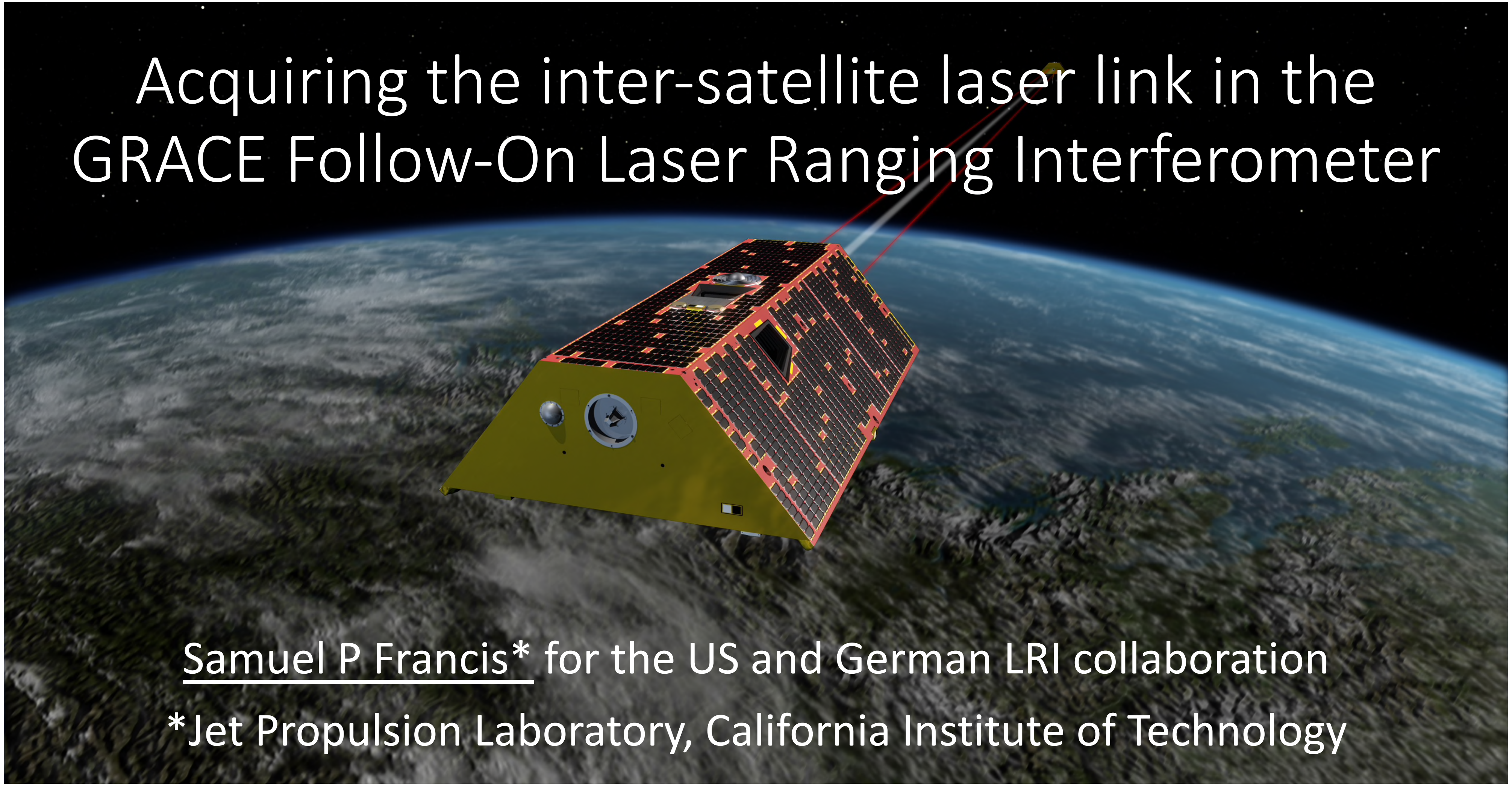
Acquiring the inter-satellite laser link in the GRACE Follow-On Laser Ranging Interferometer



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GRACE and GRACE Follow-On

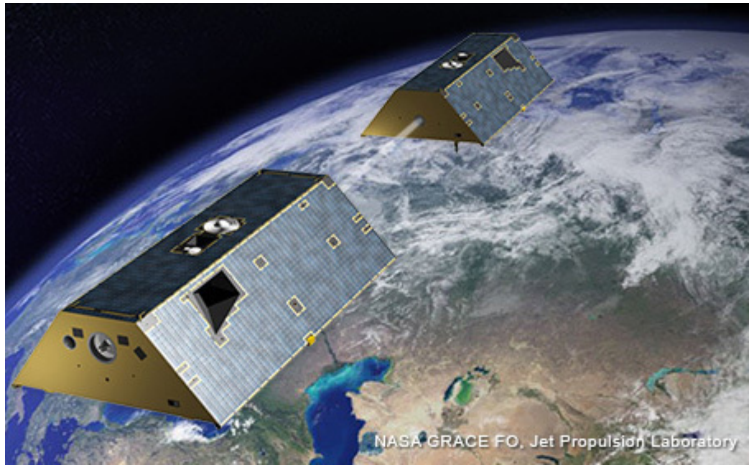
Jet Propulsion Laboratory
California Institute of Technology

- **Gravity Recovery and Climate Experiment GRACE (since 2002 to 2017):**
  - NASA/German Research Centre for Geosciences (GFZ) partnership
  - 220 km separation measurement of 2 spacecraft by dual microwave links
  - Spacecraft separation + location (GPS) yield orbit

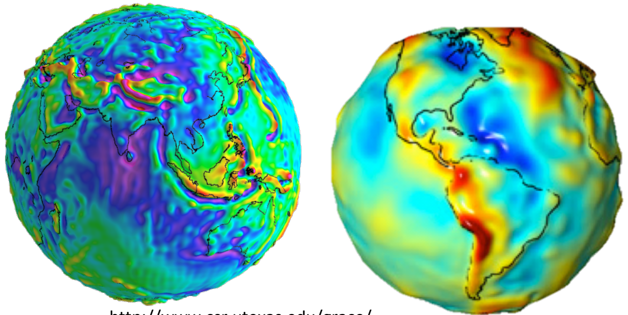
    Orbit determines gravity map
  - Gravity map evolution over months and years

    Insight into earth systems & effects of climate change

    Really impressive science!



- **GRACE Follow-On (Launched May 22, 2018) will continue science**
  - Microwave Ranging Instrument (MWI) and Accelerometer similar to GRACE
  - ***Tech-Demo for All-Optical GRACE*** : *Laser Ranging Interferometer (LRI)*
    First inter-spacecraft interferometer
  - ***Long running development Astrophysics (LISA) and Earth Science (GRACE 2) funding***



http://www.csr.utexas.edu/grace/

Laser Ranging Interferometer

The GRACE Follow-On Laser Ranging Interferometer (LRI) is a partnership between the US and Germany

US: Stabilized laser and Metrology

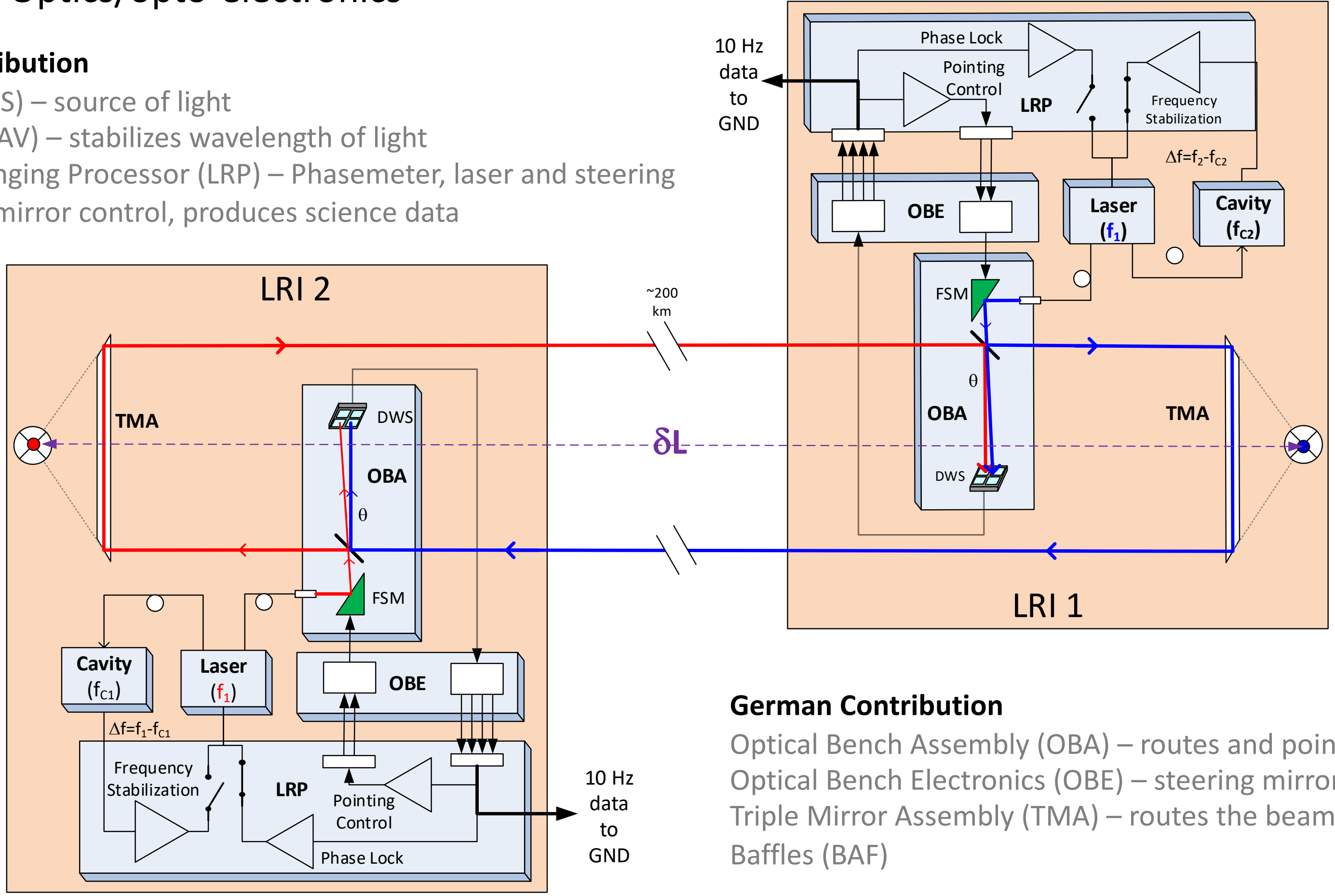
Germany: Optics/opto-electronics

US contribution

Laser (LAS) – source of light

Cavity (CAV) – stabilizes wavelength of light

Laser Ranging Processor (LRP) – Phasemeter, laser and steering mirror control, produces science data



German Contribution

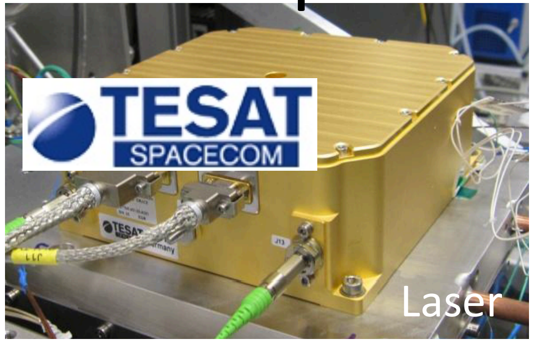
Optical Bench Assembly (OBA) – routes and points the beam

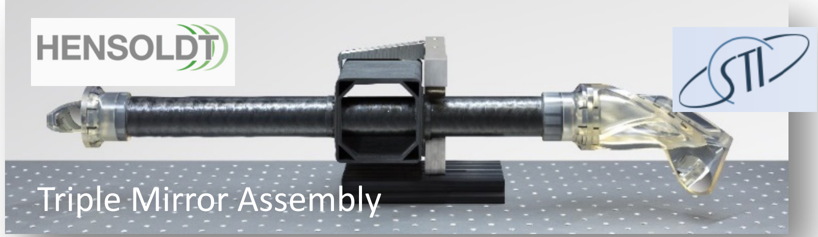
Optical Bench Electronics (OBE) – steering mirror & detector drivers

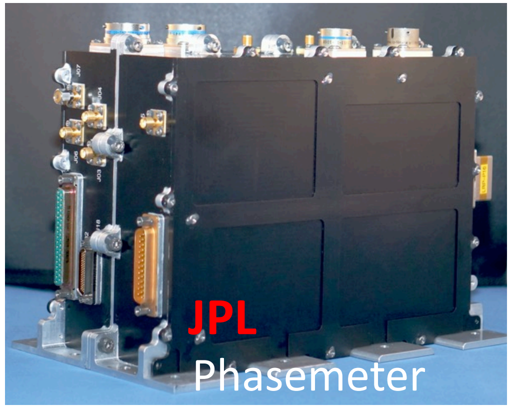
Triple Mirror Assembly (TMA) – routes the beam around MWI

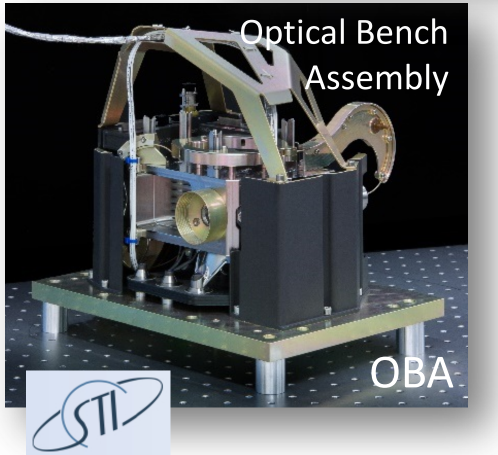
Baffles (BAF)

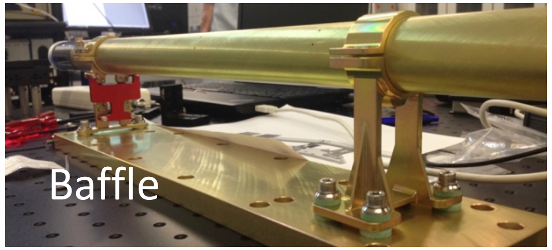
LRI Flight Components

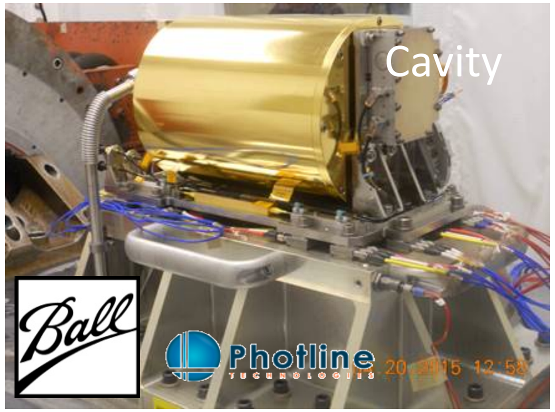












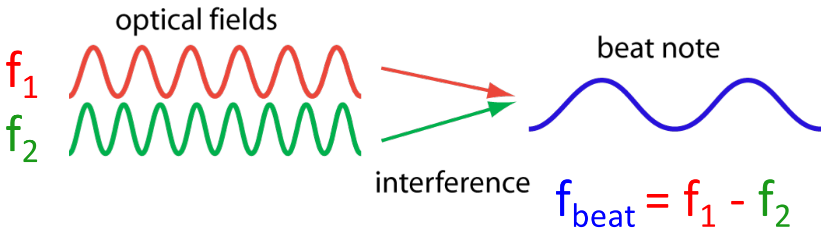
Cables not shown (complete):
LRP-CAV: power, coax (x2)
LRP-LAS: power, cmd/tel
LRP-USO: coax (x2)
OBE-LRP: coax (x4), cmd/tel
OBE-OBA: Tel, power

LRI Phasemeter

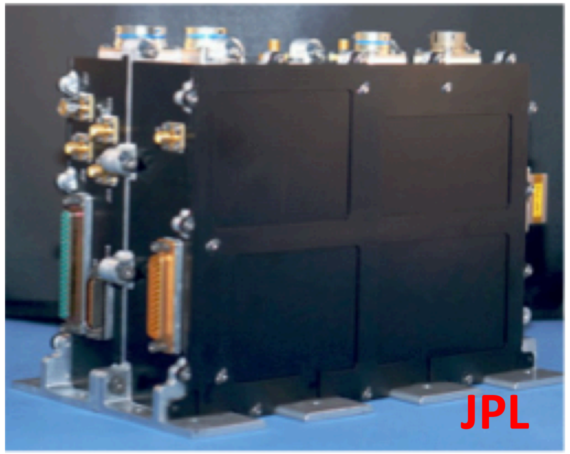
- The Laser Ranging Processor implements the LISA phase tracking and frequency control algorithms, including:
- Phase tracking
- Differential wavefront sensing (and control)
- Laser Phase Locking
- Laser frequency stabilization

LRP developed at JPL, based on the LISA Phasemeter

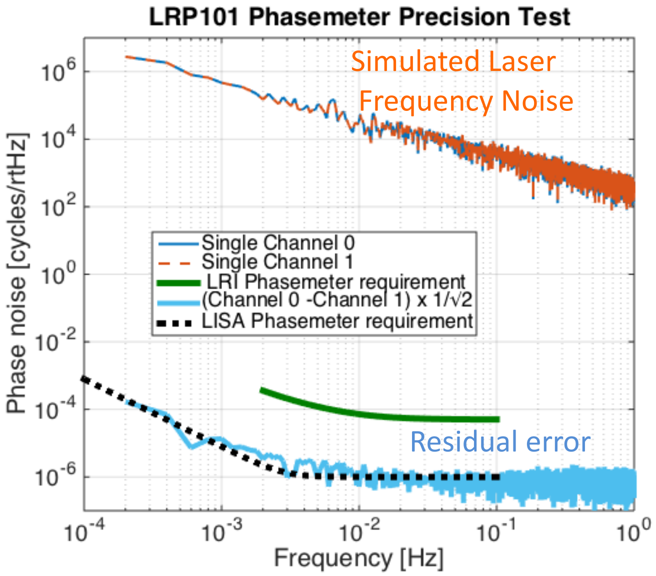
- Has only 4 input channels (vs 34 for LISA)
- Relaxed precision requirement, but ~ LISA performance



The phasemeter measures the science signal as a mHz phase modulation on a MHz beat signal.

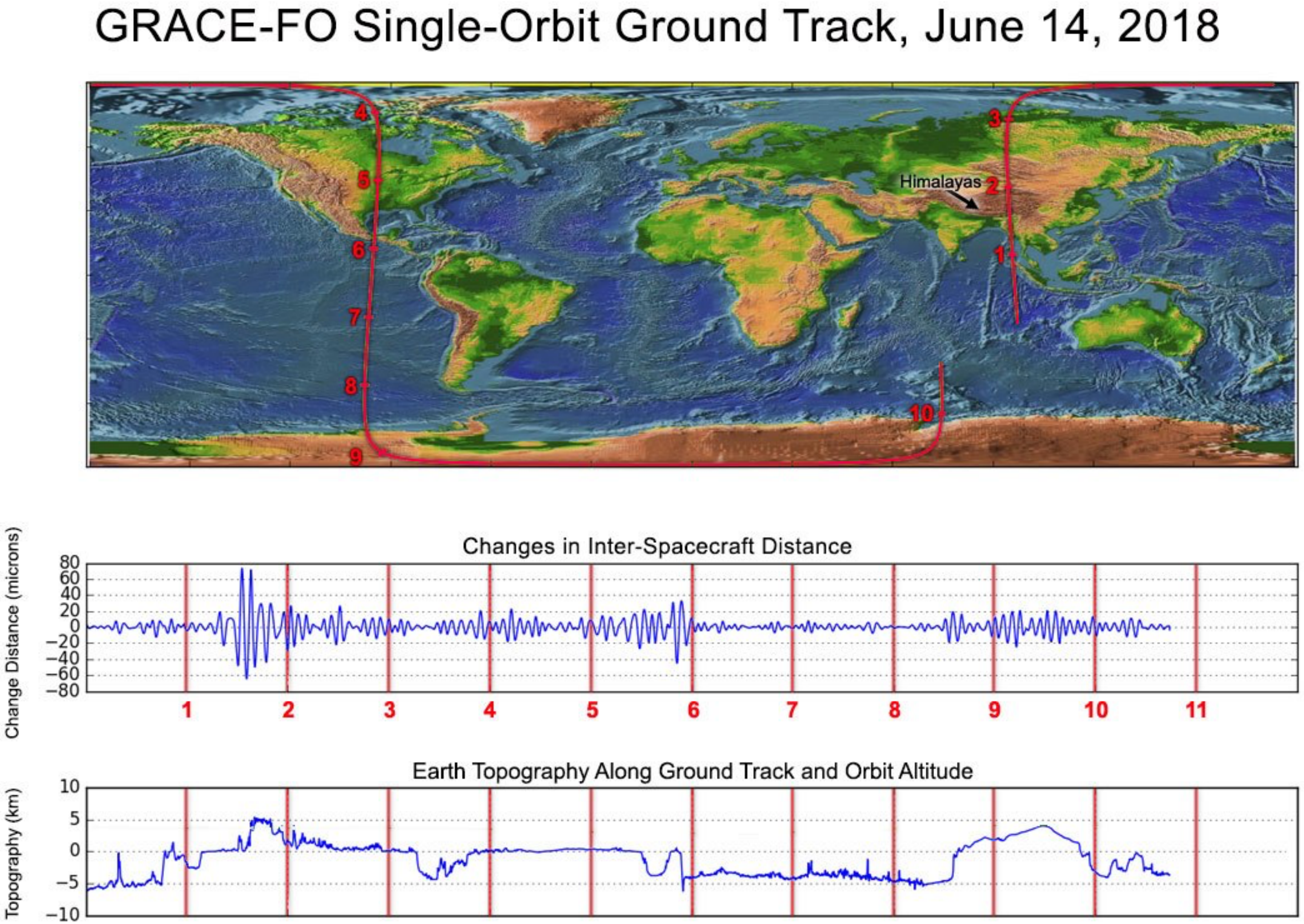


Laser Ranging Processor Flight model



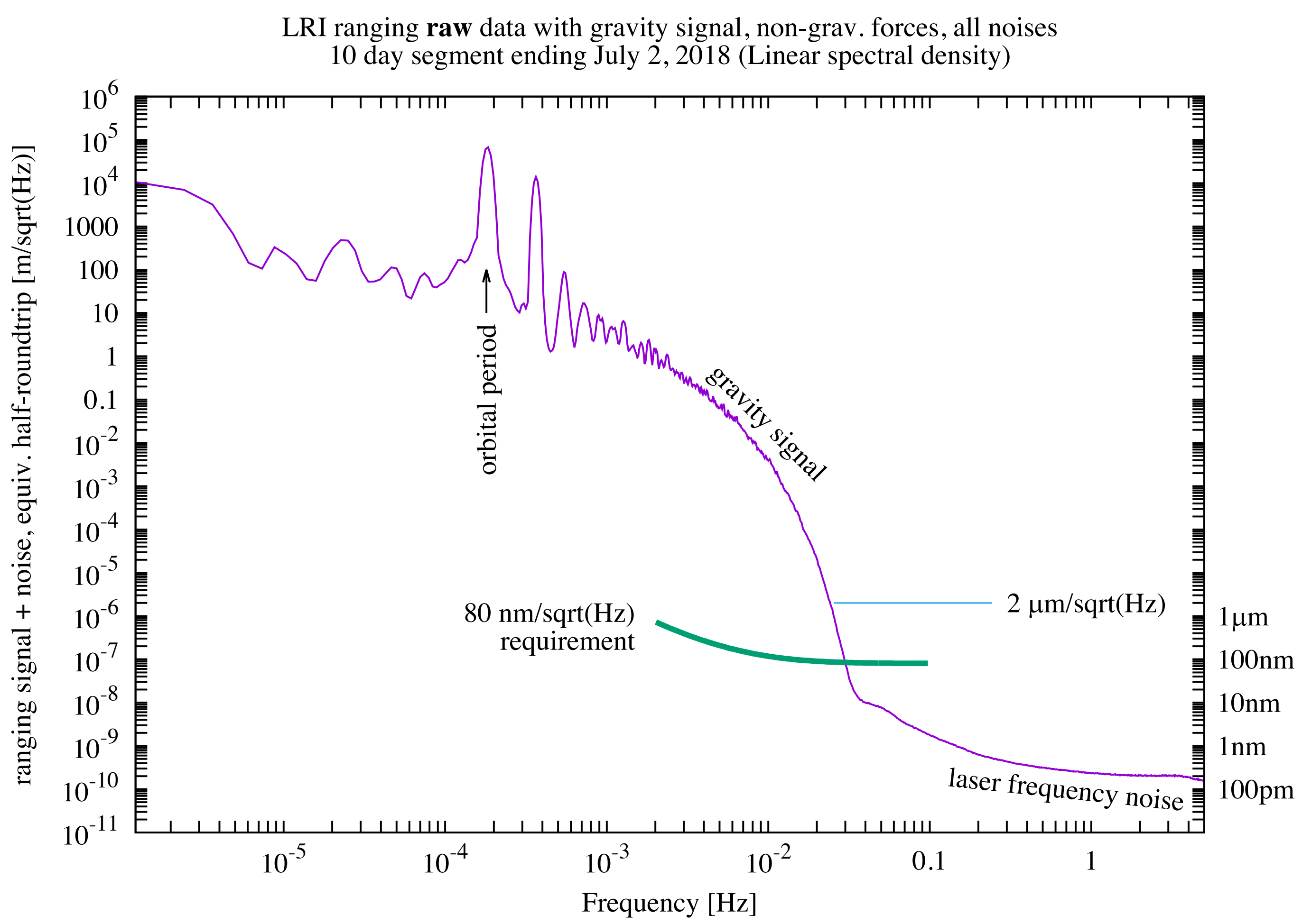
LRI measures gravity

Filtered interferometer signal correlates with topography.



https://gracefo.jpl.nasa.gov/news/138/first-laser-light-for-grace-follow-on/

LRI performance



Similarities with LISA

LRI design based on LISA technology and capabilities.

- **Designed by LISA scientists and technologists (NASA and Germany)**
- LRI top level precision relaxed
- Tighter laser stability requirement

Similar:

- Doppler shift and IF signal
- Received optical power
- mHz-band science signal frequency
- Link architecture: stabilized master and offset phase-locked slave
- Photoreceiver properties

Both LRI and LISA require:

- Low light power tracking
- Differential wavefront sensing
- 5 degree of freedom acquisition

LRI is providing technology demonstration for LISA and represents a huge step towards LISA

LRI is demonstrating the first inter-spacecraft interferometer

Parameter	LRI	LISA
Measurement Noise	**0.08 $\mu Hz^{-1/2}$**	**2 × 10-5 $\mu Hz^{-1/2}$**
Shot Noise	*0.01 $nm/Hz^{1/2}$*	*7 $pm/Hz^{1/2}$*
Photoreceiver Noise (but note carrier to noise density requirement)	*1 $nm/Hz^{1/2}$*	*3 $pm/Hz^{1/2}$*
Phasemeter Noise	*1 $nm/Hz^{1/2}$*	*1 $pm/Hz^{1/2}$*
Optical Pathlength Noise	*30 $nm/Hz^{1/2}$*	*3 $pm/Hz^{1/2}$*
Laser Frequency Noise	*35 $nm/Hz^{1/2}$*	*1 $pm/Hz^{1/2}$*
USO Noise	*1 $nm/Hz^{1/2}$*	*1 $pm/Hz^{1/2}$*
Satellite Separation	**170..270 km**	**5 million km**
Satellite Relative Velocity	**≤±3m/s**	**≤±15m/s**
Wavelength	**1.064 × 10^{-6}m**	**1.064 × 10^{-6}m**
Phase Precision	**10^{-3} cycles $Hz^{-1/2}$**	**1 microcycle $Hz^{-1/2}$**
Nominal Carrier-to-noise Density	**≥ 75 dB-Hz (single phasemeter channel)**	**≥ 75 dB-Hz (single phasemeter channel)**
IF Signal Frequency	**4–16 MHz**	**2–18 MHz**
IF Signal Dynamics (@ 1 Hz)		
Before Frequency Stabilization	*5000 Hz $Hz^{-1/2}$*	*5000 Hz $Hz^{-1/2}$*
After Frequency Stabilization	*30 Hz $Hz^{-1/2}$*	*300 Hz $Hz^{-1/2}$*
Science Bandwidth	**2 MHz–0.1 Hz**	**0.1 MHz–1 Hz**
Rx Optical Power	**79–625 pW**	**80 pW**
Number of Phase Channels	**4**	**44+**
ADC Clocking Rate	**38.656 MHz**	**50 MhZ**
Time Coordination	**GPS (laser ranging code could be used)**	**Laser ranging code**
Laser Phase Locking	**Required**	**Required**
Pointing Information	**Wavefront sensing**	**Wavefront sensing**
Pointing Precision	*1 $urad/Hz^{-1/2}$*	*80 $nrad/Hz^{-1/2}$*

NASA Technology Development Roadmap for a Future Gravitational-Wave Mission

Acquiring the optical link

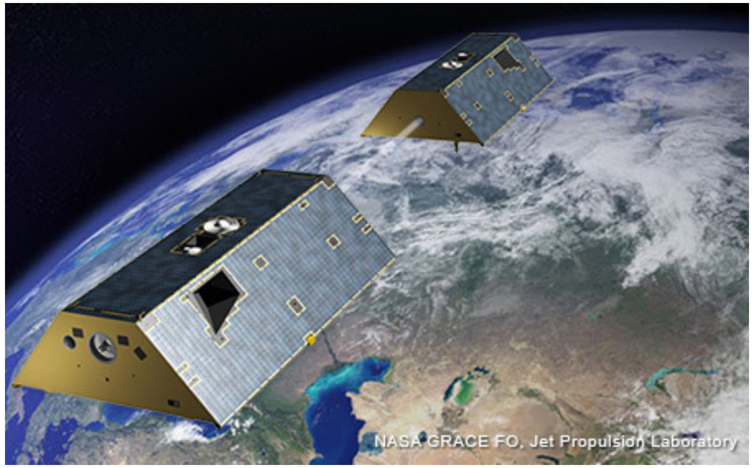
Following launch there were 5 degrees of freedom that had to be resolved:

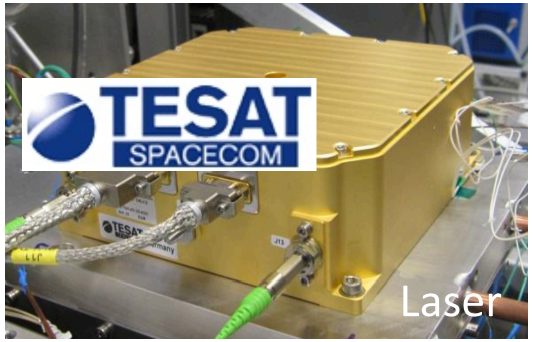
- ±3 mrad in pitch/yaw pointing of both spacecraft
- ± 160 MHz laser frequency uncertainty

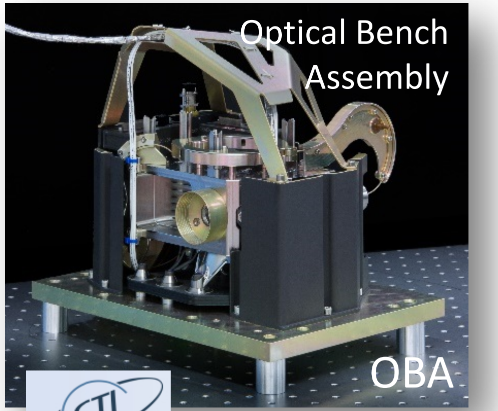
The goal of link acquisition is to get beatnotes on both detectors (pointing within ±100 µrad in pitch and yaw) with frequencies within 2 – 18 MHz bandwidth that the phasemeters are able to track.

To do this:

1. Perform initial link acquisition scans, recording pointing and laser frequency when a beatnote is seen on a detector
2. [Offline] Use data collected during initial acquisition scans to calculate line-of-sight offset and laser frequency offset. Upload these parameters to satellites.
3. Auto-acquisition (smaller scan) optimizes pointing, transitioning into science mode once a beatnote is detected.







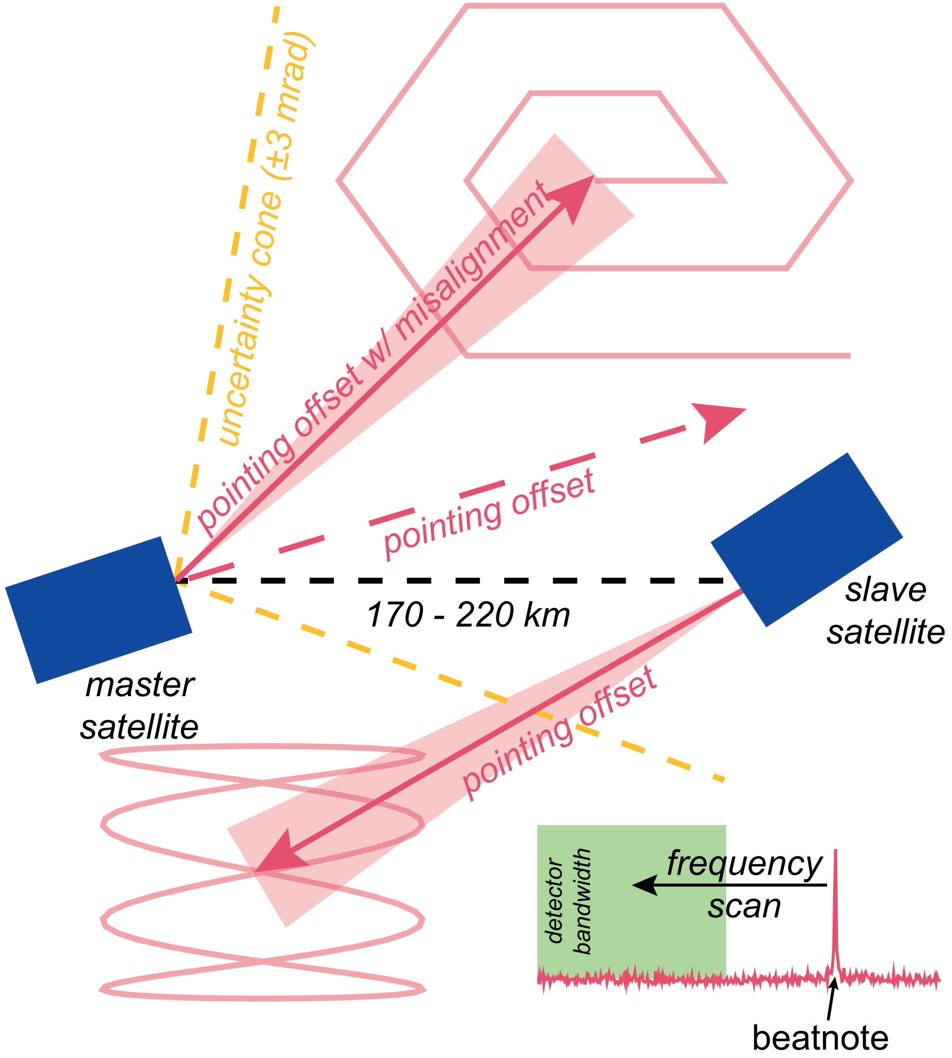
Initial link acquisition scans

Jet Propulsion Laboratory
California Institute of Technology

Master and Transponder: The master satellite locks to cavity to frequency stabilize its laser before starting the initial acquisition scan. The master performs a slow hexagonal scan and the transponder performs a fast Lissajous scan while simultaneously sweeping its laser frequency

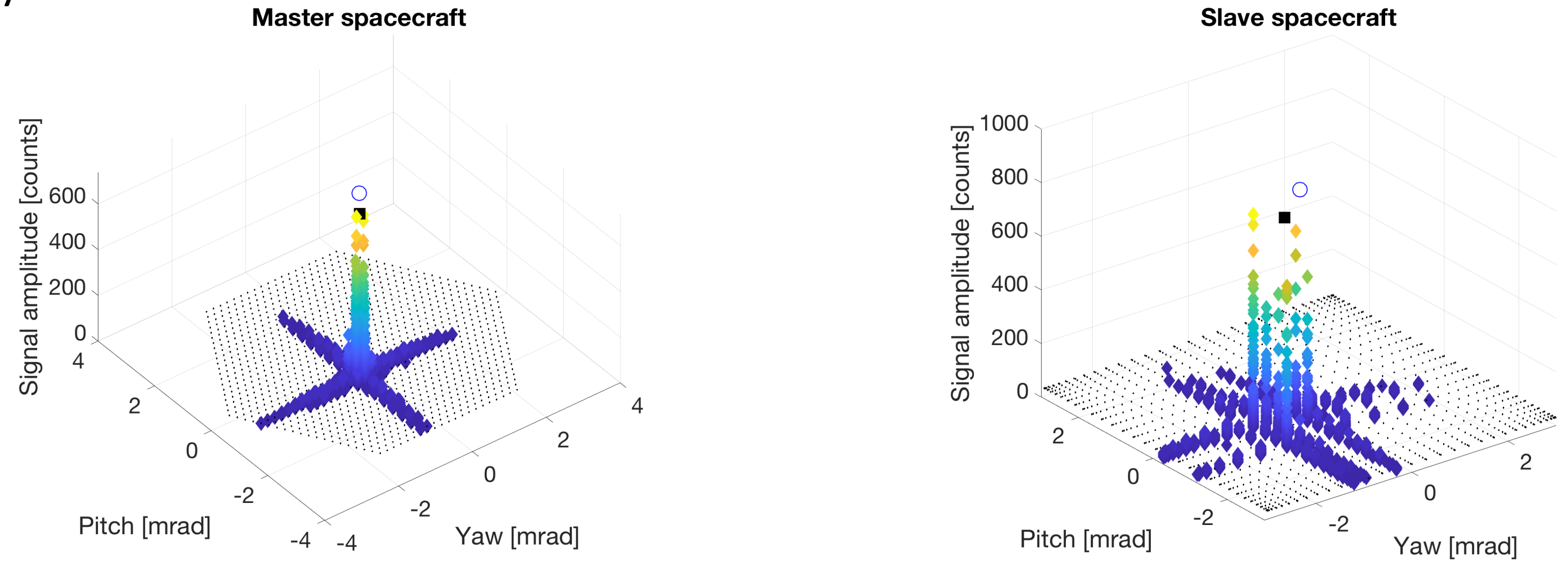
Role	Scan type	Scan rate	Frequency sweep [Hz/s]
Master	Hexagonal (Discrete)	1.8 [pts/s]	N/A
Transponder	Lissajous (Continuous)	100 [Hz], 2 [Hz]	10.5 kHz/s

There is **no dedicated acquisition sensor,** link acquisition uses the same hardware that is used in the science measurement. An FFT is used to detect when a beatnote is within band. If the received power is above threshold the current parameters are recorded.



Initial link acquisition scans

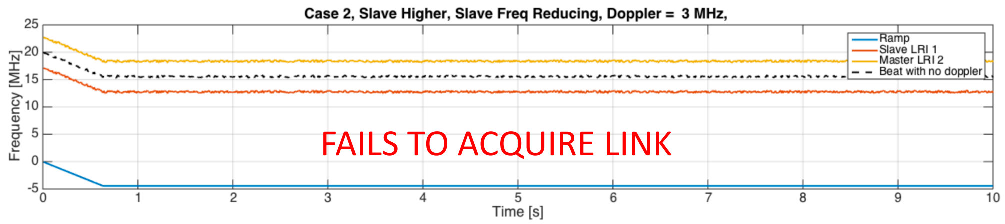
Over the **nine hour initial acquisition scan** the two GRACE Follow-On satellites recorded the laser frequency, mirror Pitch and Yaw and the amplitude each time a beatnote was detected that was within the 2-18 MHz bandwidth and above threshold. This data was downlinked for analysis:

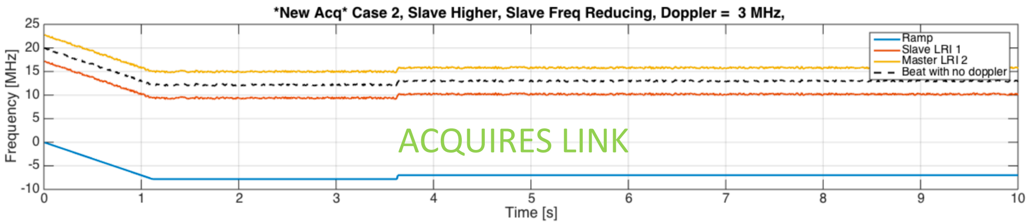


Line-of-sight offsets were determined by fitting gaussian surfaces to the downlinked data

Optimizing the optical link

- The line-of-sight and laser frequency offsets were determined on-ground for both spacecraft and uploaded to the satellites. The LRI then automatically optimized its link using smaller (300 µrad vs 3 mrad) scans
- The optimization scan stops* once a beatnote has been detected on the satellite. Differential Wavefront Sensing is then enabled to feedback in real time to the pitch and yaw of the steering mirror on both satellites to maintain the optical link





Simulation: Comparing performance of auto-acquisition algorithm without and with extra delay

*delays are built into the auto-acquisition algorithm to ensure doppler shifts between satellites don't mean one satellite has a beatnote within band, while the other satellite doesn't

The autonomous acquisition scans are used any time the link is lost or disabled to reacquire the link

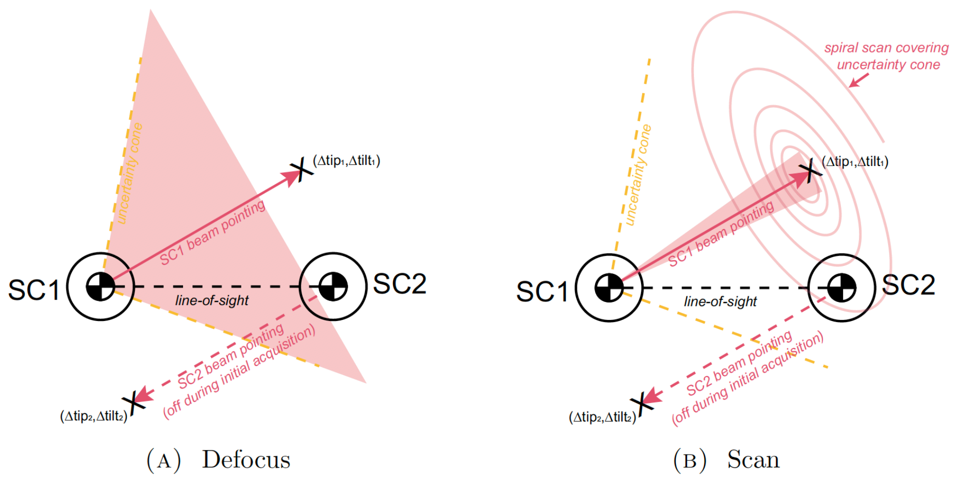
Acquisition in LISA

Acquisition on LISA is more complicated than in LRI:

- More arms to align/lasers to overlap in frequency
- Longer time-of-flight delay along arms
- (potentially) Slower point ahead actuation

Two strategies for acquisition have previously been considered:

- Defocusing the transmitted beam [Maghami, 2005]
- Spiral scan [Cirillo, 2009]



Acquisition schemes previously studied for LISA

In both schemes a dedicated (CCD) is used as an acquisition sensor. Since it is intensity based, light on the receiving spacecraft is turned off. Consequently, once a link has been aligned in one direction along an arm, the laser is disabled and the laser at the other end is enabled. The spacecraft attitude control system is tasked with maintaining pointing while the link is deactivated.

Maghami, P. G, et al. (2005). An acquisition control for the laser interferometer space antenna. *Classical and Quantum Gravity*, *22*(10).
Cirillo, F, et al. (2009). Control system design for the constellation acquisition phase of the LISA mission. *Journal of Physics: Conference Series* (Vol. 154, No. 1).

LRI acquisition on LISA?

Could an LRI-like acquisition scheme be used in LISA?

Initial (commissioning) spatial and laser frequency scans used to search for beatnotes → [Offline] Determine line-of-sight pointing and laser frequency offsets → Perform smaller, optimization scans to get beatnotes on all detectors

1. Would we want to?

Advantages?	Disadvantages?
• Don't need to turn off lasers during acquisition (no relying on attitude control) • Avoid the need for dedicated acquisition sensors • Acquisition and reacquisition use same algorithm	• Potentially more time to acquire link. A dedicated acquisition sensor disentangles degrees-of-freedom that we need to solve for

2. Could it work? Would need need to address:
   - 8.3 [s] vs 0.7 [ms] optical light time delay
   - Is pointing control achieved using *Moving Optical Subassemblies (MOSA)* or by changing spacecraft orientation?

Conclusion

- GRACE Follow-On Laser Ranging Interferometer, the *first inter-spacecraft laser interferometer* has been successfully operating since powering up in June, 2018.
- High frequency performance of nm/√Hz limited by thermal stability of cavity. Characterization of Low frequency performance is ongoing.
- LRI instrument design and many technology elements have heritage in LISA development
- LRI optical link acquisition searches for a heterodyne beatnote signal, employing the same photodetectors and signal processing hardware as the science measurement
- LISA acquisition is more complicated because of larger number of links; longer light delays; and slower point ahead actuation. Looking at whether an LRI-like acquisition scheme would be advantageous