Inter-satellite Laser Ranging for Geodesy, Formation Flying, and Fundamental Physics in Space

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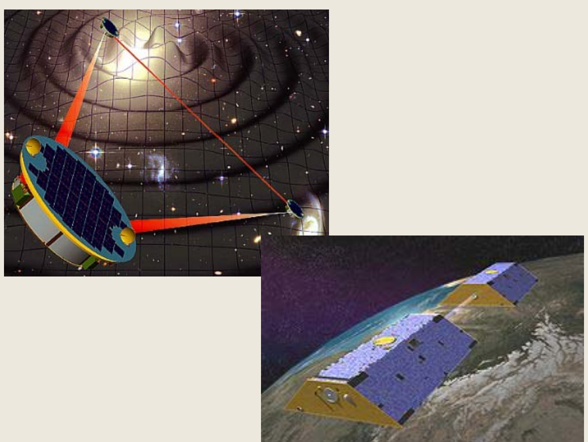
Outline

- Ranging and formation missions – required range
- Ranging architecture comparison – retro-reflector vs. active transponder
- System architecture
- Comparison to full-size missions
- MGRS – Stanford's drag-free implementation
- Small satellite ranging-precursor missions at Stanford
  - UV-LED (2013)
  - Caging on zero-g (2013) (3u)
  - DOSS (2014) (2u)
  - Drag-free cubesat (2015) (3u)

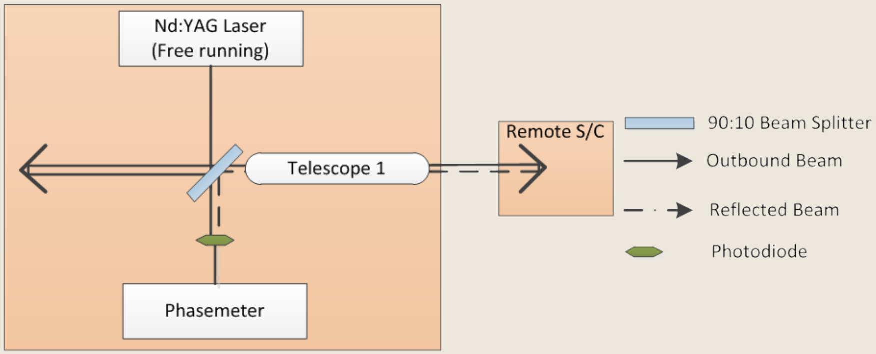
Ranging Missions

- Low unit cost for Cubesats make them an attractive choice for formation-flying missions
- How do we increase the position accuracy towards that of larger ranging missions?

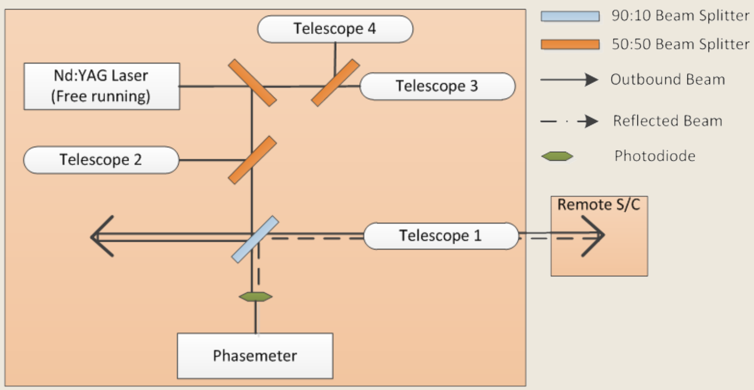
Name	Type	Position accuracy
LISA	Ranging	10 pm
GRACE (non-laser)	Ranging	2 um
GRACE-II	Ranging	50 nm
DTUsat (non-laser)	Formation, cubesat	1 mm
CanX-4/5 (non-laser)	Formation, cubesat	10 cm



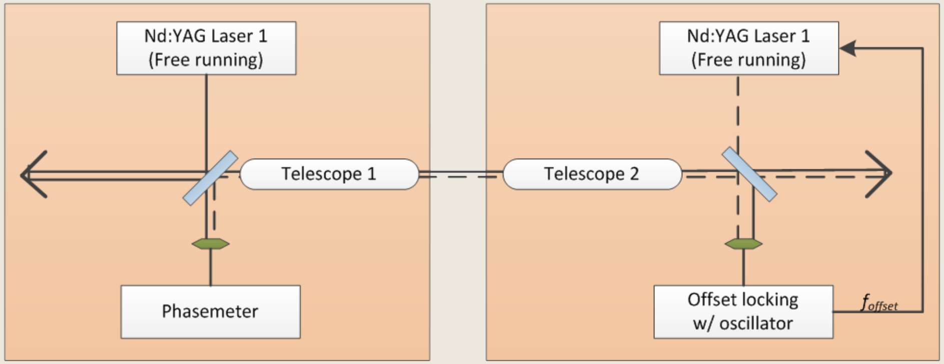
Architectures: Retro-Reflector vs. Transponder



- Single 1064 nm laser on master satellite
  - Remote satellite has a corner cube reflector
  - Ranging data measured on master satellite
- For a 200km separation: $P_{optical}$ at detector = 1.5 nW



- Can use a single master satellite with several remote satellites in formation by dividing beam



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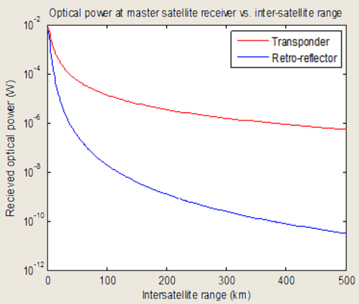
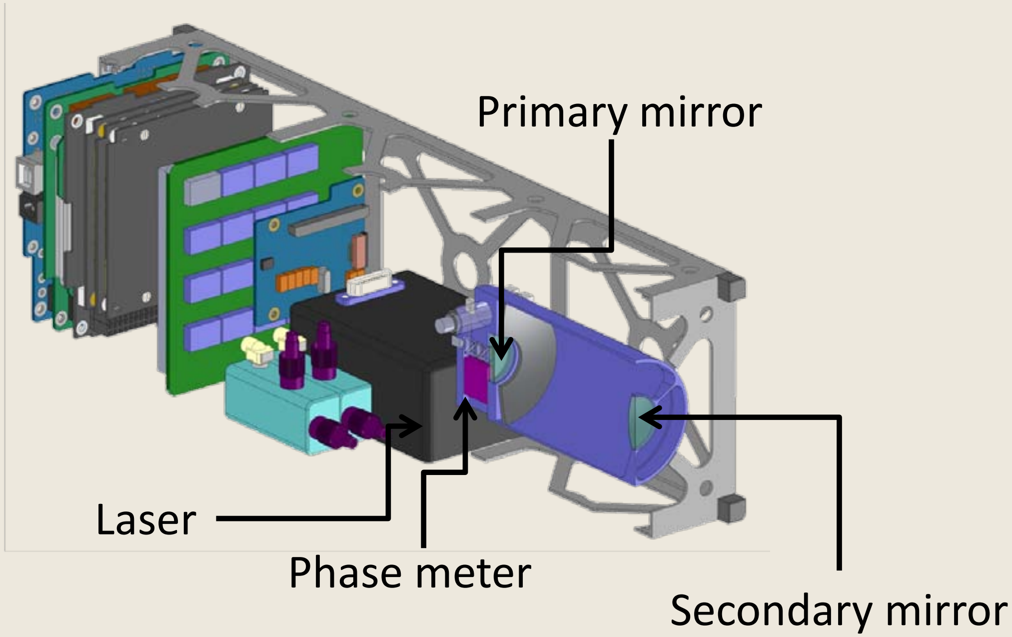


- P_0 – outbound power
- w_0 – aperture radius
- z – range
- z_R – Rayleigh length

$$P = \frac{2P_0}{\pi} w_0^2\left(1+\frac{z}{z_R}\right)\int_0^r 2\pi r\, e^{-\frac{2r^2}{r\sqrt{1+\frac{z}{z_R}}}}dr$$

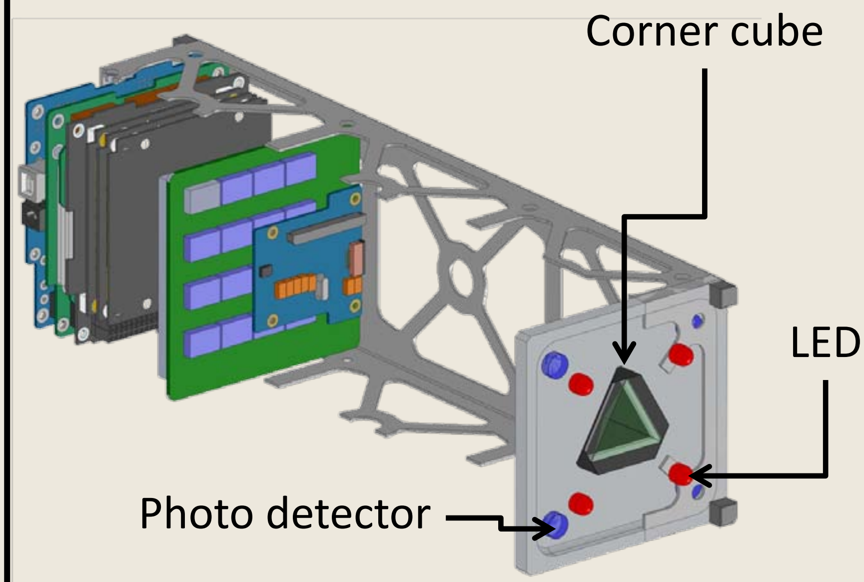
Spacecraft Configurations

Master Spacecraft



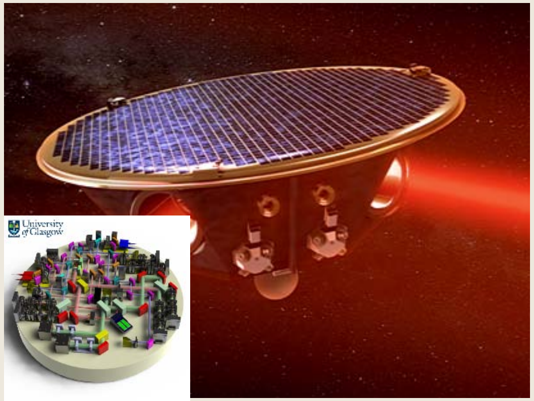
- Laser and telescope assembly: 1 to 1.5 U
- Space available to add ADCS, or cavity to improve laser frequency stability

Remote Spacecraft

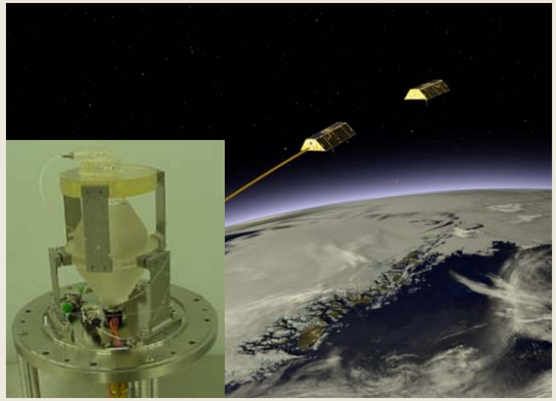


- Corner cube assy. takes <1/4 U
- Remainder of s/c is available for payload use including ADACS and thrusters
- LEDs and PDs for initial beam acquisition and alignment

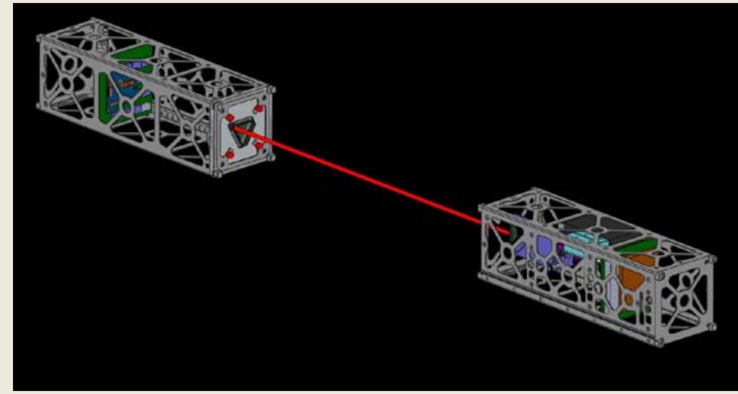
CubeSat vs. Full-Size Architecture



E-LISA Mission



GRACE-II

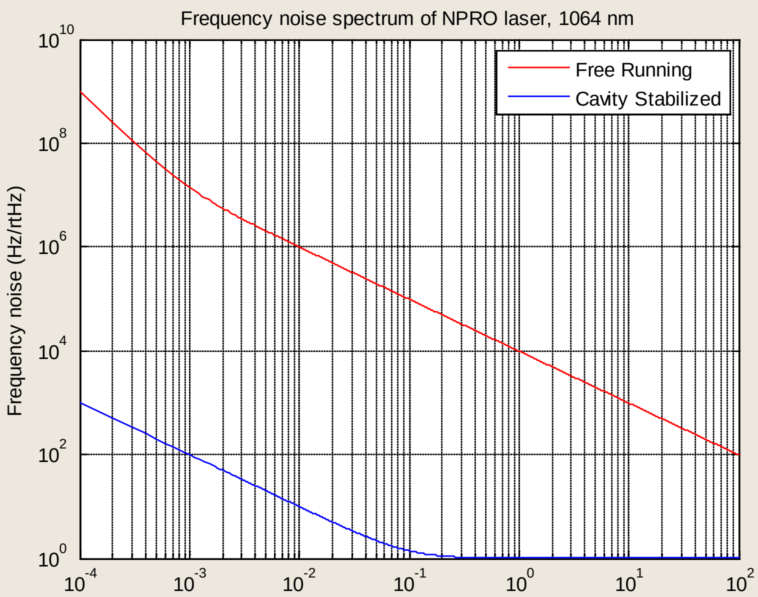


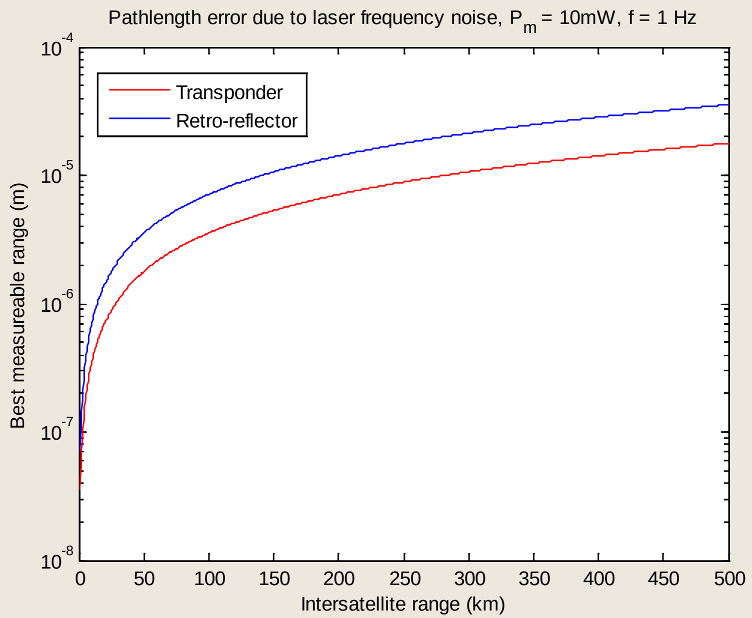
Stanford Ranging Architecture

	LISA-like	GRACE-II	Cubesat-based
Laser source	1064 nm stabilized	1064 nm stabilized	1064 nm (free running OR stabilized)
Output power	2W	30 mW	10-20 mW
One-way received power	360 pW	2000 pW	1500 pW
Aperture diameter	38 cm	1.5 cm	2 cm
S/C to S/C Distance	5x10^6 km	200 km	100-200 km
Orbit Control System	Drag free	Possible drag free	Drag free (with MGRS) Range-locked (formation)

Doppler and Laser Frequency Noise

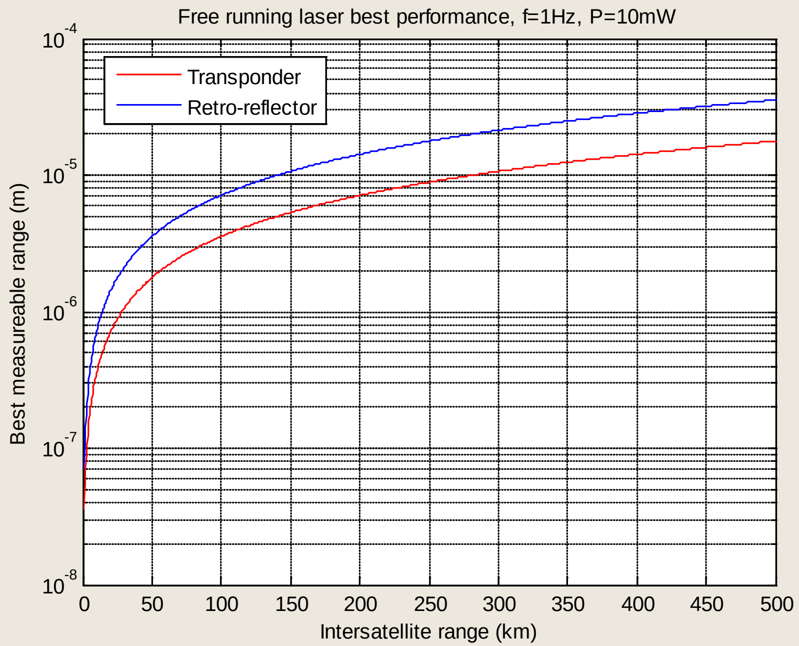
- Dominant error source is relative velocity between s/c – Doppler term $f_D \approx \frac{v_D}{\lambda}$
  - 2 m/s v_D results in ~2 MHz shift in f_{laser} → resolution limited to ~1 mm at 200 km range!
  - A few ways around this:
    - Offset phase-locked transponder, proposed for GRACE-II: $f_{heterodyne} = f_{transponder} + 2f_D$ [8]
    - Time domain interferometry, used for LISA [11],[12]
  - Ultimately requires laser source on each s/c to deal with the Doppler problem
- Use of a free-running laser: second dominant noise source
  - $\sim 10\ \mu M$ at 200 km range@1Hz frequency

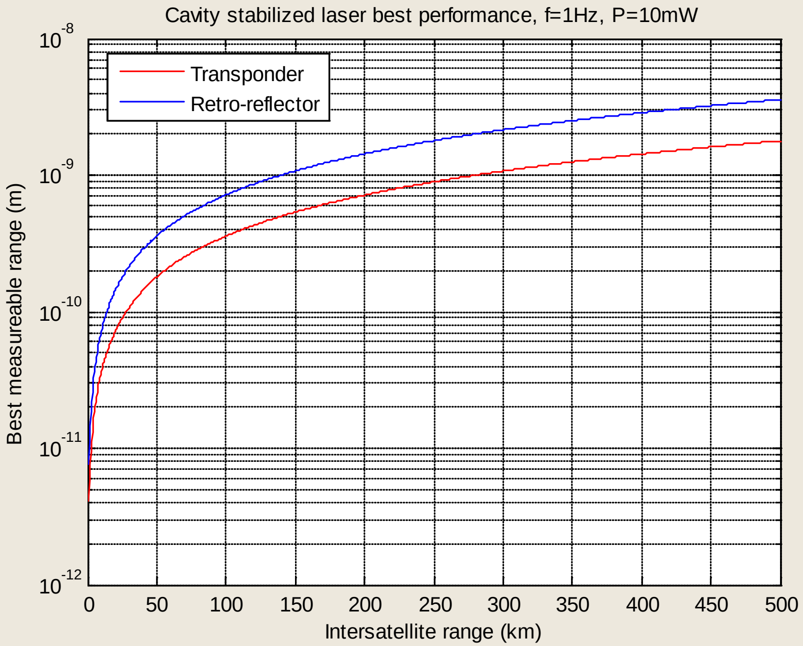




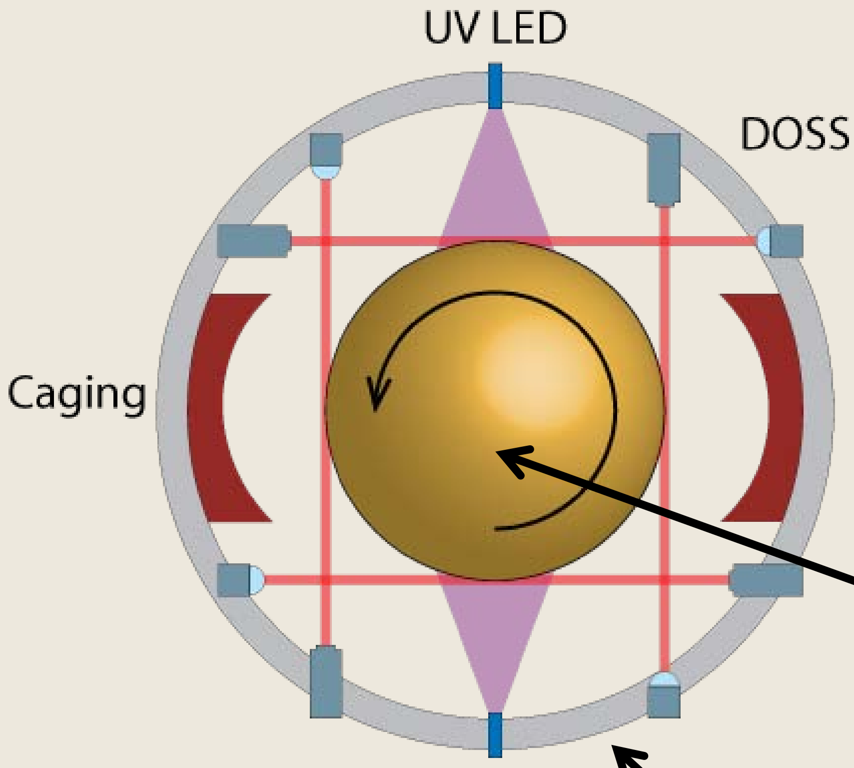
Secondary Noise Sources

- Other noise sources: USO, TDI algorithm residuals, shot noise, etc.
  - $d\phi_{shot} = \sqrt{\frac{hc}{\lambda\eta P}}$ $\quad d\phi_{USO} = \frac{\sqrt{\frac{1}{2}\left(1+\frac{\left(\frac{\alpha_{main}}{\alpha_{subtone}}\right)d\phi_{shot}\lambda}{2\pi}\right)}}{f_{1m}} f_{beatnote}$ [13]
- By stabilizing the laser with a cavity, USO and TDI residuals become dominant
- Thermal effects on optical chain – limit performance further to 50-100 nm range

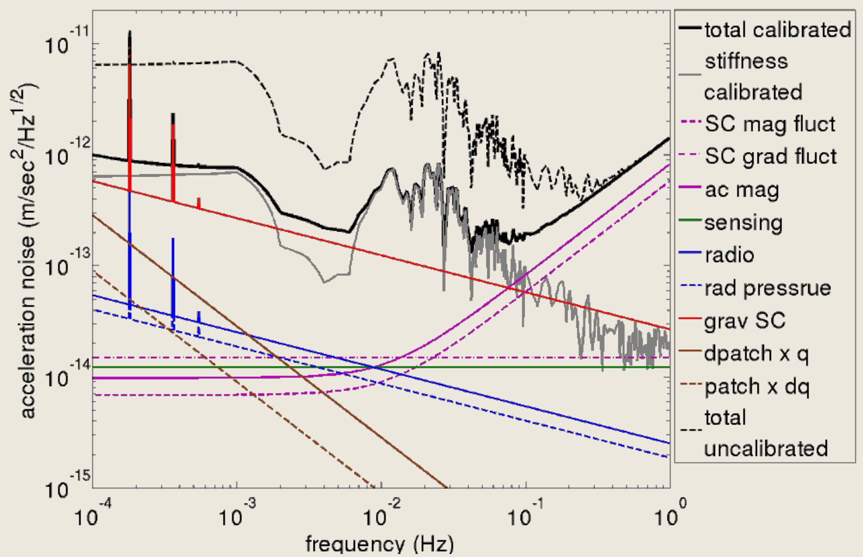




MGRS: simplified for smallsats



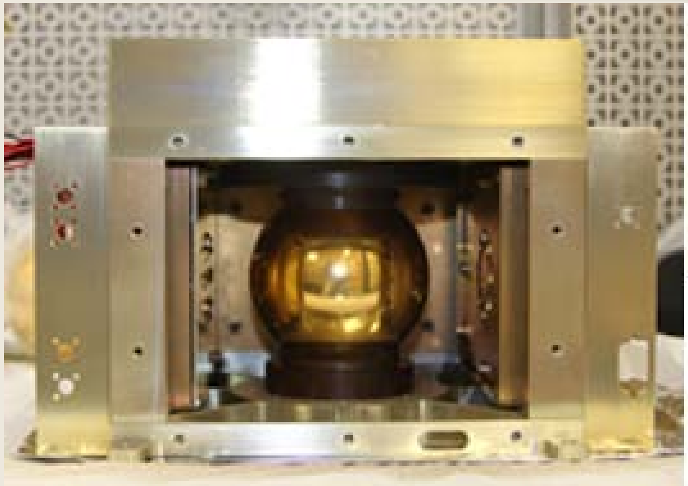
Drag-free error budget

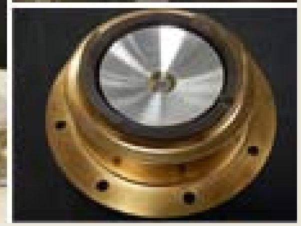


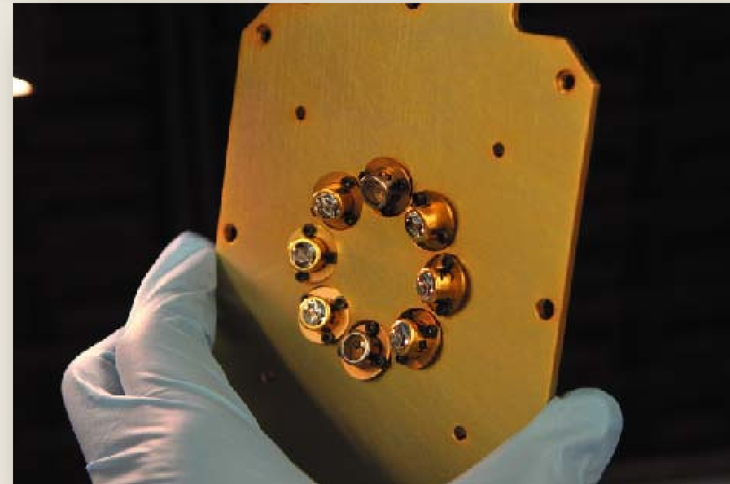
Spinning spherical Test Mass

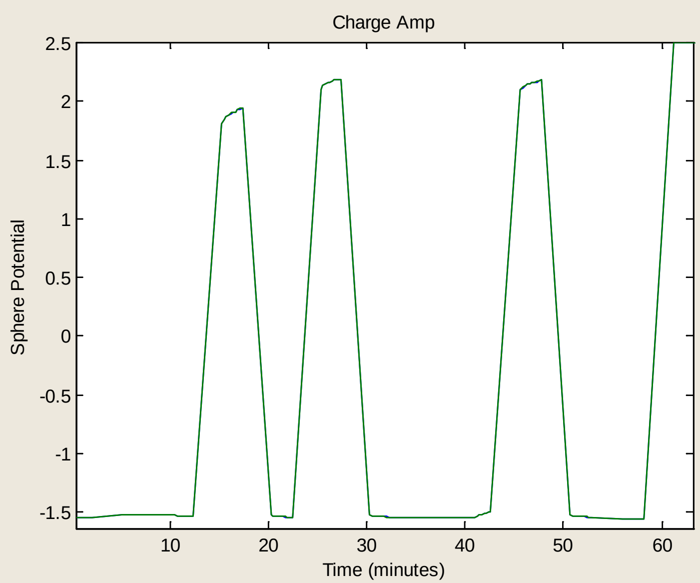
Housing (metrology reference)

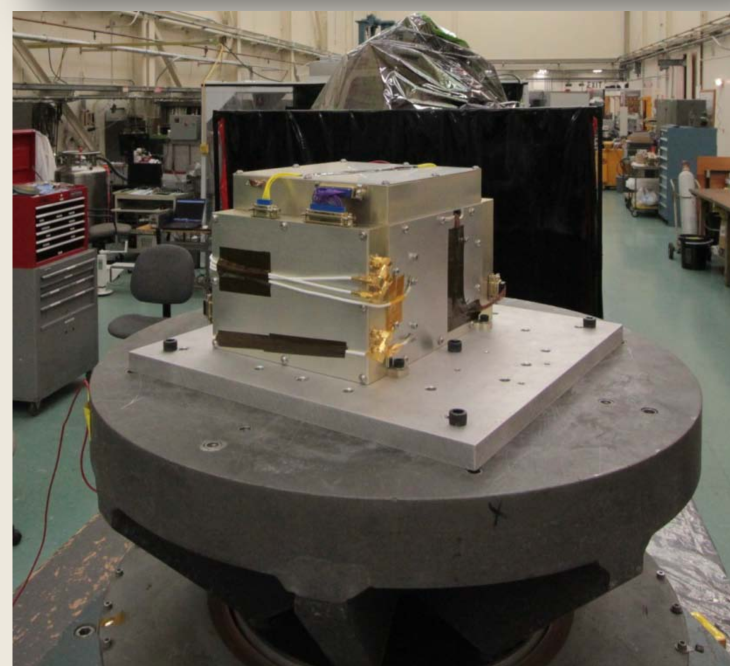
UV LED Small Sat Demonstration





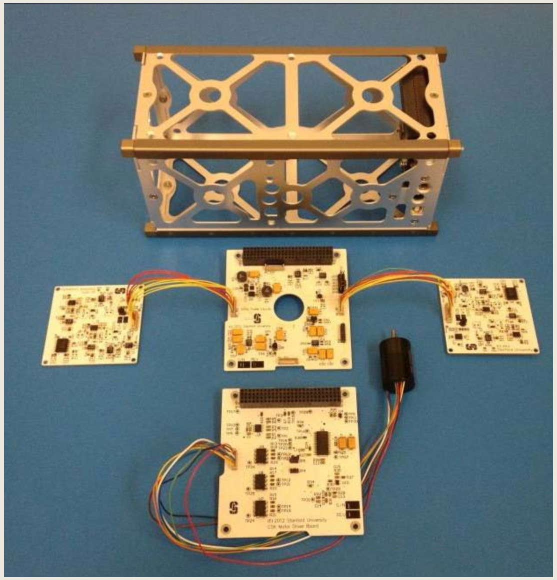




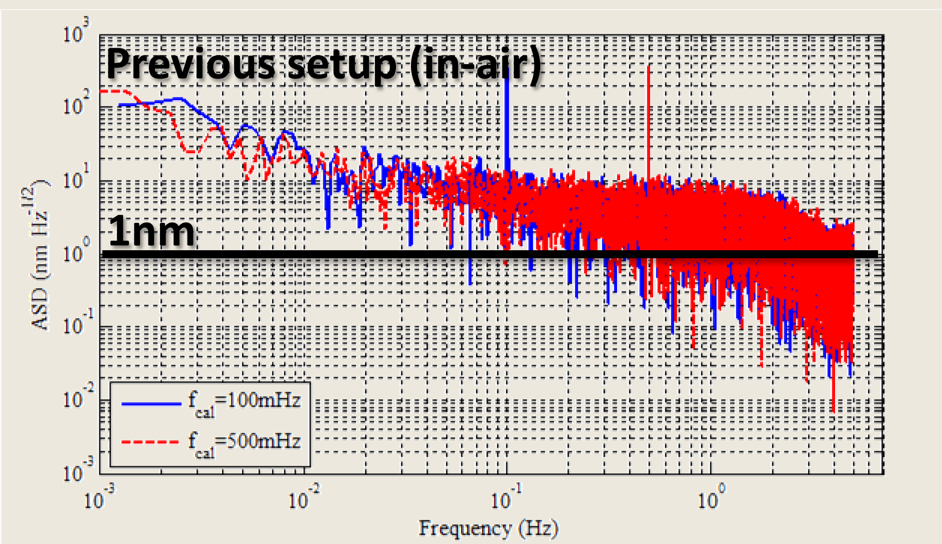


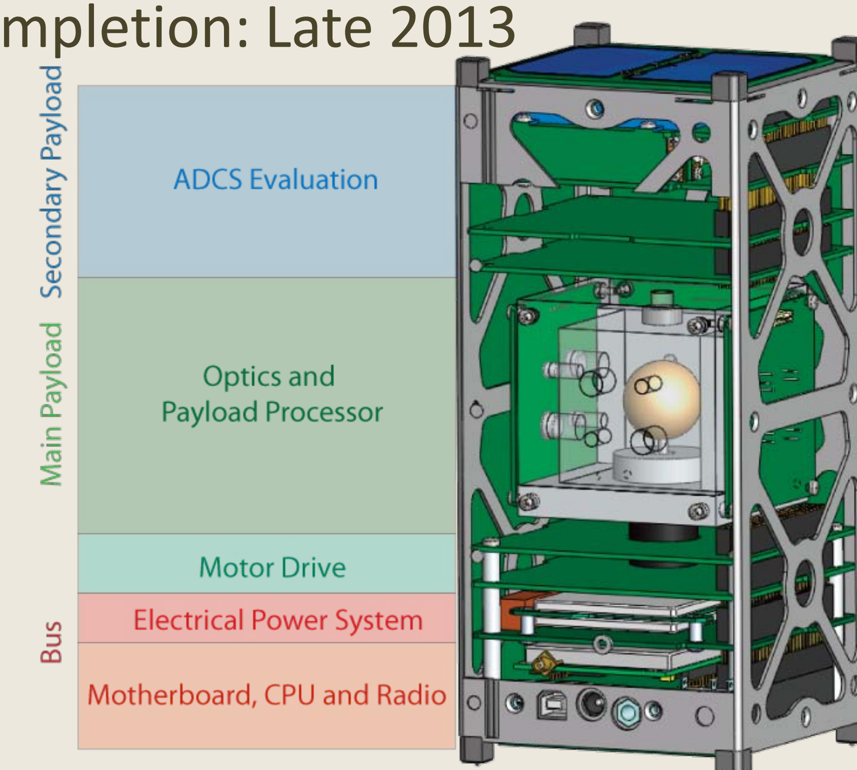
Scheduled for launch in Nov. 2013

DOSS Sat



- 2U CubeSat
- Raise Shadow Sensor TRL
- Test attitude control algorithms
- Completion: Late 2013

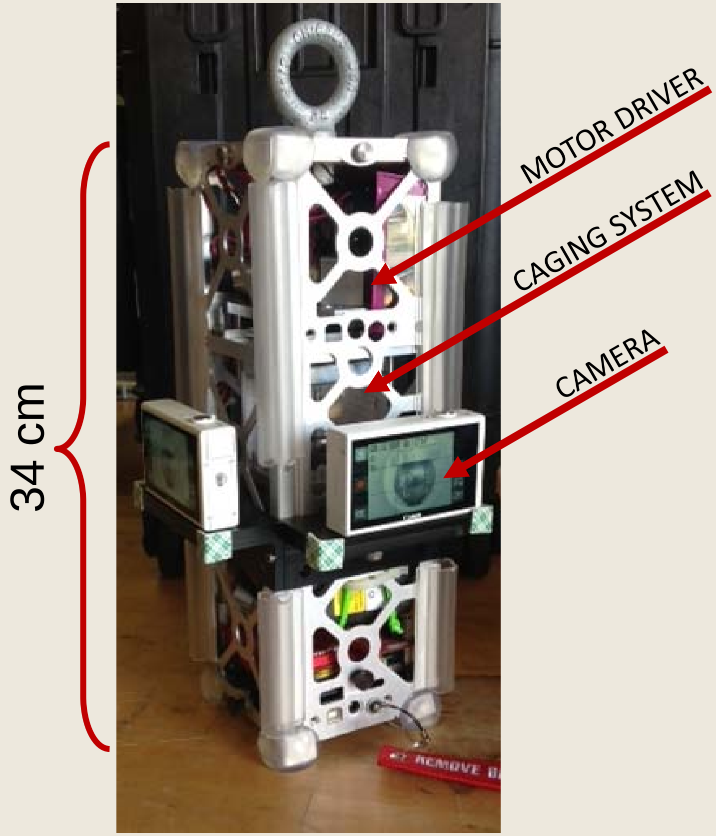


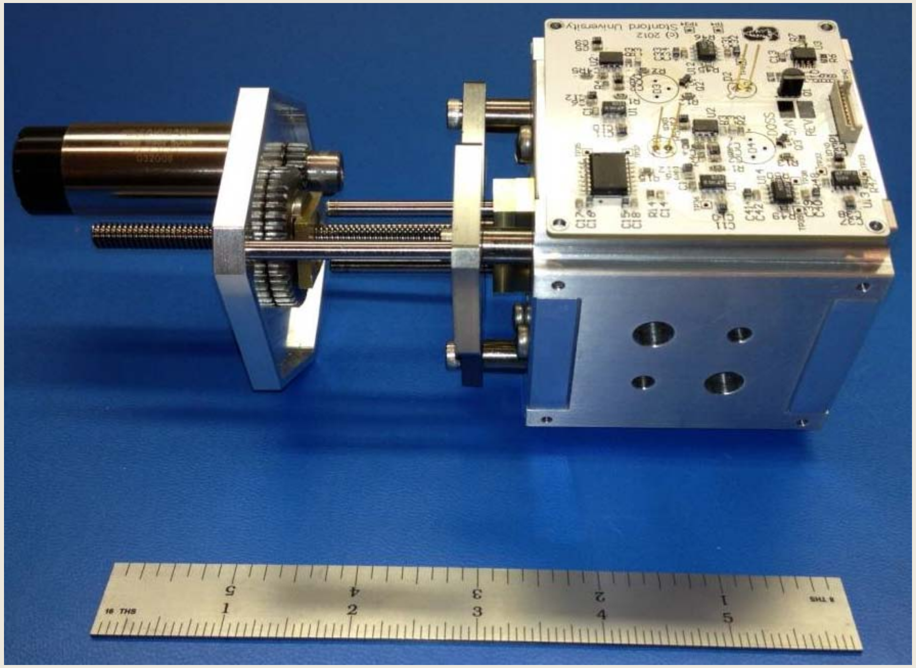


Courtesy A. Zoellner

Proof Mass Caging System

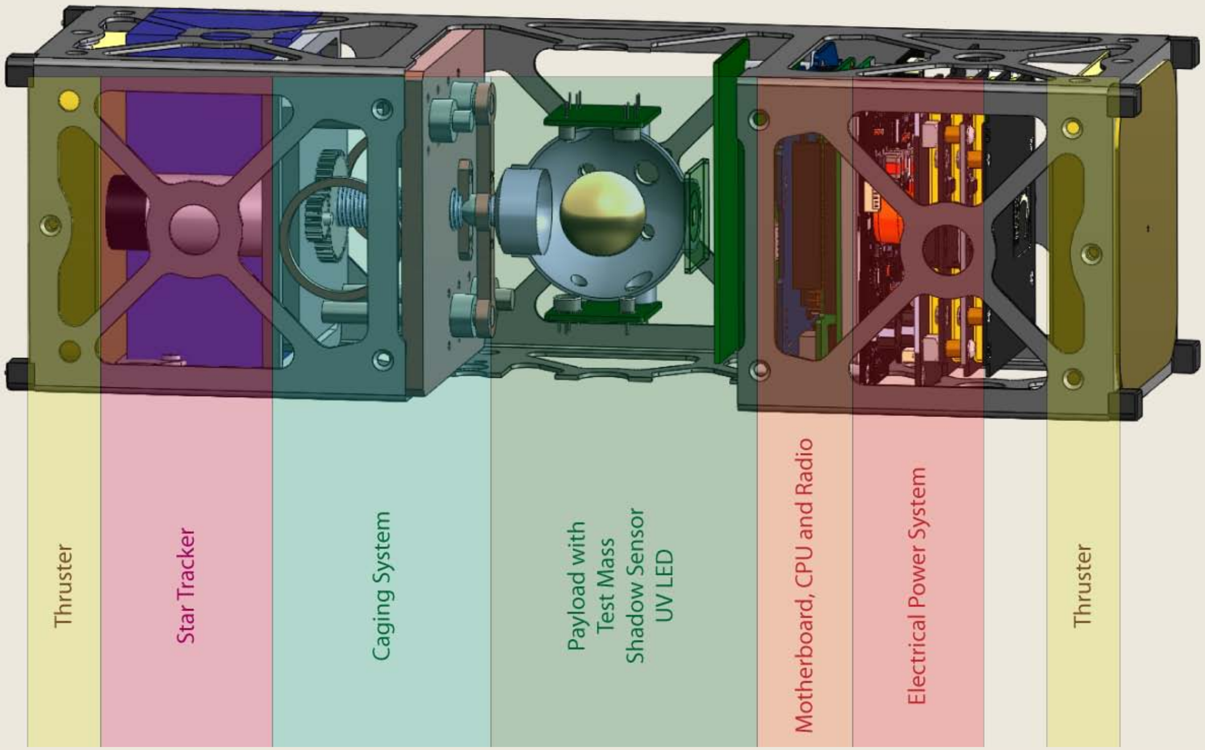
- Clamp proof mass during launch with >200 N force
- 13.5:1 gear ratio
- Currently being tested on NASA Zero-G (Eric and Andreas are in Houston right now)





Courtesy E. Hultgren, A. Zoellner

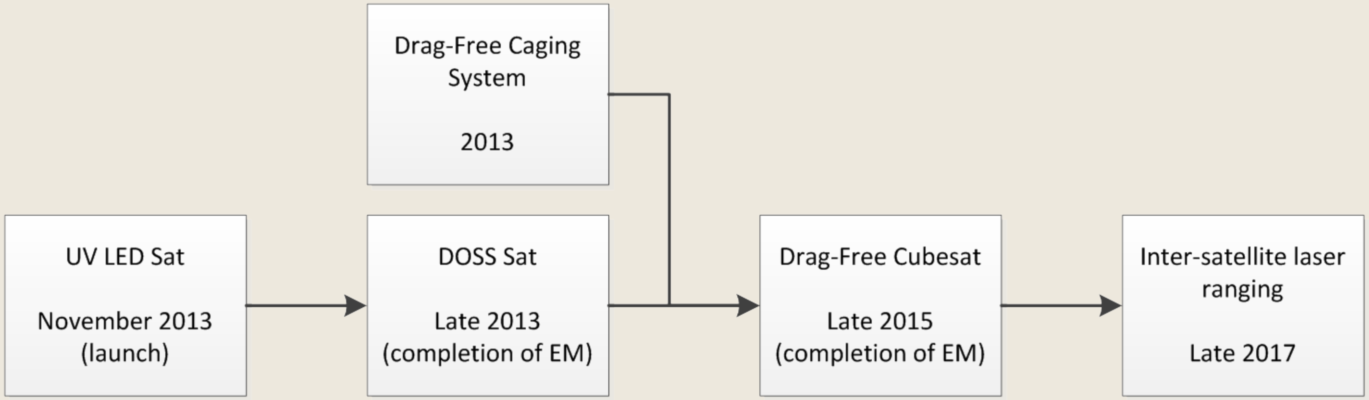
Drag Free Cubesat



- 3U CubeSat
- Full MGRS demo
- Completion: Late 2015
- Research goals:
  - Drag-free control algorithm
  - On-orbit performance evaluation of MGRS
  - Performance goal: 10^{-12} m/sec^{2}Hz$^{1/2}$ (for geodesy)

Courtesy A. Zoellner

Conclusions and Next Steps



- Plan to fly several small satellites and cubesats in series to prove out technologies step by step
- Laser ranging – next step is to build an optical breadboard model of ranging architecture and measure actual performance, and to build more detailed analyses of second order noise sources

Questions?

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