Characterization Setup of a Molecular Iodine Based Optical Clock

Long-term Optical Frequency Generation for Time and Frequency Transfer Experiments

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***Summary* — In this mansucript we present a setup and first results for long-term operation of an optical clock based on an existing Doppler-free iodine vapor cell spectroscopy unit [1] acting as an optical frequency reference system and an optical frequency comb. The combination of comb and optical frequency reference represents an ultra-stable radiofrequency source, as the comb is transferring the stability of the optical frequency reference to the radiofrequency regime. The radiofrequency is therefore generated directly from the pulse train of the optical frequency comb. The frequency comb is optically phase locked to the optical frequency reference based on molecular iodine, resulting in a full optical-to-radiofrequency chain. We will present the phase and amplitude noise performance of this radiofrequency source, i.e. an optical clock. The short-term stability in terms of Allan deviation is determined in an optical comparison measurement with a cavity stabilized laser system with a sub-Hz linewidth via the frequency comb. However, our main focus lies on the investigation of the long-term stability of the clock chain in the radiofrequency domain in comparison to the UTC realization of the German Aerospace Center (represented by the Galileo Competence Center) and the continuous operation of an optical clock.**

Keywords—optical clocks, ultrastable optical frequency source, optical frequency combs, stability transfer, radio frequency generation,

I. Introduction

Global Navigation Satellite Systems (GNSSs) became indispensable for numerous daily life applications. Beside enabling global navigation, GNS Systems also allow the distribution of a stable time scale used in various sectors such as aviation, ground and maritime traffic, surveying, synchronization of power grids and stock trading activities. One of the cornerstones of the system is the generation of a stable and robust reference frequency, which is then used for establishing the system time, to which all satellite clocks are referenced. State-of-the-Art frequency references and clocks such as (active or passive) hydrogen masers or cesium standards typically provide radiofrequency (RF) signals (5 MHz, 10MHz, 100MHz) and pulse-per-second trains (PPS) with a short-term fractional frequency stability in terms of Allan deviation in the order of $8 \cdot 10^{-14}$ s/s at 1 s integration time and a long-term stability (>1000 s) in the order of $1 \cdot 10^{-15}$ s/s. However, optical technologies for time and reference frequency generation are on a fast rise. Optical frequency references typically show a better performance in terms of frequency stability than their classical radiofrequency counterparts in both, short- and long-term measurements. Thus, they exhibit enormous potential to increase the performance of future GNSS [2], science missions and of general time generation. It is noted, that ultra-low noise optical frequency combs are required to transfer the optical frequency stability from optical frequency refence systems to the (easy countable) RF domain.

Our goal is investigating and characterizing the long-term operation for a time period of over six months of a robust optical clock chain which will function as part of the ground segment for the German Aerospace Center's COMPASSO mission aiming at in-orbit validation (on the international space station) of optical key technologies for future application in GNSS [1] [3]. The optical payload of COMPASSO consist of two optical frequency reference systems based on molecular iodine, one optical frequency comb and a laser communication and ranging terminal (LCRT). The mission goals are manifold and range from in-orbit optical clock characterization to precise time-transfer between ground and the ISS. Therefore, the optical frequency reference system serves the LCRT with an ultra-stable laser signal at 1064nm via the frequency comb, on which the transmission laser of the LCRT is subsequently stabilized. The optical clock, the combination of the iodine frequency reference and the optical frequency comb, provides the stable RF reference signal for the LCRT.

The here presented long-term characterization of the iodine frequency reference system is essential for the success of the COMPASSO mission as it is important for establishing the required ground segment capabilities as well as providing new insights which have impact on the flight model of the iodine frequency reference which is currently developed for space operation on the ISS.

II. METHODS/RESULTS

Our testbed for the COMPASSO mission consists of three parts, the optical clock itself (as a combination of an optical frequency reference based on molecular iodine, an ultra-low noise optical frequency comb and an optical-to-radiofrequency stability converter), a sub-Hz-linewidth cavity stabilized laser system and the UTC (Universal Time Coordinate) realization of the German Aerospace Center (DLR).

It is noted that UTC(DLR) is realized at DLR's Galileo Competence Center in Oberpfaffenhofen. It is based on two main components: a free-running active hydrogen maser (iMaser 3000 from T4science Neuchatel, Switzerland) and a phase and frequency offset generator (HROG-10 from Spectra Dynamics Inc., USA) which steers the maser signal towards UTC to realize UTC(DLR).

The sub-Hz-linewidth cavity stabilized laser system is a commercial ORS1500 system from Menlo Systems GmbH operating at a wavelength of 1564 nm. Here a laser source is locked to an eigenfrequency of a 7.5 cm high finesse ULN (Ultra-Low-Expansion) spacer-based cavity, using Pound-Drever-Hall techniques [4][5]. The fractional frequency stability of these optical references is typically around $1.5 \cdot 10^{-15}$ s/s at 1 s averaging time in terms of Allan deviation. Spectral purity transfer experiments [6] have shown, that the stability of an ultra-stable optical reference can be transferred via the frequency comb spectrum to other ultra-stable optical references for comparison measurements and the frequency comb is not degrading the stability transfer in the optical domain.

The optical clock itself consists of three parts: iodine frequency reference unit, optical frequency comb and optical-to-radiofrequency converter. The spectroscopy unit of the optical frequency reference is based on a Coherent Prometheus Nd:YAG laser with an NPRO (non-planar ring oscillator) design. The frequency doubled laser output at 532 nm is stabilized on a hyperfine transition frequency of molecular iodine captured in a vapor cell using Doppler-free modulation transfer spectroscopy methods [7]. In a recent evolutionary step in the iodine frequency reference setup, the original analog control electronics were replaced by digital FPGA based electronics to provide better long-term temperature stability and to increase robustness for the mentioned COMPASSO mission. The second part is a commercial optical frequency comb FC1500-250-ULN from Menlo Systems GmbH which is referenced to the continuous wave laser output of the iodine optical frequency reference system [8]. The third part is an FCP-250-10P optical-to-radiofrequency stability converter from Spectra Dynamics Inc., which generates radiofrequencies at 10 MHz and 100 MHz center frequency and a pulse-per-second signal. The FCP-250-10P optical-to-radiofrequency stability converter is referenced to the optical pulse train from the frequency comb [6]. The stability of an ultra-stable optical reference is transferred to the pulse train of the frequency comb and subsequently to a radiofrequency generation. The frequency stability of the converter is specified with $2.7 \cdot 10^{-14}$ s/s at 1 s averaging time in terms of Allan deviation. Our investigations show, that an extraordinary fractional frequency stability better than $1.0 \cdot 10^{-14}$ s/s at 1 s averaging time in terms of Allan deviation can be reached for the complete optical-to-radiofrequency stability converting chain.

Stability comparison measurements of the cavity stabilized laser ORS1500 and the stabilized laser signal originating from the iodine clock via the optical frequency comb are performed in the optical domain. The results are shown in Figure 1.

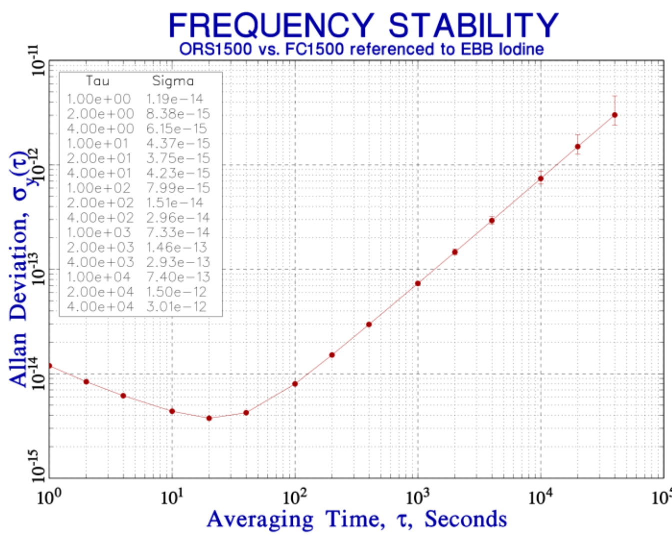

Fig 1: Frequency stability comparison of a Menlo Systems ORS1500 and the iodine optical frequency reference.

Additional stability comparison measurements of the iodine clock chain and UTC(DLR) are performed in the radiofrequency domain using the internal radiofrequency monitoring of the Menlo System optical frequency comb. The results are shown in Figure 2.

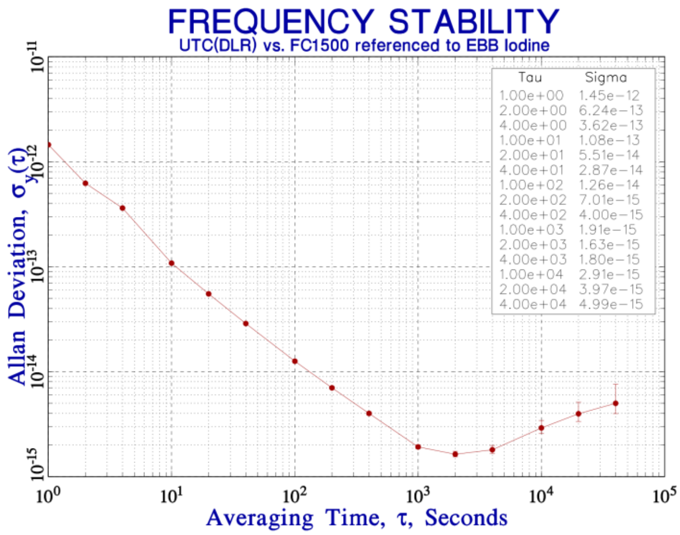

Fig 2: Frequency stability comparison of the iodine optical clock chain and UTC(DLR)

III. DISCUSSION

Figure 1 shows the Allan deviation of the optical beat between the cavity stabilized laser ORS1500 at about 190 THz and the frequency comb locked to the optical frequency reference based on the molecular iodine spectroscopy for a measurement over 300,000s.

For averaging times up to time 10 s the determined Allan deviation is limited by the stability of the iodine frequency reference performance as the optical cavity performance is superior in this time regime. The stability at 1 s is reaching $1.2\cdot10^{-14}$ s/s and is averaging down with $1/\sqrt{\tau}$. The drift of the cavity starts to dominate the Allen deviation measurement after about 20 s averaging time and thus no detailed information on the performance of the iodine frequency reference system can be gathered from this measurement for averaging times over ~50s. However, the measurement reveals that the performance of the iodine reference is clearly better than the performance of the cavity stabilized laser system for longer integration times.

Figure 2 shows the Allan deviation of the frequency comb locked to the optical iodine frequency reference and UTC(DLR) for the same time period. The measurement is performed in the radiofrequency domain (10MHz) to directly access the optical iodine clock performance compared to UTC(DLR). From 1s to 1,000 seconds averaging time the Allan deviation is dominated by the counter resolution of the Kamer and Klische FXE time and frequency interval counter in Pi mode. The stability at 2,000 s is given with $1.6\cdot10^{-15}$ s/s and at 40,000 s by $5.0\cdot10^{-15}$ s/s. Comparison measurements of UTC(DLR) and an active hydrogen maser MHM2020 from Microchip give a stability better than $2.0\cdot10^{-15}$ s/s in this averaging span. This indicates that the measurement results in this averaging time span is dominated by the iodine clock performance. This gives evidence, that the iodine clock performance is degrading for longer integration times which might be caused by thermal imbalances of the setup. However, the combination of both measurements indicates that the fractional frequency stability performance of the optical iodine reference (and most probably of the complete iodine clock chain) stays in the 10^{-15} regime for all evaluated averaging times between 1s and 300,000s.

It is noted, that a better short-term stability (factor 2) of the optical iodine frequency reference was reported earlier[7]. This can be explained by an insufficient bit resolution in our FPGA based control electronics. Nevertheless, the gain in thermal stability compensates the lower stability for short averaging times. Also, the FCP-250-10P optical-to-radiofrequency converter is limiting to clock chain to the stability level of 10^{-14} s/s for short integration times. From an averaging time of 20 s to 1,000 s we have a blind spot in our setup due to the cavity drift and the counter resolution. For longer averaging time we are in line with the results form [7].

IV. CONCLUSION

In conclusion, we demonstrate a full optical clock chain to the radiofrequency domain based on a molecular iodine optical clock. The FPGA based control electronics guaranties a high thermal stability. Our testbed accesses to the short-term performance of the clock via a comparison to a cavity stabilized laser system. The comparison to UTC(DLR) based on an active hydrogen maser gives us reliable access to the clock performance in the long-term. Our results are in line with previous results on published in [1] and [7]. All together our testbed gives the condition for further stability improvement of the optical clock chain.

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