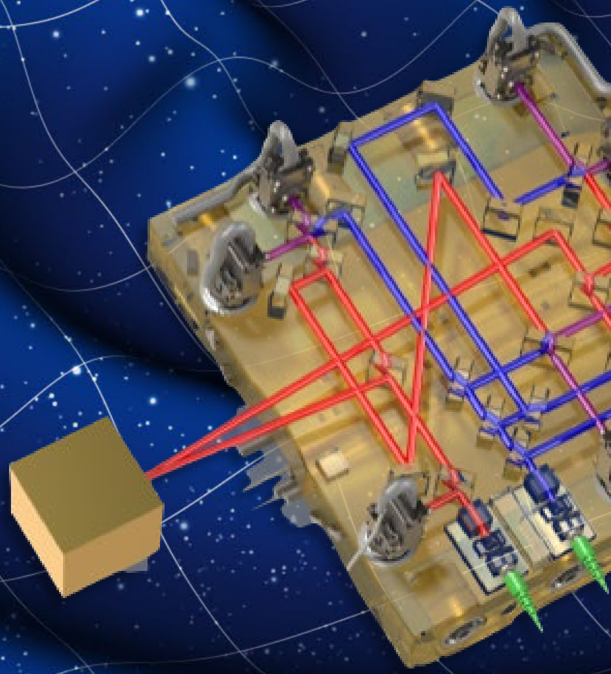
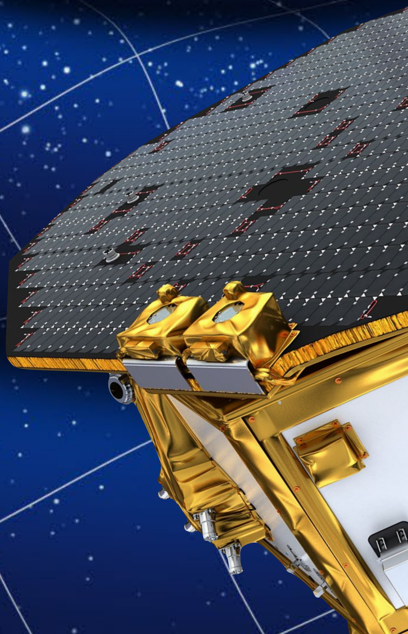
Short history of the LPF interferometer

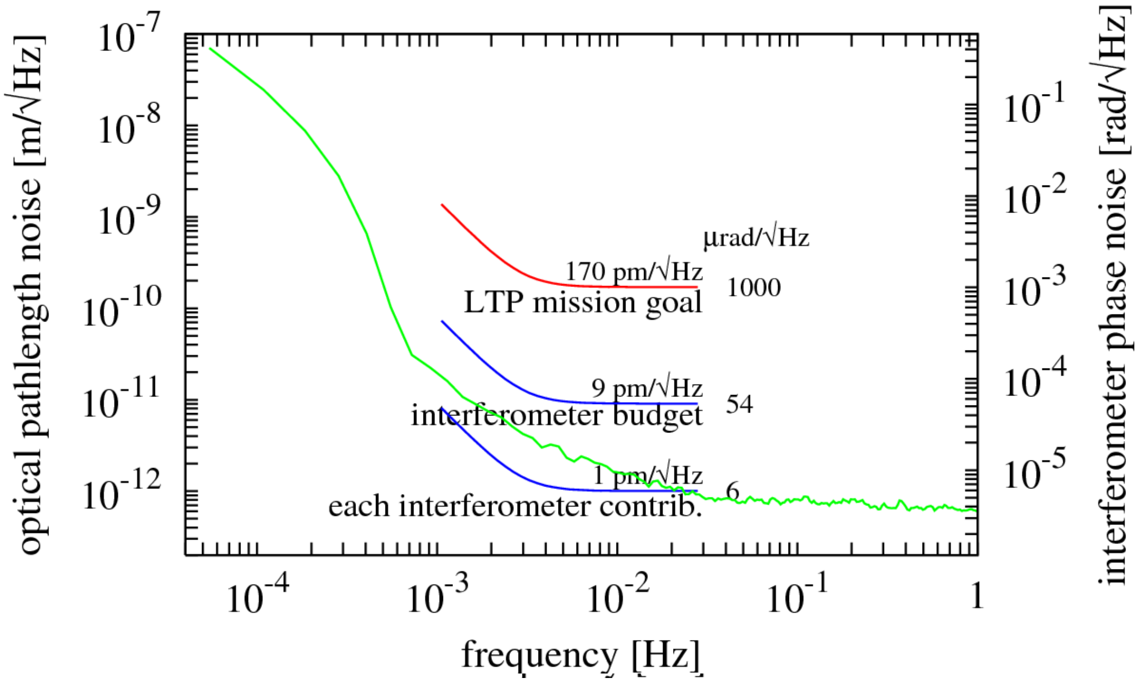




Gerhard Heinzel,
AEI Hannover,
10th anniversary, Barcelona, 12/2025

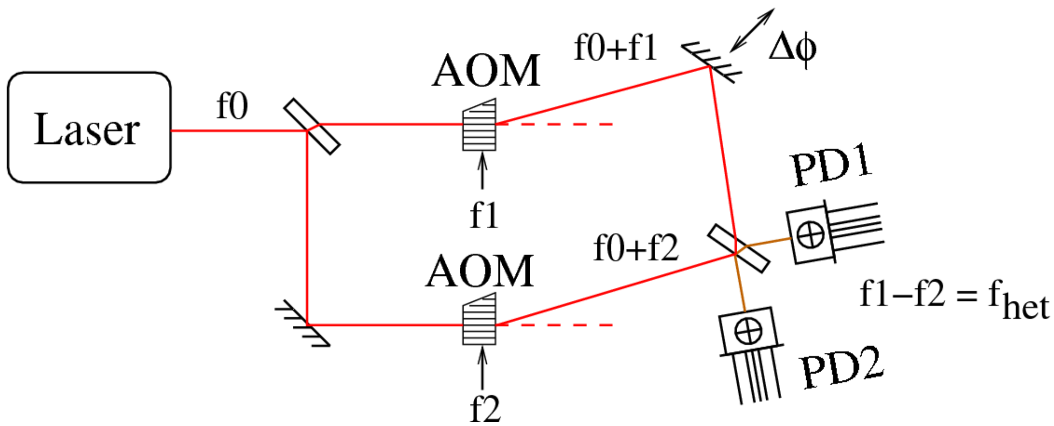
Disclaimer: Personal, biased and incomplete

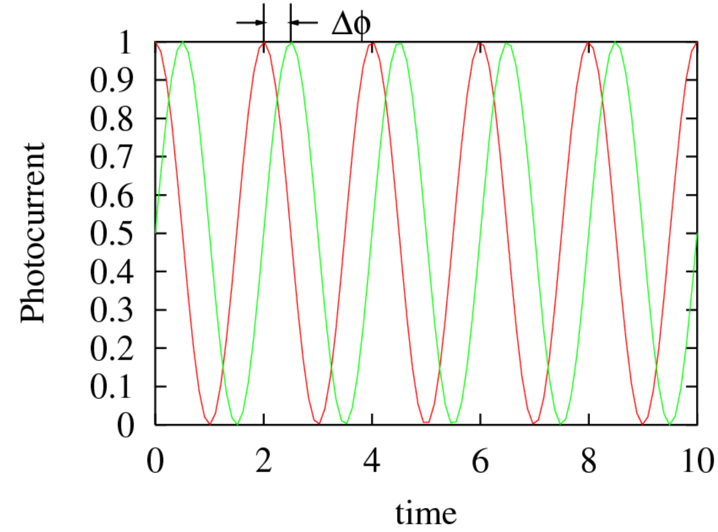
Ifo requirements



- Very simple requirements, self defined
- Pathlength noise 9 pm/sqrt(Hz) with freq. dependence
- Was assumed to be sufficient for the LISA local readout

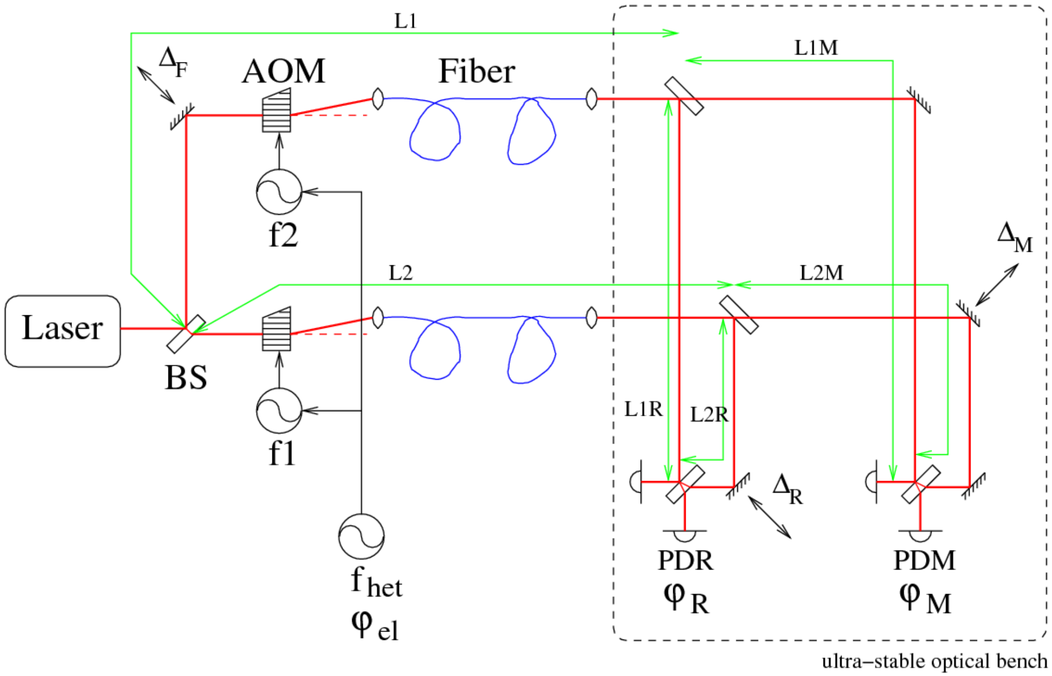
Interferometer principle





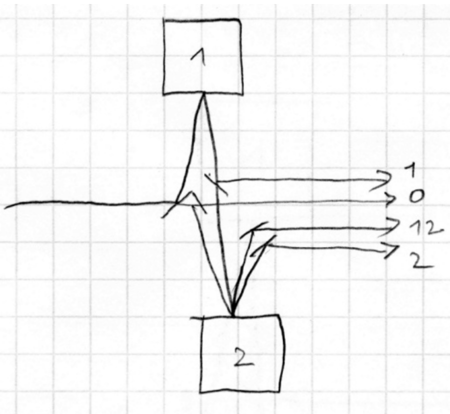
- audio-frequency heterodyne Mach-Zehnder
- independent of operating point
- wide dynamic range (many fringes)
- no lock acquisition needed, immediately ready after power-on.
- phase measurement needs no calibration, conversion to length is laser wavelength (known and constant)

Reference subtraction

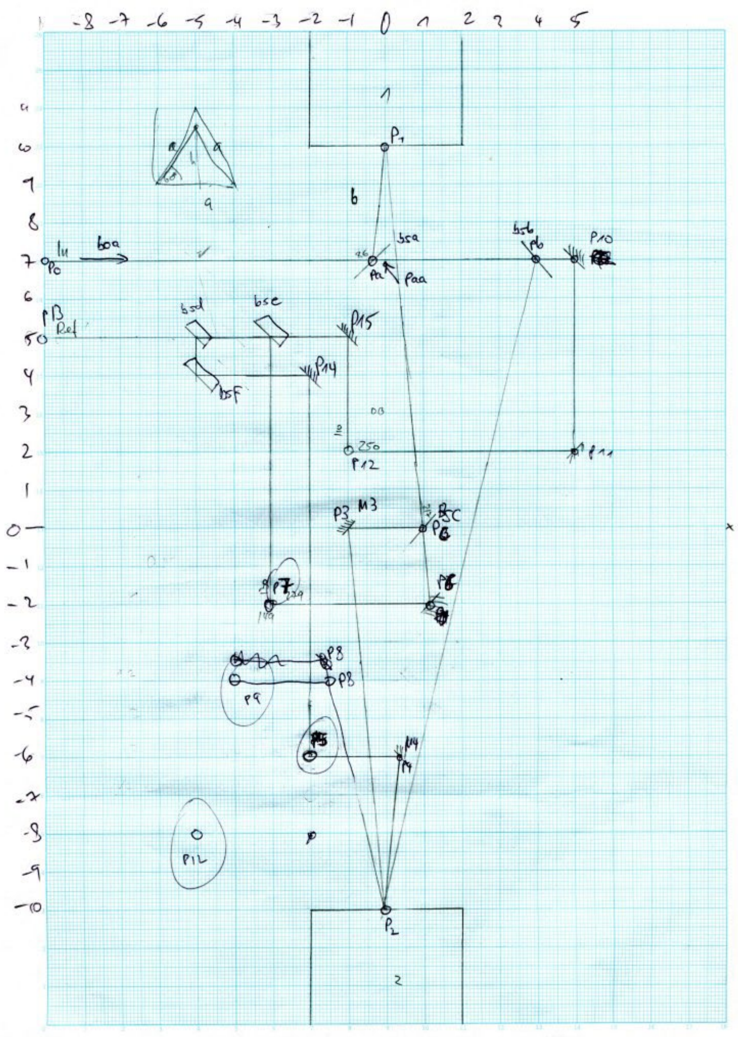


- Each photodiode measures Pathlength difference, starting from first BS
- External contributions must be subtracted via stable reference interferometer
- subtraction is imperfect, hence phase of Ref. Ifo ("OPD") must be stabilized (*later finding*)

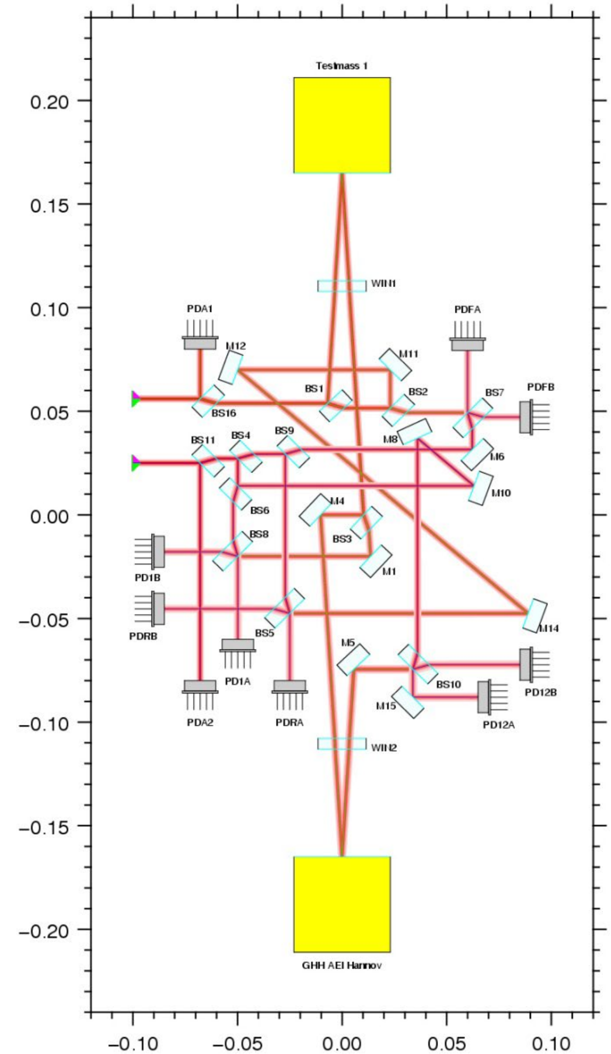
The LTP Interferometer



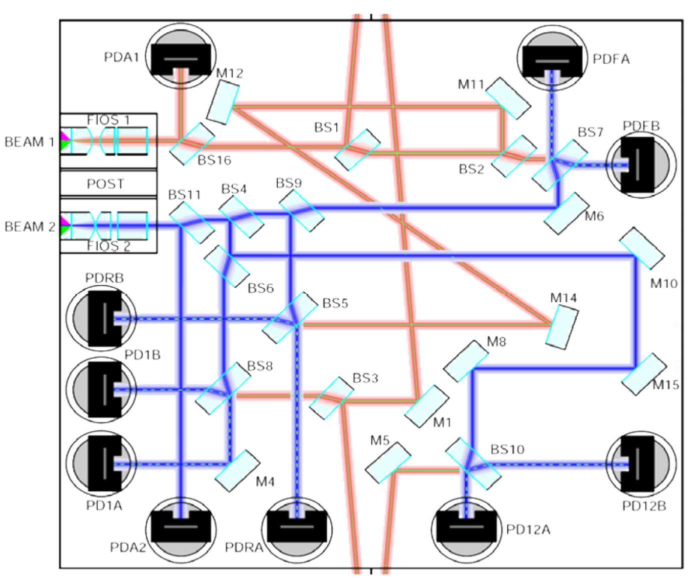
2001



2001



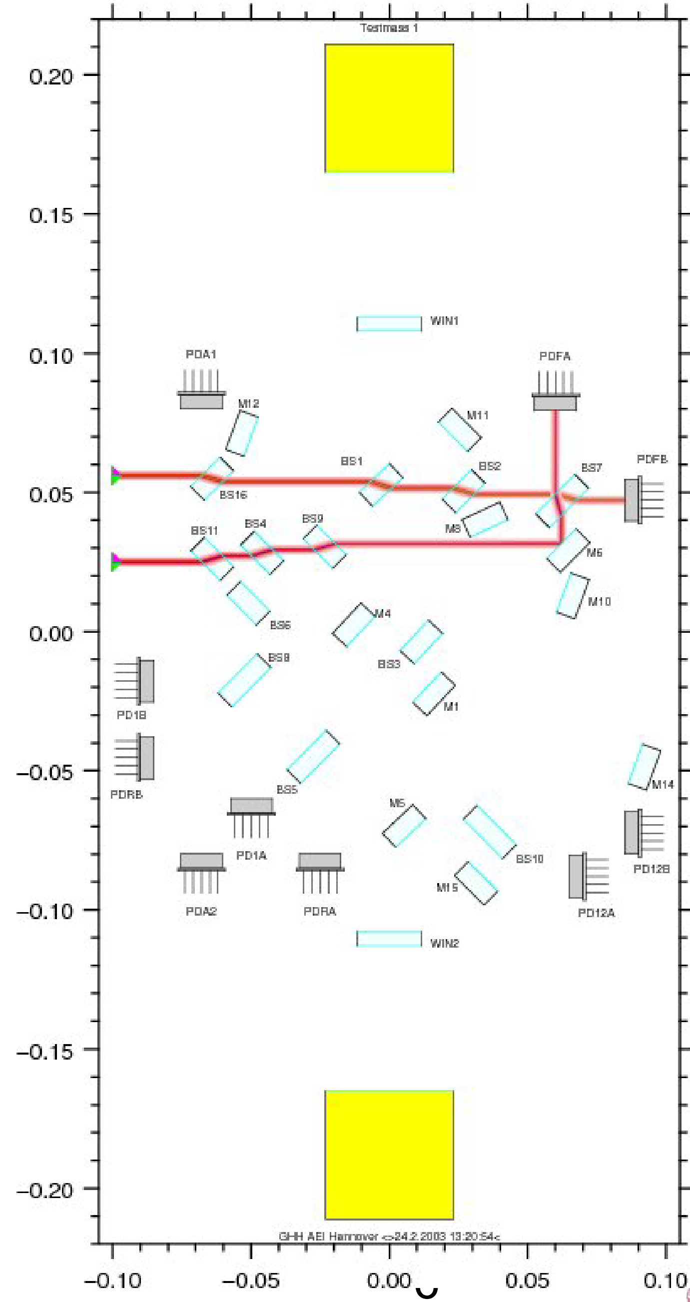
2003



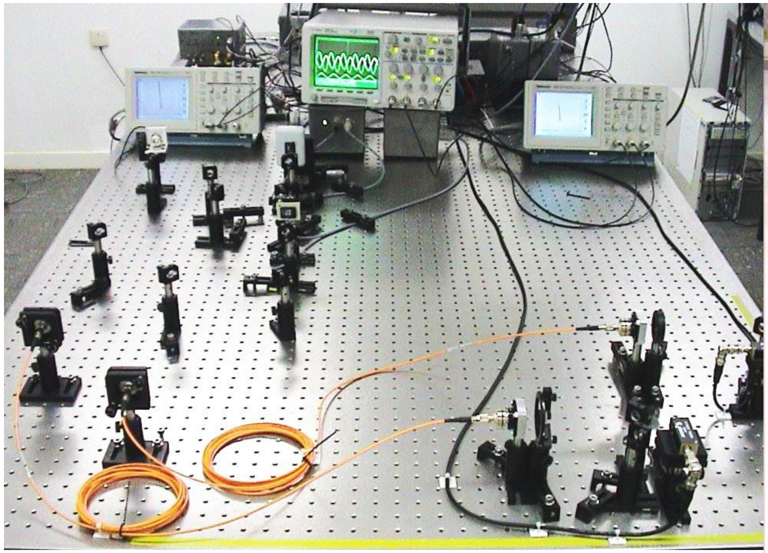
2006

4 interferometers

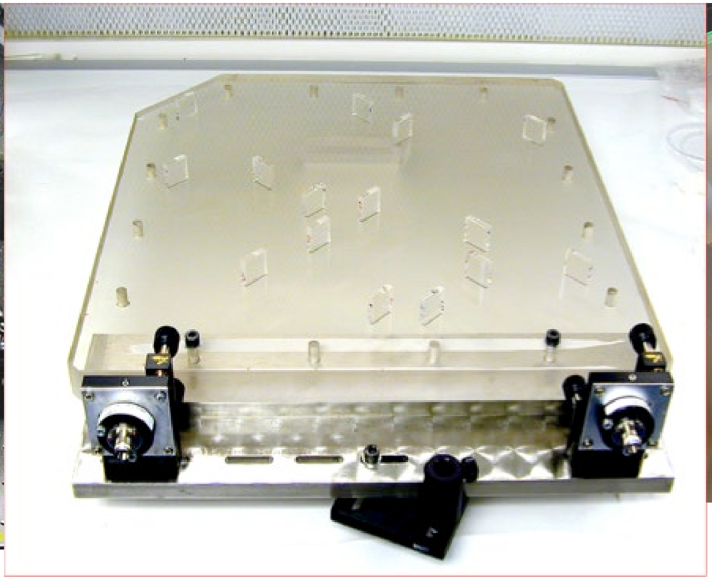
- TM1 position and orientation w.r.t. optical bench
- TM2 position w.r.t. TM1, TM2/TM1 orientation w.r.t. optical bench
- Reference phase
- Frequency noise via unequal pathlengths



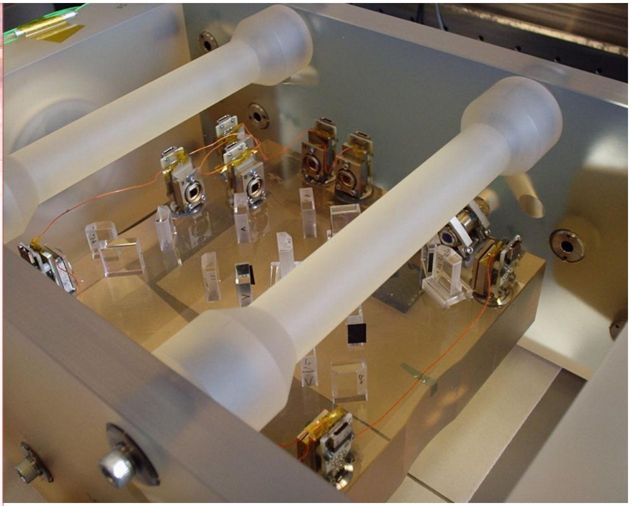
The LTP Interferometer



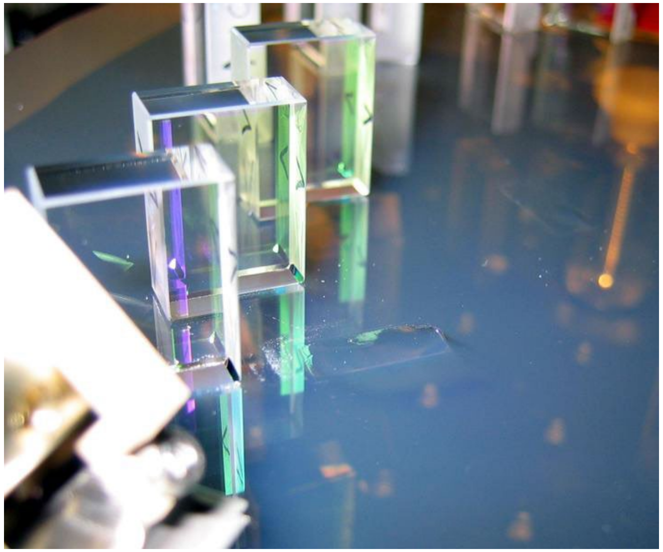
2001

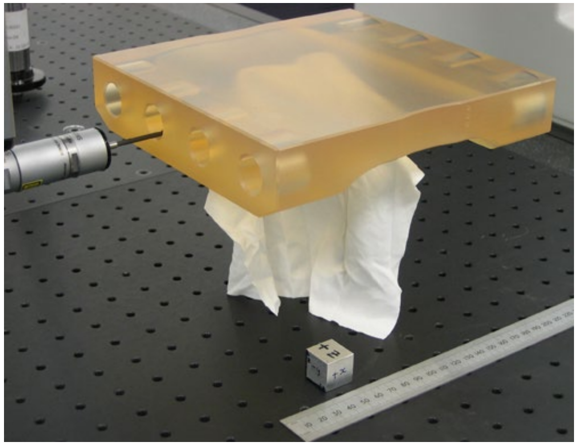


2002

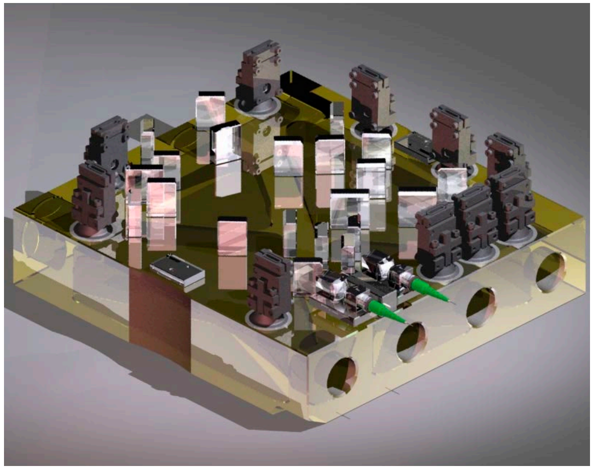


2003





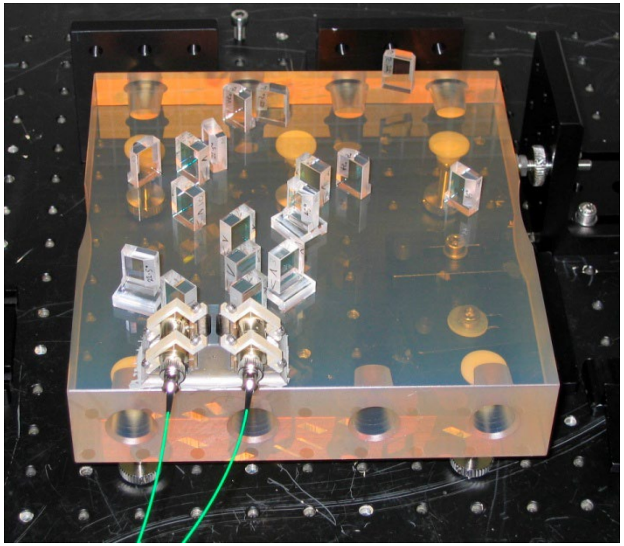
2007

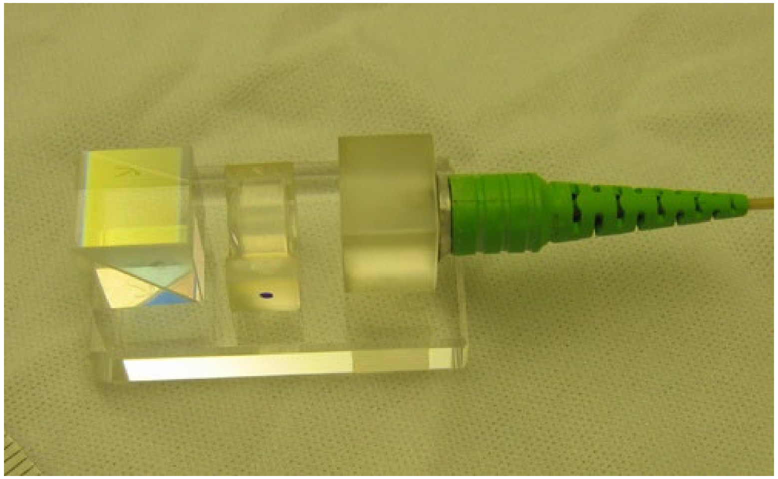


2007

Optical bench

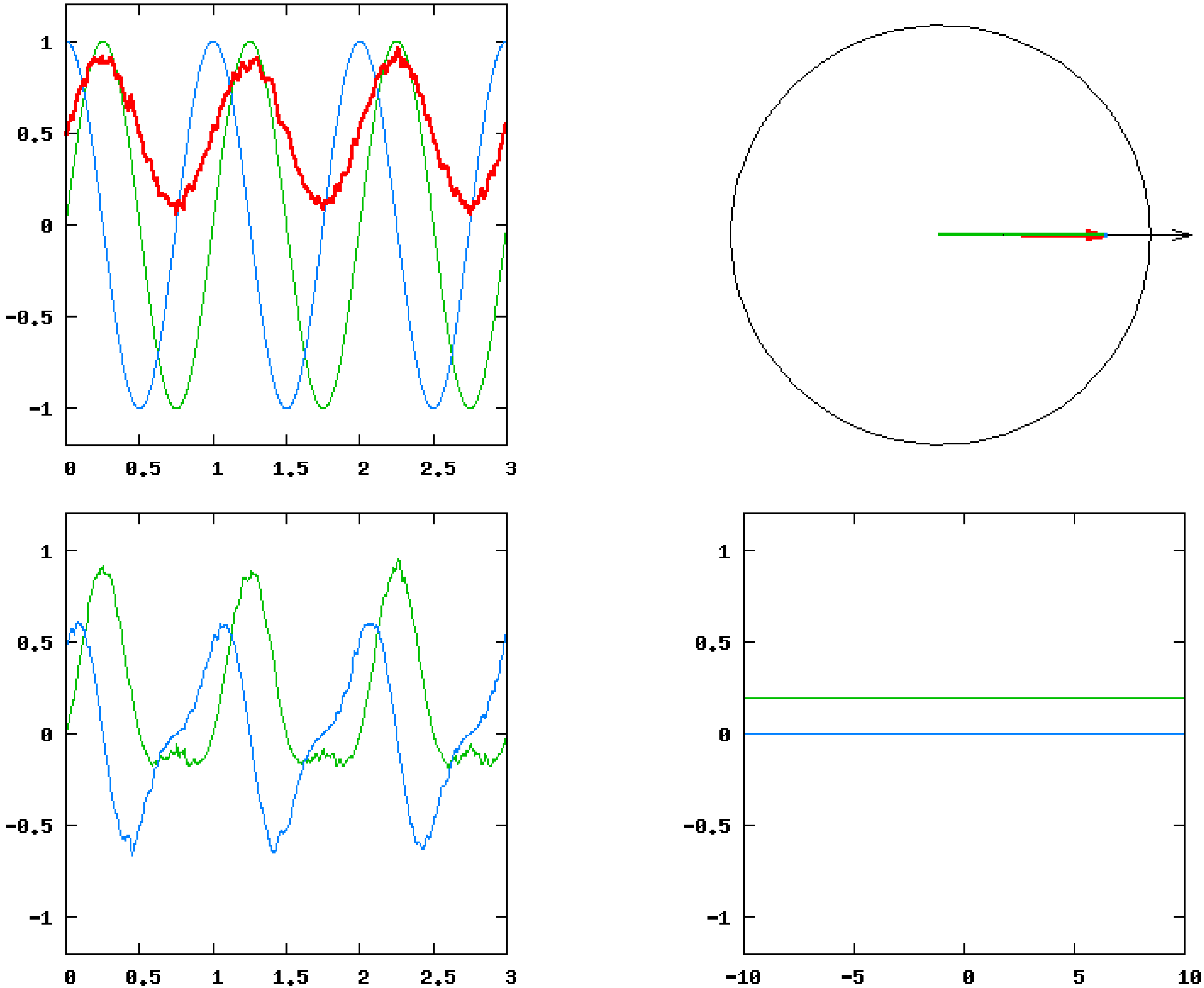
- 20*20cm Zerodur baseplate
- hydroxycatalysis bonding
- about 30 components
- 4 interferometers
- challenges:
  - vertical alignment
  - fiber launchers
  - absolute alignment w.r.t. test mass housing






University of Glasgow
VIA VERITAS VITA
PER ARDUA AD ALTA
UNIVERSITY OF BIRMINGHAM

Phasenmeter



Phasemeter

Phasemeter using SBDFT (Single-Bin Discrete Fourier Transform)

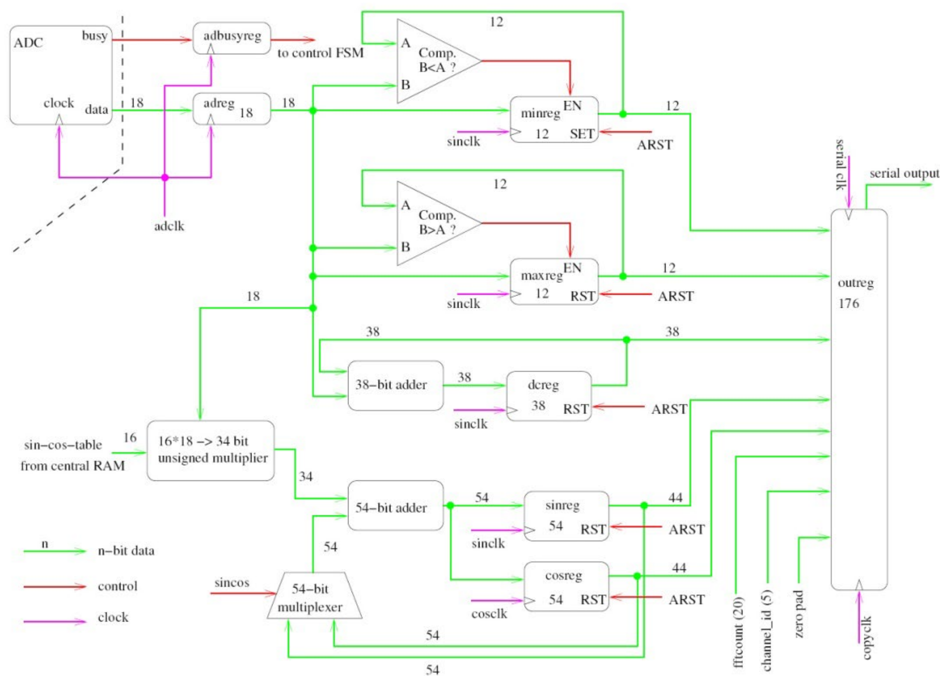
Inputs from one quadrant diode: $x_i = U_A(t_i)$, same for $U_B(t), U_C(t), U_D(t)$.
First step: **SBDFT** contains $> 99\,\%$ of the computational burden:

$$\text{DC components:} \quad \mathrm{DC}_A, \mathrm{DC}_B, \mathrm{DC}_C, \mathrm{DC}_D \quad \text{(real)}: \quad \mathrm{DC}_A = \sum_{i=0}^{n-1} x_i,$$

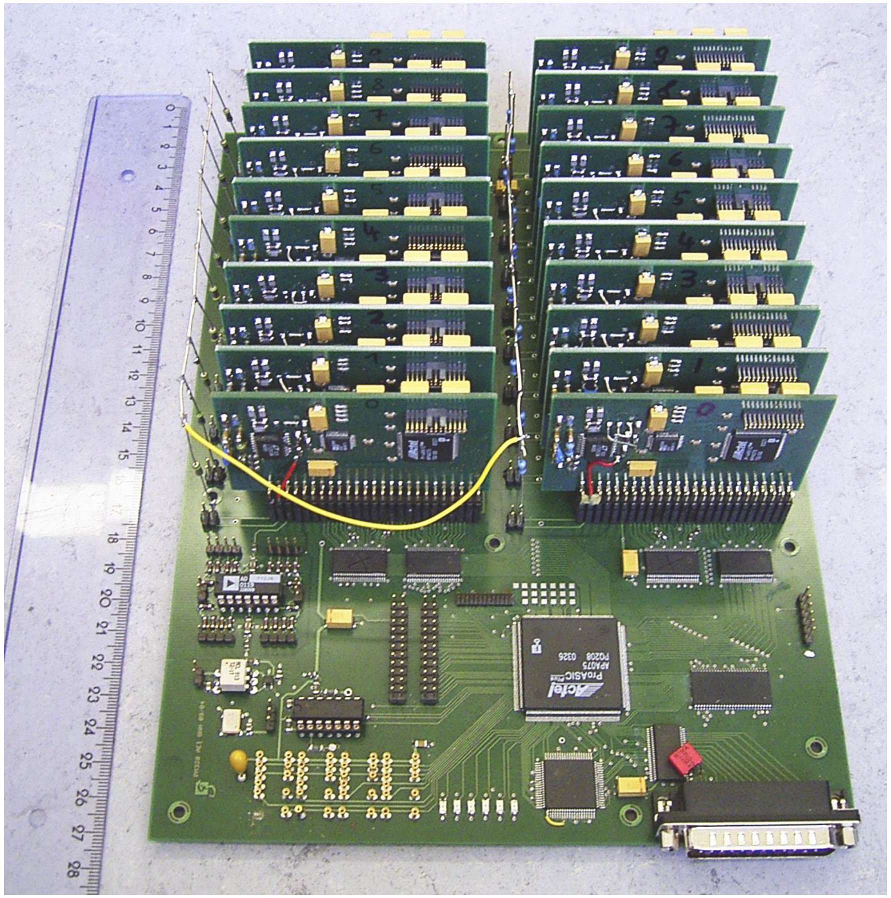
$$f_{\text{het}}\,\text{components:} \quad \mathrm{F}_A, \mathrm{F}_B, \mathrm{F}_C, \mathrm{F}_D: \quad \Re(\mathrm{F}_A) = \sum_{i=0}^{n-1} x_i \cdot c_i, \quad \Im(\mathrm{F}_A) = \sum_{i=0}^{n-1} x_i \cdot s_i.$$

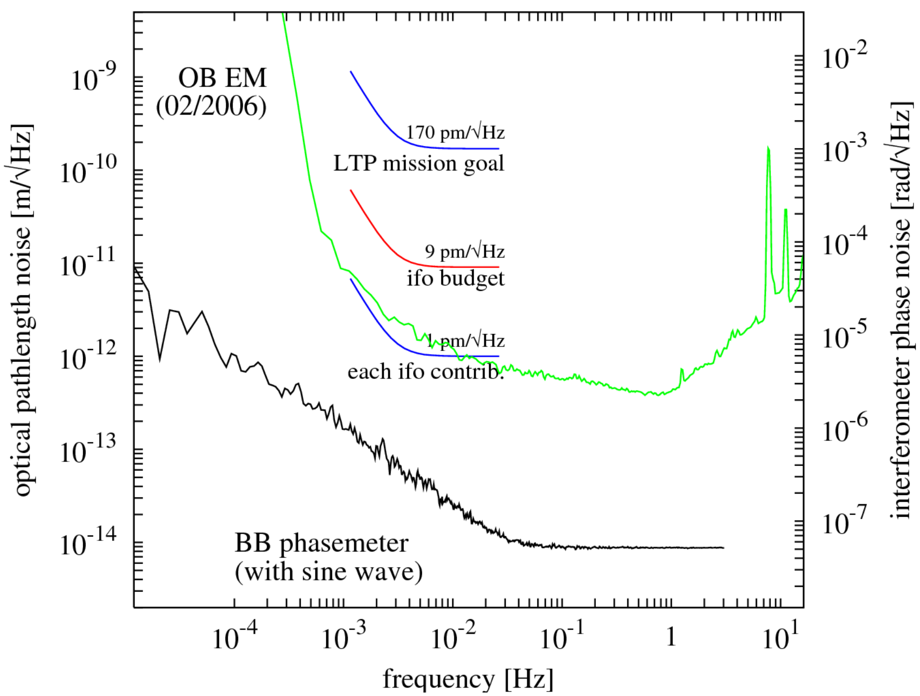
The constants s_i and c_i are pre-computed: $c_i = \cos\left(\frac{2\pi\, i\, k}{n}\right), s_i = \sin\left(\frac{2\pi\, i\, k}{n}\right)$.

FPGA

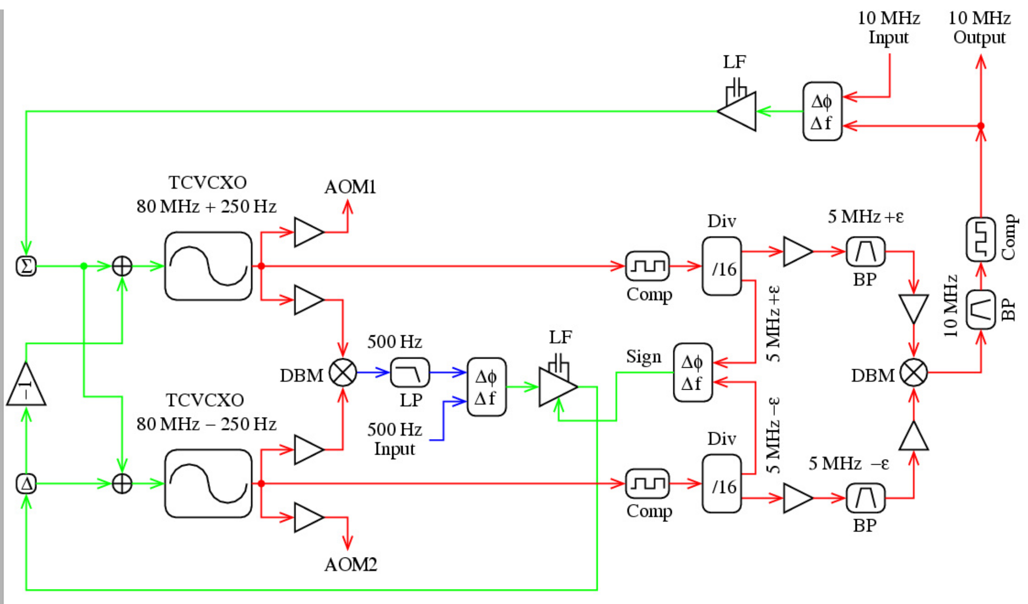


Phasemeter prototype 2005



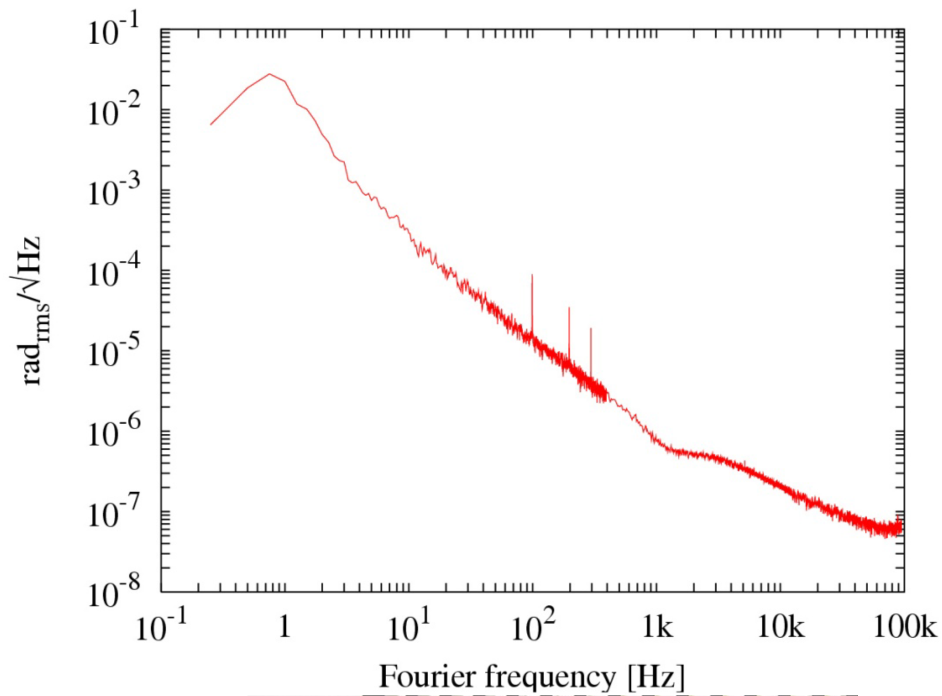


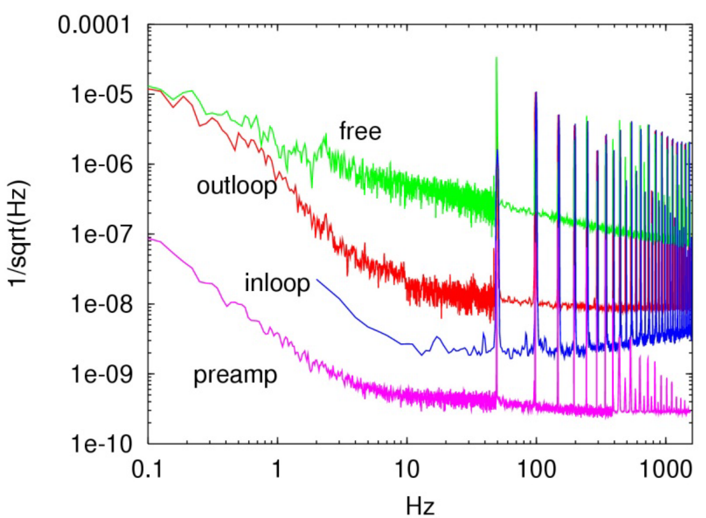
Frequency synthesizer

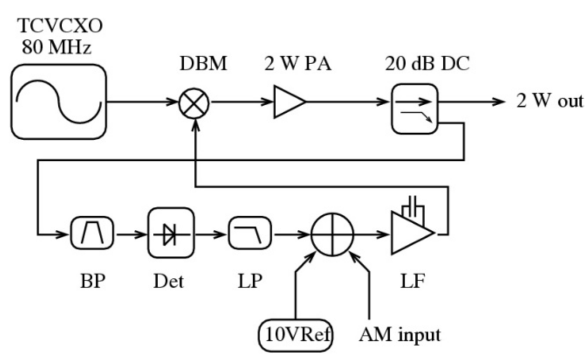


TCVCXO = temperature compensated voltage controlled crystal oscillator
LP = lowpass filter
BP = bandpass filter
LF = loop filter

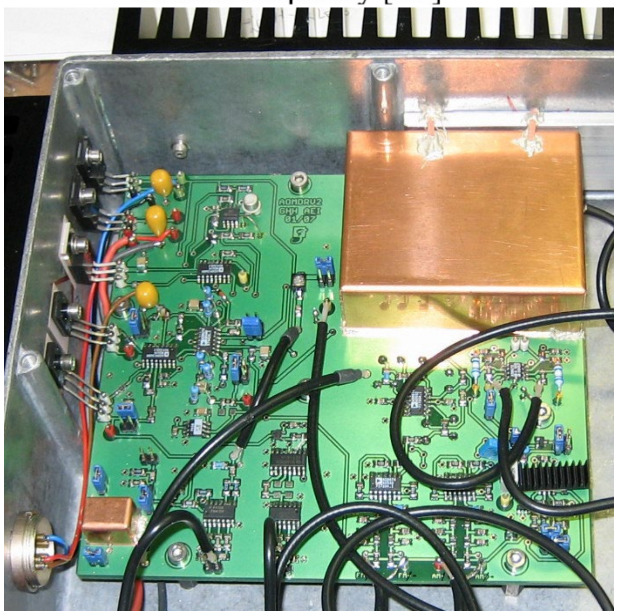
Comp = comparator to generate logic level signals
Div = digital frequency divider
DBM = double balanced mixer
ΔφΔf = digital phase/frequency detector



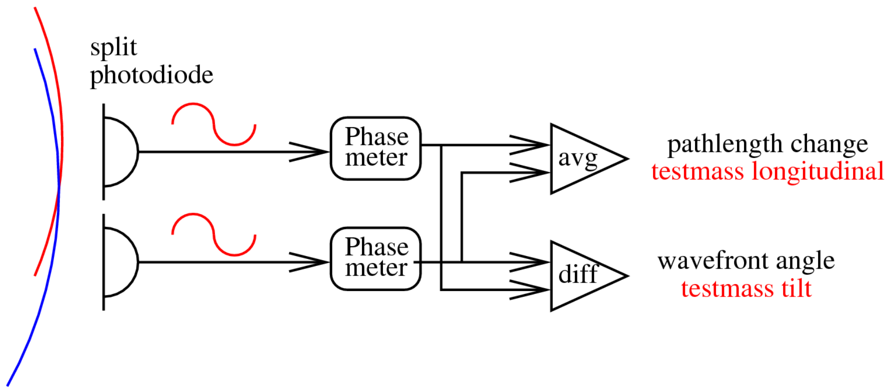


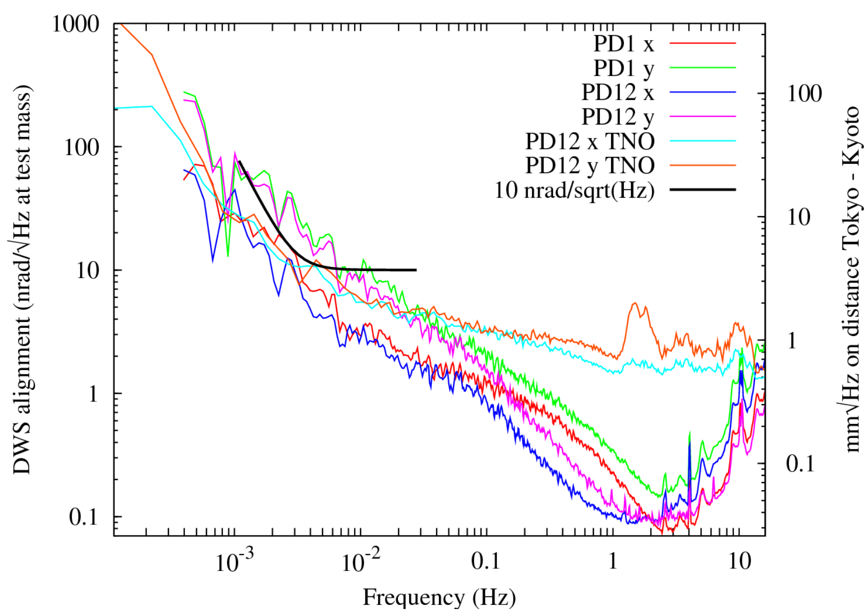


TCVCXO = Temp. compens. VCXO
DBM = double balanced mixer (used as attenuator)
PA = Power Amplifier
DC = Directional Coupler
BP = 80 MHz Bandpass
Det = Schottky Detector
LP = 10 MHz Lowpass
LF = Loop Filter



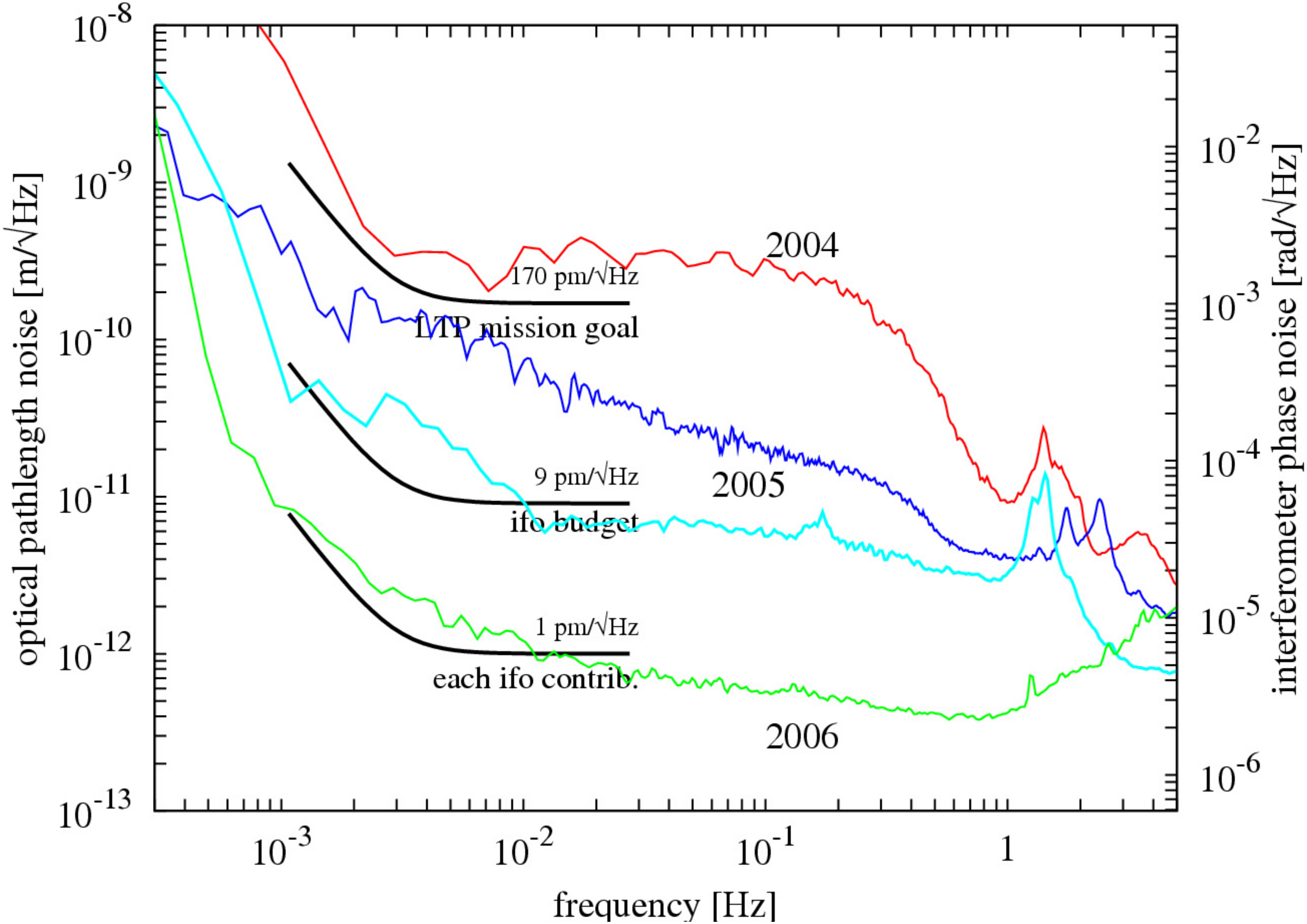
Angle measurements



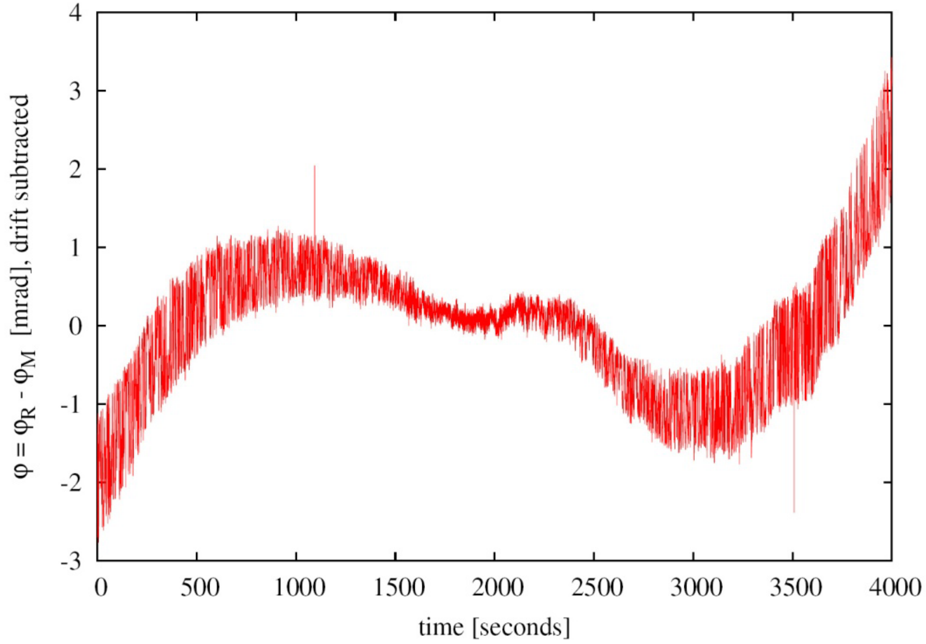


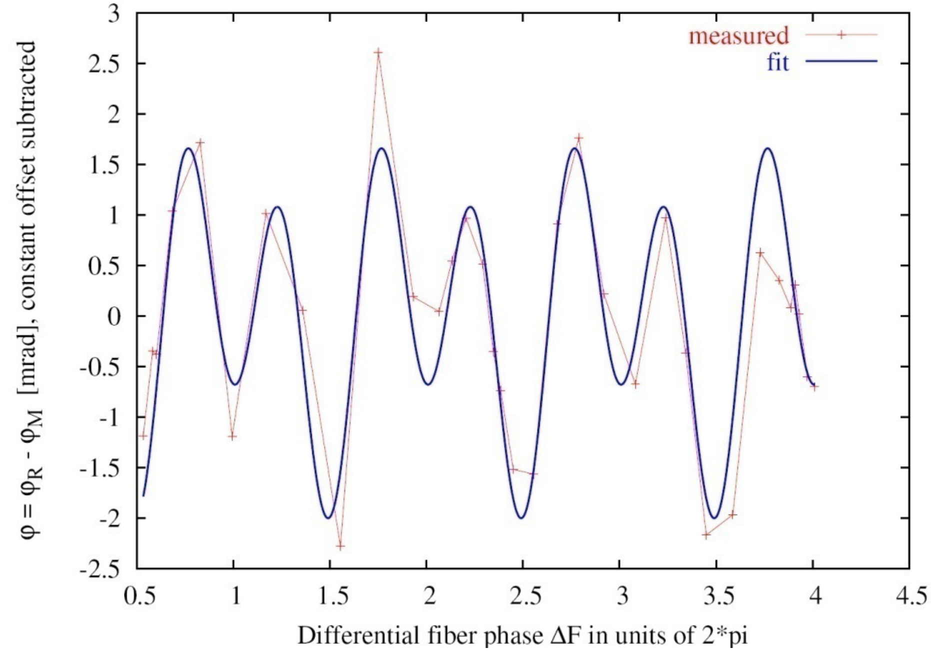
- uses Differential Wavefront Sensing (DWS)
- large amplification TM angle to audio phase difference (about 5000)
- one quadrant diode is enough, no reference needed
- immune to several noise sources
- excellent sensitivity

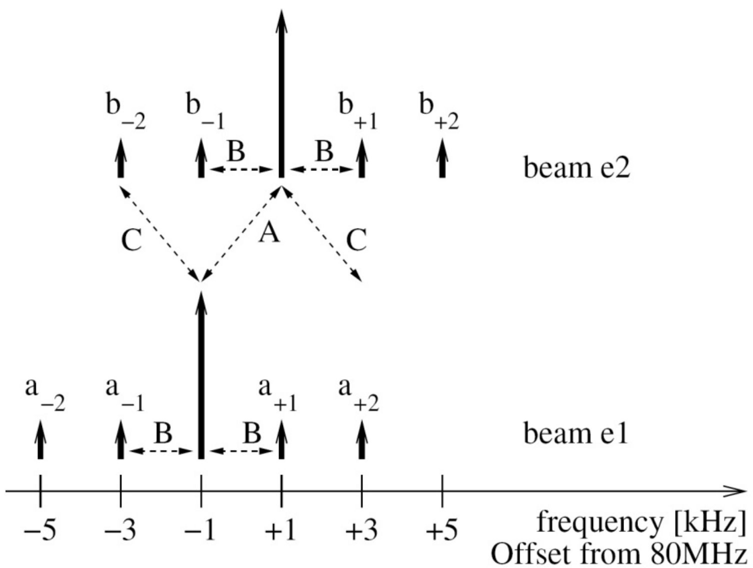
LTP Interferometer Sensitivity



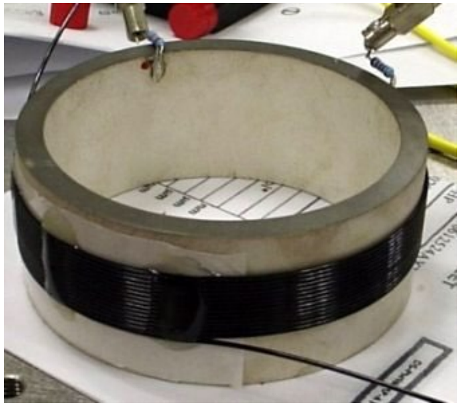
Unexpected noise







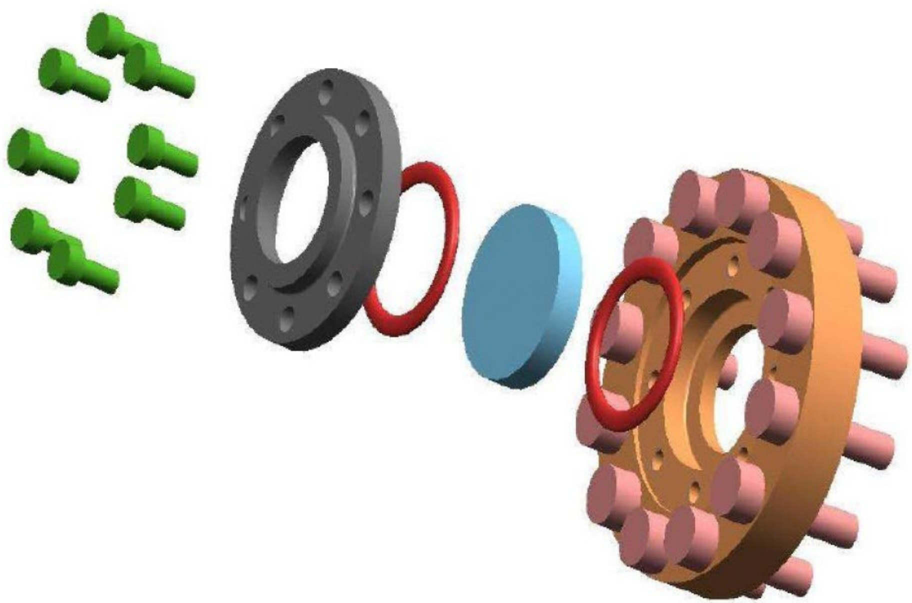
$$\frac{\delta\varphi}{\varepsilon} = \sin(\varphi_M + \gamma) - \sin(\varphi_R + \gamma)$$
$$= 2\cos\left(\Delta_F + \frac{\Delta_M + \Delta_R}{2} + \gamma\right) \cdot \sin\left(\frac{\Delta_M - \Delta_R}{2}\right)$$
$$= 2\cos\left(\frac{\varphi_M + \varphi_R}{2} + \gamma\right) \cdot \sin\left(\frac{\varphi_M - \varphi_R}{2}\right).$$



„small vector“ noise

- Caused by EMI crosstalk in prototypes
- Mitigated twice in FM:
  - stringent crosstalk requirements
  - OPD stabilization
- Result: this noise is invisible in flight

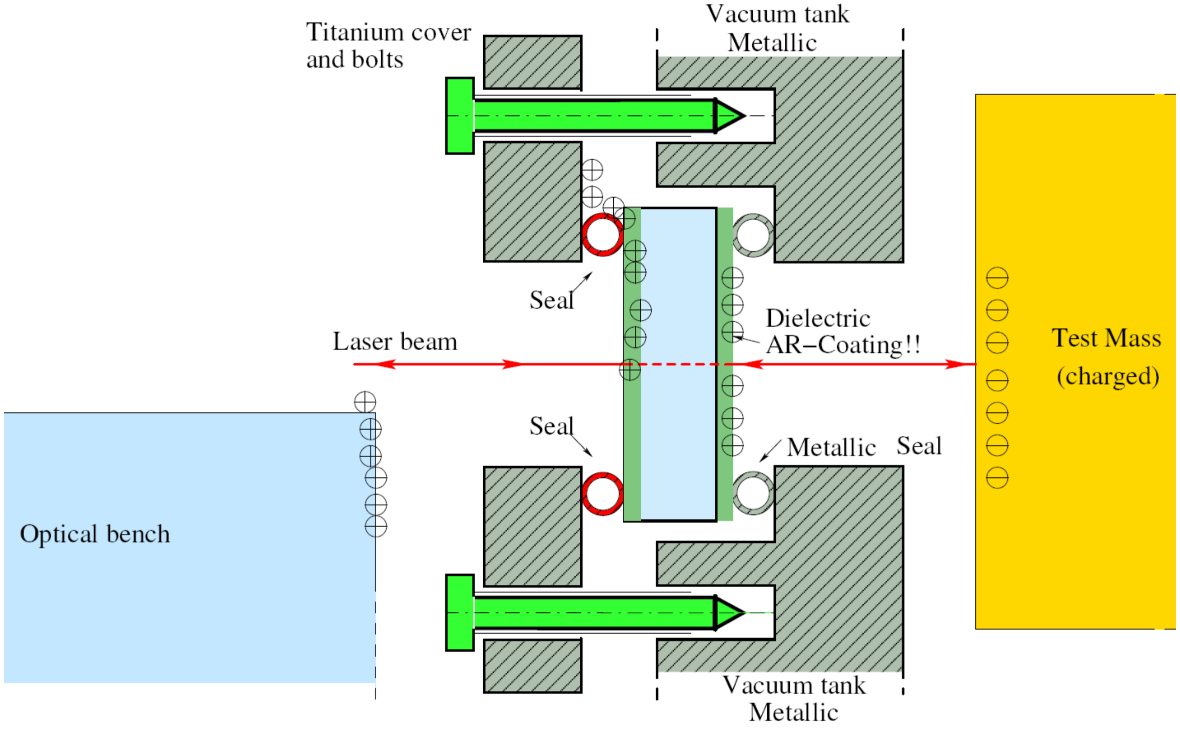
Optical Window



- needed for optical access of interferometer beams
- like a flange of vacuum tank
- optical pathlength in transmission 12mm/24mm
- “athermal” glass S-PHM52 (Ohara) minimizes pathlength error dn/dT+(n-1)a
- extensive testing at AEI for radiation hardness, pressure-dependent pathlength error and actual performance was successful.

Optical window electrostatics

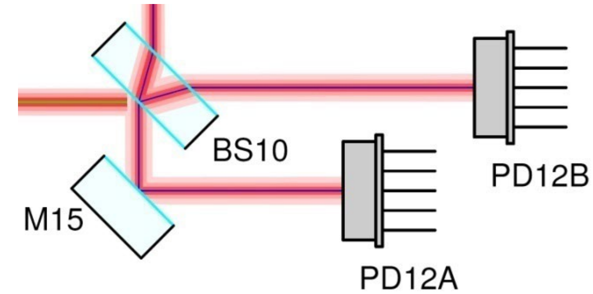
an isolating window may accumulate charges
and disturb the test mass



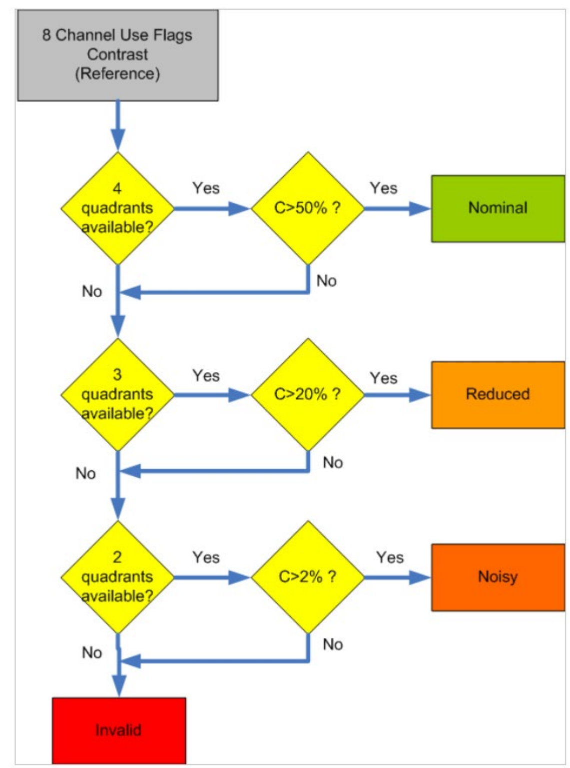
Solution: apply conductive ITO (In_2O_3/SnO_2) layer to optical window

Error handling

- redundant photodiodes and phasemeter
- occasional temporary failures by high-energy protons are expected
- advance planning for the most probable error cases
- nominal operations is 20% of the software effort, error treatment 80% !



Name	*Acronym*
overrange (value > max)	overrange_{i,j,k}
underrange (value < min)	underrange_{i,j,k}
crc-check	crc_{i,j,k}
delta-check	delta_{i,j,k}
epsilon-check	epsilon_{i,j,k}
Latch-up (L)	L_{i,j,k}
Transmission (T)	T_{i, ,k}
PM configuration register	PM_config
PM LUT checksum	PM_LUT
PM state of health	PM_healthstate
Over-Run (O)	overrun_{i, ,k}
MIL-Bus error (all MIL-Bus reasons for incorrect data reception)	Milbus_error
Ground commanded channel disable	gccd_{i,j,k}



Clock synchronization

Without synchronization, the 100 Hz within the LTP and the 10 Hz of the DFACS would invariably slowly drift against each other. Consequently, every now and then either the 9th or the 11th sample would be picked instead of the 10th sample. At this time the data age jumps by 10 ms.

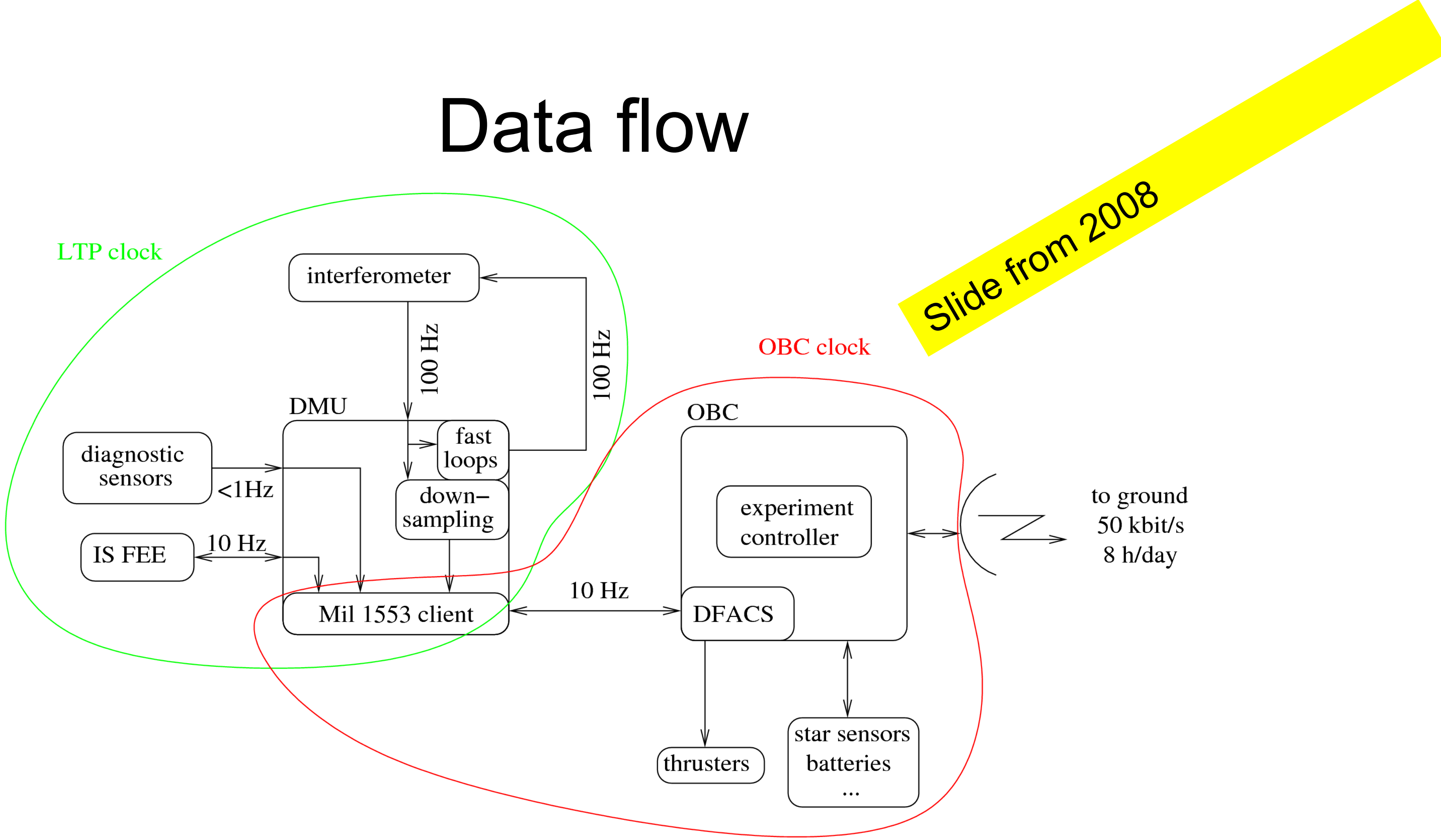
Even if such jumps were within the formal specifications of the DFACS system, it is well possible that they would produce artefacts in the science data, in particular if they occur at more or less regular intervals. Simulations of this effect at ASD are under way.

4 Conclusion

TN from 2005

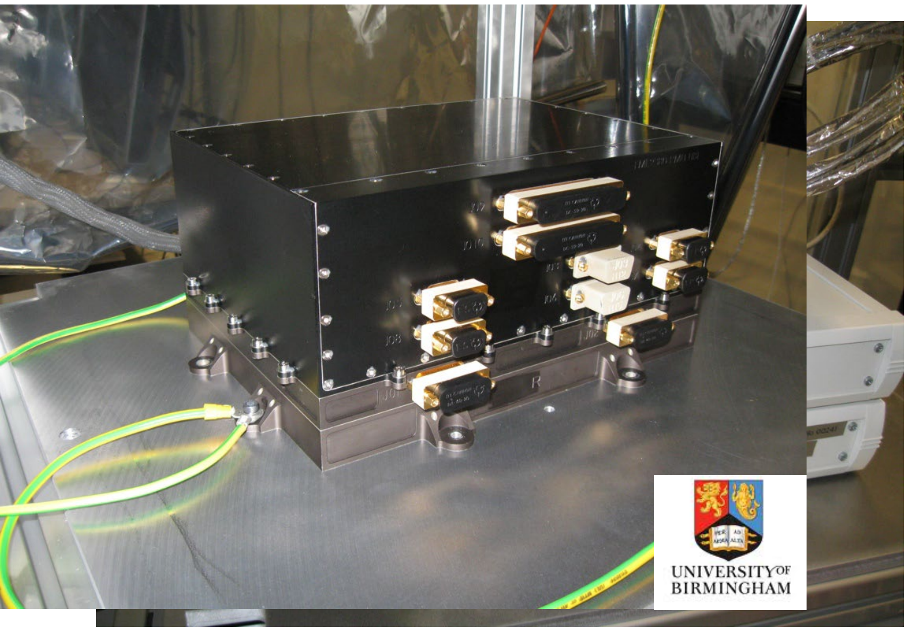
Although we cannot prove with absolute certainty that synchronization is necessary to achieve the scientific mission goals, there are compelling arguments for synchronization.

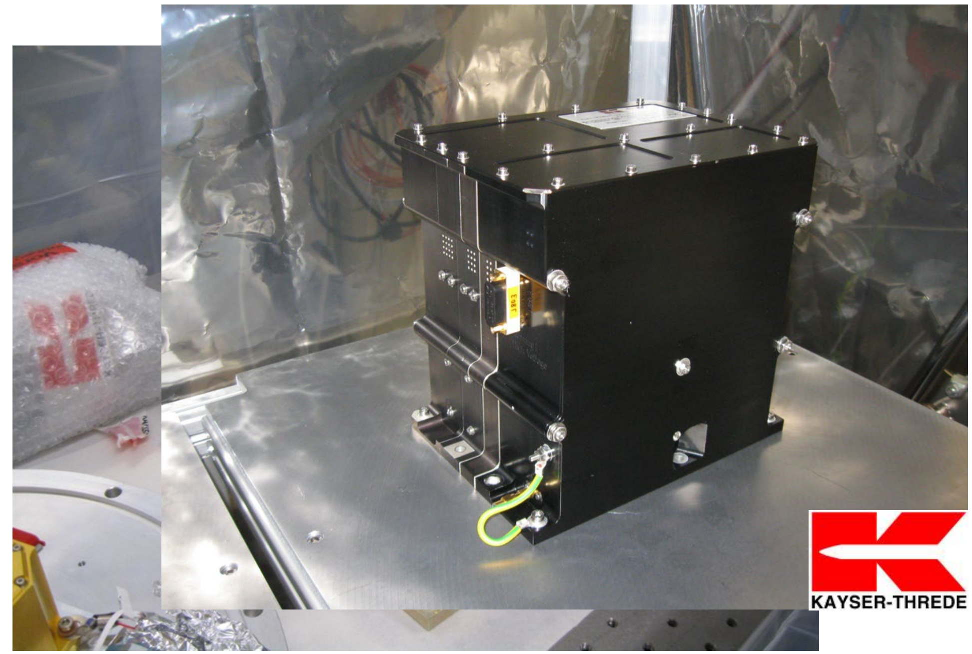
Data flow

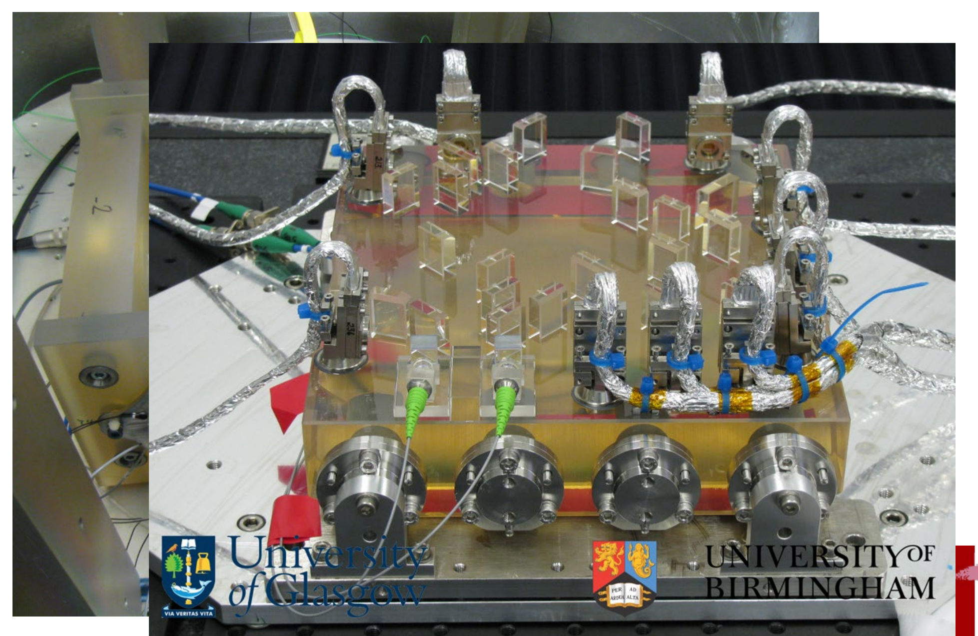


- On-board computer (OBC) does not deliver its clock
- LTP runs on nominally same frequency but not synchronized
- drag-free requires continuous intimate interaction between them
- non-synchronous operation creates many problems

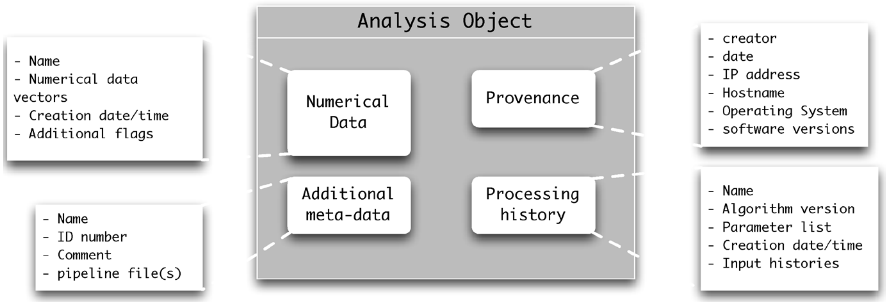
From prototypes to Ems and FMs

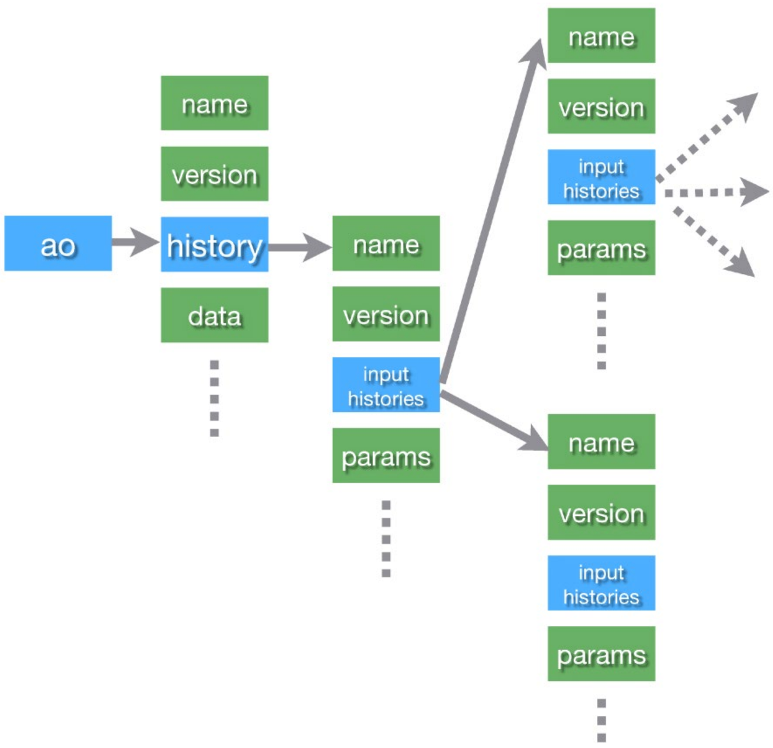






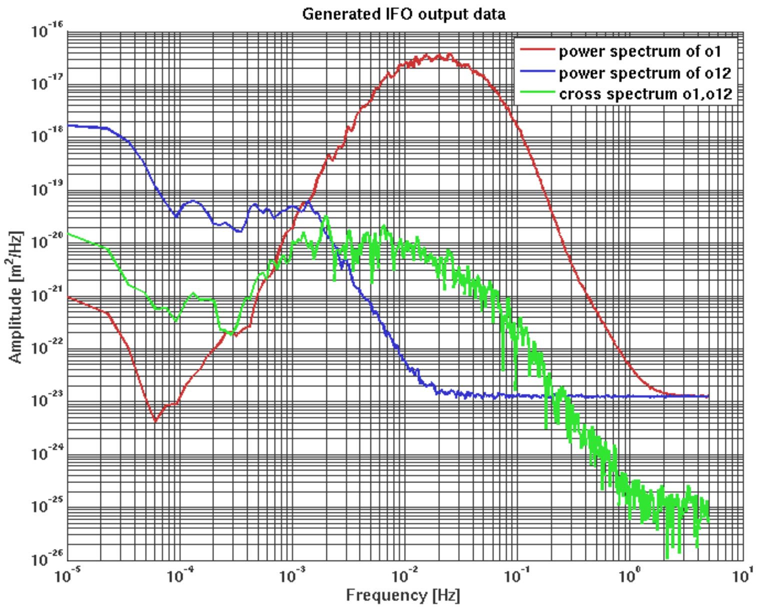
LTPDA: Analysis objects

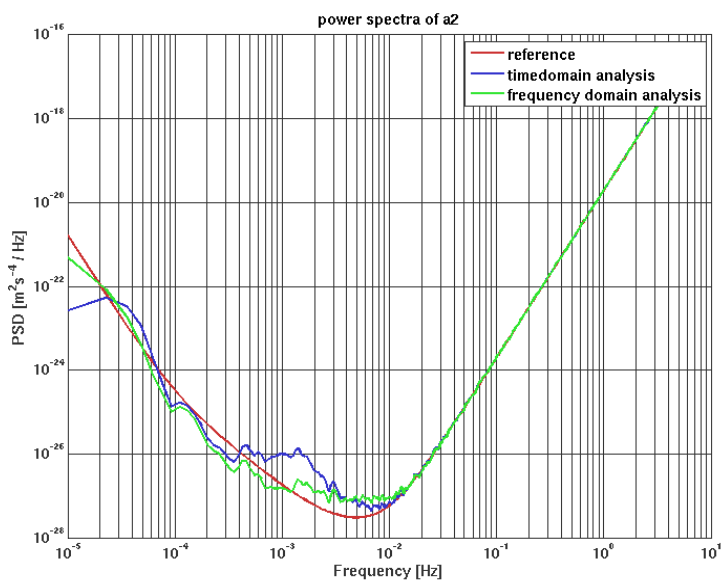




- A useful result is ***not*** a graph or a file full of ASCII data
- Each result must “know” how it was produced with all details
- Each result can be reproduced by any user with access to the raw data, also with modified processing
- All intermediate steps and final results are stored as MATLAB structures called “Analysis objects” (AO)
- Each processing step appends its name, version and parameters to the history of the resulting AO

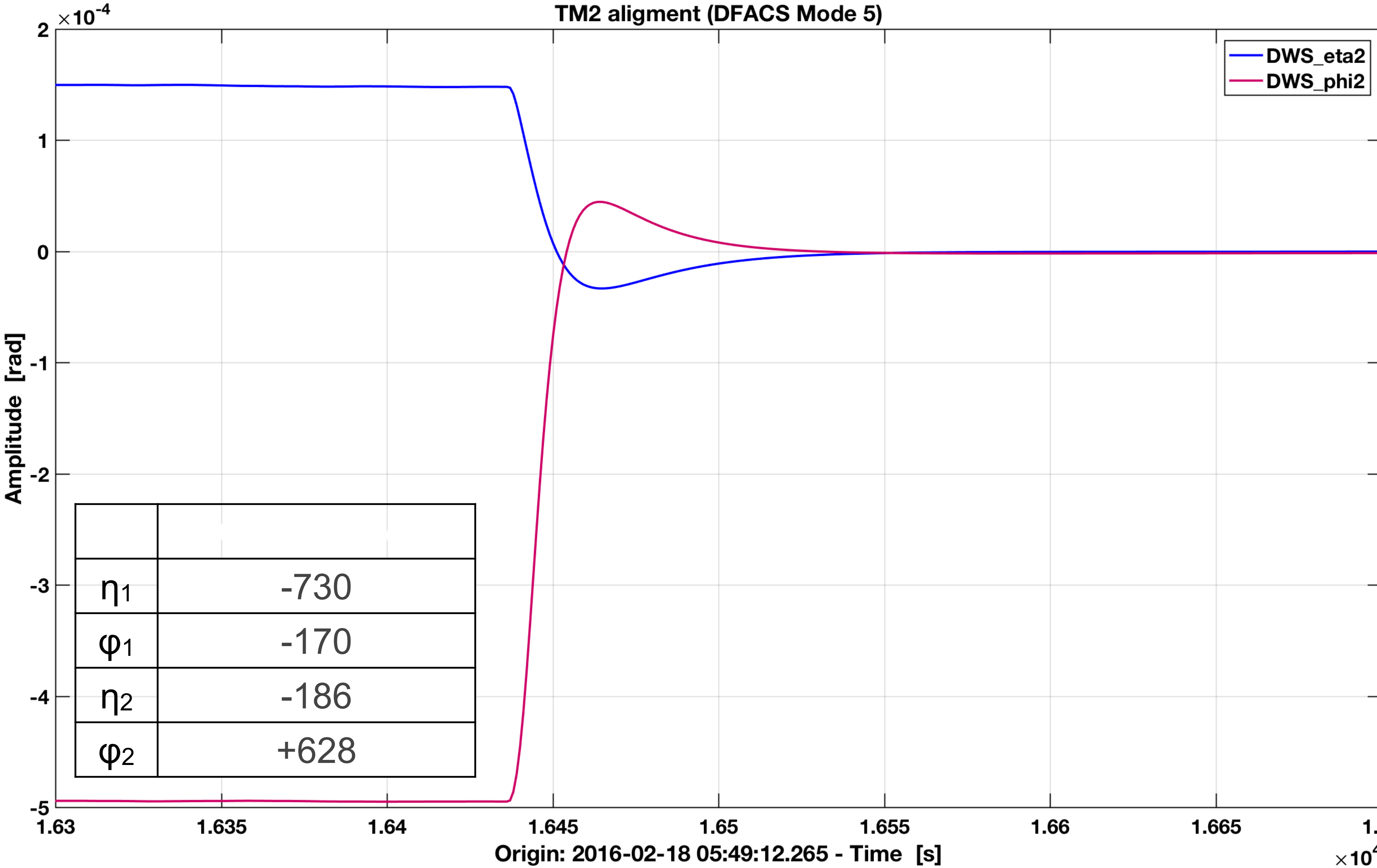
Mock data challenge





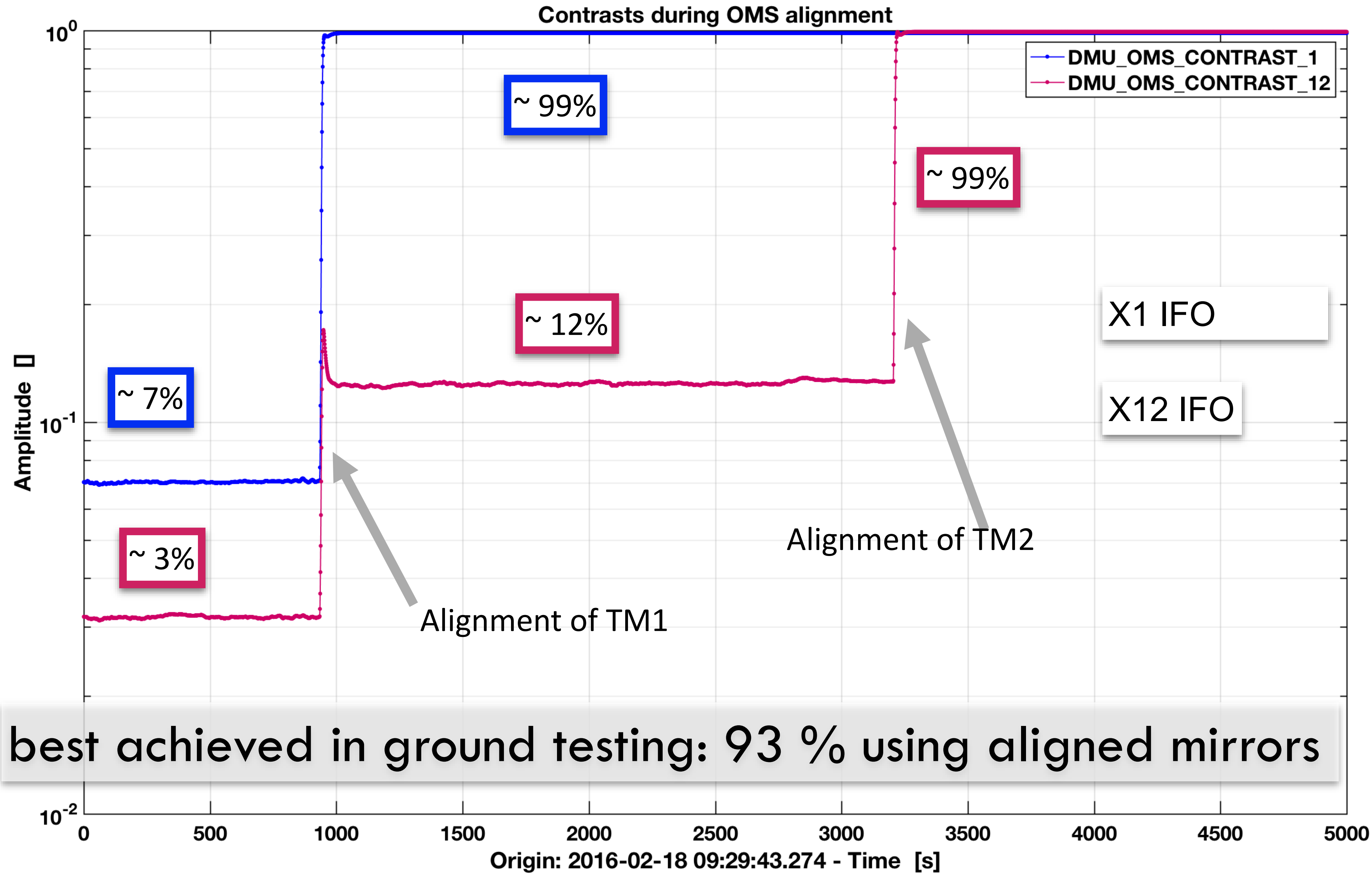
- Test of the data analysis pipeline:
- One team generates downlink data with a spectrum kept secret
- Second team uses LTPDA to recover the spectrum
- First round (simple model) successfully concluded

Finally … In orbit



η_1	-730
φ_1	-170
η_2	-186
φ_2	+628

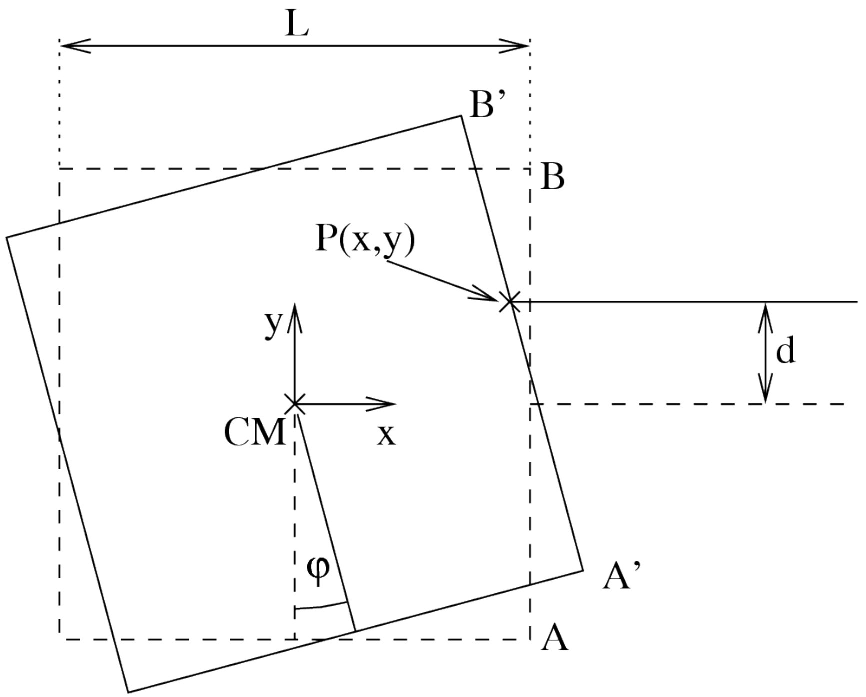
Contrasts before and after alignment



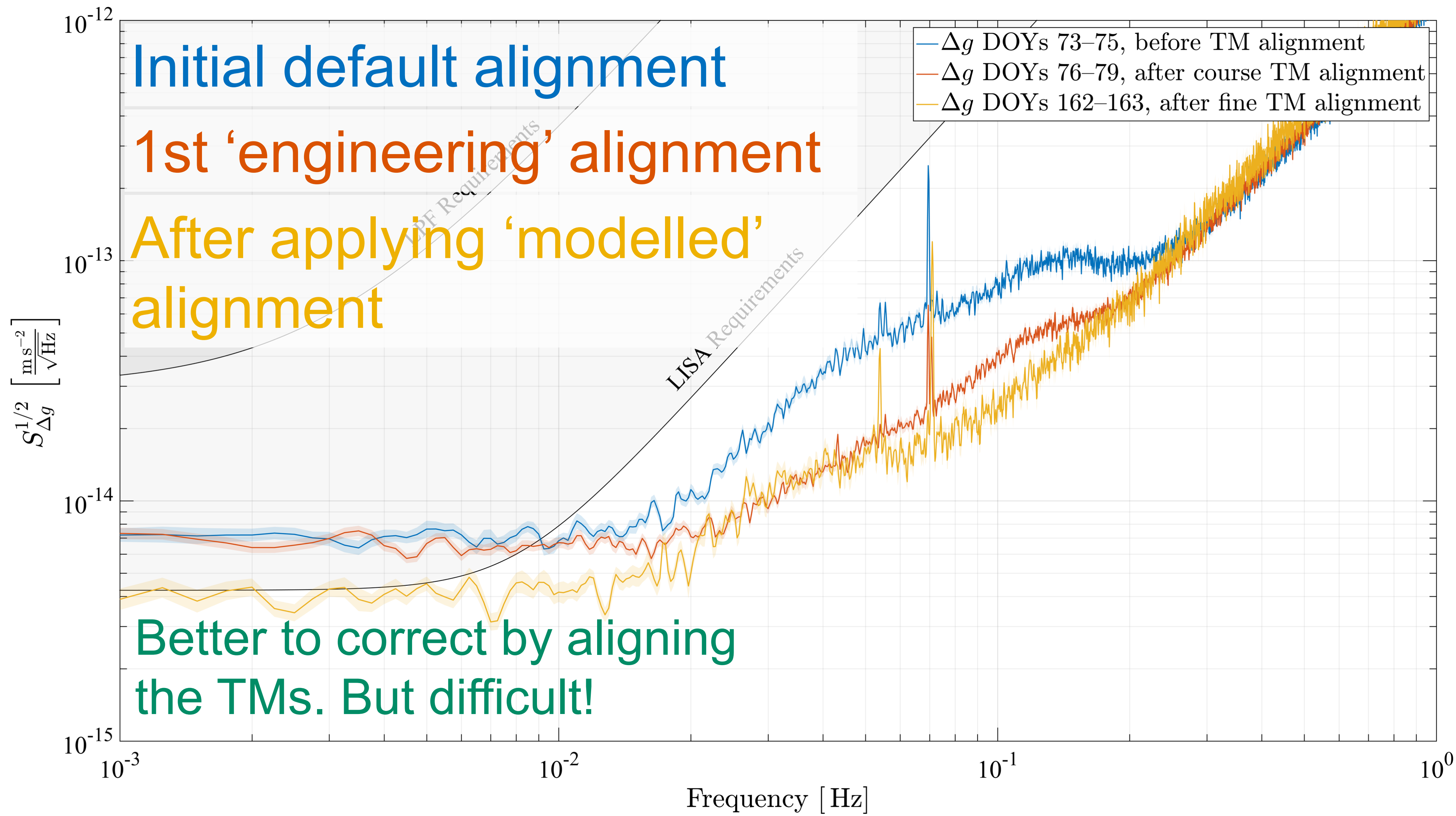
best achieved in ground testing: 93 % using aligned mirrors

Cross coupling of other degrees of freedom

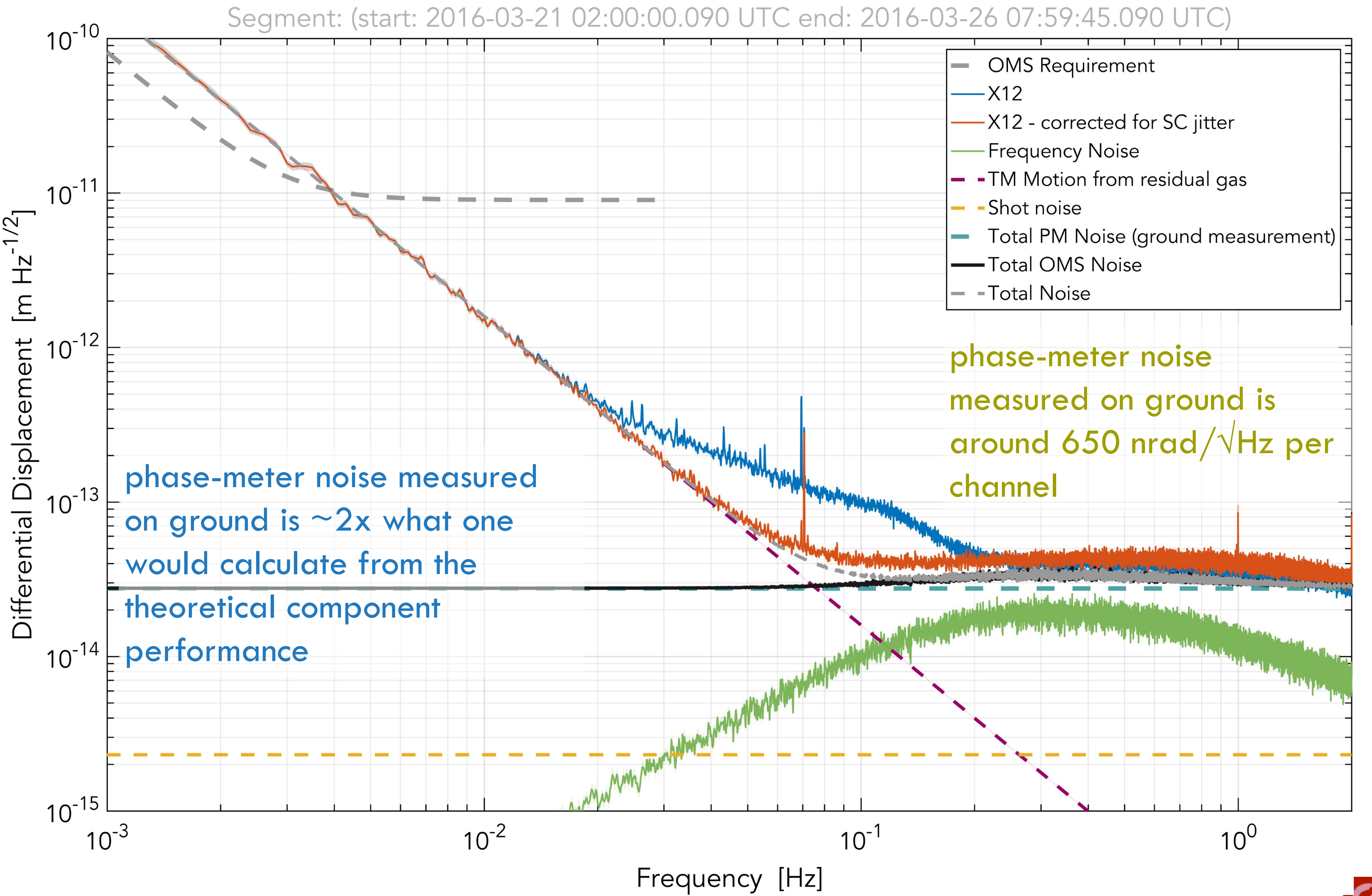
- A perfect interferometer **would** measure only ***x***
- An offset ***d*** couples rotations of test mass or spacecraft into ***x***
- An misalignment angle φ couples ***y/z*** motion into ***x***.
- depends on geometry of the interferometer and beam parameters (curvature etc.)



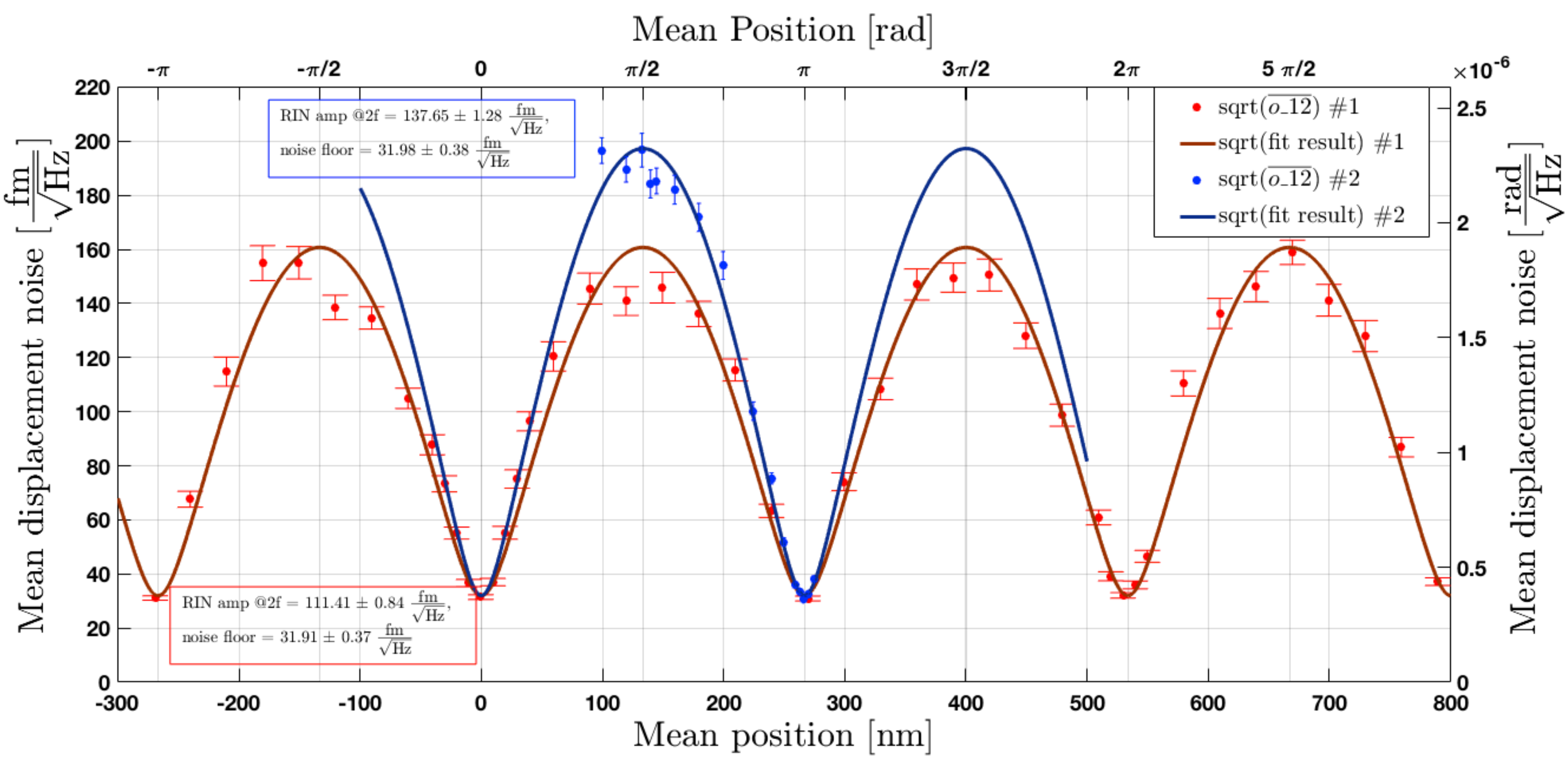
Cross-talk in raw Δg – TM alignment



In-flight Ifo noise



In-flight Experiment



The ultra low noise in flight allowed to investigate minor effects below the requirements, but relevant for LISA:

- RIN @ DC, 1f, 2f
- Stability of optics in orbit
- Polarization effects

Flowing into LISA design !

Impact

- Success of LISA Pathfinder paving the way to LISA
- Discovering, investigating and resolving many unexpected effects
- Many of the 40+ Ph.D. students are now playing important roles in LISA and other space projects
- Very similar technology is now used for Earth observation and climate research via gravity measurements from space (GRACE-FO, GRACE-C, NGGM)