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Hybrid Frequency Stabilization and Determination Unit Based on a High-Finesse Optical Cavity and Molecular Iodine

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***Summary*. This paper presents the latest developments of a hybrid system offering frequency stability at the 10^{-15}-level and simultaneous absolute frequency determination for metrology applications. The system combines a high-finesse optical cavity with an iodine vapor cell based absolute frequency readout unit. The optical cavity setup within the hybrid system is developed with emphasis on space compatibility. It utilizes a compact optical circulator-based in-coupling technique and fulfills the frequency stability requirements of ESA's NGGM mission. The absolute frequency readout unit complements the system as a laboratory setup, utilizing an offset sideband lock in conjunction with a simplified absorption spectroscopy unit based on a third derivative locking technique.**

Keywords—optical cavity, vapor cell, hybrid system, NGGM, frequency stabilization, offset sideband lock, optical metrology

I. Introduction

Multiple future space-based applications will benefit from highly stable laser systems. These include future missions from the field of global navigation satellite systems (GNSS), next-generation gravity missions (NGGM), and tests of fundamental physics, while they all impose strong requirements on the laser frequency stability.

This paper is motivated by the next generation of gravity missions, where the laser system is used as a source for the laser ranging interferometer (LRI). This instrument will measure the relative distance between two satellites, which will then be processed to create a map of the Earth's relative gravity field. In this case, precise knowledge of the absolute frequency of the stabilized laser used for interferometry is crucial because it serves as a scale factor that converts phase measurements in the interferometer into a range difference between the satellites [1].

Current concepts for determining the absolute frequency are based on measuring the free spectral range (FSR) of the cavity [2]. This paper presents a technique that references the absolute frequency to a molecular transition.

Therefore, a hybrid reference was developed that consists of an optical cavity stabilized laser at 1064 nm that is combined with a vapor cell based absolute frequency readout unit. This setup, shown in Fig. 1, enables the measurement of the absolute frequency and the long-term drift of the cavity without interfering with the laser stabilization scheme.

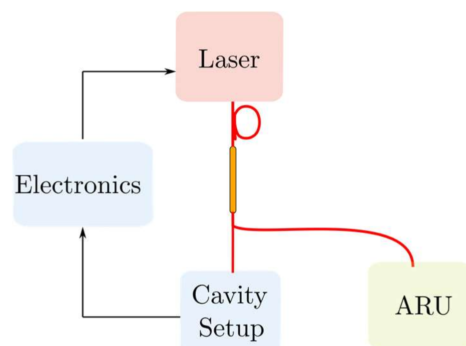

Fig. 1: The Absolute Frequency Readout Unit (ARU) is shown schematically. The ARU is intended to determine the laser's absolute frequency and long-term drifts in parallel to a cavity stabilization without interfering with it.

II. Optical cavity system

The design of the optical cavity setup is based on a thorough noise analysis, drawing on theoretical and experimental considerations, to create an optimized setup that meets the requirements on frequency stability while also optimizing the Size-,Weight-, and Power-Budget (SWaP-Budget) for future space applications.

For the optical cavity itself, a cube design by the National Physical Laboratory of Great Britain with an optical path length of 5cm is chosen [3]. The cavity spacer consists of Ultra Low Expansion Glass (ULE) with optical mirrors out of Fused Silica

(FS) optically bonded. ULE compensation rings are attached to the backside of the mirror substrates to shift the system's zero crossing point to room temperature. The mirrors are equipped with a coating out of monocrystalline AlGaAs/GaAs heterostructures offering a Finesse of F = 280 000. A tetrahedral mounting configuration of the cavity ensures a low vibration sensitivity.

A two-folded thermal shield is attached to the mounting frame and is actively thermal stabilized by resistive heaters, achieving a temperature stability in the mK range. This reduces the influence of thermal fluctuations to a level that enables the frequency stability requirements to be met.

As the whole system is developed with emphasis on space compatibility, the cavity is combined with the in-coupling optics and all optical and electro-optical components, such as modulators and photodetectors, to a fully integrated system, which is then housed in a vacuum chamber operating at Ultra High Vacuum (UHV). The in-coupling of the optical cavity is based on a fiber optical circulator to reduce the number of required free beam components. This approach enables the establishment of a robust and compact configuration. The efficiency of this principle has recently been demonstrated [4]. The remaining free-space components required for the alignment are attached directly to the outer thermal shield into a specially designed collimator mount made out of Ti-6Al-4V. Decoupled from the cavity and its thermal shields, a breadboard contains the optical and electro-optical components, while all of them are fiber-coupled with the fibers wound up at the breadboard's outer edge and the inter-connections spliced.

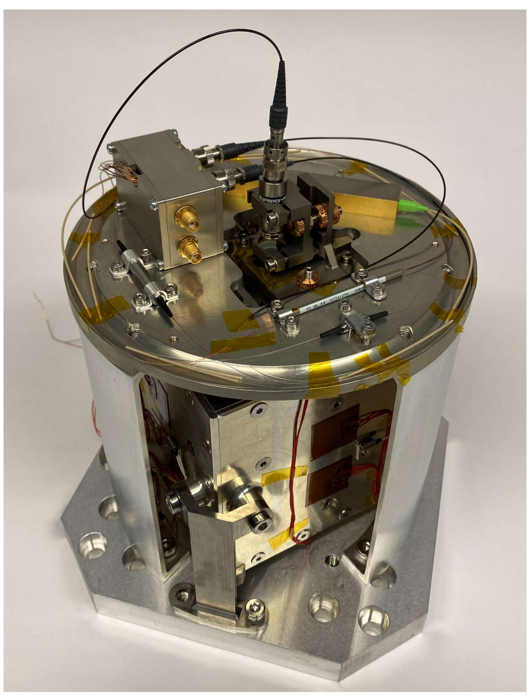

Fig. 2. Picture of a compact optical cavity reference, which is developed emphasizing space compatibility. The optical cavity is enclosed in two thermal shields and together with all optical and electro-optical components integrated on to a baseplate. The entire setup is designed to operate in a UHV.

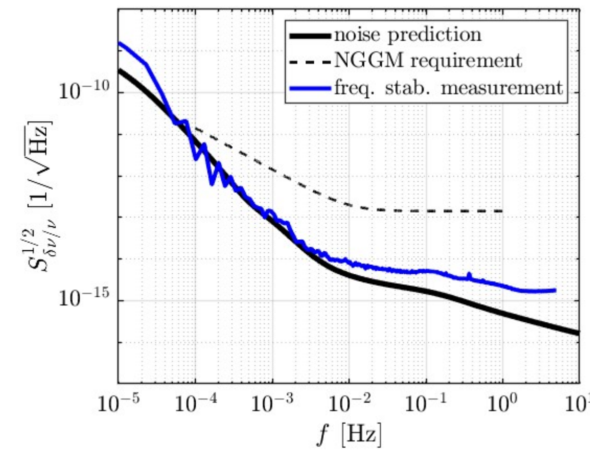

Fig. 3: The frequency stability of the cavity setup is shown in ASD together with a theoretical and experimental determined noise prediction. As a reference the frequency stability requirement of ESA's NGGM Mission is displayed.

The setup, shown in Fig. 2, is mounted to a baseplate and placed into a vacuum chamber. A first measurement of the setup's frequency stability measured against a reference setup from [5] is shown in Fig. 3. The optical cavity system fulfills the frequency stability requirements of ESA's NGGM Mission, and corresponds on long timescales to a previously performed noise prediction. At high frequencies, further analysis of the acting noise sources is required. In Allan Deviation, the setup demonstrates a short-term stability of $\sigma < 3 \times 10^{-15}$ for $\tau < 100$ s with a linear detrend applied. To represent the frequency stability of the setup, all results are scaled by a factor of $\sqrt{2}$.

III. Absolute Frequency ReadOut Unit

The system is complemented by a vapor cell based absolute frequency readout unit. This unit uses a simple design to determine the absolute frequency of the laser and any changes to it, thereby enabling the cavity's long-term drift to be measured. Therefore, a fraction of the light from the cavity-stabilized laser gets frequency doubled to 532 nm and is locked by an offset sideband lock to a rovibrational transition of molecular iodine.

This is achieved by applying an offset frequency f_1 with an EOM and a second offset f_2 by an AOM. With this combination, a wide scan over multiple rovibrational transitions in molecular iodine makes it possible to determine the transitions present precisely. Their absolute frequencies can then be taken from the literature and added to the offset frequency $f_1 + f_2$. Since the optical cavity performs the frequency stabilization, such an absolute frequency determination has a relaxed requirement for the readout that is expected to be at $\sigma_{req} = 1 \times 10^{-8}$ for $\tau > 10000$ s [6]. The presented approach thus allows for a simplified iodine

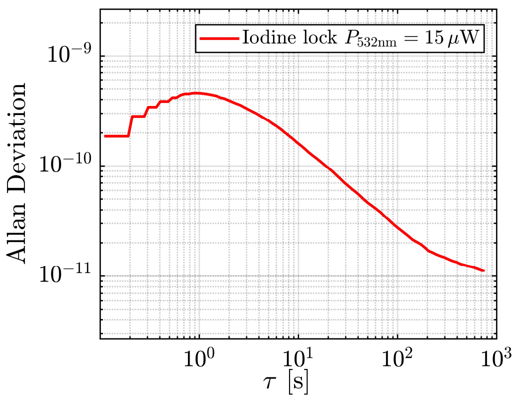

Fig. 4: Allan Deviation of a laser locked to a rovibrational transition of molecular iodine with an optical power of $P_{532\,\mathrm{nm}} = 15\ \mu\mathrm{W}$

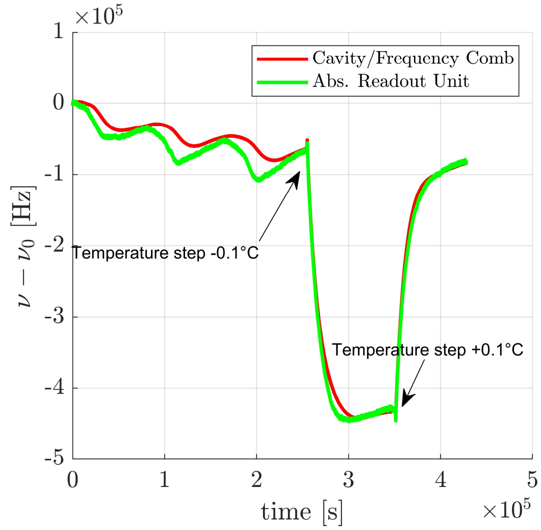

Fig. 6: Measurement of the frequency change of an optical cavity measured against a frequency comb referenced to a hydrogen maser and by the Absolute Readout Unit (ARU).

reference to significantly reduce the SWaP-Budget and particularly the required laser power.

Conventional iodine-based frequency references that meet high demands for frequency stability usually require several hundred mW of laser light. This is mainly due to inefficient frequency doubling and the multiple modulators needed in the widely used MTS method. This work uses a third-derivative lock that utilizes an identical modulated beam as the pump and probe beam. This is made possible by relaxed requirements for the absolute frequency readout in a hybrid solution in which the laser is pre-stabilized to the optical cavity. Preliminary tests in which the laser was stabilized directly via the third derivative lock on the iodine transition without an offset sideband lock have already shown that as little as $P_{532\,\mathrm{nm}} = 15\ \mu\mathrm{W}$ of laser light is sufficient to meet the readout requirement, the results are shown in Fig. 4.

Motivated by this measurement, the overall setup was implemented as a breadboard model according to Fig. 5. This model was then combined with a cavity setup different from the one designed for this work. Its configuration is explained in more detail in [7]. The reason for this is that the functionality of the ARU should be proven in the first step, and therefore, a setup with a larger drift and higher temperature susceptibility is more suitable.

For the functionality test, a setup has been built in which the cavity-stabilized laser was measured optically against a frequency comb as indicated in Fig. 5, while the comb was referenced to a hydrogen Maser. On the other hand, the ARU's RF frequency was recorded, which results from the sum of the signal applied to the AOM and EOM.

In this first experiment, the exact determination of the absolute frequency was omitted, and the difference between the optical measurement against the comb and the offset measured by the ARU was initially set to $\nu_{\mathrm{Cavity/Comb}} - \nu_{\mathrm{ARU}} = 0$. Both measurements are shown in Fig. 6 for a continuous operation of almost 5 days. The utilized laser power for the ARU was $P_{532\,\mathrm{nm}} = 1$ mW.

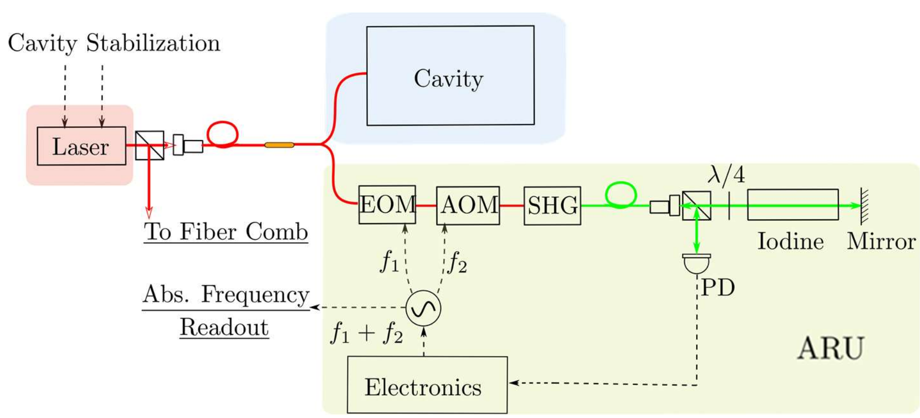

Fig. 5: Detailed overview of the proposed Absolute Readout Unit (ARU). Light of the cavity stabilized laser is guided to an Electro-Optical-Modulator (EOM) to bridge the frequency gap between the optical cavity resonance and a nearby rovibrational transition of molecular iodine, utilizing a so-called Offset Sideband Lock (OSL). At the same time, the EOM is used to apply a frequency modulation for a third derivative lock. A subsequent Acousto Optic Modulator (AOM) is used for active frequency control to lock one sideband to the iodine transition after it is then doubled in frequency at the following Second Harmonic Generator (SHG)

Both measurements, the optical beat of the frequency comb against the optical cavity and the ARU, show a long term drift of about $300\ \mathrm{mHz/s}$, which is overlaid by a day-night cycle.

At 2.5×10^5 s a temperature step of $0.1°$ C was applied to the thermal shield of the optical cavity to create a frequency shift of the cavity's resonance frequency, which results in a frequency change of $\Delta\nu \approx 0.4$ MHz. After 3.5×10^5 s, and thus after a constant state had been reached again, this step was reversed.

In the case of the temperature step, it can be seen that the ARU follows the optical measurement against the comb, even if there are still deviations in the kHz range during the day and night fluctuations. For a more precise analysis, the optical measurement was taken as a reference in the following and subtracted from the ARU measurement to determine only the uncertainties of the ARU, which is shown in Fig. 7. Here, it can be clearly seen that the ARU is subjected to day-night fluctuations in addition to the cavity. Analyses showed that these correlate with the changing temperature of the lab. The artificially generated jump caused by the change in cavity temperature, on the other hand, does not force any difference between the optical measurement with the frequency comb and the ARU, thus demonstrating its functionality.

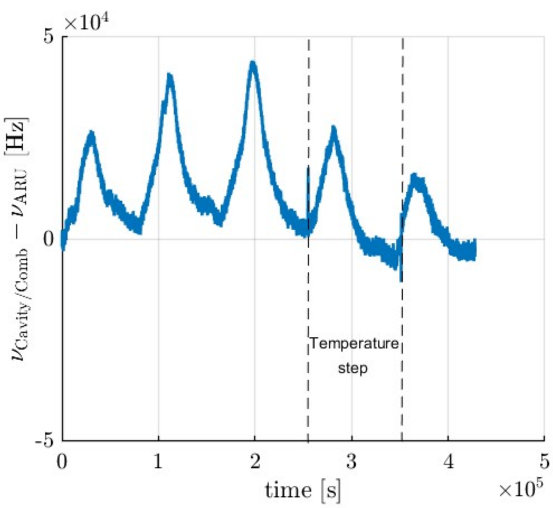

Fig. 7: Difference between the measured frequency fluctuations of the optical cavity by a frequency comb and the ARU.

IV. Conclusion

In conclusion, we have developed a system that can bring a decisive advantage for future satellite missions in the field of gravimetry. This comprises a high finesse optical cavity developed for space applications, combined with an absolute frequency readout unit. For this, the cavity stabilized laser is referenced to a rovibrational transition of molecular iodine and achieves a relative accuracy on long time scales of 1×10^{-11} at $100\,000$ s, as shown in Fig. 8. In the future, it will be examined whether one of the modulators (EOM or AOM) can be dispensed with and how far the required laser power can be reduced to further optimize the system regarding laser power and robustness.

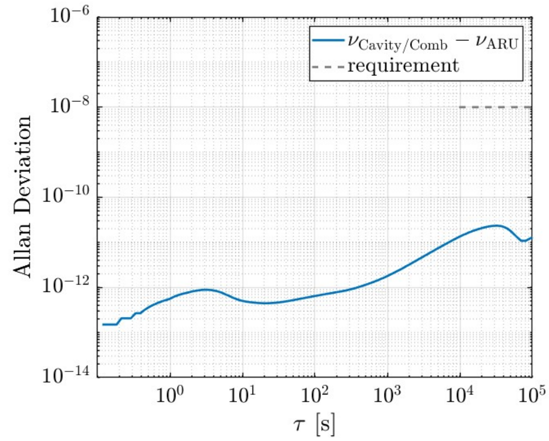

Fig. 8: Measured frequency instability of the ARU as Allan Deviation.

V. Acknowledgments

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