



# Optical clock technologies for global navigation satellite systems

Thilo Schuldt<sup>1</sup> · Martin Gohlke<sup>1</sup> · Markus Oswald<sup>1,2</sup> · Jan Wüst<sup>1</sup> · Tim Blomberg<sup>1</sup> · Klaus Döringshoff<sup>3,4</sup> · Ahmad Bawamia<sup>3</sup> · Andreas Wicht<sup>3</sup> · Matthias Lezius<sup>5</sup> · Kai Voss<sup>6</sup> · Markus Krutzik<sup>3,4</sup> · Sven Herrmann<sup>2</sup> · Evgeny Kovalchuk<sup>3,4</sup> · Achim Peters<sup>3,4</sup> · Claus Braxmaier<sup>1,2</sup>

Received: 5 October 2020 / Accepted: 3 March 2021 / Published online: 5 April 2021  
© The Author(s) 2021

## 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

✉ Thilo Schuldt  
Thilo.schuldt@dlr.de

<sup>1</sup> German Aerospace Center (DLR), Institute of Space Systems, Bremen, Germany

<sup>2</sup> Center of Applied Space Technology and Microgravity, University of Bremen, Bremen, Germany

<sup>3</sup> Ferdinand-Braun-Institut gGmbH, Leibniz-Institut Für Höchstfrequenztechnik, Berlin, Germany

<sup>4</sup> Institute of Physics, Humboldt-Universität zu Berlin, Berlin, Germany

<sup>5</sup> Menlo Systems GmbH, Martinsried, Germany

<sup>6</sup> SpaceTech GmbH, Immenstaad, Germany

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  $^{88}\text{Sr}$  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  $1.8 \times 10^{-15}$  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  $2.1 \times 10^{-15}$  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 Leonardo data-sheet (2017)	Ca beam Shang et al. (2017)	I <sub>2</sub> MTS Schuldt et al. (2017); Döringshoff et al. (2019)	Rb MTS Zhang et al. (2017)	Rb TPT Martin et al. (2018)	Sr Lattice clock Bongs et al. (2015); Origlia et al. (2018)	Ca single ion clock (Delehay and Lacroute 2018; Cao et al. 2017)
Frequency stability (in RAV @ integration time $\tau$ )	3 × 10 <sup>-12</sup> 1 × 10 <sup>-12</sup> 3 × 10 <sup>-13</sup> 6 × 10 <sup>-14</sup> 3 × 10 <sup>-14</sup>	2 × 10 <sup>-12</sup> 3 × 10 <sup>-13</sup> 7 × 10 <sup>-14</sup> 2 × 10 <sup>-14</sup> 7 × 10 <sup>-15</sup>	5 × 10 <sup>-14</sup> 2 × 10 <sup>-14</sup> 5 × 10 <sup>-15</sup> 2 × 10 <sup>-15</sup> n/s	6 × 10 <sup>-15</sup> 3 × 10 <sup>-15</sup> 2 × 10 <sup>-15</sup> 2 × 10 <sup>-15</sup> 3 × 10 <sup>-15</sup>	1 × 10 <sup>-14a</sup> 4 × 10 <sup>-15a</sup> 3 × 10 <sup>-15a</sup> n/s n/s	4 × 10 <sup>-13</sup> 1 × 10 <sup>-13</sup> 4 × 10 <sup>-14</sup> 1 × 10 <sup>-14</sup> 5 × 10 <sup>-15</sup>	n/s 1 × 10 <sup>-16</sup> 4 × 10 <sup>-17</sup> 1 × 10 <sup>-17</sup> 4 × 10 <sup>-18</sup>	n/s 6 × 10 <sup>-15</sup> 2 × 10 <sup>-15</sup> 6 × 10 <sup>-16</sup> 2 × 10 <sup>-16</sup>
Longest reported (continuous) $\tau$ (s)	Long-term drift < 10 <sup>-10</sup> / year	Long-term drift < 10 <sup>-15</sup> / day	n/s n/s n/s	< 2 × 10 <sup>-14</sup> n/s n/s	n/s n/s 600	n/s n/s 180,000	n/s n/s 30,000	n/s 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 <sup>b,c</sup>	3.4	18.2	n/s	21 + 10 <sup>b</sup>	10 <sup>d</sup> + 10 <sup>b</sup>	12 <sup>e</sup> + 10 <sup>b</sup>	< 250	n/s
Mass (kg)	35	60 <sup>f</sup>	n/s	44 + 66 <sup>b</sup>	20 <sup>d</sup> + 66 <sup>b</sup>	25 <sup>e</sup> + 66 <sup>b</sup>	n/s	n/s
Power (W)	3.2	26.3	300 + 7 <sup>b</sup>	33 + 7 <sup>b</sup>	n/s	8 <sup>e</sup> + 7 <sup>b</sup>	< 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 <sup>g</sup>	4	4	4	4

<sup>a</sup>Values on frequency instabilities deduced from the error signal (Zhang et al. 2017).

<sup>b</sup>The 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

<sup>c</sup>The SWaP budgets for the optical clock technologies include the laser(s)

<sup>d</sup>Estimation based on current state-of-the-art implementation techniques using a similar design as for the iodine references

<sup>e</sup>Estimation 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<sup>-15</sup> level

<sup>f</sup>At +10 °C baseplate; 70 W at -5C baseplate

<sup>g</sup>Iodine 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  $8.9 \times 10^{-12}$  (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

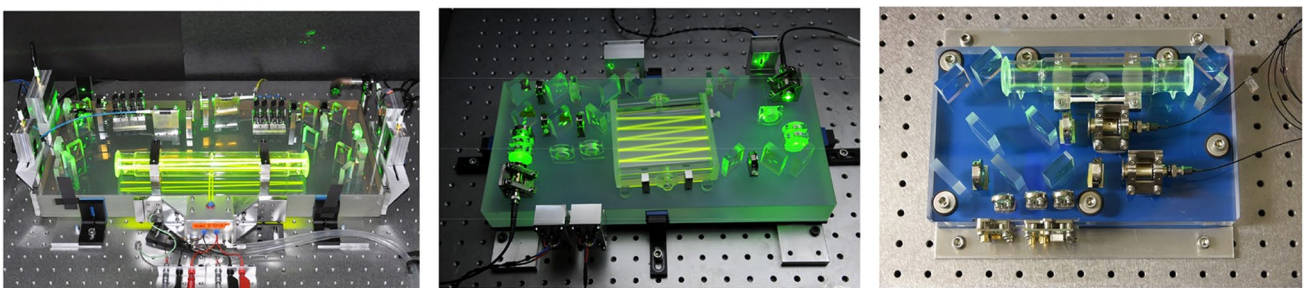
frequency instabilities as the currently used PHM. Relying on an extensive heritage, a flight model fulfilling the Galileo requirements could be realized on short timescale and at moderate costs. As a perspective, this technology is seen as an initiating step toward a routinely applied and reliable optical 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.

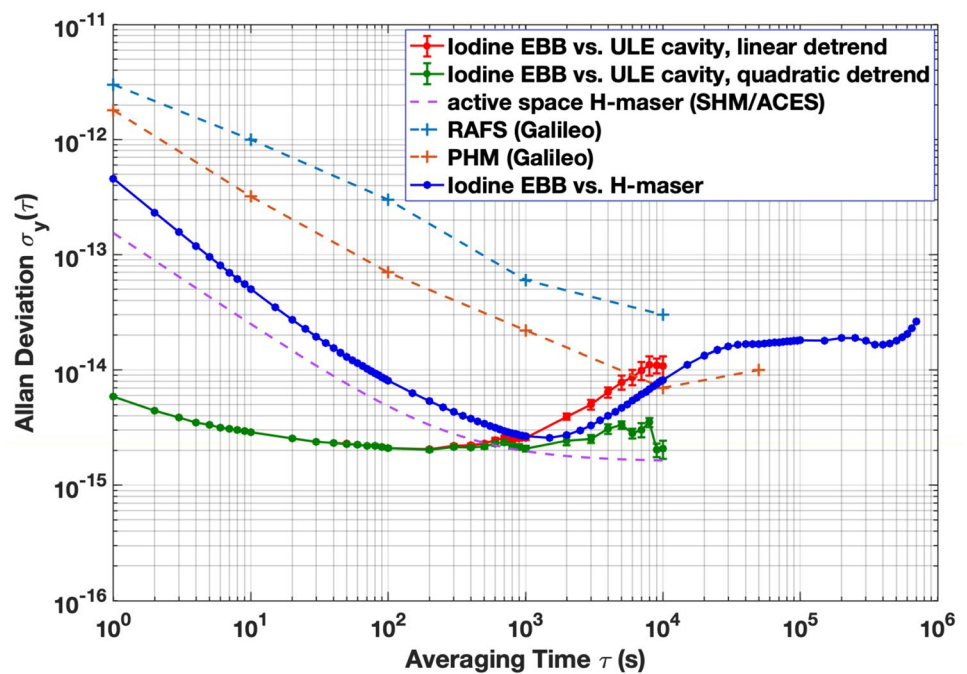
With a setup on Elegant Breadboard (EBB) level (Fig. 1, left), frequency instabilities of  $6 \times 10^{-15}$  at 1 s integration time and below  $3 \times 10^{-15}$  for integration times between 100 s and 10,000 s have been demonstrated (Schuldt et al. 2017). This is, to our knowledge, the best published 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  $3 \times 10^{-15}$  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  $25.1$   $g_{\text{rms}}$ . 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  $\pm 5$  °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  $(22 \pm 0.1) \text{ }^\circ\text{C}$ . 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

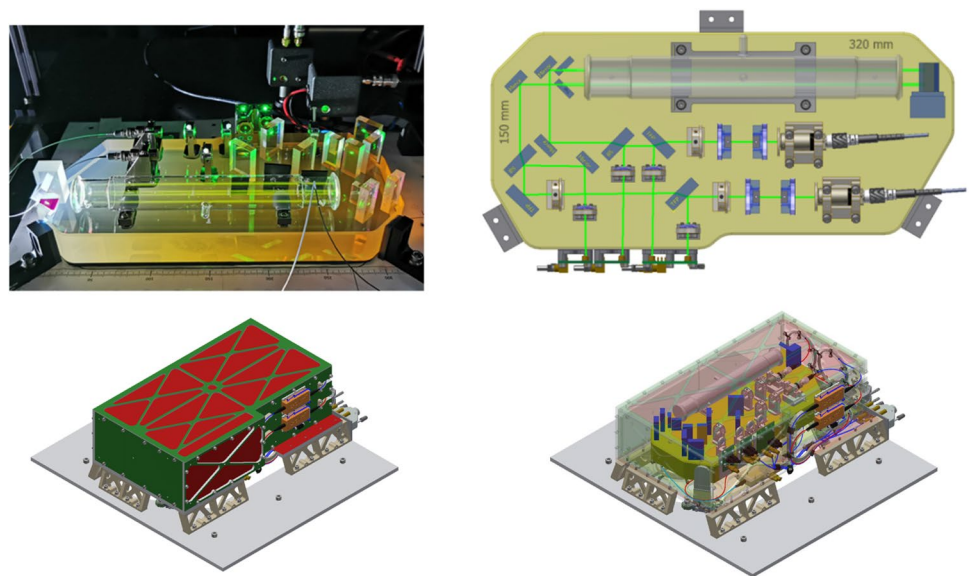
controllers, AOM and EOM drivers, servo control loops for intensity, RAM and frequency stabilization). The stable light at a wavelength of 1064 nm is input to an optical frequency comb, which delivers a stable 10 MHz clock signal.

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).

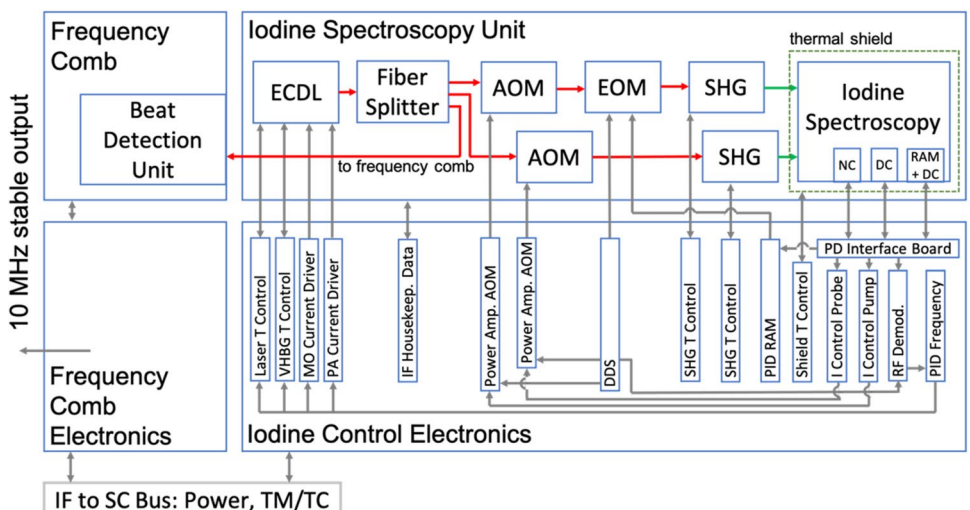
### In-orbit verification mission

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

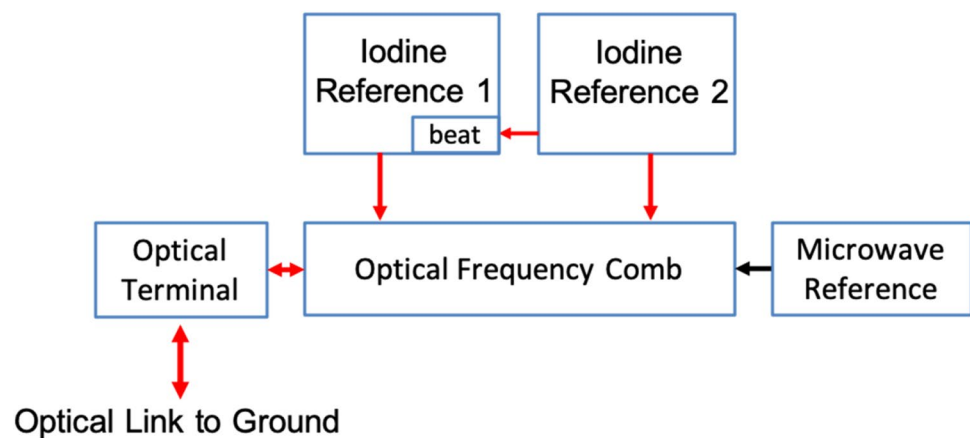
**Fig. 3** ADVANTAGE setup of the iodine reference. Top: Photograph and schematic of the spectroscopy board using a 22 cm long iodine cell in 4-pass configuration. Bottom: CAD at system level, showing the spectroscopy board within a thermal shield. The fiber-optic components for the laser system (including 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.

**Acknowledgements** This work is supported by the Helmholtz-Gemeinschaft Deutscher Forschungszentren e.V. under grant number ZT-0007 (ADVANTAGE, Advanced Technologies for Navigation and Geodesy) and by the German Space Agency DLR with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) under grant numbers 50QT1102, 50QT1201, 50WM1646 and 50NA1905. The iodine reference is investigated within the “Iodine Optical Clock

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

**Funding** Open Access funding enabled and organized by Projekt DEAL.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Argence B, Halloin H, Jeannin O, Prat P, Turazza O, de Vismes E, Auger G, Plagnol E (2010) Molecular laser stabilization at low frequencies for the LISA mission. *Phys Rev D* 81:082002. <https://doi.org/10.1103/PhysRevD.81.082002>
- Barbarat J, Gillot J, Alvarez-Martinez H et al (2018) Compact and Transportable Iodine Frequency-Stabilized Laser. In: *Proc SPIE* 11180, International Conference on Space Optics, ICSO 2018, 111800T. <https://doi.org/10.1117/12.2535948>
- Bongs K, Sing Y, Smith L et al (2015) Development of a strontium optical lattice clock for the SOC mission on the ISS. *C R Phys* 16:553–564. <https://doi.org/10.1016/j.crhy.2015.03.009>
- Brewer AM, Chen JS, Hankin AM, Clements ER, Chou CW, Wine-land DJ, Hume DB, Leibrandt DR (2019)  $^{27}\text{Al}^+$  Quantum-logic clock with a systematic uncertainty below  $10^{-18}$ . *Phys Rev Lett* 123:033201. <https://doi.org/10.1103/PhysRevLett.123.033201>
- Cao J, Zhang P, Shang J, Cui K, Yuan J, Chao S, Wang S, Shu H, Huang X (2017) A compact, transportable single-ion optical clock with  $7.8 \times 10^{-17}$  systematic uncertainty. *Appl Phys B* 123:112. <https://doi.org/10.1007/s00340-017-6671-5>
- Chang P, Zhang S, Shang H, Chen J (2019) Stabilizing didoe laser to 1 Hz-level Allan deviation with atomic spectroscopy for Rb four-level active optical frequency standard. *Appl Phys B* 125:196. <https://doi.org/10.1007/s00340-019-7313-x>

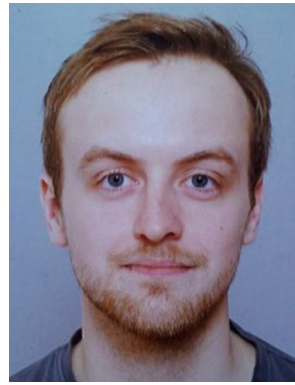
- Delehay M, Lacroute C (2018) Single-ion, transportable optical atomic clocks. *J Mod Opt* 65(5–6):622–639. <https://doi.org/10.1080/09500340.2018.1441917>
- Döringshoff K, Schuldt T, Kovalchuk E, Stühler J, Braxmaier C, Peters A (2017) A flight-like absolute optical frequency reference based on iodine for laser systems at 1064 nm. *Appl Phys B* 123:183. <https://doi.org/10.1007/s00340-017-6756-1>
- Döringshoff K et al (2019) Iodine frequency reference on a sounding rocket. *Phys Rev Appl* 11:054068. <https://doi.org/10.1103/PhysRevApplied.11.054068>
- Droz F, et al. (2006) The onboard Galileo clocks: Rubidium standard and Passive Hydrogen Maser—current status and performance. Proceedings of the 20th European Frequency and Time Forum, pp. 420–426.
- Giorgi G et al (2019) Advanced technologies for satellite navigation and geodesy. *Adv Space Res* 64(6):1256–1273. <https://doi.org/10.1016/j.asr.2019.06.010>
- Goujon D et al (2010) Development of the space active hydrogen maser for the ACES mission. In: Proceedings of the 24th European Frequency and Time Forum, Noordwijk, pp 1–6. <https://doi.org/10.1109/EFTF.2010.6533730>
- Gutsch et al (2019) Towards a strontium beam optical reference based on the  $^1S_0$   $^3P_1$  intercombination line on a sounding rocket. In: 2019 Joint Conference of the IEEE international frequency control symposium and european frequency and time forum (EFTF/IFC), Orlando. <https://doi.org/10.1109/FCS.2019.8856031>
- Hannig S et al (2019) Towards a transportable aluminium ion quantum logic optical clock. *Rev Sci Instrum* 90:053204. <https://doi.org/10.1063/1.5090583>
- Koller SB, Grotty J, Vogt S, Al-Masoudi A, Dörscher S, Häfner S, Sterr U, Lisdat C (2017) Transportable optical lattice clock with  $7 \times 10^{-17}$  uncertainty. *Phys Rev Lett* 118:073601. <https://doi.org/10.1103/PhysRevLett.118.073601>
- Kürbis C, Bawamia A, Krüger M, Smol R, Peters A, Wicht A, Tränkle G (2020) Extended cavity diode laser master-oscillator-power-amplifier for operation of an iodine frequency reference on a sounding rocket. *Appl Opt* 50(2):253–262. <https://doi.org/10.1364/AO.379955>
- Leonhard V, Camp JB (2006) Space interferometry application of laser frequency stabilization with molecular iodine. *Appl Opt* 45(17):4142–4146. <https://doi.org/10.1364/AO.45.004142>
- Lezius M et al (2016) Space-borne frequency comb metrology. *Optica* 3(12):1381–1387. <https://doi.org/10.1364/OPTICA.3.001381>
- Martin KW et al (2018) Compact optical atomic clock based on a two-photon transition in rubidium. *Phys Rev Appl* 9:014019. <https://doi.org/10.1103/PhysRevApplied.9.014019>
- Maurice V et al (2020) Miniaturized optical frequency reference for next-generation portable optical clocks. *Opt Express* 28(17):24708–24720. <https://doi.org/10.1364/OE.396296>
- McGrew WF et al (2018) Atomic clock performance enabling geodesy below the centimetre level. *Nature* 564:87–90. <https://doi.org/10.1038/s41586-018-0738-2>
- Newman ZL et al (2019) Architecture for the photonic integration of an optical atomic clock. *Optica* 6(5):680–685. <https://doi.org/10.1364/OPTICA.6.000680>
- Nicklaus K et al (2017) High stability laser for next generation gravity missions. In: Proc SPIE 10563, International Conference on Space Optics, ICSSO 2014, 105632T. <https://doi.org/10.1117/12.2304161>
- Nyholm K, Merimaa M, Ahola T, Lassila A (2003) Frequency Stabilization of a Diode-Pumped Nd: Yag Laser at 532 nm to Iodine by using third-harmonic technique. *IEEE Trans Instrum Meas* 52(2):284–287. <https://doi.org/10.1109/TIM.2003.811679>
- Origlia S et al (2018) Towards an optical clock for space: Compact, high-performance optical lattice clock based on bosonic atoms. *Phys Rev A* 98:053443. <https://doi.org/10.1103/PhysRevA.98.053443>
- Pröbster BJ, Lezius M, Mandel O, Braxmaier C, Holzwarth R (2021) FOKUS II—space flight of a compact and vacuum compatible dual frequency comb system. Accepted for publication by JOSA B
- Riehle F, Gill P, Arias F, Robertsson L (2018) The CIPM list of recommended frequency standard values: guidelines and procedures. *Metrologia* 55(2):188–200. <https://doi.org/10.1088/1681-7575/aaa302>
- Schkolnik V et al (2017) JOKARUS—design of a compact optical iodine frequency reference for a sounding rocket mission. *EPJ Quantum Technol* 4:9. <https://doi.org/10.1140/epjqt/s40507-017-0063-y>
- Schuldt T et al (2019) In-orbit-verification of optical clock technologies. In: Proc. 70th International Aeronautics Conference (IAC), IAC-19-A2.1.2
- Schuldt T, Döringshoff K, Kovalchuk E, Keetman A, Pahl J, Peters A, Braxmaier C (2017) Development of a compact optical absolute frequency reference for space with  $10^{-15}$  instability. *Appl Opt* 56(4):1101–1106. <https://doi.org/10.1364/AO.56.001101>
- Schuldt T, Döringshoff K, Oswald M, Kovalchuk EV, Peters A, Braxmaier C (2019) Absolute laser frequency stabilization for LISA. *Int J Mod Phys D* 28:12. <https://doi.org/10.1142/S0218271818450025>
- Shang H, Zhang X, Zhang S, Pan D, Chen H, Chen J (2017) Miniaturized calcium beam optical frequency standard using fully-sealed vacuum tube with  $10^{-15}$  instability. *Opt Express* 25(24):30459–30467. <https://doi.org/10.1364/OE.25.030459>
- Steimle C, Walz C, Fuchs C, Pedersen D, Lombardi CM (2019) Bartolomeo external platform entering into commercial service. In: Proc. 70th International Aeronautics Conference (IAC), IAC-19-B3.3
- Suemasa A, Shimo-oku A, Nakagawa K, Musha M (2017) Developments of high frequency and intensity stabilized lasers for space gravitational wave detector DECIGO/B-DECIGO. *CEAS Space J* 9:485–491. <https://doi.org/10.1007/s12567-017-0151-y>
- Takamoto M, Ushijima I, Ohmae N, Yahagi T, Kokado K, Shinkai H, Katori H (2020) Test of general relativity by a pair of transportable optical lattice clocks. *Nat Photonics* 14:411–415. <https://doi.org/10.1038/s41566-020-0619-8>
- Ushijima I, Takamoto M, Das M, Ohkubo T, Katori H (2015) Cryogenic optical lattice clocks. *Nat Photonics* 9:185–189. <https://doi.org/10.1038/nphoton.2015.5>
- Zang EJ, Cao JP, Li Y, Li CY, Deng YK, Gao CQ (2007) Realization of four-pass i2 absorption cell in 532-nm optical frequency standard. *IEEE Trans Instrum Meas* 56(2):673–676. <https://doi.org/10.1109/TIM.2007.890816>
- Zhang S et al (2017) Compact Rb optical frequency standard with  $10^{-15}$  stability. *Rev Sci Instrum* 88:103106. <https://doi.org/10.1063/1.5006962>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.





**Thilo Schuldt** joined the German Aerospace Center (DLR), Institute of Space Systems (Bremen) in 2013 and is group leader for “System Enabling Technologies”. He received his Ph.D. from the Humboldt-Universität zu Berlin for his work on the space-based gravitational wave detector LISA. Thilo Schuldt has been working on many ESA and DLR funded projects in optical metrology, focusing on optical frequency references and high-sensitivity laser interferometry.



**Tim Blomberg** joined the German Aerospace Center (DLR), Institute of Space Systems (Bremen) in 2018. He received his master’s degree from the RWTH Aachen University for the development, integration and test of an isostatic mounting for the iodine spectroscopy board of ADVANTAGE. Assembly, integration and test activities within ADVANTAGE are part of his current responsibilities.



**Martin Gohlke** joined the German Aerospace Center (DLR), Institute of Space Systems (Bremen) in 2012. He worked on the optical ground support equipment for the GRACE follow-on mission in cooperation with DLR institutes and space companies (Airbus, STI and JPL). LISA related topics such as laser interferometry, optical frequency references and temperature sensors are part of his current activities.



**Klaus Döringshoff** joined the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Berlin) in 2020, and works on the development of optical frequency references based on high resolution laser spectroscopy. He received his Ph.D. from the Humboldt-Universität zu Berlin in 2018 for his work on the optical frequency references based on ro-vibronic transitions in molecular iodine.



**Markus Oswald** is doing his Ph.D. on iodine frequency references for space at the University of Bremen. After his master’s degree from the HTWG Konstanz – University of Applied Sciences, in 2014, he worked on an FPGA-based digital laser locking system. Within the scope of his Ph.D. program, he has contributed to the development and realization of various iodine frequency reference setups for DLR and ZARM.



**Ahmad Bawamia** received a bachelor’s degree in mathematics and physics at Université Bordeaux I in Bordeaux, France in 2001 and his master’s in optoelectronics engineering at école nationale supérieure des sciences appliquées et de technologie in Lannion, France in 2004. He then joined the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) in Berlin, Germany in 2005, working on the improvement of the spatial beam characteristics of broad-area semiconductor lasers.



**Jan Wüst** joined the German Aerospace Center (DLR), Institute of Space Systems (Bremen) in 2019. He received his master’s degree from the HTWG Konstanz – University of Applied Sciences. The thesis was about residual amplitude modulation in modulation transfer spectroscopy for frequency stabilized laser systems. Within the ADVANTAGE project, he is responsible for the mechanical and thermal design of the iodine spectroscopy subsystem.

He obtained his doctoral degree at the technical university of Berlin in 2011. Since 2010, Ahmad is a full-time scientist at FBH, where he specialized in the development of micro-integrated semiconductor laser modules for precision spectroscopy applications, especially in space.



**Andreas Wicht** heads the Joint Lab Quantum Photonic Components at FBH. He is an expert in the development of micro-integrated diode laser modules for applications that require stable lasers, including quantum optics with ultra-cold atoms. After receiving his Ph.D. from the University of Hannover, he joined Stanford University as a postdoc in 1999 to work on precision atom interferometers. Between 2002 and 2008 he was affiliated with the Universität of Düsseldorf as an assistant professor.

In 2008 he joined the FBH to establish the Joint Lab Quantum Photonic Components, a Joint Lab between the FBH and the Humboldt-Universität zu Berlin.



**Matthias Lezius** is group leader and senior scientist for “Space Combs” at Menlo Systems GmbH in Martinsried. He received his Ph.D. at the Innsbruck University in Austria for laser-interaction with rare-gas clusters. Since 2010 he has managed various DLR and ESA funded projects advancing the technology readiness, robustness and compactness of optical frequency combs. These combs have subsequently been used for scientific experiments on TEXUS sounding rockets.



**Kai Voss** is the head of optical instruments group at SpaceTech GmbH (STI). He received his Ph.D. in physics in 2004 and is working on laser-optical systems for space since 2011. He has been the system engineer at STI for the Laser ranging interferometer on GRACE FO, has led several technology studies and hardware projects.



**Markus Krutzik** is head of the Joint Lab Integrated Quantum Sensors (IQS) operated by Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) and the Humboldt-Universität zu Berlin. R&D activities focus on the development of integrated atomic systems for frequency metrology, timing and field sensing applications. He got his Ph.D. in 2014 (HU Berlin), worked at the University of California, Berkeley, and NASA Jet Propulsion Laboratory,

Pasadena.



**Sven Herrmann** is a research scientist at the Center of Applied Space Technology and Microgravity at the University of Bremen. He received his Ph.D. from the Humboldt-Universität zu Berlin for his work on optical cavity-based frequency references for tests of fundamental physics. He has since contributed to several DLR and ESA funded activities in the field of fundamental physics, quantum sensing and cold atoms.



**Evgeny Kovalchuk** is a research scientist at the Humboldt-Universität zu Berlin, where he received his Ph.D. for his work on optical parametric oscillators for precision IR spectroscopy and metrology. His main research interests are laser stabilization, femtosecond combs, optical clock development, precision measurements, optical frequency metrology and phase noise measurements.



**Achim Peters** is professor for Optical Metrology at the physics department of the Humboldt-Universität zu Berlin. Since 2008 he is also affiliated with the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) and the Joint Lab Quantum Photonic Components. He obtained his Ph.D. in physics at Stanford University in 1998 and has since then worked on many projects pursuing a variety of precision measurements as well as advancing the related technologies.



**Claus Braxmaier** is chair of Space Technology, University of Bremen, in cooperation with DLR. Braxmaier is head of the DLR-department “System Enabling Technologies” in Bremen. He received a Ph.D. from the University of Konstanz and has been working on many ESA and DLR funded projects in space sciences, gravity missions, cold atom optics, quantum metrology, frequency references and laser interferometry.