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In-Orbit Verification of an Optical Frequency Reference on the ISS Bartolomeo Platform

Thilo Schuldt*[a], Klaus Abich[a], Tasmim Alam[a], Jonas Bischof[a], Tim Blomberg[a], Ludwig Blümel[b],
Alex Boac[a], Andre Bußmeier[a], Martin Gohlke[c], Frederik Kuschewski[a], Markus Oswald[a], Jan Wüst[a,j],
Thomas Zechel[b], Xavier Amigues[d], Andreas Eckardt[d], Winfried Halle[d], Bernd Zender[d],
Jan Hrabina[e], Jindrich Oulehla[e], Ahmad Bawamia[f], Klaus Döringshoff[f], Christian Kürbis[f],
Markus Krutzik[f], Andreas Wicht[f], Stefan Oschkera[g], Michael Jentsch[h], Salome Schweikle[h],
Christopher Speidel[h], Norbert Beller[i], Christian Dahl[i], Martin Großmann[i], Timo Liebherr[i],
Kai Voss[i], and Claus Braxmaier[a,j]
[a]German Aerospace Center (DLR), Institute of Quantum Technologies,
Wilhelm-Runge-Straße 10, Ulm, Germany;
[b]German Aerospace Center (DLR), Institute of Communications and Navigation,
Münchener Str. 20, 82234 Wessling, Germany;
[c]German Aerospace Center (DLR), Institute of Space Systems,
Robert-Hooke-Str. 7, 28359 Bremen, Germany;
[d]German Aerospace Center (DLR), Institute of Optical Sensor Systems,
Rutherfordstraße 2, 12489 Berlin, Germany;
[e]Institute of Scientific Instruments of the Czech Academy of Sciences,
Kralovopolska 147, 61264 Brno, Czech Republic;
[f]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik (FBH),
Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany;
[g]Syentec GmbH, Geitenedt 8, 4202 Kirchschlag bei Linz, Austria;
[h]Airbus Defence & Space GmbH, Claude-Dornier-Straße, 88090 Immenstaad, Germany;
[i]SpaceTech GmbH (STI), Seelbachstr. 13, 88090 Immenstaad, Germany;
[j]University of Ulm, Institute of Microelectronics, Albert-Einstein-Allee 43, 89081 Ulm, Germany;

ABSTRACT

Within the DLR project COMPASSO, optical clock and link technologies will be evaluated in space on the Bartolomeo platform attached to the Columbus module of the ISS. The system utilizes two iodine-based frequency references, a frequency comb, an optical laser communication and ranging terminal and a GNSS disciplined microwave reference. While COMPASSO is specifically dedicated to test optical technologies relevant for future satellite navigation (i.e. Galileo), the technologies are also crucial for future missions related to Earth observation and science.

The optical frequency reference is based on modulation transfer spectroscopy (MTS) of molecular iodine near a wavelength of 532 nm. An extended cavity diode laser (ECDL) at a wavelength of 1064 nm is used as light source, together with fiber-optical components for beam preparation and manipulation. The laser light is frequency-doubled and sent to a mechanically and thermally highly stable free-beam spectroscopy board which includes a 20 cm long iodine cell in four-pass configuration.

The iodine reference development is lead by the DLR-Institute of Quantum Technologies and includes further DLR institutes, space industry and research institutions. Phase B of the project will be finalized soon and an Engineering Model of the iodine reference, which represents the flight models in form, fit and function, will be realized by mid 2023. The launch of the COMPASSO payload is planned for 2025.

Keywords: optical frequency reference, optical clock, COMPASSO, satellite navigation, GNSS, modulation transfer spectroscopy

*thilo.schuldt@dlr.de; phone +49 (421) 24420-1038; www.dlr.de/qt/en

1. INTRODUCTION

Satellite navigation requires high-performance and reliable clocks. Current systems rely on microwave clock technologies, however, optical technologies have advanced over the last few decades, demonstrating frequency stabilities of 10^{-18} for integration times of a few thousand seconds [1][2]. They surpass microwave clocks' performance by several orders of magnitude. While ultimate frequency stability is shown using optical ion clock and lattice clock technologies in complex laboratory setups, optical frequency references based on Doppler-free spectroscopy of molecular iodine can be realized in space compatible compact and ruggedized setups in a relatively short time. Up to integration times of 10.000 s, these setups have demonstrated frequency instabilities comparable to the active hydrogen maser as currently integrated for the ACES (Atomic Clock Ensemble in Space) mission [3][4][5].

An iodine-based frequency reference – in combination with an optical frequency comb – is a possible clock candidate for future Global Navigation Satellite Systems (GNSSs), e.g. Galileo [6]. Iodine clocks could back-up or replace the currently used microwave clocks, with the potential to improve GNSS position determination due to their lower frequency instabilities. In combination with optical inter-satellite links, optical clocks enable new GNSS architectures, cf. e.g. the proposed Kepler architecture [7] which foresees synchronization of distant optical frequency references within the GNSS constellation using time and frequency transfer techniques.

Within the DLR mission COMPASSO, two iodine-based frequency references, together with a frequency comb and a laser communication and ranging terminal (LCRT) will be operated on the Bartolomeo platform, externally attached to the Columbus module of the ISS [8]. It will in orbit demonstrate the operation of optical technologies, which are relevant for future generations of Galileo. The idea of COMPASSO and the iodine references in particular are based on the developments at DLR within the department of Quantum Metrology at the DLR Institute of Quantum Technologies where several prototypes of iodine references using modulation transfer spectroscopy, also with respect to applications in space, have been realized in the past.

An overview on the COMPASSO overall architecture is shown in Figure 1. The single payload elements are mounted to the ArgUS multi-payload adapter which is provided by Airbus Defence & Space and interface to the Bartolomeo slot. Within the COMPASSO payload, the two iodine-based frequency references are 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 282 THz (corresponding to a wavelength of 1064 nm). The optical frequency comb can be referenced to either one of the two iodine references and transfers its frequency stability from the optical frequency range to the radio frequency range. Furthermore, the frequency comb can be referenced to the onboard microwave reference (i.e. a GNSS disciplined OCXO) and thus enables multiple comparison measurements with which the frequency stability in the relevant time period of the references can be evaluated. Employing the two-way optical laser communication and ranging terminal, the performance of the optical references onboard the ISS can additionally be compared to ground-based clocks. The optical link furthermore enables data communication and high-accuracy ranging.

The COMPASSO iodine reference is developed under lead of the DLR-Institute of Quantum Technologies (Ulm and Bremen) with the Institute of Scientific Instruments of the Czech Academy of Sciences (Brno, Czech Republic) as partner, responsible for the development of the iodine cell technology. Systems engineering and test support is provided by the DLR-Institute of Space Systems (Bremen), detector development by the DLR-Institute of Optical Sensor Systems (Berlin) and support for iodine reference operation as part of the system-level COMPASSO breadboard and development models by the DLR-Institute of Communications and Navigation (Oberpfaffenhofen). The iodine control electronics with corresponding software is developed by SpaceTech GmbH (Immenstaad), who is also in charge of overall product assurance. The Ferdinand-Braun-Institute Berlin is developing the ECDL laser sources and delivers general support on the iodine reference including performance analysis. The mechanical and thermal design is supported by Airbus DS (Immenstaad). The COMPASSO mission is lead by the DLR Galileo Competence Center (Oberpfaffenhofen).

The COMPASSO project foresees the realization of the following models on system level: Breadboard Model (BBM), Development Model (DM), and Proto Flight Model (PFM). For the COMPASSO iodine reference (as one of the COMPASSO subsystems), the following models are realized/under development/planned: Breadboard Model, Engineering Model (as part of the system-level DM), Structural Thermal Model (STM), and two Proto Flight Models. Qualification is executed on component level, parallel to the EM development. With an EM realization by mid 2023 and a PFM realization by end 2024, a launch in 2025 is targeted. The COMPASSO payload has a foreseen mission lifetime of 1.5 years and will return to ground for further investigations.

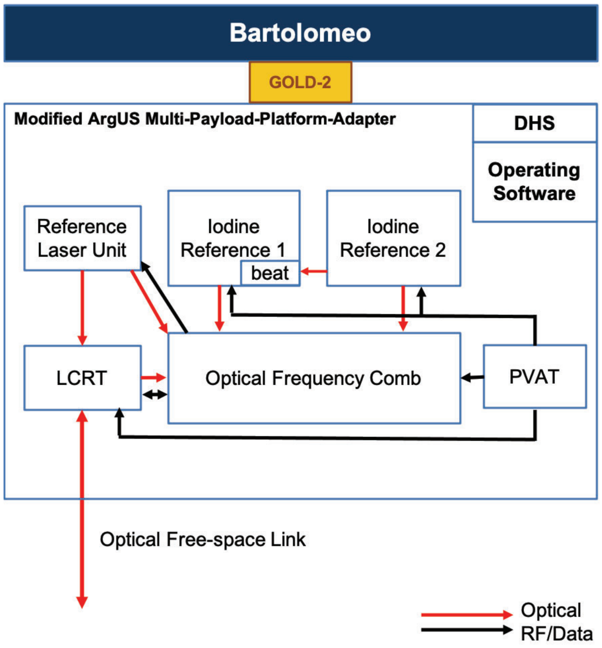

Figure 1. COMPASSO payload architecture (LCRT: Laser Communication and Ranging Terminal; DHS: Data Handling System; PVAT: Position, Velocity, Attitude and Time Subsystem).

2. IODINE-BASED FREQUENCY REFERENCES

Molecular iodine has strong absorption lines near a wavelength of 532 nm which can easily be accessed with a laser system at a wavelength of 1064 nm using second harmonic generation (SHG). Many realizations exist using modulation transfer spectroscopy (MTS) and frequency modulation spectroscopy (FMS) to resolve the hyperfine structure where state-of-the-art setups have achieved a frequency stability of $4{\cdot}10^{-15}$ at long integration times up to several 1000 seconds [9][3][4].

At the DLR-Institute of Quantum Technologies – in collaboration with the Humboldt-University Berlin (HUB) – several setups of iodine references have been developed with focus on space applications, see Figure 2. The EBB setup – using an NPRO (non-planar ring oscillator) Nd:YAG laser – shows the highest frequency stability and the best published results for an iodine-based frequency reference [3]. The so-called EM-setup was optimized with respect to size and mass, mainly by using a specifically designed iodine gas cell, and was subject to environmental testing [4]. The JOKARUS setup – using an ECDL by the Ferdinand-Braun Institut für Höchstfrequenztechnik (FBH, Berlin) as light source – was optimized with respect to the specific sounding rocket requirements and showed a lower performance due to its compact design (short iodine cell, no intensity and residual amplitude modulation (RAM) stabilization) [10][11]. Together with a frequency comb, it was successfully operated on a sounding rocket. Within the project ADVANTAGE (Advanced Technologies for Navigation and Geodesy) a next iteration of the iodine setup has been developed, based on the EBB-, EM- and JOKARUS developments. Here, the next step towards space instrumentation is carried out by a system design where all components for the laser system and the spectroscopy are integrated within one physical box together with a thermal shield around the spectroscopy board.

The performance of the EBB-, EM- and JOKARUS iodine references are shown in Figure 3. Also included are the current mission objectives as defined for the COMPASSO mission. The mission objectives distinguish between the iodine reference (IR) itself and the iodine clock (IC) which refers to the COMPASSO frequency comb, locked to one of the COMPASSO iodine references.

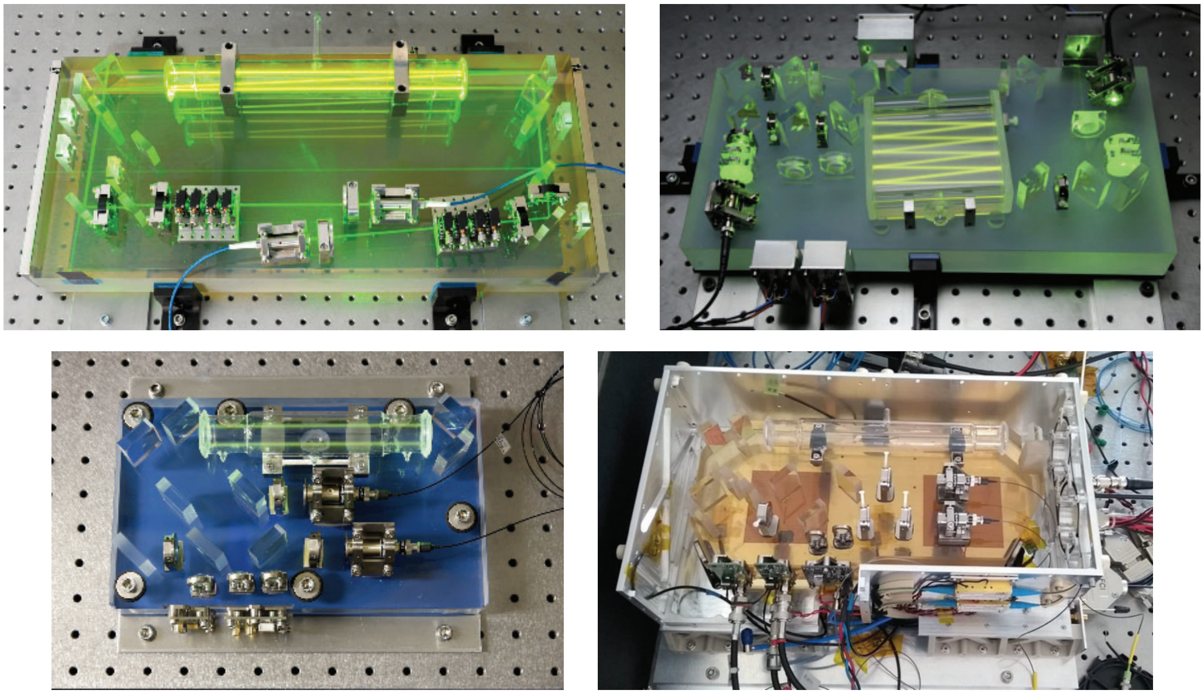

Figure 2. Several implementations of the iodine spectroscopy unit. Top left: Setup on Elegant Breadboard (EBB) Level [3]; Top right: Setup on Engineering Model (EM) Level [4]; Bottom left: Setup used on the sounding rocket mission JOKARUS [10][11]; Bottom right: Setup developed within the ADVANTAGE project with the spectroscopy board placed within a thermal shield where the fiber-optical components of the laser system are mounted to the bottom plate of the thermal shield.

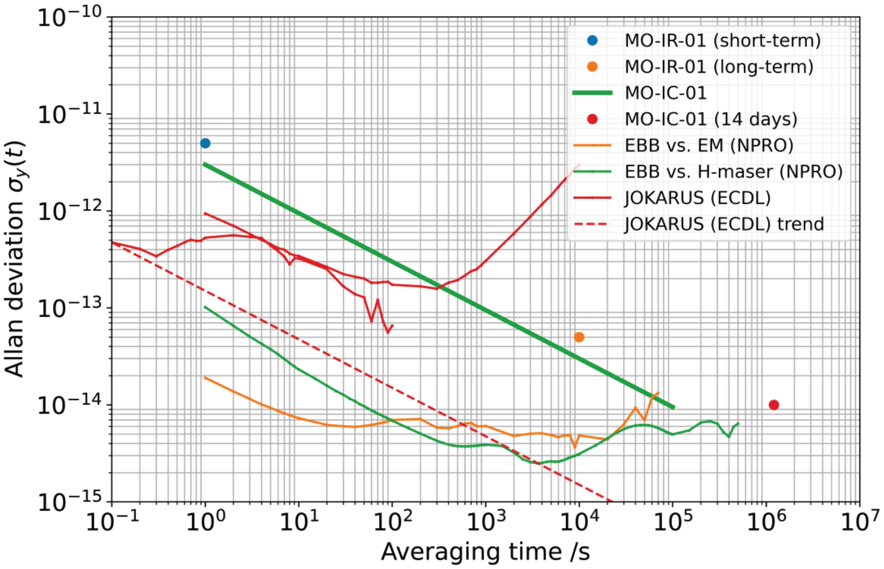

Figure 3. Frequency instability of previously developed iodine references at DLR/HUB, as detailed in the text, in comparison to the COMPASSO mission objectives (MOs, where IR is related to the iodine frequency reference and IC to the iodine frequency reference in combination with the COMPASSO frequency comb). EBB and EM setups use a non-planar ring-oscillator type Nd:YAG laser, JOKARUS uses an ECDL.

3. PRELIMINARY DESIGN OF THE COMPASSO IODINE REFERENCE

An overview on the COMPASSO iodine reference architecture is shown in Figure 4, reflecting its design and development status as of the Preliminary Design Review. The optical iodine reference consists of two sub-units, the iodine spectroscopy unit (ISU) and the iodine control electronics unit (ICE), cf. Figure 5. Both sub-units are integrated in two separate housings. The housing of the ISU has a mechanical interface to the ArgUS platform and the ICE. To separate the ICE mechanically and thermally from the ISU, it is held by a thin walled aluminum frame structure above the ISU. The housing of the ISU and ICE is made from aluminum alloy to provide both a lightweight and a good thermal conductivity structure. The electrical and optical interfaces are located on one side of the iodine reference where also the harness connecting the ICE and the ISU is placed. The opposite side of the iodine reference is used for thermal radiation and will provide the mechanical and thermal interface for an external radiator.

The ISU includes all (electro-)optical components required for Doppler-free spectroscopy of molecular iodine. An ECDL at a wavelength of 1064 nm is used as light source, cf. Figure 6 [12][13]. It is followed by an optical isolator and the output beam is split into pump and probe beams for spectroscopy. Acousto-optical modulators (AOMs) in both beams are used for generating a frequency offset between pump and probe beam and are actuators for individual intensity stabilization control loops of both beams. An electro-optical modulator (EOM) is used for phase modulation of the pump beam. Using SHG modules, the light is frequency doubled to a wavelength of 532 nm, which is input to a free-beam spectroscopy board. The laser and the components of the laser system (such as isolator, AOM, EOM, SHG) are all fiber-coupled and spliced. Tapped photo diodes are included for power monitoring.

The iodine spectroscopy is realized as free-beam optics integrated on a Zerodur baseplate (with a coefficient of thermal expansion coefficient of ~10^{-8} K^{-1}), using a space-qualified two-component epoxy. This ensures the mechanical and thermal stability of the setup needed for operation in space and ensures the pointing stability of the counterpropagating beams in the iodine gas cell. The layout of the spectroscopy board is shown in Figure 7, depicting the beam paths for pump and probe beams. The spectroscopy board includes a 20 cm long gas cell, filled at underpressure (~1 Pa) without the need of a cold finger with corresponding temperature stabilization. The iodine cell is operated in a four-pass configuration. Photodetectors for intensity and RAM stabilization as well as for the spectroscopy signal are mounted to the side of the spectroscopy board. The spectroscopy board is surrounded by an actively controlled thermal shield with ±0.1°C temperature stability.

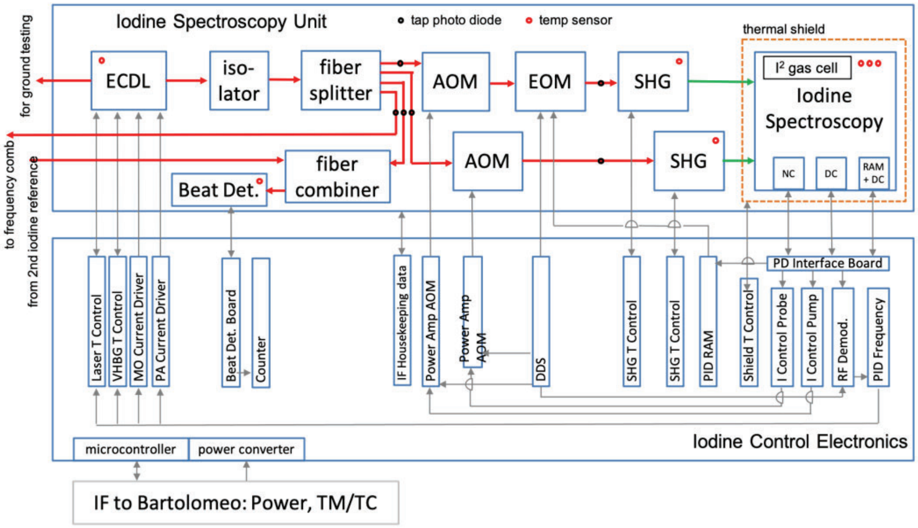

Figure 4. Overview of the Iodine Reference (IR1). It consists of two sub-units, the Iodine Spectroscopy Unit (ISU, top) and the Iodine Control Electronic (ICE, bottom). The minor difference between IR1 and IR2 is the beat detection unit which is only included in IR1.

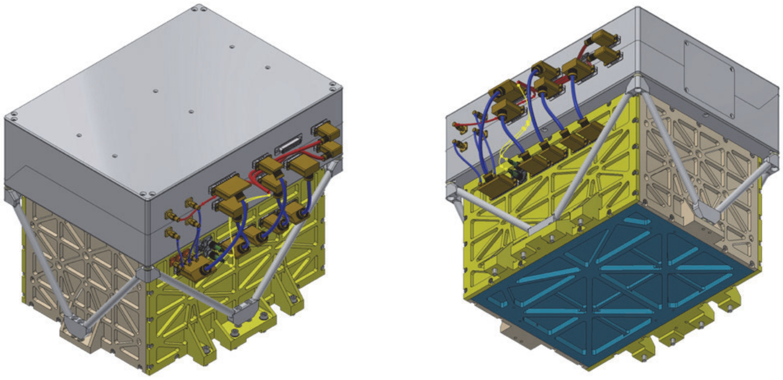

Figure 5. Preliminary CAD-Model of the COMPASSO iodine reference consisting of the ISU (bottom) and the ICE on a frame structure (top). The electrical and optical interfaces are located on the front side. The mounting flanges on the side walls (marked yellow) are the interface to the ArgUS platform and the ICE frame.

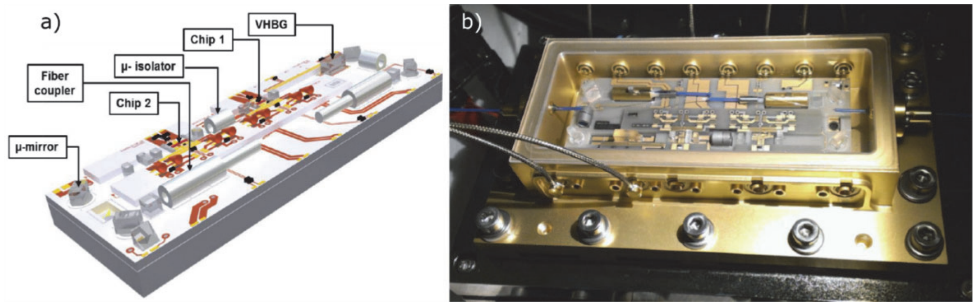

Figure 6. ECDL laser module, developed by the Ferdinand-Braun-Institute (Berlin), (a) CAD-Model of the micro-optical bench, (b) picture of a micro-integrated and packaged ECDL laser module. VHBG: Volume Holographic Bragg Grating. Figure adapted from [12].

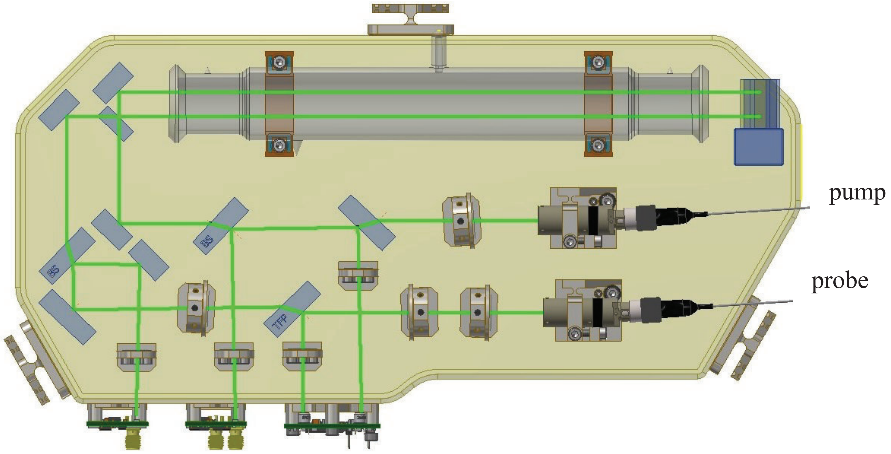

Figure 7. Layout of the COMPASSO spectroscopy board using a 20 cm long iodine gas cell in four-pass configuration. Pump and probe beams are fiber-coupled to the spectroscopy board. Photodetectors for intensity and RAM (residual amplitude modulation) stabilization and for the spectroscopy signal are mounted to the side of the spectroscopy board.

The ICE includes all functionalities for controlling and operating the iodine reference. This includes the control of all electro-optical components required to lock the ECDL to a dedicated iodine transition of choice as well as a complete set of housekeeping and diagnostic functions in order to operate the iodine reference according to its nominal performance. The ICE directly interfaces with the ArgUS On-Board Computer (OBC) in order to exchange TM/TC and mission data. Figure 8 illustrates the interplay between the main (physical) subunits of the ICE and the external (non-ICE) components of the iodine reference and the OBC.

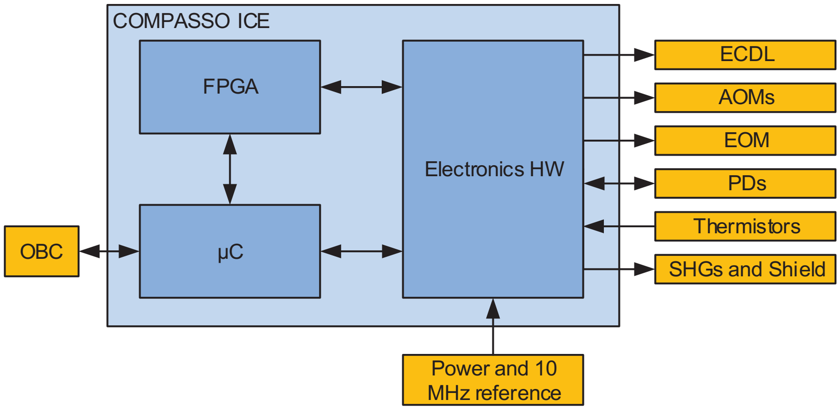

Figure 8. Schematic overview of the ICE physical implementation (FPGA: Field Programmable Gate Array; μC: microcontroller; PD: photo detector; HW: hardware).

The iodine reference (ISU together with ICE) has outer dimensions of 315 mm x 386 mm x 321 mm, a total mass of 26.7 kg (including 20% margin), and a typical power consumption of 50.6 W (maximum power consumption 76.7 W, both values including 20% margin).

ACKNOWLEDGEMENTS

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REFERENCES

[1] Bloom, B. J., Nicholson, T. L., Williams, J. R., Campbell, S. L., Bishof, M., Zhang, X., Blomley, S. L., Ye, J., “An optical lattice clock with accuracy and stability at the 10^{-18} level” Nature 506, pp. 71-75 (2014).
[2] Ushijima, I., Takamoto, M., Das, M., Ohkubo, T., Katori, H., "Cryogenic optical lattice clocks," Nature Photonics 9, pp. 185-189 (2015).
[3] Schuldt, T., Döringshoff, K., Kovalchuk, E., Keetman, A., Pahl, J., Peters, A., Braxmaier, C., “Development of a compact optical absolute frequency reference for space with 10^{-15} instability” Applied Optics 56, vol. 4, pp. 1101-1106 (2017).
[4] Döringshoff, K., Schuldt, T., Kovalchuk, E., Stühler, J., Braxmaier, C., Peters, A., “A flight-like absolute optical frequency reference based on iodine for laser systems at 1064 nm” Applied Physics B 123:183 (2017).

[5] Goujon, D., Rochat, P., Mosset, P., Boving, D., Perri, A., Rochat, J., Ramanan, N., Simonet, D., Vernez, X., Froidevaux, S., Perruchoud, G., "Development of the Space Active Hydrogen Maser for the ACES Mission" Proceedings of the 24th European Frequency and Time Forum, pp. 1-6 (2010).

[6] Schuldt, T., Gohlke, M., Oswald, M., Wüst, J., Blomberg, T., Döringshoff, K., Bawamia, A., Wicht, A., Lezius, M., Voss, K., Krutzik, M., Herrmann, S., Kovalchuk, E., Peters, A., Braxmaier, C., "Optical clock technologies for global navigation satellite systems" GPS Solutions **25**, 83 (2021).

[7] Giorgi, G., Schmidt, T.D., Trainotti, C., Mata-Calvo, R., Fuchs, C., Hoque, M.M. , Berdermann, J., Furthner, J., Günther, C., Schuldt, T., Sanjuan, J., Gohlke, M., Oswald, M., Braxmaier, C., Balidakis, K., Dick, G., Flechtner, F., Ge, M., Glaser, S., König, R., Michalak, G., Murböck, M., Semmling, M., Schuh, H., "Advanced Technologies for Satellite Navigation and Geodesy" Advances in Space Research 64, vol. 6, pp. 1256-1273 (2019).

[8] Steimle, C., Walz, C., Fuchs, C., Pedersen, D., Lombardi, C. M., "Bartolomeo external platform entering into commercial service" Proc. 70th International Aeronautics Conference (IAC), IAC-19-B3.3 (2019).

[9] Zang, E., Cao, J., Li, Y., Li, C., Deng, Y., Gao, C., "Realization of Four-Pass I2 Absorption Cell in 532-nm Optical Frequency Standard" IEEE Transactions on Instrumentation and Measurement 56(2), 673 (2007).

[10] Schkolnik, V., Döringshoff, K., Gutsch, F. B., Oswald, M., Schuldt, T., Braxmaier, C., Lezius, M., Holzwarth, R., Kürbis, C., Bawamia, A., Krutzik, M., Peters, A., "JOKARUS – design of a compact optical iodine frequency reference for a sounding rocket mission" EPJ Quantum Technology **4**, 9 (2017).

[11] Döringshoff, K., Gutsch, F., Schkolnik, V., Kürbis, C., Oswald, M., Pröbster, B., Kovalchuk, E., Bawamia, A., Smol, R., Schuldt, T., Lezius, M., Holzwarth, R., Wicht, A., Braxmaier, C., Krutzik, M., Peters, A., "Iodine Frequency Reference on a Sounding Rocket" Phys. Rev. Appl. 11, 054068 (2019).

[12] Wicht, A., Bawamia, A., Krüger, M., Kürbis, C., Schiemangk, M., Smol, R., et al., "Narrow linewidth diode laser modules for quantum optical sensor applications in the field and in space" In: Glebov AL, Leisher PO, editors. Components and Packaging for Laser Systems III. vol. 10085, p. 100850F (2017).

[13] Kürbis, C., Bawamia, A., Krüger, M., Smol, R., Peters, A., Wicht, A., Tränkle, G., "Extended cavity diode laser master-oscillator-power-amplifier for operation of an iodine frequency reference on a sounding rocket" Appl. Opt. 59, 253-262 (2020).