Experimental studies of cryogenic optical resonators

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ABSTRACT

We report on the development of optical resonators operated at cryogenic temperature. A miniature monolithic quartz crystal ring resonator has been operated at liquid Helium temperature with a finesse of 330 at the Nd:YAG wavelength 1064 nm. A 3 cm long Fabry-Perot cavity with mirrors optically contacted to a hollow fused silica spacer has been used for the frequency stabilization of two diode-pumped Nd:YAG lasers. The cavity exhibited a finesse of 240 000 at liquid Helium temperature. The root Allan variance of the beat signal of the two lasers locked to two transverse modes of the cryogenic optical resonator (CORE) was below 10 Hz for integration times up to 100 s. Requirements for reaching sub-Hz instability for long times are briefly discussed and it is pointed out that COREs have interesting applications in high-precision fundamental physics experiments.

Keywords: Nd:YAG laser, frequency stabilization, optical resonators, cryogenic temperature, thermal expansion, metrology, optical clocks, special relativity, general relativity.

1 Introduction

Clocks of highest accuracy and stability are required for both time-keeping purposes as well as for the dedicated study of a number of fundamental physics experiments.[1] In the microwave frequency range the hydrogen maser offers outstanding frequency-stability reaching an instability of 10^{-15} for integration times > 1000 s. In the optical frequency range a number of trapped-ion, trapped-atom or atomic fountain oscillators are being developed, with stabilities expected to eventually reach similar levels. These laser clocks will typically be supplemented with so-called flywheel oscillators, which serve to provide a resonator-derived reference with sufficient short-time stability for prestabilization of the laser oscillator.

Over the last decade, the stabilization of lasers to Fabry-Perot cavities has reached a very high level of sophistication due to two important developments. First, ultra-low loss dielectric mirrors with finesse up to

10^6 are now commercially available[2]. Second, the FM technique of frequency stabilization[3] permits to reach a locking-instability at the quantum (shot) noise level. The lowest instability for the frequency-lock of a laser to a cavity, measured by locking two lasers to a single Fabry-Perot cavity, reached 9×10^{-17}.[4] Unfortunately, the best absolute instability for cavity-stabilized lasers[5] is about two orders of magnitude worse than the above level of relative instability. The reason for this discrepancy lies in both intrinsic and extrinsic fluctuations of the optical length of the cavity. The former fluctuations are usually mainly due to temperature fluctuations and vibrations exciting mechanical modes or causing deformations of the cavity. The latter are induced by the interaction of the laser wave with the cavity. Technical noise (power and beam coupling fluctuations) induces thermal fluctuations.

In the past, minimization of the thermal fluctuations of the cavity length has been pursued mainly at room temperature, by a combination of active temperature stablization and use of low-thermal expansion cavity materials (ULE) with expansion coefficient $\beta \simeq 4 \times 10^{-8}$/K.

2 Cryogenic Resonators

The advantage of operating cavities at cryogenic temperatures is twofold. First, the thermal expansion coefficient β is reduced compared to room temperature, since for crystalline materials $\beta \sim T^3$ for $T \rightarrow 0$. For example, the expansion coefficients of crystalline quartz (c-axis), sapphire and fused silica are $-1 \times 10^{-11}T^3$/K, $6 \times 10^{-13}T^3$/K, and $-3 \times 10^{-10}T^3$/K, respectively. Second, more precise temperature stabilization is possible, due to a reduced thermal diffusivity. The thermal diffusivity $\kappa/c\rho$ is a measure of the characteristic frequency of the thermal response of a sample of thermal conductivity κ, heat capacity c and density ρ. For sapphire, it increases by almost 7 orders of magnitude between room temperature and 1 K. The ultimate potential for temperature stability is truly remarkable, as temperature stabilization at the nK level has been demonstrated for other purposes.[7]

The potential of cryogenic cavities was demonstrated clearly in the microwave regime by the work of Turneaure and Stein.[8] A superconducting niobium cavity, operated at 1.3 K with a 0.5 Hz linewidth, served as a reference for a 9 GHz oscillator. The frequency-lock was accomplished using the microwave analog of the FM-technique. With the temperature stable at the μK level, an absolute instability of 2×10^{-16} over 200 s was obtained, measured by comparison of three independent devices. The superconducting cavity oscillator thus represents the most stable oscillator ever demonstrated in this time range.

Richard and co-workers[9] extended the concept of cryogenic resonators to the optical regime. A He-Ne laser was frequency-locked to a cavity employing a silicon spacer, cooled to 4.2 K, and with a finesse of 300. These authors also showed that an optical cavity could reach a finesse up to 20 000 at cryogenic temperature.[10] Until now, no characterization of the absolute stability of COREs has been reported.

Our initial work on cryogenic optical resonators was aimed at exploring different types of COREs, at extending the finesse to higher values, and at characterizing the frequency-stability of cavity-stabilized laser oscillators. The first step in such a program is to stabilize two lasers to a single cavity and to characterize the stability of their beat frequency. This yields information on the quality of the stabilization electronics and on the thermal drift of the cavity length.

2.1 Monolithic quartz resonator

Two different types of resonators are of interest as COREs. In a standard Fabry-Perot cavity the optical wave travels in vacuum. Residual gas atoms deposit on the (internal) mirror surfaces at a rate which depends

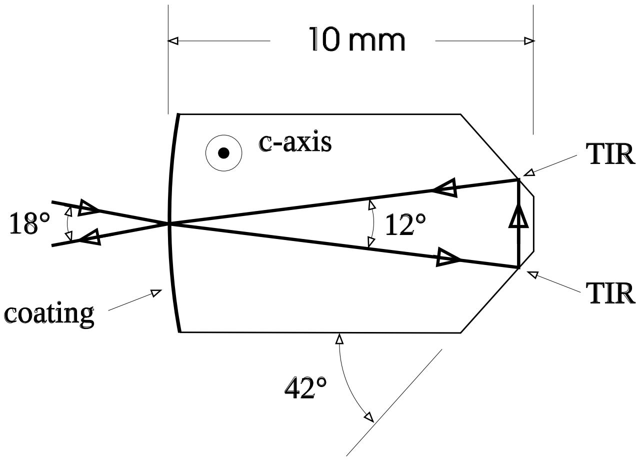

Figure 1: The monolithic quartz crystal ring resonator.

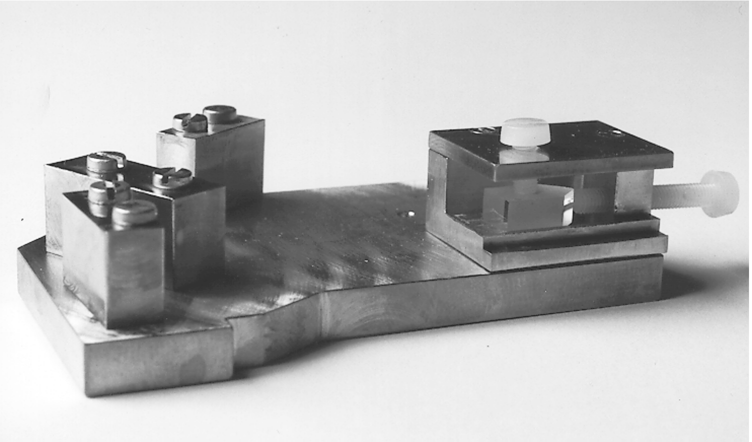

Figure 2: The ring resonator (on the right) mounted in its holder. Three mirrors are mounted on the copper blocks on the left.

on the quality of the vacuum. These will change the optical path length of the cavity and will therefore lead to frequency shifts. This effect may be avoided using monolithic cavities; for example, a block whose endfaces are spherically polished and on which dielectric mirrors are deposited, forming a standing-wave resonator. Since the electric field of the resonated wave is very small at the outer surface of the coating, the sensitivity to attachment of monolayers will be greatly reduced. Monolithic resonators can in principle exhibit high finesse, if materials with low impurity content and high homogeneity are used. Absorption coefficients as low as $\alpha(1.06\mu\text{m}) = 1 \times 10^{-5}/\text{cm}$ have been measured in quartz crystals.[11] These values imply minimum linewidths of $\Delta\nu = \alpha c/2\pi n = 30$ kHz, if the resonator is long enough so that mirror losses are negligible.

Our monocrystalline quartz ring resonator[12] has been fabricated by PMS (Frankfurt, Germany). Its geometry is shown in Figure 1. Inside the crystal the wave is confined by two total internal reflections (TIRs) and by one curved dielectric mirror. The curvature of the coated side is 25 mm. The round-trip length is 21 mm, yielding a free spectral range of 10 GHz given the indices $n_e = 1.543$, $n_o = 1.534$. The coating (reflectivity 98.5% at

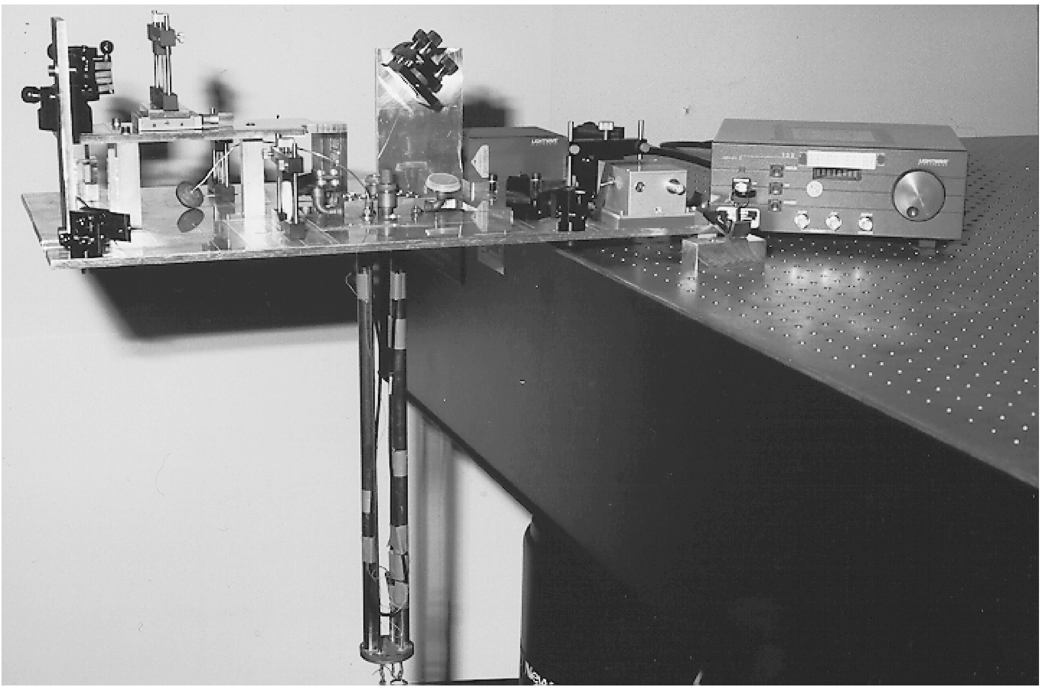

Figure 3: Experimental setup. The cryostat insert consists of a sample chamber (not shown) supported by a pair of tubes connected to a vacuum flange. The helium/nitrogen dewar (not shown) is bolted to this flange, as is the optics plate, on which the laser (at center), the focusing/alignment optics and the photodetector are mounted.

1064 nm) was produced by electron beam deposition. The internal losses of the resonator (absorption and scatter losses in the bulk and at the coating and the TIR faces) were measured by approaching a coupling prism to one of the TIR faces to provide an output port from the resonator. The transmission efficiency through the output port is measured with the prism positioned such that the reflected wave has minimum power (impedance-match). A round-trip loss of 2×10^{-3} was calculated from the observed throughput efficiency.

The crystal was mounted on a copper plate located inside an evacuated probe chamber (Figure 2). This chamber was immersed in a liquid Helium bath contained within a glass cryostat. Figure 3 shows a picture of the setup with the dewar removed. The probe chamber was connected to the room temperature environment by two 50 cm long tubes sealed by windows. The Nd:YAG laser beam was directed to the resonator and from the resonator back out of the cryostat via these tubes and 3 aluminum mirrors on the ground plate. The large path length between the cryostat exterior and the resonator rendered alignment difficult. The laser beam reflected from the cavity was used to detect resonance between laser frequency and cavity.

At liquid helium temperature a finesse of 330 (30 MHz linewidth) was observed with only a slight reduction from the room temperature value of 410. This test indicates that dielectric coatings withstand cooling even if the thermal expansion of the substrate is anisotropic, as is the case for the quartz resonator.

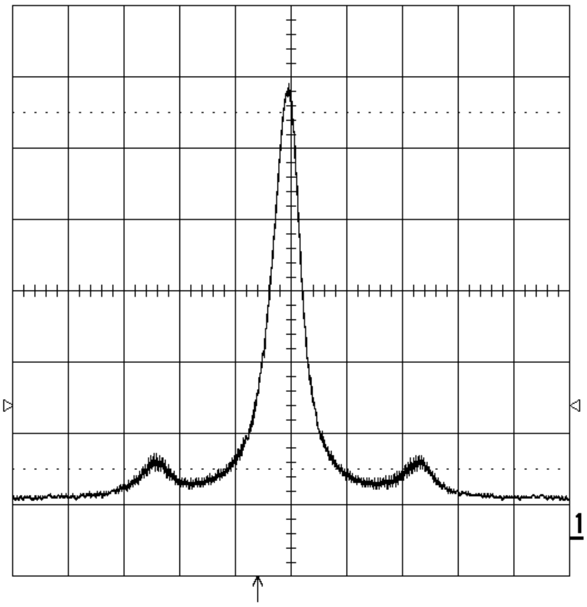

Figure 4: TEM_{00} mode of the fused silica cavity at liquid helium temperature. The laser is frequency-modulated at 100 kHz and scanned across the resonance line. The measured linewidth of 25 KHz (corresponding to a finesse of 200 000) is an upper limit to the cavity linewidth due to the finite laser linewidth.

2.2 High-finesse fused silica cavity

In our present CORE experiment we employ a high-finesse cavity in an glass cryostat with direct optical access to the probe chamber via windows. The cryostat used simplifies coupling of the laser beam into the resonator considerably, since the distance between resonator front mirror and atmosphere is only 6 cm. The resonator consists of a 29 mm long fused silica spacer (Herasil 1, Heraeus) with a central 15 mm diameter bore and two fused silica mirrors (Research Electro-Optics, Boulder) optically contacted to the spacer. This contacting method is intended to minimize thermal drift effects. The radius of curvature of these mirrors is 50 cm. The uncoated side of the mirrors has a wedge of about 2 degrees to reduce parasitic resonances. The free spectral range of the cavities is 5.1 GHz. The resonator is supported horizontally by blade springs attached to the cold plate at the bottom of the liquid helium dewar.

Finesse and transmission of the cavity have been measured both at room and at liquid helium temperature. In both cases, a finesse of 2.4×10^5 and 30% transmission were determined for the TEM_{00} mode. A measurement of the cavity linewidth is shown in Figure 4. The cavity loss was also determined by a decay time measurement. For this, a laser is frequency-locked to the cavity and then rapidly frequency-shifted off-resonance. The $1/e$ decay time of the transmitted intensity was measured with a high-bandwidth photodetector to be 7.4 μs.

To perform the characterization of the frequency-stability of the CORE-stabilized lasers, we used a standard set-up consisting of two diode-laser pumped monolithic Nd:YAG ring lasers (10 and 50 mW output power, respectively) locked to a single cavity.[13,14] The set-up is schematically depicted in Fig.5. The lasers are locked to the cavity using the Pound-Drever-Hall technique. We tested two techniques for generating FM sidebands: using a conventional electro-optic modulator (EOM) and direct frequency-modulation of the laser in the 1 MHz range via the piezo-ceramic glued to the laser crystal.[15] We have found the first technique to be superior for high precision locking since the residual amplitude modulation is lower. The EOMs are modulated at $\Omega_1 = 13.4$ MHz

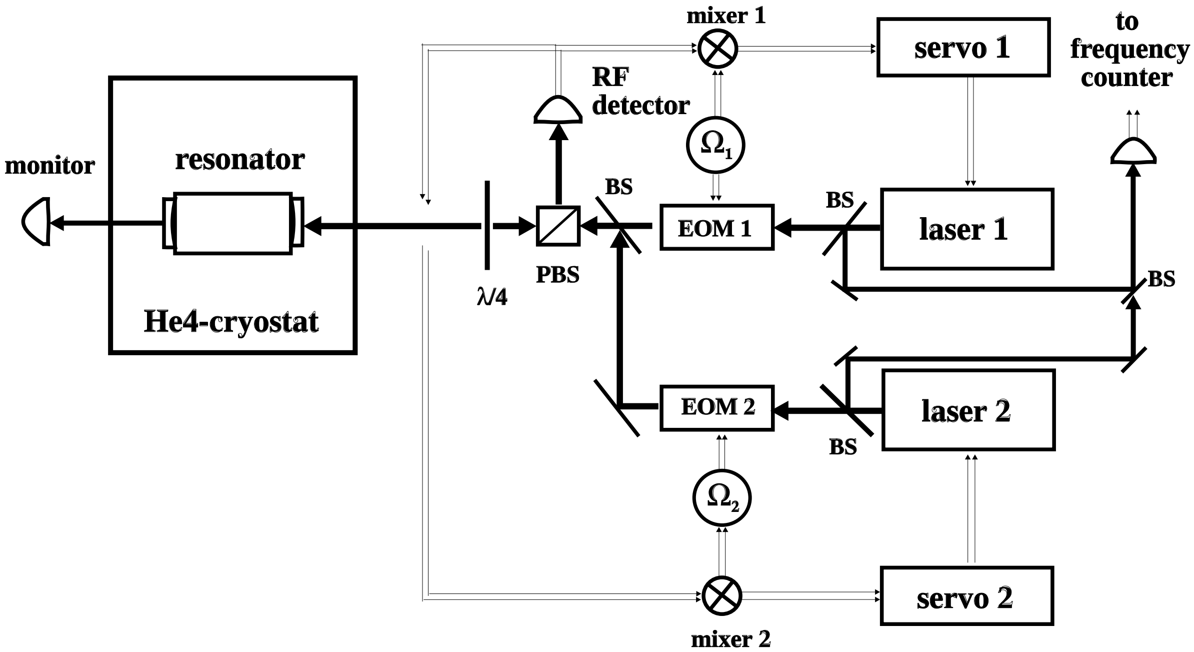

Figure 5: Schematic of the experimental set-up to measure the Allan variance of two diode-pumped Nd:YAG lasers locked to the high-finesse Fabry-Perot cavity. BS=beamsplitter.

and $\Omega_2 = 11.2$ MHz with modulation index 0.7. The waves reflected from the cavity have powers of 230 and 130 μW, respectively, and are detected by a single RF detector. Its output is split and mixed to d.c. using the two local oscillators driving the EOMs. The error signals are amplified and filtered by two servo systems, and fed back to the piezoelectric frequency transducers on the lasers.

The lasers are locked onto a TEM_{00} and a TEM_{01} mode of the cavity, respectively. The beat frequency at 562.5 MHz is detected by a 1 GHz bandwidth detector and analyzed by a SRS 620 frequency counter. The first data for the time domain instability of the beat frequency is shown in Fig.6. For short integration times τ the two-sample Allan variance falls with increasing τ with a slope consistent with a white frequency noise spectrum. As the servo system is not fully optimized, the instability is much higher than the shot-noise limit. At integration times $> 1\,\mathrm{s}$, the root Allan variance levels off at less than 10 Hz and remains at this level up to the longest integration times accessible at present. This instability level compares favourably with the results obtained in other Nd:YAG stabilization experiments.[13,16] The instability floor is probably due to drifts in the servo electronics. These first measurements also indicate that the cryogenic environment of the cavity does not degrade the stability of the cavity length, at least at the resolution level attainable by a beat frequency measurement, where the common mode rejection is about a factor 10^6. Indeed, the liquid helium boil rate is very low due to the good thermal insulation of the cryostat, leading to low vibration noise.

3 Outlook

The availability of optical oscillators with instability lower than 10^{-17} over long periods of time (days) would allow to repeat a series of fundamental physics experiments with improved accuracy. Among these are tests of special relativity,[17–19] and of the principle of local position invariance,[20] a postulate of General Relativity. In

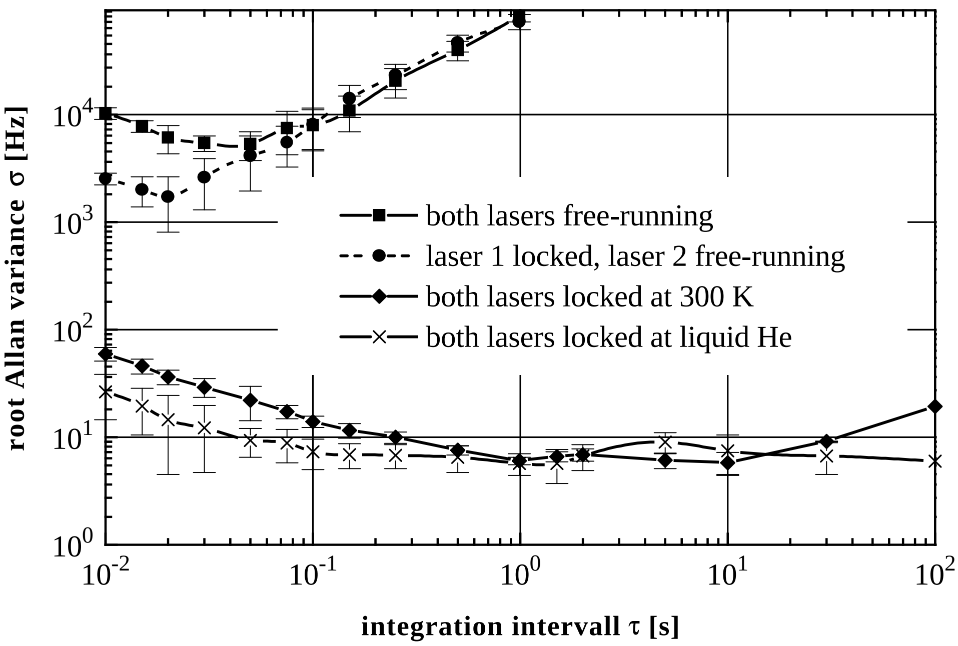

Figure 6: Allan variance of two diode-pumped Nd:YAG lasers locked to the high-finesse Fabry-Perot cavity.

addition, it appears feasible to use appropriately constructed COREs to measure changes in local gravitational acceleration, the gravitational constant,[21] and the dislocation dynamics in solids. Another interesting application is as a displacement sensor for monitoring the excitation of gravitational bar antennas.[22]

Certainly, significant improvements in reducing the disturbances affecting the cavity frequency will have to be reached to permit such experiments. A large number of effects influences the optical length of cavities.[8,6] Apart from those mentioned above, other sources of error are drifts of the cavity temperature due to drifts of the sensor resistor properties or of the voltage reference in the stabilization circuit, thermodynamic temperature fluctuations, Brownian length fluctuations, density fluctuations in the volume between the mirrors, changes in local gravitational acceleration which deform the cavity, Doppler shifts caused by the fluctuations in the distance between laser and resonator. Model calculations[6] indicate that the frequency noise associated with these processes can be reduced below the shot noise of the frequency-lock. The situation is different as far as the influence of effects that occur on longer time-scales are concerned. The long-term stability ($>$ 1 day) will require intense study. In particular, the characteristics of long-term relaxation effects have so far been studied only at room temperature,[23] but not at cryogenic temperature. Finally, it should be noted that according to General Relativity any oscillator, including a cavity-stabilized laser, experiences a gravitational frequency shift[24] which is due to the daily and yearly variation of the solar gravitational potential at the clock's location. The daily component causes a peak-to-peak variation of $\delta\nu/\nu \simeq 10^{-13}$.

4 Conclusion

We have reported on our initial studies of cryogenic optical resonators (COREs). We have tested a 1 cm long monolithic quartz crystal ring resonator at liquid helium temperature. Such resonators have the potential of reaching sub-MHz linewidths through use of low bulk loss materials. With linewidths of this order, their small size and thus insensitivity to gravitational deformation, as well as insensitivity to cavity length perturbations by surface contamination, they represent one possible approach to ultra-stable reference cavities.

A Fabry-Perot CORE with a finesse of 240 000 and a linewidth of less than 30 kHz at liquid helium temperature has been demonstrated. This represents the highest finesse reported up to date for 1064 nm. Two single-frequency Nd:YAG lasers were frequency-locked to cavity modes spaced by 562 MHz. The instability of the beat frequency was less than 10 Hz for integration times up to 100 s. We expect that this value may be significantly improved by optimization of the servo electronics, better temperature stabilization, and vibration isolation of the CORE.

Our initial results suggest that with further development COREs have the potential to be used as flywheel oscillators and for a number of ultra-high precision measurements in Special and General Relativity, and gravitational physics.

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