STAR

SPACE-TIME ASYMMETRY RESEARCH

The STAR program:

Science and advanced clock technology on small satellites

Sasha Buchman for the STAR Collaboration

GWADW 2011, Elba

May 25th, 2011

STAR concept

Science

1) Lorentz Invariance Violations
2) Velocity boost c dependence
   "Kennedy-Thorndike Experiment"
3) >100x state of the art

Science & Technology on Small Satellites

Education driven

International collaborations

Education

1) Graduate & Undergraduate
2) 3-5 year projects
3) Student led tasks

Technology

1) "Capable" small satellite bus
   180 kg, 185 W, secondary payload
2) Advanced frequency standards
3) Precision thermal control

STAR collaboration

Collaborating Institutions
Main Contributions
ALL
Science and EP&O
Ames Research Center
PM, SE, I&T, and SM&A
KACST
Spacecraft and Launch
Stanford University
PI and Instruments ***to TRL 4***
German Space Agency et al
Instruments, Flight Clock
JILA
Instruments ***to TRL 4***
Industrial Partner
Flight Instrument

- **Germany**
  - *German Aerospace Center (DLR)*
  - *ZARM & Bremen University*
  - *Humboldt University, Berlin*
  - *University of Konstanz*
- **Kingdom of Saudi Arabia**
  - *King Abdulaziz City for Science and Technology (KACST)*
- **United States**
  - *NASA Ames Research Center (ARC)*
  - *Stanford University*
  - *Joint Institute for Laboratory Astrophysics (JILA)*
  - *University of California-Davis*
  - *Industrial partner*

Advanced frequency standards

$$\delta f / f \leq 10^{-13} / \sqrt{\mathrm{Hz}}$$

Optical cavities

1064 nm

>100,000 finesse

Molecular clocks

Iodine

532 nm

Phase compensated fiber coupling

Compact & robust fiber coupler to cavity

NANO KELVIN THERMAL CONTROL

$$\delta T_{(Instrument)} / \Delta T_{(Outer\ shield)} \leq 10^{-9}$$

Nested **thermal shields**

Advanced control algorithms

Optical cavity thermometry

Stanford MGRS group developments parallel to STAR work

UV-LED AC charge management

- UV-LED source
- AC charge control
- Non-contact electrometer charge measurement

Grating angular sensor

- $< 10^{-9}$ rad/√Hz precission

Why measure *c* invariance?

Colladay and Kostelecky (1997)

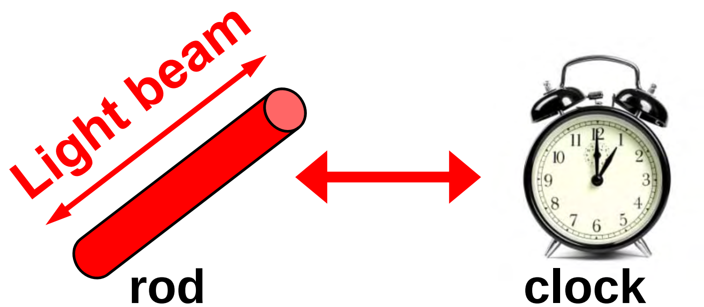
"The natural scale for a fundamental theory including gravity is governed by the Planck mass M_P, which is about 17 orders of magnitude greater than the electroweak scale m_W associated with the standard model. This suggests that observable experimental signals from a fundamental theory might be expected to be suppressed by some power of the ratio:

$$r \approx \frac{m_W}{M_P} \sim 10^{-17}$$

THE STAR SENSITIVITY COULD CLOSE THAT GAP

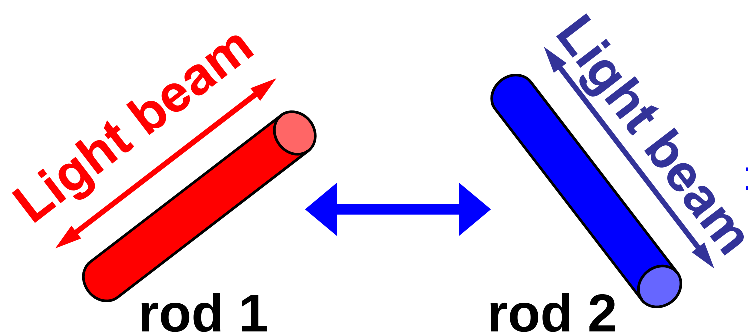
HOW DOES ONE MEASURE CHANGES IN *C*?

(1) By comparing the length of a **rod** (measured by light beam) to the rate of a ticking **clock**



⇒ **KT coefficient (function v_{INSTR})**

(2) By comparing the length of two **rods** ‘perpendicular’ to one another (both measured with a light beam)

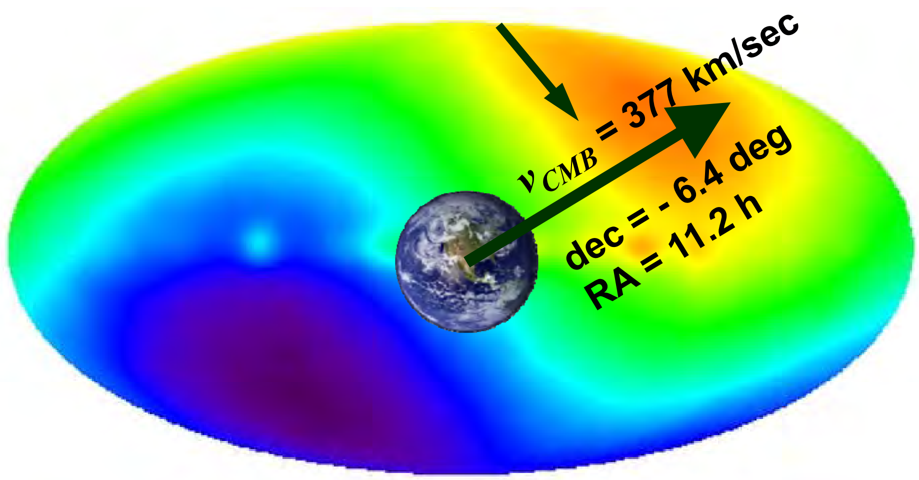


⇒ **MM coefficient** (function θ_{INSTR})

Kinematic approach to LIV

RMS approach:
- -Robertson (1949)
- -Mansouri &
- -Sexl (1977)

Is the CMB a preferred frame?



$$\frac{\Delta c}{c} = C_{MM} \sin^2 \theta_{INSTR} \left(\frac{v_{INSTR} - v_{CMB}}{c} \right)^2 + C_{KT} \left(\frac{v_{INSTR} - v_{CMB}}{c} \right)^2$$

C_{MM}: Michelson Morley Coefficient

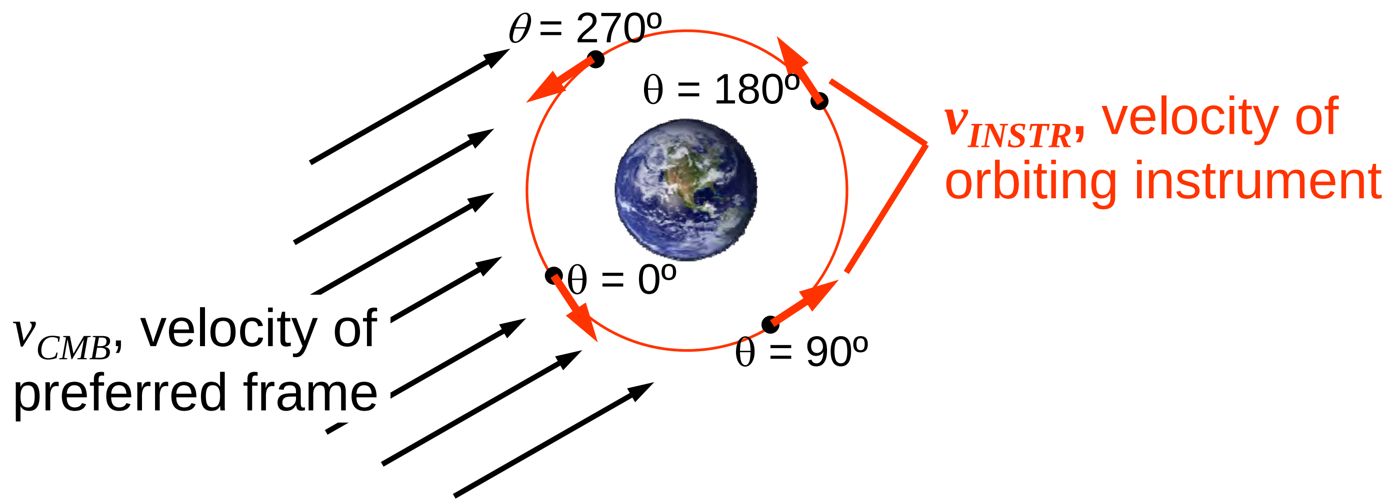
C_{KT}: Kennedy Thorndike Coefficient

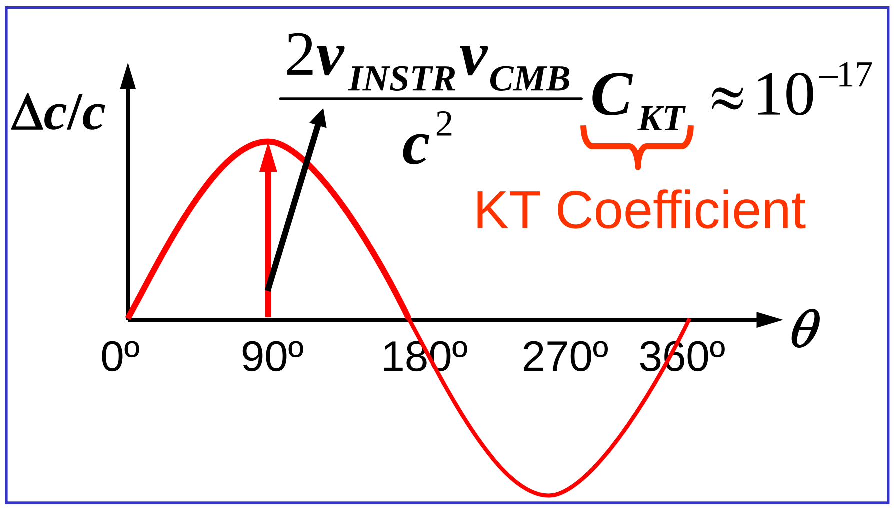
v_{INSTR}, v_{CMB} = velocity of instrument, preferred frame

θ_{INSTR} = angle of light beam (instrument) to the PF

in Special Relativity $C_{MM}=C_{KT}=0$

Measuring KT





A velocity-dependent LIV would cause a $\Delta c/c$ variation at the orbital rate

Why KT in space?

- **Kennedy-Thorndike signal enhancement**
  - Signal modulated at satellite orbital variation **~1.5 hr**
  - Signal modulated at orbital velocity differences **±7 km/s**
    - Diurnal Earth rotation signal **<0.30 km/s @ 24 hr**
    - Yearly Earth orbital motion signal at **30 km/s @ 8766 hr**

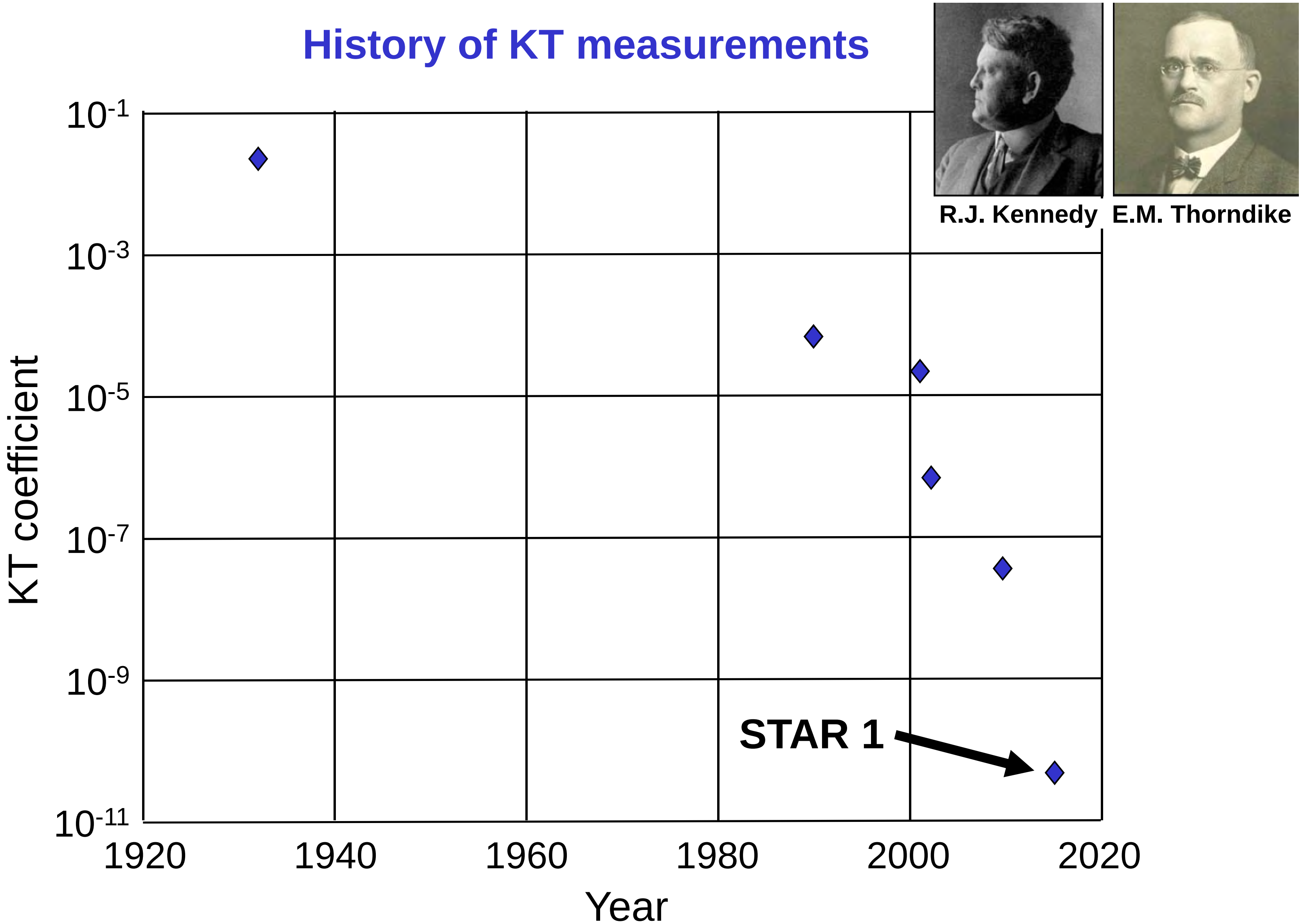
- **Disturbance reduction**
  - Microgravity
  - Seismic quietness
  - Relaxed stress due to self weight
  - Far away from time dependent gravity gradient noises

KT Improvement in Space:

- **Faster signal modulation** **×4 (√16)**
- **Higher velocity modulation** **×20 to ×30**
- **Other considerations** **~ 1 to 3**

Net Overall Advantage ≥ 100

KT history


History of KT measurements
KT coefficient
10-1
10-3
10-5
10-7
10-9
10-11
1920
1940
1960
1980
2000
2020
Year
STAR 1
R.J. Kennedy
E.M. Thorndike

Optical cavity

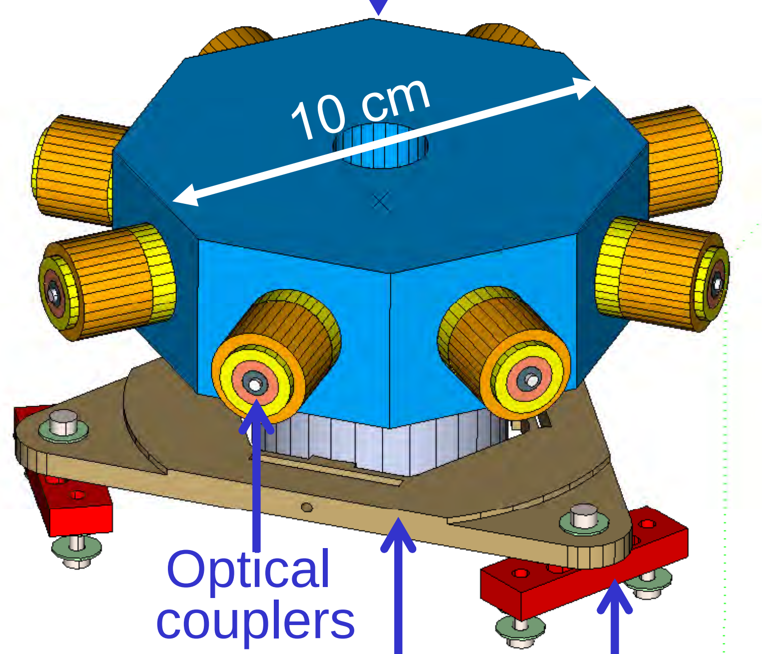
Key optical cavity parameters:

- $\delta L/L < 10^{-17}$ at orbit and harmonics with 2 years of data
- $\delta L/L < 10^{-17}$ at twice spin period with 2 years of data

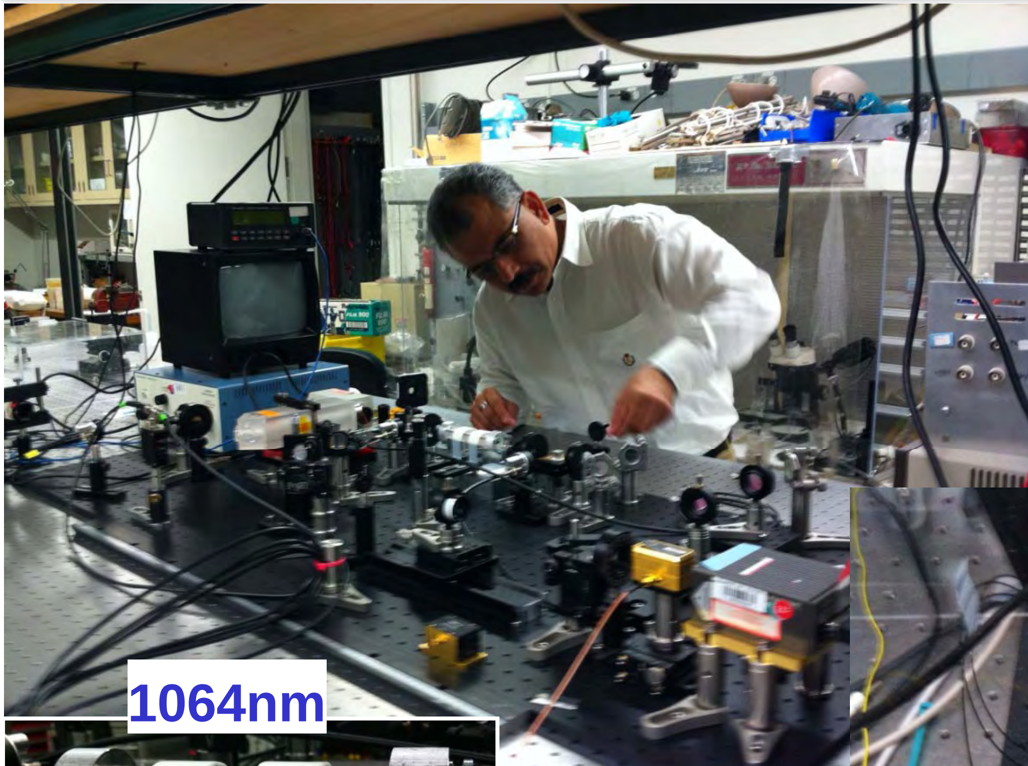
Derived requirements:

- Expansion coefficient: $< 10^{-9}$ per K
- Operating temperature: within 1 mK of expansion null (~ 15°C nom)
- External strain attenuation: $> 10^{12}$
- Stiffness: $\delta L/L < 10^{-9}$ per g, 3-axis
- Implied material: ULE glass

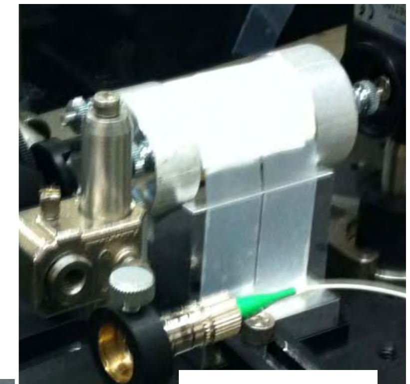
ULE cavity block (4 cavities@ 45 deg)



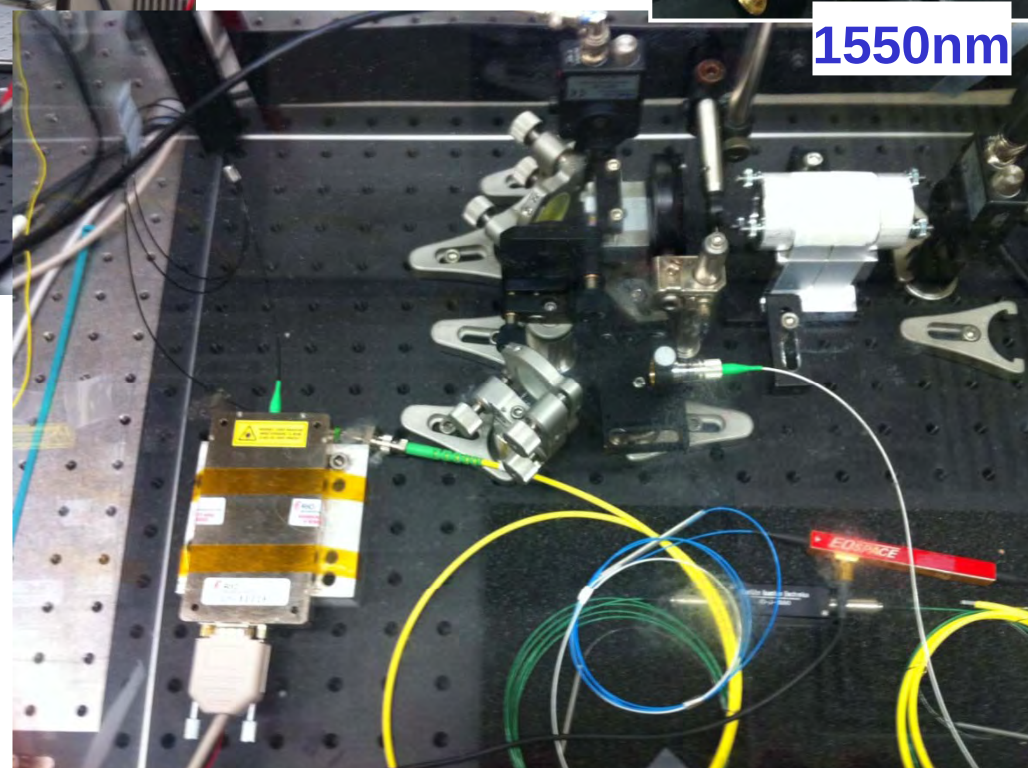
Optical cavity work at Stanford



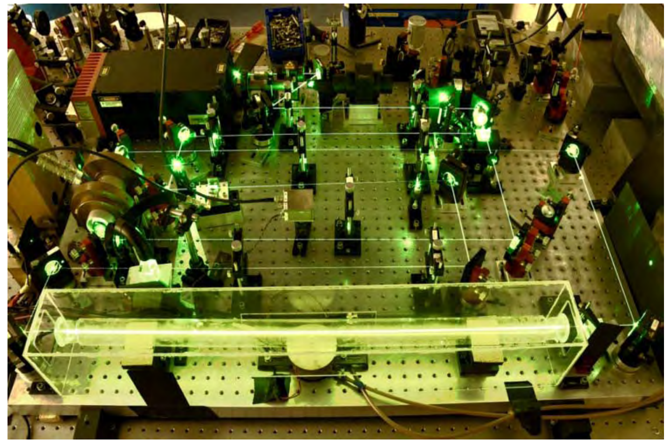
1064nm

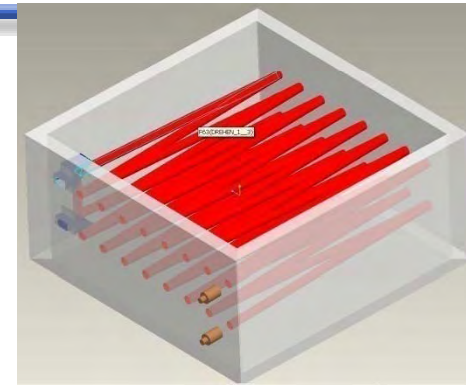


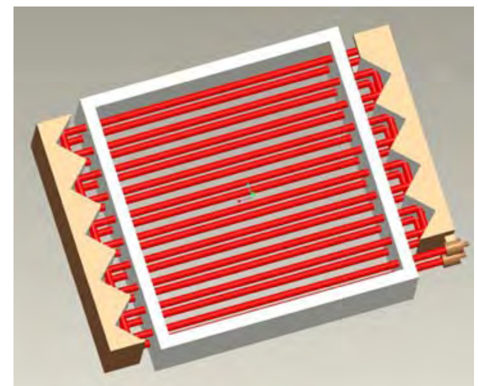
1550nm

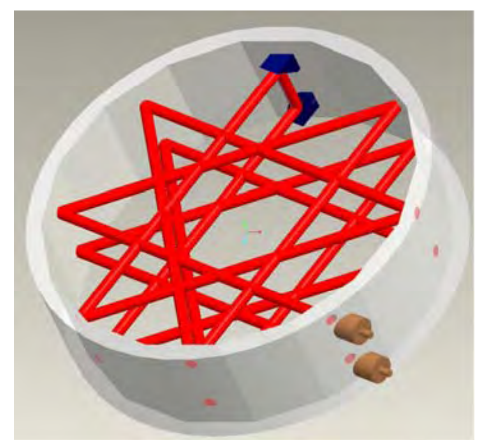


Atomic reference





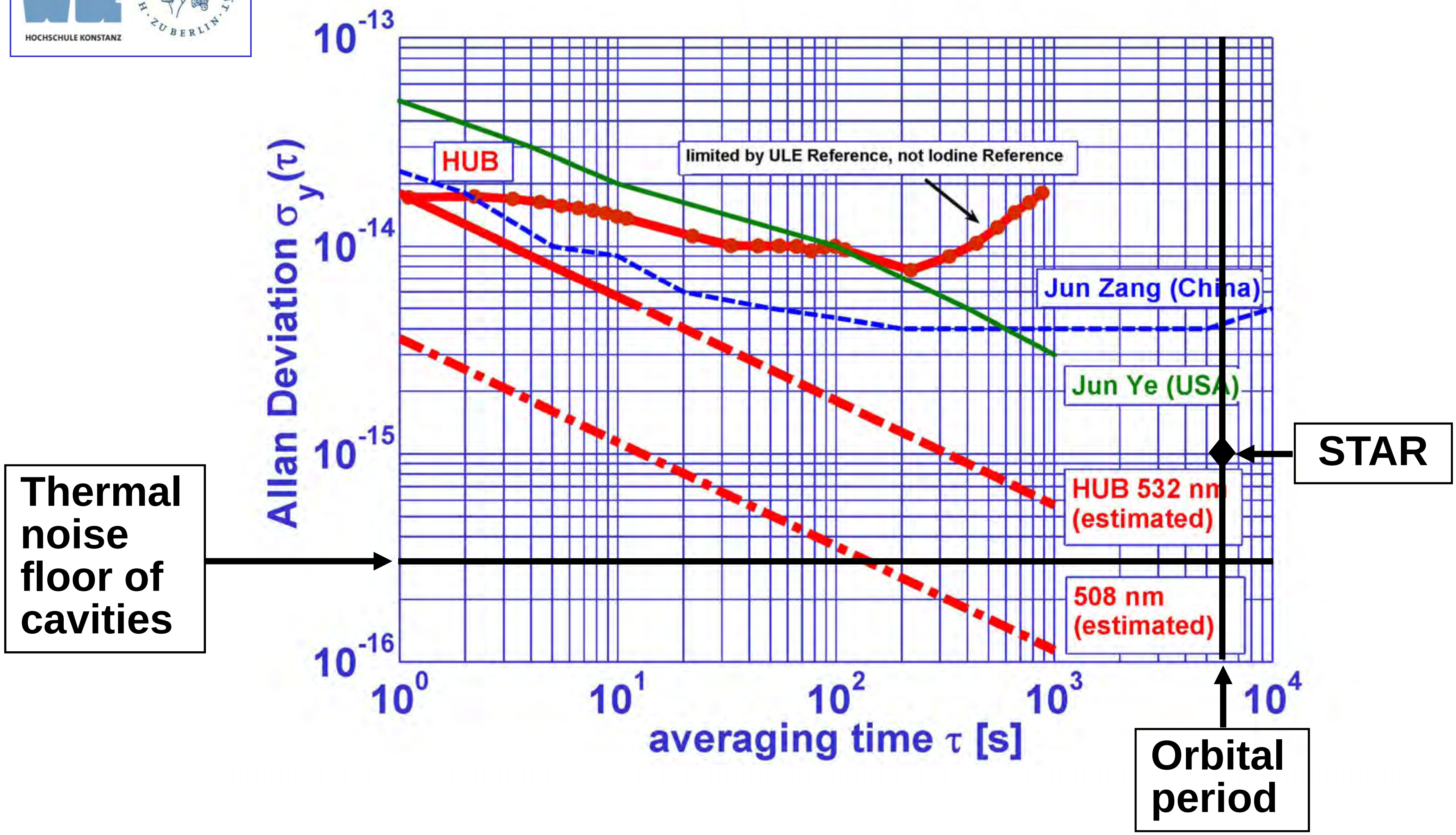




Next steps:

- set up of a compact Iodine standard multi-pass cell
- baseplate made of Zerodur (for space-qualification and pointing stability)
- Using s.q. AI-Technology
  (HTWG Konstanz / EADS Astrium)

State of the art: Iodine vs. cavity



Thermal enclosure

Main Requirements:

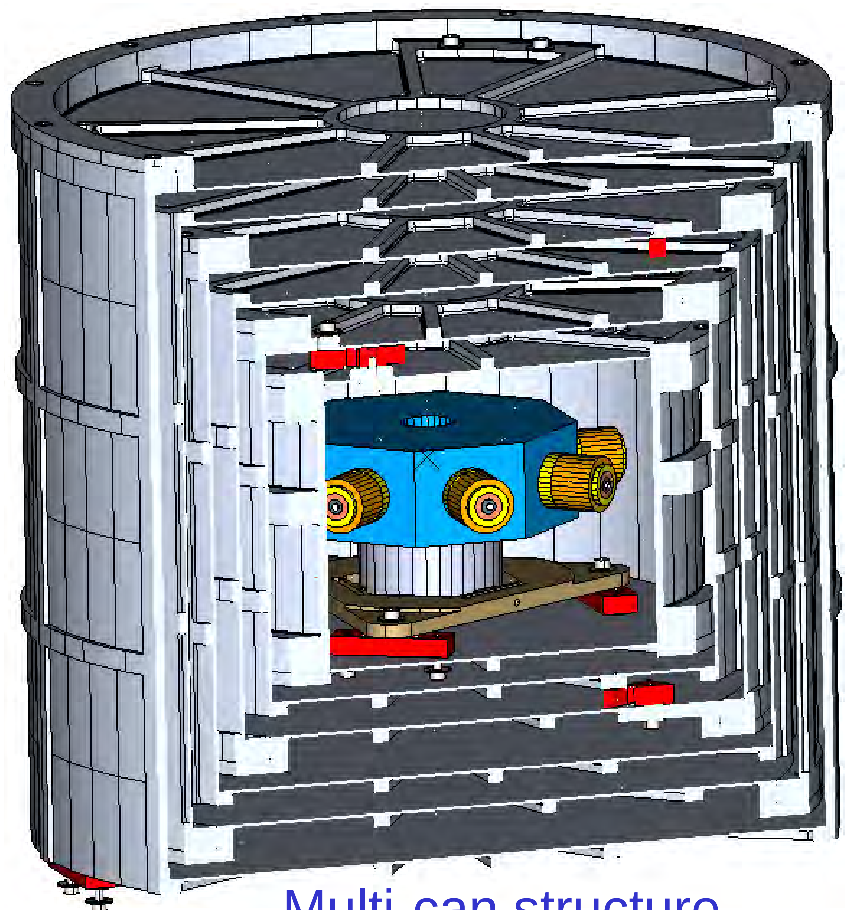
- Thermal stability
- Stress attenuation
- Launch and space compatible

Thermal performance:

- Cavity $\delta L/L < 10^{-17}$ (2 yr data) at:
  - orbital period and harmonics
  - twice spin period

Derived requirements (2 yr average):

- Thermal stability of 10^{-8} K at orbit
- Thermal gradient ~ 10^{-9} K/cm at orbit
- Maintain cavities temperature to 1 mK

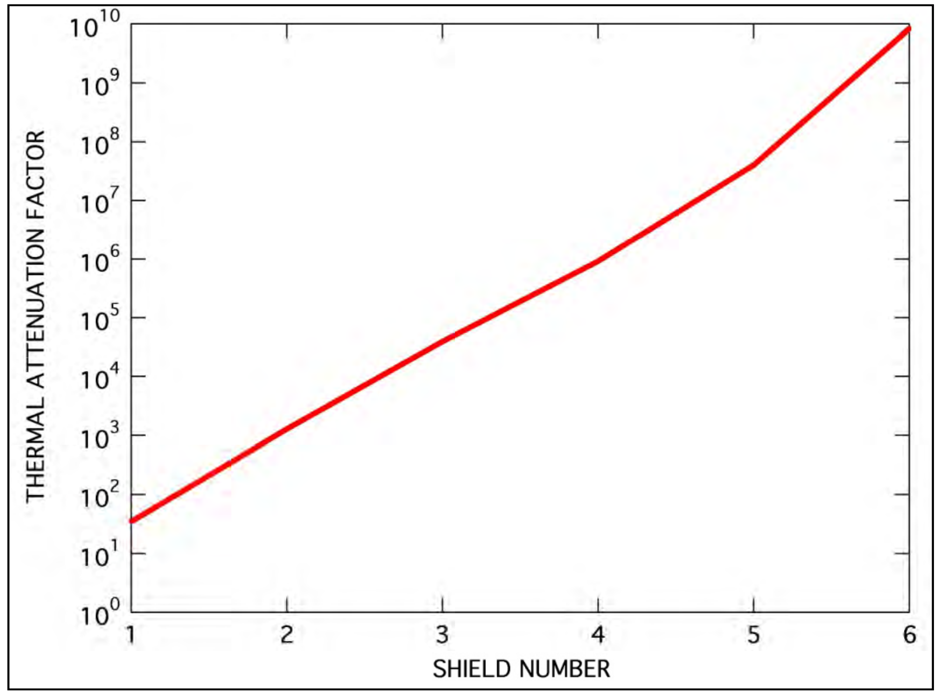


Multi-can structure

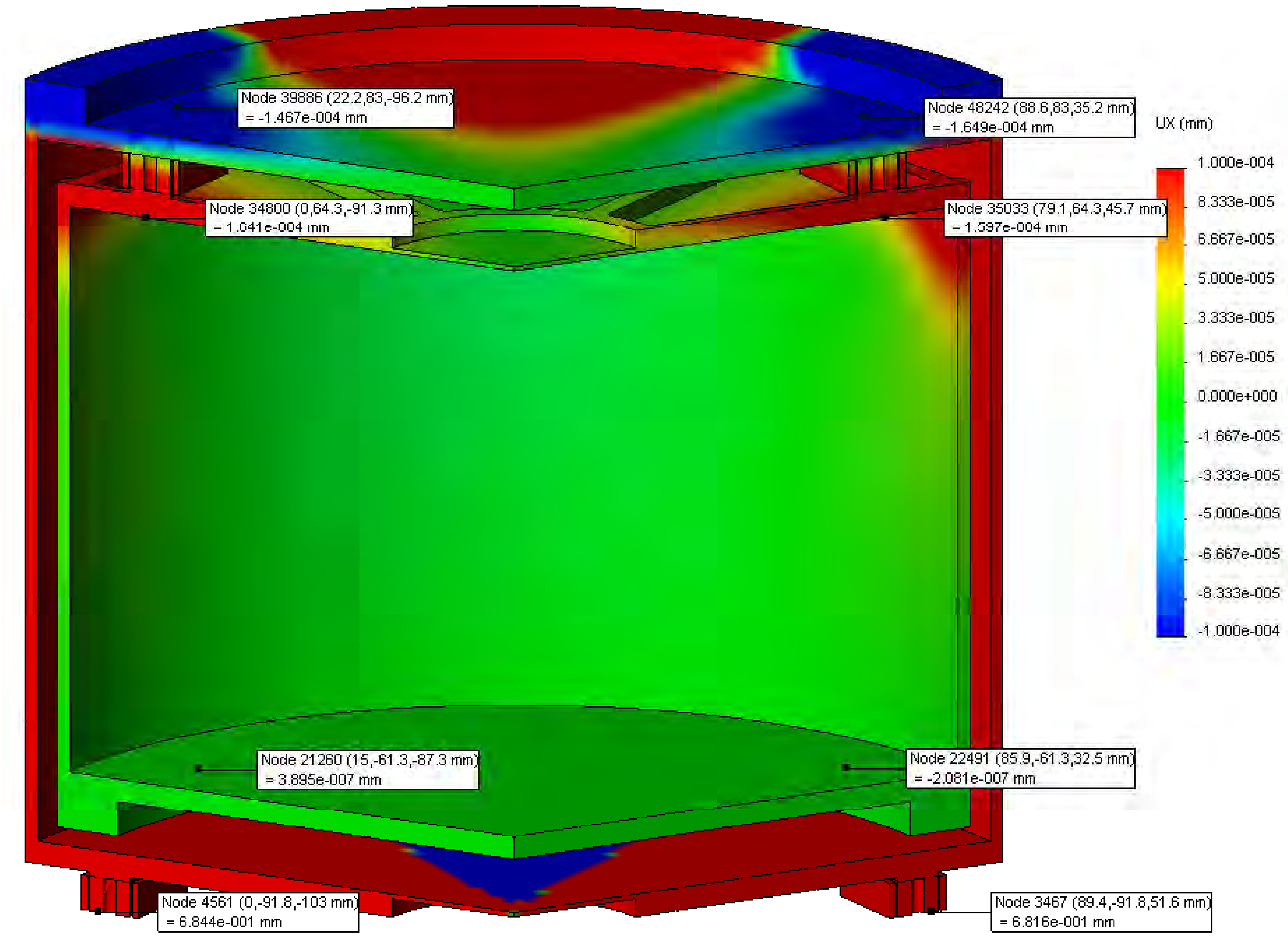
Thermal attenuation of shields

The 31st day			
Shield # n	**A (K)**	**A_n/A_{n+1}**	**A_1/A_{n+1}**
1 (Outer)	1×10^{1}	1.0	1.0
2	2.9×10^{-1}	35.0	3.5×10^{1}
3	7.8×10^{-3}	36.6	1.3×10^{3}
4	2.6×10^{-4}	30.4	3.9×10^{4}
5	1.1×10^{-5}	23.5	9.1×10^{5}
6	2.5×10^{-7}	44.2	4.0×10^{7}
Cavity	**1.2×10^{-9}**	**210**	**8.5×10^{9}**

A_n: *amplitude of thermal modulation at orbital period*



Strain attenuation model - FEA



- ➢ Estimated strain attenuation: > 10^3 per can
- ➢ Extrapolating to entire enclosure: > 10^{15}
- ➢ Exceeds requirement by x1000

Advanced frequency standards

Optical cavities

Molecular clocks

$$\delta f / f \leq 10^{-13} / \sqrt{\mathrm{Hz}}$$

nano Kelvin thermal control

Thermal shields

Control algorithms

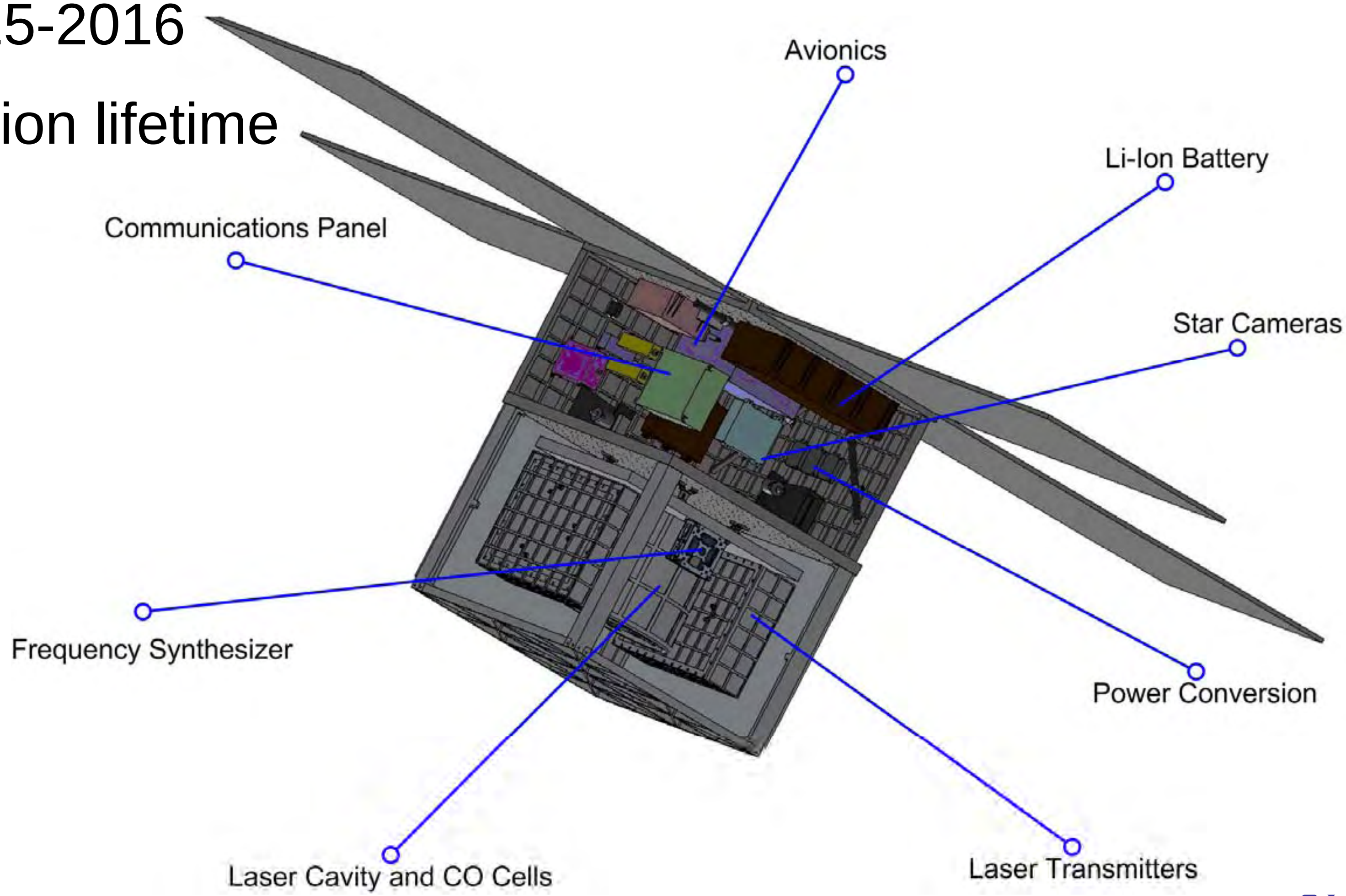
Optical thermometry

$$\delta T_{(Instrument)} / \Delta T_{(Outer\ shield)} \leq 10^{-9}$$

$$\delta F_{(Instrument)} / \Delta F_{(Outer\ shield)} \leq 10^{-12}$$

STAR mission characteristics

- ESPA compatible secondary payload on an EELV launch
- Circular sun-synchronous ~ 650 km orbit
- Launch 2015-2016
- 2-year mission lifetime



MGRS technology development on multiple mini-satellites

MGRS Small Satellite Series
7 Nanosats + 2 Microsats + 1 Constellation
Low Cost, High Impact

MGRS System Design
Science and Technology Goals

UV LED Charge Management
& Proof Mass Holding

Grating Angular Sensor
& Laser Frequency Stabilizer

Grating Displacement Sensor
& Grating Angular Sensor

Lasers, Nonlinear Optics
& Grating Interferometer

Optical Shadow Sensing
& Proof Mass Caging

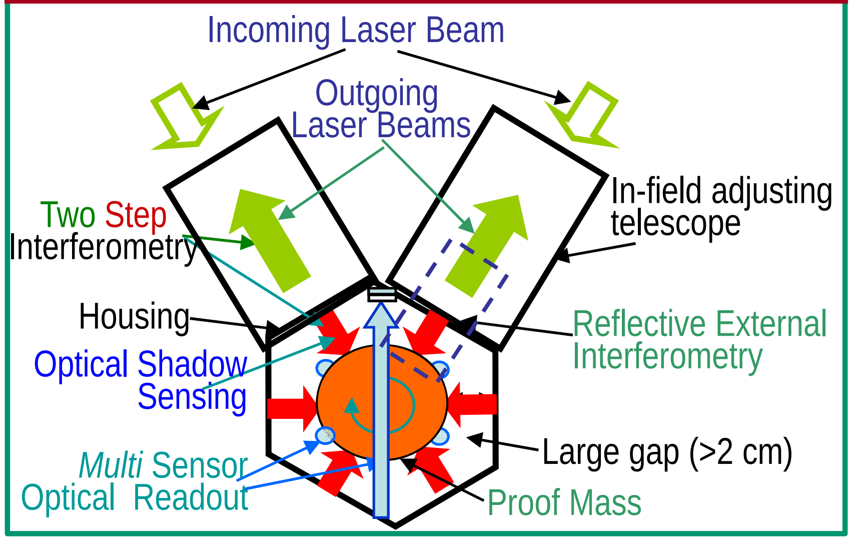
Micro Thruster
& Nano Thruster

ATC Control, Thruster
& Release Proof Mass

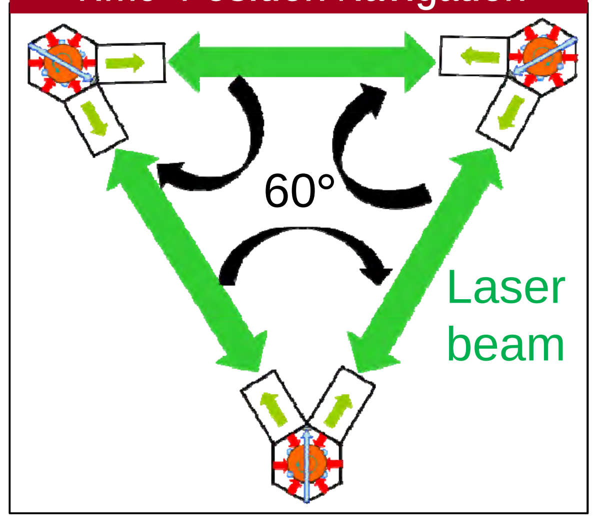
MGRS System Combined
from Previous Flights

MGRS for Science Mission
MGRS Constellation

Modular GRS



MGRS Constellation for
Scientific Experiments & Space
Time- Position Navigation

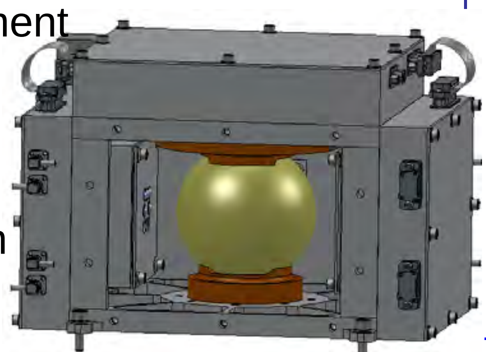


UV LEDs for Precision Non-contact Charge Management

Current TRL: 4 **Target TRL: 7/8**

Concept Description: Space qualification

- AC charge management
- Deep UV light emitting diodes
- Multiple UV LED's
- Complete charge management system
- Replicate ground experiment in space

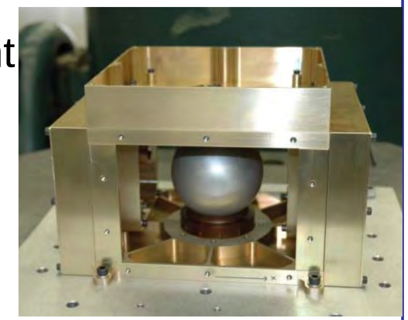


Target Program:

- Miniature drag free technology

Related/Prior Technology Development :

- LED's radiation tested
- AC charge management laboratory tested
- Flight experiment performed in laboratory
- Mechanical prototype passed vibe test
- Electronics in protyping



Partnership/Development Team:

- Ames: PM, SE, SMA, Mission operations
- Stanford: Science and Payload Design
- KACST: Spacecraft and Launch

Development Risk/Reward:

- Replace existing Hg lamp technology
- Support high profile NASA missions with key technology demonstration in orbit (LISA)

Development Focus:

- Demonstration of complete flight experiment in laboratory environment prior to flight build

Potential Applications:

- Active charge control of free flying test mass
- Active charge control of isolated masses

Potential Customers:

- LISA, LPF, BBO, GRACE (next), DECIGO

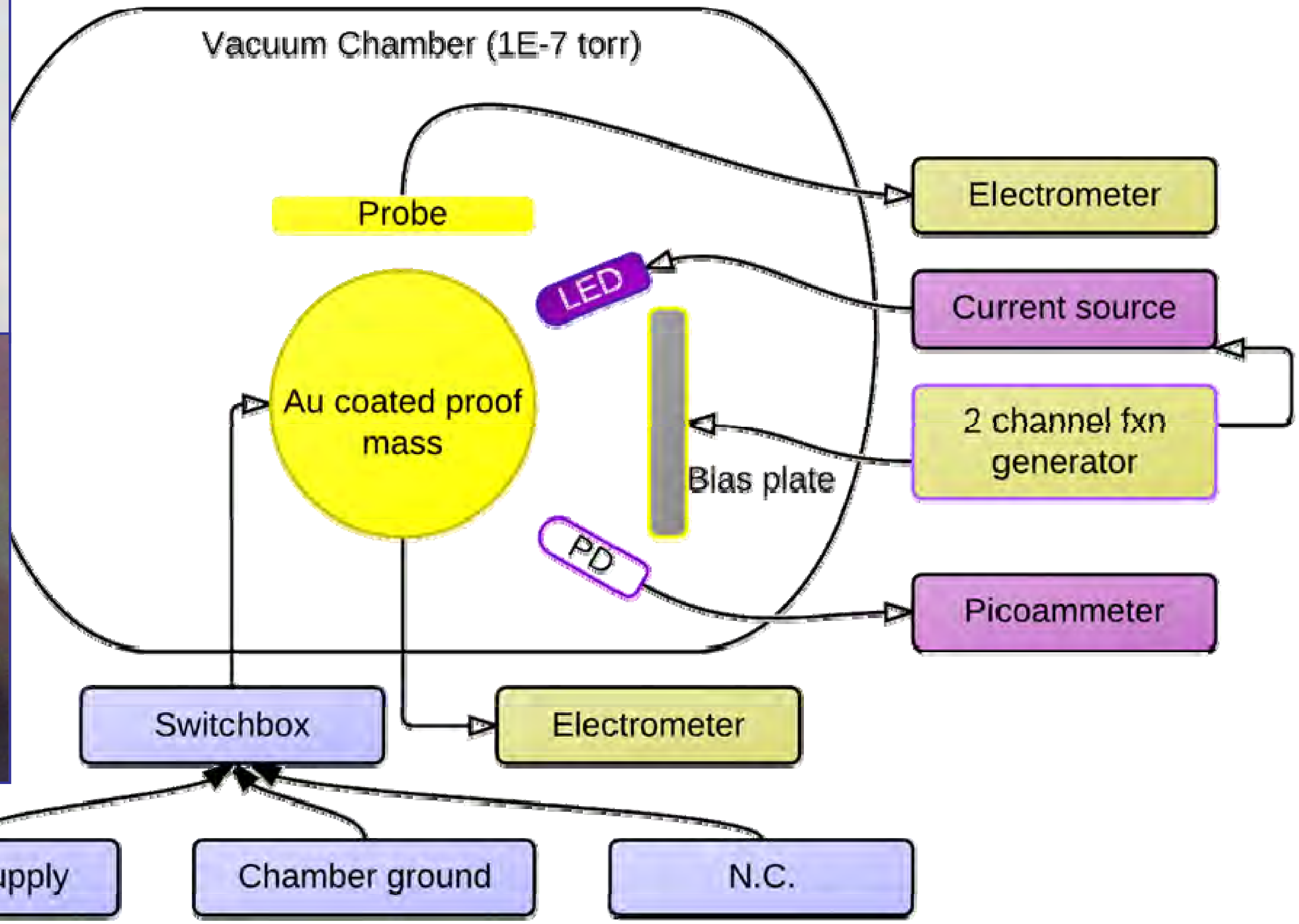
Benefit to NASA:

- Lay groundwork for STAR
- Develop ties with academia and key international partners
- Develop groundbreaking technology for flagship missions (LISA) on small satellites

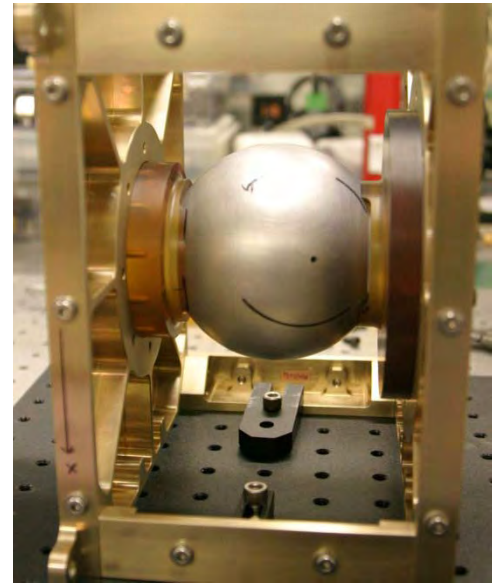
Schedule:

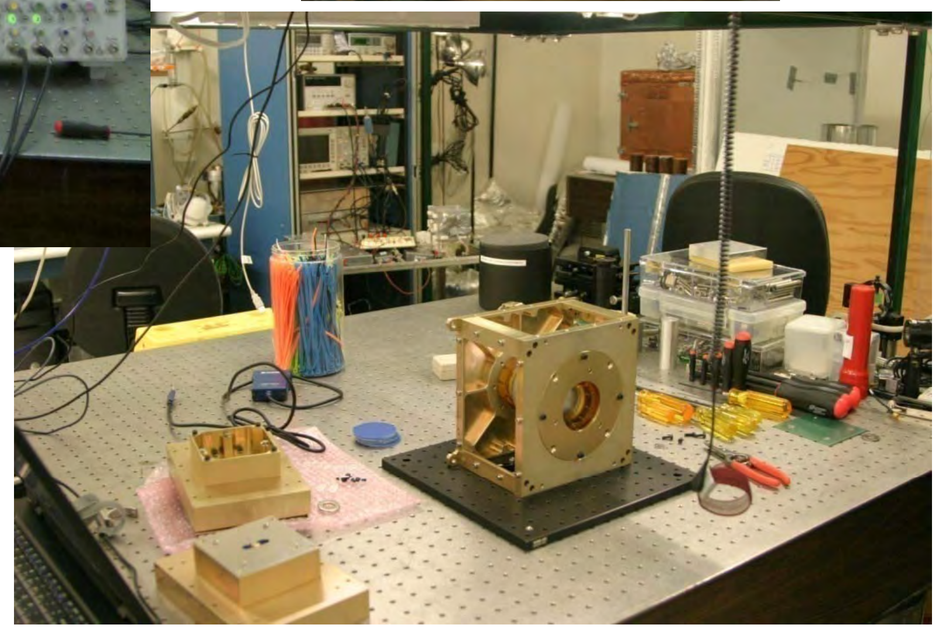
- Engineering Model Complete: 5/24/2011
- Critical Design Review: 7/6/2011
- Flight Payload Complete: 11/1/2011
- Launch: 9/1/2012
- Mission Completion: 9/1/2013

UV-LED experimental setup



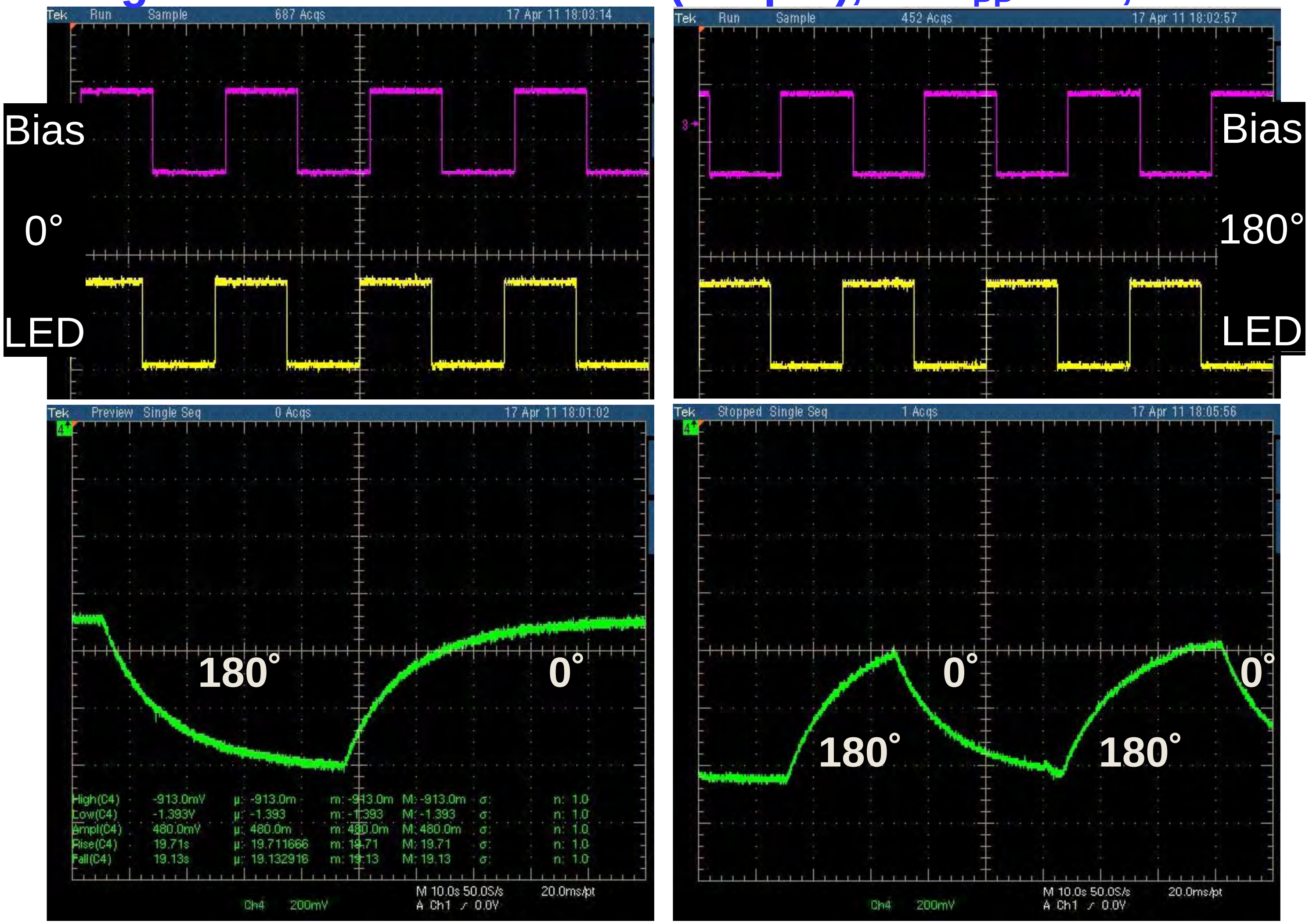
UV-LED laboratory





Charge management results

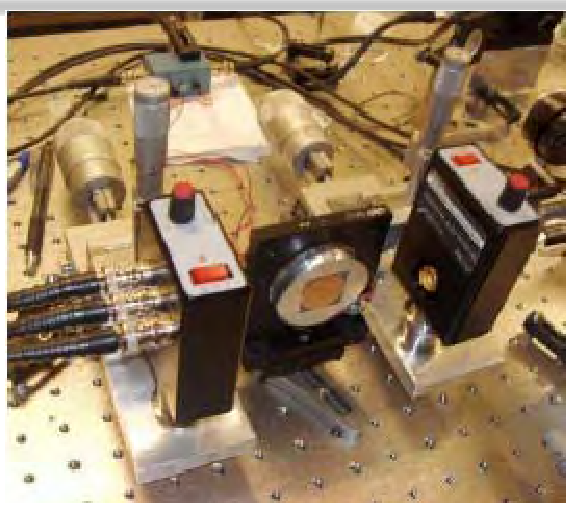
Single LED driven at 6.4mA (~10µW), 3.0V_{PP} bias, 100Hz



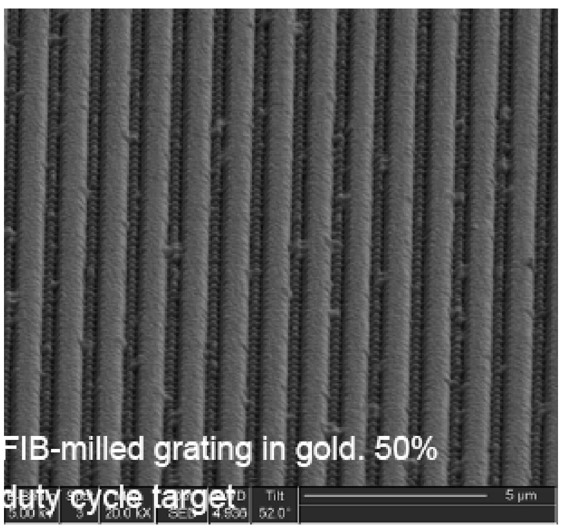
500mV/40seconds = 12.5 mV/s = 0.125 pC/s (Capacitance = 10 pF)

Note that the inputs to the oscilloscope were flipped –
in-phase driving leads to positive charge transfer as expected

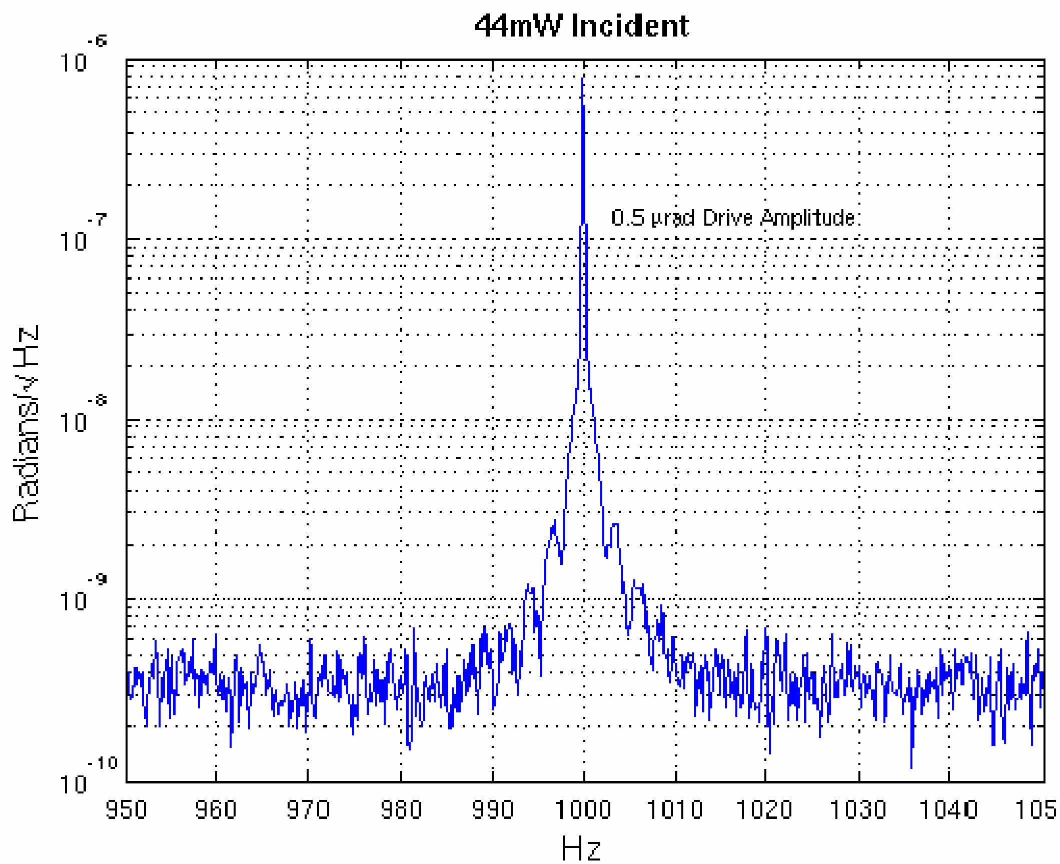
GAS Experiment



Grating angular sensor setup



Grating detail



Results

Thank You

Back-up Slides

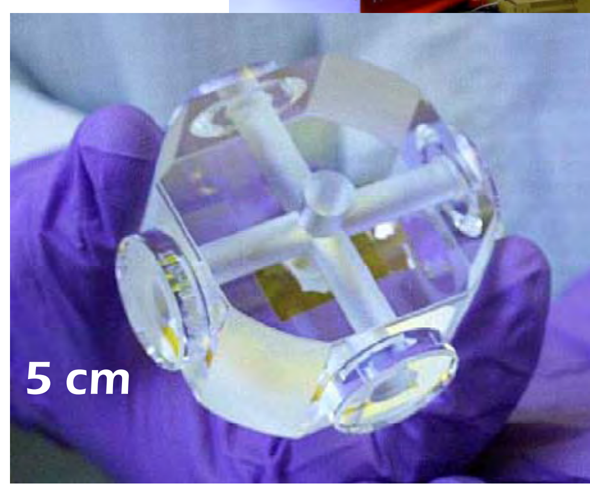
Earthbound experiments

Berlin MM Experiment

- Rotating crossed optical resonators
- 1 year of measurement / 100000 rotations
- 10^{-15} relative laser stability
- no anisotropy at 1 part in 10^{17}

$$\left|1/2-\beta+\delta\right| \equiv \boldsymbol{C}_{MM} \le 8\times10^{-12}$$

S. Herrmann et al., PRD 80, 105011 (2009)



Paris KT Experiment

- Comparison of cryogenic microwave oscillator to hydrogen maser
- 6 year span of data record. September 2002 to December 2008.
- Analyzed as KT experiment for systematic siderial or annual modulation

$$\left|\beta - \alpha - 1\right| \equiv \boldsymbol{C_{KT}} \leq 4 \times 10^{-8}$$

M. Tobar, P. Wolf et al., PRD 81, 022003 (2010)

STAR "Quad Chart"

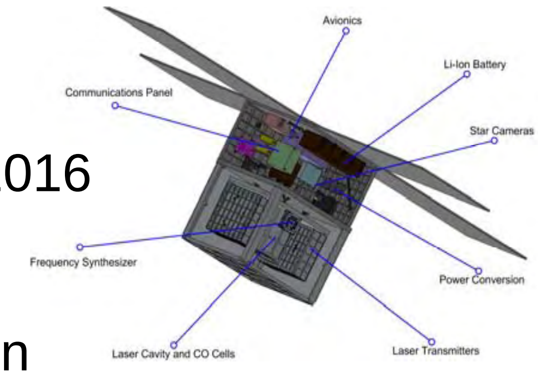
SCIENCE

- What is the nature of space-time? Is space isotropic?
- Is the speed of light isotropic?
- If not, what is its direction and location dependency?

3×10^{-18} to 10^{-17}

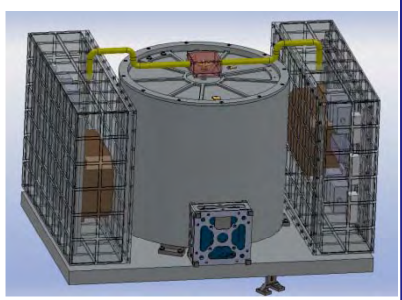
Mission design

- Circular sun-synchronous 650 km circular orbit
- 180 kg,150 W
- Launch 2015-2016
- 2-year lifetime
- Class D Mission



Payload

- Optical cavities ×4
- 1 nK enclosure
- I_2 clocks ×2
- Laser-based comparator
- BATC is payload consultant



Management

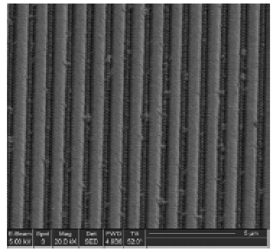
- NASA Ames: PM, SE, SMA, Mission Operations
- Stanford: Science and Payload
- KACST: Spacecraft and Launch
- DLR: Payload Design & I_2 Clock
- ALL: Science & EPO

High resolution Grating Angular Sensor (GAS)

Second microsat of MGRS series

Current TRL: 3 **Target TRL:** 7/8

Concept Description:

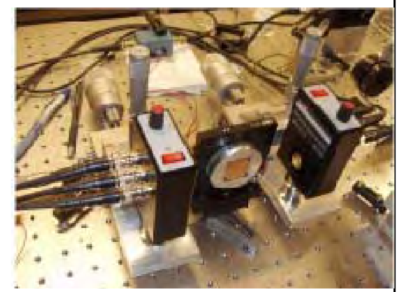


- Space qualify
  - Grating angular sensor(GAS)
  - Laser system and read-out for GAS
  - Piezo system for motion simulation
- Main components
  - GAS
  - Angular motion simulator
- Replicate ground experiment in space

Target Program: Franklin/Edison

GNC: miniature drag free technology

Related/Prior Technology Development Efforts:



- Existing GAS laboratory technology
- Stanford University/KACST ongoing GAS program
- Complete experiment in laboratory
- Required bus developed by KACST for prior mission
- 50% of electronics developed

Partnership/Development Team:

- NASA Ames: PM, SE, SMA, Mission Operations
- Stanford: Science and Payload Design
- KACST: Spacecraft and Launch

Development Risk/Reward:

- **Low; low Risk/high Reward**
- Laboratory prototype functional

Development Focus:

- Demonstration of complete flight experiment in laboratory environment prior to flight build

Potential Applications:

- Multi-satellite Operations, Sensor Swarm, Laser comms

Potential Customers:

- LISA, LISA Pathfinder, Big Bang Observatory, GRACE Follow-on, DECIGO

Benefit to Ames:

- Lay groundwork for STAR
- Develop ties with academia, industry, and key international partners
- Develop groundbreaking technology for flagship missions (LISA) using small satellites

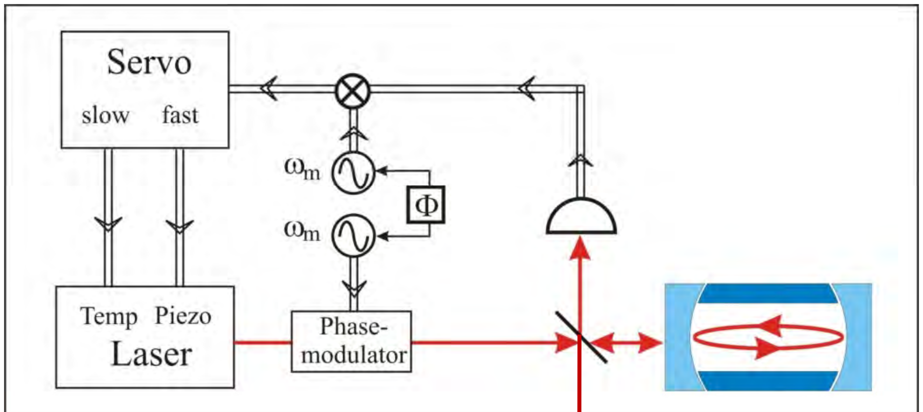
ROM Work Breakdown/Cost **$2,100K**

Milestone Schedule:

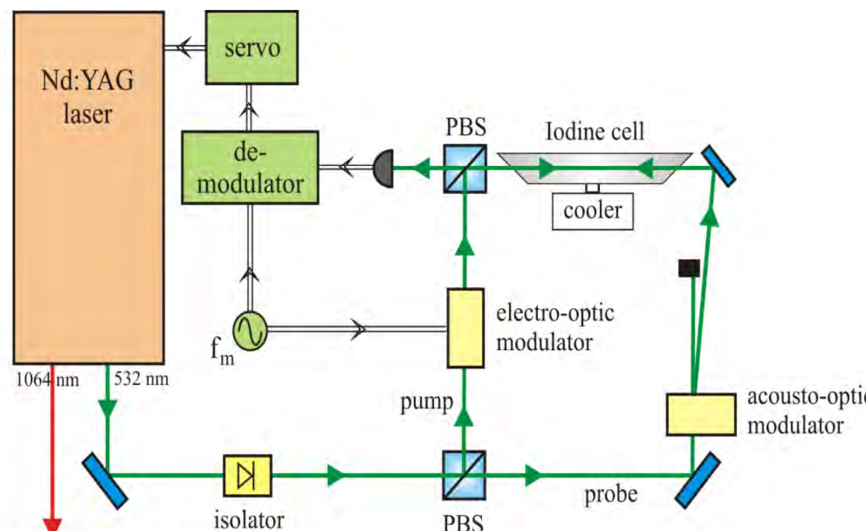
- Engineering Model Complete: 2/1/12
- Critical Design Review: 4/1/12
- Flight Payload Complete: 2/1/13
- Launch: 10/2013
- Mission Completion: 4/14

Modern Kennedy-Thorndike tests

clock based on length standard

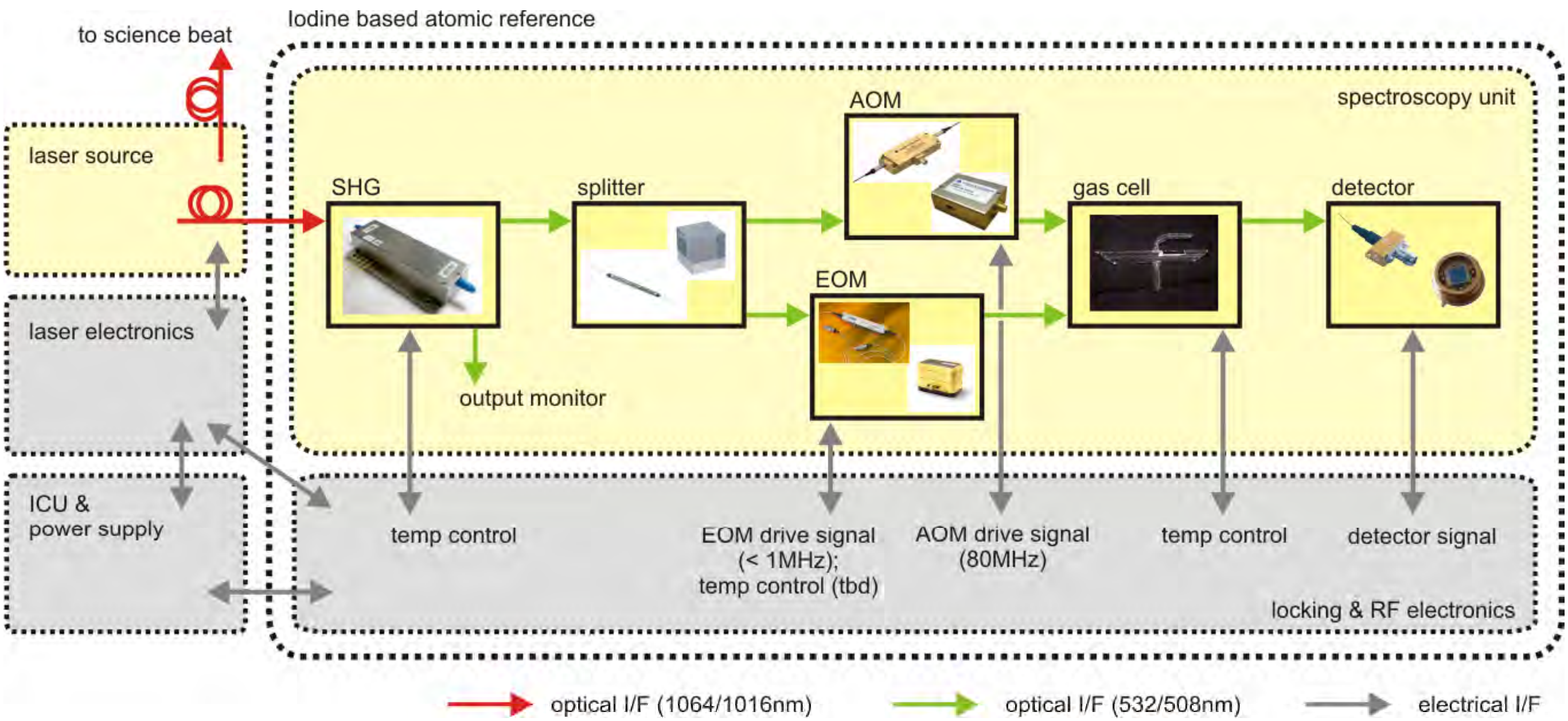


clock based on atomic transition



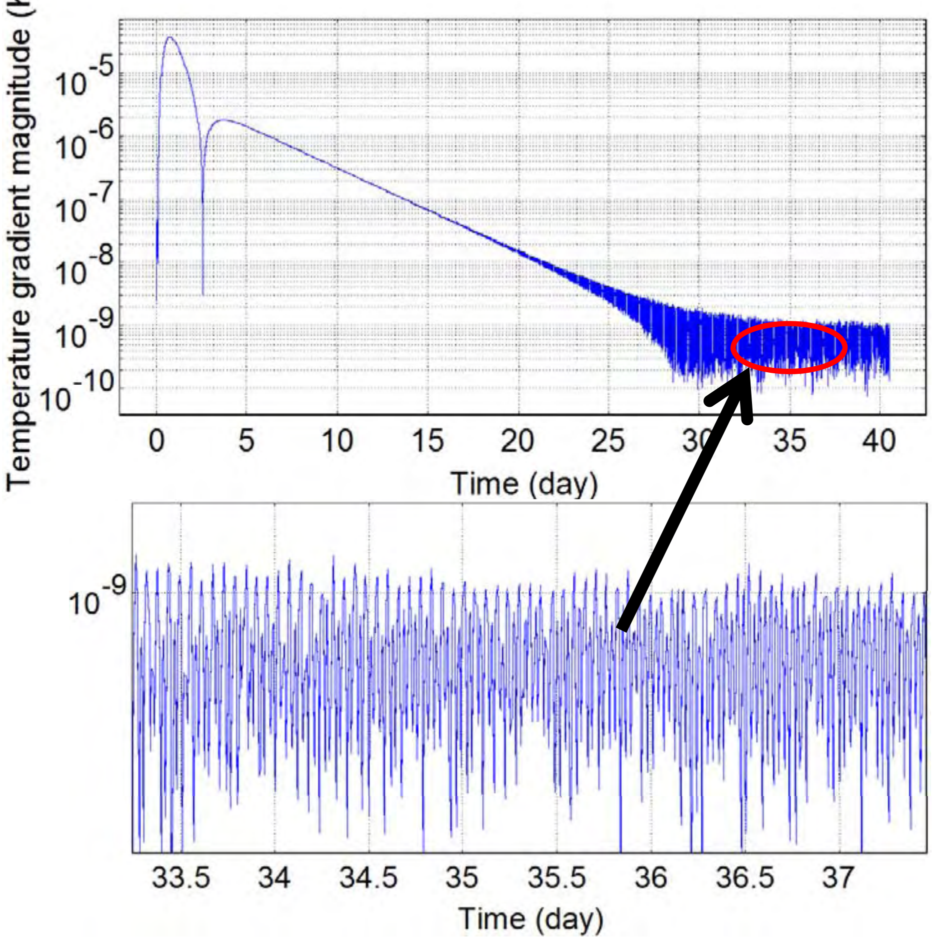
beat measurement
with
varying laboratory velocity

State of the art: Iodine vs. cavity

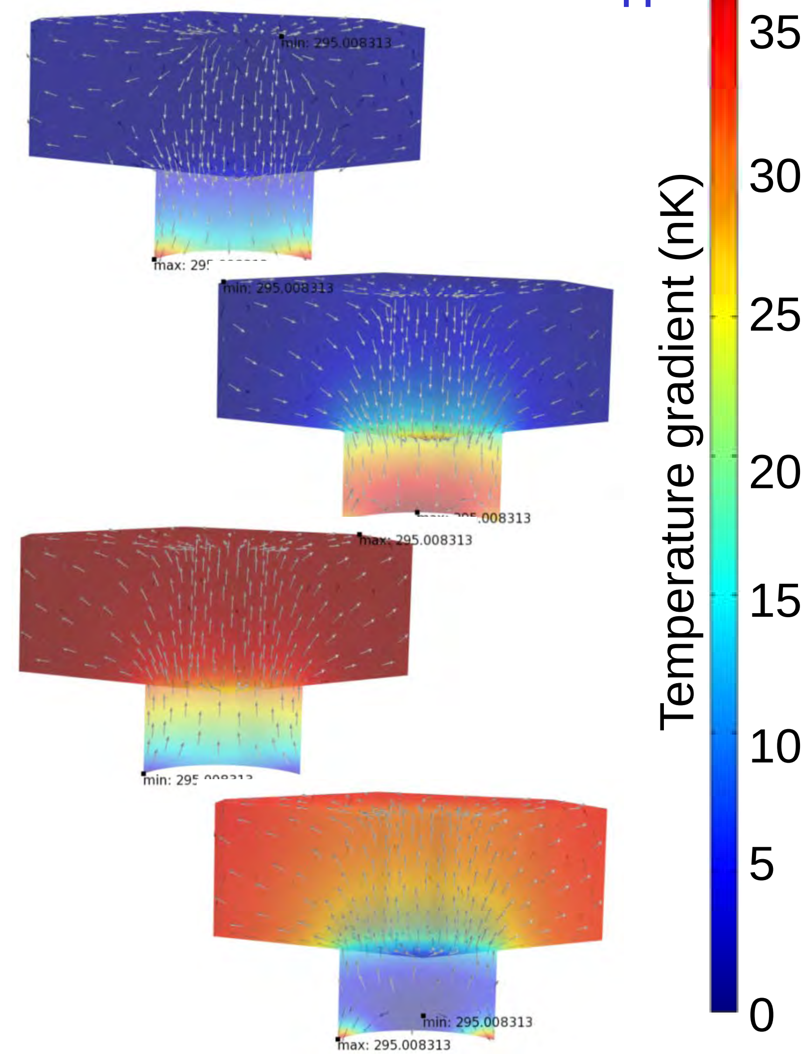


Cavity block “COMSOL model”

Cavity Block "Temperature gradient magnitude (K/m)“
Boundary around the enclosure ±5 K



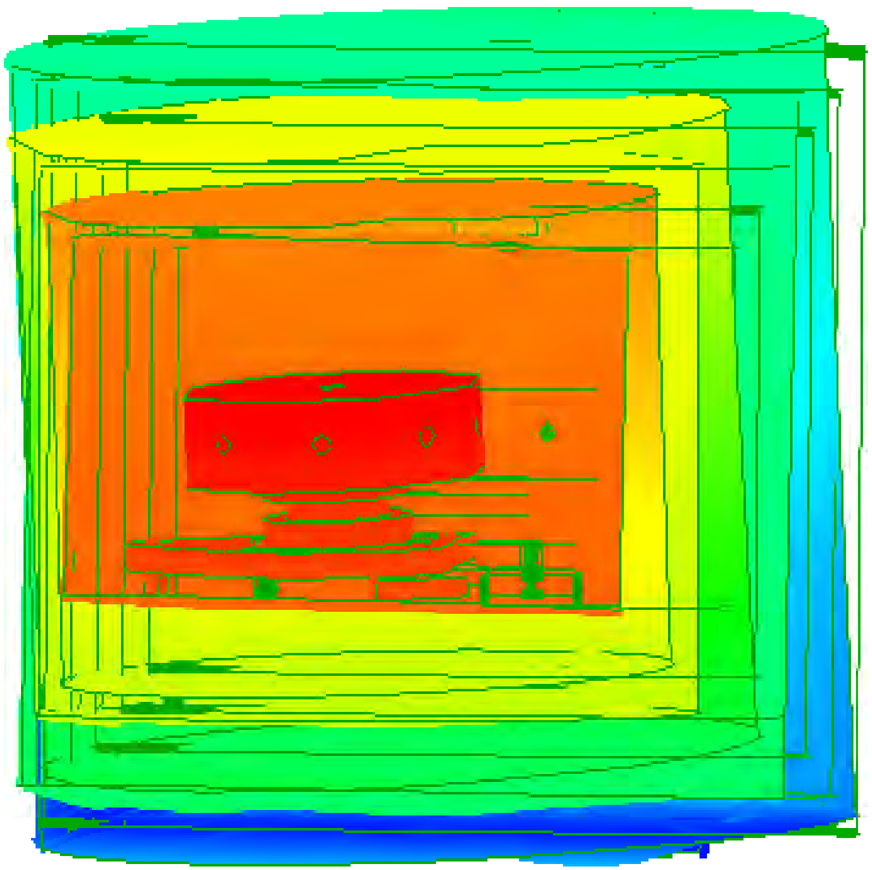
Temperature distribution
Day #35, one orbit, **38 nK$_{pp}$**



Fundamental frequencies

The first mode of the assembly was found to be 77 Hz

First lateral mode: 77.6 Hz



First axial mode: 93.9 Hz