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Towards Compact, Robust and Highly Stable Optical Frequency References for Space Applications

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Abstract. Future space missions from different fields of applications, like global navigation satellite systems (GNSS), next generations of gravity missions or tests of fundamental physics will rely on optical frequency references. While laboratory setups of various optical frequency reference technologies already demonstrate frequency stabilities orders of magnitude better than current microwave references for space applications, another step must be accomplished for high performance optical references in space. One promising technology for this is Doppler-free spectroscopy of molecular iodine, for which we have already developed several iterations of laboratory setups with frequency instabilities down to the 10^{-15} level for integration times $> 100\,\mathrm{s}$. Based on the experience gained from this laboratory setups, we are now working on an iodine reference that will become the first optical clock in space as part of the COMPASSO mission. It will be delivered to the international space station in 2026 for a mission time of 2 years. In addition to the iodine development, we are currently working on a next iteration of a high-finesse optical cavity designed with emphasis on space compatibility to meet the requirements of the next generation of gravity missions. Both technologies together, the iodine spectroscopy unit and the high-finesse optical cavity, should form a hybrid setup suitable for new GNSS architectures.

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1 Introduction

State-of-the-art optical frequency references such as ion clocks have demonstrated frequency stabilities at the 10^{-18} level and below [1]. With these new technologies, many applications will benefit from either time or distance measurements. In terrestrial applications, optical references are already replacing microwave references, but for space applications, optical references are not yet as widely used because reliability, size, weight, and power budgets are key considerations in addition to the performance. One technology already being used for space missions is optical cavities. Optical cavities can offer high short-term stability, small volumes, low power consumption and comparable low complexity. This makes them suitable for communication applications or space based laser-interferometry applications such as the future gravitational wave detector LISA (Laser Interferometer Space Antenna) or the LRI (Laser Ranging Interferometer) on present and future gravity field missions [2–4]. With current frequency stabilities at the 10^{-17} level on short timescales for terrestrial applications and 10^{-15} for space applications, there is still a need for development. In addition, cavities have the disadvantage of being relative references, which limits their suitability to applications where long-term stability or absolute frequency knowledge is required only to a certain level. Here, absolute frequency references are the technology of choice, based on the principle that a laser is stabilized to an atomic or molecular transition. This results in high long-term stability and absolute frequency knowledge, but at the cost of reduced short-term stability and more complex setups. At the DLR Institute of Quantum Technologies, in cooperation with the Universities of Bremen and Ulm, frequency references covering both, short- and long-term stability are currently under development with a focus on space compatibility. The demonstrated frequency stabilities of two laboratory setups are depicted and compared to operational space clocks in Fig. 1.

2 Iodine references

One well known - and compared to ion clocks less complex technology of an absolute reference - is Doppler-free spectroscopy of molecular iodine. This technology has demonstrated frequency stabilities at the 10^{-15} level for integration times $> 100\,\mathrm{s}$ in laboratory experiments, been flown on a sounding rocket and is currently being further developed to be launched within the COMPASSO project to the ISS Bartolomeo platform in 2026, becoming the first optical clock in space [5, 7–9].
Over the last decades, several iterations were carried out to reach this goal, with a selection of them shown in Fig. 2. Molecular iodine has a rovibronic transition at around 532 nm with hyperfine components spanning over several hundred MHz and a natural line-width of each transition of about 300 kHz. These transitions are well studied and its absolute frequency was determined with around 1 kHz accuracy, which is at the same range as the reproducibility of the locking scheme.[10–12]
The locking principle of choice for high performance setups is known as Modulation Transfer Spectroscopy (MTS). Two counter propagating laser beams are sent on the same optical path but in opposite directions through a gas cell containing molecular iodine. A strong pump beam burns a so called 'Bennet-hole' into the velocity distribution of the gas. The counter propagating probe beam then addresses only molecules moving perpendicular to the beam, hence eliminating the Doppler shift. The MTS signal (comparable with an error signal in the widely used Pound-Drever-Hall (PDH) technique for cavity locking) is then generated by phase modulating the pump beam and demodulation of the absorption signal with the same frequency.

2.1 EBB-Design

After several modular breadboard experiments a new setup on Elegant-Breadboard (EBB) level was realized using a Nd:YAG 1064 nm Laser with an internally doubled second output at 532 nm. The 532 nm light is then used for generation of probe and pump beams whereby the required modulation is applied accordingly with an acusto-optic modulator (AOM). The spectroscopy unit of the EBB setup utilizes an OHARA Clearceram-Z HS board with a size of $550\,\mathrm{mm} \times 250\,\mathrm{mm} \times 50\,\mathrm{mm}$ as basis to achieve a minimum level of mechanical deformation. All optical components are made out of fused silica and bonded by a space-qualified two-component epoxy, thus resulting in a semi-monolithic optical assembly. As reference cell, a triple pass 300 mm cell is used. The MTS signal is detected by a balanced noise cancelling (NC) detector and used for a feedback loop for laser frequency stabilization. In addition, a correction for Residual Amplitude Modulation (RAM) as well as intensity stabilization for probe and pump beam are integrated.
This setup demonstrated a frequency stability in Allan deviation of below 1×10^{-14} at integration times of 1 s and below 4×10^{-15} for integration times between 10 s and 1000 s.

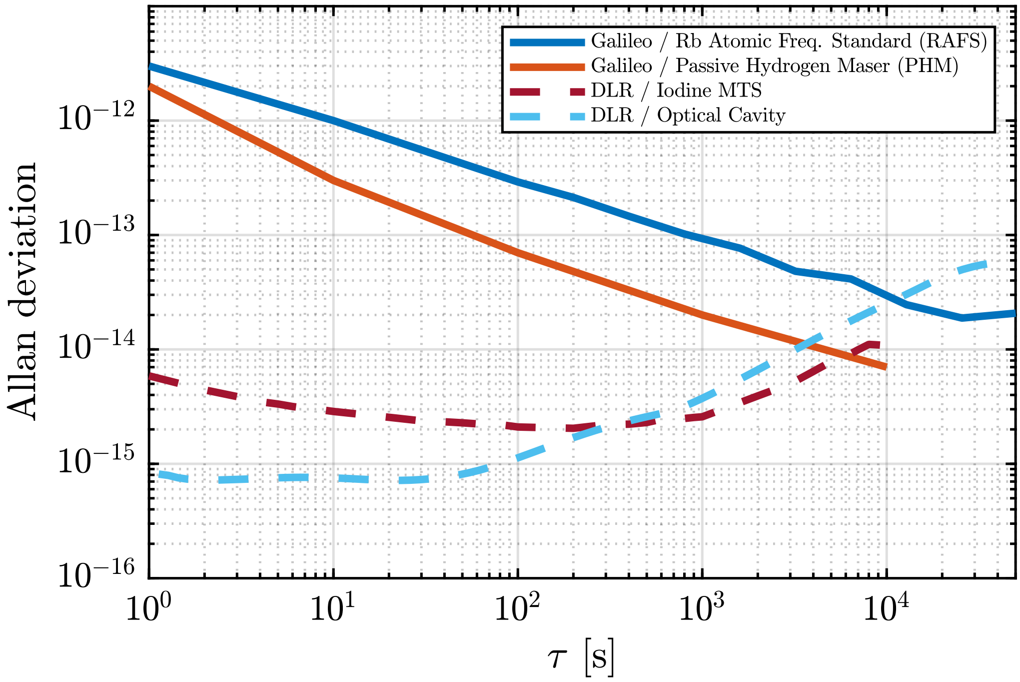

Figure 1: Relative frequency stability of two laboratory setups that are being further developed towards space suitability and are, therefore, compared here with two current space clocks. The Iodine spectroscopy reference is using Modulation Transfer Spectrscopy (MTS) and its frequency stability is determined over a record time of 76 000 s [5]. The optical cavity setup was characterized against a duplicated system over a record time of 170 000 s and subtracted by a linear detrend with a slope of about 100 mHz/s [6].

2.2 EM-Design

Upon a further development, a setup on Engineering Model (EM) level was realized and thus further optimized with respect to compactness, mechanical-, and thermal-stability. The core of the optimization was a special nine-pass gas cell with dimensions of 100 mm × 100 mm × 30 mm mounted on a fused silica breadboard with dimensions of 380 mm × 180 mm × 40 mm only, which corresponds to a reduction in size of about 50 %. Fused silica is utilized in this new iteration after considering that such high mechanical stability for the breadboard is not necessary. In addition, the gas cell and optics are all made out of fused silica and thus a material match between the optical components and the baseplate is given. All optical components are integrated using adhesive bonding technology. The spectroscopy was subjected to thermal cycling (-20°C to 60°C) and vibrational testing with test levels of up to 30 g for sine vibration and 25.1 g_{rms} for random vibration. A frequency stability of 5×10^{-15} for integration times $\tau > 1000$ s was achieved before and after the tests.

2.3 ADVANTAGE

In order to take the next step into space applications, a new iteration based on the knowledge of the EBB and EM developments was designed within the ADVANTAGE project (Advanced Technologies for Navigation and Geodesy). Here, one main objective was further development towards a fully integrated physics box combining the spectroscopy unit with the laser system in a compact and robust package. At the same time, the temperature requirements of this package were set to 15 °C ± 5 °C. Within this range, an active control system guarantees the operation of the spectroscopy board within 22 °C ± 0.1 °C. As laser source a Nd:YAG laser provides 1064 nm light, which is then coupled into a

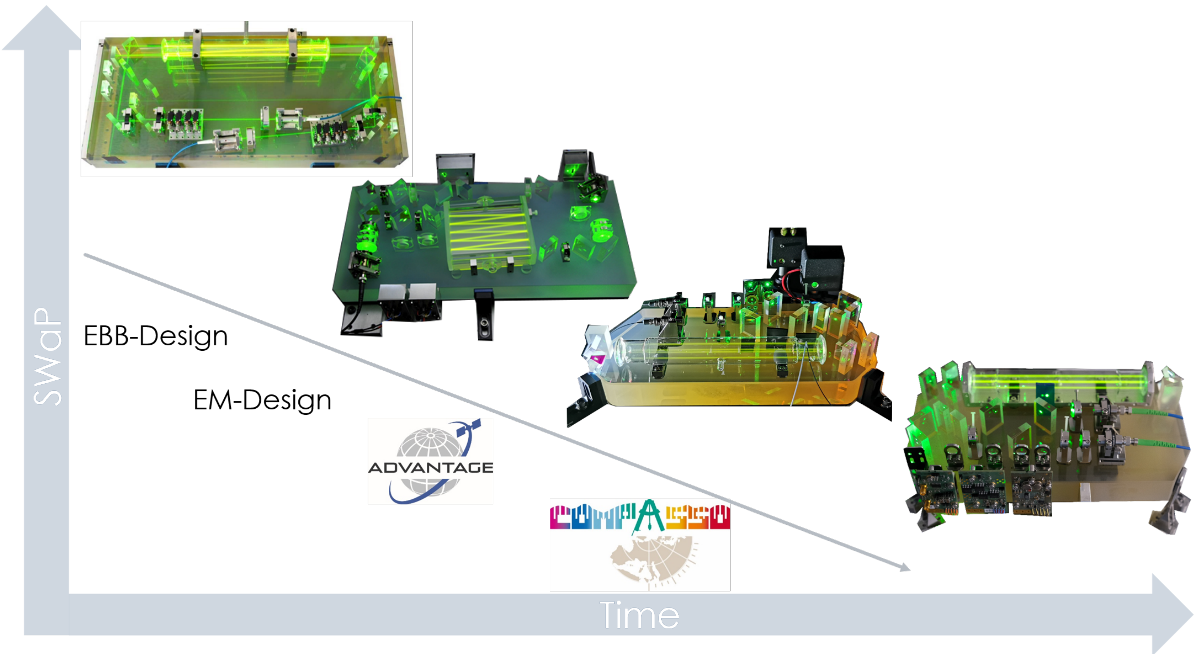

Figure 2: Qualitative illustration of the further development in Size-, Weight and Power-Budget of the iodine spectroscopy iterations.

fiber and splitted into probe and pump beam. The pump beam is guided to an AOM for RAM correction and intensity-stabilization and then phasemodulated by an electro-optic phase modulator (EOM) for modulation transfer spectroscopy (MTS). Also, the AOM creates a frequency offset between probe and pump beam. The intensity of the probe beam is controlled by an electro-optic amplitude modulator (EOAM). Both modulated beams are then guided to second harmonic generators (SHG) to create 532 nm light. All modulators are fiber-coupled. This principle was intended as a baseline for future designs using an External Cavity Diode Laser (ECDL).

2.4 COMPASSO

With the upcoming COMPASSO mission, an iodine clock will become the first optical clock in space. COMPASSO is a mission of the German Aerospace Center with the aim to demonstrate high-performance quantum optical technologies in space. The mission includes two laser-based absolute iodine references, a frequency comb, and a laser communication and ranging terminal (LCRT). The mission will be delivered to the International Space Station (ISS) in 2026 for a mission time of 2 years. Primary goals include the technology demonstration and performance evaluation of the two iodine references and a frequency comb referenced to a GNSS disciplined oven-controlled crystal oscillator (OCXO), while secondary goals also include the transfer of time and frequency via the LRCT. [9]
The iodine references are built on heritage of the previously introduced iterations and a CAD model of the COMPASSO-EM spectroscopy unit is shown in Fig. 3 with it's zerodur breadboard illustrated in yellow and one part of the thermal shield in red. The COMPASSO breadboard dimensions are $300\,\text{mm} \times 150\,\text{mm} \times 35\,\text{mm}$ with a honeycomb structure milled into its body. The spectroscopy uses the same 4-pass layout as in ADVANTAGE but with a shorter 200 mm gas cell. All components are mounted by adhesive bonding to achieve the rigidity for spaceflight and are arranged to achieve a crossed-polarized beam distribution scheme. This, on one hand, adds the complexity of using polarizing optics in space, but on the other hand, allows for an efficient distribution and dumping of the beams. The board is mounted with adhesive bonded titanium holders to a base-plate and encapsulated by an actively controlled thermal shield. The spectroscopy and laser system are then integrated together into one exterior housing, forming the Iodine Spectroscopy Unit (ISU). A CAD model of the overall iodine reference consisting of ISU and Iodine control electronics (ICE) is shown in Fig. 4.

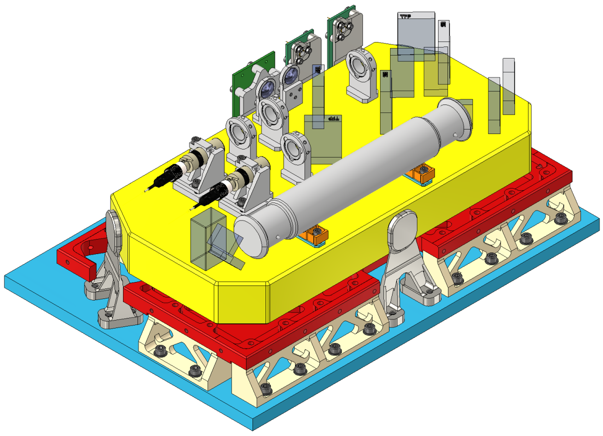

Figure 3: CAD of the COMPASSO-EM optical bench.

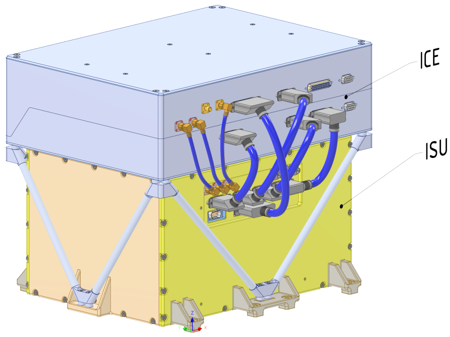

Figure 4: CAD of the COMPASSO-EM iodine reference including the Iodine-Control-Electronics (ICE) and the Iodine-Spectroscopy-Unit (ISU).

3 Optical cavities

For applications where no absolute frequency references are required, optical cavities are well suited due to less complexity, small dimensions and low power consumption. Here, the further development of high finesse optical cavities towards space compatibility is the research field of the DLR Quantum Metrology group. One goal is the development of an optical cavity with respect to the requirements of future gravity missions, global navigation satellite systems, and special relativity tests in space. The baseline for all cavity setups is the cube design of the National Physical Laboratory of Great Britain (NPL), that is shown in Fig. 5. [13]

The first setup on EBB-level was designed as a technology demonstrator of a space based Kennedy-Thorndike experiment within the BOOST project [14]. The requirements for this setup were quite challenging for a cavity, as the setup should provide a frequency stability of 1×10^{-14} on 90 min integration time. This is realized by covering an 8.7 cm cavity in a five folded thermal shield, where the outer shield is actively stabilized by peltier-elements to the pre-characterized cavity's zero crossing point. A theoretical model based on [15] served as the basis for the thermal design. The system is placed in a vacuum chamber and optical breadboards are rigidly mounted to it, containing in-coupling optics on one side and components for active intensity stabilization on transmission side. This setup demonstrated a frequency stability of 7.5×10^{-16} for $\tau < 90$ s and fulfilled the required 1×10^{-14} on 90 min. Furthermore, with this setup an extensive noise study and characterization was performed to allow for improvements and simplifications for subsequent experiments. [6, 16]

With this knowledge and investigations, a new compact setup is under development focusing on a compact and robust setup on EM-level that should fulfill the requirements for the next generations of gravity missions and, as a hybrid system that is further described in section 4, the requirements of a proposed architecture of future global navigation satellite systems.[17]

Therefore, a 5 cm cube cavity made out of ultra low expansion (ULE) glass with fused silica mirrors and crystalline coatings is covered by two thermal shields, while a customized 6-axis collimator mount is directly contacted to the outer shield to improve the in-coupling stability in rough environments. The 6-axis collimator mount is made out of Ti6Al4V and gets aligned by additional fine adjustment screws. The six sides of the outer shield are actively temperature stabilized by using kapton heaters and NTC sensors. Decoupled from the cavity shield, an optical breadboard surrounds the translation stage and carries all required optical and electro-optical components beside the laser. This includes components for PDH laser stabilization, intensity stabilization and RAM correction. It should be noted here that the reduction to a minimum of free beam components is made possible by the use of an optical circulator. All components are fiber coupled by polarization maintaining fibers and all connections are spliced. Together with the cavity itself, the breadboard is enclosed in a vacuum chamber, creating a fiber-coupled robust assembly with a minimum amount of free-beam optics. First performance validations are ongoing and a picture of the experimental setup without the vacuum chamber is shown in Fig. 6.

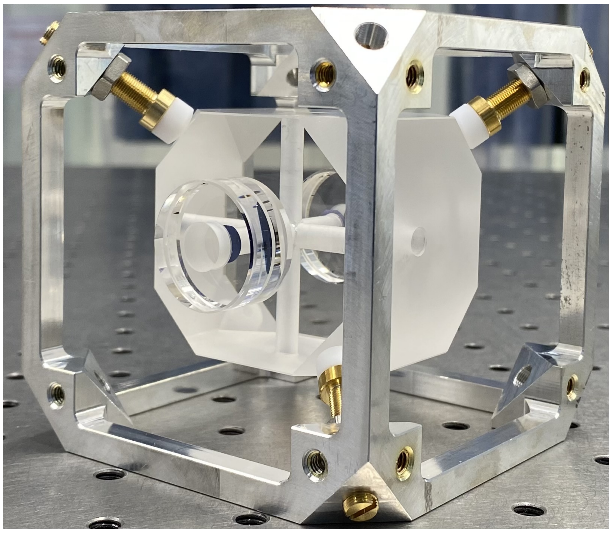

Figure 5: Picture of a 5 cm cube cavity with crystalline mirror coating and compensation rings mounted in a tetrahedral configuration.

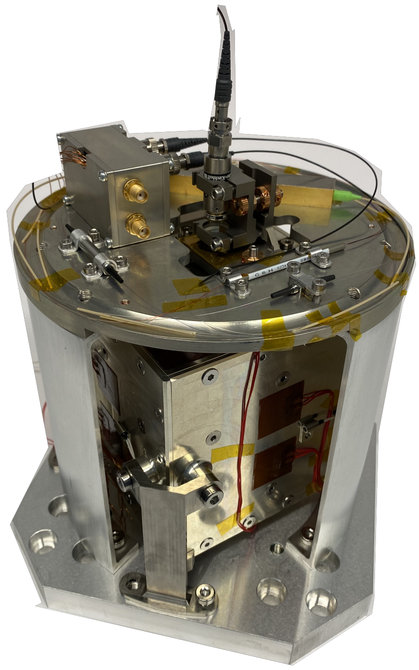

Figure 6: Compact cavity setup based on a cubic cavity enclosed by two actively controlled thermal shields. All electro-optical components required for this setup beside the laser are fiber coupled and placed on a breadboard next to the cavity.

4 Hybrid lock

With a combination of both previously introduced technologies, work on a so called 'hybrid lock' is ongoing and was first demonstrated in [18]. The hybrid lock offers the advantages of both technologies and thus resulting in an optical frequency reference offering the long-term stability, reproducibility and absolute accuracy of an iodine reference, with the short term stability of an optical cavity. The principle of the first step is analogous to the iodine lock described in section 2, while a portion of the laser light is then locked to the resonance of an optical cavity by offset sideband locking. The control parameters of both, the iodine lock and cavity lock, define the cutoff frequency until the laser follows the iodine transition and then the cavity takes over, as shown in Fig. 7. For the next step, a more compact setup is currently under development where both parts, iodine spectroscopy unit and cavity setup are especially designed for being part of a hybrid lock. In addition, theoretical work on the scalability and thus possible simplifications of the principle is ongoing. Depending on actual mission requirements, the principle can become an alternative for future absolute frequency determination of optical cavities, where the full capabilities of the hybrid lock do not need to be exploited, and thus size, weight, and power can be further reduced.

5 Conclusion

We presented our current progress in the further development of optical frequency references for space applications. Multiple iterations of laboratory iodine references were evolved providing frequency stabilities up to 4×10^{-15} for long integration times. Now, following on from this development, iodine spectroscopy units are currently being built that will become the first optical clocks in space as part of the COMPASSO project and will be sent to the ISS in 2026. In addition, we presented our work on a compact and robust high finesse optical cavity setup, which is also being developed with an emphasis on space compatibility. Based on the knowledge of an extensively characterized laboratory setup as well as theoretical models, a setup with a minimum of free beam optics has been designed. After the ongoing performance validation, the next step will be to integrate this setup into a hybrid lock consisting of a compact iodine reference and a compact cavity setup.

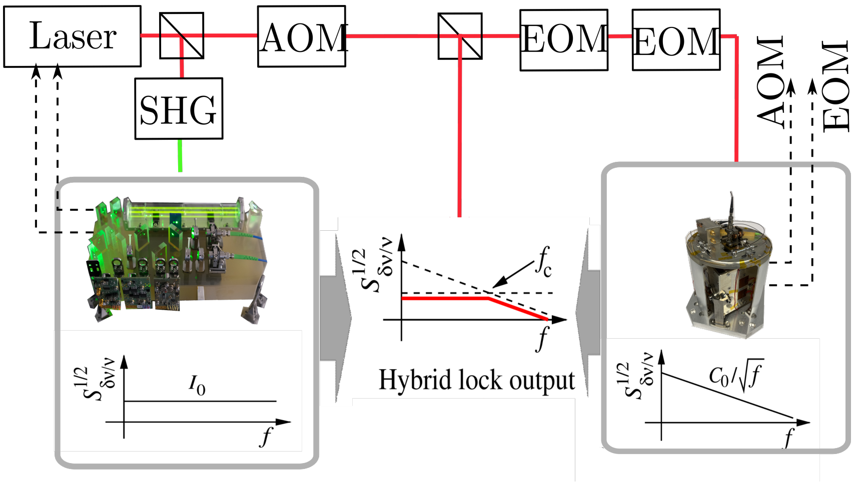

Figure 7: Schematic of the hybrid lock concept showing the laser lock to an iodine spectroscopy unit and the subsequent offset sideband lock to an optical cavity. The first EOM is bridging the frequency gap between the iodine transition and the cavity resonance by creating sidebands for a so-called offset sideband lock. The second EOM is then responsible for the phase modulation for the PDH technique. An additional AOM, even before the EOMs, acts as fast frequency actuator to generate the short- and long term stable laser which simultaneously provides absolute frequency knowledge.

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