Optical Ranging and Synchronization for Distributed Sensing with Small Satellite Formations

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***Abstract* — Frequency-comb based optical ranging and synchronization has the potential to support future space-based distributed sensing. However, comb-based systems cannot yet meet the requirements on size/weight and power (SWaP) needed for space-based operation even though the performance of these systems can achieve extremely high precision and accuracy. Here, we describe a ground-based experiment that demonstrates progress on utilizing low size/weight and power frequency combs, data processing and optical terminals for precision ranging measurements over free space. The small platforms and techniques described here are a first step towards future integration onto a spacecraft platform.**

Keywords— frequency combs, optical synchronization, optical ranging

I. Introduction

Distributed sensing techniques, such as multi-static synthetic aperture radar (SAR) and the related very long baseline interferometry (VLBI), rely on an array of sensors working synchronously for high resolution sensing. Coordination of these sensor arrays requires a significant level of synchronization, relative position knowledge, and signal processing to properly recover weak signals from noisy data. A space-based sensing array could currently use GPS for synchronization and positioning, limiting achievable synchronization to ~300 ps [1] and relative position knowledge of 25 cm [2]. Improvements in the accuracy of distributed coherent sensing by increased sensing frequencies will require improvements in both time synchronization and relative range knowledge between nodes of the coherent sensor. A frequency comb-based approach for optical time transfer and ranging can potentially provide the synchronization and relative range knowledge required for next generation distributed sensing systems.

Optical time transfer has been shown to synchronize optical timescales to sub-fs over extremely long terrestrial distances [3] and in 3-node configuration [4]. Dual comb-based ranging has been shown to support 5 nm accuracy/precision [5] and does not have the issues of non-ambiguity range in continuous wave measurements. Recent work has shown that frequency comb-based approaches can reach the quantum limit [6]. Here we demonstrate first steps towards extending these techniques to space-based operation. We focus on demonstration of high precision ranging over a 2-km free space link in a comb-based system using primarily commercially available components with significantly lower size, weight and power (SWaP) than previous comb-based ranging and synchronization systems.

Initial demonstrations demonstrate dual-comb based ranging measurements in Boulder CO between the NIST building and the University of Colorado (CU) Aerospace Engineering Sciences building via a roof-mounted retroreflector. The frequency combs are packaged, commercial, low-power combs. The range measurements are computed from linear optical sampling (LOS) processing of the interferograms (IGMs) on Red Pitayas [8] – a compact, low SWaP processor. Future experiments will explore further reductions in power through higher photon efficient detection, incorporation of the comb control within Red Pitayas, and reduced free-space terminal size, with the goal of a reference design that demonstrates future SWaP compatibility with small satellites.

II. Methods/Results

Figure 1 shows the system setup. The dual-comb ranging system was located at NIST and the ranging measurements performed over an optical link to a retroreflector on the roof of the CU Aerospace building. As shown in Fig. 1A, the pulses from one frequency comb were split, with half the light launched over the air and the other half sent to a FC/PC connector to generate a reference signal. Both pulse trains were sampled by a second local oscillator frequency comb that was offset in repetition frequency by ~ 2 kHz. The resulting interference signals were digitized with a commercially available compact FPGA platform running custom firmware. The signals (see inset) show a peak from the reference reflector and the target reflector. Differential range measurements are produced by measuring the distance between these peaks, as shown in the second inset in Figure 1A.

To maintain the necessary relative coherence between the frequency combs, both were self-referenced and optically phase-locked to a compact, free-running continuous wave (cw) laser. Future work will explore system performance if this cw laser is omitted since the free-running optical phase-noise on the frequency combs may be sufficient. This would allow further SWaP reduction. To provide accurate ranging measurements, the resulting repetition rates of the two frequency combs were measured with respect to a reference 10 MHz signal, which was provided here by a H-maser but would ultimately be provided by GPS. For future distributed sensing, the system would also synchronize the clocks at the two sites

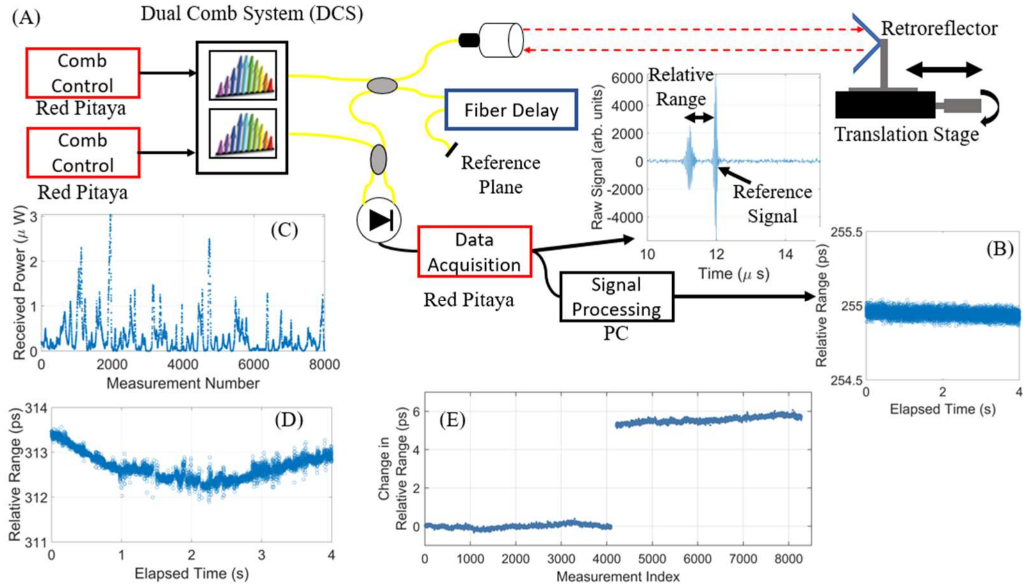

Fig. 1. (A) Compact dual comb system with one comb serving as the local oscillator and the other as the transmit light source. The transmitted comb light is split into two branches, one directed to a reference plane and one to the "signal reflector", which is either a fiber end reflection for shorted tests or a a retroreflector for over the air tests. Both returning reflections are mixed with the LO comb light, sent through a balanced detector, and digitized with a Red Pitaya. (first inset) Example of the raw digitized signal showing the two peak signals corresponding to the signal and reference reflections, allowing for a precise measurement of relative range. (B) Example of the relative range for a fiber shorted measurement. The standard deviation is 26 fs. (C) Variation in the received power from the retroreflector after propagation over the 4 km link. (D) Corresponding variation in the relative range due to atmospheric turbulence and building sway for a fixed retroreflector position. (E) Change in the relative range recorded for an aproximate ~ 1 mm change of the position of the retro reflector which results in the easily resolved nearly 6 ps jump in the data.

providing a common time-base for both ranging and frequency measurements that is independent of GPS.

The performance of the system was first verified with a fiber shorted system, representative data shown in Fig. 1B. For the over-the-air data, about 1.9 mW of comb light was transmitted over the air to the retroreflector with a mean return of 270 nW compared to a detection threshold of ~ 10 nW. The actual received power varied significantly from turbulence (Figure 1C), and leads to piston-induced range changes (Figure 1D).

To test the accuracy, a separate measurement was made using a larger-SWaP comb system where the retroreflector was moved on a translation stage by 1 mm, 500 µm, and 50 µm step sizes. For these data, the comb launch power was 255 µW and typical return powers were 20 nW. One example of the measured differential range is shown in Fig. 1E showing that this approach can easily resolve mm-scale jumps in path length.

As part of this on-going effort, the SWaP envelope will be further reduced through careful reduction of the SWaP of all components required for simultaneous frequency comb based optical time transfer and optical ranging.

III. Conclusions

The inability to precisely measure inter-satellite clock offsets and relative slant range position currently represent a bottleneck in high frequency space-based distributed sensing. Future satellite sensing nodes will require advancements in synchronization and relative ranging to enable science goals. The work demonstrated within describes the development of a low SWaP, frequency comb ranging system designed for future use on a small satellite platform.

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[8] Certain equipment or instruments are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement of any product by NIST, nor is it intended to imply that the equipment identified are necessarily the best available for the purpose.