mSTAR: Testing Lorentz invariance in a low Earth orbit with high performance optical frequency standards

Shailendhar Saraf[†], Sasha Buchman, Grant D. Cutler, John Lipa, Si Tan and Robert Byer
Stanford University, Hansen Experimental Physics Laboratory, Stanford, California, USA

[†]E-mail: saraf@stanford.edu
spacegrav.stanford.edu

Thilo Schuldt, Hansjörg Dittus and Claus Braxmaier
Deutsches Zentrum für Luft- und Raumfahrt (DLR),
Institut für Raumfahrtssysteme, Bremen, Germany

Achim Peters and Klaus Döringshoff
Humboldt-Universität zu Berlin, Institut für Physik, Berlin, Germany

John Hanson, Belgacem Jaroux and Simon P. Worden
NASA Ames Research Center (ARC), Mountain View, California, USA

Abdul Alfauwaz, Abdulaziz Alhussien, Badr Alsuwaidan and Turki Al Saud
King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi-Arabia

Norman Gürlebeck, Sven Herrmann and Claus Lämmerzahl
Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation (ZARM),
Universität Bremen, Germany

Ulrich Johann
Airbus Defence and Space GmbH, Friedrichshafen, Germany

The mini Space Time Asymmetry Research (mSTAR) is a proposed space mission to perform an advanced Kennedy-Thorndike (KT) test of Special Relativity using the large and rapid velocity modulation available in low Earth orbit (LEO). The mission goal is to test special relativity by performing a clock-clock comparison experiment in LEO, thereby testing the boost dependence of the speed of light. Clocks with stabilities better than 10^{-15} level at orbit time will allow the KT coefficient to be measured with up to two orders of magnitude higher accuracy than current ground-based experiments, with an additional factor of 10 possible using more advanced technology. In the current baseline, mSTAR utilizes an absolute frequency reference based on modulation transfer spectroscopy of molecular iodine and a length-reference based on a high-finesse ultra-stable optical cavity. Current efforts aim at a space compatible design of the two clocks and improving the long-term stability of the cavity reference. In a recently completed Phase A study, the feasibility of accommodating the mSTAR experiment on a SaudiSat 4 bus was investigated.

Keywords: Lorentz invariance; Kennedy-Thorndike; clocks; ultra-stable cavities; low Earth orbit.

1. The mSTAR Mission

The mSTAR mission [1] will improve our understanding of the range of applicability of the theory of Special Relativity (SR), a cornerstone for understanding the laws governing the universe and its evolution. The goal is to obtain a 100X improvement on the resolution of the Kennedy-Thorndike (KT) coefficient over the current limit. The measurement will be performed by comparing the frequency of an optical transition in molecular iodine with the resonant frequency of a high finesse optical cavity while they are in Earth orbit in the presence of a preferred frame as shown in Fig. 1. An international

collaboration including KACST, DLR, NASA-Ames, Airbus-DS, Stanford University, ZARM-Bremen, and Humboldt University has developed a small-instrument concept called mini-STAR, or mSTAR, which would achieve a two order of magnitude improvement in the search for Lorentz invariance violations using technologies well-developed on the ground, but performing the observations in space.

Fig. 1. KT experiment concept and velocity of Earth relative to cosmic microwave background radiation.

2. Science motivation and objectives

It is well known that Special Relativity (SR) owes its experimental foundation to a minimum of three types of classical experiments: those of Michelson and Morley (MM), Kennedy and Thorndike (KT) [2] and Ives and Stilwell [3]. Extreme precision has been obtained in verifying SR in many areas, yet the basis for accepting it must remain experimental, as with all laws of physics. The intrinsic boost-dependence of a KT experiment can easily be seen from the idealized model of Mansouri and Sexl (MS) [4] that separates small LIV terms into angle and boost dependent groups. Analyzed by Robertson [5] and MS, the RMS model of Lorentz violations can be parameterized as:

$$\delta c/c = \epsilon_{KT} (v/c)^2 + \epsilon_{MM} (v/c)^2 \sin^2 \theta \quad (1)$$

where the quantities ϵ_{KT} and ϵ_{MM} are small dimensionless coefficients, θ is the angle of propagation of light relative to some preferred direction, v is the velocity of the apparatus relative to the frame, and δc is the deviation of c from an exact constant. In SR the two terms on the right hand side are zero. In the RMS model a MM experiment can be viewed as measuring the quantity ϵ_{MM} via the θ -dependence of c , while a KT experiment measures the quantity ϵ_{KT} via the velocity dependence of c , independent of θ . A generalized experiment may be sensitive to both terms.

The mission described here will search for variations in c to the level $\delta c/c < 10^{-17}$ over the entire sky with the possibility of higher resolution depending mostly on optical cavity performance. The goal of the mission is to make a $100\times$ improvement of the limit on the KT coefficient in Eq. 1. The KT coefficient is obtained from a data analysis that compares a rod length to the ticking rate of a clock as a function of velocity direction. It uses Eq. 1 to look for a preferred frame effect manifested by the velocity dependence of $\delta c/c$ independent of orientation. The derived quantity is then the θ -independent term in Eq. 1, $\epsilon_{KT}(v/c)^2$. Since it is very difficult to measure c directly with high precision, the only way this analysis can generate an observable $\delta c/c$ is if v varies. To obtain extra sensitivity over ground we make use of the orbital velocity of the spacecraft to maximize

the change in v , denoted δv . By convention v is taken as the velocity relative to the CMB and any signal detected is referenced to this frame, but can easily be transformed to any other frame. To get the maximal sensitivity to the KT coefficient we then multiply the $\delta c/c$ data by $c^2/2v\delta v$. In a circular orbit at 650km altitude we obtain 2.2×10^7 giving a resulting limit on ϵ_{KT} of $< 3 \times 10^{-10}$ including some margin. This can be compared with the ground limit of $\epsilon_{KT} < 4 \times 10^{-8}$ supporting our claim of a potential factor of 100 improvement in the resolution of this parameter. To test for other potential preferred frames the analysis would proceed by analogy with that for the CMB.

3. Instrument description

The mSTAR instrument comprises of a highly stable optical cavity located in a thermal enclosure that maintains high vacuum conditions, an iodine frequency reference with very high stability and low noise, and associated electronics and software. It is designed to be accommodated in a SaudiSat with generic interfaces modeled on the UV-LED payload launched in 2014. A functional diagram of the mSTAR payload is shown in Fig. 2. It consists of the following subsystems:

- Iodine based frequency reference (clock 1) with laser source Beam Preparation Unit (including second harmonic generator (SHG) and acousto-optic modulators (AOMs)).
- Cavity based frequency reference (clock 2) with thermal enclosure and Modulation Bench (including AOM and electro-optic modulator (EOM))
- Control electronics for clocks 1 and 2.
- Laser control electronics.
- Data Management Unit (DMU) and Power Conditioner.

There are two input signals, emanating from the common source – clock 1, an absolute clock – a laser stabilized to an energy transition in molecular iodine (I_2). The first signal is the baseline used to compare the signal from clock 2, the ‘rod’. It goes directly from the laser clock to a frequency comparator. The second signal is fed into a resonant cavity, clock 2, via a frequency shifter. The cavity and the shifter are in a feedback loop such that the frequency shifter can maintain the light frequency at the proper cavity resonance at all times. Either length contraction in the rod and/or time dilations will manifest themselves as deviations in the required frequency shift to keep the rod resonant with the laser light. The output of the rod laser light is then compared with the baseline signal to

Fig. 2. Functional diagram of the mSTAR payload (IF = interface).

generate the KT science output. The rod is made of Ultra-low expansion (ULE) glass to reduce spurious thermal effects. The payload also includes the corresponding control electronics for the two clocks (incl. temperature stabilization, frequency control feedback loop) and the laser (incl. temperature stabilization, low-noise current drive). A data management unit (DMU) controls the experiment, collects the data and is interface to the on-board computer (OBC), which is assumed to be part of the spacecraft bus.

For the KT measurement the signal from the reference clock is initially compared to the signal from the rod via the frequency comparator while the apparatus is in an initial velocity state. There will be some difference in the two frequencies that is recorded. Later when the apparatus is travelling in the opposite direction around the orbit relative to its initial state, the signals are compared again. If there is no difference from the recorded value, the KT portion of the experiment is null. If there is a difference from the recorded value, the KT coefficients may be precisely determined by the difference between the initial vs. boosted frequency values. The frequency comparison is made with opposing velocities in three orthogonal directions.

3.1 Iodine frequency reference

The mSTAR baseline design is directly based on the DLR-funded engineering model (EBB/EM) development carried out at HTWG/ZARM/HUB. The iodine instrument is based on modulation-transfer-spectroscopy (MTS) techniques applied to a molecular species in gas phase [5][6]. These techniques employ two counter-propagating laser beams through an iodine sample for Doppler-free resolution of narrow transitions (pump and probe beam). MTS has been applied extensively to hyperfine transitions in molecular iodine using frequency doubled Nd:YAG lasers operating at 1064 nm. Nd:YAG lasers feature a superior intrinsic frequency and intensity stability, while I_2 features strong, narrow hyperfine transitions at 532 nm. These can be addressed with a frequency-doubled portion of the fundamental output of a Nd:YAG laser. The natural linewidth of the most used transition (the a_{10} component of R(56) 32-0) is 280 kHz. Taking into account transition broadening, pressure broadening and power broadening the typical linewidth is ~ 800 kHz.

Current setups have achieved a stability of 4×10^{-15} at orbit time [7][8] meeting the requirement of the mSTAR mission. Many issues limiting the long-term performance have been identified [9][10][11][7]. Some of the major issues are residual amplitude modulation (RAM) and pointing stability of the beams in the cell. Methods for control of RAM have been developed [7][12]. In the setup proposed for mSTAR, the pointing instability will be significantly reduced through the use of a thermally and mechanically stable assembly-integration technology. The mSTAR baseline iodine frequency reference is directly based on the EBB/EM developments carried out at ZARM/HTWG/HUB [9]. The schematic of the EM iodine setup and baseline for mSTAR is shown in Fig. 3. The main trade-offs were carried out during these studies, resulting in the following key characteristics:

Fig. 3. Iodine setup as realized for the EM development at ZARM/HTWG/HUB/DLR.

- Modulation transfer spectroscopy (MTS) is used for enhanced long-term frequency stability (compared to frequency modulation spectroscopy, FMS)
- Spectroscopy setup will be realized using a baseplate made of glass (either fused silica or specific ultra-low expansion glass ceramics such as ULE, Zerodur, Clearceram) in combination with adhesive bonding technology using a space-qualified two-component epoxy.
- The laboratory setup at HUB is taken as basis for the development with respect to space applications. This includes active intensity and in-quadrature RAM stabilization and also an interaction length of approx. 80cm of the laser beams in the iodine gas cell.
- Laser source is an NPRO type Nd:YAG laser @ 1064nm, also available in a space-qualified version. The light is frequency doubled in a Second Harmonic Generator (SHG) module to get to 532nm for interrogating the hyperfine transitions in Iodine.

Fig. 4. Measured frequency stability of the EM iodine setup by performing a beat measurement with the EBB iodine setup and a ULE cavity setup.

With this setup, frequency stability below 5×10^{-15} for integration times > 1000 s was achieved, similar to the EBB and laboratory setups, the root Allan deviation is shown in Fig. 4. The spectroscopy unit was subjected to thermal cycling (-20°C to $+60^{\circ}\text{C}$) and vibration testing (sine vibration up to 30g; random vibration up to 25.1g). The frequency stability was measured before and after the tests where no degradation was observed.

3.2 Optical cavity system

The effectiveness of the cavity as a frequency sensor depends strongly on the line width and stability of the laser sources, the thermal-mechanical stability of the cavity itself, and the sensitivity of the cavity to velocity-induced length perturbations. The sensitivity correlates most directly to cavity finesse which is defined as the ratio of the free spectral

range of the cavity to the full width at half maximum (FWHM) of the cavity resonance peak. The required finesse is $>100,000$ to detect length perturbations at sensitivities necessary to meet the science requirement (i.e., $\Delta l/l = 10^{-15}$ at orbit period, where l is the cavity length). Modern cavities readily reach finesse values well above 100,000 [13]. The cavity design supports the finesse requirement using pairs of low-absorption (<5 ppm), partially transmitting ($T < 20$ ppm) mirrors (achievable finesse $> 160,000$). A design developed for flight by Ball Aerospace is shown in Fig. 5.

High elastic moduli and the thermal behavior of ULE glass drive the material selection for the cavity body. ULE has a low coefficient of thermal expansion (CTE) of $\sim 10^{-9}/\text{K}$ within an operating temperature range of $10 - 30^\circ\text{C}$, and a null CTE near 15°C [14]. Higher null temperatures are available on special order. In conjunction with thermal enclosure providing temperature stability between $0.1 - 1\ \mu\text{K}$, the mechanical stability of ULE is adequate to meet the 10^{-15} length stability at orbit period required to achieve the science objective. The thermal enclosure houses the optical cavity assembly and controls its thermal and structural environment. The most important requirement for this assembly is to filter the orbital period temperature variations of the spacecraft to a level so low that the science signals from the optical cavity are unperturbed. With the choice of ULE for the cavity spacer material, the CTE has a null at a temperature determined during its production. This can be tailored to be near room temperature. By measurement of the temperature dependence of the iodine-cavity beat note frequency, the null in the CTE of the cavity can be approached very closely. This allows an effective CTE of $\sim 10^{-10}/\text{K}$. With a length stability of 10^{-17} at orbital period when averaged over 2 years of data, it is clear that we need the systematic temperature change of the cavity block to be $< 10^{-7}\ \text{K}$ at orbital period. This extreme requirement has driven us to design a 4-stage thermal isolation system with active and passive control on various layers, and the selection of a thermally benign orbit.

Fig. 5. Optical cavity developed for GRACE-FO.

Fig. 6. Schematic of the cavity inside the thermal enclosure.

An exploded view of the thermal enclosure is shown in Fig. 6. It consists of a set of 4 nested aluminum cans with titanium alloy supports on alternating sides. The purpose of this arrangement is to greatly attenuate the effect of thermal expansion at the outside layer on the cavity lengths. This attenuation factor is modeled to be $> 10^{10}$. This allows 1K swings at the outer shell to have negligible stress effect on the cavity block. The cans are gold coated on both sides to reduce radiative heat transfer, and multi-layer insulation is used between the outermost layers. However, the system cannot be completely passive because we need to hold the cavity at a set temperature to minimize its CTE. With 2 stages of active control, the orbital effect appears to be negligible and the p-p temperature swing of the cavity is $\sim 8\text{nK}$ with a 1K p-p external swing.

3.3 Cavity Optics

The optical signals to be compared for the KT experiment are generated through optical elements coupling the clock and cavity. A conceptual view of the optical layout for the cavity system is shown in Fig. 7. The light is derived from a Nd:YAG laser operating at 1064nm that is frequency stabilized to better than 5×10^{-15} at orbit time using the iodine system. The modulation scheme for locking the cavity to the Iodine-stabilized laser light cannot be standard Pound-Drever-Hall (PDH) [15] since the cavity resonance can occur at a variable offset to the input light. One scheme is to frequency shift and phase-modulate the input light using an electro-optic modulator (EOM) [16]. The non-standard PDH techniques carry a noise penalty that stem from the smaller frequency discriminants. However, the cavity will be thermal-noise limited and there is a substantial margin to the shot-noise limit. Therefore, we believe that the sideband locking will not be the limiting factor in the cavity sensitivity to length changes. The sideband power along with the finesse of the cavity defines the cavity sensitivity to length changes. Sideband locking has an issue with a fair amount of laser power at other frequencies besides the auxiliary sidebands around the “resonant sideband”. Filtering the light that is non-essential to locking is helpful for improved lock stability and shot-noise-limited performance. A fiber band-pass Bragg filter can accomplish this function if the carrier is at about 20-50pm away from the FM triplet that interrogates the cavity.

Fig. 7. Schematic of cavity optics and associated electronics.

For the KT measurement the signal from the reference clock is initially compared to the signal from the rod via the frequency comparator while the apparatus is in an initial velocity state. There will be some difference in the two frequencies that is recorded. Later when the apparatus is travelling in the opposite direction around the orbit relative to its initial state, the signals are compared again. If there is no difference from the recorded

value, the KT portion of the experiment is null. If there is a difference from the recorded value, the KT coefficients may be precisely determined by the difference between the initial vs. boosted frequency values.

4. Conclusions

We presented the mission concept of a small satellite mission dedicated to perform a test of the boost dependency of the speed of light. By using state-of-the-art optical frequency references aboard a satellite flown in low-Earth orbit, the Kennedy-Thorndike coefficient can be determined with an up to two orders of magnitude higher accuracy than the currently best ground-based experiment. The payload consists of two frequency references, one based on modulation-free-spectroscopy of molecular iodine, the other based on a high-finesse optical cavity, with assumed frequency instability at or below the 10^{-15} level. The experiment will be accommodated in a SaudiSat 4 satellite bus flying in a sun-synchronous orbit for enhanced science signal and thermal stability of the payload.

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