OPTICAL IODINE CLOCKS FOR FUTURE GNSS

Jan Wüst(1,2), Markus Oswald(1), Martin Gohlke(1), Frederik Kuschewski(1), Tasmim Alam(1), Tim Blomberg(1), André Bußmeier(1), Jonas Pollex(1), Niklas Röder(1), Markus Weller(2,4), Ludwig Blümel(3), Thomas Zechel(3), Martin Rixius(4), Benjamin Samson(4), David Fehrenbacher(4), Kai Voss(4), Thilo Schuldt(1), Claus Braxmaier(1,2)

Email: jan.wuest@dlr.de
(1) German Aerospace Center, Institute of Quantum Technologies, Wilhelm-Runge-Str. 10, 89081 Ulm, Germany,
(2) Ulm University, Institute of Microelectronics, Albert-Einstein-Allee 43, 89081 Ulm, Germany
(3) German Aerospace Center, Institute of Communications and Navigation,
Münchener Str. 20, 82234 Weßling, Germany
(4) SpaceTech GmbH, Seelbachstraße 13, 88090 Immenstaad, Germany

ABSTRACT

The clock technology in Global Navigation Satellite Systems is one major driver of the achievable position accuracy. While high performance terrestrial optical lattice clocks outperform current microwave clocks deployed on satellites, they are not feasible for space applications due to their size, weight and power budget. Meanwhile clocks based on Doppler-free spectroscopy of optical transitions are promising candidates for next generation space clocks in the near future.

The COMPASSO mission by the German Aerospace Center (DLR) will demonstrate optical key technologies including an optical clock and a laser communication and ranging terminal on the International Space Station. Especially it features two independent optical frequency references based on the spectroscopy of molecular iodine and an optical frequency comb for the transfer from the optical domain to the radio frequency domain.

In addition, the next iteration of the iodine clock with SpaceTech GmbH aims at the full space qualification of an optical clock meeting the stringent requirements of GNSS.

1. INTRODUCTION

While the capability of Global Navigation Satellite Systems (GNSS) geolocation can be improved with improved orbit determination and the modeling of atmospheric effects, it is also inherently linked to the deployed clock technology. With the current and mature atomic clocks based on microwave technology deployed on the Galileo satellites, the Rubidium Atomic Frequency Standard (RAFS) and the Passive Hydrogen Maser (PHM) [1, 2], instabilities at the level of 10^{-12} at 1 s integration time and 10^{-14} at 1000 s have been achieved. In terrestrial systems, optical clock technology outperforms these state-of-the-art atomic space clocks by several orders of magnitude. Very high frequency stability is achievable with ion and lattice clocks in controlled laboratory settings. They can reach frequency instabilities in the 10^{-18} level at the 10.000 s timescale, see e.g. [3, 4], but require complex systems, with significant size, weight and power (SWaP) demands.

Consequently, the development of optical technologies for space clocks ensures the reliability of GNSS in the medium and long term. The European Space Agency (ESA) is therefore promoting the evolution of alternative clock technologies [5]. Promising approaches with respect to power consumption, weight and technology-readiness-level (TRL) are clocks based on Doppler-free spectroscopy of optical transitions. Paired with an optical frequency comb, this technology is capable to back-up or replace current clocks for GNSS in the near future [6].

Over the past decade we demonstrated several iterations of iodine frequency references based on Modulation Transfer Spectroscopy (MTS). They range from laboratory setups towards compact integrated models and proofed their suitability in environmental tests and on a sounding rocket [7, 8, 9]. The highly stable optical frequency can be directly transferred with an optical frequency comb to the radio frequency (RF) domain, providing a highly stabilised RF oscillator. A next step for the optical clocks is the COMPASSO mission by the German Aerospace Center (DLR), which shall demonstrate the necessary technologies on the International Space Station (ISS) [10]. Furthermore, a next iteration of the optical clock for space is developed with industry partners SpaceTech GmbH (STI) and Menlo Systems GmbH and the Ferdinand Braun Institute Berlin (FBH).

2. OPTICAL FREQUENCY REFERENCES

Two fundamental techniques for optical frequency references are ultra-stable cavity stabilised laser systems and the stabilisation on an atomic or molecular transition. Cavities provide a very good short-term performance up to the minute-timescale but are susceptible to temperature drifts. For high long-term stability and an absolute frequency reference, the stabilisation on an atomic reference can be utilised. Molecular iodine is considered to be a good candidate for an optical frequency reference due to its wide range of long-term stable optical resonances down to 500 nm [11]. The transition is insensitive to environmental influences such as electric and magnetic fields. A general advantage of a reference to an optical transition, like in this iodine reference, is the higher quality factor of the resonance (Q-factor) in comparison to the microwave clocks. The absolute frequency of an iodine clock at 562 THz with a resulting linewidth of less than 1 MHz, result in a Q-factor that is orders of magnitude higher and results in an inherently better stability. Optical technology at 1064 nm is established in space and the second harmonic at 532 nm fits well to many strong absorption hyperfine structures in molecular iodine.

To probe the iodine, a gas cell with optical windows is used. The velocity of the molecules in the gas cell is Maxwell–Boltzmann distributed. Due to the Doppler-effect the natural linewidth (about 300 kHz at the chosen transition R(56)32-0 at 532 nm) is broadened by hundreds of MHz. With Doppler-free saturation spectroscopy the broadening can be circumvented. Saturation Absorption Spectroscopy methods utilise two collinear counter-propagating beams in the gas cell and allow to probe the hyperfine transitions of a rovibronic state of the iodine molecules. The Modulation Transfer Spectroscopy (MTS) adds modulation of the pump beam to shift the detection to the modulation frequency in order to reduce background noise, and the resulting signal gives a steep zero-crossing at the resonance suitable for feedback locking. The detected hyperfine transition is fed into a feedback loop which controls the laser frequency. As soon as the laser is locked to the transition, the iodine reference outputs a stable optical frequency. To generate a suitable clock signal, an optical frequency comb is locked to the MTS setup, which transfers the optical frequency into the RF domain.

Fig. 1 shows the Allan Deviation of the current Galileo clocks in comparison to the optical frequency references developed at DLR. The RAFS and the PHM show instabilities of $>10^{-12}$ for integration times of 1 s and reach in the 10^{-14} range for integration times of 1000 s. The DLR optical cavity has a very good short-term instability of $<10^{-15}$ on the minute timescale but starts to drift due to thermal influences.

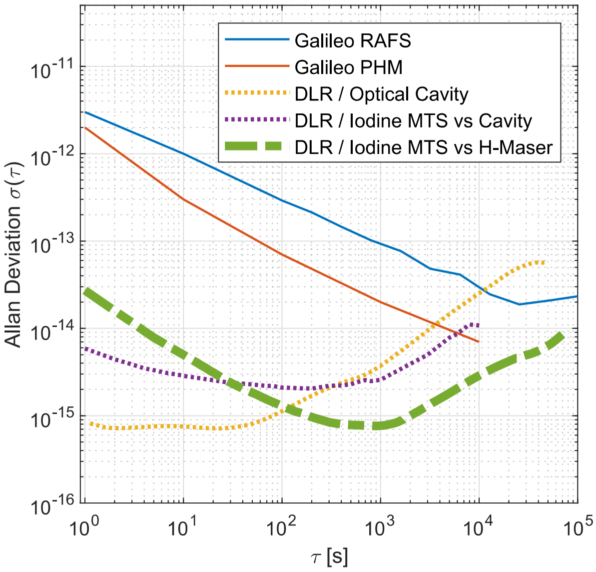

Figure 1. Comparison of current GNSS microwave clocks with optical clock technologies from DLR QT. The currently on Galileo deployed microwave clocks (solid lines) reach from $>10^{-12}$ at 1 s integration time to $>10^{-14}$ at 1000 s integration time. The DLR optical frequency references (dashed lines) have instabilities in the low 10^{-15} range.

In the DLR Institute of Quantum Technologies (DLR-QT), we have developed several iterations of iodine frequency references over the past decade. Together with the University Bremen (Center of Applied Space Technology and Microgravity, ZARM), the Humboldt University Berlin and the space company Airbus Defence & Space (Friedrichshafen), we built multiple compact iodine-based frequency references at different development stages.

With the Elegant Breadboard Model (EBB) new assembly and integration techniques were implemented to achieve a rigid optical bench [7]. It is based on a glass-ceramic baseplate with a very low coefficient of thermal expansion and adhesive bonded optical components using a space-qualified two component epoxy. This ensures high pointing stability of the two laser beams in the iodine cell and increases the long-term frequency stability. Fig. 2 (left) shows a photograph of

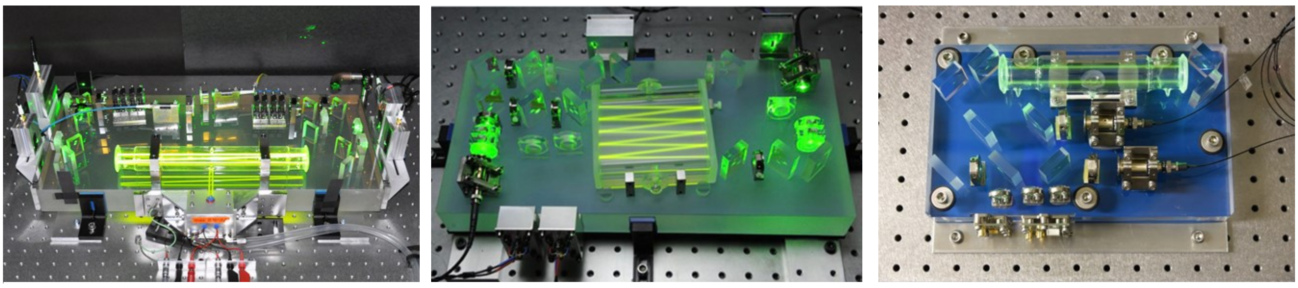

Figure 2. Photographs of realised iodine spectroscopy units at DLR QT
left: Elegant Breadboard Model (EBB) [7], center: Engineering Model (EM) [8], right: JOKARUS flight model [12]

the EBB spectroscopy. A frequency instability of $6 \cdot 10^{-15}$ at 1 s integration time, a flicker floor below $3 \cdot 10^{-15}$ for integration times between 100 s and 1.000 s and long-term instability at the 10^{-15} level for integration times up to 70.000 s have been demonstrated with the EBB and is shown in Fig. 1.

The Engineering Model (EM) is half the size of the EBB and introduced an alternative square cell design with a 9-pass configuration with roughly the same interaction length as in the EBB setup [8]. In contrast to the EBB gas cell, the EM cell was filled with an unsaturated vapor pressure, which eliminates the need for an active cooling of the cell to achieve the appropriate pressure. This reduction in complexity is a crucial advancement towards space applications and showed very similar frequency stabilities in comparison with a cell using a cooling finger to control the vapor pressure. The EM was subjected to environmental tests to validate its performance in expected operational environments. This included a thermal cycling test under vacuum conditions from -20 °C to +60 °C, vibrational loads up to 30 g and random vibration up to 25.1 g_{rms}. Further analysis has shown no frequency stability degradation and no absolute frequency shift after the vibration tests. Fig. 2 (center) shows a photograph of the EM spectroscopy.

A simplified compact design of the iodine spectroscopy was developed for the JOKARUS Mission. It was launched on a sounding rocket in 2018 and demonstrated the first iodine-based optical frequency reference in space [9, 12]. The EBB and EM previously used solid-state Nd:YAG lasers due to their inherently low frequency noise. With JOKARUS a micro-integrated extended cavity diode laser (ECDL), which was developed by the Ferdinand-Braun-Institut Berlin (FBH) [13, 14], was implemented. The compact but powerful laser module is an important improvement towards optical frequency references in space. The free-space optics for laser manipulation and distribution, which was used in the EBB and EM, was exchanged with polarisation maintaining fiber optics due to their smaller size and weight. Fig. 2 (right) shows a photograph of the JOKARUS spectroscopy unit.

3. THE COMPASSO MISSION

The COMPASSO mission is an in-orbit-verification of quantum-optical key technologies with focus on future GNSS. The DLR-funded mission shall demonstrate and evaluate the performance of the optical frequency references in low Earth orbit on the ISS [10]. The payload will be mounted on the BARTOLOMEO platform operated by Airbus outside of the European COLUMBUS module [15]. The COMPASSO space segment features two independent iodine frequency references to perform an optical beat measurement. With an optical frequency comb, the stabilised optical frequency is transferred to the RF domain. Additionally, it features a bi-directional laser communication and ranging terminal (LCRT) to establish a link between the COMPASSO space and ground segments to demonstrate optical time and frequency transfer. Furthermore, the link enables a test of general relativity by measuring the gravitational red shift. The COMPASSO mission is led by the Galileo Competence Center of the DLR working in close collaboration with other DLR Institutes and industry partners. The project began in early 2021 and is currently in the development phase, with flight payload delivery scheduled for 2026, a launch in 2027 and a planned operational deployment of two years. After the operational phase the payload will be returned to Earth for further analysis.

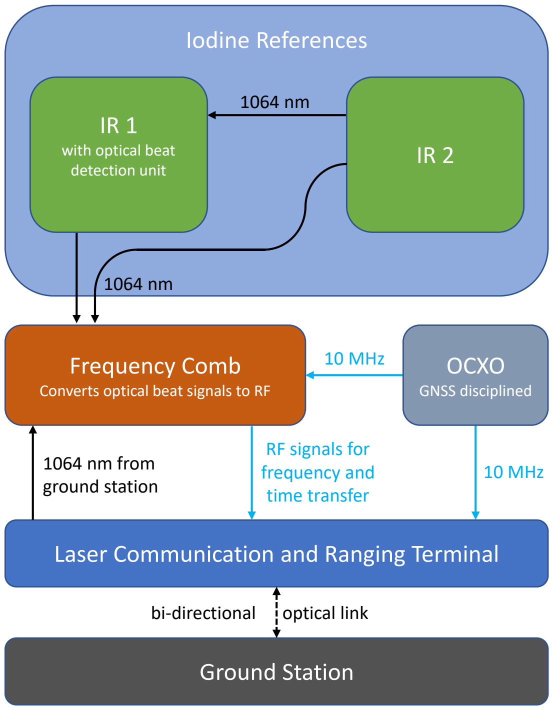

Figure 3. Block diagram of the COMPASSO architecture [10]. The two iodine references (IR 1 and IR 2) can be compared to each other with the included beat detection unit. With the frequency comb the optical frequency can be transferred to the RF domain and compared to an GNSS disciplined OCXO or stabilised laser which is transferred with a bi-directional optical link between the LCRT and the ground station.

The block diagram in Fig. 3 shows the key systems of the COMPASSO payload. The two iodine references (IR 1 and IR 2) are almost identical, except that IR 1 also includes an optical beat detection unit with a frequency counter to measure the performance in the optical domain. Both IRs have a 1064 nm fiber connection to the frequency comb (FC), developed by Menlo Systems GmbH, which can be locked to one of them to convert the optical frequency into the RF domain. Each

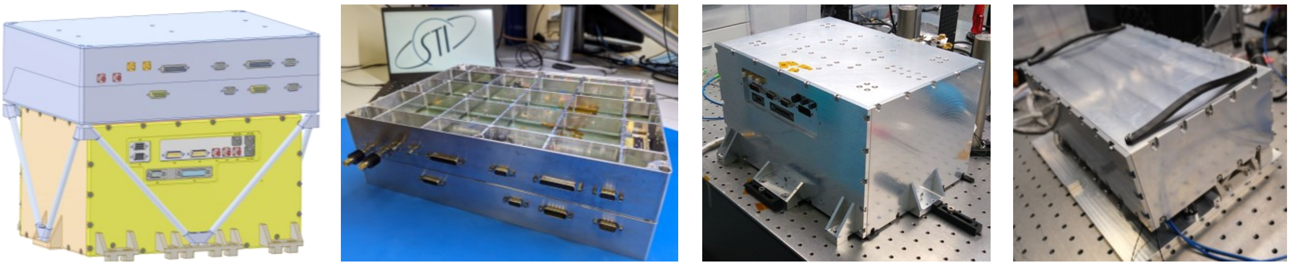

Figure 4. Photographs and CAD model of the COMPASSO iodine reference from DLR QT and STI left: CAD model of the iodine reference, center left: Photograph of the iodine control electronics, center right: Photograph of the iodine spectroscopy unit, right: Photograph of the active thermal shield inside the ISU

IR forms an optical clock with the frequency comb. The performance can also be verified by comparing the clock signal to a GNSS disciplined oven-controlled crystal oscillator (OCXO) or a stable optical frequency from an iodine reference as part of the ground segment on Earth via the LCRT, which is provided by Tesat-Spacecom GmbH with added ranging functionality developed by the DLR Institute for Communication and Navigation (DLR-KN). It establishes a bi-directional optical link between the ground station (Oberpfaffenhofen, Germany) and the COMPASSO space segment on the ISS.

Each COMPASSO IR is based on the previous developments and tailored to the requirements of the space mission. The reference consists of the iodine spectroscopy unit (ISU) developed by DLR-QT and the iodine control electronics (ICE) developed by SpaceTech GmbH. Each of the units is integrated in their own housing, is connected with an external harness and thermally decoupled from each other. Fig. 4 (left) shows a CAD model of the IR with the ISU on the bottom and the ICE mounted on a frame on top of the ISU. A photograph of the ICE is also shown in Fig. 4. (center left). The lightweight aluminium housing of the ICE contains two connected printed circuit boards with a fast field programmable gate array (FPGA) and a micro-controller. Fig. 4 (center right) shows the ISU, which contains the laser board, the spectroscopy board (Fig. 6) inside of an active thermal shield (Fig. 4 right) and in case of IR 1 the beat detection unit.

A schematic overview of the IR is shown in Fig. 5. The ECDL delivers 500 mW of 1064 nm light and the following isolator protects the laser from harmful back reflections. A fiber splitter unit divides the beam into pump and probe beam for MTS detection and distributes a small portion of the light to the frequency comb and the beat detection unit. With a first order acousto-optic modulator (AOM), the pump beam is shifted by 140 MHz and stabilised in intensity while the electro-optic modulator (EOM) takes care of the frequency modulation, which is needed for MTS. A zero order AOM is used for the intensity stabilisation of the probe beam. The 1064 nm light is then frequency doubled to 532 nm with one second harmonic generator (SHG)

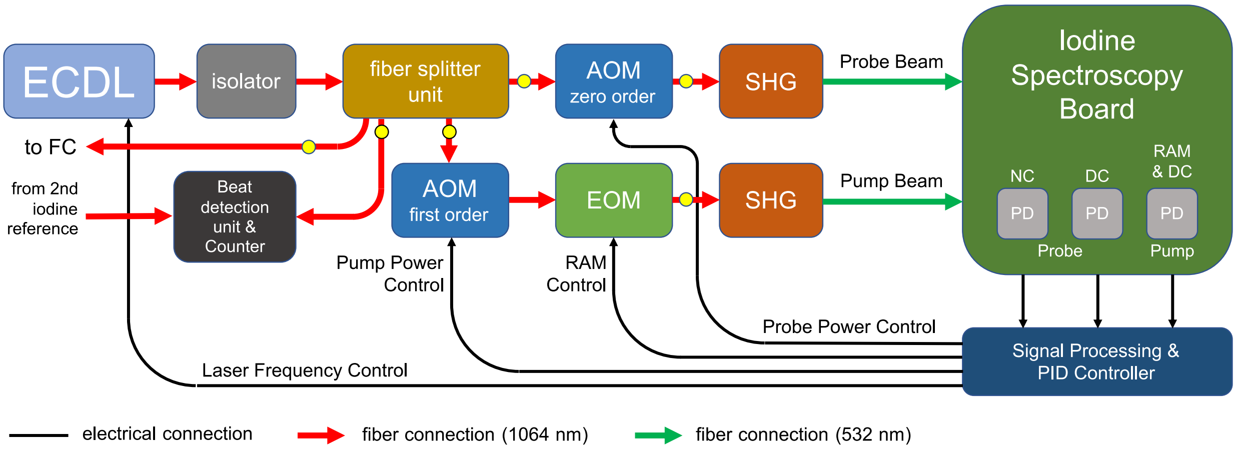

Figure 5. Block Diagram of the Iodine Spectroscopy Unit [10]. The ECDL emits 1064 nm light which is passed through an optical isolator to prevent back reflections. The fiber splitter unit distributes the fiber coupled laser beams to the pump and probe branch, the frequency comb and the beat detection unit. With AOMs, the intensity of the pump and probe beam is stabilised. The EOM modulates the frequency of the pump beam. The SHG modules convert the 1064 nm light to 532 nm by frequency doubling. On the Iodine Spectroscopy Board, the beams pass the iodine cell for the MTS detection. Three detectors are used as the input of the signal processing and PID control.

module per beam. On the spectroscopy board (see Fig. 6), the fiber coupled light is collimated and distributed as a free beam on the optical bench. The 20 cm iodine cell is passed four times, resulting in 80 cm interaction length. Three detectors deliver the electronic input signals for the signal processing and PID-control in the ICE. A noise cancelling detector (NC) captures the probe beam before and after the cell and is the main MTS detector. The probe intensity detector (DC) gives feedback for the probe intensity stabilisation while the pump intensity and residual amplitude modulation detector (RAM & DC) is used for the stabilisation of the pump beam. RAM is another critical disruptive effect which is causing an additional unwanted amplitude modulation on the frequency modulated beam with the same modulation frequency when using an EOM or AOM. This results in a vertical offset in the error signal and causes a frequency shift, which lowers the frequency stability of the reference. The yellow dots in Fig. 5 mark the position of inline photodiodes, that can be used to monitor the intensity of the light between the fiber components for power level monitoring.

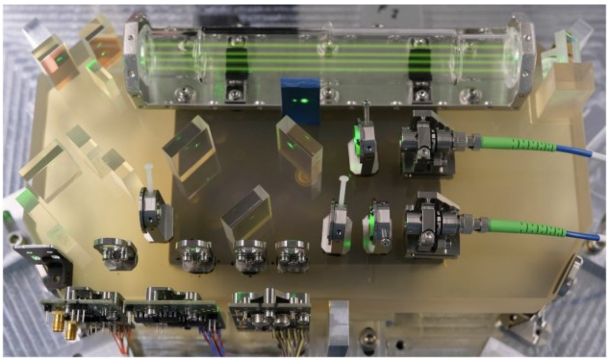

Figure 6. Photograph of the COMPASSO iodine reference spectroscopy board from DLR QT [10]

The iodine reference has a size of 34 l, weighs 27 kg and consumes up to 51 W of power. Together with the frequency comb the SWaP is 46 l, 32 kg and 120 W.

The COMPASSO Engineering Model of the IR is currently integrated and will be finalised in 2024. It represents the form, fit and function of the final flight model. Next, a structural thermal model (STM) is built to test the environmental influences such as thermal cycling and mechanical loads. Some components will be exchanged with mass dummies and the qualification of those parts will be done on component level by the respective manufacturer.

4. IODINE CLOCKS FOR FUTURE GNSS

While COMPASSO is paving the way for optical clock technologies in space, a further step is already taken towards applications in future GNSS. Together with SpaceTech GmbH, DLR-QT is developing an optical iodine clock meeting the stringent requirements for operation on GNSS satellites. This covers all aspects including lifetime of reliability in orbit, performance and SWaP.

The system is significantly smaller and features a compact and integrated spectroscopy unit with a shorter gas cell. An optimized laser and modulation unit with fewer components is realised by a new compact scheme while keeping the same functionality. A breadboard model was developed and is currently tested. Following this, an engineering model will demonstrate the performance. The goal is to develop a reliable clock suitable for a 15-year medium Earth orbit (MEO) mission with a SWaP budget comparable to the PHM from the current Galileo generation.

5. SUMMARY AND OUTLOOK

Optical iodine clocks are promising candidates to backup or replace current microwave clocks for GNSS in the near future. We demonstrated frequency instabilities in the 10^{-15} range up to 70.000 s integration time and built several iterations of iodine references ranging from breadboard to engineering model state and a successful mission on a sounding rocket.

The COMPASSO mission is the next step in advancing optical iodine clock technology for space and is set to operate for two years aboard the International Space Station. The mission will demonstrate optical key technologies including optical clocks and a laser communication and ranging terminal. The iodine reference engineering model shall be finalized by end of 2024. Meanwhile the next iteration of a compact iodine clock is in development with SpaceTech GmbH, targeting to meet the stringent requirements of GNSS satellites, including long-term reliability, performance stability and a SWaP budget suitable for missions in MEO.

While iodine frequency stabilisation at 532 nm is well established, promising hyperfine transitions at 508 nm offer potential for even higher frequency stability due to a lower natural linewidth. Therefore, these transitions are currently being investigated.

The optical frequency reference hold potential for other advanced scientific applications like the gravitational wave detector LISA (Laser Interferometer Space Antenna) or earth gravity missions like NGGM (Next Generation Gravity Mission).

6. ACKNOWLEDGEMENTS

We acknowledge the funding of the COMPASSO mission by the German Aerospace Center. We are thankful for the coordination of the project by the Galileo Competence Center and appreciate cooperation with industry partners within the project. We would like to express our gratitude toward every team member of the COMPASSO project and the excellent work which is put into the project.

We appreciate support 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 Climate Action (BMWK) under grant numbers 50OO1602 (BOOST), 50NA1905 (Optical Clocks for Galileo 2nd Generation, OG2G) and 50WM2260 (µCOMBINE). The work is also supported by the Federal Ministry of Education and Research (BMBF) in the future cluster QSENS (project 03ZU1110JA QSPACE) which is highly appreciated.

The iodine reference has been investigated within the "Iodine Optical Clock (IOC)" project funded by the EU Horizon 2020 program (prime SpaceTech GmbH, Immenstaad, Germany).

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