Characterization of Short-Term Ultra-Stable Radio Frequency Sources Generated from Cavity Based Optical Reference Systems

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***Summary*— Optical frequency references have evolved during the past years, providing an optical continuous wave signal with a better stability than traditional radio frequency references such as atomic clocks by several orders of magnitude. However, as the optical frequency is hardly directly countable, what is needed to provide timing and clock signals, the current limitation of the application of the system is given by the optical-to-RF converter, which generates an RF-Signal (radiofrequency, e.g. 10MHz). Typically, this is achieved by an optical frequency comb locked to the optical reference. In this manuscript we fully characterize a complete optical-to-RF converting chain based on commercially available products, showing a fractional frequency stability (ADEV) better than $1x10^{-14}$ at one second integration time.**

Keywords*— *optical clocks; ultra-stable optical frequency source; frequency combs; stability transfer; radio frequency generation; optical-to-RF convertor

I. INTRODUCTION

Ultra-stable clock signals are indispensable for numerous scientific and civilian applications. This is e.g. also the case in Global Navigation Satellite Systems (GNSS), in which the stability of the clock, both onboard the satellite but also on ground generating the system time, directly impacts the accuracy of the positioning. The generated radio frequency (RF) signals (usually in the range 5-100 MHz) of ultra-stable clocks can be used for synchronizing many kinds of optical and electronical devices. Currently, hydrogen masers are still the most common frequency reference used as source of precise clock signals, typically showing a short-term stability in terms of Allan Deviation of $8x10^{-14}$ [s/s] after 1 second averaging time. The long-term stability (>1000s) is in the order of $1x10^{-15}$ [s/s]. A possible step towards more precise frequency reference systems, which can be deployed both on ground and in space, could be optical based systems. In this manuscript, we will show how using an ultra-low noise optical frequency comb, stabilized to an optical frequency reference, can lead to an improvement in the short-term stability of the generated 10 MHz signals by at least one order of magnitude compared to classical radiofrequency references such as hydrogen masers or cesium clocks.

Our motivation for the integration and characterization of our setup lies in providing ultra-stable optical and radiofrequency sources as well as time references for experiments e.g. in our labs and for outdoor two-way free-space optical frequency and time-transfer field experiments [1]. Future applications are e.g. clock ensembles based on optical frequency references as well as optical free-space time-transfer applications. Our long-term goal is the operation of a molecular iodine vapor cell spectroscopy based optical clock chain for the optical ground segment of the German Aerospace Center's mission COMPASSO [2]. COMPASSO is an in-orbit verification mission for optical key technologies for future GNSS application. The optical clock chain demonstrated in this paper shall be used as the optical frequency reference and time reference for an optical two-way frequency and time-transfer experiment between COMPASSO's ground segment and a space-based counterpart payload on the International Space Station (ISS).

II. METHODS/RESULTS

Our radiofrequency sources are built up as chains, consisting of three parts. First part is a commercial optical reference system ORS from Menlo Systems GmbH. Here a laser source is locked to a high finesse ULN (Ultra-Low-Expansion) spacer-based cavity, using Pound-Drever-Hall techniques [3] [4] [5]. The fractional frequency stability of these optical references is typically around $2.0x10^{-15}$ [s/s] at 1s averaging time in terms of Allan deviation (Pi counter mode). Second part is a commercial optical frequency comb FC1500-250-ULN from Menlo Systems GmbH which is referenced to one of the optical frequency reference systems [6]. Third part is a FC-250-10P converter from Spectra Dynamics Inc., which generates a 10 MHz and 100 MHz radiofrequency referenced to the optical pulse train from the frequency comb [7]. The fractional frequency stability of the converter is specified with $3.0x10^{-14}$ [s/s] at 1s averaging time in terms of Allan deviation, however as we will show later the device performs much better. Investigations on the generation of ultrastable radiofrequency signals via optical frequency division [8] and on spectral purity transfer [9] have shown, that the stability of an ultra-stable optical reference can be transferred via the comb spectrum to other ultra-stable optical references for comparison measurements, to the pulse train of the frequency comb and to a radiofrequency signal generation. In the latter case, the stability of the repetition rate of the optical pulses of the frequency comb locked on an external stable laser source are used to generate a radiofrequency signal with a corresponding stability.

Two different phase noise and frequency stability measurement devices has been used for characterizing our radiofrequency generation setup: a) the Microchip 5120A and b) the Microchip 53100A. Both devices have been connected to 10MHz signals from two independent optical-to-RF converter (FC-250-10P) seeded by the same frequency comb. Finally, the optical power at the input of the FC-250-10P has been successively changed in order to find the sweep spot (i.e. the best performance in terms of fractional frequency stability) of the device.

Measurements with 5120A

The 5120A is able measuring the fractional frequency stability (Allan Deviation, ADEV, $\sigma_y(\tau)$) simultaneously for several measurement bandwidths (tau_0=1s is equivalent to a noise equivalent bandwidth (BW) of 0.5Hz, tau_0=1ms is equivalent to 500Hz BW), as well as phase evolution and phase noise. This is a major advantage with respect to other devices, since it displays the impact of the measurement bandwidth to the ADEV statistics at once.

The optical power was tuned in both FC-250-10P until a minimum was reached in the $\sigma_y^{0.5Hz}(1s)$ (measurement BW 0.5Hz, see Figure 1). The search has been performed in a complete automated manner by using a self-made Python script. For the device shown in this section, this optimal optical input power corresponds to 1.35mW.

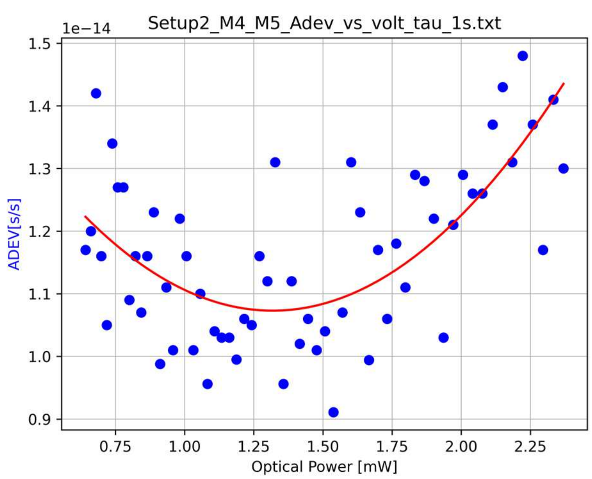

Fig. 1: Optimization of the fractional frequency stability as function of the optical power for one of the FC-250-10P. The data shown was measured with the 5120A using a measurement BW of 0.5Hz.

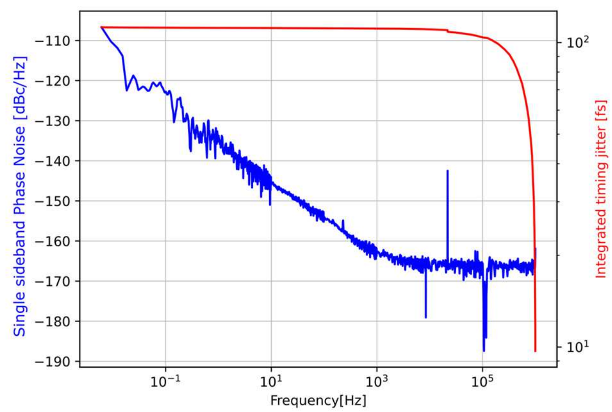

Fig. 2: Phase Noise and integrated timing jitter of the generated 10 MHz signal using optical power 1.35mW.

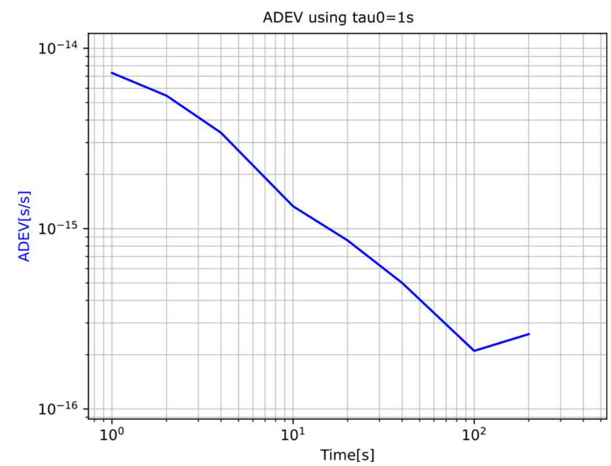

Fig. 3: Allan deviation of the generated 10MHz using a measurement BW of 0.5Hz and optical power 1.35 mW.

Figure 2 and 3 are showing the results of the phase noise and the Allan deviation, respectively, for the optimized optical power input (sweet spot). The phase noise shows a typical linear behavior for frequencies between 10^{-1} and 10^{3} Hz starting at a very good value of -120dBc/Hz at 10^{-1} Hz and hitting the noise floor (-165dBc/Hz) around 3 kHz. The corresponding integrated timing jitter [1Hz-1MHz] is 113 fs. The Allan deviation starts at an extraordinary value of $8.0 \cdot 10^{-15}$ at 1s integration time and reaches $2 \cdot 10^{-16}$ after 100s.

After identifying the sweet spot of both FC-250-10P, a series of 20 consecutive measurements has been taken all using the same measurement parameters. The measurements (Allan Deviation at 1s integration time) are well reproducible, showing $\sigma_y^{0.5Hz}(1s)$ = $(8.5 \pm 0.5) \cdot 10^{-15}$. Similar results have been achieved when exchanging one of the FC-250-10P by a regenerative amplifier-based radiofrequency generation (data not shown).

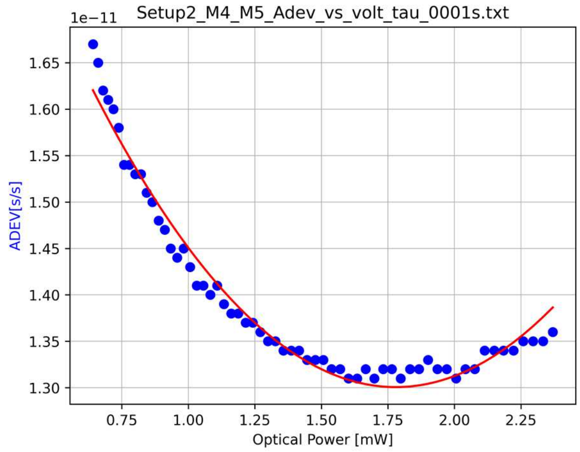

Fig. 4: Influence of the measurement bandwidth on the ADEV. The data shown was measured with the 5120A using a measurement BW of 500Hz and has a significantly higher noise than the measurements with BW 0.5Hz.

For completeness, Figure 4 is showing the reached ADEV values at 1 s integration time for a BW of 500Hz. Due to the much higher noise level in this measuring mode, only values in the low 10^{-11} region are achieved for the fractional frequency stability.

Measurements with 53100A

Measurements with the Microchip 53100A connected to the same 10MHz signals show a fractional frequency stability of $\sigma_y^{0.5Hz}(1s) = 3.0\text{x}10^{-14}$ [s/s] which is limited by the device counter. Instead when using the crossADEV measurement mode [10], an Allan Deviation below $1\text{x}10^{-14}$ has been measured (Figure 5). The only draw-back from this measurement is that the crossADEV cannot be started from an external python script, limiting its integration in wider experimental setups. Moreover, the 53100A can only measure fractional frequency stability with a fixed measurement BW. In comparison, the 5120A provides the data for four different measurement BWs simultaneously.

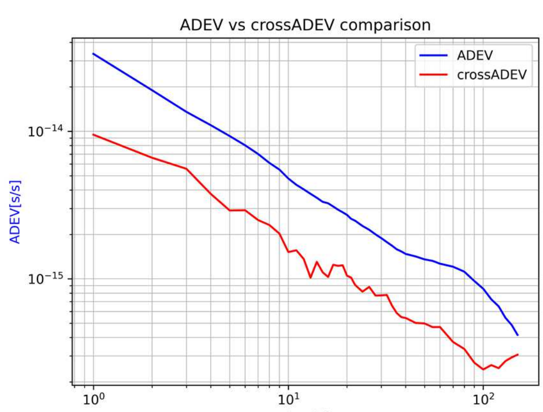

Fig. 5: Fractional frequency stability measured with the 53100A using a measurement bandwidth of 0.5Hz.

III. DISCUSSION/INTERPRETATION

Frequency comb-based comparison measurements between the used ORSs systems show an out-of-loop fractional frequency stability of about $1.5\text{x}10^{-15}$ [s/s] at 1s averaging time in terms of Allan deviation (data not shown). Therefore, the degradation of the frequency stability of the radiofrequency output (10MHz) can be attributed to the optical-to-RF converter and to the phase noise of the measurement device as the frequency comb shows much better stability than the used optical frequency reference systems [11].

Measurements with the Microchip 5120A connected to two RF 10 MHz signals from independent optical-to-RF FC-250-10P devices show a clear dependency of optical input power vs. fractional frequency stability. Its behavior is different for $\sigma_y^{0.5Hz}(1s)$ and $\sigma_y^{500Hz}(1ms)$ (Figure 3 and Figure 4). Interestingly, the optimal value for $\sigma_y^{0.5Hz}(1s)$ is about 1.35mW, while the optimal value for $\sigma_y^{500Hz}(1ms)$ is at 1.75mW input power. We suspect that the optical-to-RF device induces noise-components on shorter timescales (<1s) which have a different response to the input optical power than the white phase noise, which is predominant for timescales between 1-100s. The collected data from several measurements show that the FC-250-10P is indeed performing better than specified by the manufacturer when seeded by an ultra-stable optical reference, with a fractional frequency stability $\sigma_y^{0.5Hz}(1s) < 1\text{x}10^{-14}$. Similar results can be found in the recent literature for an extracted signal at 10MHz ([12]), however with a more complex down-conversion scheme. Other groups have demonstrated the generation and optimization of a radiofrequency around 10-12 GHz with similar results as presented here, but without using a down-conversion scheme ([13], [14], [15]).

IV. CONCLUSIONS

We demonstrated a complete optical-to-radiofrequency converting system using commercial components. Therefore, an optical frequency comb was locked on the output signal of an ultra-stable laser based on an optical cavity setup. The pulse train of the stabilized frequency comb was subsequently used to generate a radiofrequency output at 10MHz with a corresponding stability. The measurements revealed that an extraordinary fractional frequency stability of $8.5 \cdot 10^{-15}$ could be reached at 1s integration time, which averages further down to the low 10^{-16} level after 100s. Results are consistent between the phase noise analyzer Microchip 5120A and Microchip 53100A.

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