Compact Coherent Laser Ranging (CCLR)

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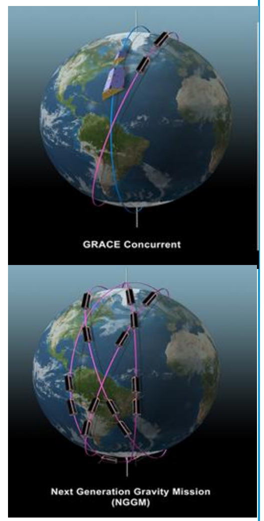
Architecture Quad Chart

Description

- *SST*
- *2 S/C*
- *MiniSat/CueSat (16U,25W)*
- *LEO (460km altitude, 200km spacing, 89 degree inclination*
- *CubeSat/MiniSat launch*



Instrumentation

- *Instruments overview,*
    - *2 16U CubeSat with precision pointing (50uRad), Precision Orbit Detemination, precision Star tracker*
    - *3.5mRad FOV*
    - *Spacecraft at 9*
    - *Precision laser ranging*
    - *TRL 5*

Programmatic

- *Rough ROM $10 million*
- *Development schedule 5 years*
- *Risk assessment:*
- *Partnering opportunities*

Industry partners on CubeSat
In-house partners on integrated CubeSat and GPS POD

Technical Performance

- *Optical ranging match GRACE FO LRI requirement (80nm/sqrt(Hz) at 1S*
- *Measurement accuracy*
- *Launch mass: 16kg*
- *Power: 26W*
- *16U CubeSat with integrated attitude control system, close loop optical pointing and tracking*

Contents

1. Development goals
2. System overview
3. Instrument concept
4. Key components and state of art
   - Space Craft
   - Accelerometer
   - GPS and USO precision obit determination (POD) and timing tagging
   - Pointing, acquire, and tracking
   - Laser ranging interferometer (LRI)
5. Conclusion

Development Goals

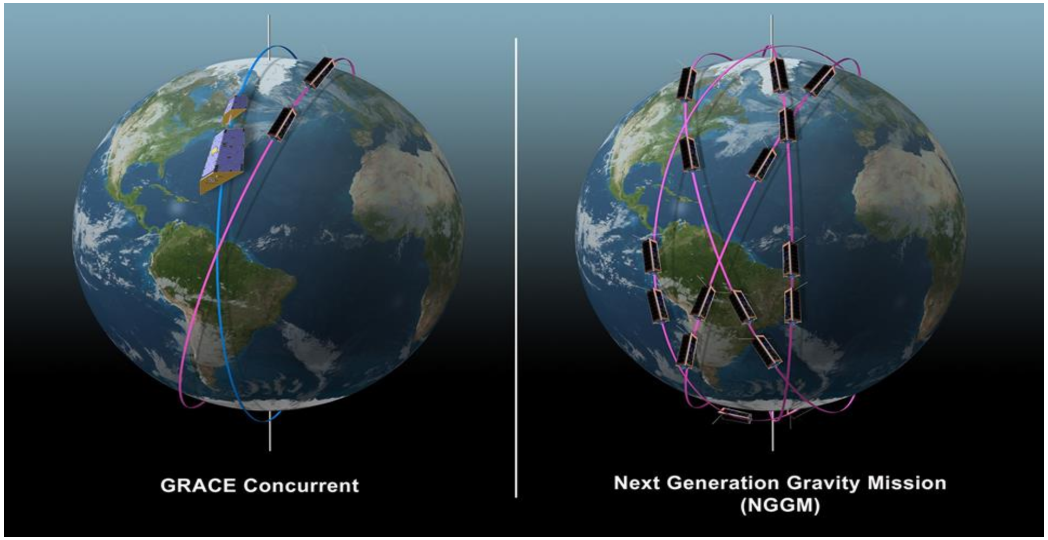
Goals

1. Match the performance as GRACE-FO
2. With much reduced SWaP to fit on mini-Sat or CubeSat
3. Enables low cost and more frequent LL-SST gravitational missions
4. Immunes from ionosphere propagation delay with optical ranging
5. Increases the body pointing capability due to small satellite

Underline reasons

- Vast progresses in CubeSat and SmallSat technologies
- Large progress in metrology on coherent laser sources
- LISA and GRACE missions promoted component technology progresses
- In-house LISA metrology expertise and laser communication with precision ranging and pointing expertise

System overview
Compact laser ranging L-L-SST

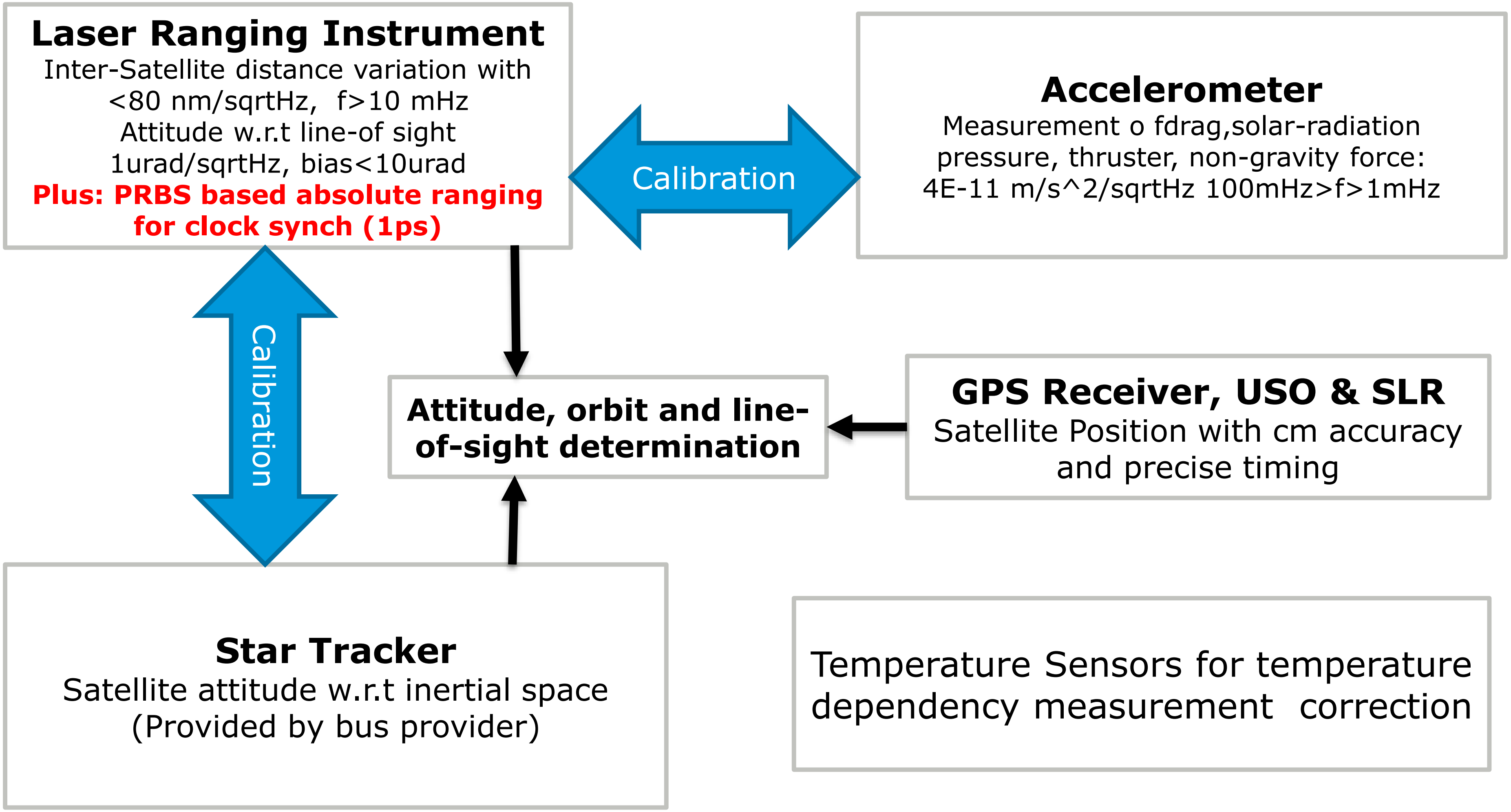


- Double low-low pair
- Near polar 89 degree inclining
- 420km altitude
- Nominal 200 km inter-satellite spacing, or tailored to specific mission goals
- 31 day repeat

Top Level Requirements for CCLR Gravity Missions

- Laser range interferometer (LRI) error <80nm/sqrt(Hz)
  - Auxiliary pseudo-random-sequence absolute ranger <1mm
- Precision Orbit Determination (POD) GPS + SLR + USO
  - ~1cm location error, 100ps time tag error
- Star tracker precision 50uRad
- Size, Power & mass per satellite
  - 16U, 16kg, 26W
- Lifetime
  - 1 yr (on ground, post delivery) + 4 yr (science) + 4 yr (extension)

Instrument concept



Key Parts Status

part name	part number	TRL	power	size (cm)	volume in U	weight (grams)	cost ($k)	vendor
total			7.27		1.81	2887	5,000	
USO	DS-9700	**9**	1.3	3.4x3.4x3.4	0.038	100	150	microsemi
GPS receiver	OEM729	**9**	1.3	0.9x6x10	0.31	48	6	Novaltek
retroreflector	GSFC/MIT	**9**	0	6.25	0.244	25	10	internal reference
MicroStar Accelerometer	MicroStar Accelerometer	**6**	2	10x10x10	1	1400	500	ONERA
mNPRO master laser	inhouse	**5**	1.33	7x4.5x1.5	0.05	500	TBD	GSFC
mNPRO slave laser	inhouse	**5**	1.33	7x4.5x1.5	0.05	500	TBD	GSFC
Reference cavity	inhouse	**6**	NA	5	0.125	300	TBD	Stable Laser Systems
attitude control Star Tracker	XCAT50	**9**		Included in Spacecraft				BCT
spacecraft	XB12	**9**			2		560	GSFC or BCT (16U)
Launch		**NA**						

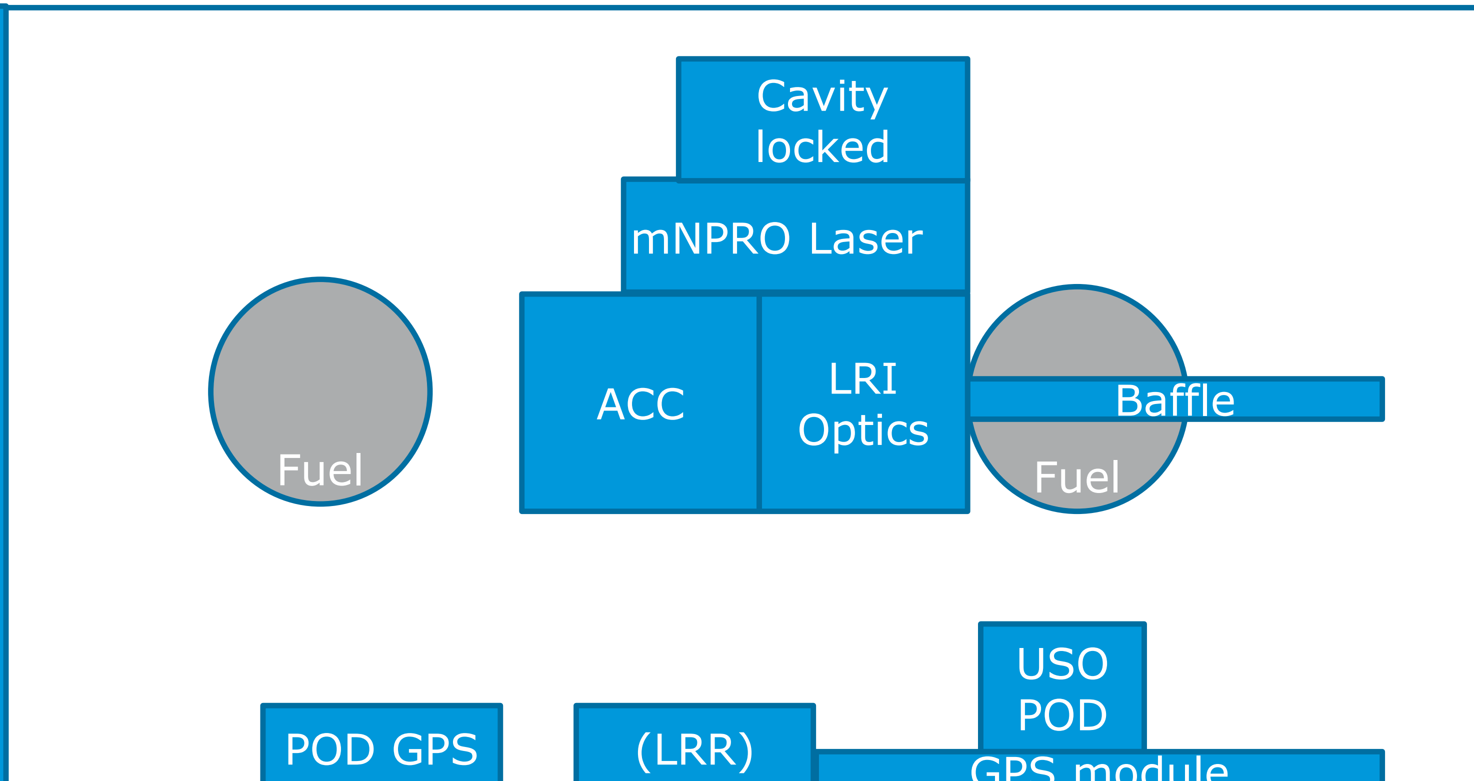
Spacecraft System (BCT)

- **16U bus, 25W power, 50uRad pointing error**
- **14U user bus space**
- **4U, 7W used by key components**
- **10U, 18W left for electronics and mechanical and thermal**

BCT 50CAT (2U)

16 U Spacecraft System

- Star Trackers
- Precision Pointing ADCSC&DH
- Sun sensor
- GPS+Antenna
- EPS
- S-band comm
- Reaction Wheels,
- Torque Rods,
- IMU,
- Magnetometer

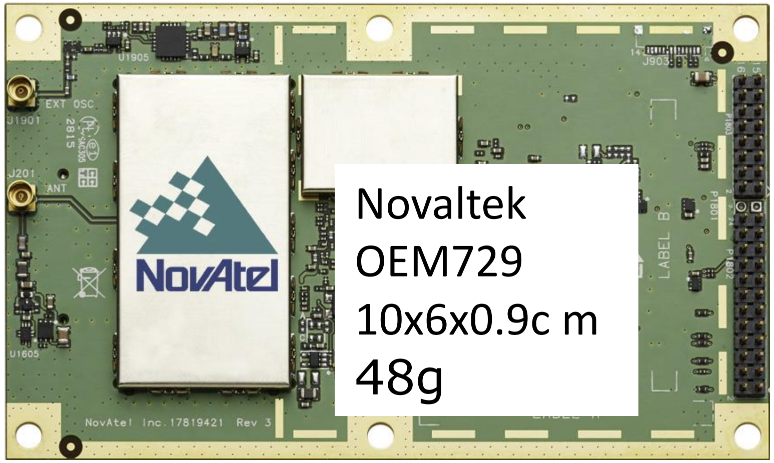


Precision Orbit Determination (POD)
GPS and USO and laser ranging retroreflector

Key Parameters	
Time Accuracy	20 ns RMS
POD	1cm
Time tag Error	100ps
USO temperature coefficient	4ppb/c

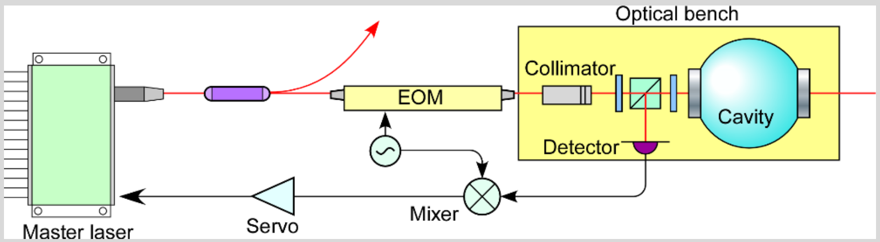
Microsemi
DS-9700 OCXO
3.4cmx3.4cm
100g

NASA GSFC/MIT
5cm, 21g

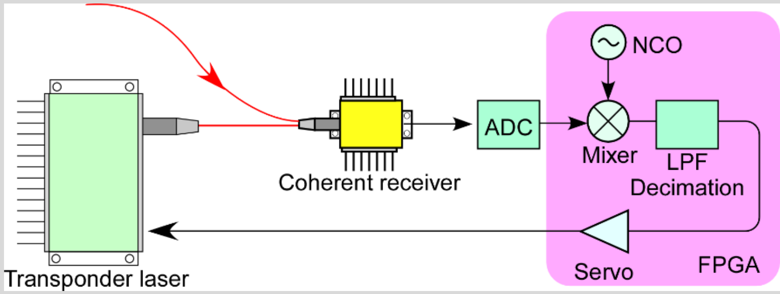


Novaltek
OEM729
10x6x0.9c m
48g

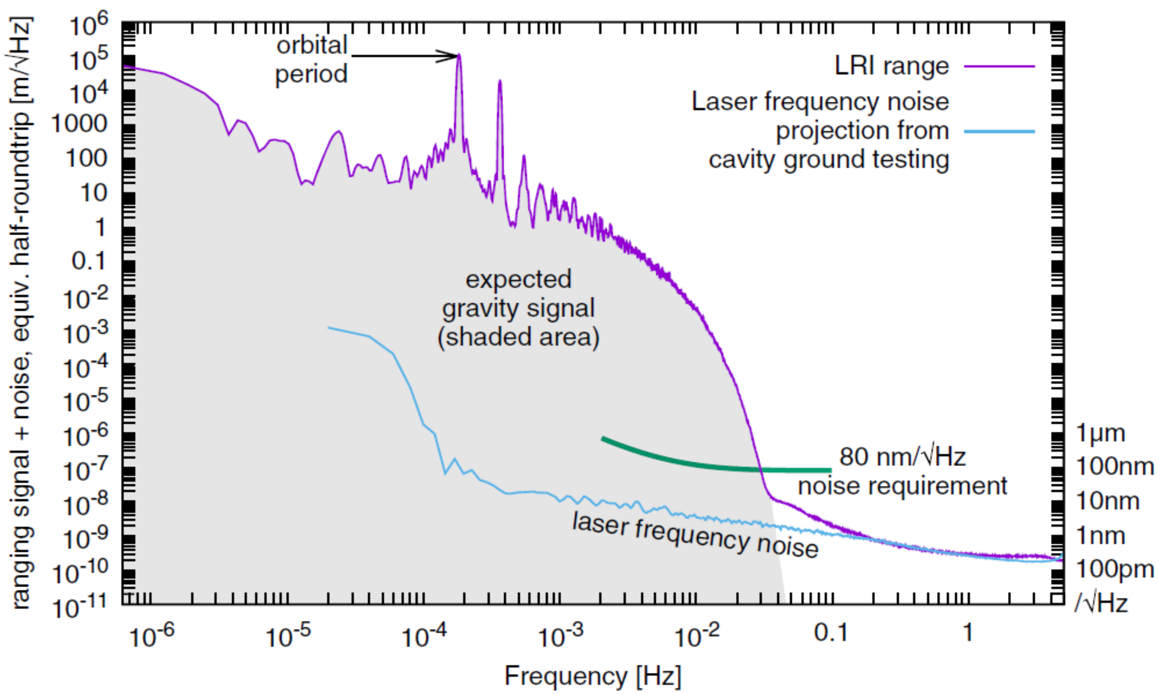
m-NPRO laser with cavity locked master and offset frequency locked slave laser



Master laser (cavity locked)



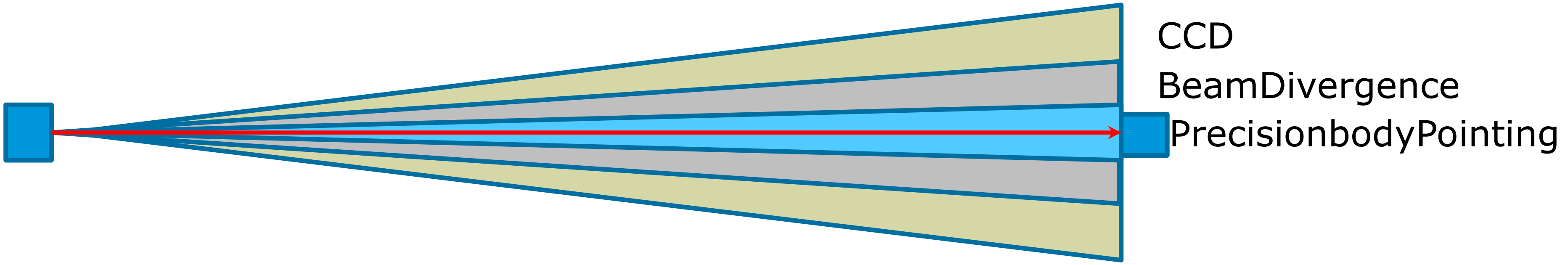
Transponder laser (offset F locked)



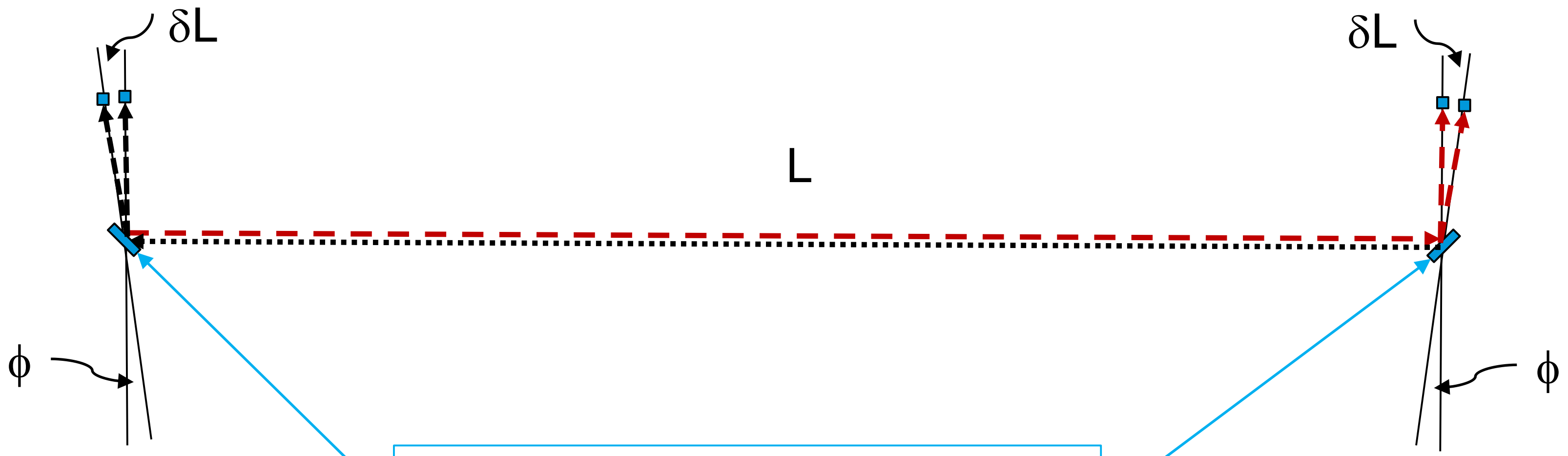
Cavity 5cm sphere

Point and tracking (PAT) Sequencing

- Location knowledge 5uRad (GPS orbit determination error < 1m, and 200km spacing)
- Precision Body Pointing (Star Tracker based) error <50uRad,
- Beam divergence 135uRad (5 mm diameter @1/e^2)
- MEMS mirror scan for initial optical axis and star tracker reference offset
- CCD camera enabled wide FOV angle sensing FOV (3400uRad) and Resolution (8uRad)
- Quad-detector achieves final pointing and tracking FOV (20uRad) and Point error 0.002uRad)

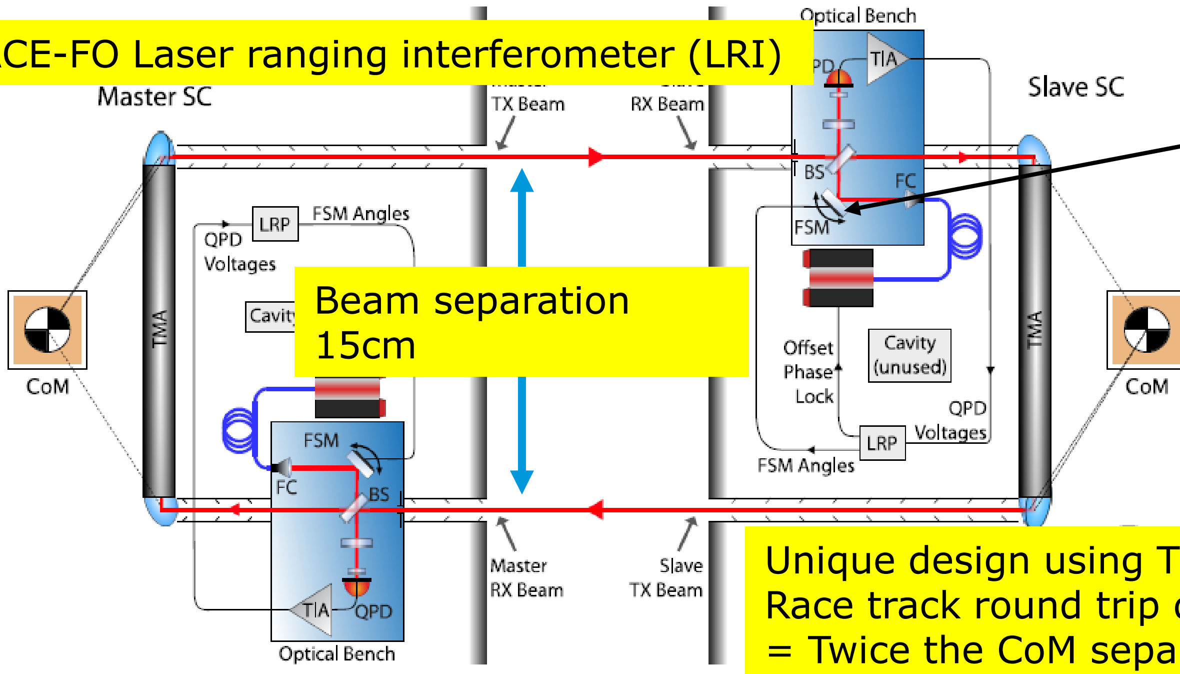


PAT and Pitch and Yaw error Configuration for PAT for SST



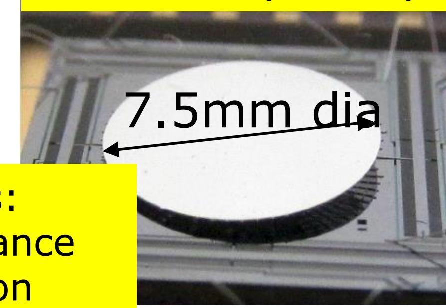
A fast steering mirror is placed at the Center of Mass of each satellite

Approach 1: Improvements over GRACE-FO



25mm dia PZT (10W)

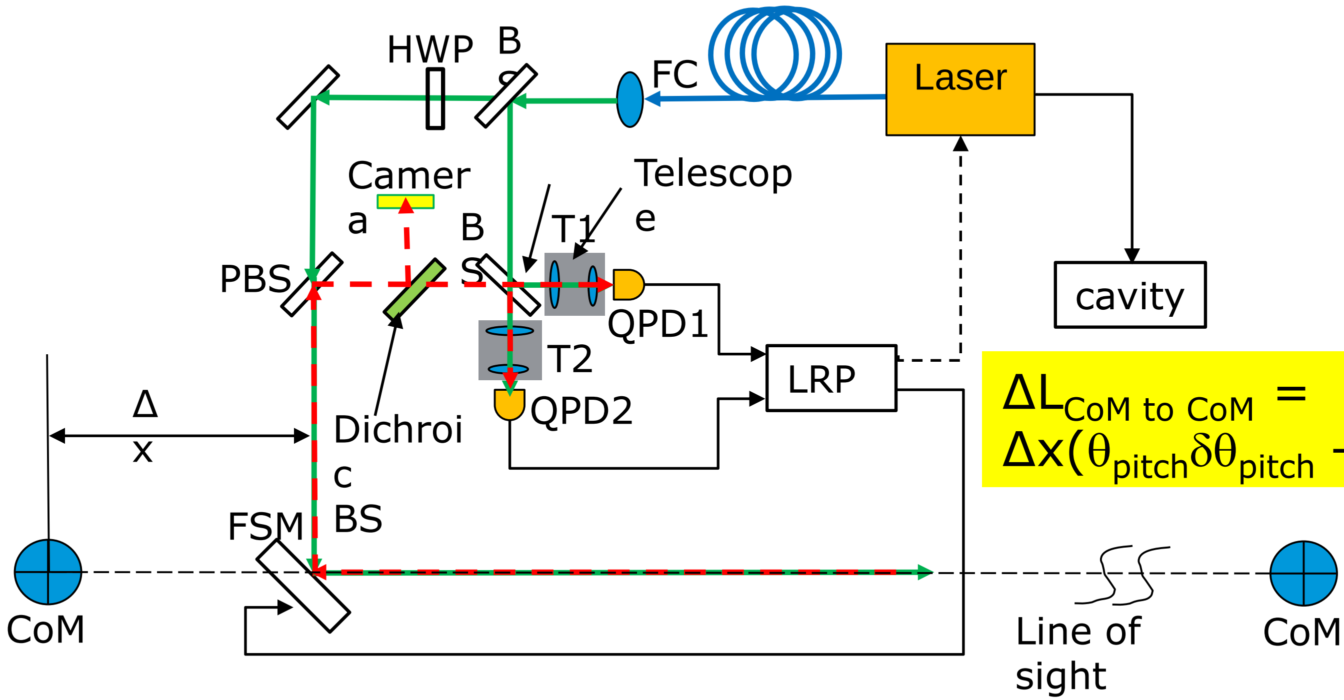
MEMS FSM (<0.5W)



CoM: center of mass, FSM: fast steering mirror, BS: beam-splitter. FC: fiber collimator, TIA: trans-impedance, amplifier, QPD: quadrant photodiode, LRP: laser ranging processor; TMA: Tripple mirror assembly.

- LRI measures range variation between CoMs to 80nm/Hz$^{1/2}$ from 2 mHz to 100 mHz [1];
- 60 cm triple mirror assembly (TMA) can be reduced to 15 cm to fit SmallSats [2];
- Replace PZT FSM with more compact MEMS FSM (order placed) [3];
- Communication over the laser link by sideband modulation (as LISA does) [4];
- Add an acquisition camera to shorten pointing acquisition from 9 hours to 100s [5, 6];

Approach 2: Patent pending PAT design for SST one arm

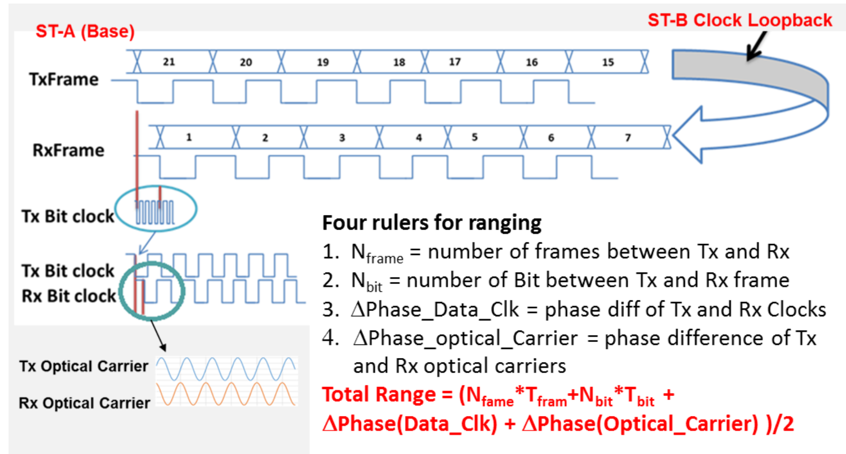


$$\Delta L_{\text{CoM to CoM}} = \Delta x(\theta_{pitch}\delta\theta_{pitch} + \theta_{yaw}\,\delta\theta_{yaw})$$

- LISA-like design with shared TX and RX aperture;
- FSM is placed along line of sight (LOS) close to CoM, ideally on CoM;
- TX and RX beams are multiplexed by polarization;
- Balance detection cancels backscattering from telescope [7];
- Error due to offset Δx from CoM is ~2nm/Hz$^{1/2}$ for Δx =10cm, θ=200urad(4xRMS), $\delta\theta$=100μrad/Hz$^{1/2}$, which is a small fraction of total error budget of 80nm/Hz$^{1/2}$.
- Such error can be estimated and removed with accurate pointing knowledge.
- Beacon beam is directed to the acquisition camera by wavelength multiplexing.

From Ranging over optical communication To Communication over ranging

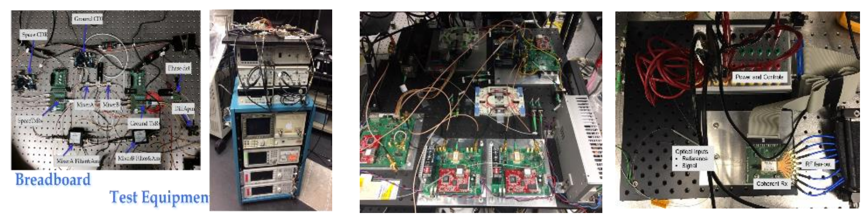
- Pseudo-random-code ranger
  - ✓ Clock and frame loopback
  - ✓ Absolute range error 6 um
  - ✓ Provide clock synch between two satellite better than 1ps
- Optical carrier phase ranging
  - ✓ Error < 90nm

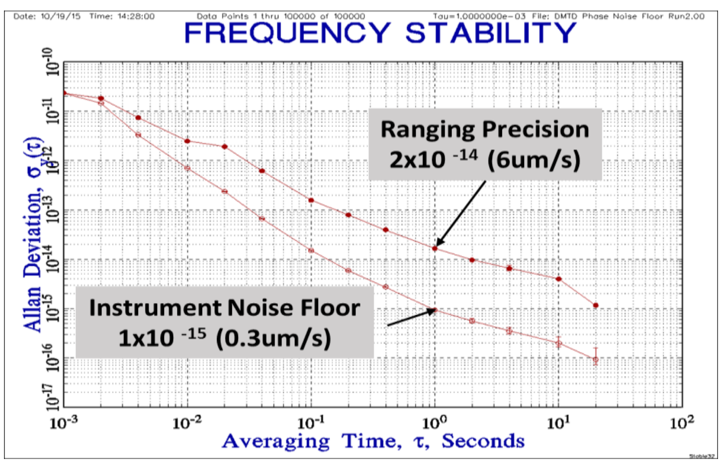


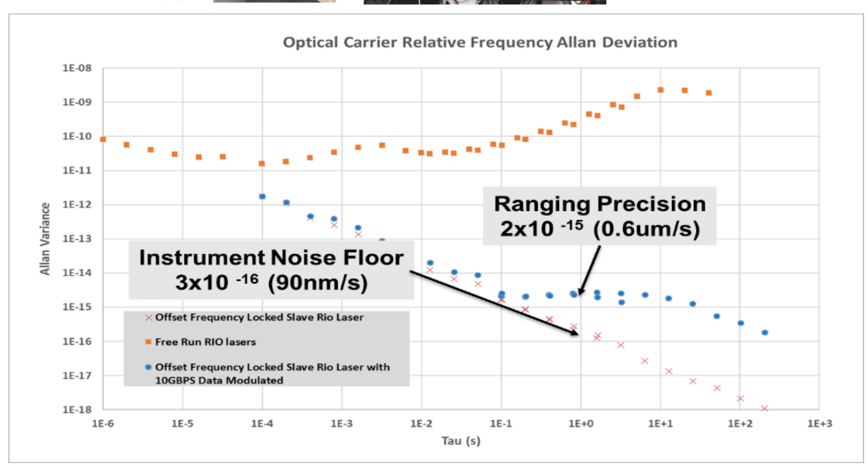
Four rulers for ranging

1. N_{frame} = number of frames between Tx and Rx
2. N_{bit} = number of Bit between Tx and Rx frame
3. ΔPhase_Data_Clk = phase diff of Tx and Rx Clocks
4. ΔPhase_optical_Carrier = phase difference of Tx and Rx optical carriers

Total Range = (N_{fame}*T_{fram}+N_{bit}*T_{bit} + ΔPhase(Data_Clk) + ΔPhase(Optical_Carrier))/2







Conclusion

Presented:

1. Compact coherent laser ranging (CCLR) on CubeSat platform
2. With ranging precision matches the GRACE-FO performance
3. It enables nominal 200 km inter-satellite spacing, or tailored to specific missions
4. As Laser ranging is insensitive to plasma (interplanetary and Earth ionosphere) noise source
5. Small CubeSat size increases the satellite body pointing capabilities.

Leverages:

1. In-house LISA low noise m-NPRO laser development and LISA high Q-cavity locked and frequency offset lock expertise
2. In-house high precision ranging over laser communication (Optimetrics) and active pointing and tracking expertise
3. Major high TRL level components developed recently (USO, GPS, micro-Accelerometer, CubeSat precision attitude control system)
4. Grace and LISA interferometer design