



Optical clock technologies for global navigation satellite systems

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Abstract

Future generations of global navigation satellite systems (GNSSs) can benefit from optical technologies. Especially optical clocks could back-up or replace the currently used microwave clocks, having the potential to improve GNSS position determination enabled by their lower frequency instabilities. Furthermore, optical clock technologies—in combination with optical inter-satellite links—enable new GNSS architectures, e.g., by synchronization of distant optical frequency references within the constellation using time and frequency transfer techniques. Optical frequency references based on Doppler-free spectroscopy of molecular iodine are seen as a promising candidate for a future GNSS optical clock. Compact and ruggedized setups have been developed, showing frequency instabilities at the 10^{-15} level for averaging times between 1 s and 10,000 s. We introduce optical clock technologies for applications in future GNSS and present the current status of our developments of iodine-based optical frequency references.

Keywords Optical clock · Iodine reference · Space instrumentation · Future GNSS

Introduction

Over the last decades, optical clock technologies evolved, recently demonstrating frequency instabilities at the 10^{-18} level for integration times of a few thousand seconds (Ushijima et al. 2015; McGrew et al. 2018). While becoming more and more widespread technology in and outside laboratories on Earth, also space applications—including GNSS—can benefit from the recent advancement of optical technologies. Optical clocks surpass the performance of the currently used GNSS microwave clocks by several orders of magnitude.

On the one hand, optical clocks could back-up or replace the currently used microwave clocks (Droz et al. 2006), on the other hand, optical clock technologies—in combination with optical inter-satellite links—enable new GNSS architectures. One example is the proposed Kepler architecture (Giorgi et al. 2019) which foresees 24 satellites in medium-earth orbits (MEO, in three orbital planes, similar to the current Galileo system), together with 6 satellites in low-Earth orbit (LEO). All Kepler satellites carry optical frequency references which are intra-system synchronized using bi-directional optical inter-satellite links together with time and frequency transfer techniques. In the current baseline, the satellites are equipped with frequency references based on optical resonators, providing the required high short-term stability where the round-trip time of the light within one orbital plane (of about 0.1 s) is relevant. The LEO satellites additionally carry mid- to long-term stable absolute optical clocks based on Doppler-free spectroscopy of molecular iodine for the definition of the system time.

In the following, we first give a short overview of optical clock technologies for space, together with their current technology development status. We then detail our developments with respect to iodine-based optical frequency references for applications in space and present the mission

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concept COMPASSO, a proposed DLR in-orbit verification mission on the International Space Station (ISS).

Please note that we refer to a “clock” for a system which delivers a countable frequency signal in the radio frequency range, and where a time signal can be derived from, as it is e.g., the case in GNSS applications. When being based on an absolute and known frequency, such a system is often also referred to as a “frequency standard”.

Optical clock technologies for space applications

Optical clock technologies include a variety of different implementations, all having their own assets and drawbacks. Looking at space applications, in addition to the demonstrated performance such as frequency stability and accuracy, it is necessary to consider the size, weight, power consumption, robustness, and reliability of the optical reference.

Ultimate frequency stability at the 10^{-18} level is shown by optical lattice and single-ion clocks in rather complex laboratory setups (Ushijima et al. 2015; McGrew et al. 2018; Delehay and Lacroute 2018). Technology development with respect to transportable setups has been initiated (Koller et al. 2017; Cao et al. 2017; Brewer et al. 2019; Hannig et al. 2019), and a compact setup of a ^{88}Sr lattice clock has been realized, where space-related design criteria have been considered (Bongs et al. 2015; Origlia et al. 2018). Such optical clocks require several lasers, a vacuum chamber and a cavity pre-stabilization of the clock laser to achieve their outstanding frequency instability enabled by millihertz linewidth transitions.

Optical atomic beam standards, e.g., using Ca or Sr atoms show a lower complexity and can be realized in more compact setups. However, similar to optical lattice and single-ion clocks, they require a vacuum chamber and use cavity pre-stabilization of the clock laser. With a compact setup of a Ca beam standard, frequency instabilities of 1.8×10^{-15} at an integration time of 1600 s have been demonstrated (Shang et al. 2017). A compact and ruggedized Sr beam standard for application on a sounding rocket is currently developed at HU Berlin (Gutsch et al. 2019).

Gas-cell-based optical frequency references have modest complexity without need of a vacuum chamber or pre-stabilization and can be realized with small dimensions, weight and power budgets. They typically employ modulation transfer spectroscopy (MTS) or frequency modulation spectroscopy (FMS) of optical transitions with linewidths of the order of MHz. With a compact Rubidium-based frequency reference using MTS near 420 nm, frequency instabilities of 2.1×10^{-15} at an integration time of 80 s have been claimed, deduced from the error signal (Zhang et al. 2017; Chang et al. 2019). Iodine-based frequency references near

532 nm have been realized for many decades, resulting in compact and ruggedized setups, also with respect to applications in space (Nyholm et al. 2003; Leonhard and Camp 2006; Zang et al. 2007; Argence et al. 2010; Schuldt et al. 2017; Döringshoff et al. 2017), showing frequency instabilities at the 10^{-15} level for integration times between 1 and 1000 s. A very compact setup has been successfully flown on a sounding rocket, together with a frequency comb (Schkolnik et al. 2017; Döringshoff et al. 2019). Frequency stabilization to iodine transitions near 515 nm is investigated within the Japanese proposed space gravitational wave detector DECIGO (Deci-Hertz Interferometer Gravitational Wave Observatory) where a compact setup has been realized (Suemasa et al. 2017) and by a French collaboration using a frequency tripled output at 514 nm of Telecom laser technology at a wavelength near 1542 nm (Barbarat et al. 2018).

The Rb two-photon transition (TPT) at 778 nm is often used as a frequency standard, providing Doppler-free spectroscopy. No laser pre-stabilization and no vacuum chamber are required. While several setups have been realized in the past, recent developments include a compact setup for applications as a successor to the atomic frequency standard in GPS with demonstrated frequency instabilities at the 10^{-15} level (Martin et al. 2018). Furthermore, an integrated Rb clock has been realized, using a micro-fabricated rubidium gas cell in combination with a microcomb (Newman et al. 2019; Maurice et al. 2020).

Optical clocks require a frequency comb to transfer the stability of the clock laser to a radio frequency and thus to provide a countable clock signal. Developments for space applications are already initiated, and compact frequency combs have been successfully flown on a sounding rocket (Lezius et al. 2016; Döringshoff et al. 2019; Pröbster et al. 2021).

Table 1 summarizes the key figures of the technologies detailed above. For comparison, it also includes the space-grade microwave references currently used on Galileo [rubidium atomic frequency reference (RAFS) and passive hydrogen maser (PHM)] where data are taken from the publicly available data sheets. For the optical references, the given values on performance, i.e., frequency stability, are taken from the corresponding publications, together with the values on size, weight and power (SWaP) budgets, if given. As the technology development status of the technologies is quite different—ranging from transportable and compact setups to implementations dedicated for space—the entries cannot directly be compared. It is e.g., assumed that within a dedicated development, the budgets of lattice and ion clocks can be significantly reduced with respect to the current transportable setups (Takamoto et al. 2020). Also, long-term stability of the optical reference is often not yet investigated. However, the summary in Table 1 can be taken as the basis for necessary trade-offs, e.g., between required

Table 1 Summary of the key figures of the different optical clock technologies, together with the corresponding figures of the Galileo RAFS and PHM

References	Galileo RAFS (2016)	Galileo PHM sheet (2017)	Ca beam Shang et al. (2017)	I ₂ MTS (2017); Döringshoff et al. (2019)	Rb MTS Zhang et al. (2017)	Rb TPT Martin et al. (2018)	Sr Lattice clock (2015); Origlia et al. (2018)	Ca single ion clock (Delehay and Lacroute 2018; Cao et al. 2017)
Frequency stability (in RAV @ integration time τ)	3 × 10 ⁻¹² 1 × 10 ⁻¹² 3 × 10 ⁻¹³ 6 × 10 ⁻¹⁴ 3 × 10 ⁻¹⁴	2 × 10 ⁻¹² 3 × 10 ⁻¹³ 7 × 10 ⁻¹⁴ 2 × 10 ⁻¹⁴ 7 × 10 ⁻¹⁵	5 × 10 ⁻¹⁴ 2 × 10 ⁻¹⁴ 5 × 10 ⁻¹⁵ 2 × 10 ⁻¹⁵ n/s	6 × 10 ⁻¹⁵ 3 × 10 ⁻¹⁵ 2 × 10 ⁻¹⁵ 2 × 10 ⁻¹⁵ 3 × 10 ⁻¹⁵	1 × 10 ^{-14a} 4 × 10 ^{-15a} 3 × 10 ^{-15a} n/s n/s	4 × 10 ⁻¹³ 1 × 10 ⁻¹³ 4 × 10 ⁻¹⁴ 1 × 10 ⁻¹⁴ 5 × 10 ⁻¹⁵	n/s 1 × 10 ⁻¹⁶ 4 × 10 ⁻¹⁷ 1 × 10 ⁻¹⁷ 4 × 10 ⁻¹⁸	n/s 6 × 10 ⁻¹⁵ 2 × 10 ⁻¹⁵ 6 × 10 ⁻¹⁶ 2 × 10 ⁻¹⁶
Longest reported (continuous) τ (s)	Long-term drift < 10 ⁻¹⁰ / year	Long-term drift < 10 ⁻¹⁵ / day	n/s n/s 1600	< 2 × 10 ⁻¹⁴ n/s 700,000	n/s 600	n/s 180,000	n/s 30,000	n/s 30,000
Clock transition frequency/wavelength	6.8 GHz	1.4 GHz	657 nm	532 nm	420 nm	778 nm	698 nm	729 nm
Clock transition natural linewidth			0.4 kHz	300 kHz	1450 kHz	330 kHz	6 mHz	140 mHz
SWaP Budgets ^{b,c}	3.4	18.2	n/s	21 + 10 ^b	10 ^d + 10 ^b	12 ^e + 10 ^b	< 250	n/s
Mass (kg)	35	60 ^f	n/s	44 + 66 ^b	20 ^d + 66 ^b	25 ^e + 66 ^b	n/s	n/s
Power (W)	3.2	26.3	300 + 7 ^b	33 + 7 ^b	n/s	8 ^e + 7 ^b	< 1000	540
Volume (l)	n/a	n/a	2	1	1	1	5	6
# Lasers	n/a	n/a	Yes	No	No	No	Yes	Yes
Vacuum chamber	n/a	n/a	Yes	No	No	No	Yes	Yes
Cavity pre-stabilization	n/a	n/a	Yes	No	No	No	Yes	Yes
TRL	9	9	4	4-5 ^g	4	4	4	4

^aValues on frequency instabilities deduced from the error signal (Zhang et al. 2017).

^bThe values for the frequency comb are explicitly given for the optical references (10 kg, 66 W, 7 l) (Döringshoff et al. 2019; Pröbster et al. 2021). It is assumed that the values on mass and power consumption can be further reduced in a design upgrade of the frequency comb

^cThe SWaP budgets for the optical clock technologies include the laser(s)

^dEstimation based on current state-of-the-art implementation techniques using a similar design as for the iodine references

^eEstimation based on the QUEEN study by HU Berlin, which includes 2 ECDL-MOPA laser systems and is not yet designed for highest frequency stability at the 10⁻¹⁵ level

^fAt +10 °C baseplate; 70 W at -5C baseplate

^gIodine reference successfully flown on a sounding rocket (not designed for highest performance), component level space heritage within other space missions (LISA, LISA Pathfinder, GRACE follow-on, NGGM)

frequency stability, SWaP budgets and robustness/complexity, and also concerning the necessary time frame to develop a space-qualified optical clock.

In Table 1, also the technology maturity is assessed and quantified by the so-called Technology Readiness Level (TRL). The highest level (TRL9) is reached for flight-proven components and systems with demonstrated performance in space operation. The lowest level (TRL1) corresponds to the observation and reporting of basic principles. Functional verification in a typical laboratory environment corresponds to TRL4, the full-scale engineering model with successful environmental testing to TRL6.

At DLR and the University of Bremen, iodine-based frequency references using modulation transfer spectroscopy have been investigated for several years with respect to applications in space, including missions to measure the earth's gravity field (Nicklaus et al. 2017) and space-borne gravitational wave detection (Schuldt et al. 2019). Such references can be realized compact and ruggedized, with small dimensions, mass and power consumption. Typically, the a_{10} component of the R(56)32–0 transition in $^{127}\text{I}_2$ near a wavelength of 532 nm is used for frequency stabilization. It is a standard frequency, recommended by the International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM) with a relative standard uncertainty of 8.9×10^{-12} (Riehle et al. 2018). As the laser is operated at 1064 nm, iodine-based frequency references can rely on space heritage of the laser and laser components, developed e.g., within the missions LISA (Laser Interferometer Space Antenna), LISA Pathfinder and GRACE (Gravity Recovery and Climate Experiment) follow-on as well as mission concepts developed within the NGGM (Next Generation Gravity Mission) program by the European Space Agency (ESA). Furthermore, commercial laser communication terminals operate at the same wavelength. Iodine-based optical frequency references are seen as a promising candidate for an optical clock for future GNSS showing lower

frequency instabilities as the currently used PHM. Relying on an extensive heritage, a flight model fulfilling the Galileo requirements could be realized on short timescale and at moderate costs. As a perspective, this technology is seen as an initiating step toward a routinely applied and reliable optical clock technology in space, also paving the way for future ultra-high performance optical single-ion and lattice clocks in space.

Absolute frequency references based on Doppler-free spectroscopy of molecular iodine near 532 nm

Molecular iodine offers very strong absorption lines near 532 nm which can easily be accessed with a laser system at a wavelength of 1064 nm using second harmonic generation (SHG), also realized in compact and ruggedized setups for applications in space.

Over the last years, DLR—in collaboration with the Humboldt-Universität zu Berlin and the University Bremen—has developed several setups of iodine-based frequency references with a roadmap toward space applications. The optical setups for modulation transfer spectroscopy are realized using an adhesive bonding technology where the optical components are joint to a baseplate made of glass (or glass ceramics, respectively) with a space-qualified two-component epoxy, see Fig. 1. This ensures the high thermal and mechanical stability of the optical system needed for operation in space.

With a setup on Elegant Breadboard (EBB) level (Fig. 1, left), frequency instabilities of 6×10^{-15} at 1 s integration time and below 3×10^{-15} for integration times between 100 s and 10,000 s have been demonstrated (Schuldt et al. 2017). This is, to our knowledge, the best published performance for such an iodine-based frequency reference. The frequency instabilities of the EBB setup—given in

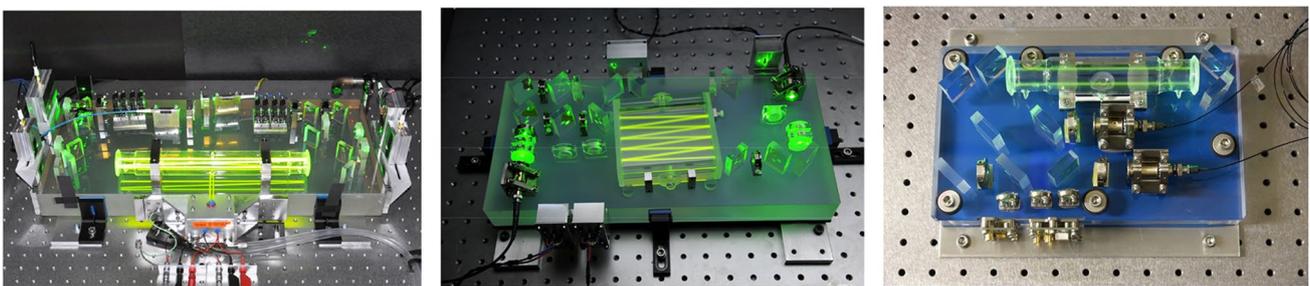
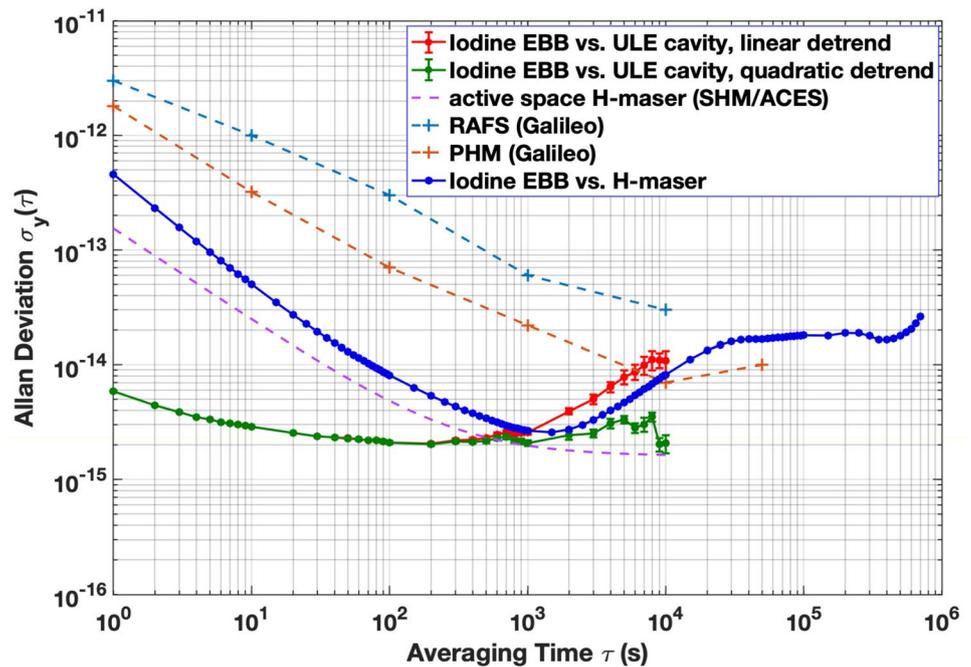


Fig. 1 Several implementations of the iodine spectroscopy unit, realized at DLR in collaboration with the universities HU Berlin and Bremen. Left: Elegant Breadboard (EBB, 25 cm×55 cm) (Schuldt et al. 2017); Middle: Engineering Model (EM, 18 cm×38 cm)

(Döringshoff et al. 2017); Right: Setup used on the sounding rocket mission JOKARUS (15 cm×25 cm) (Schkolnik et al. 2017; Döringshoff et al. 2019)

Fig. 2 Measured frequency stability of the Iodine-EBB reference, given in Allan deviation. Shown is a beat measurement with a cavity setup (Schuldt et al. 2017), together with the frequency stabilities of the current Galileo clocks (RAFS, PHM) and the active hydrogen maser for ACES (SHM). Also shown is a beat measurement with a hydrogen maser (first measurement, not yet optimized, the degradation > 1000 s is believed to be an artefact). The measurement is limited by the H-maser performance for integration times < 1000 s



Allan deviation—are shown in Fig. 2, evaluated from a beat measurement with an ultra-low expansion (ULE) cavity setup. A linear and a second-order polynomial drift have been removed from the corresponding time records where the linear drift is attributed to the iso-thermal creep of the cavity. The Allan deviation shows white frequency noise for integration times between 1 and 10 s and Flicker noise of about 3×10^{-15} at integration times > 1000 s. For integration times up to 1000 s, the frequency instabilities are 1–2 orders of magnitude lower than the one of the current Galileo clocks, i.e., RAFS and PHM. At longer integration times, the iodine reference approaches the performance of the Space Hydrogen Maser (SHM), an active hydrogen maser which is currently implemented within the ACES (Atomic Clock Ensemble in Space) mission on the ISS (Goujon et al. 2010). As our measurement of the iodine performance is most probably limited by the cavity reference, we started an investigation of the long-term stability of the EBB setup which is currently ongoing. A first frequency stability evaluation where the iodine EBB is compared to a hydrogen maser via an optical frequency comb is shown in Fig. 2 (blue curve). It is based on a 16 days continuous operation of the iodine reference.

The engineering model (EM) setup was further developed with respect to compactness and uses a specifically designed compact iodine cell, see Fig. 1, middle (Döringshoff et al. 2017). The EM spectroscopy unit was subjected to thermal cycling from -20 °C to $+60$ °C and vibrational loads with sine vibration up to 30 g and random vibration up to 25.1 g_{rms} . The frequency stability was measured before and after the tests where no degradation was observed. The

frequency offset between the EBB and EM setups is below 1.5 kHz with a reproducibility below 250 Hz (Döringshoff et al. 2017). While gas cells typically use a cold finger for setting the pressure inside the cell, the EM setup was also operated with a gas cell filled at an unsaturated vapor pressure of about 1 Pa, showing similar performance. This allows lowering the complexity of the setup by omitting a temperature control and reducing the SWaP budgets.

An iodine-based frequency reference has been successfully operated on a sounding rocket (Schkolnik et al. 2017; Döringshoff et al. 2019) as part of the JOKARUS mission, showing autonomous operation during the 6 min long space flight. The setup was optimized with respect to the specific sounding rocket requirements, especially regarding dimensions. The compact spectroscopy unit with a 15 cm long iodine cell, is shown in Fig. 1, right, using a micro-integrated extended cavity diode laser (ECDL) including a semiconductor power amplifier as light source (Kürbis et al. 2020). A short-term instability of the iodine reference of $1.5 \times 10^{-13}/\sqrt{\tau}$ has been demonstrated (Döringshoff et al. 2019), probably limited due to its very compact design, intermodulation noise and the lack of intensity and RAM stabilization.

Within the ongoing project ADVANTAGE (Advanced Technologies for Navigation and Geodesy), a next iteration of the iodine setup is developed, based on the EBB-, EM- and JOKARUS developments. The next step toward space instrumentation is carried out by a system level design where all components for the laser system, and the spectroscopy are integrated within one physical box. For the design, an absolute temperature of 15 °C with a stability of ± 5 °C is

assumed for the spacecraft interface plate. An actively controlled thermal shield within the iodine reference guarantees an operation of the spectroscopy board at $(22 \pm 0.1)^\circ\text{C}$. The laser is fiber-coupled to this unit in the current design, where a Nd:YAG solid state laser is assumed baseline. In a design upgrade, a compact ECDL module will be integrated within the unit. Figure 3 shows a photograph of the integrated spectroscopy board, the corresponding optical layout for modulation transfer spectroscopy and a CAD model of the overall system level design of the reference.

The design of the ADVANTAGE setup is taken as basis for an optical reference developed for future GNSS. The corresponding schematic is shown in Fig. 4 where the frequency reference is split into two functional units: the iodine spectroscopy unit (including laser, fiber-optic components for beam preparation and frequency doubling) and the iodine control electronics (including laser driver, temperature

controllers, AOM and EOM drivers, servo control loops for intensity, RAM and frequency stabilization). The stable light at a wavelength of 1064 nm is input to an optical frequency comb, which delivers a stable 10 MHz clock signal.

A component-level breakdown, based on the design shown in Fig. 4 results in an overall mass of 20.1 kg (including a 20% component level margin), a power consumption of 43.1 W (including a 10% component level margin) and a volume of 32.3 l (without margin) of the optical reference (without frequency comb).

In-orbit verification mission

As part of a general technology development roadmap for future Galileo, DLR plans an in-orbit verification mission, called COMPASSO. This mission will demonstrate optical

Fig. 3 ADVANTAGE setup of the iodine reference. Top: Photograph and schematic of the spectroscopy board using a 22 cm long iodine cell in 4-pass configuration. Bottom: CAD at system level, showing the spectroscopy board within a thermal shield. The fiber-optic components for the laser system (including AOM and EOM) are mounted to the bottom side of the thermal shield, the SHG modules at one of its side plates. The laser is fiber coupled to this unit

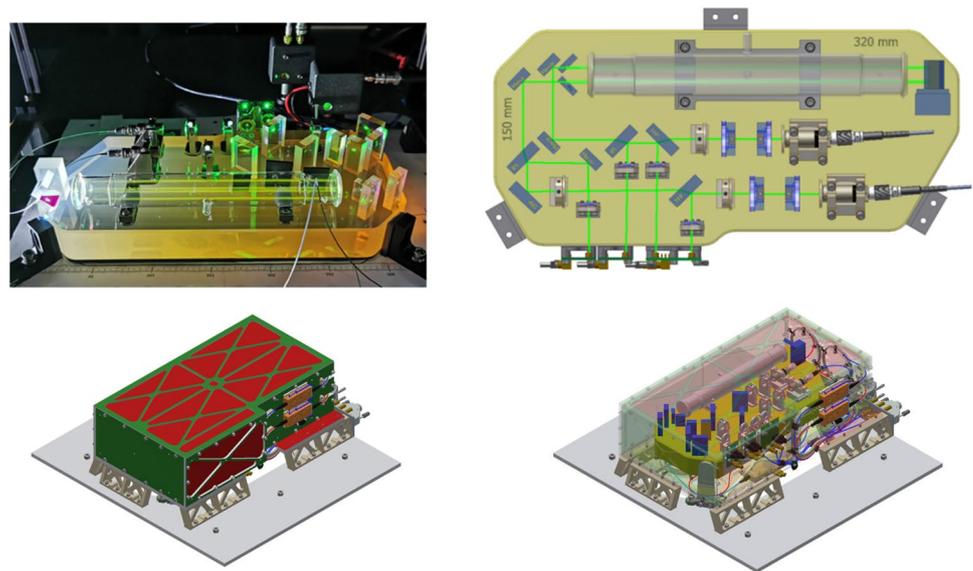


Fig. 4 Layout of the iodine reference with interfaces to the frequency comb, which delivers the stable 10 MHz output signal. *ECDL* extended cavity diode laser, *AOM* acousto-optical modulator, *EOM* electro-optics phase modulator, *SHG* second harmonic generation, *VHBG* volume holographic bragg grating, *RAM* residual amplitude modulation, *NC* noise-canceling photo-detector, *PD* photo-detector, *DDS* direct digital synthesizer, *MO* master oscillator, *PA* power amplifier, *PID* proportional-integral-derivative servo control, *TM/TC* telemetry and telecommand

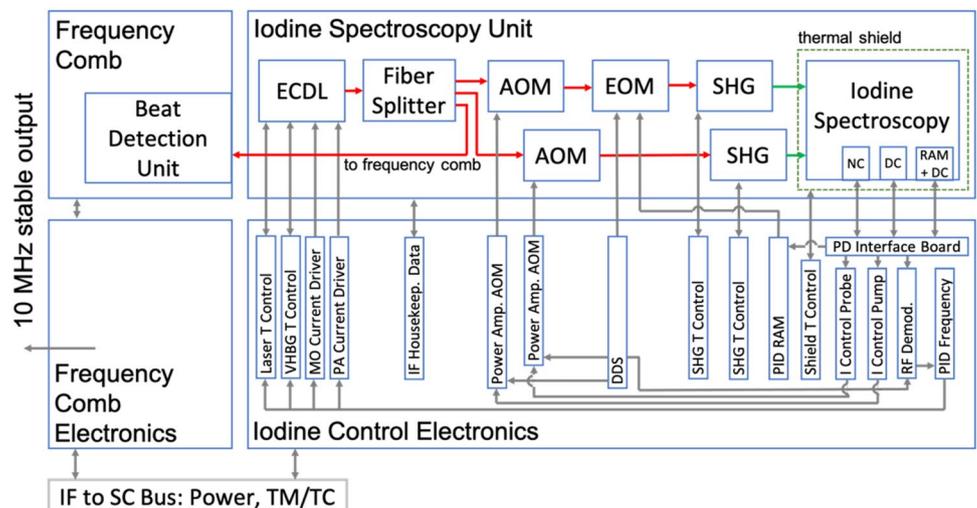
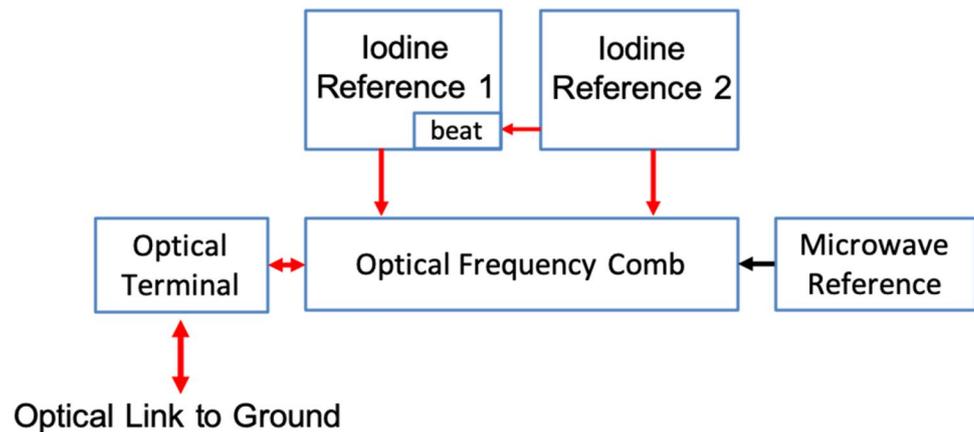


Fig. 5 High-level architecture of the COMPASSO payload



clock and optical link technologies on the Bartolomeo platform (Steimle et al. 2019) which is externally attached to the Columbus module of the ISS. Based on the mission concept presented by Schuldt et al. (2019), the mission feasibility of COMPASSO is currently investigated within a Phase A study at DLR where a mission lifetime of 2 years is assumed.

The payload consists of two iodine-based frequency references as detailed above, together with an optical frequency comb, a microwave frequency reference and an optical laser communication and ranging terminal, cf. the architecture shown in Fig. 5. The optical link is used for time- and frequency transfer and synchronization of a ground-based (microwave or optical) frequency reference to the space-based optical frequency references. Furthermore, it enables data communication and high-accuracy ranging.

The two iodine-based frequency references can be stabilized to the same or to different (nearby) ro-vibronic transitions. Their frequency stabilities are evaluated by comparing both references in the optical frequency range, i.e., near 282THz (corresponding to a wavelength of 1064 nm). The optical frequency comb can be referenced to the iodine reference and transfers its frequency stability from the optical frequency range to the radio frequency range. Furthermore, the frequency comb can be referenced to an onboard microwave reference (e.g., a Galileo PHM or RAFS) and thus enables multiple comparison measurements with which the frequency stability in the relevant time period of the references can be evaluated. Using the two-way optical laser communication and ranging terminal (LCRT) the performance of the optical references onboard the ISS can additionally be compared to ground-based clocks.

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(IOC)” project under lead of SpaceTech GmbH, Immenstaad, Germany, with funding by the EU Horizon 2020 program.

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