Supplementary Information

Supplement 1 – Oscillator Measurements

The frequency stability measurements of the various oscillators and configurations discussed in the paper are characterized using two figures of merit: Phase noise and modified Allan deviation (MDEV). The phase noise, in units of dBc/Hz, represents the short-term frequency stability of the oscillators, whilst the MDEV characterizes the long-term stability of the oscillators. Phase noise provides information about the background noise levels achievable in each individual radar, in the presence of significant clutter [23], whereas MDEV equates to the level of phase drifts that will be present between the radar nodes if operated with independent oscillators.

The phase noise is measured using a Rohde & Schwarz FSPN analyser, at f_{LO} in Fig. S1a. The oscillators compared are the Leo Bodnar GPSDO, Rakon OCXO and the optical cavity-derived oscillators in the free running configuration as well as in the common mode configuration, both with and without phase noise stabilization. The optical cavity-derived oscillator can provide significantly reduced phase noise at the low offset frequencies, with 32 dB improvement over the OCXO at a 1 Hz offset. At the same time, the optical cavity-derived oscillator's thermal noise floor is also very low, matching that of the best electronic oscillators. The optical cavity-derived oscillator without phase noise stabilization (fiber out-of-loop) exhibits an increased phase noise, especially in the 10 - 50 Hz regime, where it is raised by up to 15 dB, which is the typical region corresponding to drone targets. This raised phase noise of the remote system is suppressed after the fiber phase noise stabilization (fiber in-loop) is applied, the resulting phase noise then matches that of the local system.

The MDEV measurements are performed using a K+K FXE frequency counter, within the lab. The measurements consisted of a frequency ratio between two identical oscillators while both channels are referenced to a T4 science iMaser (Hydrogen maser). A Rakon OCXO with low drift is compared with a Leo Bodnar GPSDO. OCXOs are typically limited to the low 10^{-11} region on short time scales. High-spec OCXOs such as the one used in this paper can reach 10^{-13}. Also, disciplining a crystal oscillator to the atomic reference via GPS is able to provide similar levels of stability in the longer term. Due to the orders of magnitude increase in frequency of optical signals, as well as the development of F-P cavities, the frequency stability of optical cavity-derived oscillators pushes far beyond what is achievable with electronic oscillators.

A measurement between the F-P optical cavity used for this paper and a lab-based reference cavity with higher known stability is carried out via an optical beatnote. This provides fractional frequency stability of 5×10^{-15} at 0.1 s averaging time. The Allan deviation value exceeds the OCXO by 3 orders of magnitude.

The F-P optical cavity is used for the generation of the optical cavity-derived oscillators and two identical systems are compared in both a free running and common mode configuration. For the free running configuration, a constant linear de-drift is applied to the comb repetition rate of the two systems to minimize the drift of the output. However, the resulting slow drift is still visible beyond time scales of 1000 s. The common mode regime solves this problem, allowing for the cancellation of the cavity drifts which reach below 2×10^{-15} at 10000 s averaging time. The MDEV measurements of the optical cavity-derived oscillators are carried out from 20 s averaging time, but they are limited below approximately 100 s due to the noise floor of the frequency counter. This shows that the optical cavity-derived common mode configuration can take advantage of the superior stability at all averaging times to benefit radar networks.

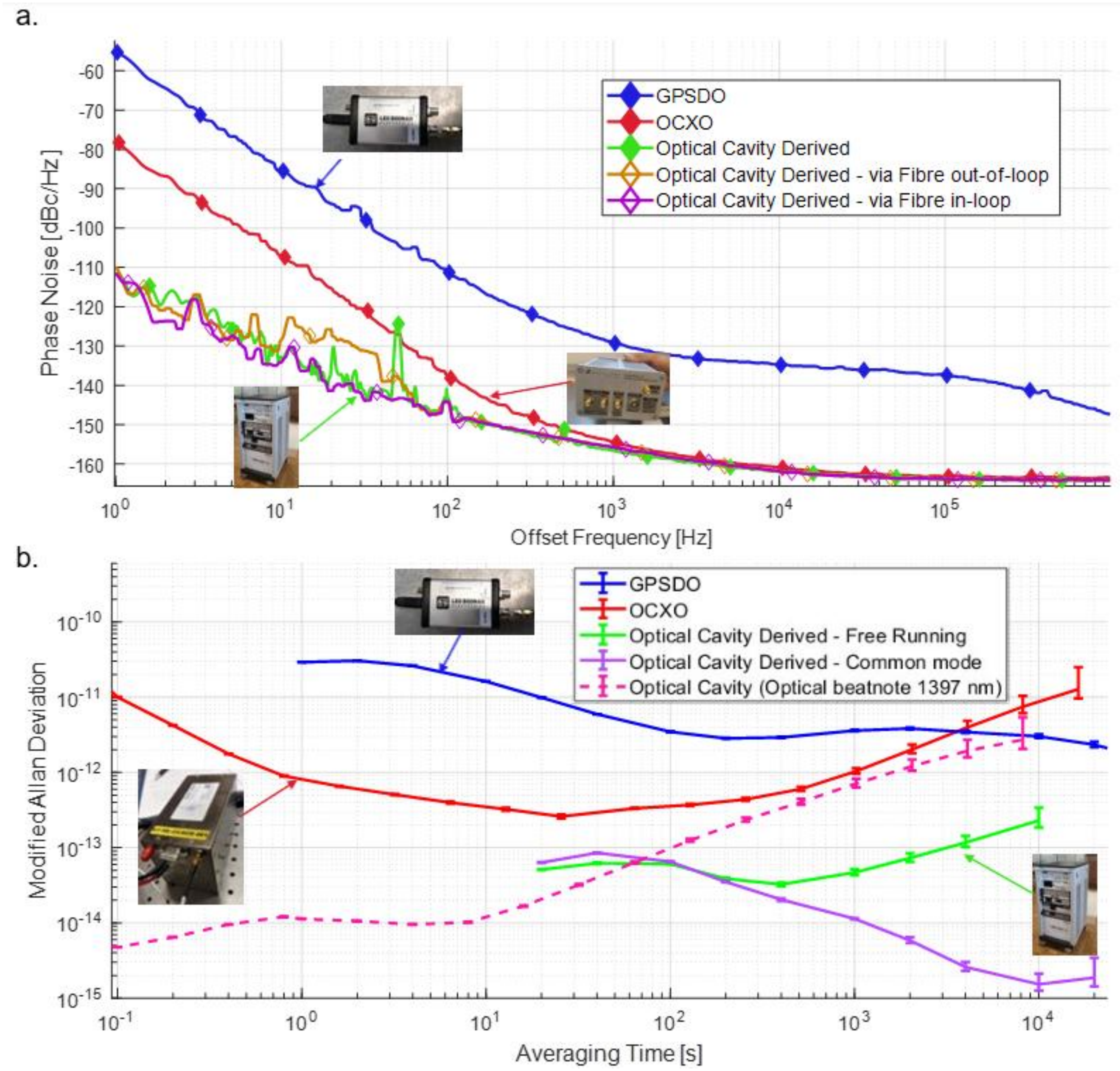

Fig. S1: Phase noise and frequency stability measurements of the oscillators under test. (a) Phase noise, (b) Modified Allan deviation (MDEV). Phase noise measurements of different oscillator types/configurations are performed, at f_{LO}, using a Rohde & Schwarz FSPN phase noise analyser. MDEV is measured using a K+K FXE frequency counter, by comparing two equivalent oscillators as a frequency ratio, using a hydrogen maser as the reference counting source.

Supplement 2 - Phase Noise Stabilization - Schematics and Characterization

The schematic diagram for the HARPO active phase noise stabilization system used within this work is shown in Fig. S2a with modifications to the measurement path for characterization using a loopback shown in Fig. S2b.

The phase noise stabilization of the fiber link is a crucial part of maintaining the phase coherence between the network radar nodes. The additive noise of the fiber link is measured in terms of MDEV. The Fig. S3a compares the MDEV of the optical fiber link with and without the phase noise stabilization by switching the in-house stabilization system ‘HARPO’ between on and off configuration respectively using loop-back test.

The measurement of the fiber out-of-loop is limited by an additive noise floor of 10^{-14}. The fiber in-loop measurement has an MDEV value of 3 x 10^{-16} at an averaging time of 1 s, and reaching almost 10^{-18} at averaging time of 10,000 s. The additive noise floor of the phase stabilized fiber link is at least two orders of magnitude lower than the MDEV of optical cavity-derived oscillator given in Fig. S1. The comparison shows the capability of the phase noise stabilised fiber link to actively cancel any phase noise fluctuations and to provide optical frequency dissemination with stability in 10^{-18} level. The F-P cavity signal can thus be reliably disseminated via the fiber link between the transmitter and receiver radar nodes. The frequency traces of the out-of-loop and in-loop measurements in Fig. S3b and Fig. S3c also clearly indicates the improvement in the stability of the optical fiber link with active phase noise stabilization using HARPO. In addition, the stabilization is able to remove any frequency offsets induced by the fiber link.

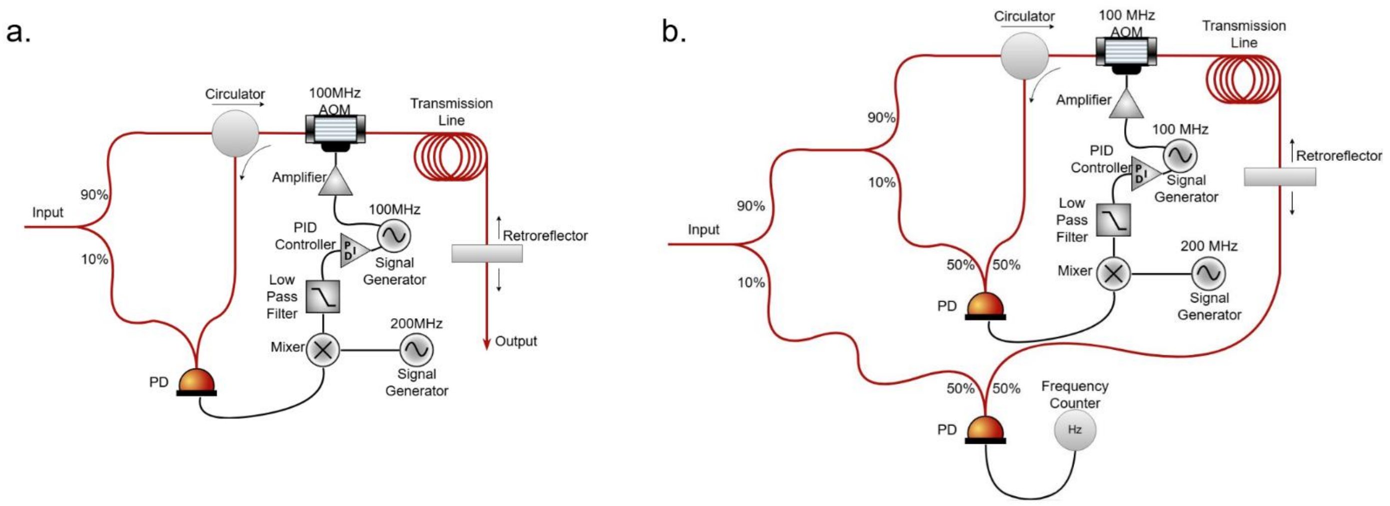

Fig. S2: Schematic diagram of the HARPO active phase noise stabilization for (a) use within the radar system, (b) characterization of the fiber link stability. The system is based on a feedback loop where light travels through an AOM, shifting the frequency of the light by 100 MHz before going through the transmission line. At the end of the transmission line, half of the light is then back reflected through the same transmission line, and through the same AOM, shifting the light by another 100 MHz. This light is then coupled with light directly from the input, resulting in a 200 MHz signal going onto a PD, creating an error signal. This signal is then passed back to the signal generator, through a PID Controller, that modifies the frequency of the AOM to adjust for noise through the transmission line. In (b), the retroreflector is positioned within the HARPO box, so that the output light can be coupled with the input light, so that the resulting 100 MHz signal represents the instability caused by the transmission line.

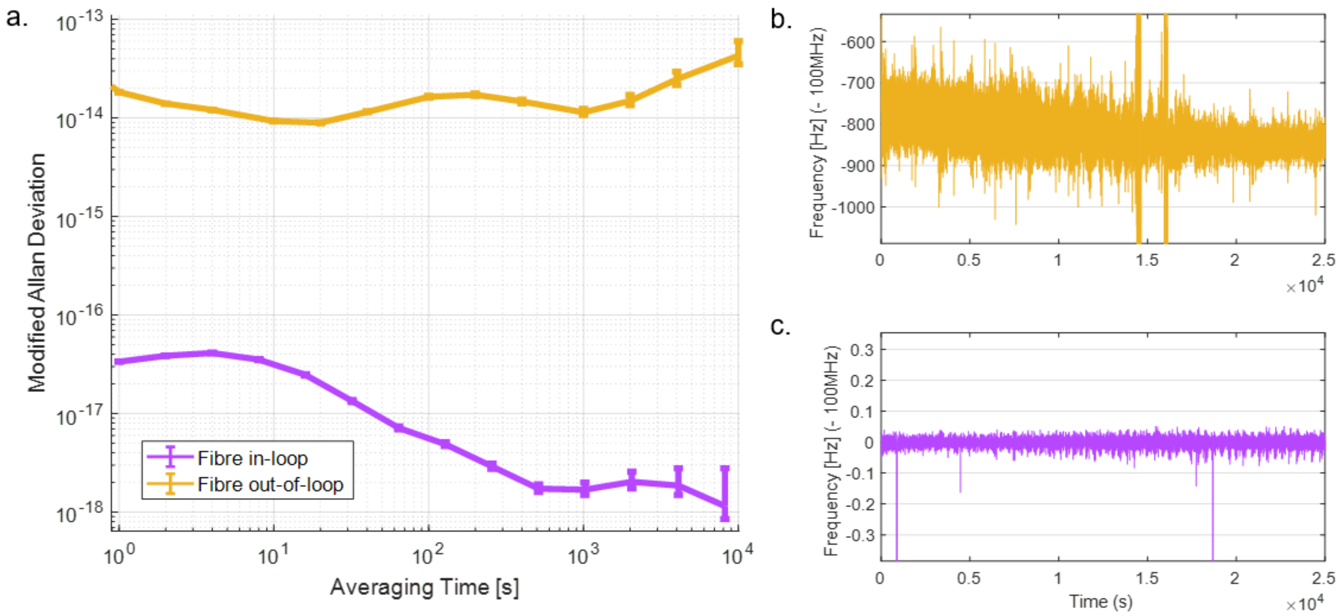

Fig. S3: Measurements showing the additive noise of the fiber link. (a) Link stability in MDEV measured by using the loop-back test method on the optical fiber link by switching the HARPO between on and off configuration. When in-loop, the additive phase noise of the link is much better than the stability of the master F-P cavity, (b) Frequency trace for the out-of-loop measurement, (c) Frequency trace for the in-loop measurement. Also notice the absence of the frequency offset between the two radar nodes.

Supplement 3 – Common Mode Optical Frequency Comb Configuration

A critical step in ensuring the optical cavity-derived oscillators to be operating in common mode is to account for any systematic frequency offset. Within the optical cavity-derived common mode configuration, there is a frequency offset (f_{Offset}) of 100 MHz produced by the phase noise stabilization unit. Several mechanisms are involved to ensure the comb modes align between the two radar nodes. This is via changing the carrier envelope offset (f_{CEO}) polarity and then changing the f_{beat} frequency to compensate for the 100 MHz difference in the optical reference frequency at the input to the frequency combs.

The configuration used in this work utilises a phase lock between mode M of the optical frequency comb and the optical reference. The comb parameters (n, f_{CEO}, f_{beat}) were selected in the transmitter node OFC to ensure f_{RR} is calibrated to 125 MHz. The calibration is limited by the reference oscillator used for the measurement of f_{RR}. In this case, a standard GPSDO is used which allows for mHz accuracy. However, there is likely to be some small offset between f_{RR} and the desired value and also it will change over time due to the frequency drift present in the cavity stabilized laser.

The common mode OFC configuration ensures that small frequency offsets are equal in both nodes by selecting the comb parameters in the receiver node OFC to satisfy the relation in Equation 3.1.

$$f_{\text{Offset}} = f_{\text{beat1}} + f_{\text{beat2}} + 2f_{\text{CEO}} \quad \text{(Equation 3.1)}$$

Where f_{beat1} and f_{beat2} are the beat frequencies of the transmitter and receiver node OFCs, respectively. In this way, the frequency comb repetition rate remains correlated in both radar nodes. An illustration of the coherent comb locking is shown in Fig. S4.

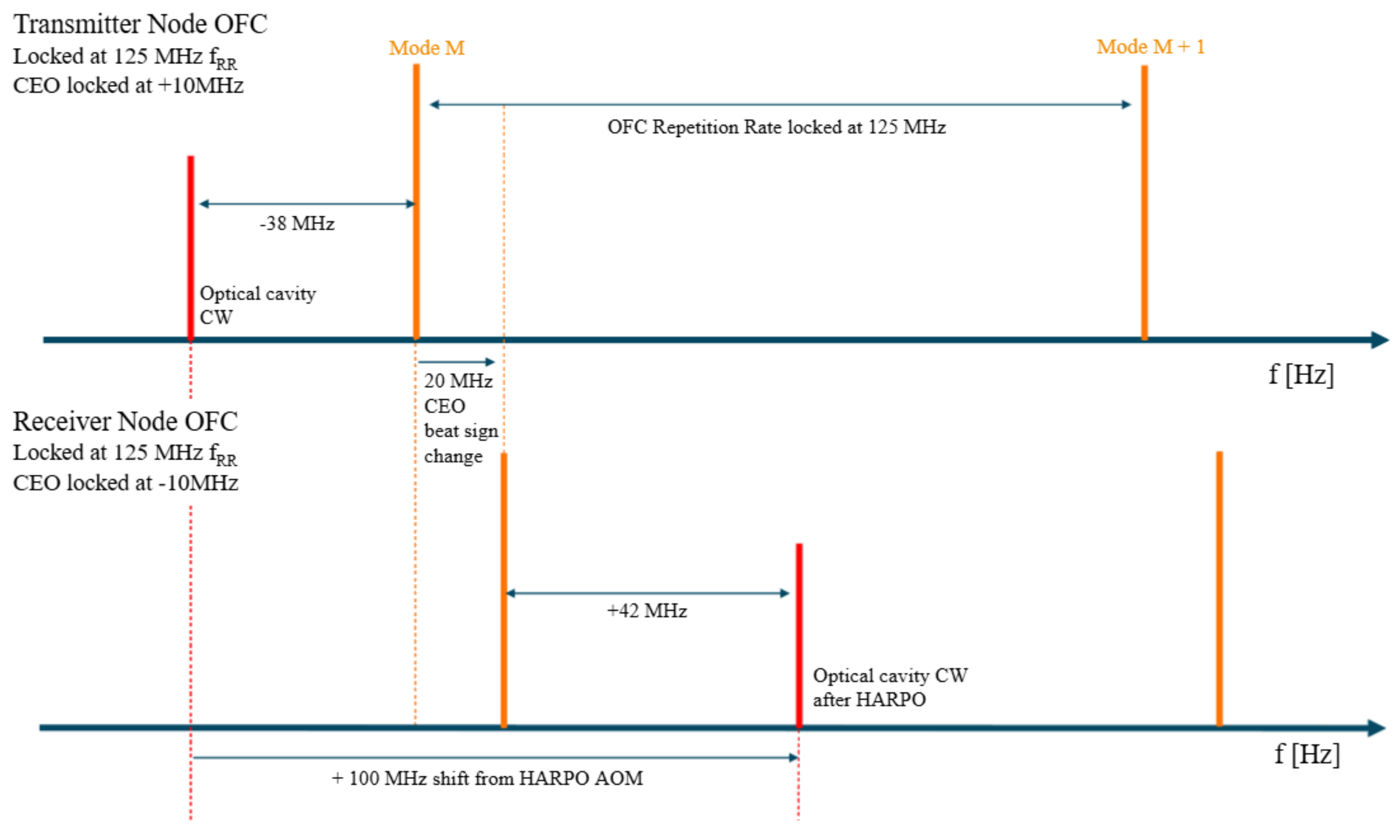

Fig. S4: Comb locking parameters used for coherent comb locking for the optical cavity-derived common mode configuration. The 100 MHz offset from the HARPO is compensated by fixing the frequency between the optical cavity and mode M of the OFC in the transmitter and receiver nodes. The combined optical beat frequencies and the contribution of the CEO beat sign change ensure the 100 MHz shift is compensated which ensures accurate microwave downconversion.