Satellite interferometry from LTP and GRACE Follow-On to LISA

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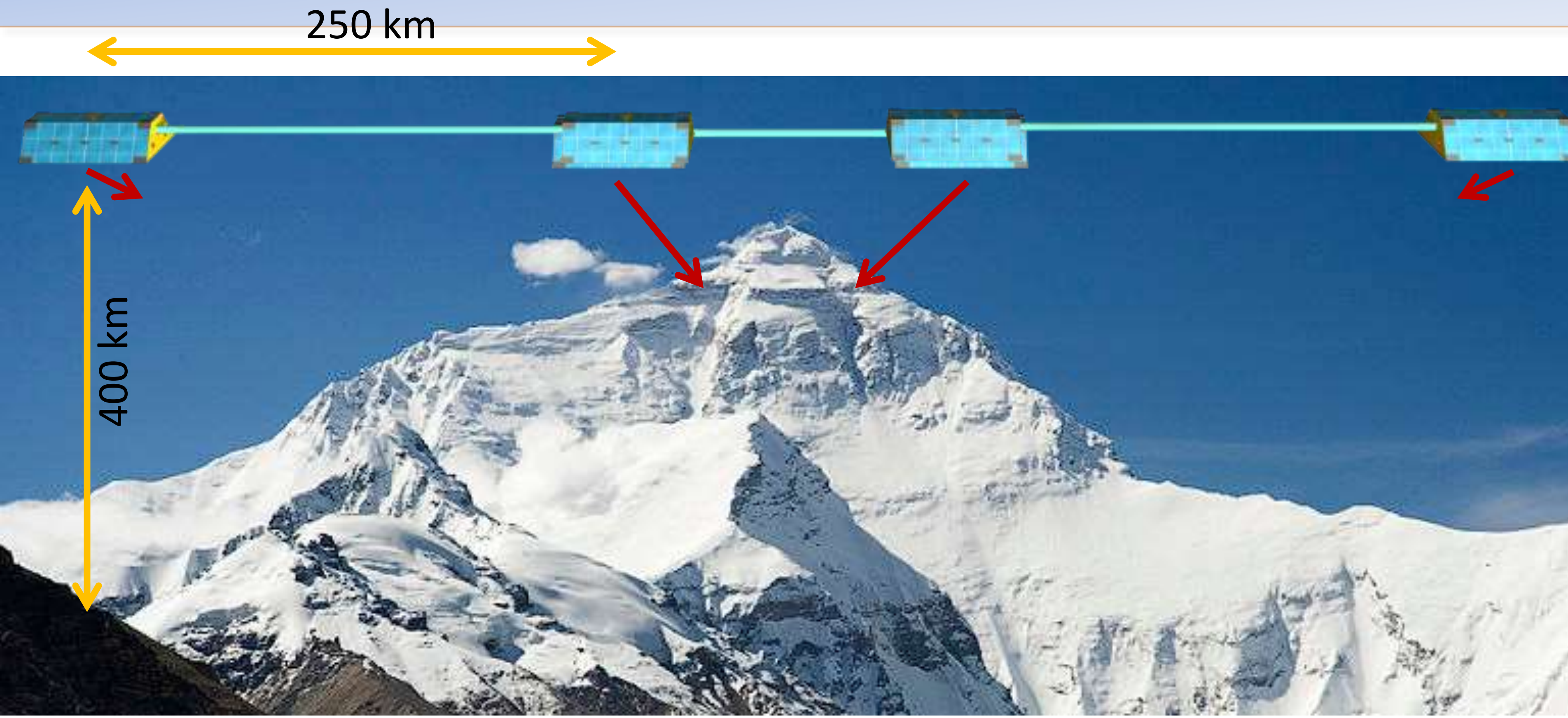
AEI Hannover

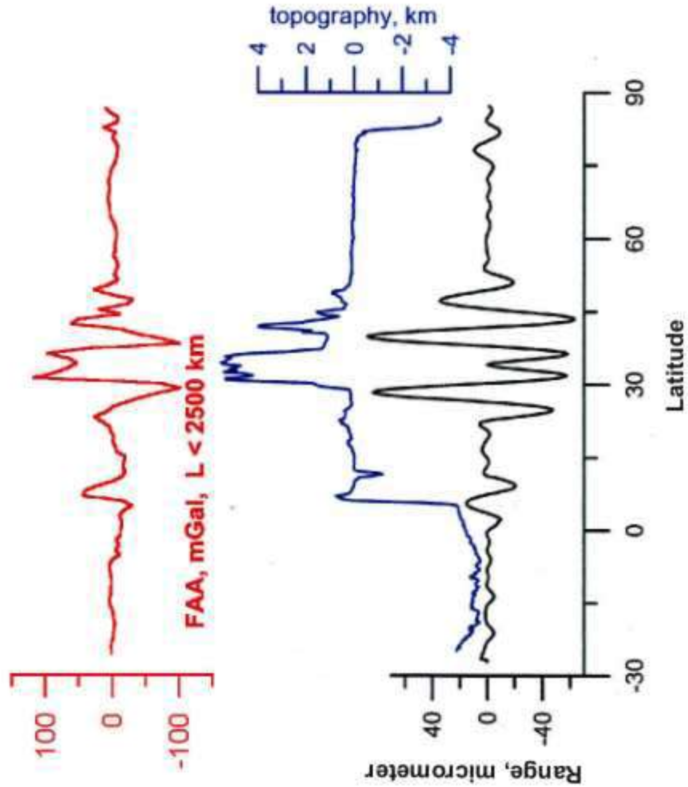
LISA Symposium Zürich Sept. 6 2016

GRACE: Satellite-to-satellite tracking



- US-German collaboration
- Launched 2002, still working
- μ-wave ranging

GRACE signals



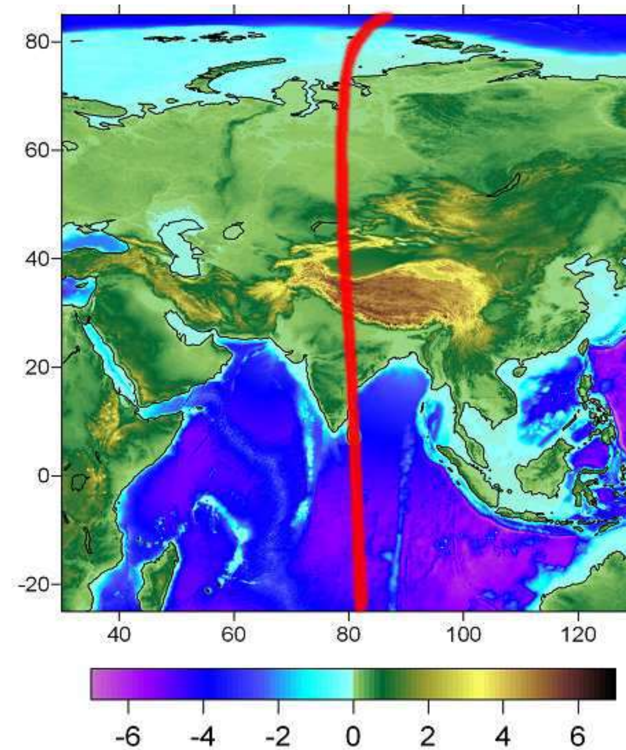
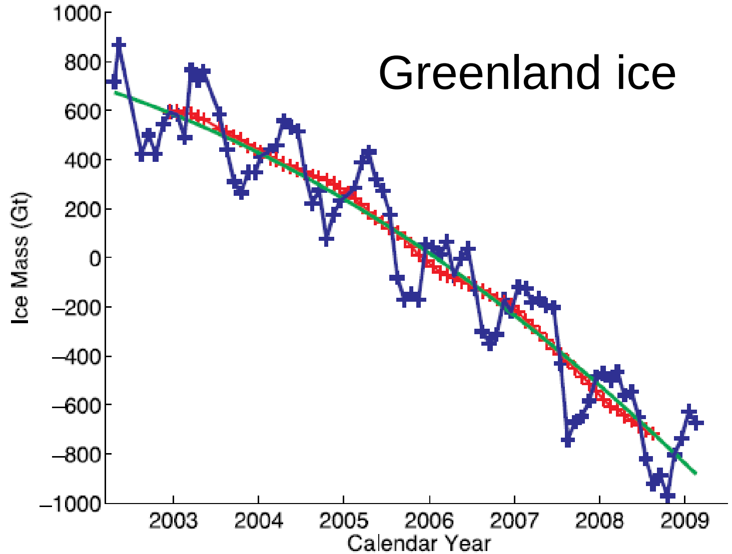


Image credit: AIUB

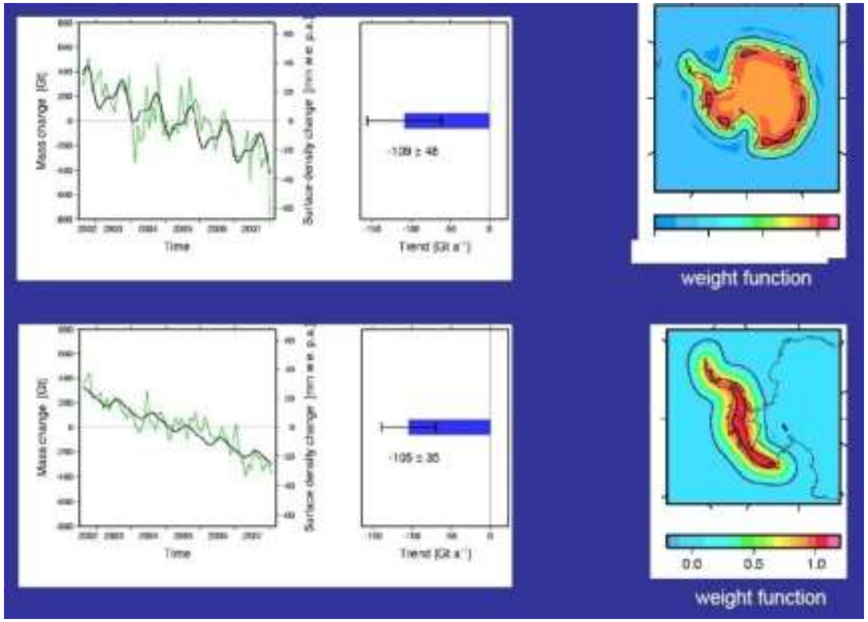
- Changes of order μm … mm
- No absolute measurement of separation (GPS is enough)
- Rather complicated data analysis to recover Earth gravity field and remove effects of ocean tides, atmosphere etc.

Some GRACE results

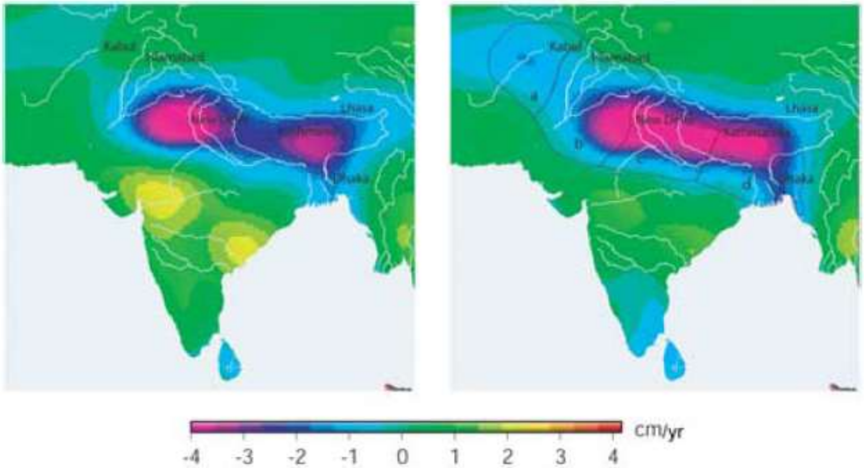


Velicogna, *"Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE"* Geophys. Research Lett. **36**, L19503 (2009).

Antarctica



Horwath and Dietrich, Geophys.J.Int 2009



Ground water in India

Tiwari et al., *"Dwindling groundwater resources in northern India, from satellite gravity observations",* Geophys. Research Lett. **36**, L18401 (2009).

Changing water level

Annual geoid variations due to rainy/dry seasons

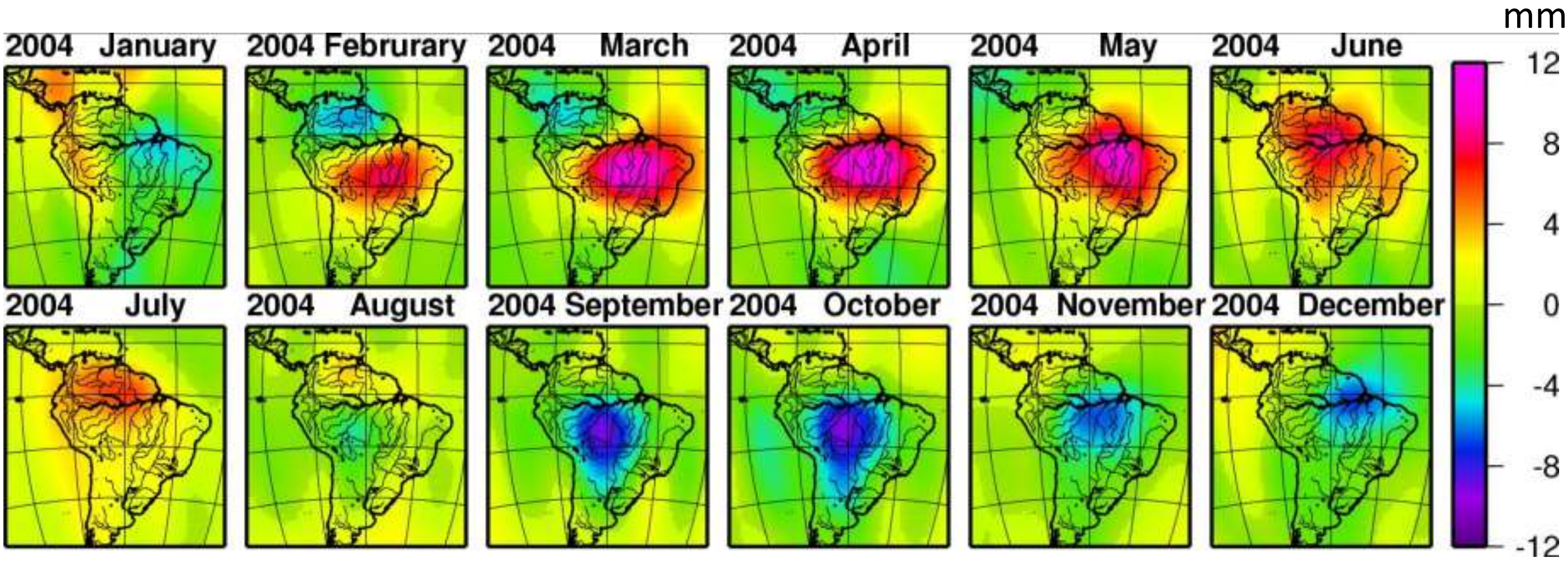
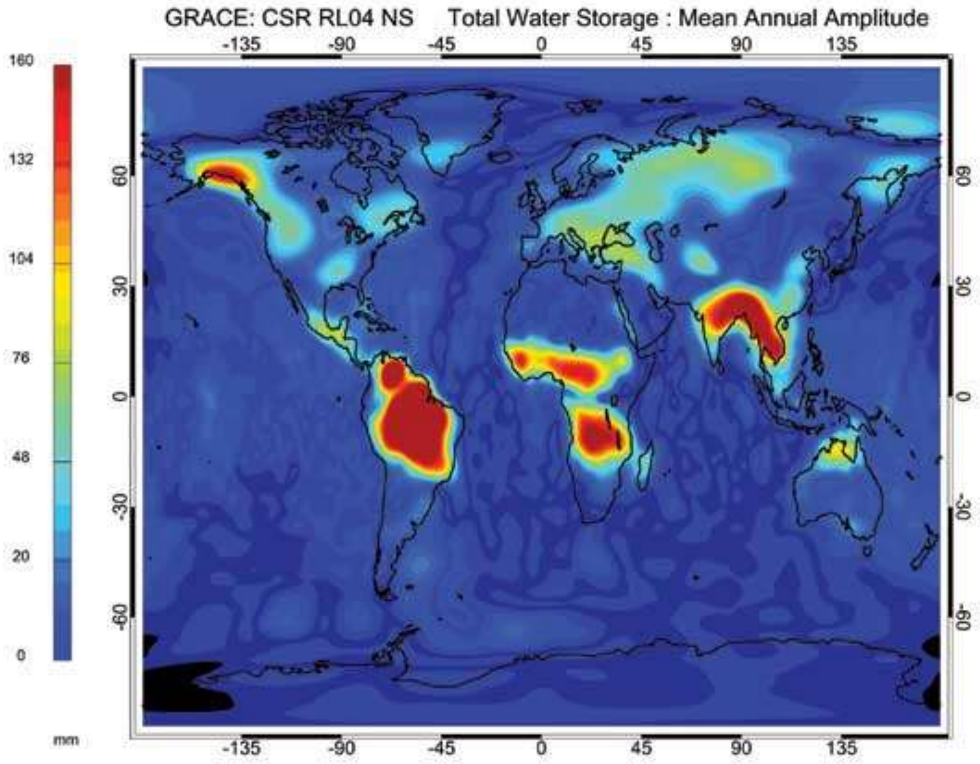
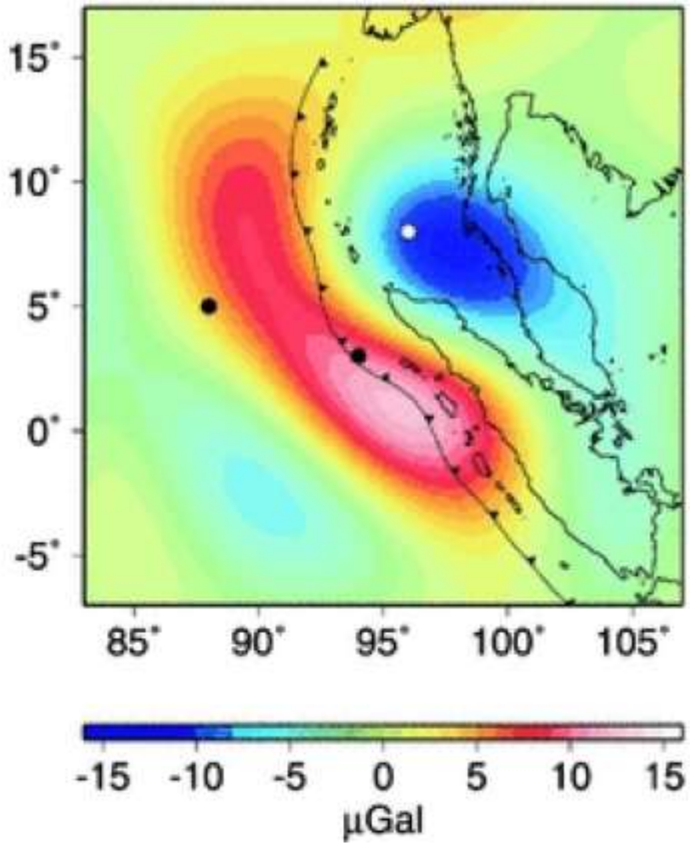


Image Credits: NASA/JPL

Some GRACE results

Annual periodic mass change

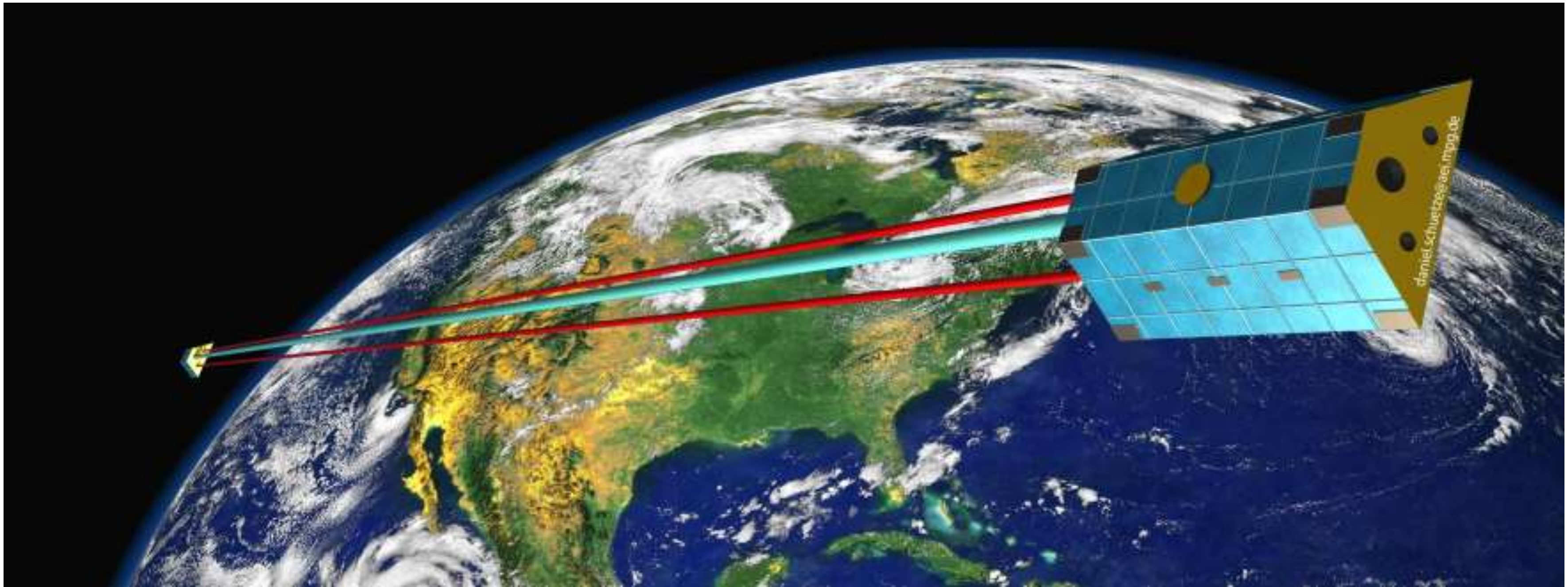




Sumatra earthquake before-after

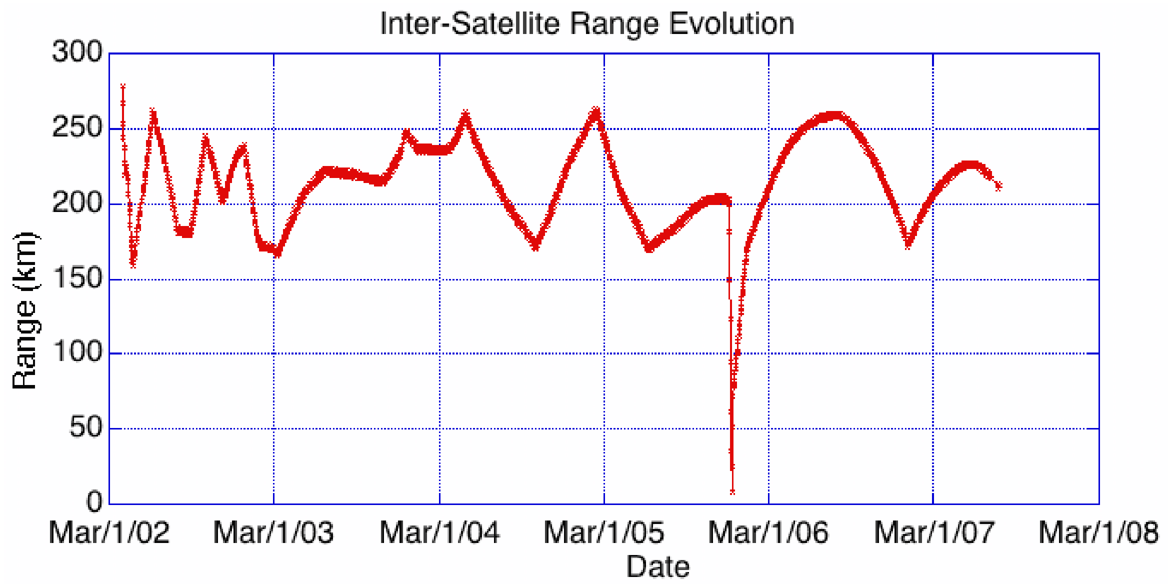
GRACE Follow-On

- GRACE mission nearing the end of its on-orbit life (long past design life)
- New mission for continued data with minimal gap:
  - near rebuild of GRACE using microwave ranging, launch 2017/18.
  - New: **<u>laser interferometer</u>** as experimental demonstrator, first laser interferometer between satellites.
  - LRI is a US-German joint project, in a collaborative partnership resulting from earlier LISA work:
    - US: phasemeter, cavity, laser (lead: JPL)
    - Germany: optics (design lead: AEI)

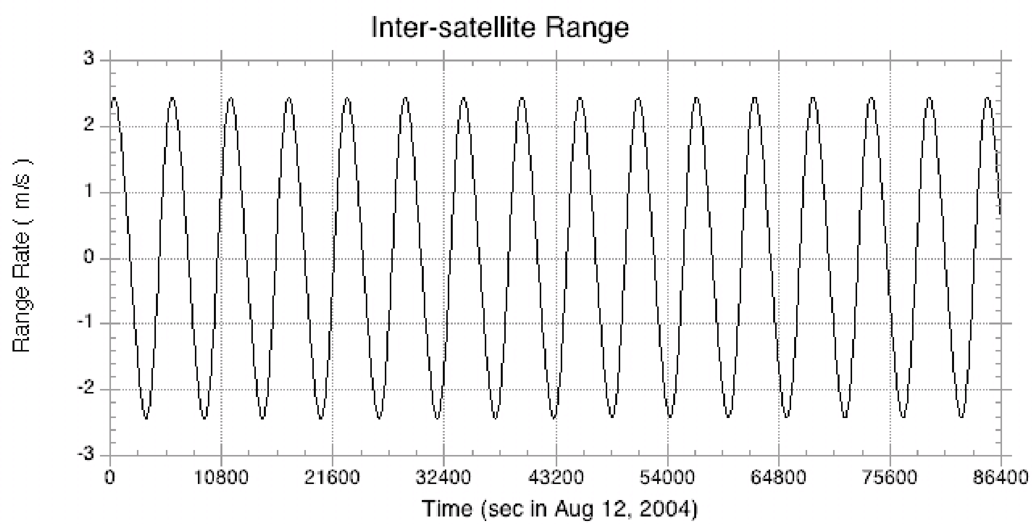


GRACE intersatellite range and range-rate

- Range too large for passive reflector approach to be used

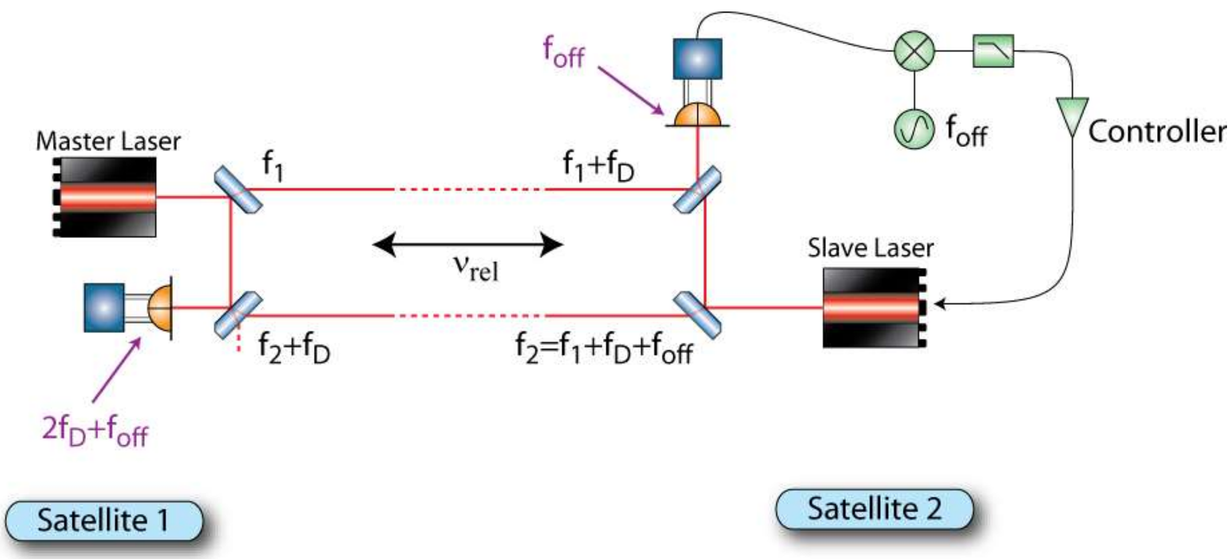


- 1 m/s LOS velocity gives roughly 1 MHz Doppler shift



Transponder configuration

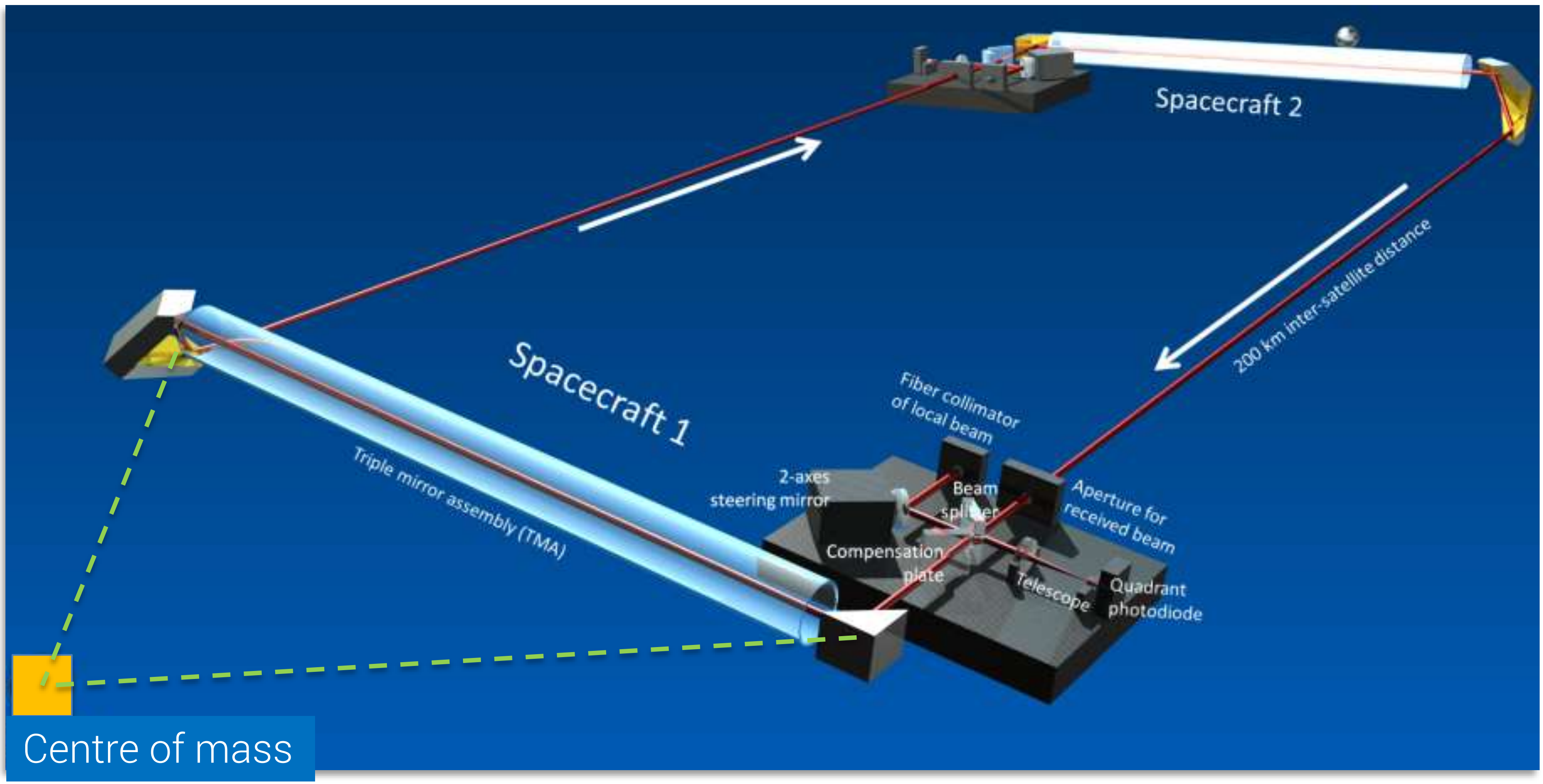
- Offset phase locked transponder
  - Similar to one LISA arm
  - Doppler shift is ±3 MHz, operate with offset of 10 MHz to escape 0-2 MHz band
- Distance variations leads to phase changes which are continuously tracked
  - Offset phase lock on transponder S/C, zero signal if perfect
  - Range variations appear accumulated in beatnote signal on master S/C



$$|f_D| = \frac{|v_{rel}|}{\lambda}$$

LRI optics

- **„Racetrack“ configuration with triple mirror, first proposed by B. Folkner (JPL)**
- Originally conceived to evade constraints, we now think it might be chosen even with free line of sight



GRACE rebuild

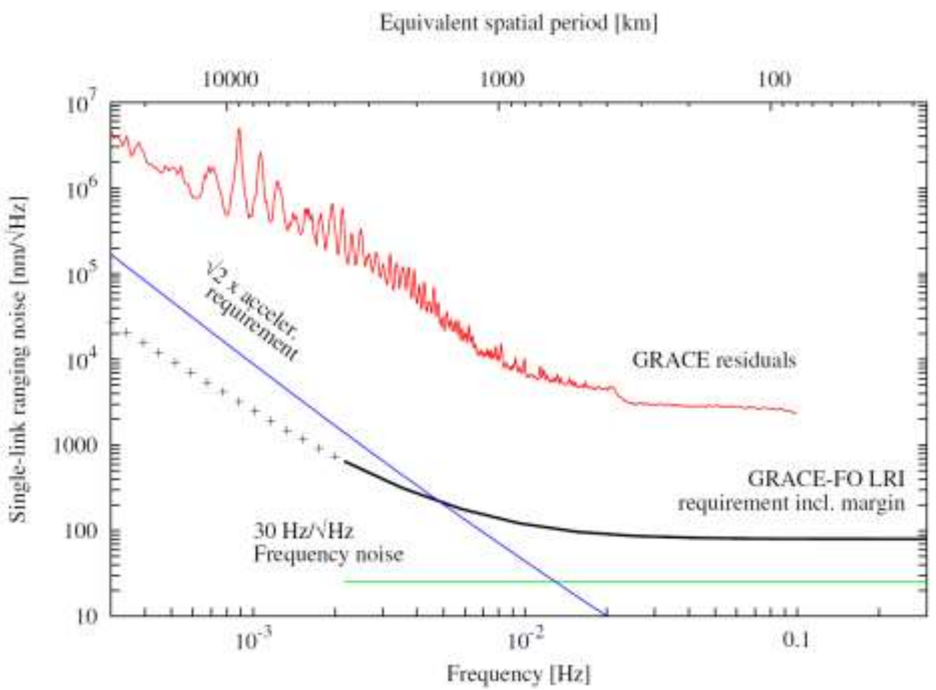
http://www.csr.utexas.ed/grace/gallery

GRACE Follow-On 2016

Airbus/JPL

- Nearly identical rebuild, but many detailed improvements:
  - 3 star cameras (not 2), improved AOCS pointing accuracy
  - Improved thermal insulation
  - Many small changes in subsystems and electronic units
- Same team and operations concept
- Except, of course the new LRI

LRI performance requirement



LISA: 0.01 nm/√Hz ↙

- Final gravity field accuracy limited by other factors (tides, aliasing…)
- Noise budget designed to be not dominant at any frequency
- LRI is conceived as experimental demonstrator
  - Reduced requirements on lifetime and reliability
  - No redundancy
- Aim for reliable long-time operation nevertheless

LRI Laser ranging noise sources

- Laser frequency noise (requirement 30 Hz/√Hz, like LISA)
  - Reference cavity on one spacecraft, offset phase lock on second spacecraft
- Pointing jitter
  - Beam steering mechanism and special properties of triple mirror
- Thermally driven effects
  - Mitigate with appropriate material choice, thermal shielding and control
- Readout noise (important for acquisition):
  - USO noise
  - Shot noise
  - Laser power noise
  - Photodetector electronic noise
  - Parasitic signals (e.g. scattered light and electronic cross-talk)
  - ADC quantization noise
  - Spurious electronic phaseshifts

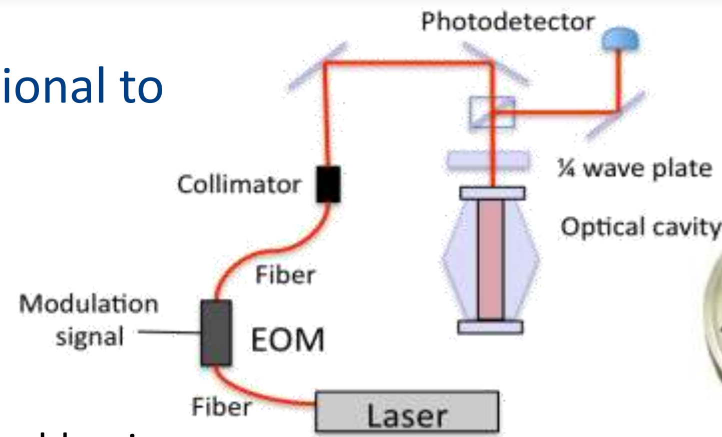
Laser frequency stabilisation

- Frequency noise coupling proportional to arm-length mismatch:

$$\delta x = \Delta L \frac{\delta \nu}{\nu}$$

- Stabilisation is required
  - LISA tricks (armlocking, TDI) not applicable, since there is only one link (“arm”)
  - Space qualified reference cavity developed by Ball Aerospace and tested at JPL
  - Even with stabilisation laser frequency noise will be a significant component of error budget
- **Performance significantly better than 30 Hz/√(Hz), sufficient for LISA**
- Similar efforts ongoing in Europe

See talk by Bill Klipstein



JPL Ball

W. M. Folkner et al., *“Laser Frequency Stabilization for GRACE-2”*, Proc. ESTF 2011.

Laser Ranging Interferometer

- Elegant and efficient beam steering that aligns both TX and RX with a single steering mirror that is outside of the sensitive path
- Measurement is exactly the round-trip distance, insensitive to paths on optical bench

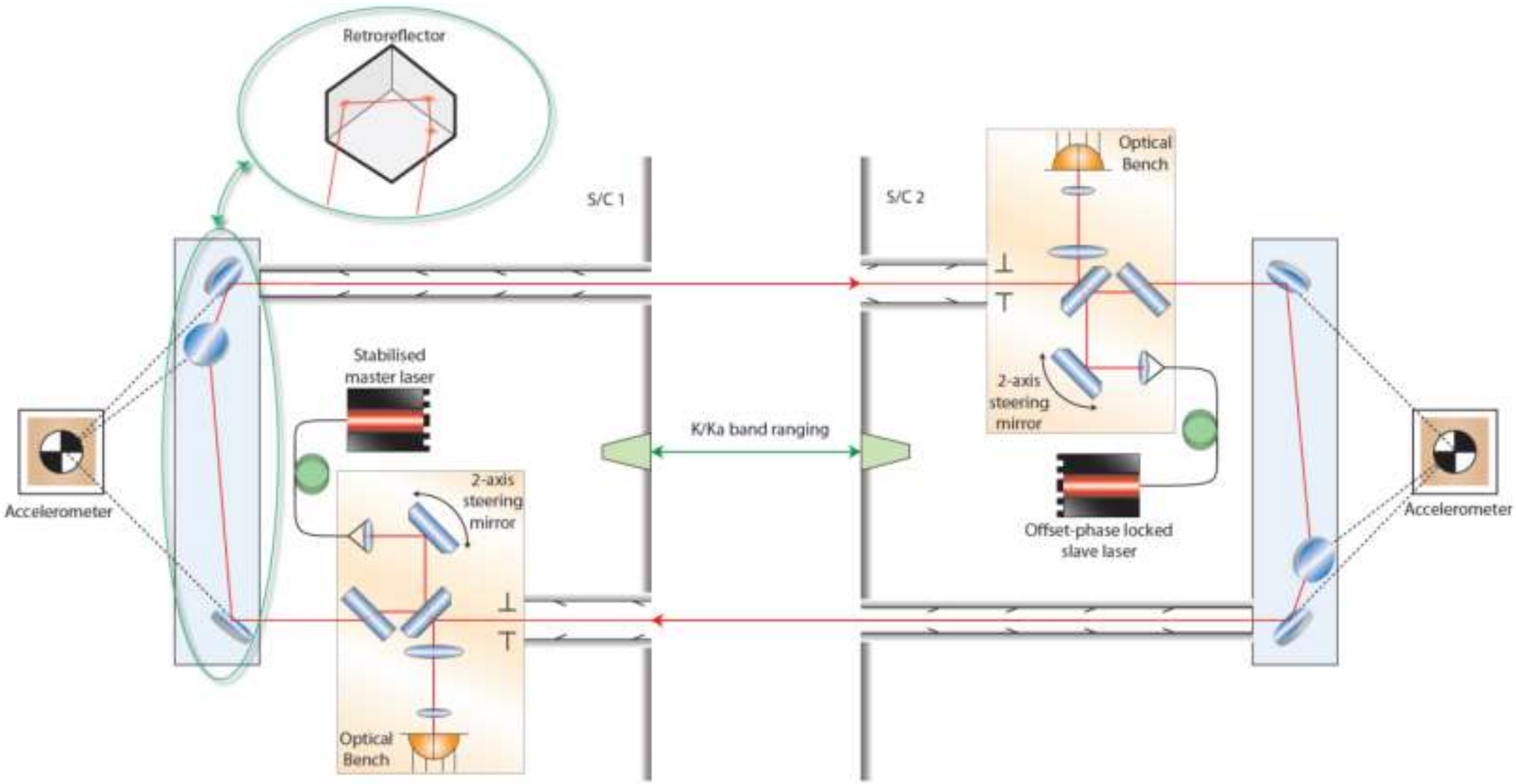
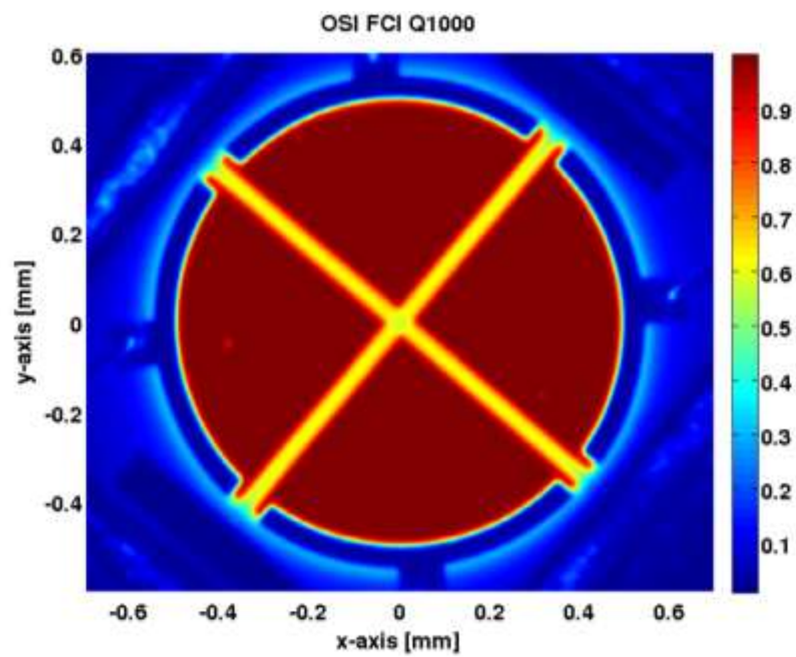


Image © Springer, from: Sheard et al. *"Intersatellite laser ranging instrument for the GRACE follow-on mission"*, Journal of Geodesy, 2012 (DOI: 10.1007/s00190-012-0566-3).

Photoreceivers

- Critical part for both LISA and GRACE-Follow on with similar key requirements:
- input current noise, bandwidth, phase stability
- LRI Photoreceivers contributed by DLR Adlershof

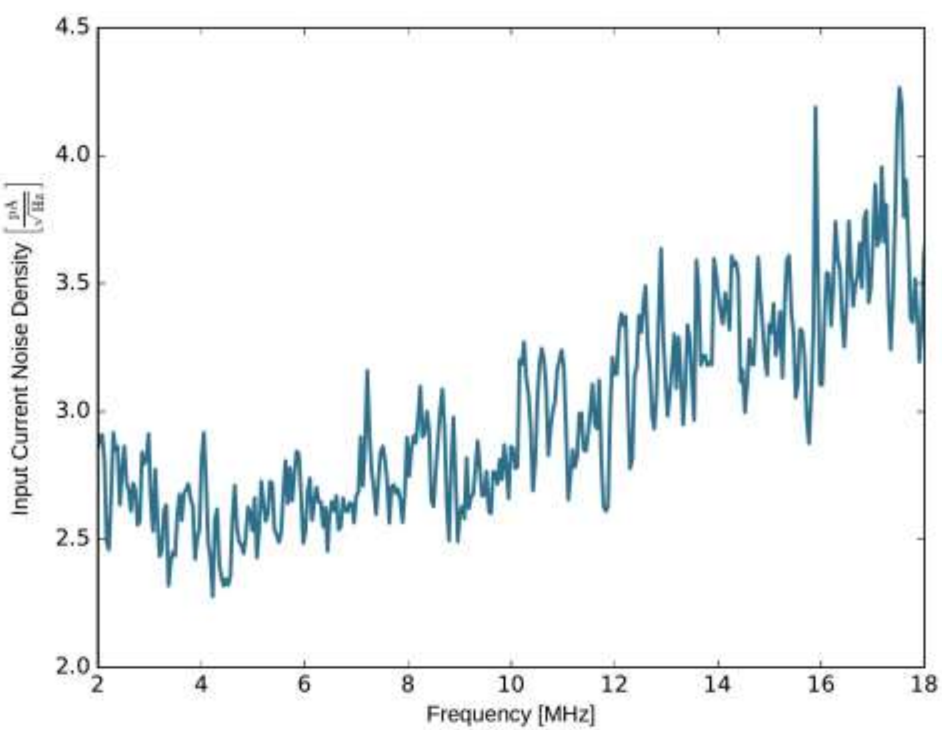


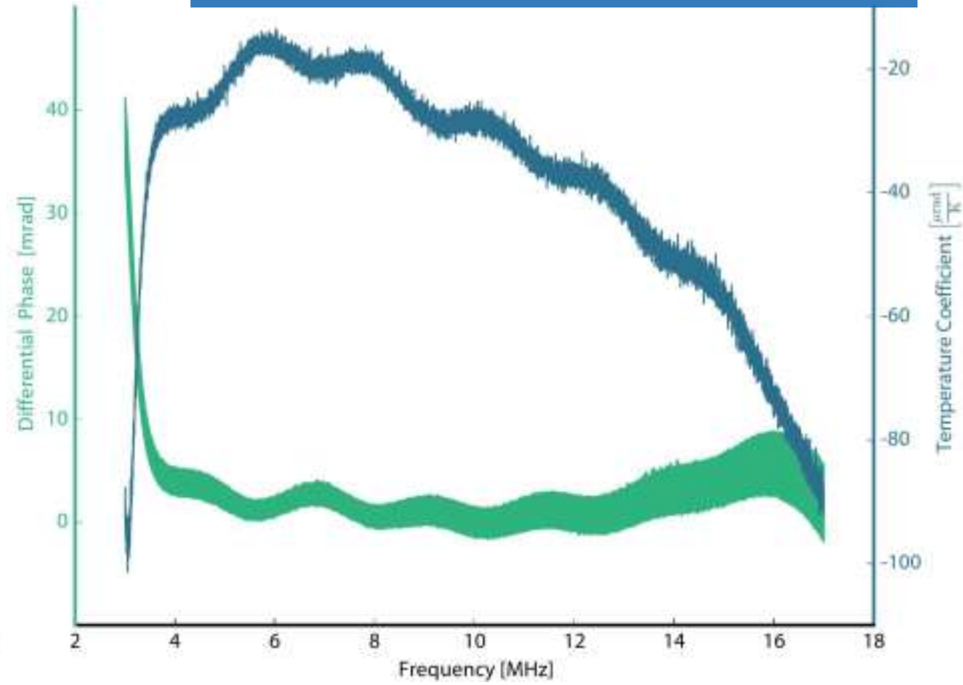
See poster by German Fernandez Barranco

Photoreceivers

- LRI Photoreceivers nearly fulfill LISA requirements:
  - bandwidth 18 MHz → 25 MHz
  - Noise <2pA/sqrt(Hz) desirable
  - Larger area with same electrical properties desirable
  - Temperature dependence is probably ok even for LISA

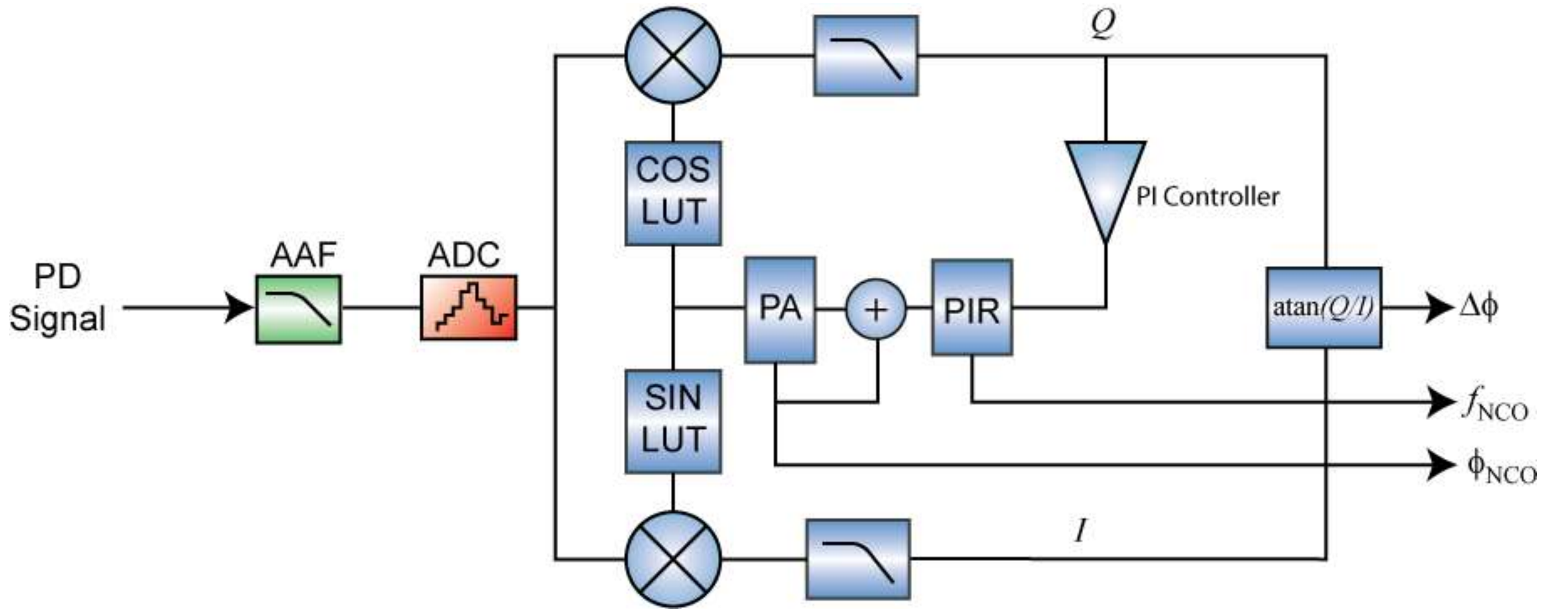
See poster by German Fernandez Barranco





LRI Phasemeter

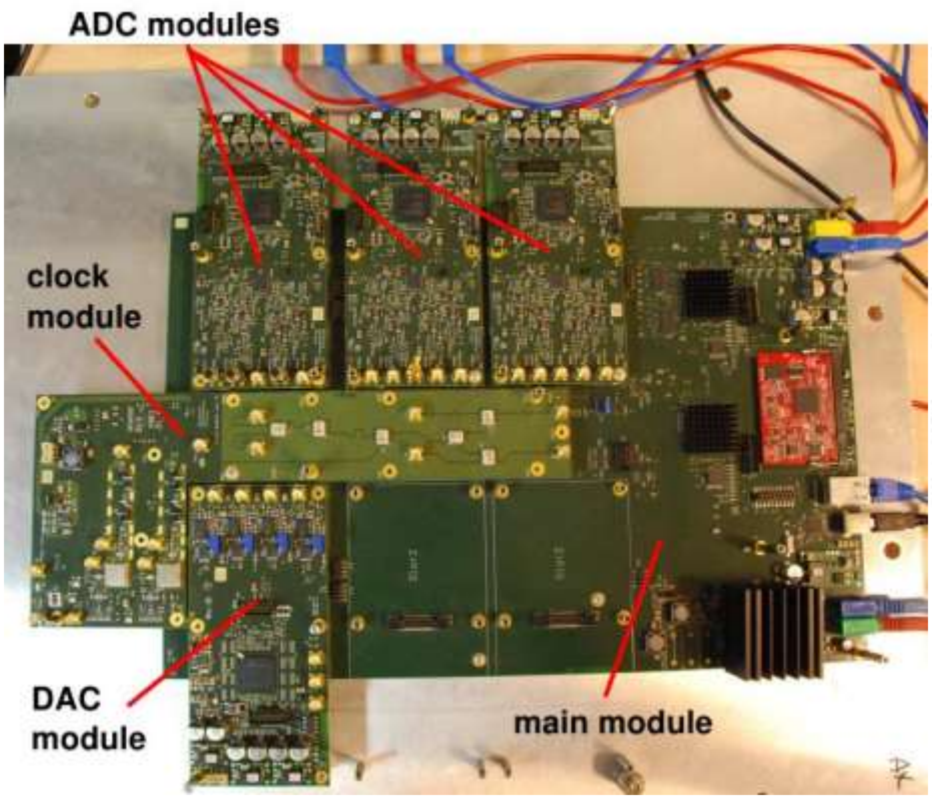
- Derived from LISA Phasemeter work at JPL, built by JPL.
- Frequency range 4…16 MHz
- Architecture: **Digital PLL**
- Fast ADC samples beatnote, servo makes NCO (numerically controlled oscillator) track the input
- Output is digital phase and frequency of NCO

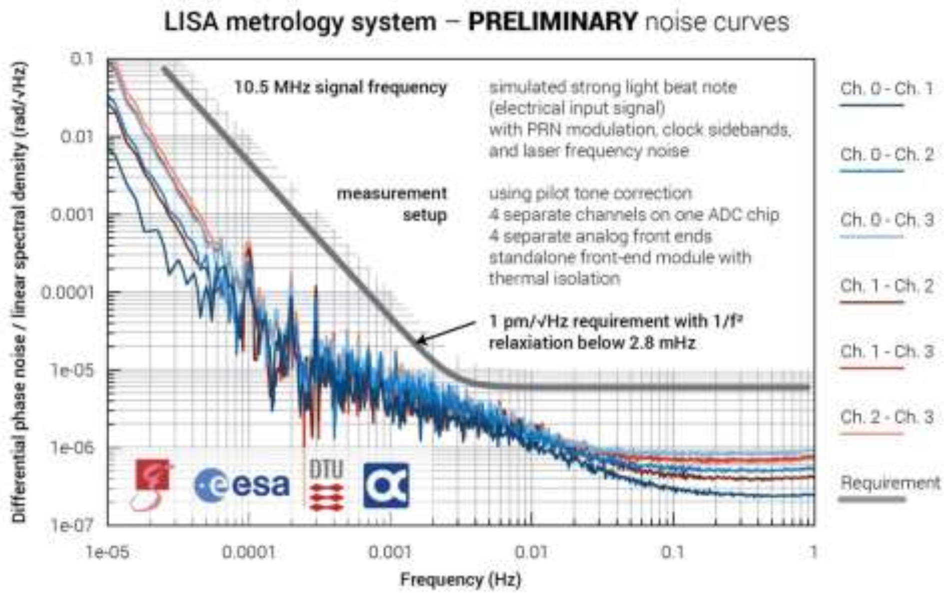


See talk by Bill Klipstein

D/DK Phasemeter for LISA

- ESA contract (AEI with Danish partners), independent development
- Has delivered LISA phasemeter with full performance and all functions
- Includes extra functions for:
  clock distribution, absolute ranging, clock transfer, data transfer (*)
- Next step: thermal management and development into flight hardware



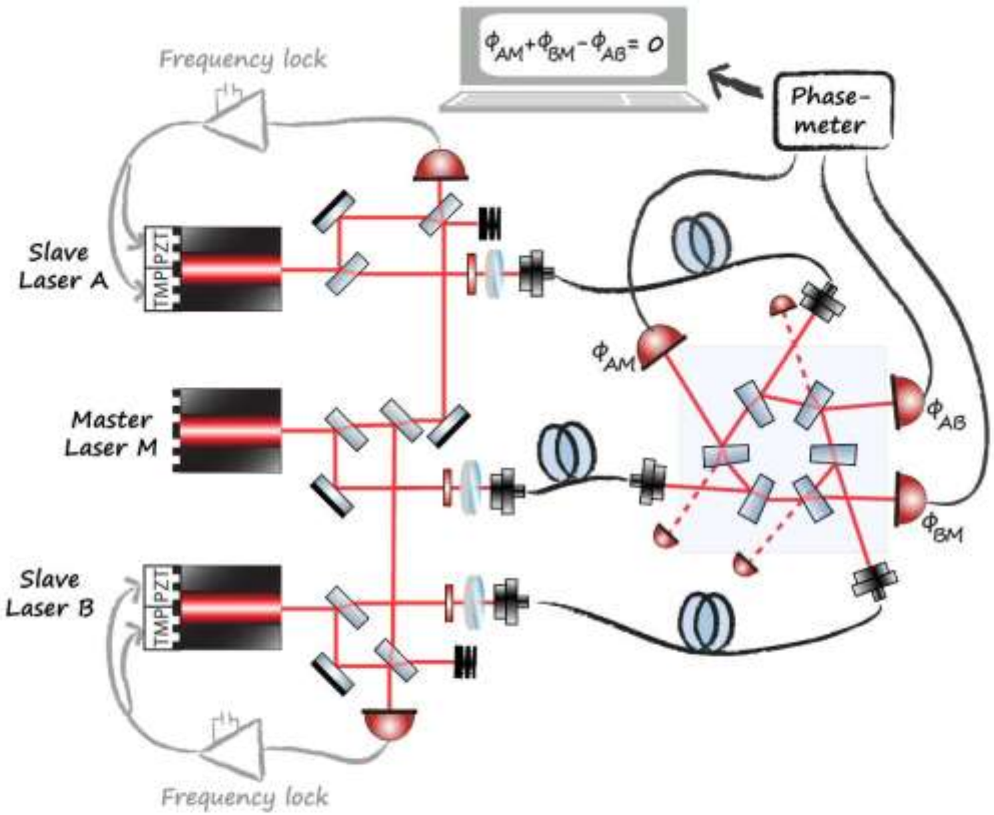


See talk by Thomas Schwarze
See poster by Daniel Penkert

* Delgado et al 2009

Optical phasemeter test for LISA

- Create 3 signals with a+b+c=0, with arbitrary dynamics
- Has been done digitally, our setup is first optical test (full chain)
- Can also test TDI with 3 independent phasemeters
- Status: noise hunting approaching requirements



See talk by Thomas Schwarze
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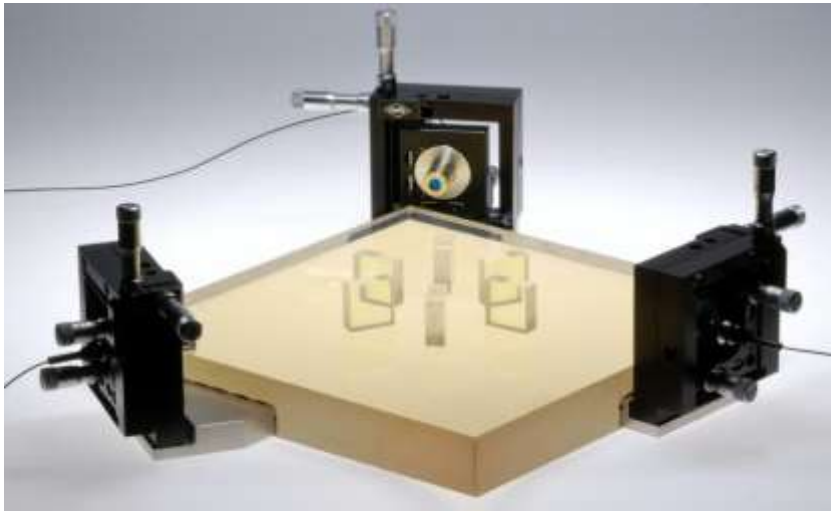
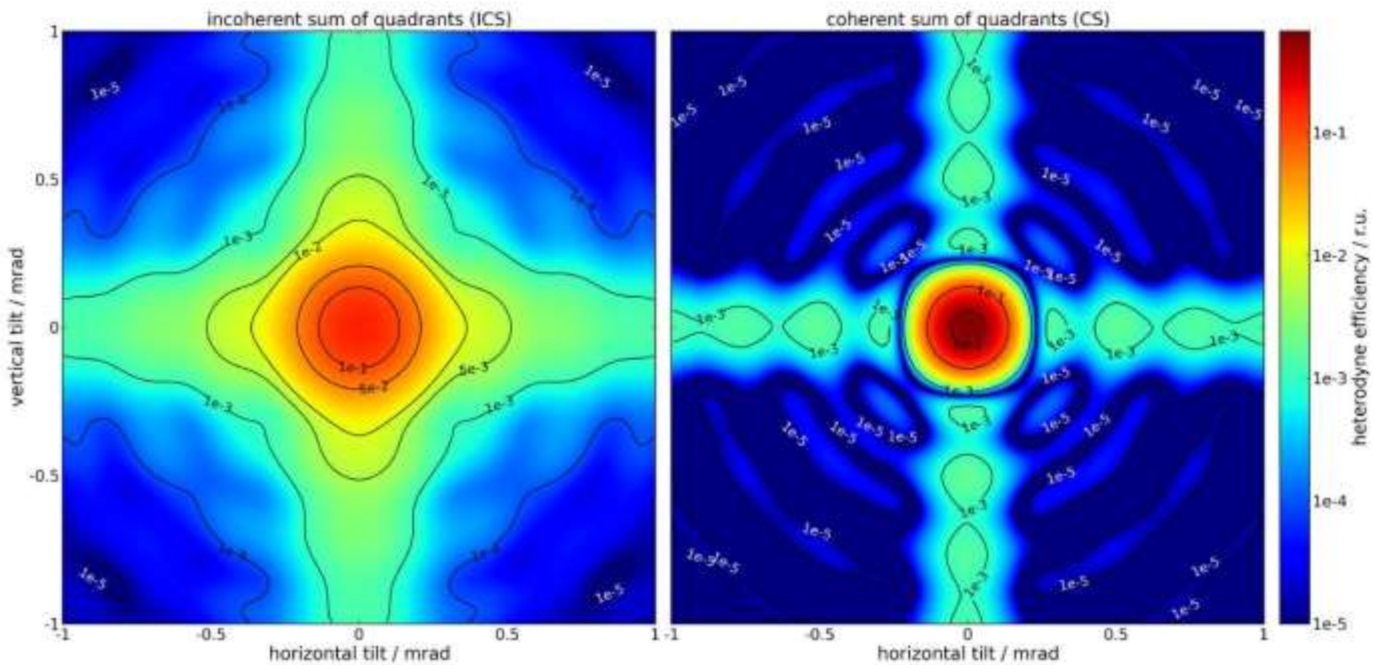
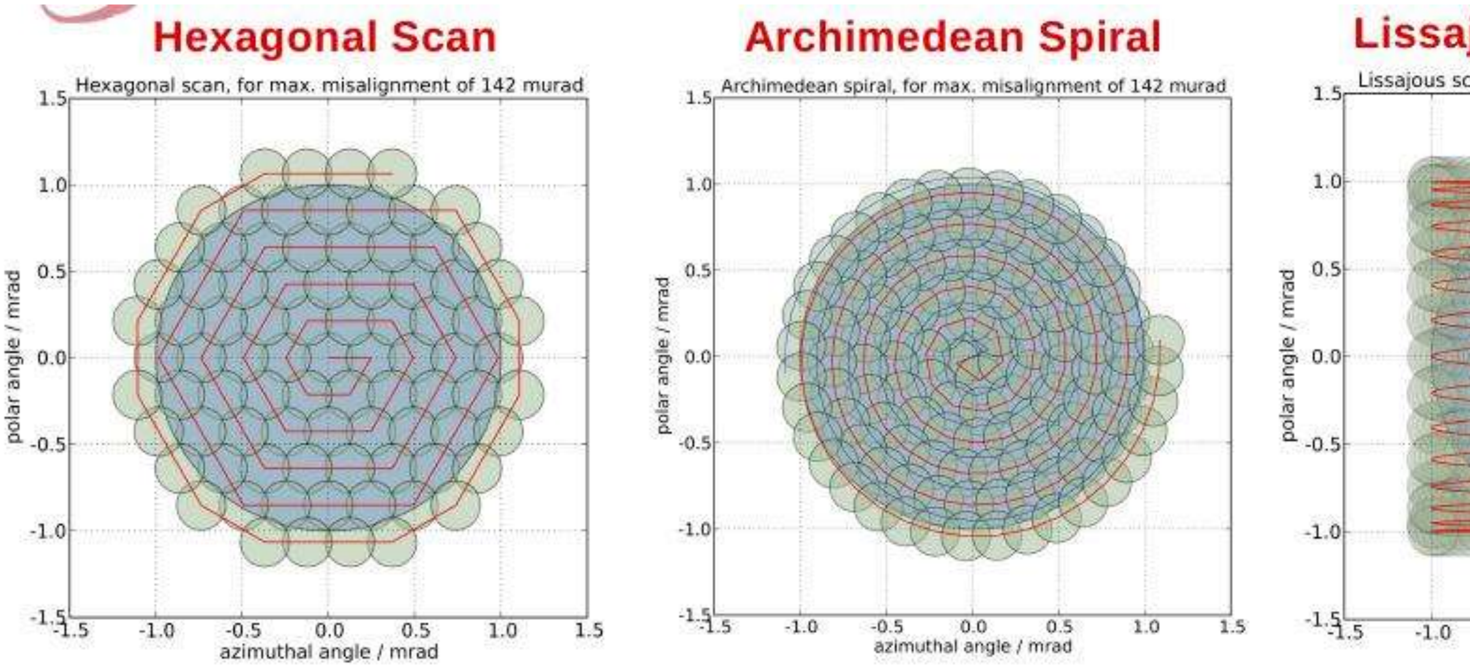


LRI Link acquisition

- Large initial pointing uncertainty must be calibrated
- Later reacquisition has smaller range but must be autonomuous
- detailed simulations and experiments (AEI, JPL, ANU) have led to reliable algorithms now implemented in LRI flight models



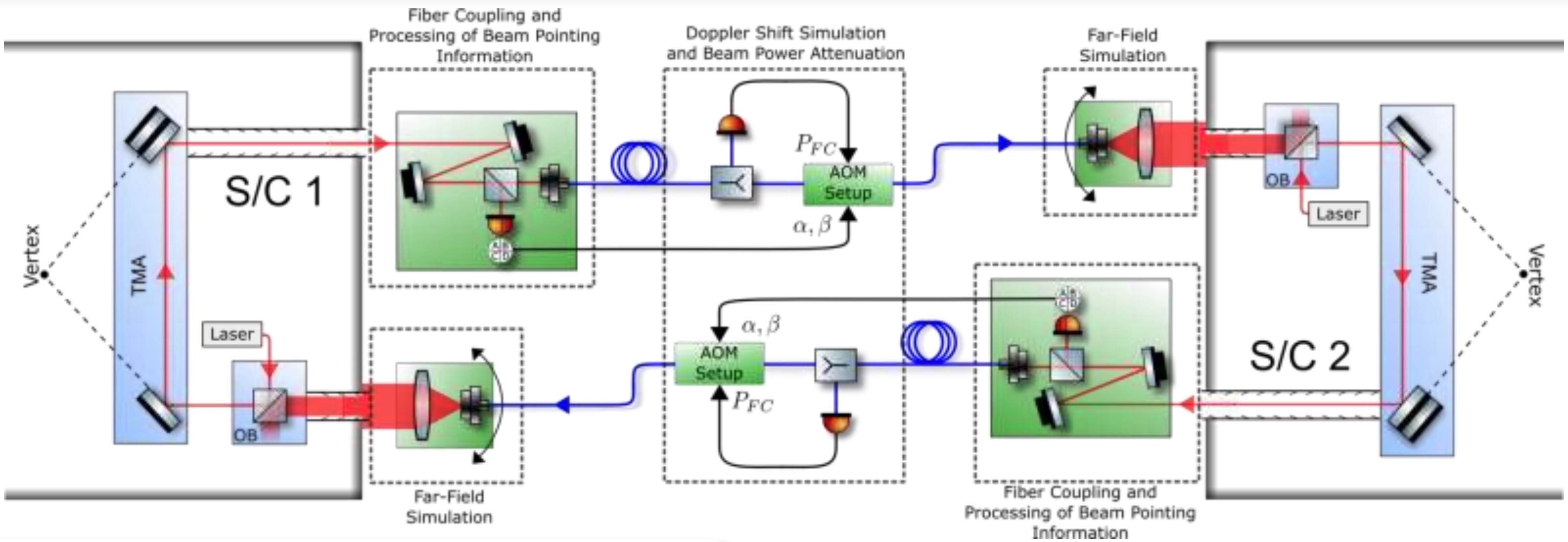
LRI Acquisition etc.



Many details we learned in the LRI development are useful for LISA:

- Acquisition algorithm development and test
- Optical simulations
- Characterization of near-Gaussian beams
- Generation of flat-top beams
- Precise control of hexapods and steering mirrors

Laser Link Simulator for LRI



Processing of the Transmitted Beam

- Launch light into fiber
- Measure / process beam angle + power
- Simulate tilt of local spacecraft

Frequency Shifts & Attenuation

- Simulate Doppler shifts
- Attenuate beam power (mW → pW)

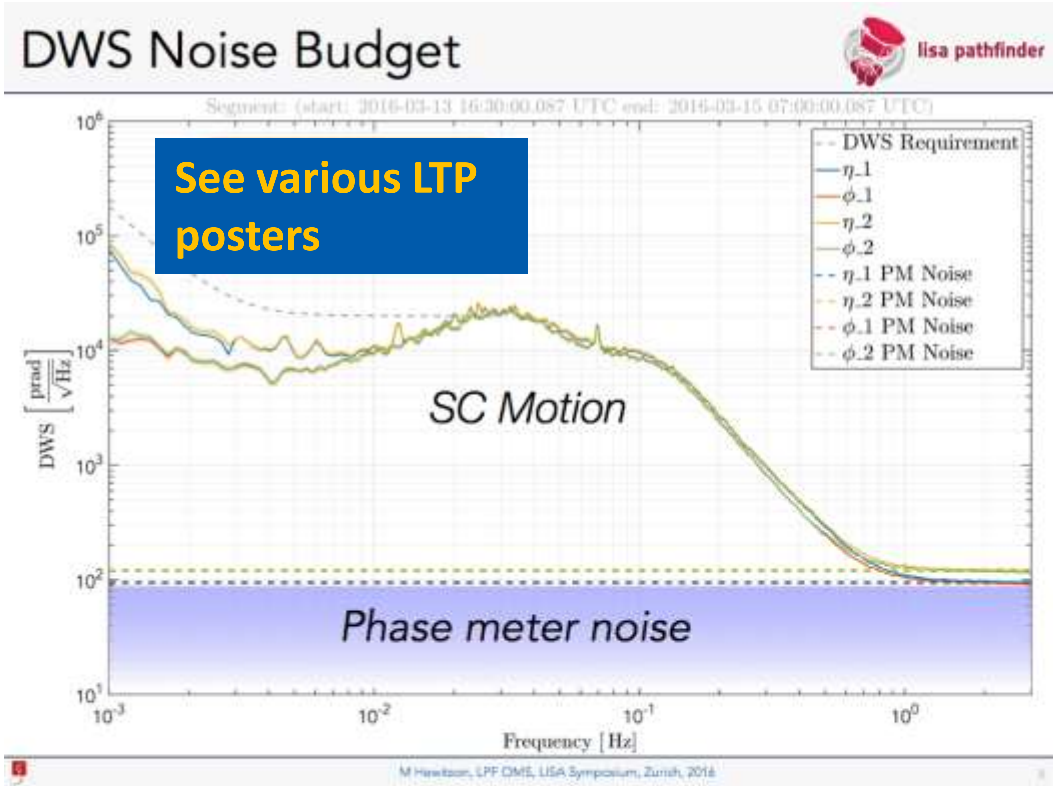
Received Beam Generation

- Create beam with flat wavefront & homogeneous intensity profile (on ~1cm aperture)
- Simulate tilt of local spacecraft

Contributed to LRI by DLR Bremen with AEI support

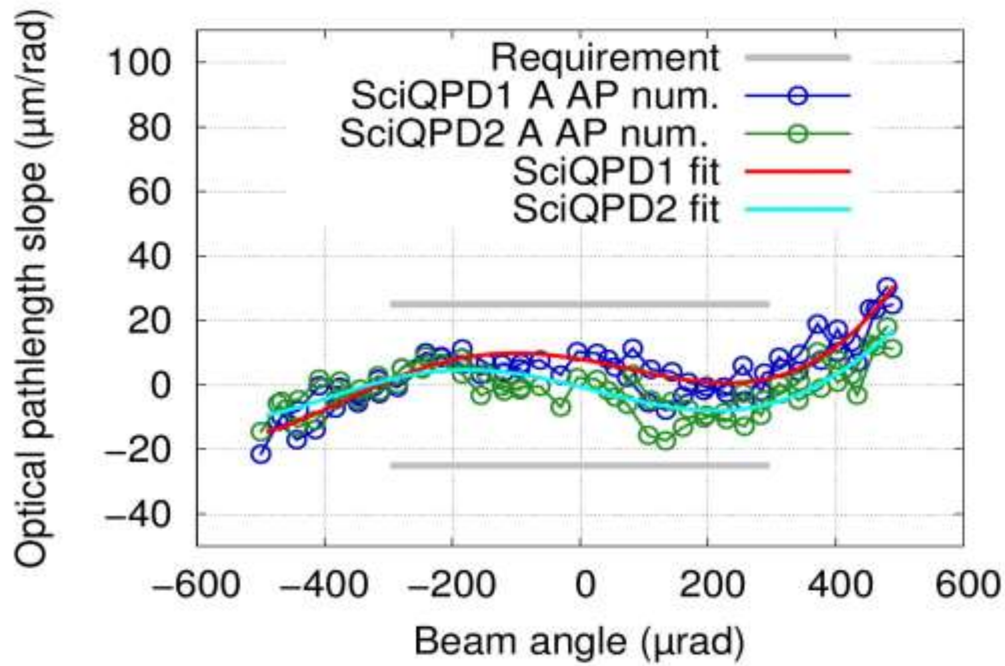
Similar equipment will be very useful for LISA development

LISA Pathfinder heritage

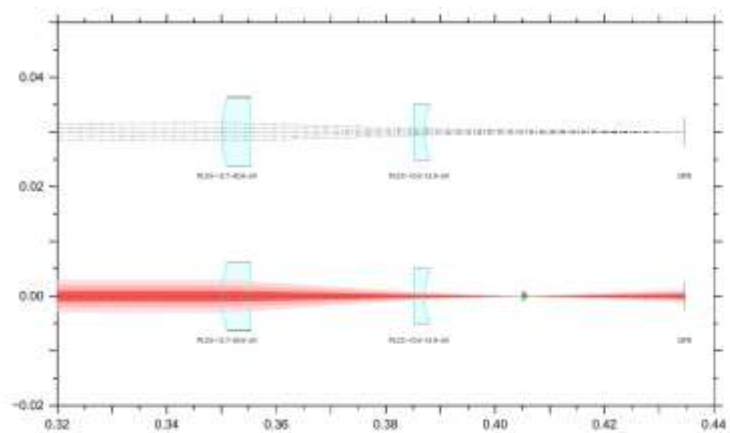


- We understand the local interferometer at the 30 fm/sqrt(Hz) / 100 prad/sqrt(Hz) level.
- We have learned many details, e.g. about:
  - tilt-to-length coupling and its subtraction,
  - RIN at twice the heterodyne frequency,
  - the impact of operating unsynchronized instruments.

Imaging systems on Optical Bench

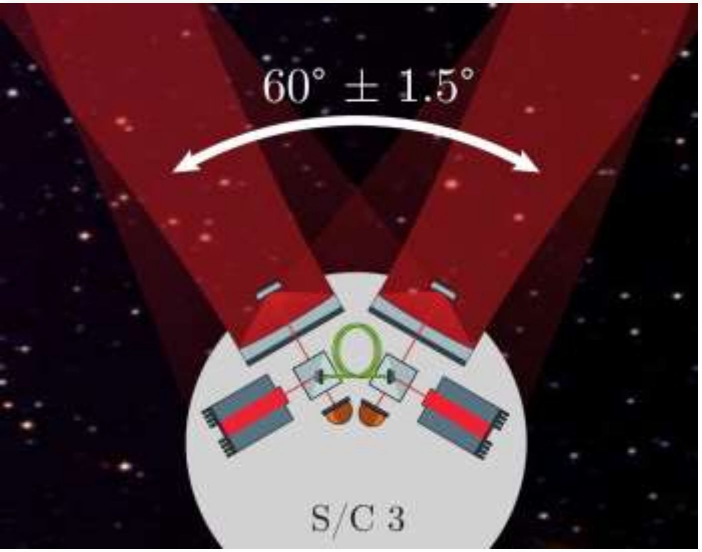


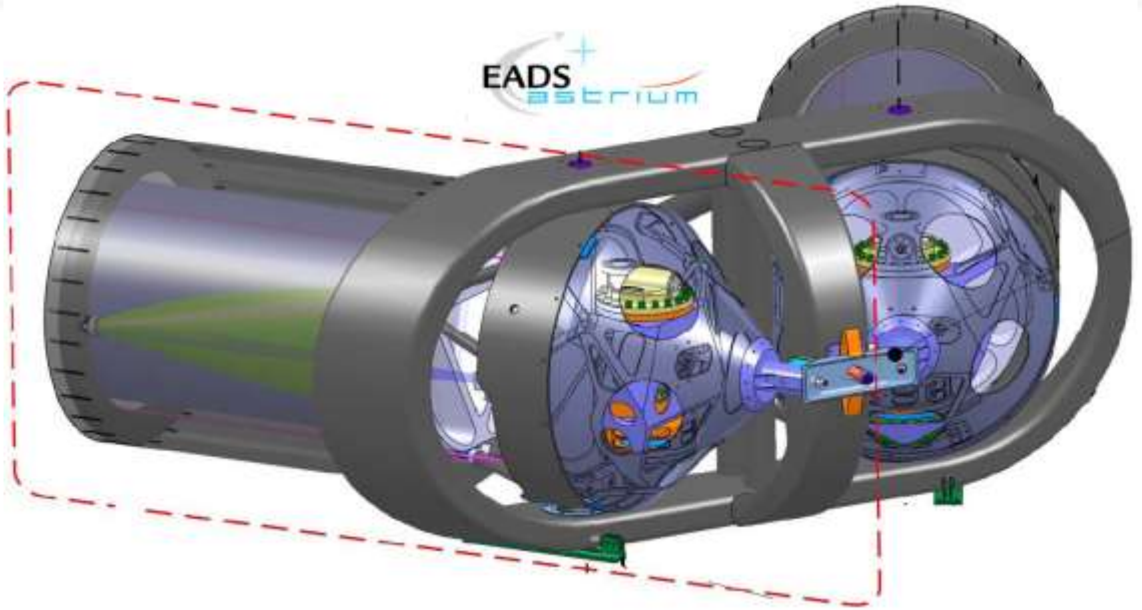
- ESA contract with Airbus, Glasgow and AEI concluded in 2016
- Use of realistic „flat-top“ beams instead of benign Gaussian beams
- Coupling requirements fulfilled for 2-lens and 4-lens imaging systems.



See poster by Maike Lieser

Breathing angle





2 separate optical benches with one test mass each:

+ narrow field of view sufficient
+ actuator errors not in optical path measurement
– backlink fiber necessary

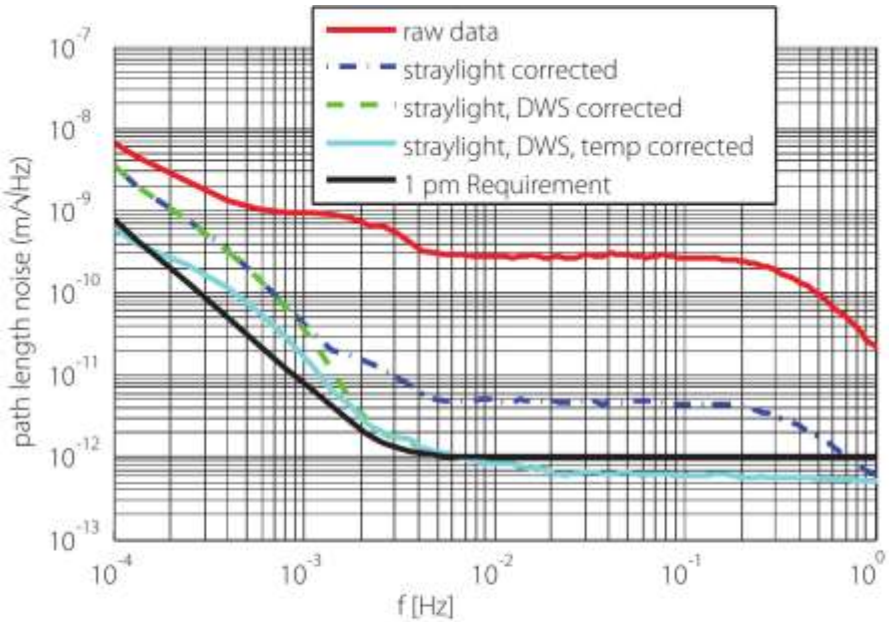
See talk by Katharina Isleif

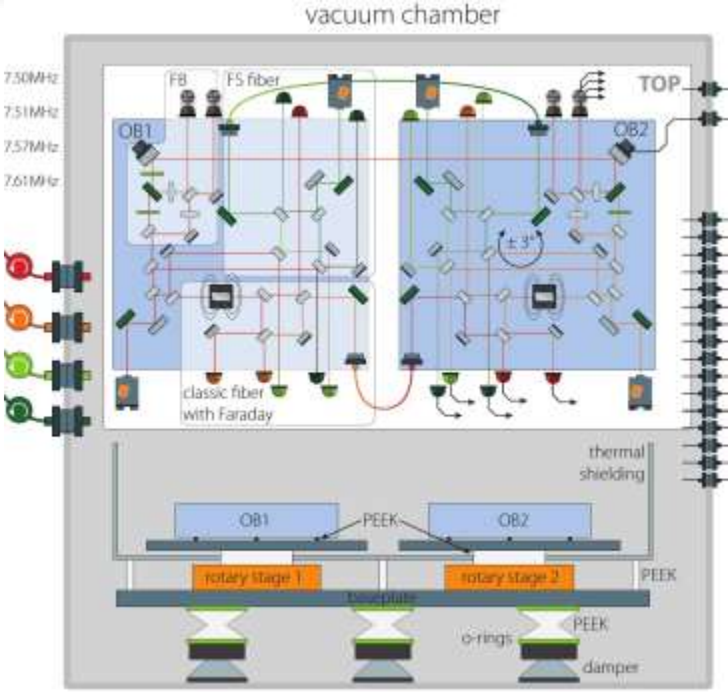
Alternative: single optical bench with wide-range pointer:

+ can be smaller, lighter
+ would allow single test mass
+ no backlink fiber
– telescope needs wide field of view
– actuator with ≥ ±30° range in optical path

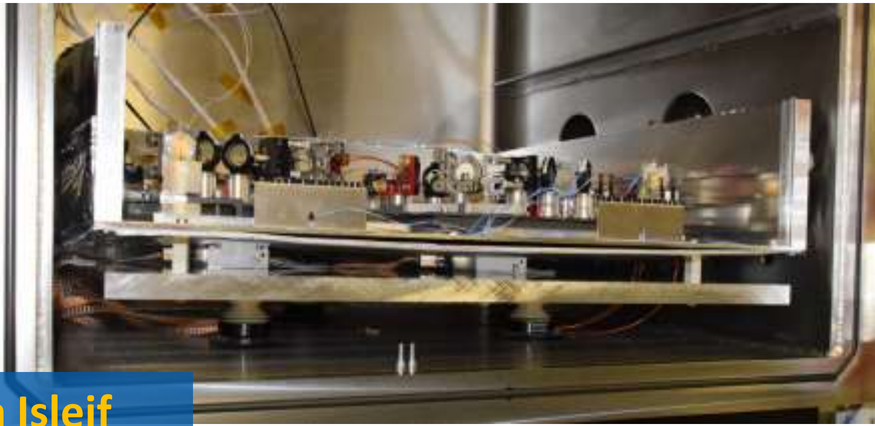
See poster by Christina Brugger
See talk by Jeff Livas

Backlink



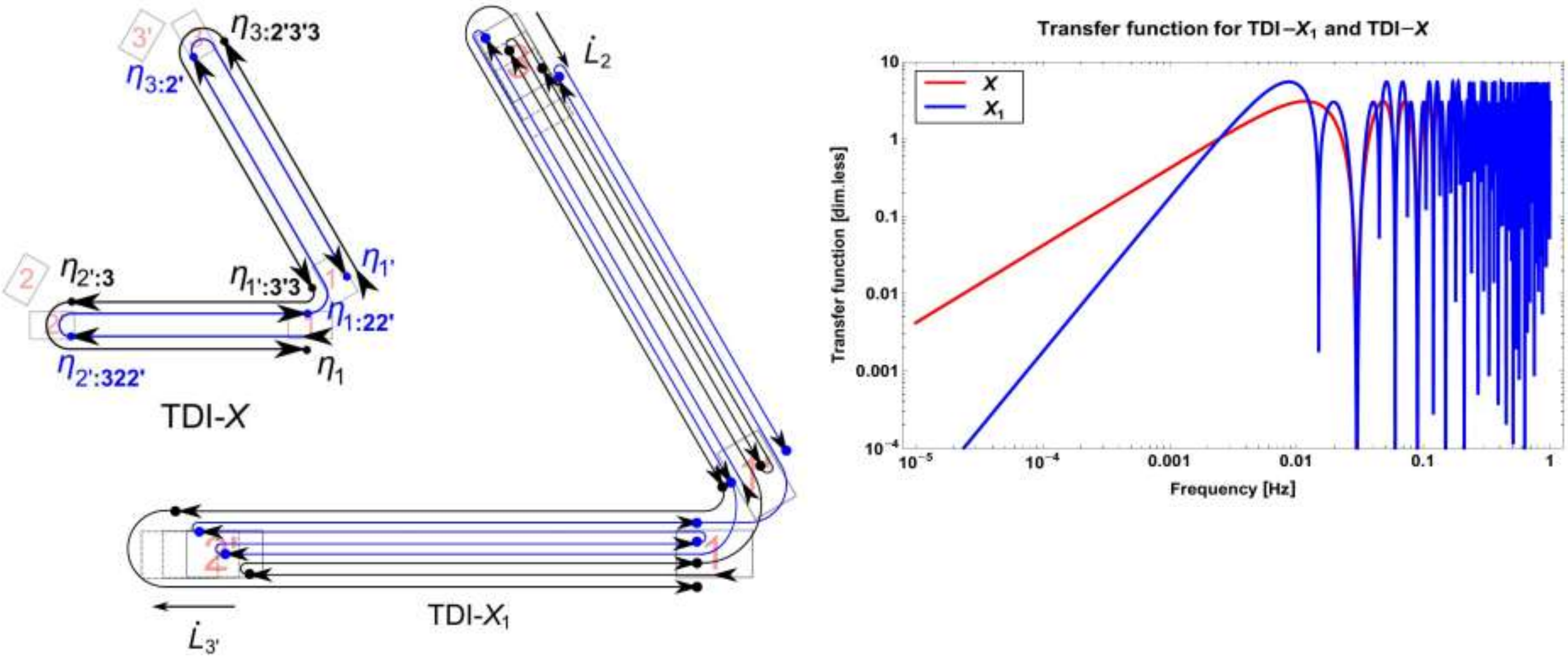


- Earlier Experiments showed that fiber backlink works but only with huge effort and balanced photoreceivers
- New experiment ongoing to compare 3 different methods
- Alternative „in-field pointing“ uner investigation at Airbus



See talk by Katharina Isleif

TDI for LISA



- TDI is essential to remove frequency noise in postprocessing
- Based on pioneering work at JPL (Tinto et al 1999...)
- 2nd generation necessary for moving spacecraft
- Complicated transfer function for GW signal

TDI noise propagation

$$
\begin{aligned}
X_1 \;=\;& \eta_{1'} + \eta_{3;\mathbf{2'}} + \eta_{1;\mathbf{22'}} + \eta_{2';\mathbf{322'}} + \eta_{1;\mathbf{3'322'}} + \eta_{2';\mathbf{33'322'}} \\
&+\eta_{1';\mathbf{3'33'322'}} + \eta_{3;\mathbf{2'3'33'322'}} - \eta_1 - \eta_{2';\mathbf{3}} - \eta_{1';\mathbf{3'3}} - \eta_{3;\mathbf{2'3'3}} \\
&-\eta_{1';\mathbf{22'3'3}} - \eta_{3;\mathbf{2'22'3'3}} - \eta_{1;\mathbf{22'22'3'3}} - \eta_{2';\mathbf{322'22'3'3}} \,.
\end{aligned}
$$

η: result of preprocessing, combination of multiple phasemeter channels

Multiple nested delay operators

- Many phasemeter readings are combined in final X combination
- Noise sources may have different transfer function from GW signal
- Noise sources have different correlation properties (i.e. Local oscillator RIN is correlated between local interferometers, shot noise is not)
- LISA simulation working group is addressing these questions

See talk by Antoine Petiteau
See poster by Henri Inchauspe

Interferometry summary

	LTP	*GRACE Follow-On LRI*	*LISA test mass*	*LISA long arm*
Separation	40cm	**270km**	<1m	Mio km
Meas. beam	1 mW Gaussian	**100 pW flat-top**	1 mW Gaussian	100 pW flat-top
Meas. band	**mHz-Hz**	**mHz-Hz**	mHz-Hz	
Het. Frequency	1 kHz, fixed	**4-16 MHz, variable**	3-20 MHz, variable	
Interferometer principle	**Heterodyne Mach-Zehnder with local Reference ifo**	**Offset phase-locked transponder**	Heterodyne Mach-Zehnder with local Reference ifo	Offset phase-locked transponder
Phasemeter	SBDFT	**DPLL**	DPLL	DPLL ***with extra functions***
Modulators	AOM @ 80MHz	EOM for cavity	—	***EOM @ 2 GHz***
Frequency stability req.	> kHz/sqrt(Hz)	**30 Hz/sqrt(Hz)**	> kHz/sqrt(Hz)	30 Hz/sqrt(Hz)
Laser	30 mW Nd:YAG	30 mW Nd:YAG	Few mW, part of TX laser	***few W***
Photoreceiver	5mm InGaAs QPD, kHz operation, no special noise req.	**1mm InGaAs QPD, MHz operation, 3...4 pA/sqrt(Hz)**	1mm InGaAs QPD, MHz operation, no special noise req.	1mm InGaAs QPD, MHz operation, 2...3 pA/sqrt(Hz)
Optical Bench	**Complex, ultra-stable**	Simple, metal	Complex, ultra-stable	
Imaging Systems	—	**2-lens**	None / 2...4-lens	2...4-lens
Telescope	—	—	—	***20...25cm***
Ifo noise	**35 fm/sqrt(Hz)**	80 nm/sqrt(Hz)	some pm/sqrt(Hz)	
Ifo pointing control	**DFACS of test mass**	Steering mirror (not in meas. path)	DFACS of test mass	***DFACS of S/C and backlink or in-field pointing***
Data processing	**In DMU/OBC for DFACS**	on ground (LTPDA)	In OBC for DFACS, ***on ground for science (TDI)***	
Link acquisition	**One TM after the other**	**5 DOF simultaneously**	One TM after the other	5 DOF simultaneously