# SPACE-TIME ASYMMETRY RESEARCH


| | |
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| Floyd Stecker | *NASA/GSFC* |
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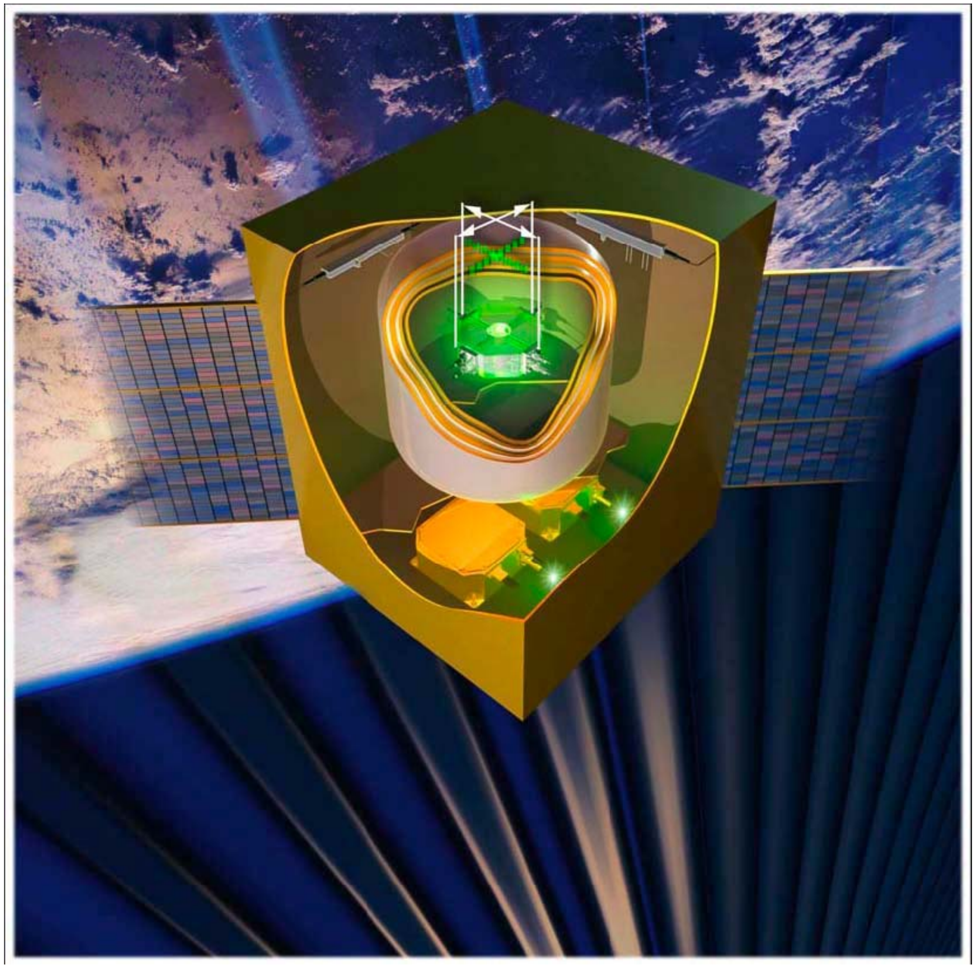
***Q2C3***
***Virginia, 2008***



# 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:***

$$r \approx m_W / M_P \sim 10^{-17}."$$

**STAR's one part in $10^{18}$ sensitivity could easily close that gap.**

# Science Objectives

## *Test Lorentz Invariance to $10^{-18}$*

$$\frac{c(\theta)}{c} = \left[1 + (\beta - \varepsilon - 1)\frac{v^2}{c^2}\right] + \left[(1/2 - \beta + \delta)\frac{v^2 \cdot \sin^2(\theta)}{c^2}\right]$$

KT ($\beta - \varepsilon - 1$)

MM ($1/2 - \beta + \delta$)

$\beta$ Lorentz contraction parameter
$\varepsilon$ time dilation parameter
$\delta$ tests for transverse contraction

GR: $c(\theta)/c = 1$, KT = MM = 0
CMB: preferred frame $(v_{CMB}/c)^2 = 10^{-6}$

| Measurement Objectives | Mission Objectives and Relevance | Ground Experiment (No previous Missions) | Improvement Over Ground Experiment | Future Mission Objectives (LISA is the nearest analogue mission) |
|---|---|---|---|---|
| Lorentz Invariance Violation (LIV) | dc/c ~ $10^{-18}$ | dc/c ~ $10^{-16}$ | 100 | dc/c ~ $10^{-20}$ |
| Improve Kennedy Thorndike (KT) | ~ $7 \times 10^{-10}$ | ~ $10^{-8}$ | ~400 | ~ $10^{-11}$ |
| Improve Michelson Morley (MM)[1] | $10^{-12}$ | $10^{-10}$ | 100 | < $10^{-12}$ |
| Refine (SME)[2] | $10^{-14}$ to $7 \times 10^{-18}$ | $10^{-13}$ | 50-500 | < $10^{-13}$ |

[1] Test space/time symmetry
[2] Improve understanding of cosmological parameters in Standard Model Extension

**Targeted Outcomes for Astrophysics—**
1. *"Test the validity of Einstein's General Theory of Relativity;"*
2. *"Investigate the nature of space-time through tests of fundamental symmetries; (e.g., is the speed of light truly a constant?)"*

**NASA Science Plan 2007-2016**

# Michelson Morley

**STAR will improve on the best measurements of the effect by > 100**

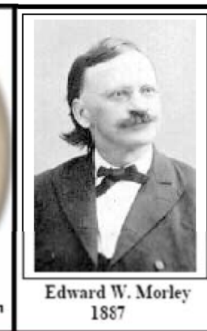
***MM STAR Mission Objectives***

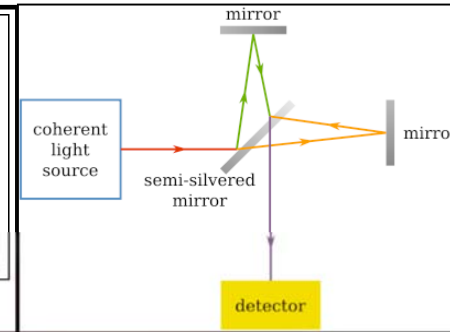
**Measure the anisotropy of *c* to $10^{-18}$**

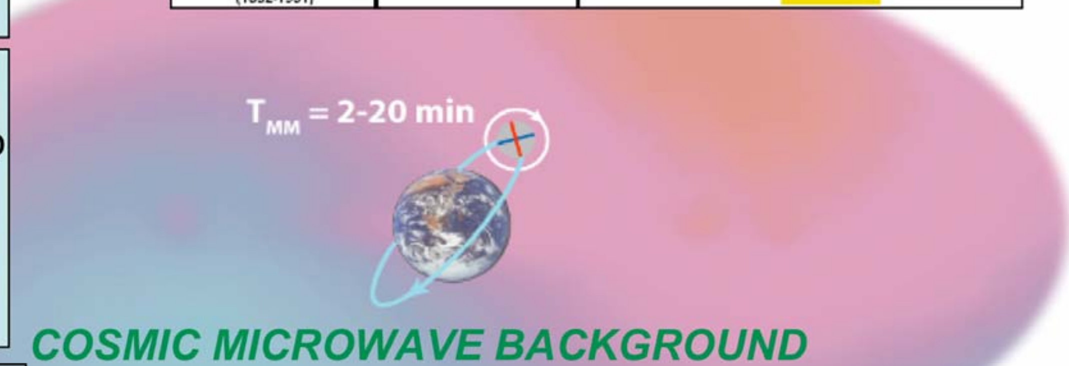
- Derive the MM coefficient to **~ $10^{-12}$**
- Derive the generalized coefficients of LIV
  - *boost independent:* **< $7 \times 10^{-18}$**
  - *boost dependent:* **~ $10^{-14}$**

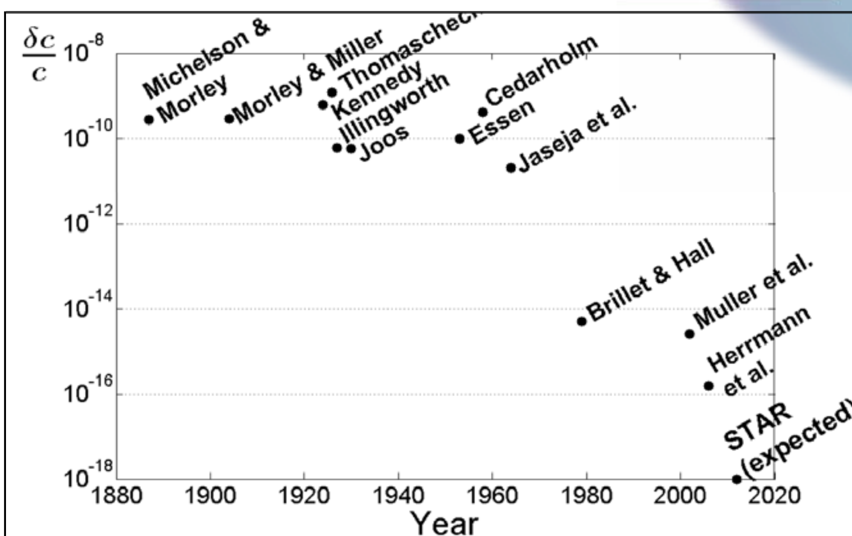
***Readout Description***

- Compare the resonant frequencies of two orthogonal high-finesse optical cavities
- Signal at $1/2 \times T_{MM}$ ($T_{MM}$ = 2 – 20 min)
- Configuration conceptually similar to MM

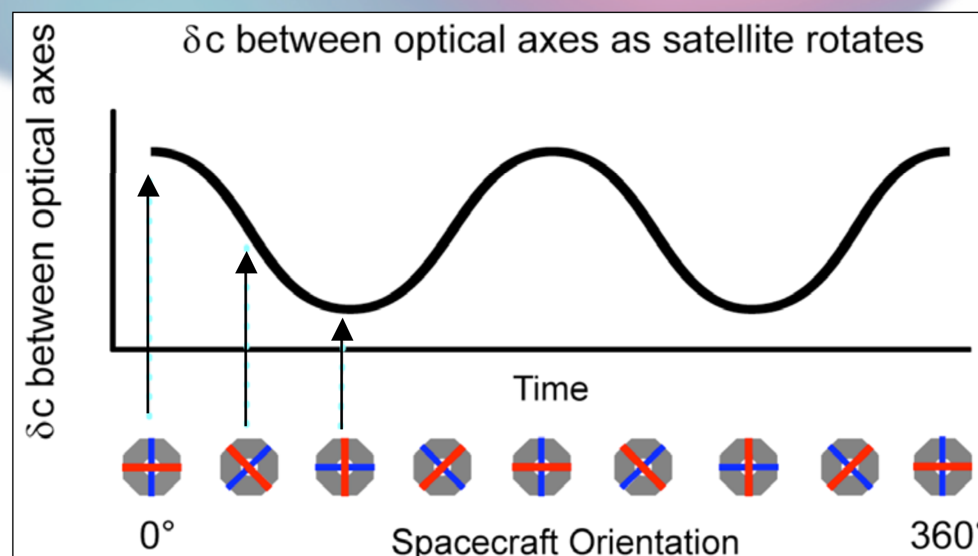




**History of MM resolution**



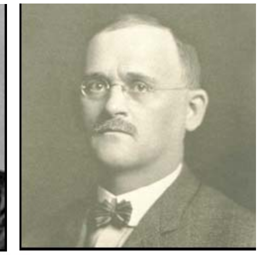
# Kennedy-Thorndike

## STAR will gain a factor of 400 over the best KT measurement

***KT STAR Mission Objectives***

**Measure the boost anisotropy of the velocity of light to $10^{-18}$**

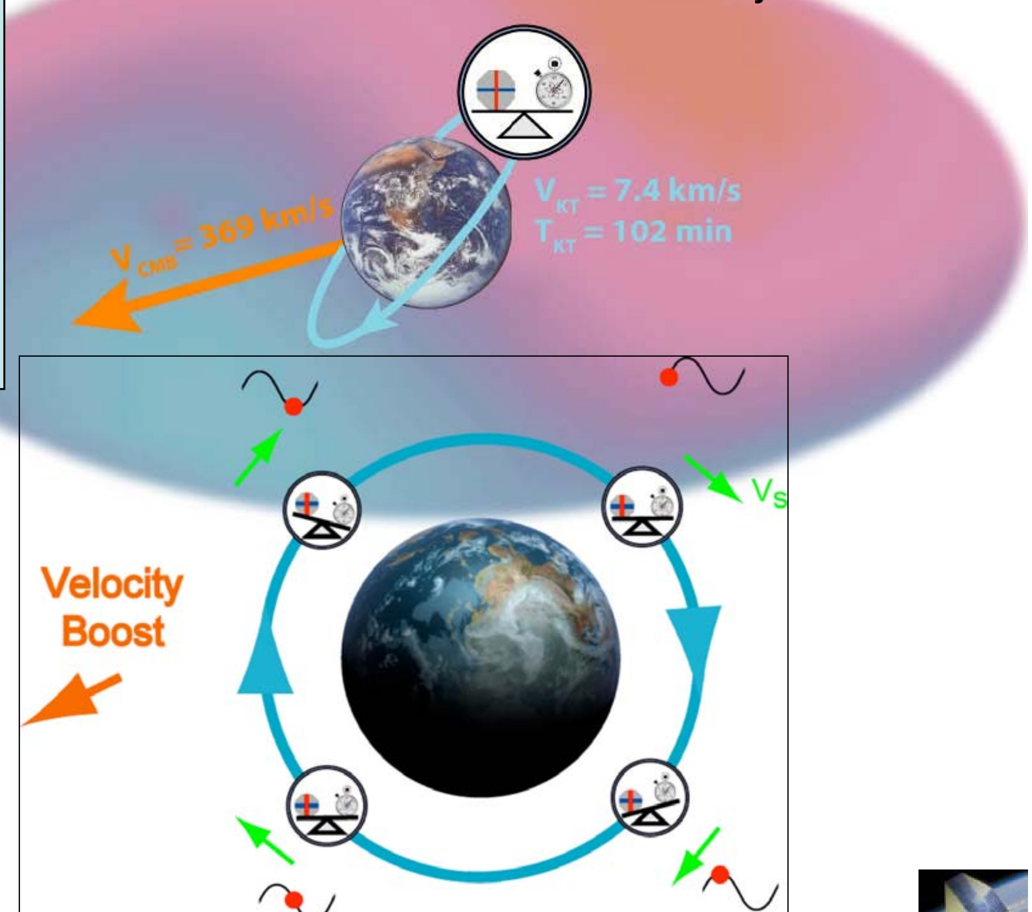
- Derive KT coefficient to the corresponding resolution, **~ $7 \times 10^{-10}$**

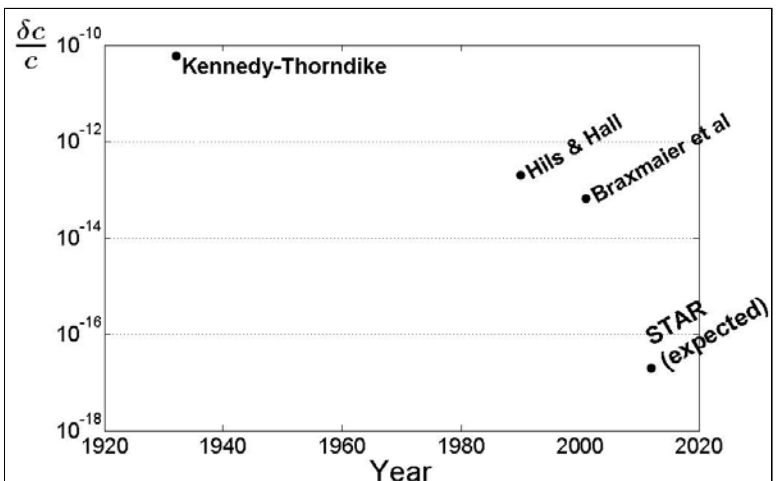



**R.J. Kennedy** **E.M. Thorndike**

***Readout Description***

- Orbital velocity varies with respect to CMB.
- If *c* depends on $v_S$ relative to CMB, the resonant frequency of the cavities changes.
- Signal at orbital period $T_{KT}$ ($T_{KT} \approx 100$ min)
- STAR compares the frequency of cavity to wavelength of molecular-iodine stabilized laser as absolute frequency reference.




**History of KT resolution**

# Optical Layout and Critical Components

**Commercially available components reduce risk and keep STAR low cost.**

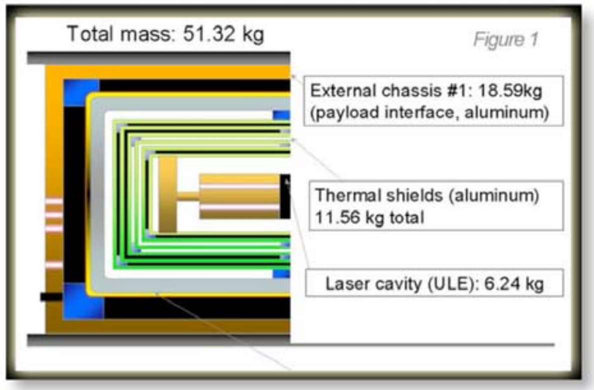



Fig. 1: Multi-Layer Thermal Shield sub-μK Thermal Stability
Approach to thermal stability is simple yet highly effective.

Fig. 2: High-Finesse ULE Cavity Resonators

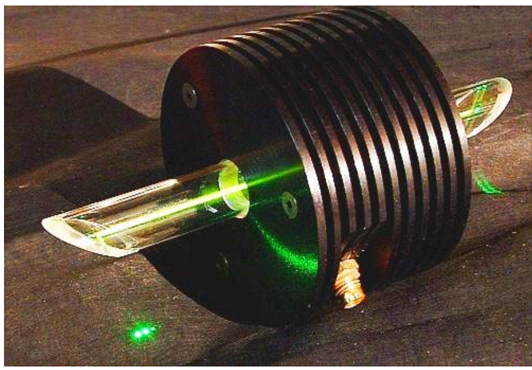


Fig. 5: Iodine Gas Cell Absolute Frequency Reference

Fig. 4: 1064 nm Nd:YAG Laser

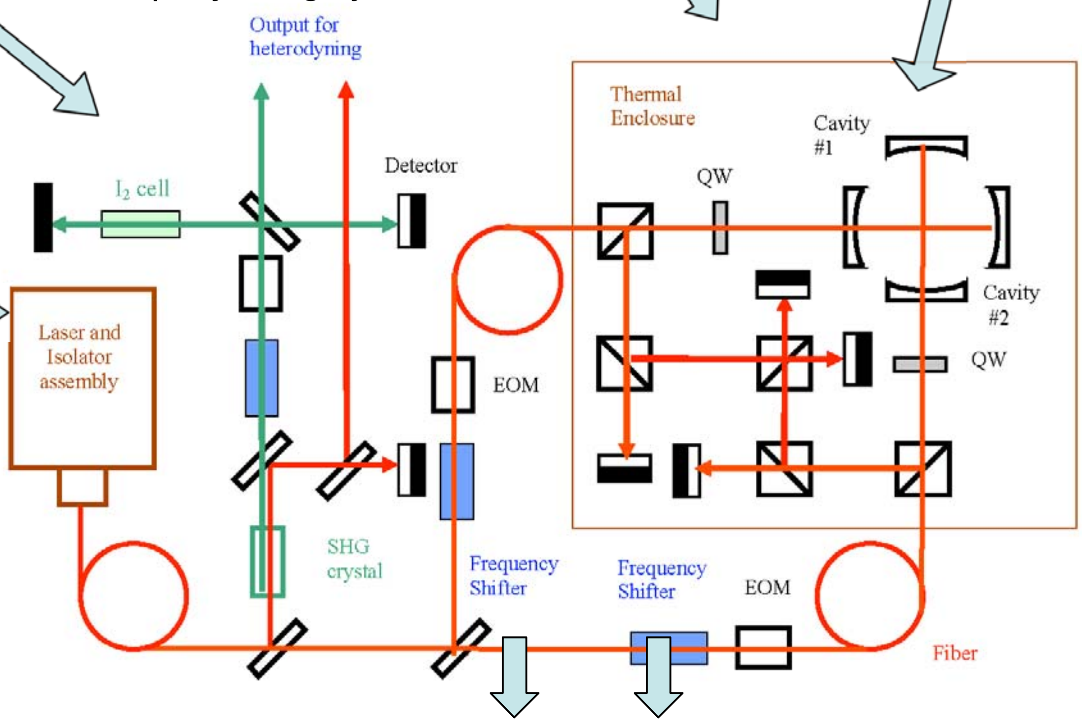
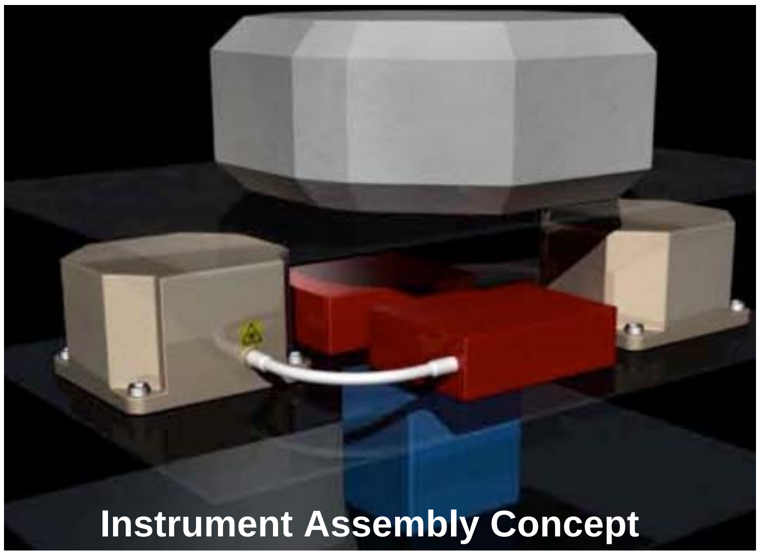



Fig. 3: Frequency Shifters ➡ ν1, ν2

# Experiment description

**Two identical optics platforms**
- Two-cavity resonator
- Monolithic ULE block
- Iodine cell

**Redundancy and twice the signal**


Instrument Assembly Concept

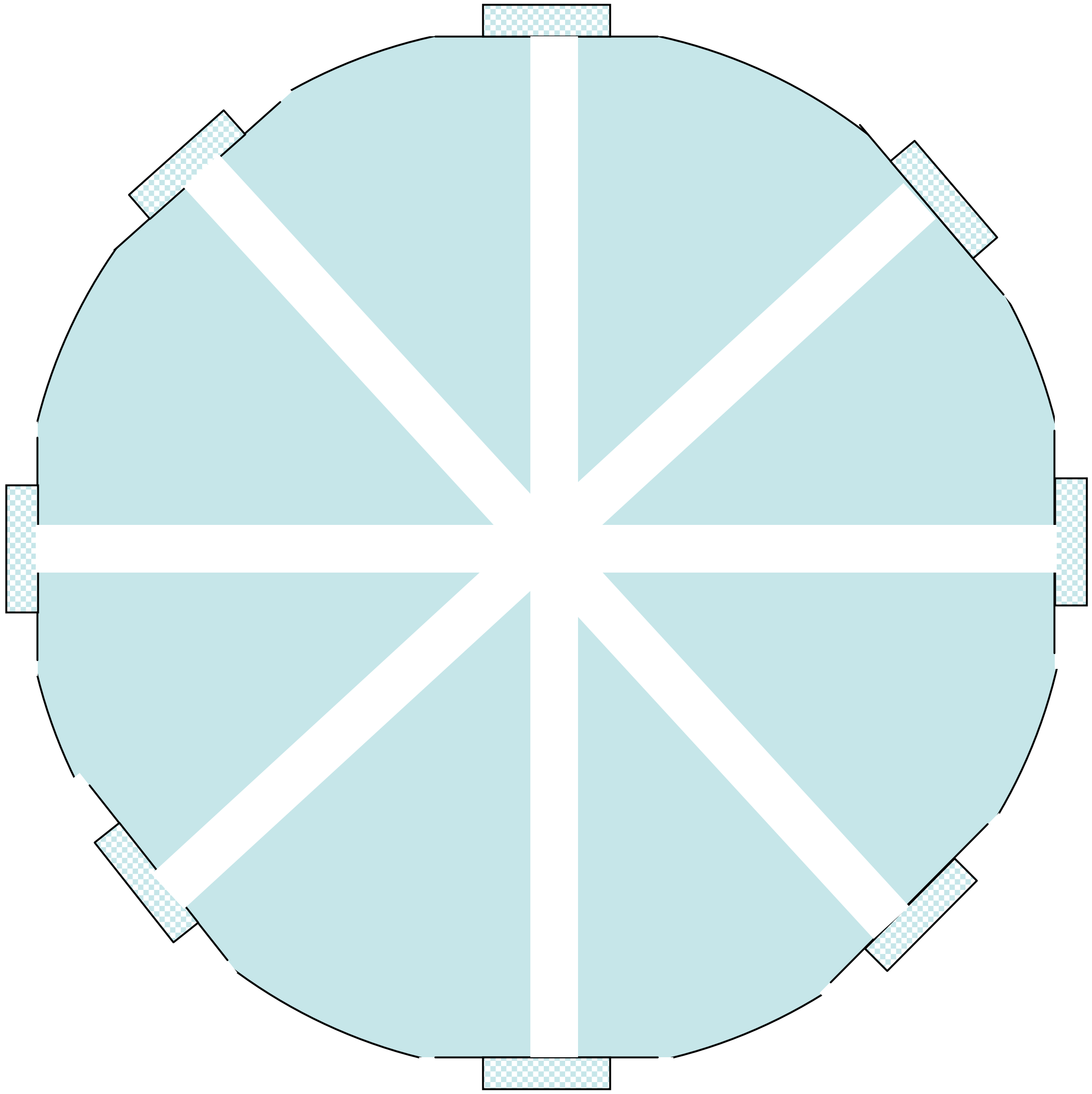
- We measure asymmetries in the propagation of light by comparing a molecular iodine absolute frequency standard and two super-stable cavity resonators.
- Variations in the propagation of light will manifest themselves as frequency shifts between these different standards.
- The Michelson-Morley experiment compares the frequency shift between the two cavity resonances.

$\delta c_{MM} \propto (\nu_1 - \nu_2)$ **@ half the satellite roll period**

- The Kennedy-Thorndike experiment compares the frequency shift of one cavity relative to the Iodine standard as the satellite velocity vector is modulated in inertial space by the orbital motion.

$\delta c_{KT} \propto \nu_1$ **or** $\nu_2$ **@ satellite orbital period**

| Science Objectives | Scientific Measurement Requirements | Instrument Functional Requirements | Mission Functional Requirements (Top-Level) |
|---|---|---|---|
| Speed of light anisotropy | $dc/c \sim 10^{-18}$ in one year<br>$dc/c \sim 1.5\times10^{-15}$ in one sec | Frequency stability and resolution for cavities<br>$d\nu \sim 0.4$ Hz in one sec | Dual cavities locking for one year with **50% duty ratio** |



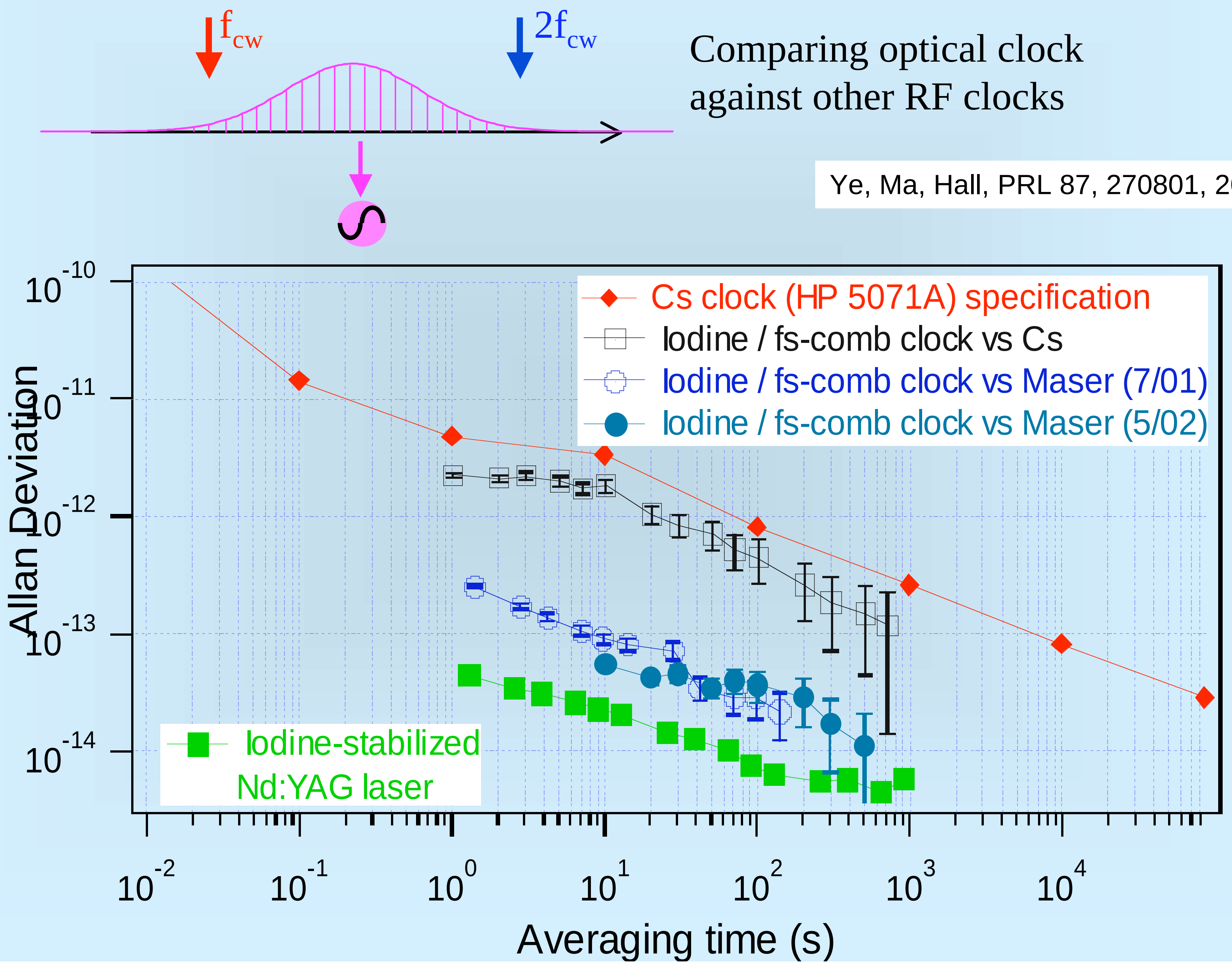
4 Cavities gives 2 Anisotropy Measurements and 4 Kennedy-Thorndike Tests

Mechanical contacting points need to respect the symmetry ideas of vertical cavity idea

# Molecular Clock of Iodine

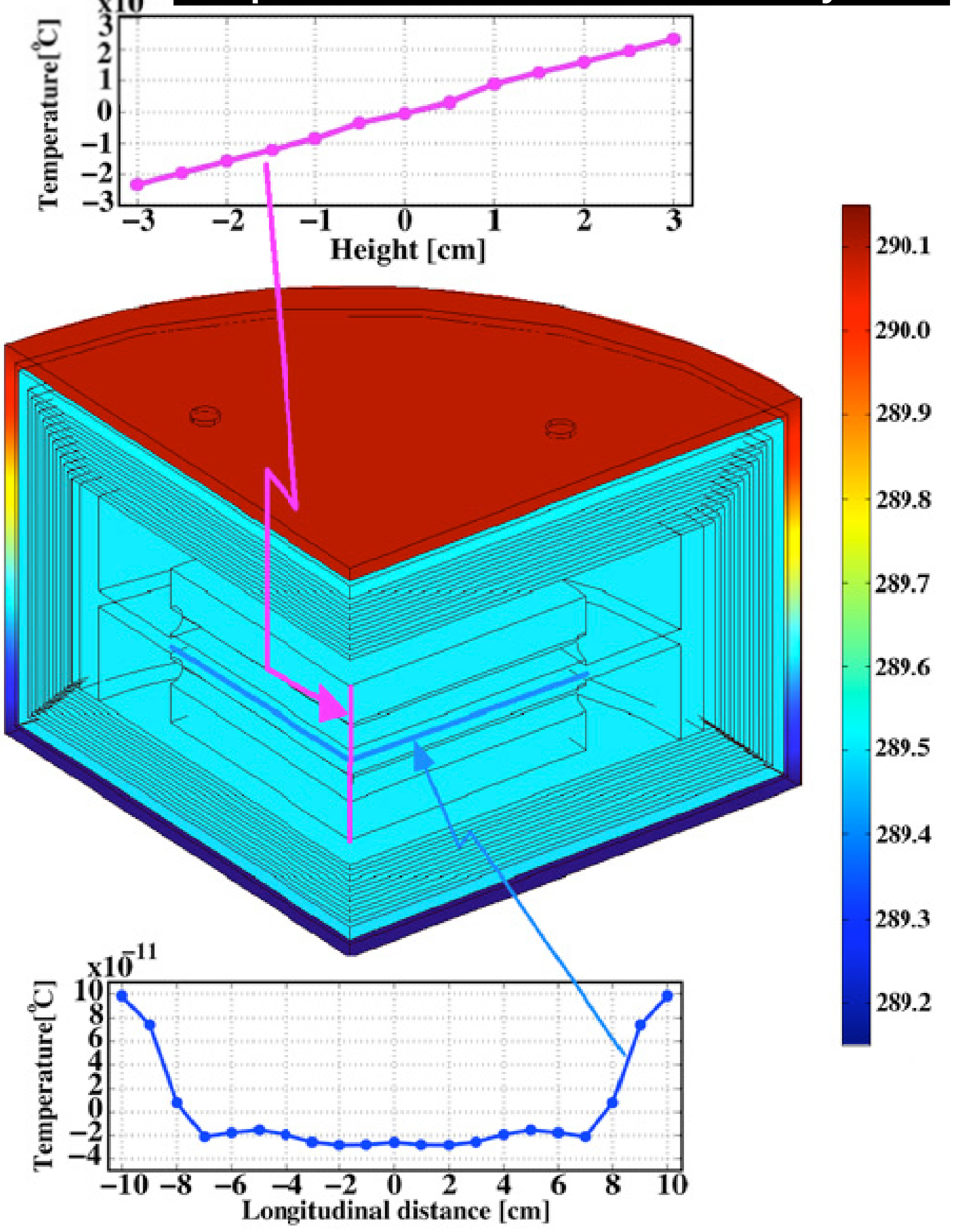
Comparing optical clock against other RF clocks

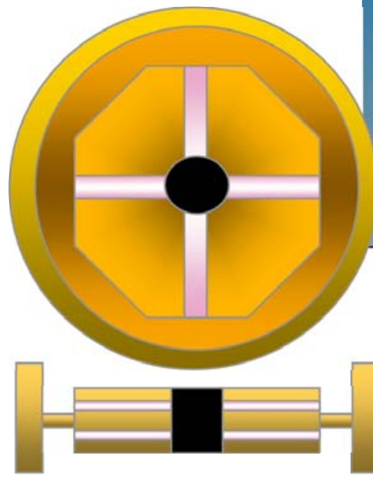
Ye, Ma, Hall, PRL 87, 270801, 2001



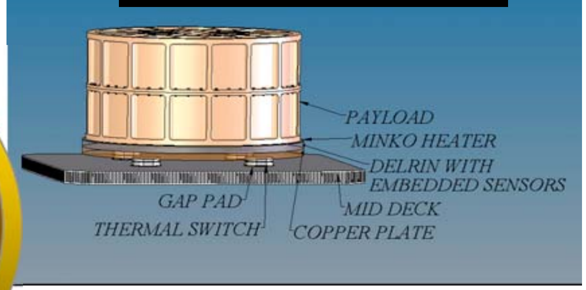
# Temperature Control

Temperature distribution at the cavity block

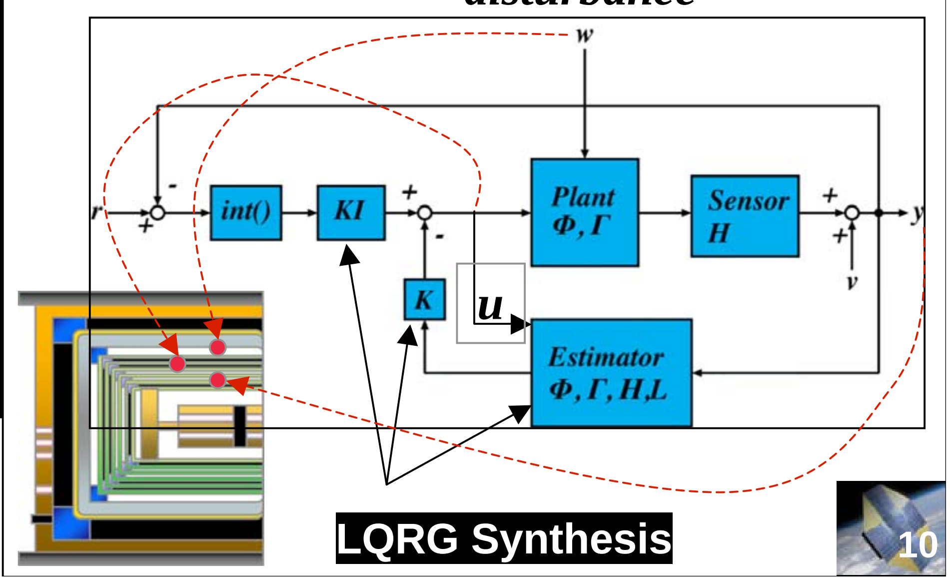


ULE double cavity

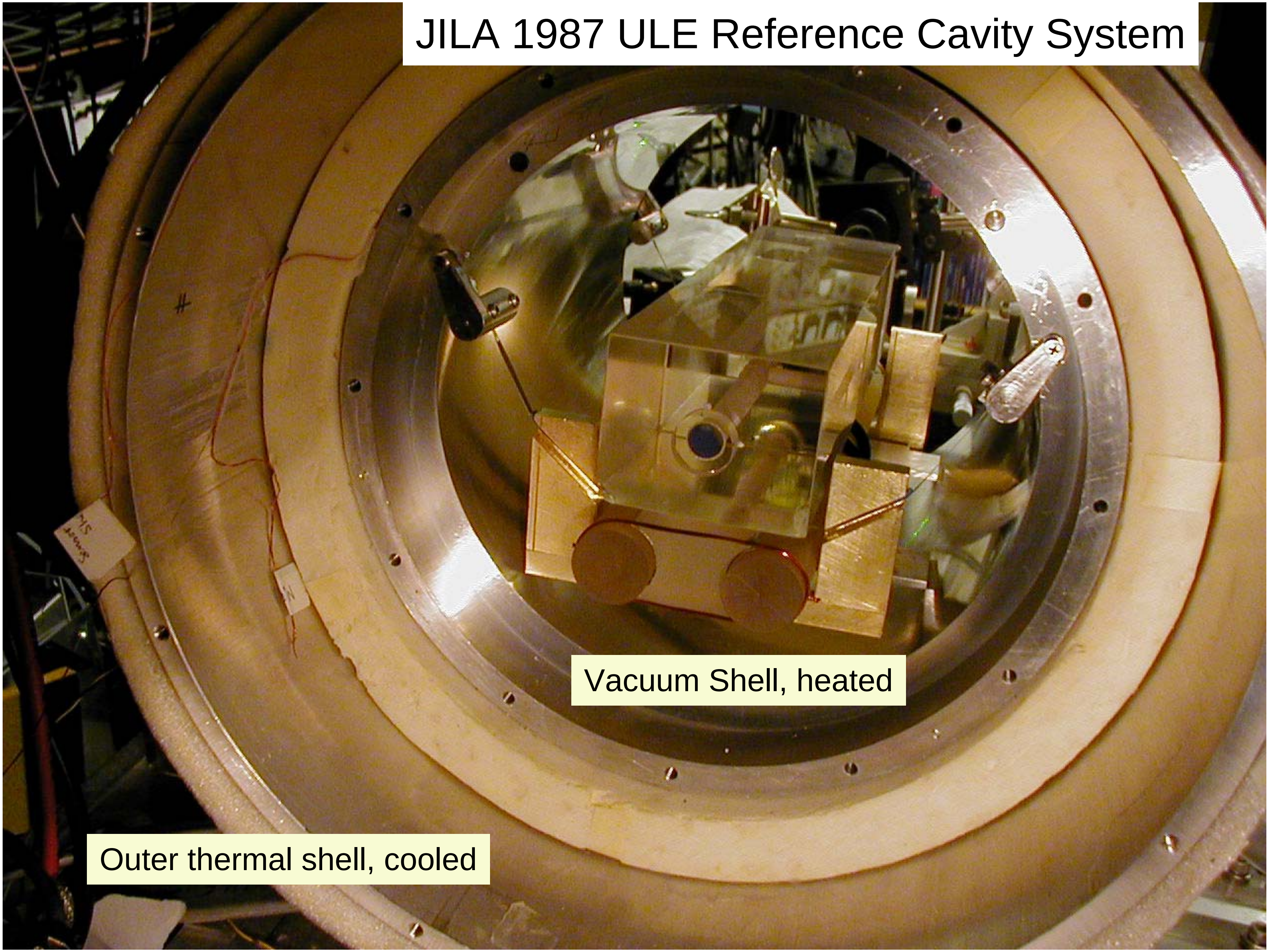


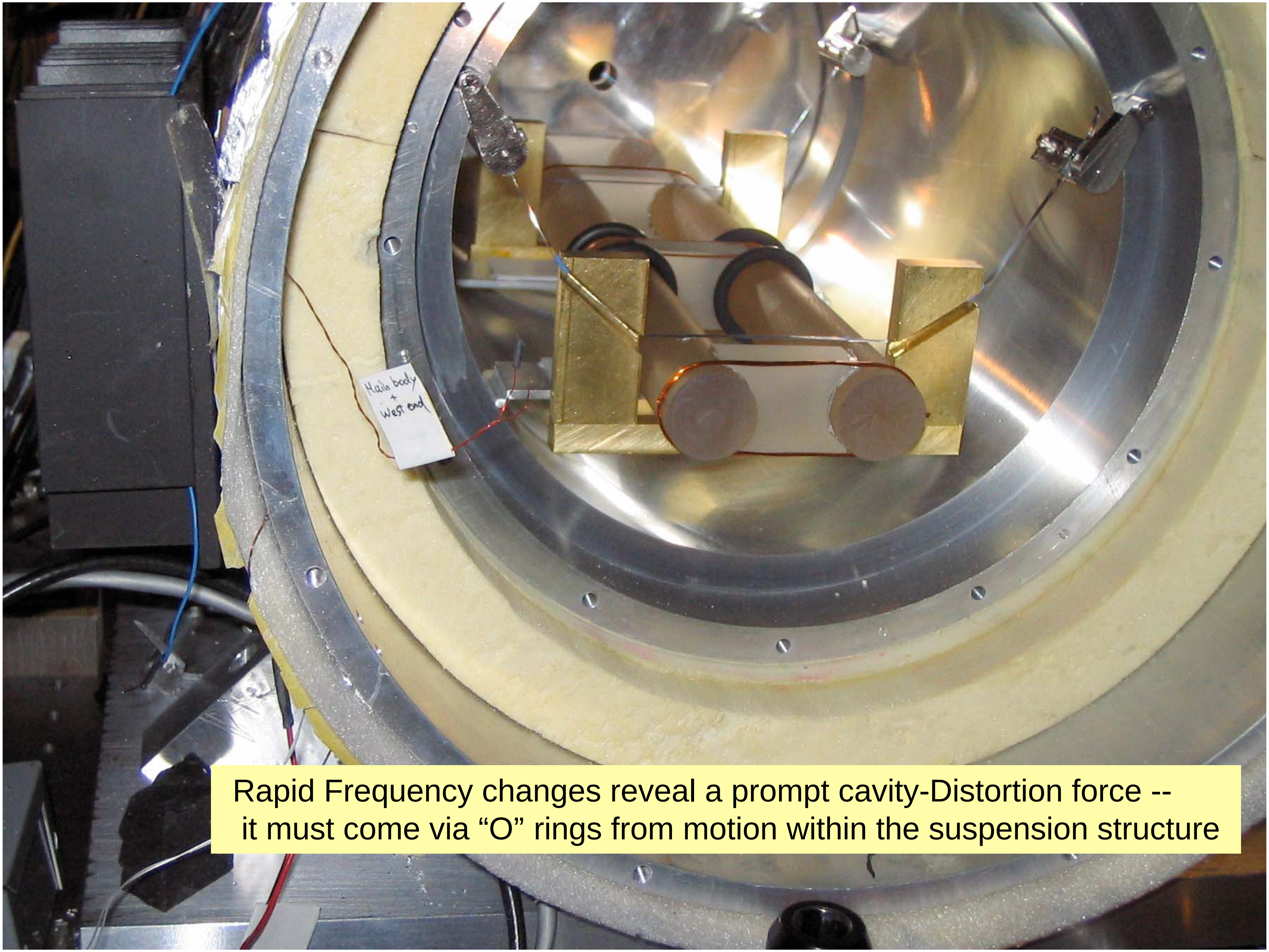

*disturbance*




- Top: *Vertical* ΔT ~ $10^{-10}$ K
- Middle: *3D* ΔT = 2 K top to bottom
- Bottom: *Horizontal* ΔT ~ $10^{-10}$ K

# JILA 1987 ULE Reference Cavity System






Rapid Frequency changes reveal a prompt cavity-Distortion force --
it must come via “O” rings from motion within the suspension structure

# S/C Key sub-system block diagrams

## Major Interfaces

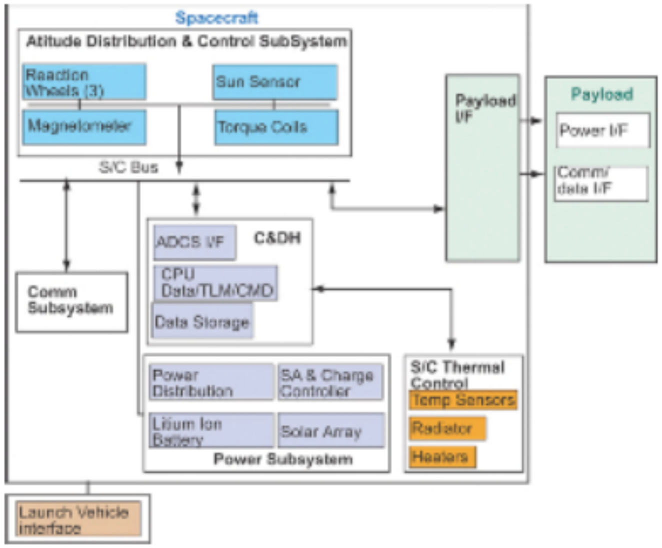
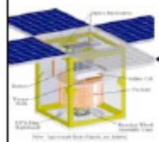



Fig. 1: Block diagram: Major interfaces



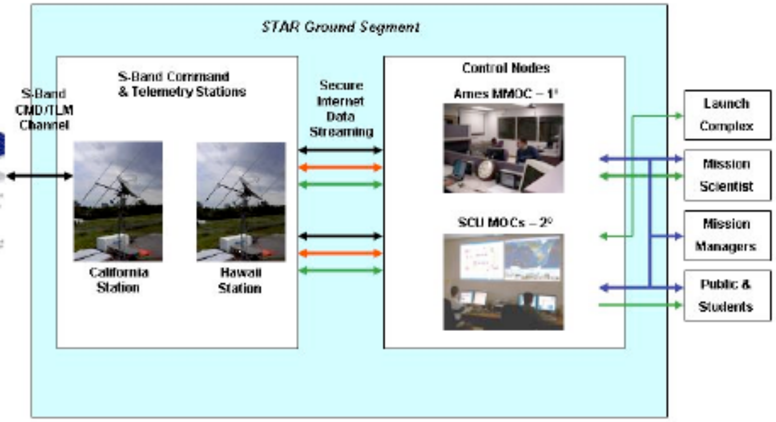



Fig. 3: Block diagram: Ground segment



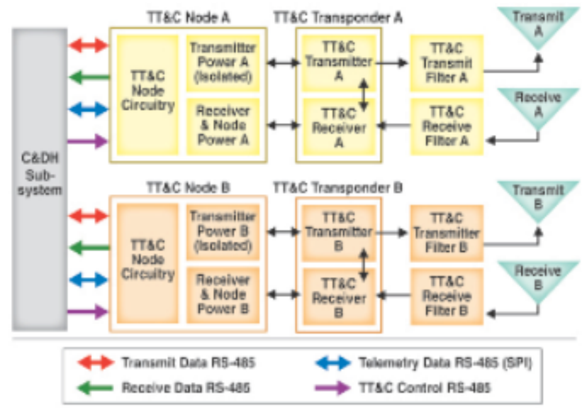



Fig. 4: Block diagram: C&DH

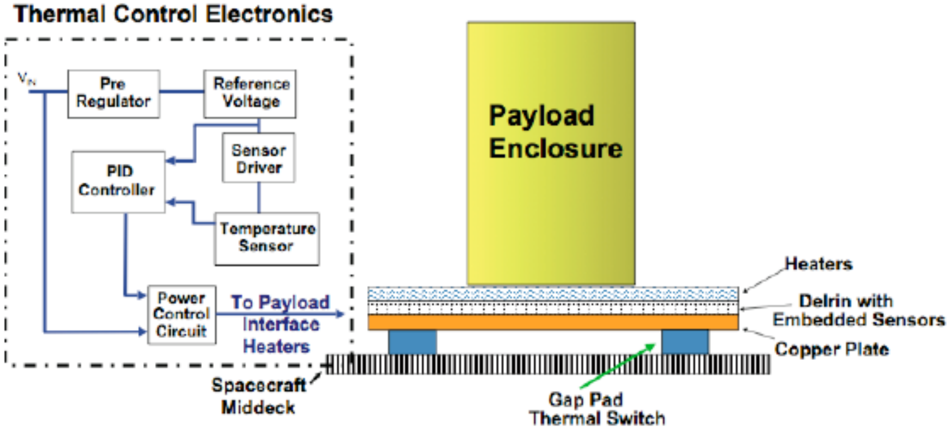
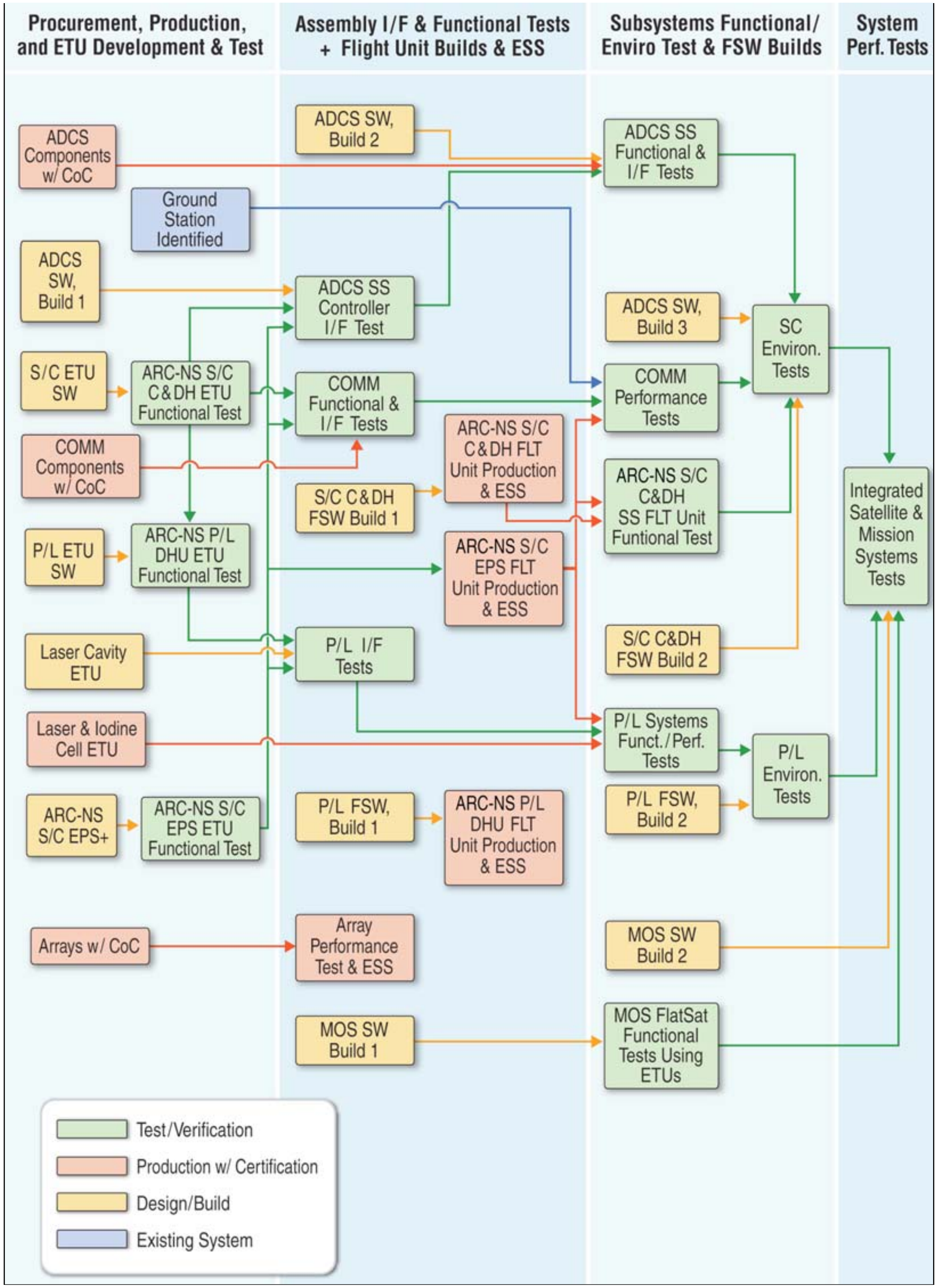



Fig. 2: Block diagram: Thermal Control


Fig. 5: Block diagram: ADCS

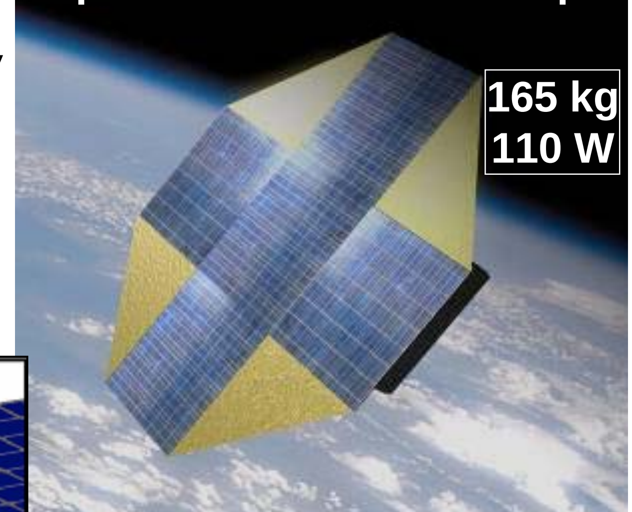
# Assembly, Integration, and Test Flow



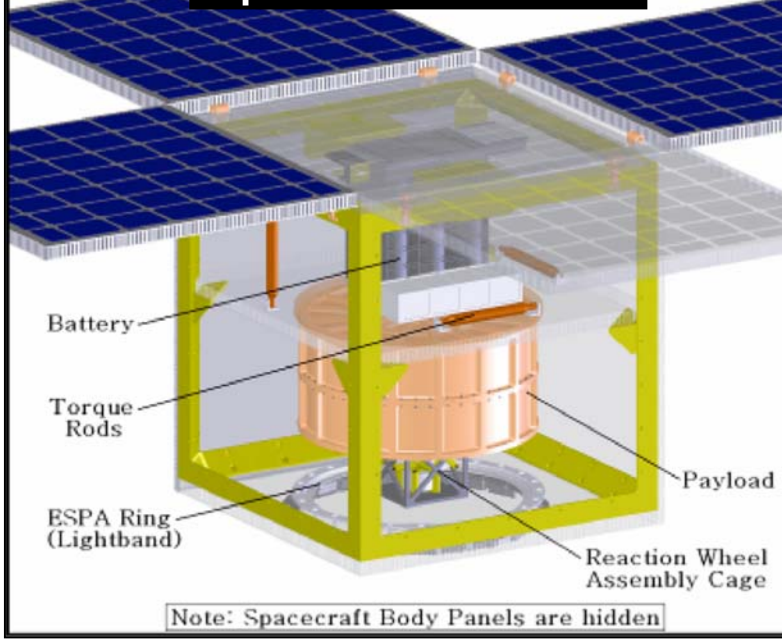
# Major Mission Characteristics

- Measure the anisotropy of the velocity of light to $10^{-18}$
- Primary data product: map of local values of *c*
- Orbit: most precessing sun-synchronous LEO's
- Launch vehicle: Secondary payload on a Delta IV
- Altitude: 850 km
- Mission duration: One year
- Launch: late 2012
- Cost: $40M

**Spacecraft in orbit concept**

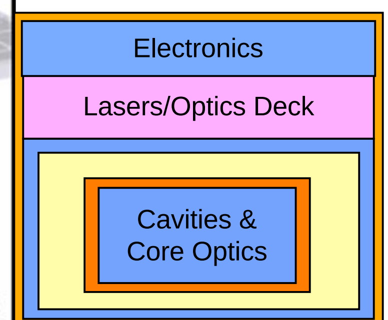



**Spacecraft structure**




### LISA technologies

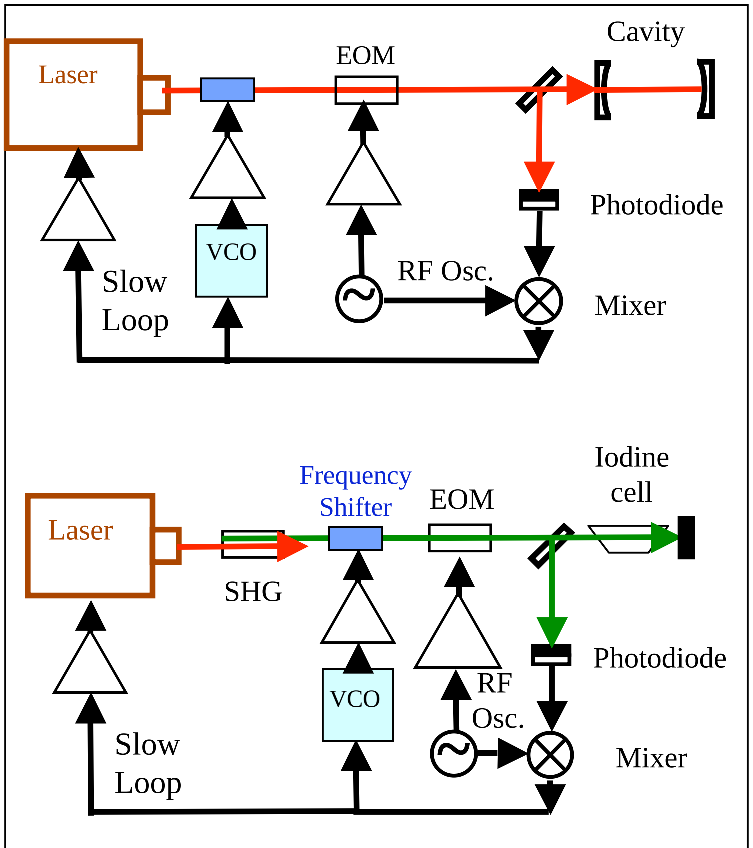
- Frequency doublers
- Thermal enclosure
- Iodine clocks
- Optical cavities



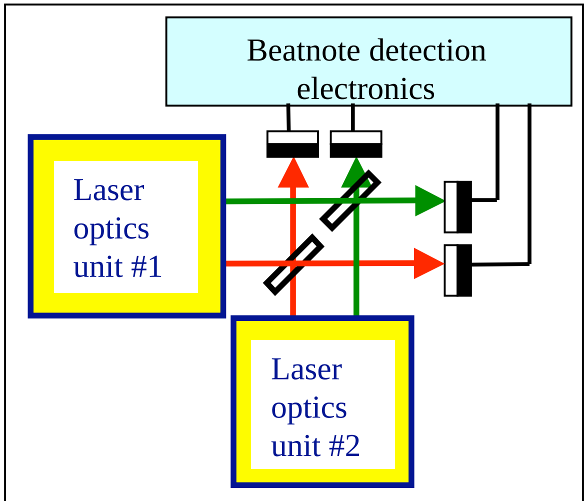

**Payload layout**

# Thank you

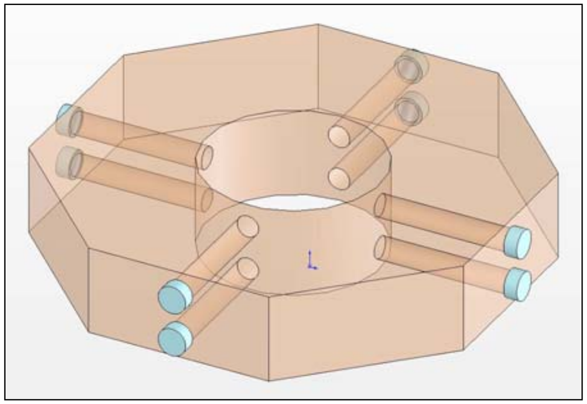
# Optical Components




**PDH locking control block diagrams**




**Heterodyne detection of beat note signals from two laser optics units**



**Two optical cavities in one ULE block**

# Why another Isotropy Experiment?

- Extension of std model: D. Colladay and V.A. Kostelecky´, Phys. Rev. D **55**, 6760 (1997); **58**, 116002 (1998).
- A Kostelecky and Matthew Mewes "**Signals for Lorentz violation in electrodynamics,"** PHYSICAL REVIEW D **66**, 056005 (2002)

- Predict Birefringence & loss of Local Lorentz Invariance
- Predict Velocity & Angular dependences (appendix E)
- Two-clock test: Bear, Stoner & Walsworth (2000)
- Kennedy-Thordike is weakest exptl test of SR

Speed of light is constant? Yes, at $10^{-9}$ /10 years (Sakuma, BIPM)

# Michelson Morley