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Microwave Photonics in Networked Staring Radar

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Microwave Photonics in Networked Staring Radar

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***Abstract*—Modern radar systems are capable of detecting small moving objects such as drones on the kilometer scale. The complex and evolving environment poses challenges such as interference, clutter induced phase noise and obstruction of targets. Networked radar systems are a potential solution but also bring their own challenges such as synchronization. In this paper, the effect of the oscillator on the networked radar is discussed and how microwave photonics are able to be integrated into the network for superior phase noise and synchronization performance.**

***Keywords*— Network Radar, Synchronization, Photonic Microwave Generation, Frequency Stability, Phase Noise, Allan Deviation, Time Interval Error**

I. INTRODUCTION

The oscillator is essential to the operation of modern digital radars because they not only provide the reference frequency signal used to generate the transmit waveform but also provide the timing trigger which controls the transmit and receive sequence. This enables the radar to operate in a fully coherent manner. For a single monostatic radar, the local oscillator is common for both transmission and reception, so any fluctuations in frequency are common and therefore does not affect the radar coherency. However, in a networked radar, it is of utmost importance to have a level of frequency and timing synchronization as the transmitter and receiver node could be more than a few kilometres apart. For example, two separate radars operating with independent free running crystal oscillators without any external control, the relative frequency will drift, potentially causing phase and timing errors. In the received data, these errors will lead to Doppler and range misalignment. A typical example of this effect is shown in Fig. 1, where two L-band staring radars, clocked using separate free running oven-controlled crystal oscillators (OCXOs) were run in a bistatic configuration [1]. The OCXOs have relatively good short-term stability but generally are limited by the long-term temperature drift and aging of the crystal. Fig. 1a shows the range-Doppler output of the bistatic node where the timing error equates to an arbitrary range error and the lack of calibration of the frequency of the OCXOs relates to an overall frequency offset of the two radars local oscillator. Although target detection can still occur, accurate localization cannot happen without using some form of software-based synchronization approaches such as in [1] or by using some form of disciplined oscillators [2] or timing protocols such as NTP or white rabbit [3], to distribute the clock signal to each radar node.

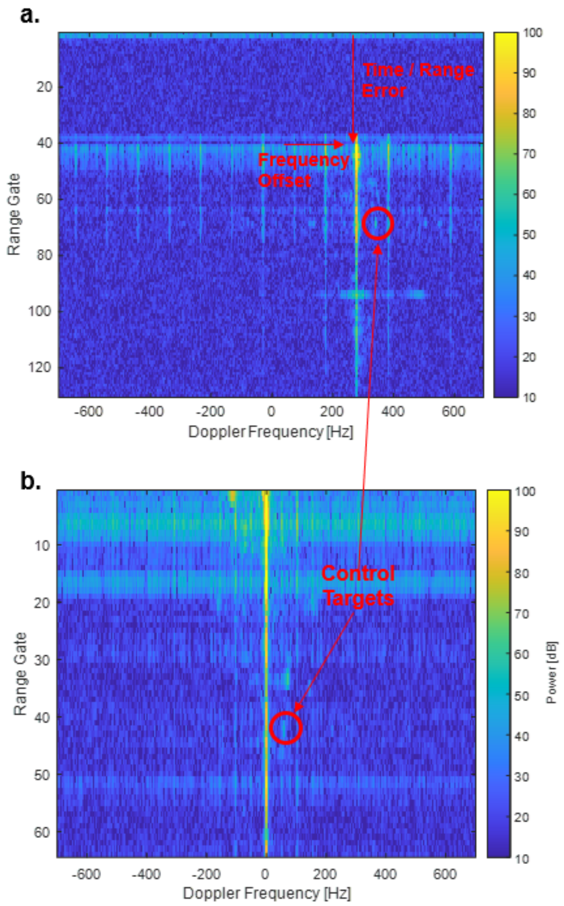

Fig. 1. Range-Doppler output from L-band staring radar data showing the effect of synchronization errors in a two node non-coherent network (a) misaligned bistatic node, (b) monostatic node

In this paper we focus on the use of driftless oscillators and disciplined oscillators as the radar frequency reference. Timing stability and synchronization performance is compared for three class of oscillators for integration into a networked radar system. These are;

- Conventional OCXO, these would be free running

- GPS disciplined oscillators (GPSDO), these are conventional oscillators disciplined to the 1pps signal from the GPS satellites.
- Microwave photonics (MWP) oscillators, a new class of ultra-low phase noise highly stable oscillators derived from an optical source

Within this work, each class of oscillator was characterised in the laboratory for the low relative drift between two sources over the long term and high short-term frequency stability. These measurements will enable to understand the level of synchronization that can be attained when these oscillator configurations are used to operate a radar network. The remainder of this paper is organized as follows. Section 2 provides an overview of the radar testbed that will eventually be used to assess the candidate oscillators in a real radar network. Section 3 details the method used to quantify the relative stability of the oscillators in a controlled laboratory setting and the degree of achievable synchronization performance is reported. Section 4 will analyze and discuss the results with respect to the radar network and finally the work is concluded in section 5.

II. RADAR NETWORK SYSTEMS OVERVIEW

At the University of Birmingham, a networked radar testbed has been set-up using two L-band staring radar systems [4] to conduct surveillance of low observable aerial objects over an urban area. The radars themselves are shown in Fig. 2. Each radar can operate independently or as part of a two-node network. The measurements undertaken in this work are with the specific architecture of the radar systems in mind where there is a local oscillator at f_{LO} at 50-100MHz which controls the overall timing and scheduling of the radar system and is upconverted to the carrier frequency, vector modulated and amplified to provide the pulsed transmit waveform. . The conventional free running local oscillators are not suited for network operation and therefore the radars have been modified to accept an external reference source to aid with synchronisation but also enable low phase noise alternatives. A potential candidate is the ultra-low phase noise MWP oscillators that can potentially bring a step change in the level of synchronization performance achievable, possibly without the use of external methods of calibration that would rely on additional communication links.

Fig. 2. Two L-band staring radars installed at UoB campus providing a testbed of networked radar to benchmark the MWP oscillator technology within a realistic urban environment.

III. FREQUENCY STABILITY MEASUREMENTS

The frequency stability measurements consist of 2 parts; (i) a brief comparison of the close to carrier phase noise, (ii) extended analysis on the long-term stability, termed the Allan deviation (AD) and the derived synchronization errors.

The following measurement equipment is utilized for the respective measurements:

- Rohde & Shwartz FSWP phase noise analyser [5] for phase noise measurement.
- K+K FXE frequency counter [6] was used for long term stability measurements.

The main oscillators under test (OUTs) are briefly described. A 100MHz Axtal OCXO with low form factor is converted to f_{LO} using a phase locked oscillator (PLO). The second OUT is the Leo Bodnar GPSDO [7] which is low cost and formfactor and contains an internal synthesizer that is locked to GPS satellites. The other is the MENLO microwave generation unit (MGU) [8] The MGU contains a mode-locked laser, this frequency comb is stabilized to a repetition rate frequency of 125MHz using an ultra-stable optical reference system (ORS) consisting of a 1542nm laser stabilized to a cavity to produce sub-Hz level linewidth in optical domain. The optical stability is then transferred to the RF domain to produce ultra-low phase noise characteristics.

A. *Phase Noise*

Firstly, the measured phase noise profiles for both the standard radar oscillator i.e., PLO and the MGU are shown in Fig. 3. The phase noise plots demonstrate the superior phase noise of the MWP oscillator. At 1Hz offset frequency the improvement over the current PLO is approximately 30dB. At the frequency of interest for target detection of small targets at low altitude where phase noise becomes a limitation is at 10-100Hz where the phase noise improvement is 10-20dB. In a network radar, operating in bistatic mode means the amount of self-phase noise cancellation occurring is reduced since the phase fluctuation of transmitter and receiver are uncommon. Therefore, improving the phase noise for both transmitter and receiver is vital. Improvements in phase noise can improve the radar system sensitivity in environments with strong clutter returns where the clutter induced phase noise can mask small target returns.

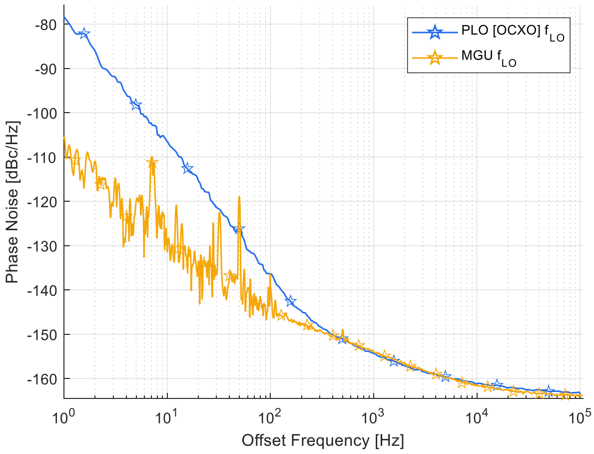

Fig. 3. Phase noise comparison of PLO and MGU at f_{lo}

B. *Long Term Frequency Stability and Synchronization*

The frequency counter setup for the conventional oscillators (GPSDOs and OCXOs) are shown in Fig. 4a where the two OUTs are connected to different channels of the counter and measured synchronously for at least 24 hours. For the MWP oscillator, two MGUs were used and measured in two different configurations. Configuration 1 is shown in Fig. 4b which consists of two MGU systems, in which both frequency combs are locked to a separate ORS. Configuration 2 consists of a single ORS where the ultra-stable laser light is split and delivered via fibre to the two MGU units as shown in Fig. 4c. For each of the long-term stability measurements, a 10MHz hydrogen maser signal [9] was used to reference the frequency counter.

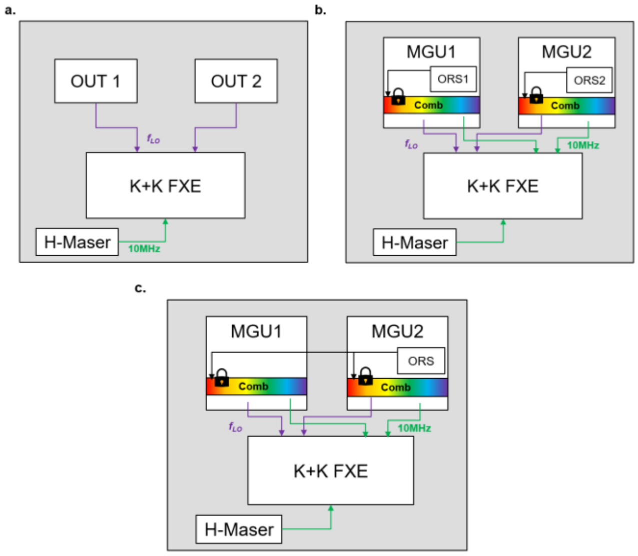

Fig. 4. Measurement setup (a) measurement of conventional oscillators, (b) measurement of the frequency combs in the multiple ORS configuration, (c) frequency combs in common ORS configuration

Each OUT used for the frequency stability measurements are at the same frequency of f_{LO} and represent the clocks of two different radar network nodes and allows the measurement of the level of synchronization achievable when relying solely on oscillator stability. Measurements are undertaken by using channels 1 and 2 of the frequency counter and the frequency ratio technique is used [10] to allow for measurement of relative oscillator stability at f_{LO}. The overlapping AD is calculated using the frequency data outputs of the counter and the results shown in Fig. 5 for the OCXOs, GPSDOs and the two different MGU configurations.

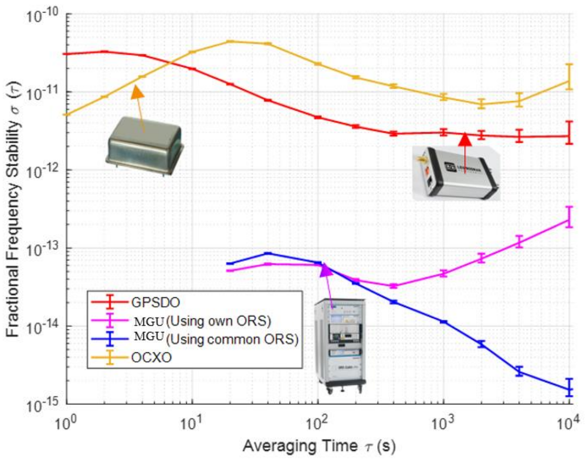

Fig. 5. Comparison of the overlapping AD for conventional OCXOs, GPSDOs, and the ultra-stable MGUs in two different configurations.

The fractional frequency y(t) of each of the oscillators can be seen in Fig. 6a for each of the oscillator types, due to the difference in magnitude of the fractional frequency of the photonic oscillator, the axis limits have been reduced in Fig. 6b to show how y(t) for the different MGU configurations compare.

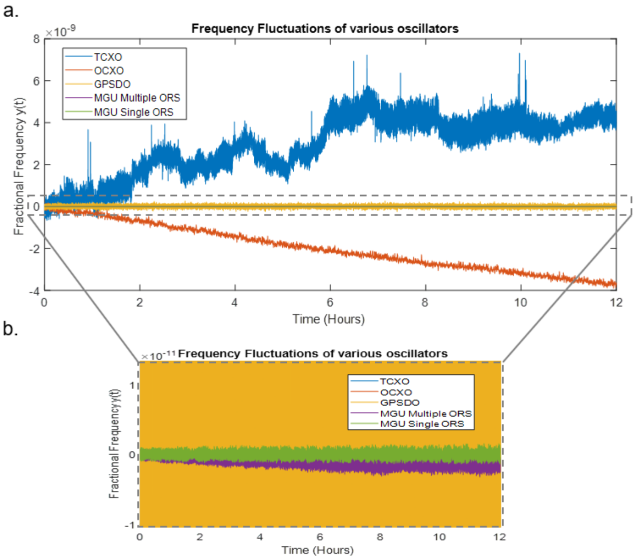

Fig. 6. Plot of the frequency fluctuations over time for each of the OUTs (a) unscaled, (b) zoomed in to view the MGU data

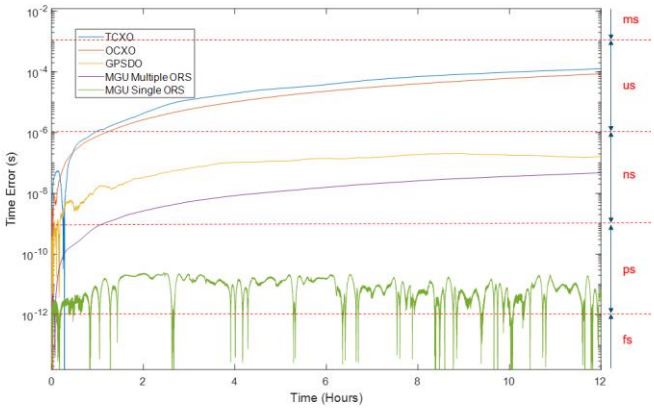

Fig. 7. Measured timing error due to oscillator instability for each OUT

Also, the cumulative phase difference between the two clocks was calculated to determine the time interval error

(TIE) [10] and is shown in Fig. 7 for a period of 12 hours for each of the oscillator types.

IV. DISCUSSION

In the overlapping Allan deviation plots in Fig. 5, the OCXO exhibits better short-term stability than the GPSDO. However, other GPSDOs of higher quality would have a low noise OCXO as the reference clock and would likely match in stability in the short term. In the long term, as expected, the GPSDO would surpass that of the OCXO. One noticeable trend is that the MGU stability is better that the GPSDO at medium to long term. In the multiple ORS configuration, the drifting of the optical reference will result in a drifting of the RF outputs. Short term stability of the MGU is determined by the laser stability, the optical transfer stability to the frequency comb and the electronics to generate the low noise RF. In this case, the short-term stability of the MGU far surpasses that of the OCXO and is likely better than shown, since the data below 100s is limited by the resolution of the frequency counter. Due to the sub-Hz linewidth, the RF stability is expected to be less than 10^{-14} at 1s averaging time. If synchronization requirements are more stringent, noise limitations are being further pushed for development of optical cavities and are approaching the 10^{-17} level [11], which would further push the limits of phase noise achievable in MWP systems. While the frequency comb transfer and microwave generation have been found to not be limiting factors in transferring the stability to at least 5×10^{-17} at 1s [12]. Also, the common ORS configuration is promising as it could be possible to implement over a phase noise stabilized fibre link [13] which would allow ultra stable laser systems to be distributed over large distances with minimal added instability.

Furthermore, the fractional frequency instability of the MWP is shown to be orders of magnitude better than that of the GPSDO (see Fig. 6). The drift of the OCXO is very noticeable compared to that of the cavity locked MGU, mostly due to the leverage achieved via coherent down conversion of optical frequencies of 100s of THz compared to 10s of MHz for the OCXO. MGUs, used in the multiple ORS configuration, are shown to have sufficient stability at medium term but eventually would require frequency stabilization to a reference to compete with the GPSDO.

The measured TIE in Fig. 7 shows that the TIE of the GPSDO is ~100ns whereas the TIE of the MGU with common ORS configuration is ~10ps after a period of 12 hours. Due to the slow drift of the cavity length in the single ORS configuration its TIE is still better than the GPSDO after 12 hours but would eventually exceed that. This shows that using a MWP system with very low synchronization intervals would still achieve very good performance.

The next step is to operate the UoB network testbed with different oscillator configurations to assess the level of synchronisation that can be achieved with a real radar system. Extended bistatic radar measurements will quantify radar performance with the various options which consist of GPSDOs and the MWP oscillators in the two different configurations previously described. In future, other methods of configuring the MWP oscillators will be considered.

V. CONCLUSIONS

Within this work, the level of synchronization achievable when relying on the oscillator stability has been measured for various oscillator types in laboratory conditions. It was found that the photonics based MGU can provide superior performance and that they can be applied in various different configurations depending on the situation and still provide solutions comparable or better than GPSDO. The multiple ORS configuration would not require a link between the radars provides comparable medium-term stability while being immune to a GPS-denied environment. Another configuration consisting of a phase noise stabilized link between each radar node and a central ORS can provide even better performance This paper concludes that the MGUs are good candidates for use as the local oscillator networked radar and future work will involve assessing these new class of oscillator devices within a real networked radar facility.

ACKNOWLEDGMENT

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