2. Phase comparator performance 100 MHz

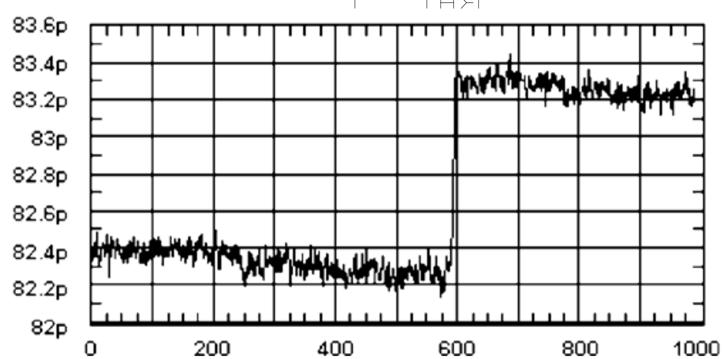


DSA2, two cleanups with combination

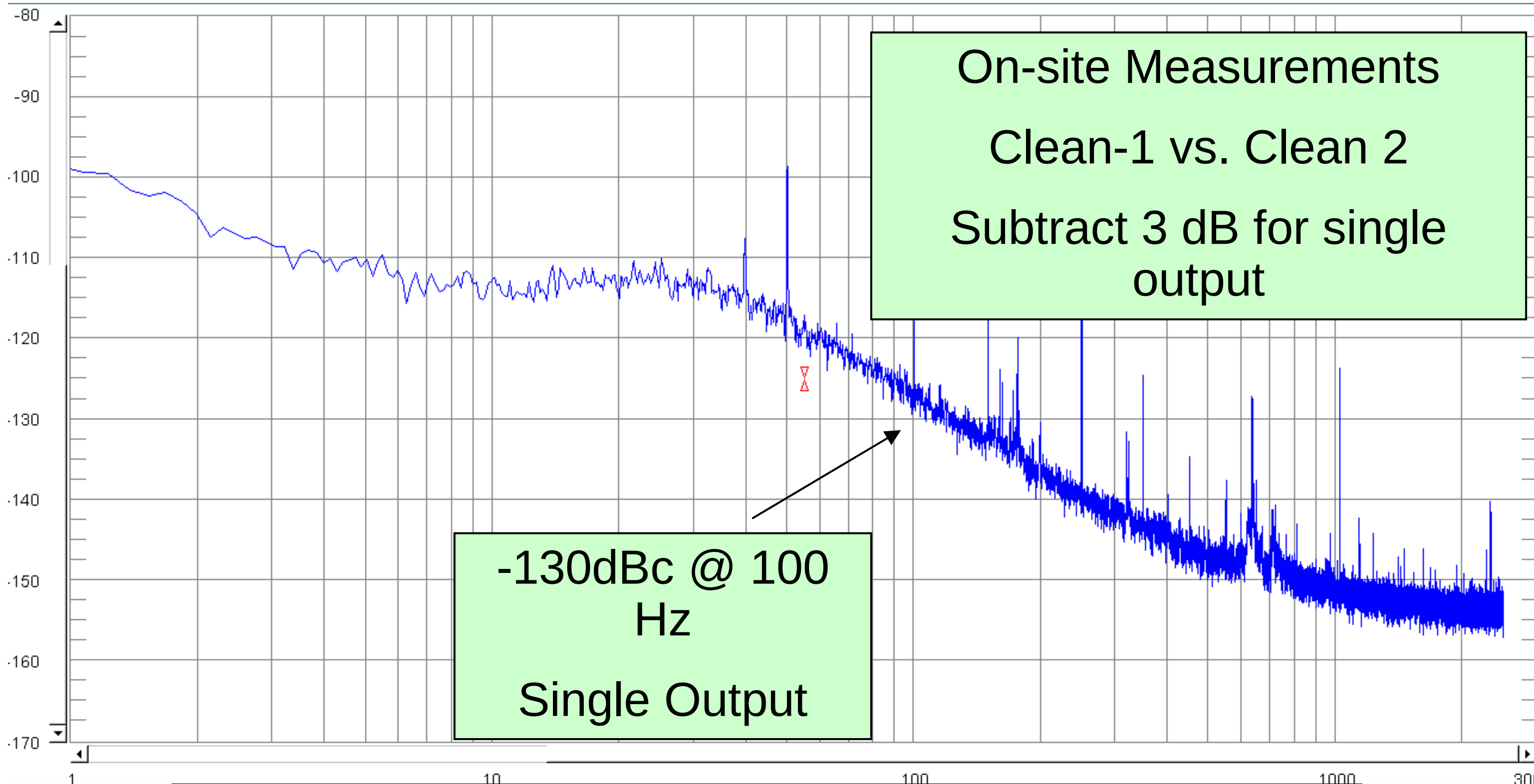








DSA2: PN improvement 1.8 dB @ 100 Hz

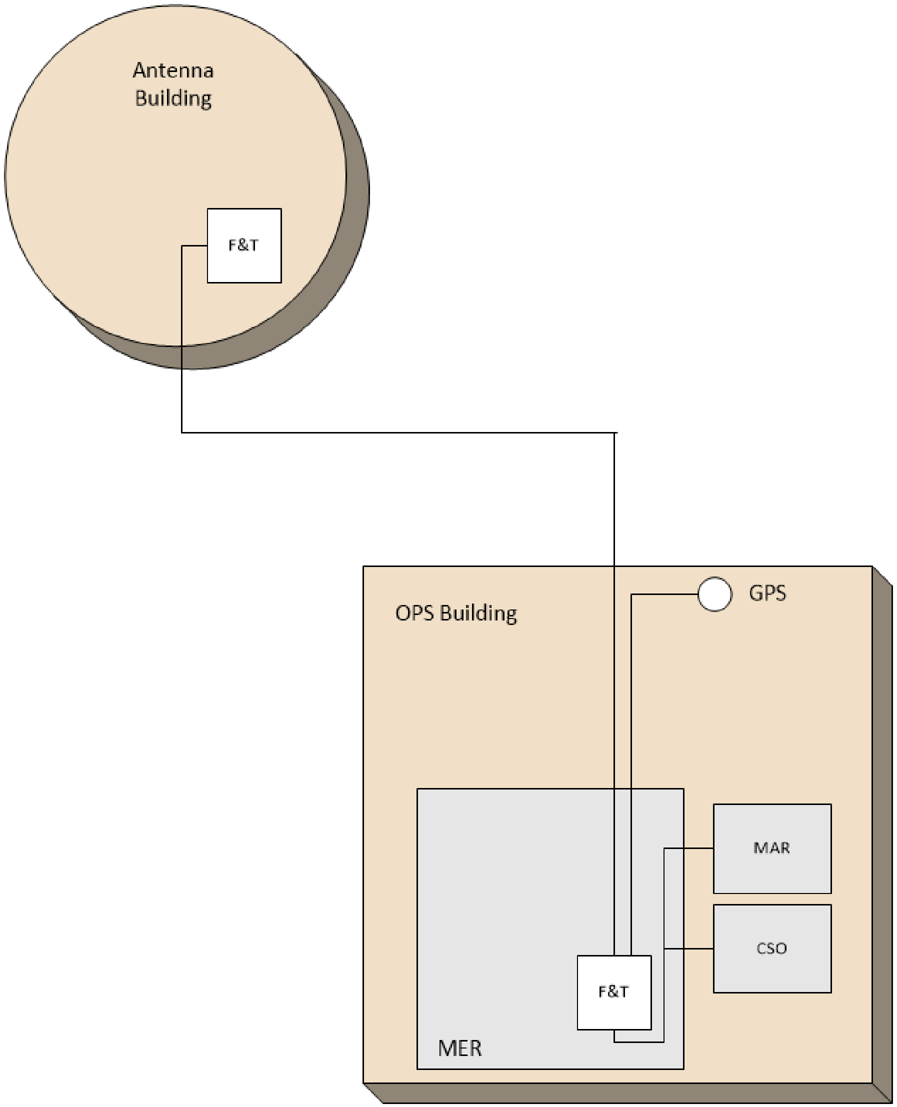


100 MHz [dBc/Hz]	1 Hz	10 Hz	100 Hz	1 kHz
Combined CLEANs	-102.7	- 118.7	-131.8	-155.7
Single CLEAN	-101.7	- 117.2	-130.0	- 154.5
Improvement [dB]	1	1.5	1.8	1.2

DSA3 design and features

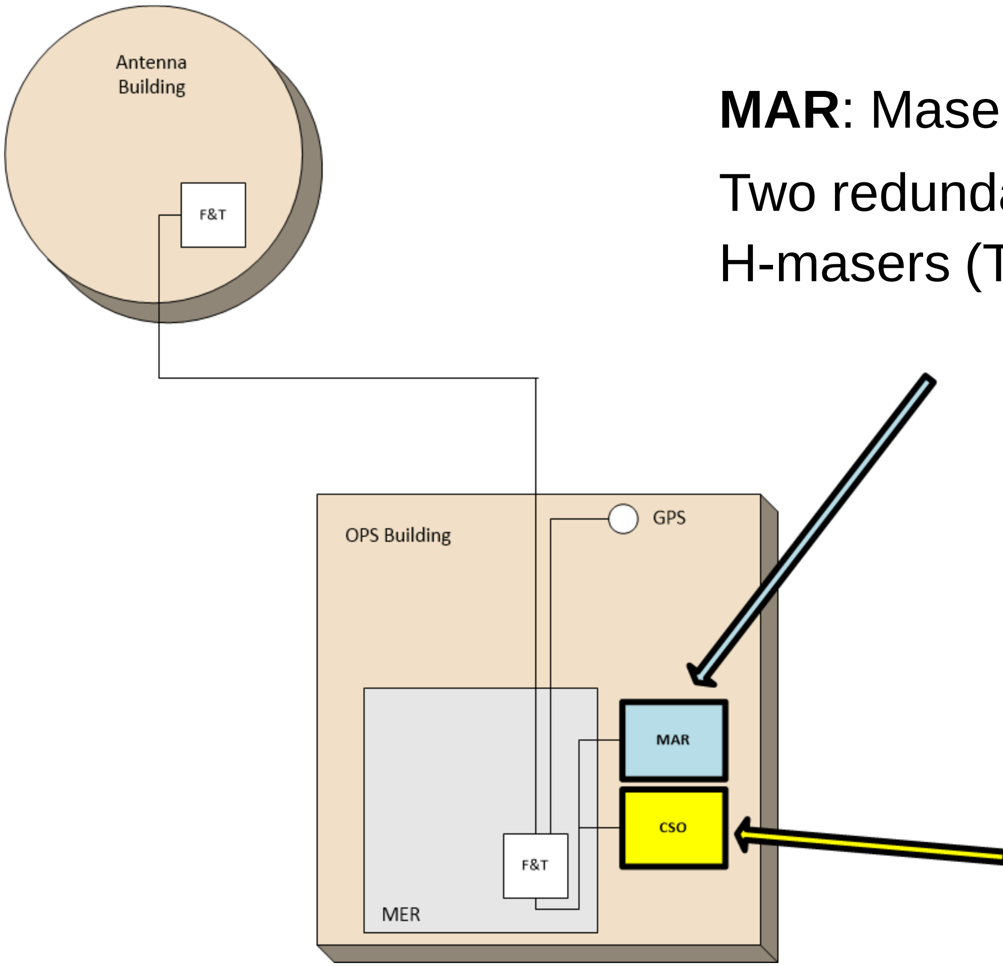
Differences with respect to previous DSA

- Until now: reference clocks located in antenna.
- For DSA3: clocks 100 m away from antenna.
  - Centralised frequency and timing system.
  - Eases introduction of future front-ends, expandable
- Introduction of a third high performing frequency source (Cryogenic Sapphire Oscillator) in addition to the two active H-Maser.



DSA3: Reference clocks

- Independent, environmentally controlled clocks room.



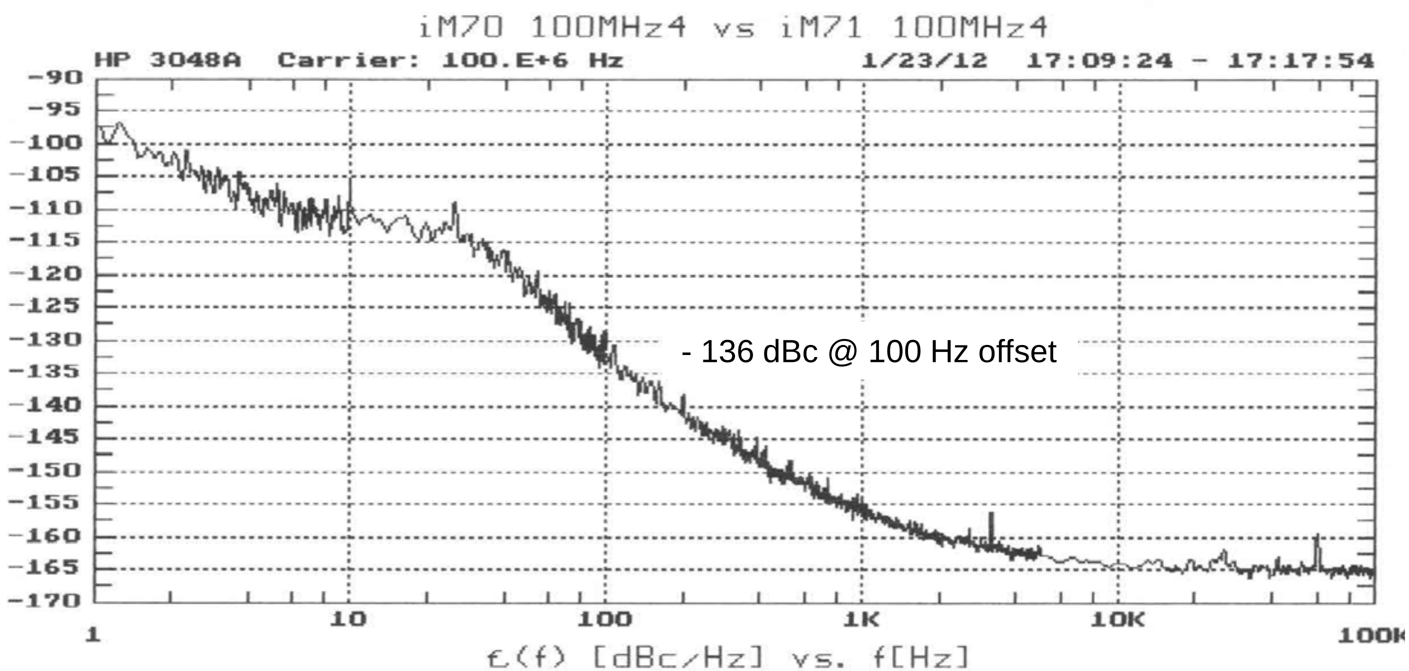
MAR: Maser room.

Two redundant active H-masers (T4Science).

CSO: Room for the Cryo-Sapphire (Femto-ST).

DSA3: Reference clocks (cont.)

- Active hydrogen masers. Modified:
  - 100 MHz improved phase noise
  - Increased number of 100 MHz outputs directly at the maser



- 100 MHz: Maser-1 vs. Maser-2. FAT (Jan. 2012)

DSA3: Reference clocks (cont.)

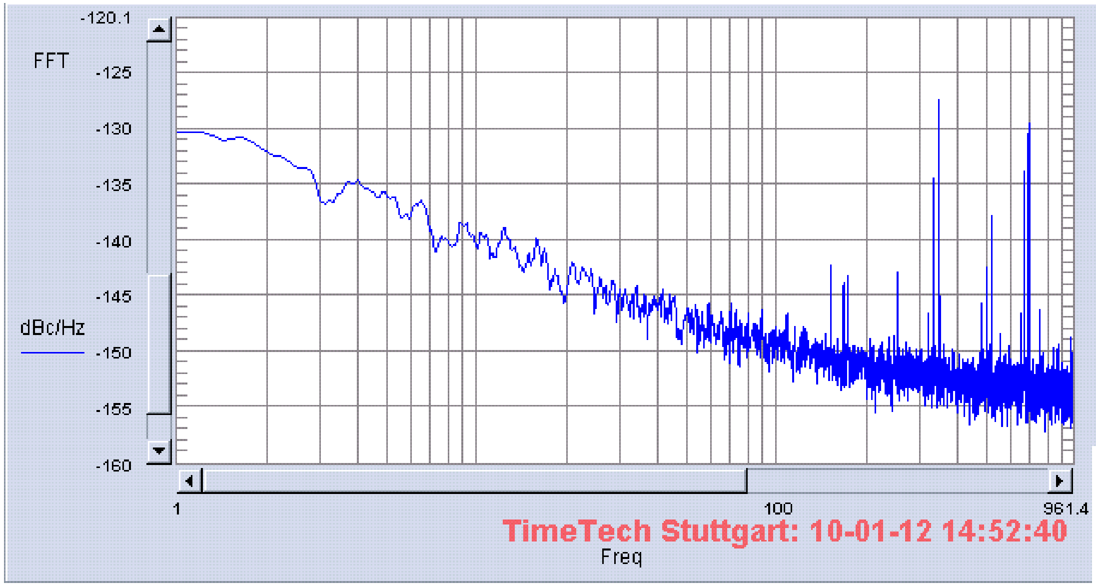
Cryogenic Sapphire Oscillator (CSO).

Once called "best macroscopic clock"

- High-Q sapphire whispering gallery mode resonator.
- Resonator set to ~6 K turn-over point by cryocooler
- Protected against environment, vacuum, vibration damping
- Synthesizer converts from 9.989 GHz to 10 GHz, w. dividers
- Excellent short-term stability
- Possibility to lock the CSO to a maser (long time constant).

10 GHz outputs, but NOT yet distributed
„No-loss dividers"

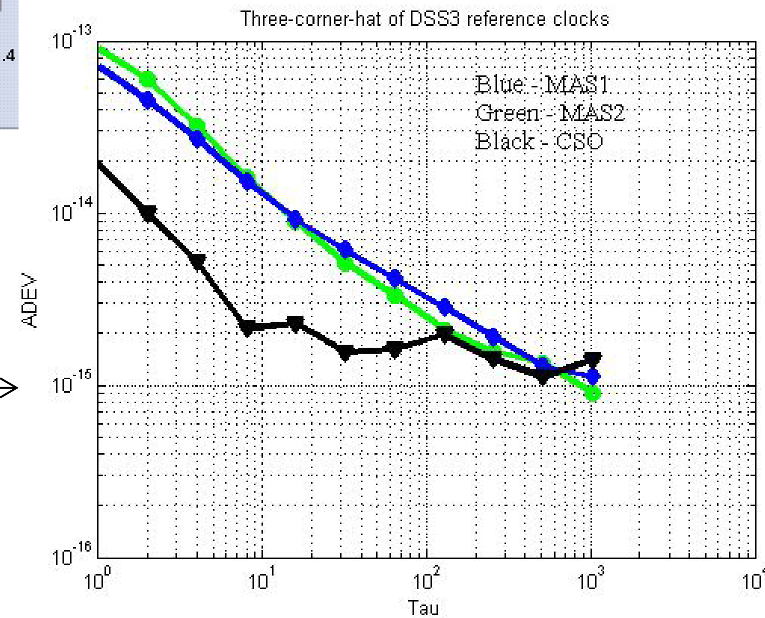
DSA3: Reference clocks (cont.)



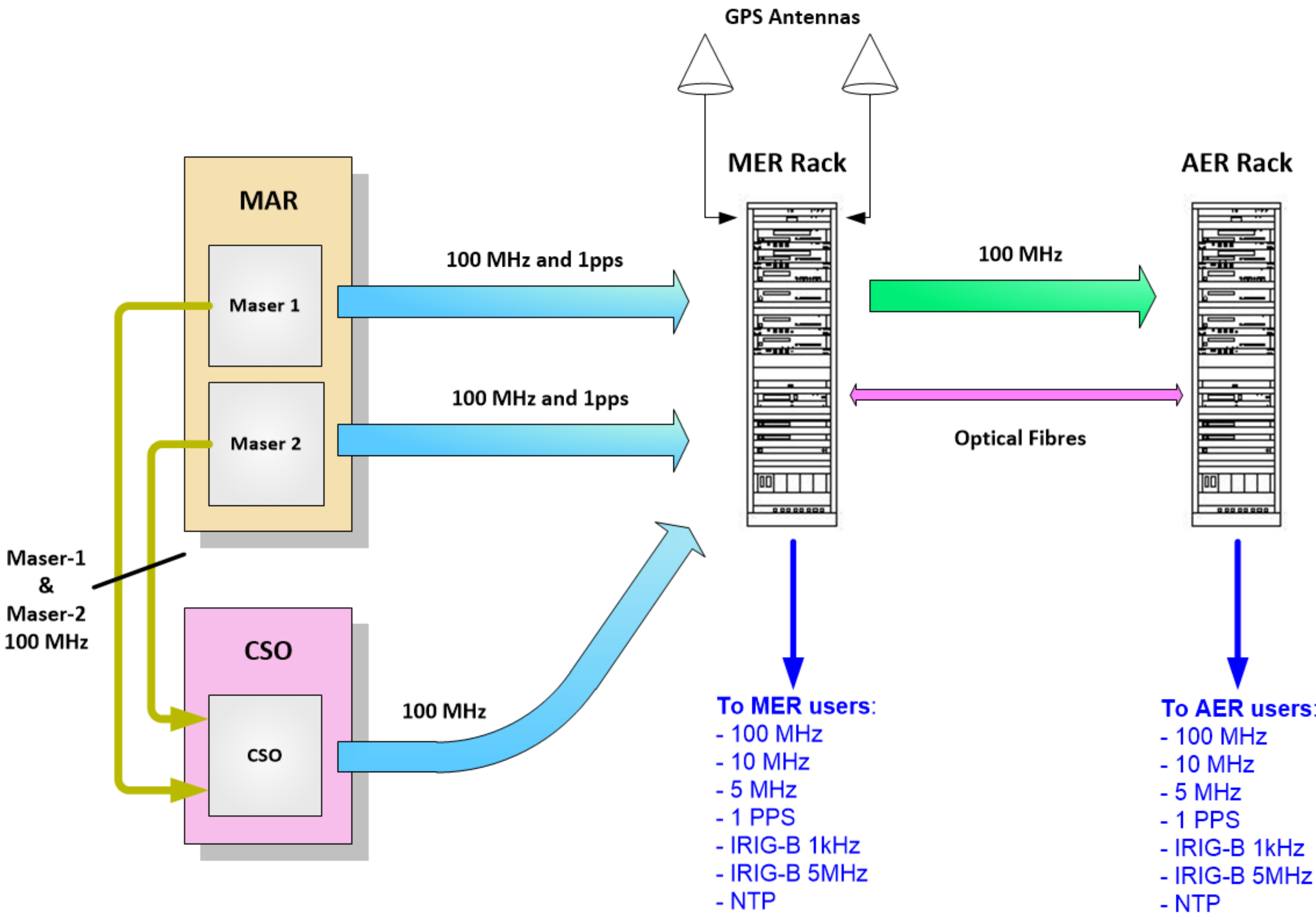
CSO synthesizer 100 MHz phase noise

Stability (individual) of the three available clocks in DSA3. Three-corner-hat.

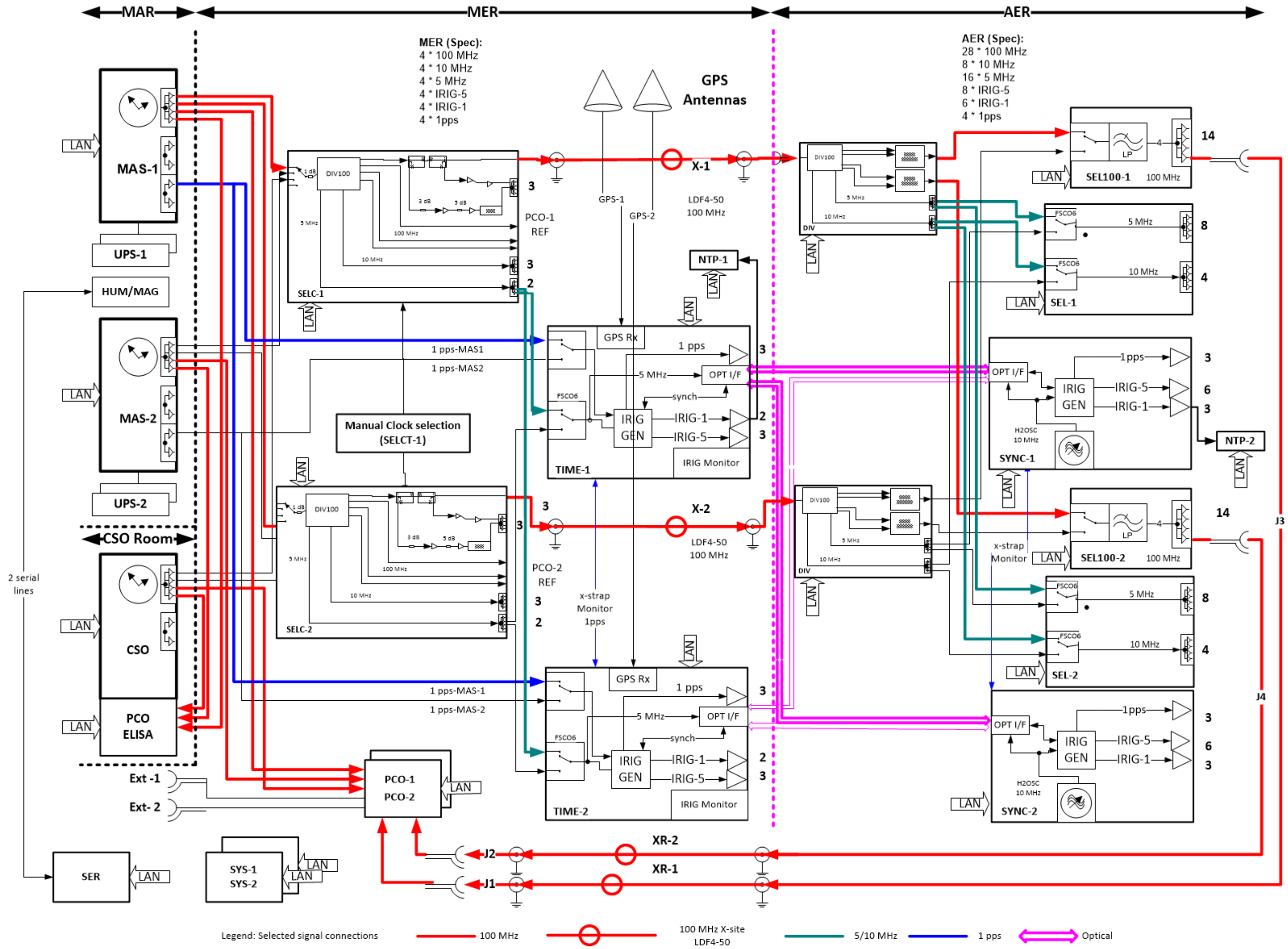
CSO: 2E-15 to > 1000 s



DSA3 System architecture

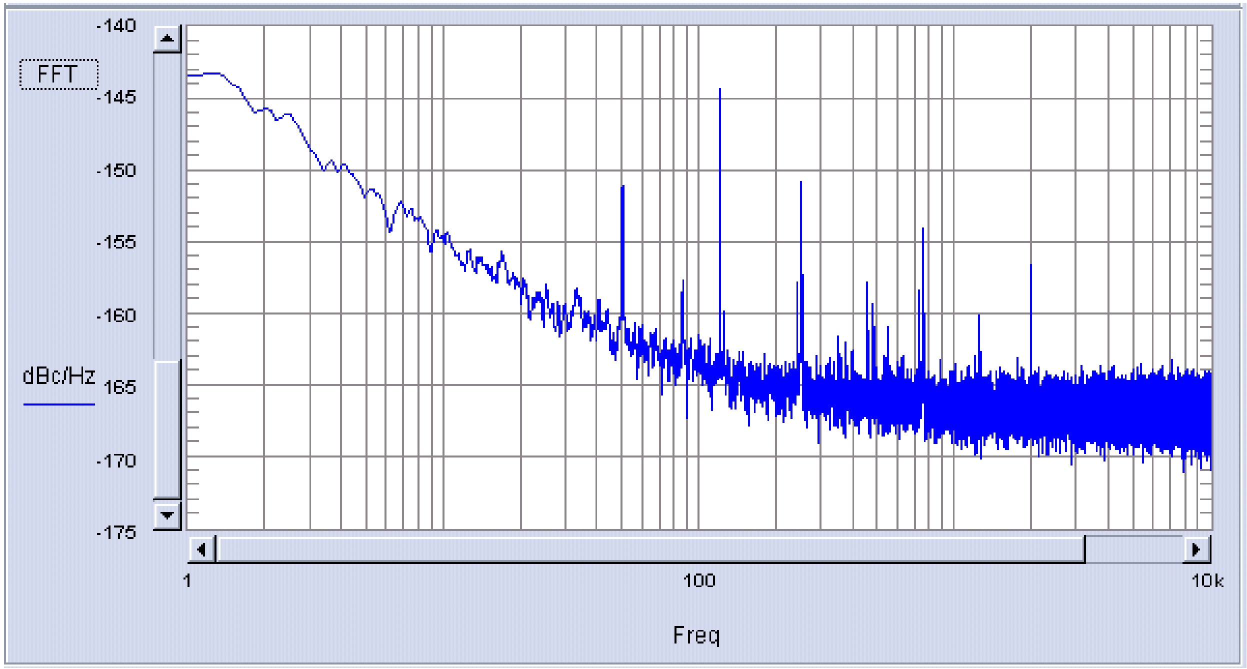


DSA3 System architecture



DSA3: Frequency distribution

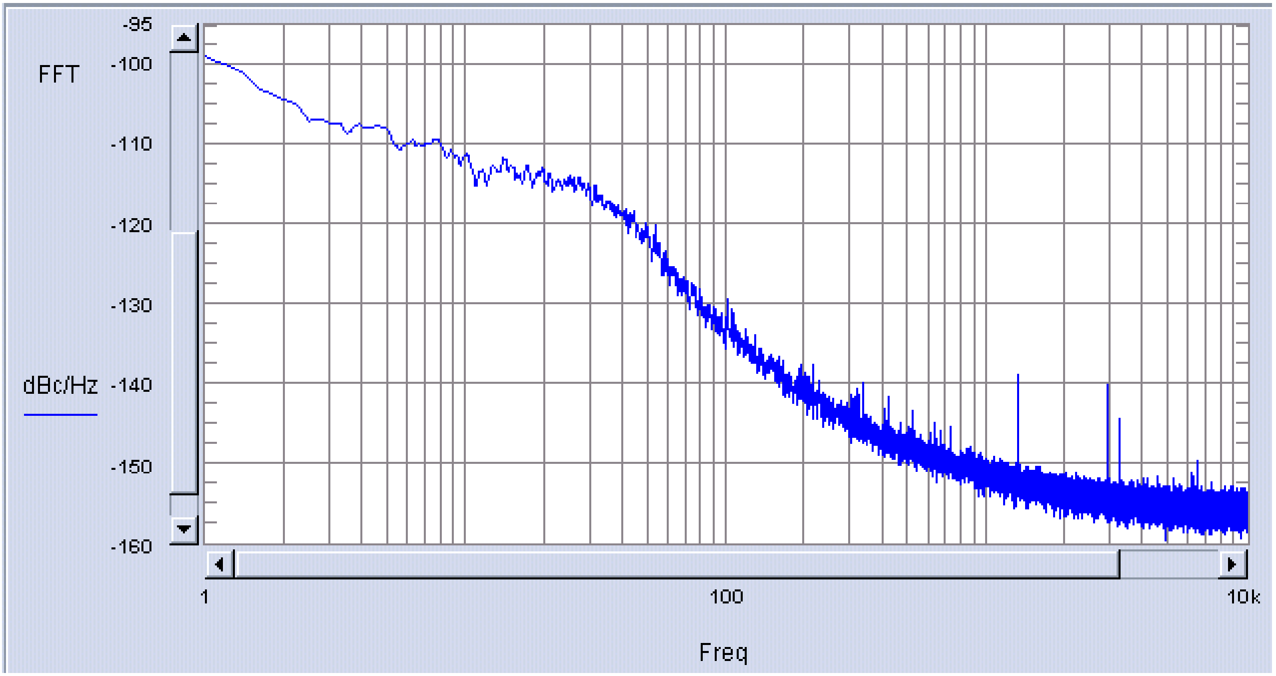
- 100 MHz distribution system.
- Low noise divider from 100 MHz to 5 MHz and 10 MHz.
- Distribution with low temperature coefficient and low noise figure electronics.



Divider phase noise at 100 MHz input, 5 MHz output.

DA3: Frequency distribution (cont.)

- Selection of low thermal sensitivity cables for the cross-sites.
  - LDF4 50 Ohm, Andrew, (0.6 ppm/K at 100 MHz)
- Cross-site cable ducts buried 80 cm deep.
- In the end, at the furtherst point from the clocks (i.e., the antenna), the system performed at 100 MHz:



Chain-1 on Maser-1
vs.
Chain-2 on Maser-2.
(SAT Apr. 2012)

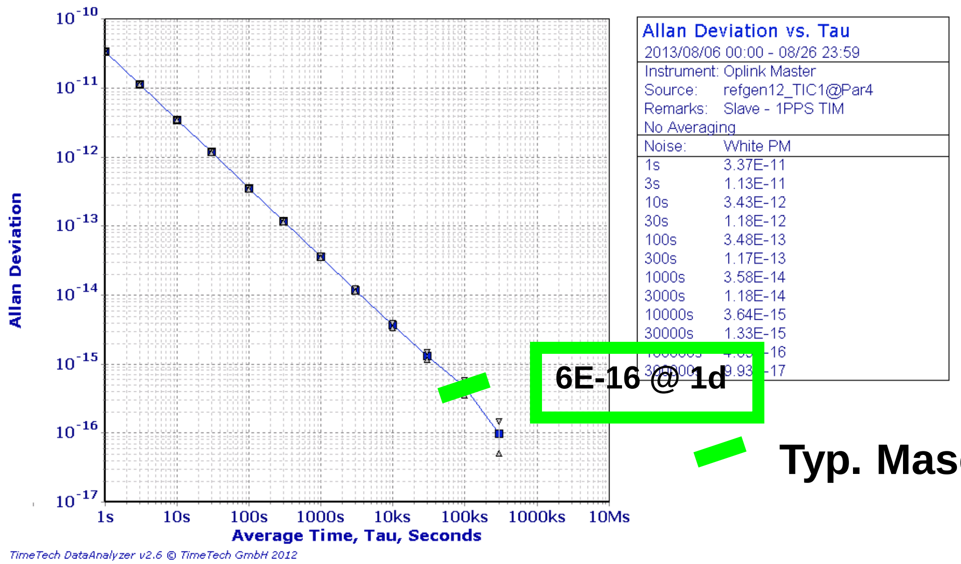
DSA3: Timing distribution

- In MER timing signals generated following the 5 MHz from the masers.
- GPS time on startup and seconds incremented according to the 1pps derived from the maser frequency.
- System 1pps monitored against GPS time and kept within 100 ns.

Timing signals and low frequency signals are not distributed to AER, but regenerated at the AER side.

- Improved Optical Link with active delay compensation, removes thermally-induced variations
  - Alignment AER 1 pps to MER 1 pps < 1ns via two-way measurement (two-way time transfer over fiber)

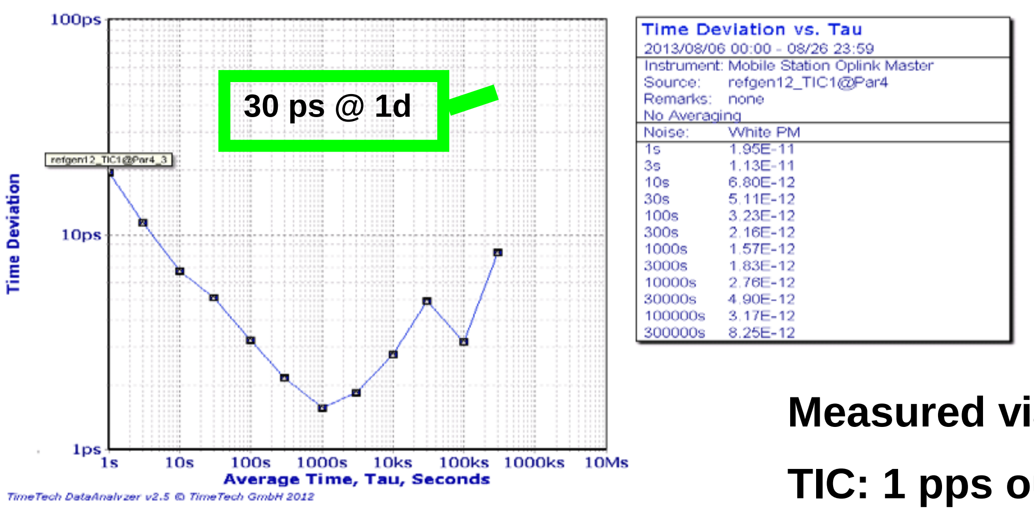
DSA3: Optical Link, time performance, typical



1 pps stability

ADEV

Typ. Maser performance



1 pps stability

TDEV

Measured via 500 m fiber spool, 20 days

TIC: 1 pps out vs 1 pps input

Summary & Conclusions

- New requirements imposed new concepts to the F&T systems.
  - Improved phase noise performance of the maser outputs
  - Design of a 100 MHz distribution system
  - Local frequency generation by high performance dividers
  - Selection of thermally stable cables, buried in duct.
  - Introduction of a third clock with exceptional short term stability
  - Improved optical link for time synchronisation via fiber
  - DSA3: First operational results successfull, in Sept 2012
- Specify your system with caution, reflect deficiencies of xDEV
- Minimise thermal impact from source to user, active & passive elements:
  - Need to model, hard to measure, most effects act in common mode (chain vs chain)
- Proposal for the new TWINS at Onsala (700 m distance): to come

Work was performed under various ESA/ESOC contracts