Astro 2010 White Paper for Technology Development

Technology Development for Space Time Asymmetry Research (STAR) Mission

Ke-Xun Sun[1], Elwood Agasid[2], Sasha Buchman[1], Robert Byer[1], Lisa Chu-Thielbar[2], Dan DeBra[1], John Goebel[2], John Hall[3], John Hines[2], John Lipa[1], Robert Ricks[2], and Peter Worden[2]

[1]*Stanford University*
[2]*NASA Ames Research Center*
[3]*JILA, NIST*

Email: kxsun@stanford.edu , voice 650-725-2159, fax 650-723-0226
Ginzton Lab N119, Stanford, CA 94305-4088

Abstract

The Space Time Asymmetry Research (STAR), recently proposed as a NASA Small Explorer Mission (SMEX) will test isotropy and symmetry of space time at unprecedented precision. We will use precision molecular iodine stabilized Nd:YAG laser interferometers to search for small deviations from Lorentz Invariance, a cornerstone of relativity and particle physics and thus our understanding of the Universe. A Lorentz violation would have profound implications for cosmology and particle physics. An improved null result will constrain theories attempting to unite particle physics and gravity. We have previously submitted a Science White Paper to Astro 2010.

While self contained, this White Paper mainly outlines technology development for the STAR mission, with emphasis on the science payload and spacecraft. With a funding level compatible with SMEX, we plan to develop a high performance, high reliability science payload in a 4~5 year time frame. The STAR mission is designed to work one-year in space, with possible extension to indefinitely longer as long as the payload remains functional.

Science and technical objectives:

- Measure the absolute anisotropy of the velocity of light to 10^{-18} (100-fold improvement), with potential to reach 10^{-19}
- Derive the Michelson-Morley coefficient to 10^{-12} (100-fold improvement)
- Derive the Kennedy-Thorndike coefficient to 7×10^{-10} (400-fold improvement)
- Derive the coefficients of Lorentz violation in the Standard Model Extension, in the range 7×10^{-18} to 10^{-14} (50 to 500-fold improvement)

The STAR mission is scientifically important and technically innovative. We have a well conceived plan, the right team and complete capability to achieve mission success.

Technology Development for Space Time Asymmetry Research (STAR)

1. Introduction

STAR, a small, self-contained mission of opportunity within the Small Explorer Program, will greatly advance the field of fundamental physics. The #1 astrophysics research objective, as stated in the NASA Science Plan for 2007-2016 is to “Understand the origin and destiny of the universe, phenomena near black holes, and the nature of gravity”. The first two Baseline Objectives for Astrophysics are:

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?)”*

Our mission directly addresses these compelling objectives. STAR will perform a fundamental, precision test of special relativity, by searching for small dependencies of the speed of light c on direction in space and on the motion of the observer, with a sensitivity of 10^{-18}. (All sensitivities quoted in this proposal refer to the relative quantity, $\Delta c/c$, where Δc is the sought-after departure of the speed of light from a rigorous constant.) Such measurements have previously only been attempted in ground-based laboratories. Recent developments in miniaturized robust optics, motivate simple, low-cost space borne experiments in this field for the first time. The STAR team is led by Robert Byer, the developer of a small, capable, fully space qualified laser, and includes one of the world’s leading experts in special relativity ground based experiments, John L. Hall (Nobel Laureate , physics, 2005). Floyd Stecker (GSFC) has collaborated with Sheldon Glashow, a giant in this field (Nobel, physics, 1979). Partnered with NASA Ames and Goddard, the team is admirably suited to conduct the mission. Previous efforts—limited not by technology, but by ground-based noise factors—have approached sensitivities of only 10^{-16} with no effect detected. STAR will achieve a two to three orders of magnitude improvement by transplanting this proven technology to the relatively noise-free environment of space. The resulting data set will, for the first time, “map” space-time velocity fluctuations in our sky.

Why is it so important to conduct this research?

The whole of modern physics is based on a class of invariances, or symmetries, describing how all measured quantities are seen by different observers in relative motion, and contained in the famous Lorentz transformations. A verifiable detection of any dependence of the speed of light on motion or direction, the object of this proposal, would signal the first needed modification of special relativity since its inception and would have profound implications for cosmology, high energy astrophysics, particle astrophysics, and relativity. Even a non-detection would be significant. An improved upper limit would give new direction to theoreticians and reduce the parameter space available to attempts to unite quantum mechanics, particle physics and gravity.

We now know of a unique rest frame: that defined by the cosmic microwave background (CMB), with respect to which the solar system is moving at a velocity of ~370 km/s. The existence of this natural frame of rest does re-energize the field of experimental relativity because it provides a rational framework for the interpretation of any asymmetry that may be discovered. The Universe is nevertheless isotropic, as far as currently known; a separate, and open, question is whether there is any preferred *direction* in space. Answering this question is another of the baseline objectives of the STAR mission.

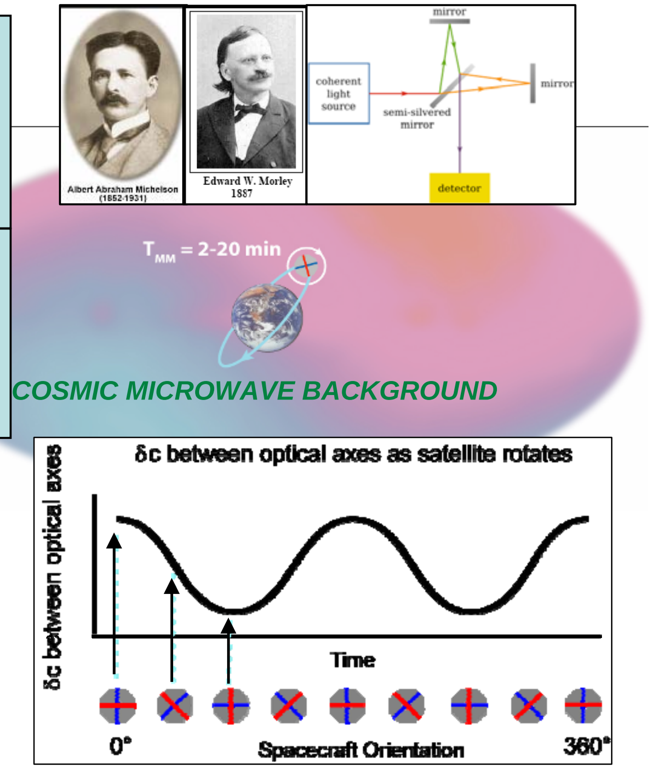
MM STAR Mission Objectives

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

- Derive the MM coefficient to ~ 10^{-12}
- Derive the generalized coefficients of LIV
  - *boost independent:* < 7×10^{-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



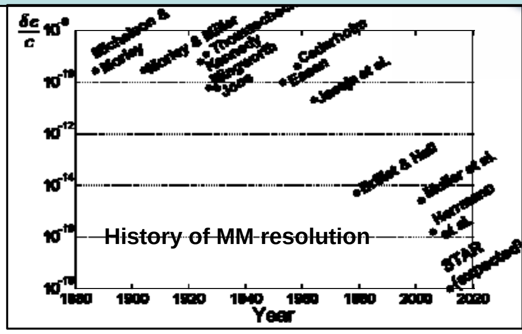


Figure 1. Michelson Morley experiment

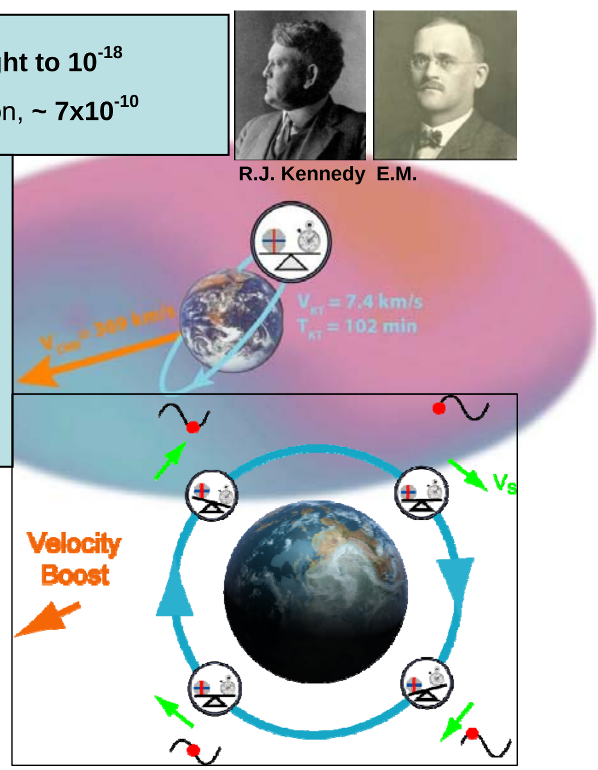
KT STAR Mission Objectives

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

- Derive KT coefficient to the corresponding resolution, ~ 7×10^{-10}

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 cavity frequency to the wavelength of a molecular-iodine stabilized laser as absolute frequency reference.



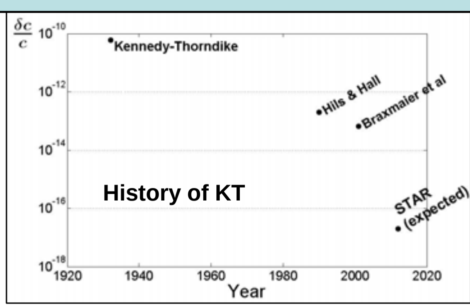


Figure 2. Kennedy Thorndike experiment

Why is it so important to extend this search by two orders of magnitude?

The one area of general agreement among the many diverse approaches to Lorentz invariance violation (LIV) theory is the plausibility that the long-sought unification of quantum mechanics and relativity will follow the pattern of the unification of electromagnetic and weak interactions, the so-called electroweak theory of Glashow, Weinberg and Salam, in the 1960's. Accordingly, the natural scale for variations of the speed of light, for example, is expected to be near the ratio of the electroweak mass to the Planck mass, approximately $\Delta c/c \sim 0.66 \times 10^{-17}$. This consideration shows that the window of sensitivity opened up by STAR plausibly contains very exciting physics. With either a detection of, or an upper limit on, variations in the speed of light, STAR will be a milestone in modern astrophysics.

2. Scientific Goals and Measurement Approaches

Measurement Objectives	**Mission Objectives and Relevance**	**Ground Experiment (No previous missions)**	**Improvement Factor Over Ground Experiment**	**Future Mission Objectives**
Detect LIV (isotropy/anisotropy of c)	$\delta c/c \sim 10^{-18}$ Test special relativity	$\delta c/c \sim 10^{-16}$	100	$\delta c/c \sim 10^{-20}$ (LISA is the nearest analogue mission)
Improve KT	$\sim 7\mathrm{x}10^{-10}$ Test symmetry of space time	$\sim 10^{-8}$	~400	$\sim 10^{-11}$ (LISA)
Improve MM	10^{-12} Test symmetry of space time	10^{-10}	100	Improvement on 10^{-12} (LISA)
Refine SME	10^{-14} to $7\mathrm{x}10^{-18}$ Improve basic understanding of cosmological parameters	10^{-13}	50-500	Improvement on 10^{-13} (LISA)

Table 1: *Mission Objectives (LIV = Lorentz invariance violation, including variable c.)*

STAR measures the anisotropy of the velocity of light $\delta c/c$ with respect to inertial space using a pair of optical cavities with their axes orthogonal to the spacecraft roll axis. One studies the difference in the resonant frequencies of two cavities as a function of angle and of the velocity of the craft around its orbit. For our configuration the expected signals appear at twice the roll rate with respect to inertial space, and at the orbital period. Precession of the orbit plane over 1 year of operations allows a search in all directions and thus the creation of a "map" of any minute variations in c. To obtain a resolution of 10^{-18} in one of these directions in a year the noise level of the two-cavity fractional frequency difference, $\delta\nu/\nu$, needs to be $< 1.6\mathrm{x}10^{-15}$ in 1 sec. of integration. This assumes a 50% 'duty cycle' of good data received on the ground and available for analysis, and a 1-year mission lifetime with a sun-pointing roll axis. Then for a single cavity the fractional frequency noise of the locked laser signal needs to be $\sim 1.1\mathrm{x}10^{-15}$ in 1 sec. $\delta\nu/\nu$ is the frequency analog of $\delta c/c$. In another aspect, one cavity signal is measured relative to an atomic clock, the iodine reference. This clock is expected to have a frequency stability or Allan deviation (AD) of $\sim 10^{-14}$ at a measurement time of 100 sec (Ye, 2001), somewhat dependent on construction, but be independent of velocity. The cavity frequency is modulated by the velocity vector changes, δv, of the spacecraft, not the roll. At 1 year the effective AD is $\sim 2\mathrm{x}10^{-17}$.

3. STAR Science Instrumentation

Scientific and technical heritage

Professors Byer and Hall are pioneers in lasers and laser frequency stabilization. In designing the science instruments, we have drawn heavily upon the extensive experience of the Byer and Hall groups in lasers, optics, nonlinear optics, interferometery, high finesse optical cavities, optical clocks, and iodine laser stabilization techniques developed over nearly four decades.

The STAR team members have pioneered the modern MM and KT experiments, in both optical and microwave frequency domains. John Hall first used high-stability Fabry-Perot cavities for the measurement of the MM and KT coefficients since 1970s (Brillet & Hall 1979, Hils & Hall 1990). The experiments improved the MM and KT coefficients measurement precision by hundreds of times when first published. The experiment is being continued today at JILA/NIST. John Lipa has long been pursuing Lorentz Invariance tests via the SUMO (superconducting microwave oscillator) experiment. He achieved the first measurements of the coefficients of Lorentz violation.

STAR Payload Scientific Instrumentation

The STAR core science instrument consists of two essentially identical laser and optics units, as shown in Figure 3. Each contains a laser, two cavities, an iodine vapor cell, and frequency shifters. The beat note signals between the two 1064 nm laser fundamentals, and between the 532 nm second harmonics will be measured using intensity balanced detection. The beat note signals can be referenced to two orthogonal cavities, or one cavity and one iodine cell, or two iodine cells, and therefore the MM experiment, KT experiment, and, if desired, the red-shift experiment can all be accomplished. Within each laser and optics unit, the various measurements can be accomplished without resort to the other unit. This dual unit configuration provides full redundancy and thus improves the reliability and signal to noise ratio. The volume, weight, and power consumption of the payload using two laser and optics units with four cavities will only increase by a small margin, compared with the version that uses only two orthogonal cavities but with two lasers.

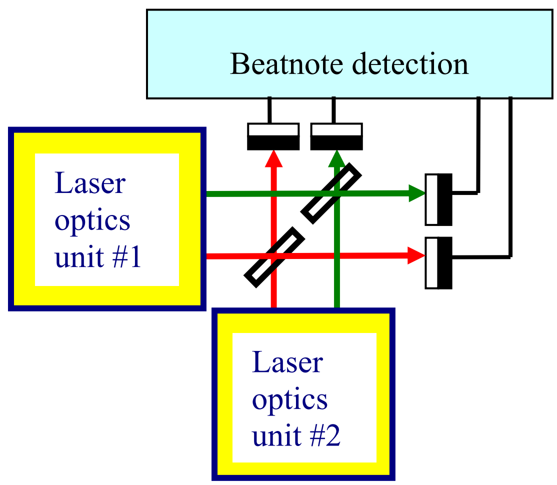


Figure 3: Heterodyne detection of beat note signals from two laser optics units.

For each optical unit, an NPRO Nd:YAG laser is frequency locked to an iodine gas cell providing a frequency standard that is independent of spacecraft orientation and velocity. Some laser light is split off and used to detect variations in the resonant frequency of an orthogonal pair of high-finesse Fabry-Perot resonant cavities using additional locking circuits. As the satellite rolls and goes through its orbital motion, asymmetries in space-time will manifest themselves as variations in the resonant frequencies of the cavities. The resonant frequency of each cavity is measured by observing the frequency shift with the Pound-Drever-Hall locking technique. The difference in the resonant frequencies of the cavities is also directly observed through interference of the two laser beams at a beam splitter attached to the cavity block. This signal is the basic data for the MM and coefficient of Lorentz violation measurements. By comparing the frequency of one cavity with an iodine line we perform the KT experiment.

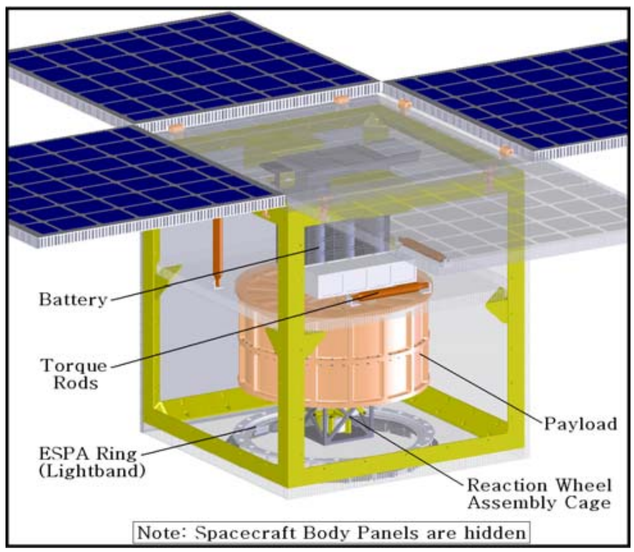
Instrumentation Rationale

To make ultra precise measurements of tiny directional asymmetries in the speed of light we need to compare its value in orthogonal directions so that we can reveal responses to those asymmetries in differential form. To convert the difference signal from d.c. to a.c. we rotate the spacecraft about its axis. This provides the directional dependence relative to an inertial reference frame for the MM coefficient measurement. The KT measurement requires a similar modulation, but this time of the velocity of a cavity relative to the inertial frame. Thus, both of the desired science results can be obtained from an orthogonal instrument design with an iodine reference and a rolling spacecraft. Modern optics configurations using lasers, resonators and detectors provide the basic signals to be measured. Recent advances in the robustness and miniaturization of lasers, detectors and related electronics enable the STAR science instrument payload to be configured in a small satellite, and such fine measurements to be made for the first time. The specific NPRO Nd :YAG laser was chosen because it is compact, well-understood and space qualified.

Spacecraft and payload configuration

The spacecraft and payload are shown in Figure 4.. The spacecraft will be a secondary payload mounted through an ESPA ring. The spacecraft is a 60 cm cube which is within the ESPA module maximum envelope of 90 cm x 60 cm x 70 cm. The spacecraft has pointing control to seek the sun direction. High efficiency solar panels generate ~200W power.

The payload consists of the science module, including the cavity section, the laser optics section, and the detector electronics section. The components of the payload can be housed in a 55 cm cube, smaller than the ESPA attachment. This allows a more flexible arrangement of the payload contents according to the needs of thermal, power and mass balancing. The core instrumentation is located on the shady side of the solar panels for better temperature stability. The laser and optics section can be stacked above the core cavity enclosure.



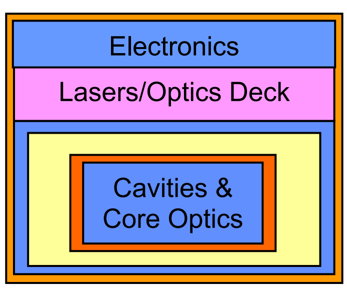


Figure 4: Spacecraft (upper) and payload (left) structure overview.

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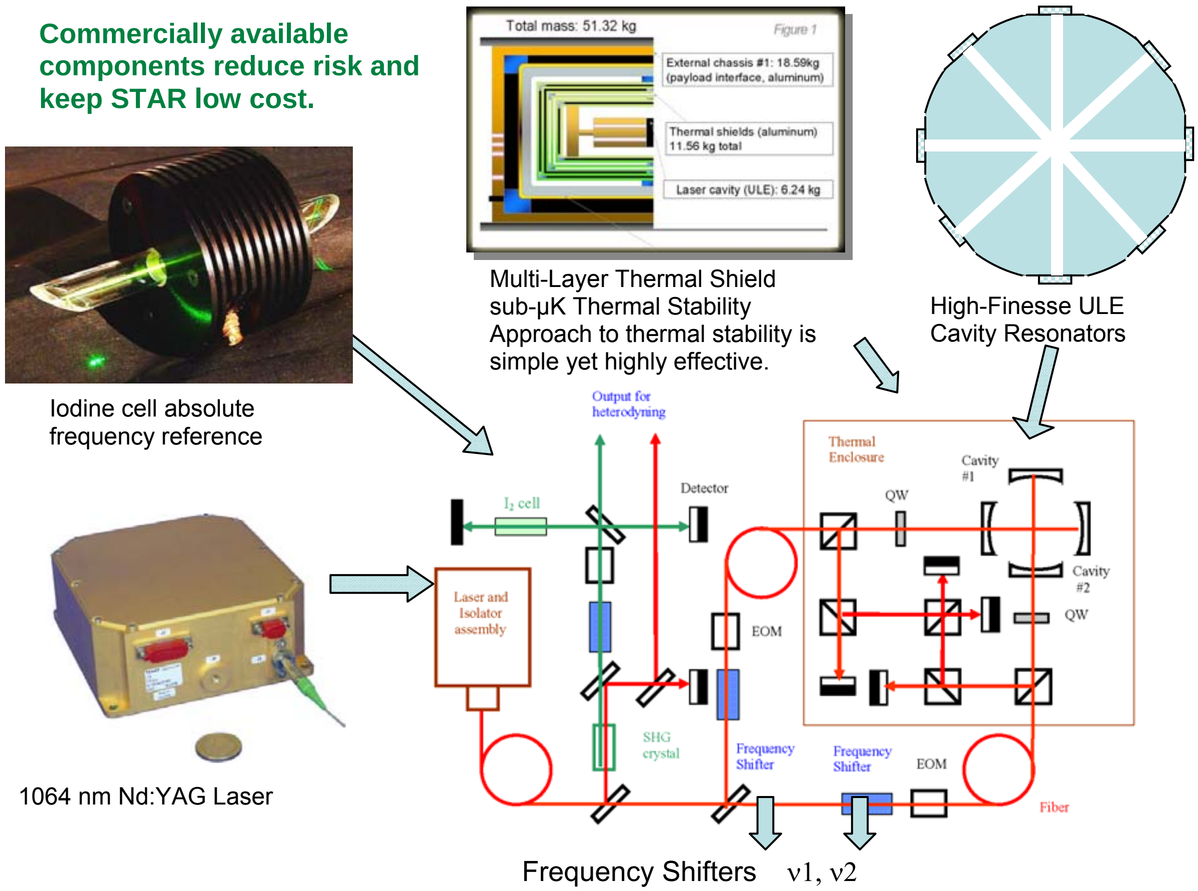

Figure 5. Optical configuration and key components

Optical configuration

Figure D6a.3 shows a simplified optical layout for each unit. A Nd:YAG NPRO laser provides a 1064 nm light source. A high efficiency second harmonic generator (SHG) converts a portion of the light into 532 nm. An iodine vapor cell provides a frequency reference at 532 nm. Two orthogonally placed high finesse Fabry-Perot cavities provide frequency references at 1064 nm. Frequency shifters with filters are used for offsetting the laser frequency, and electro-optical modulators (EOM) are used to generate frequency sidebands for cavity frequency locking.

High finesse optical cavity

The high finesse cavity defines the fundamental length for both the MM and the KT measurements. As a core component of the science instrumentation, all four cavities of the two laser and optics units are constructed in one monolithic block made of Ultra Low Expansion (ULE) glass, as shown in Figure 4. The monolithic construction of the cavities reduces noise effects such as temperature fluctuations. ULE has a low coefficient of thermal expansion (CTE) of ~10^{-9} per K, when operated in the temperature range of 10-20^{o}C, and a null near 15°C [Corning ULE Spec Sheet 2007].

The optical cavities are designed to have a length of 20 cm and a finesse of 100,000 to 250,000. Further enhancement of cavity finesse is possible by using lower transmission mirrors but will impose a higher cleanliness requirement. The Pound-Drever-Hall (PDH) technique for cavity locking will be used. NPRO lasers at 1064 nm have achieved a relative frequency stability of $\Delta\nu/\nu \sim 10^{-15}$, or $\Delta\nu \sim 0.3\,\text{Hz}$ at 1064 nm wavelength, using the high finesse cavities, and the PDH locking technique. [Hall] [Day][Sampas][Ye].

Thermal noise due to Brownian motion

The thermal noise due to Brownian motion (*kT* noise) has been proven to be a fundamental limit to the frequency stability of a cavity, when technical noise in the frequency-locking scheme is eliminated. For lower *kT* noise, the material also needs to have a low mechanical loss, or high *Q* value. The longer cavity length helps reduce the effect of the thermal noise on the measurements. For example, a 20 cm long cavity reduces the relative contribution of thermal noise by a factor of 6.7 compared to a 3 cm cavity. We will also consider the use of fused silica mirrors, which have a higher Q-value to 10^6-10^7, and will reduce thermal noise by a factor of 10 compared with ULE. The further optimization will be a part of Phase A studies.

Iodine cell

Iodine vapor has several hyperfine transitions (R(56) 32-0 a1 resonances) around the 532 nm line generated by SHG from the 1064 nm fundamental. The error signals generated by the I_2 absorption lines can be applied to lock the Nd:YAG laser to a long term stability (>1000 seconds), measured by the AD, from 10^{-14} to 10^{-16}. [Byer][Hall]. This favorable behavior improves the accuracy of the KT experiment which has a measurement time given by the orbital period which is baselined at around 95 mins.

Differential Frequency measurement using multiple frequency shifters

In all anisotropy measurements so far, two independent tunable lasers, each locked to a cavity (or one of them locked to an iodine cell), are used. In such experiments, the measurements are actually only concerned with the frequency *difference* between the resonance peaks. We plan to use only one laser in each laser and optics unit, but use several frequency shifters to acquire the three different resonant frequencies for one iodine cell and two cavities. A potential advantage of this approach is improved common mode rejection of the intrinsic laser frequency noise. The frequency uncertainty requirement is reduced to only the RF frequency generators, which have always been a part of frequency stability requirements. We expect this advantage will significantly reduce the technical complexity of the frequency locking experiment, and may lead to higher precision in the STAR experiments.

The use of frequency shifters also reduces the number the lasers on board. For six resonance devices (two iodine cells and four cavities), we will need to fly only two lasers, and yet achieve higher performance, redundancy, and reliability. Given that space qualified lasers are very expensive, this approach substantially reduces the mission cost.

Thermal requirements and thermal system design

Thermal requirement

A high finesse Fabry Perot cavity consists of a fixed length spacer and two high reflectivity mirrors bonded to the ends. The thermal expansion of the cavity spacer material is the single most important factor affecting the science measurement. The temperature stability requirements can be derived from the formula

$$\frac{\Delta\nu}{\nu} = \frac{\Delta L}{L} = \alpha\Delta T \quad \text{or} \quad \Delta T = \frac{\Delta L}{\alpha L} = \frac{1}{\alpha}\left(\frac{\Delta\nu}{\nu}\right),$$

where L is the cavity length and α is the CTE. For ULE $\alpha \sim 10^{-8}$-10^{-9}, thus the corresponding temperature requirement for $\Delta\nu/\nu \sim 10^{-15}$ is $\Delta T < 10^{-7} \sim 10^{-6}$ K, or 0.1~1 μK, which is an exceedingly tight requirement. The above requirement must apply to all four cavities. This applies to the 2-dimensional temperature stability for crossed cavities, and to the 3-dimensional temperature stability for the stacked cavities, for a fully operational STAR mission. However, it only applies over roll and orbital periods as linear and quadratic temperature drifts of this magnitude can easily be taken out in data analysis. To reach $\Delta\nu/\nu \sim 10^{-18}$ we take advantage of the expected low level and randomness of the thermal signal after slope and curvature are removed.

Thermal system design

To get the most flexibility in manifesting we have designed a thermal control system capable of operating in any earth orbit, including those with substantial earth shadowing. We have developed a combined passive and active thermal control approach to achieve the required performance. We designed the four cavities to be symmetrically distributed in one ULE block, to gain the advantage of the common mode rejection to the temperature fluctuations. We have designed a configuration with six layers of high thermal conductivity aluminum coated with a low emissivity material (gold) separated with vacuum gaps. This configuration allows the temperature profile to be uniform down to ~ 10 nK for an external temperature change of ~1°C. An additional layer of thermal control for other parts of the payload is used to reduce the environmental change for the cavity enclosure to well below this level. Figure 6 shows the 10^{-10}K cavity temperature uniformity inside the enclosure, given an external temperature gradient of 2K. Figure 7 shows the temperature variation within 10^{-8} K while the spacecraft is in and out the earth shadowing.

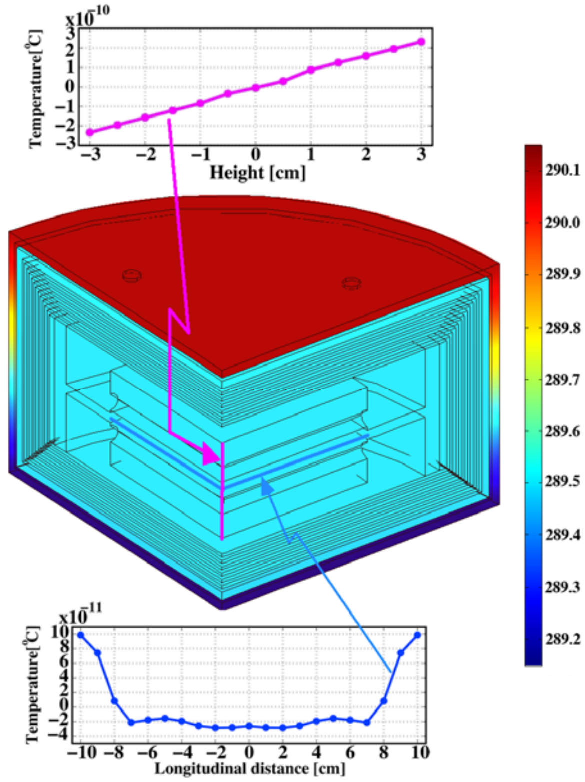

Figure 6. Temperature distribution at the cavity block. 3-dim image showing the temperature uniformity when 2 K temperature gradient exists at the top and the bottom of the thermal interfaces. Inside the enclosure: 10^{-10} K temperature uniformity is shown.

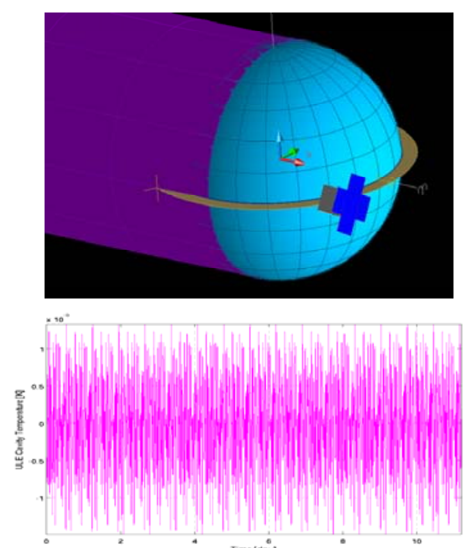

Figure 7: Temperature variation due to earth shadowing induced is attenuated.

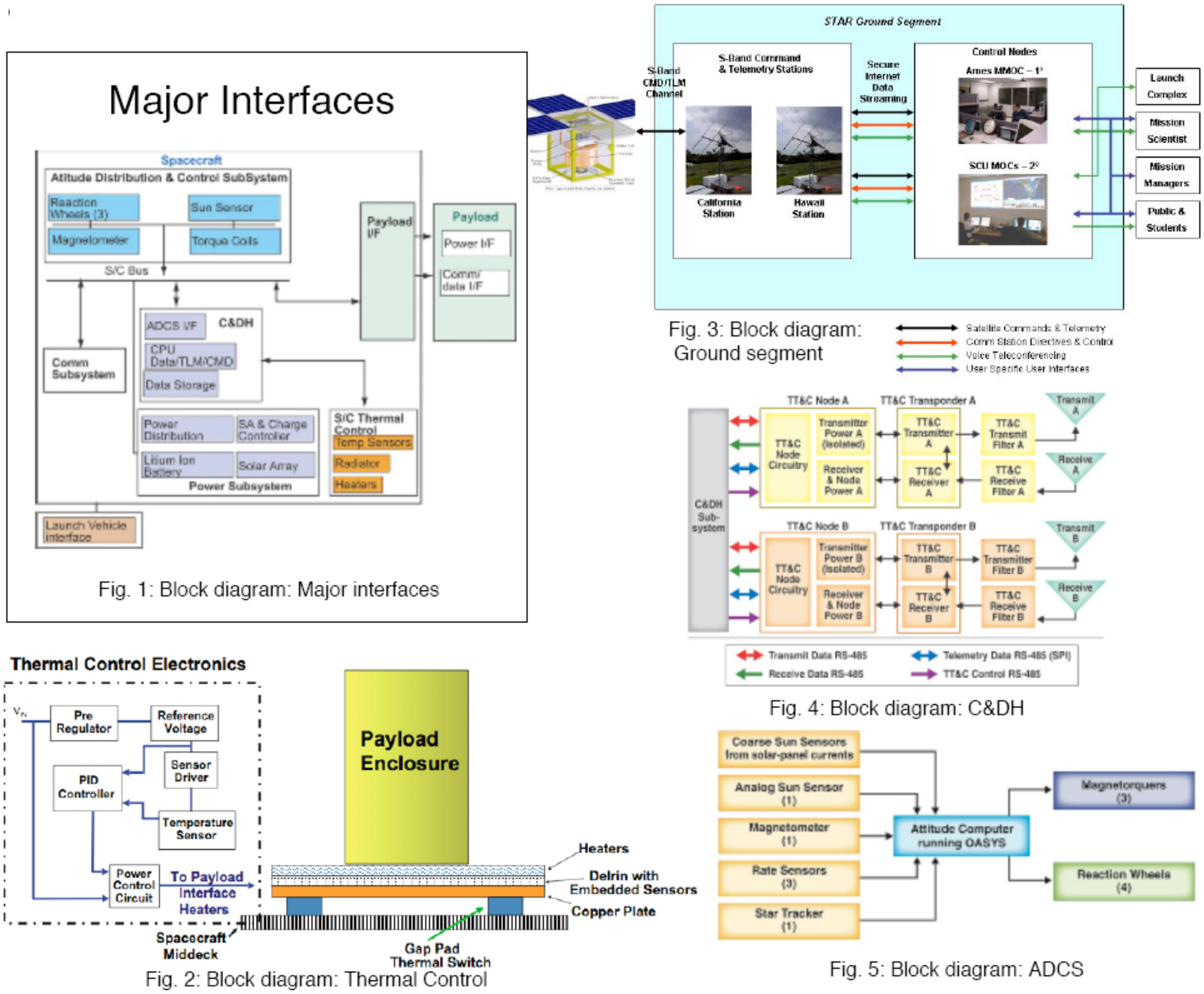

Figure 8. Interface, tests, communication, , and spacecraft control

Development, interface, tests, communication, data storage, and spacecraft control

The payload will be developed at Stanford University. The spacecraft will be developed at NASA Ames Research Center. The major interfaces will be implemented via a standard spacecraft bus. The payload and spacecraft environmental tests will be carried out at Ames facilities. The STAR payload and spacecraft is designed as small mission and can be launched using EELV vehicle, or as a ride-along of other missions. The communication to spacecraft will be using NASA ground stations in California and Hawaii. Data will be stored at Ames, Stanford, and a third NASA center.

Conclusion

The STAR mission is scientifically important and technically innovative. We have a well conceived plan, the right team and complete capability to achieve mission success.

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