mSTAR: TESTING LORENTZ INVARIANCE IN SPACE USING HIGH PERFORMANCE OPTICAL FREQUENCY REFERENCES

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The proposed mini SpaceTime Asymmetry Research (mSTAR) satellite mission will perform a test of special relativity. By comparing an absolute to a length based frequency reference, a Kennedy-Thorndike (KT) type experiment is carried out testing the boost dependency of the speed of light using the large velocity modulation in low Earth orbit (LEO). Using clocks with instabilities below the 10^{-15} level at orbit time, the KT coefficient will be measured with an up to two orders of magnitude higher accuracy than current ground-based experiments. In the baseline design, an absolute frequency reference based on modulation transfer spectroscopy of molecular iodine near 532 nm is compared to a high finesse optical cavity made of ultra-low expansion glass (ULE) as length based frequency reference. Variations between the two references indicate a violation of Lorentz invariance.

Summary of the mSTAR mission

Special Relativity is classically tested by performing three types of experiments investigating the direction-dependence of the speed of light (Michelson-Morley experiment), the boost-dependence of the speed of light (KT experiment), and the effect of time dilation (Ives-Stilwell experiment). The proposed mSTAR mission will perform a KT experiment in space by comparing an absolute iodine-based frequency reference to a length based frequency reference, i.e. a laser frequency stabilized to a cavity – both with frequency instabilities at or below the $1 \cdot 10^{-15}$ level at orbit time. This allows to determine the KT coefficient with an up to two orders of magnitude higher accuracy than current ground-based experiments.[1] Performing the experiment in space has several advantages. For KT experiments on ground, the relevant variation of the velocity of the laboratory comes from Earth's daily rotation (≈ 300 m/s) and for a space-based one from the satellite's velocity (≈ 7.4 km/s). Thus, the putative science signal is 25 times higher in this case. Additionally, the science signal is shifted to a Fourier frequency (≈ 0.2 mHz) where the stability of oscillators is better compared to sidereal frequencies. Moreover, space offers a vibration free environment and the elimination of large DC gravity forces.

In the baseline design, mSTAR employs an absolute frequency reference based on a hyperfine transition in molecular iodine near 532 nm. A frequency-doubled Nd:YAG laser is foreseen as laser that is stabilized to the iodine reference. Part of the fundamental (1064 nm) stabilized laser light is split off and sideband locked to the resonance frequency of a high finesse optical cavity made of ULE with an electro-optic modulator (EOM). The frequency difference between the two references can be extracted from the EOM sideband frequency, which is then analyzed with respect to variations at the orbit frequency yielding the KT coefficient.

The mSTAR iodine clock is based on a DLR-funded setup on engineering model level realized in a cooperation of Humboldt University Berlin, DLR Bremen, University of Applied Sciences Konstanz, Airbus D&S Friedrichshafen, and ZARM Bremen.[2] Its optical components are joined to a fused silica baseplate using adhesive bonding technology in combination with a space-qualified two-component epoxy. This technique allows for a high long-term stability of the iodine reference due to a reduced pointing instability. This setup takes space mission related criteria such as compactness, MAIVT (manufacturing, assembly, integration, verification and test), and robustness with respect to shock, vibration, and thermal stress into account. A frequency stability of $7{\cdot}10^{-15}$ and below $5{\cdot}10^{-15}$ at integration times of 1 s and between 10 s and 5000 s, respectively, is reached, which is similar to the best current laboratory setup.[4]

The mSTAR cavity is based on the development of a space qualified setup for the GRACE Follow-On mission carried out by JPL and Ball Aerospace. It foresees a mid-plane mounted cavity with a finesse > 160.000 made of ULE with a coefficient of thermal expansion (CTE) of $\sim 10^{-9}$/K within an operating temperature range of 10–30°C and a CTE zero crossing temperature near 15°C. Mirror substrates are made of fused silica in order to reduce thermal noise and ULE compensation rings are planned in order to maintain the CTE zero crossing temperature.[5] The thermal enclosure of the cavity consists of 4 gold coated aluminum cans with titanium alloy supports, for which thermal simulations show an attenuation factor $> 10^{10}$ so that a 1 K temperature swing at the outer shield, which can be provided by the satellite bus, will have negligible stress effects on the cavity.

The proposed baseline orbit for mSTAR is a circular 6 AM dawn-dusk sun-synchronous LEO with an altitude of 650 km, which provides a natural de-orbiting in 25 years. This altitude minimizes the need for radiation hardness of the components and the sun-synchronous orbit provides a good thermal stability of the payload. The spacecraft bus will be contributed by KACST based on their SaudiSat 4 spacecraft with an envelope size of $672 \times 606 \times 1227\,\mathrm{mm}^3$. It provides ∼100 W of electrical power for a scientific payload with a mass up to 30 kg and a volume up to 140 liters. In an ongoing Phase A study, the feasibility of the payload accommodation within the SaudiSat 4 satellite bus is evaluated.

The mSTAR mission is investigated in an international collaboration including KACST (Saudi Arabia), Stanford University (USA), NASA Ames (USA) and a German Team consisting of the DLR Institute of Space Systems, ZARM, and the Humboldt-University Berlin.

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