FREQUENCY COMB DEVELOPMENT FOR ULTRA-PRECISE SPACE BASED APPLICATIONS

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ABSTRACT

Frequency comb technology uses a unique combination of broadband optical coherence and unprecedented frequency stability to create a new tool for active and passive sensing and metrology. Recent developments utilize this precision to demonstrate orders of magnitude improvement over state of the art spectroscopy, long distance ranging and velocity measurement, frequency conversion, and timing transfer.

Demonstrations in comb-based high precision optical metrology for remote sensing systems are presented along with progress of an all fiber comb system being developed for spaceflight at Ball Aerospace. Near term applications for Ball's frequency comb, including long distance nanometer precision ranging and femtosecond jitter timing transfer, are discussed.

INTRODUCTION

The introduction of the self-referenced frequency comb, for which the 2005 Nobel Prize in Physics was awarded to Ted Haensch and John Hall, represented an extraordinary breakthrough in achievable optical oscillator stability and precision by providing a fully coherent broadband optical reference [1]. Frequency combs can be stabilized down to fractional frequency instabilities (Allan deviation) on the order of 10^{-18}, presenting many orders of magnitude improvement over the Rb atomic clocks currently used in space based applications [2]. Scientists in the Atomic, Molecular, and Optical Physics (AMO) community have applied this stability to demonstrate breakthroughs in many fields, including displacement metrology, long range distance absolute measurements, and optical frequency down-conversion [3, 4].

Although their primary contributions have been to the fields of metrology and frequency standards, frequency combs have made contributions to some fields directly involving the aerospace community, notably radial velocimetry and ultra-high precision spectroscopy [5, 6]. Other identified needs, such as the ability to stabilize optical systems to 10 pm in interferometers and future space telescopes, have driven the development of frequency combs for aerospace applications [7].

This paper discusses efforts at Ball Aerospace to develop frequency combs suitable for aerospace environments as well as planned applications for the technology.

FREQUENCY COMB

The comb currently being operated at Ball follows a NIST design for an all-fiber system based on widely available polarization maintaining, single mode fiber telecom components. Generation of the comb spectrum with only fiber optic components has eliminated alignment errors, greatly reduced vibration sensitivity of the system, and greatly decreased the packaging size of this high precision system, opening the door for applications in the harsh, SWAP-limited environments common to space based missions (**Figure 1**).

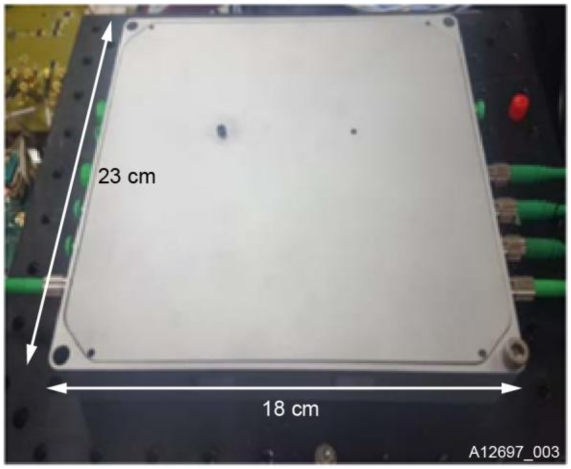

Figure 1: Current packaging for Ball frequency comb optical assembly. Dimensions: 23 x 18 x 3 cm

COMB OPTICAL SPECTRUM

In addition to researching aerospace specific applications for frequency combs, significant IR&D investments have been made at Ball to increase overall system TRL, with the end goal of a frequency comb qualified for spaceflight, including optics, packaging, and control. The Ball comb system stability is currently limited by the use of an Rb based frequency standard. Improved performance is attainable by locking the system to an optical cavity stabilization system, or through the use of an optical atomic clock [8]. Further detail on the NIST design and Ball implementation can be found at [9, 10].

The frequency comb's emitted optical spectrum consists of a many mutually coherent "teeth" evenly spaced at ~200 MHz across a full octave of spectrum. The equality of the tooth spacing, and mutual coherence of the teeth are the properties that make the comb such a useful tool for frequency measurement. The spectrum from the Ball frequency comb is shown in **Figure 2**, although the individual teeth are not directly resolvable.

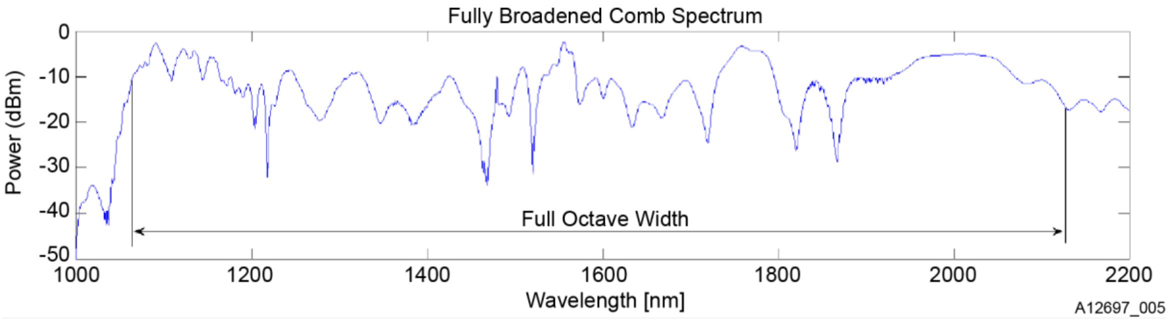

Figure 2: Optical spectrum from the Ball Aerospace laser frequency comb.

There are two distinct perspectives with which a frequency comb can be understood. For envisioning applications, the most useful picture is in the frequency domain, where the frequency comb’s unique properties are most apparent. Also useful is the picture of the frequency comb in the time domain, where the comb’s basis as a mode-locked laser is most apparent pulse propagation through the optical system is more easily understood.

In the time domain, and referencing **Figure 3**, the output of the mode-locked laser (1) consists of ultrashort pulses on the order of 100 fs FWHM, at a repetition rate of approximately 200 MHz. Spectral output spans 10 nm. Amplification of these pulses in an Erbium Doped Fiber Amplifier (EDFA) in the second stage (2) of the laser applies a significant chirp to each pulse (i.e., the higher frequency parts of the spectrum move at a different rate from the lower end of the spectrum, causing the pulse to spread out in time), which is counteracted by inserting a section of fiber with group velocity dispersion (GVD) of the opposite sign from the amplifying fiber (3). The result is a compressed pulse with a length that was measured, by autocorrelation, to be 44fs in length. The extremely high energy density of the ultrashort pulse as it enters the Highly Nonlinear Fiber (HNLF) (4) excites many nonlinear processes, causing extreme frequency broadening of the spectrum to the full octave necessary for direct comparison of the two ends of the spectrum via frequency doubling (5) and self-referencing in an interferometer (6).

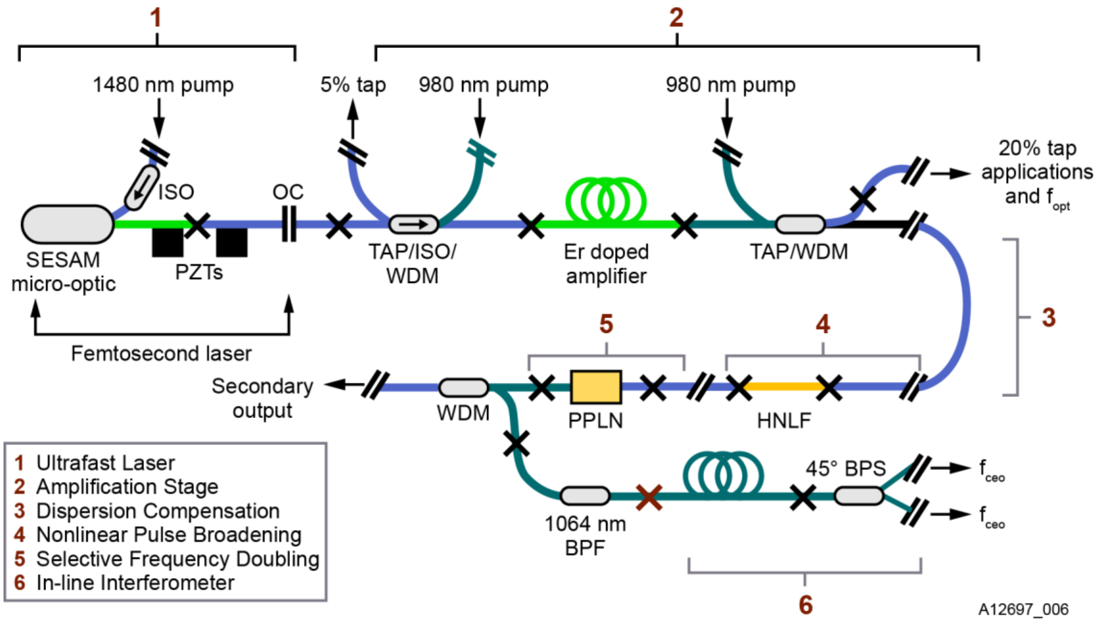

Figure 3: Ball frequency comb optical assembly schematic showing the six stages necessary for generation of a self-referenced frequency comb.

The frequency domain picture of the laser output is where the frequency comb gets its name. The output from the mode-locked laser takes the form of a soliton, as shown in the optical spectrum analyzer (OSA) data at the top of **Figure 4**. The soliton's envelope takes the form hyperbolic secant, and is comprised of a large number of discrete, mutually coherent "teeth". The spacing of the teeth is directly related to the repetition rate of the pulsed laser, with each of their linewidths in the 100s of millihertz. For a rigorous mathematical treatment of the phenomena which lead to this spectrum, see Cundiff [11].

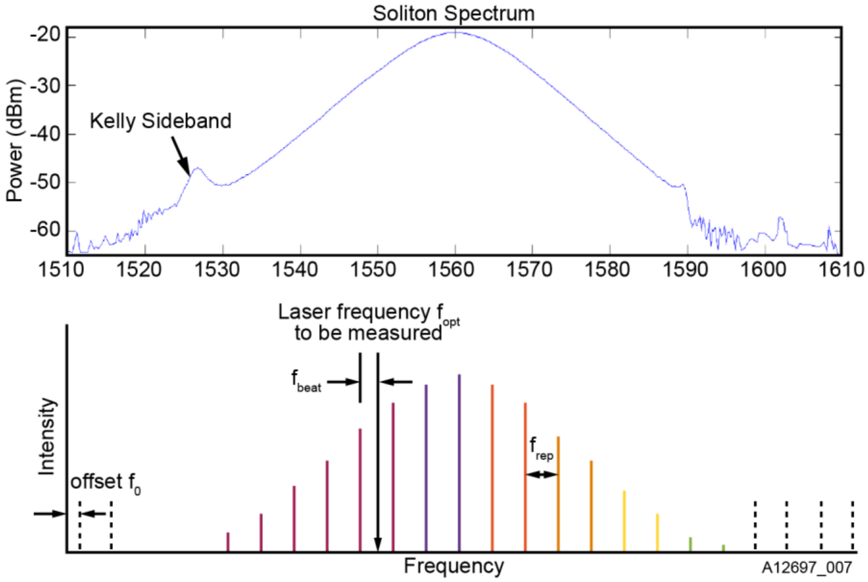

Figure 4: Top: Measurement of Ball's soliton output, showing the sech profile and Kelly sidebands typical of soliton spectra. Bottom: A schematic showing the various key parameters of a frequency comb

In order to resolve the frequency components, it is necessary to mix another laser signal, f_{opt}, within the comb's spectral range, with the comb output in order to generate a heterodyne signal which can be measured electronically. We use a laser with approximately 100 kHz linewidth to resolve our comb teeth, and measurements of such a spectrum, taken with an RF spectrum analyzer, is shown in **Figure 5**. The center frequency of the measured peak represents the frequency offset from the mixed laser signal frequency, f_{opt}, to the nearest comb tooth. When implemented with a fully stabilized comb, this yields an extraordinarily accurate and precise measurement of the mixed laser's frequency.

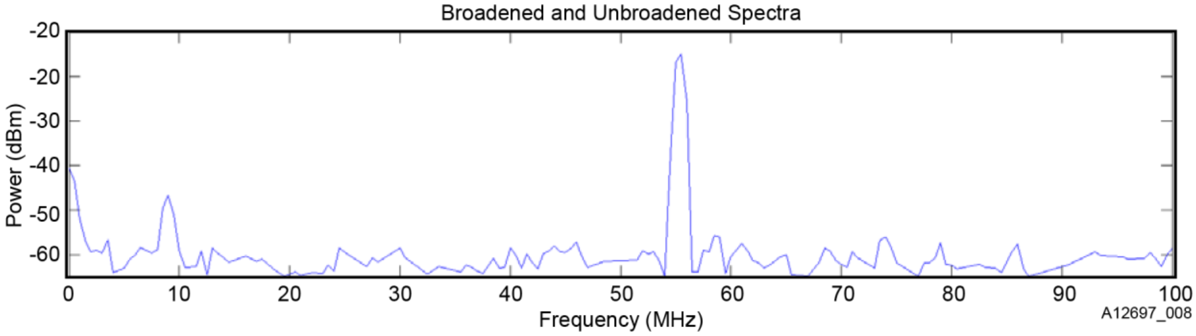

Figure 5: Heterodyne measurement showing resolved comb tooth. Note that tooth width is much narrower than shown. Width is due to relatively broad CW source with which the comb tooth was measured.

After the soliton has been amplified and temporally compressed, it enters the HNLF, which broadens the spectrum through a number of nonlinear processes. As the spectrum broadens, it maintains its comb structure, expanding the number of stable, coherent comb teeth. The Ball comb spectrum has 200 MHz spacing with more than a full octave of bandwidth, centered at 1560 nm, for a total of approximately 10^{-6} discrete fourier components, or teeth. A sample of that comb spectrum, including a representative expansion of the fine spectral details can be seen in **Figure 6**.

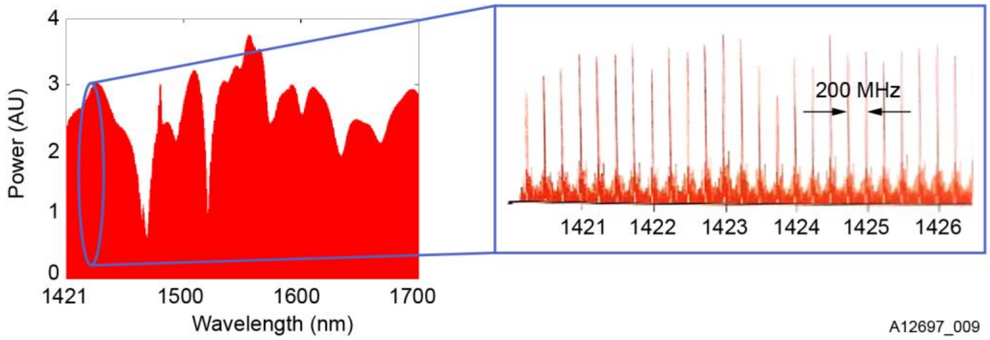

Figure 6: Illustration of Ball frequency comb spectrum and fine structure

COMB STABILIZATION

Stabilization of the entire comb spectrum only requires the control of two degrees of freedom (DOF). The first DOF, the bulk frequency translation of the full spectrum, is measured by frequency doubling a comb tooth, A, at 2128 nm down to 1064 nm and directly comparing to a comb tooth, B, that naturally exists at 1064nm.

$$2(f_A + f_{drift}) = f_B + f_{drift}$$

By tuning the 1480 nm cavity pump current, this self-referencing technique makes it possible to enforce the condition that tooth B must be exactly twice the frequency of comb tooth A, driving ν_{drift} to zero or some small fixed offset.

The second DOF is the spacing of the teeth, which can be stabilized in two ways. The simplest method, carried out in the time domain, is to compare the repetition rate of the soliton output to a frequency source such as an Rb clock or OCXO. Feedback is applied to stabilize the repetition rate of the femtosecond laser. The second method, which results in the tightest possible lock, is to take a stable optical frequency oscillator such as a cavity stabilized laser or optical atomic clock, and mix it with the comb output. Using the resulting heterodyne signal for feedback, the comb oscillator's cavity length can be tuned to stabilize the repetition rate, thereby locking the tooth frequency spacing leaving a fully stable, self-referenced comb.

PICOMETER METROLOGY

One application of interest is high dynamic range picometer scale metrology. The stability of the comb's spectrum, combined with its repetitive nature leads to an ideal reference for optical resonances. Using a high-finesse Fabry-Perot cavity, with an optical resonance dependent on cavity length, a displacement gauge is possible with sensitivities on the order of 100s of femtometers (10^{-13}m). For a discussion on the setup, sensitivity, and capabilities of this system see Schibli [4].

While the sensitivity of the Fabry-Perot based gauge is attractive for optical system control, sensitive alignment requirements of the cavity make implementation outside of a laboratory environment largely impractical. In order to decrease alignment requirements, an unequal arm Michelson interferometer was implemented in a configuration with previously demonstrated sensitivities on the order of 10 picometers [10, 12].

The reference arm, as shown in **Figure 7** remains fixed throughout length gauge operation while motion in the measurement arm represents the displacements to be measured. Operation of the picometer metrology gauge is different from the most common use case for a Michelson interferometer. Rather than observing fringe behavior for a fixed wavelength probe laser, calculating displacement based on fringe intensity variations, the Ball system changes the wavelength of the probe laser in order to maintain a constant null intensity. This allows the center wavelength of the probe laser to become the measured quantity, allowing the system to use the stable, broadband output of the comb as a reference for precise, high dynamic range, measurement of the probe laser wavelength.

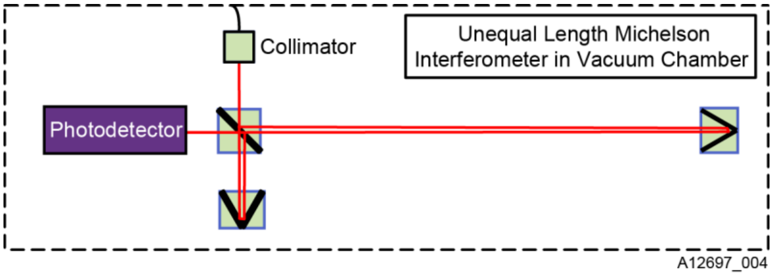

Figure 7: Need to label reference arm and measurement arm

The familiar intensity expression from beam combination on the photodetector is shown below, where $k = \frac{2\pi}{\lambda}$, λ is wavelength of the probe laser, z_1 and z_2 are the reference and measurement arm lengths, respectively.

$$\mathrm{I} = |E_1|^2(e^{ikz_1})^2 + |E_2|^2(e^{ikz_2})^2 + |E_1||E_2|e^{ikz_1}e^{ikz_2}$$

Reorganizing the above formulation to solve for probe laser wavelength as a function of z_2 reveals the below relationship where n, an integer, is the particular cavity mode corresponding to the fringe null to which the system has locked.

$$\lambda = \frac{c}{f} = \frac{z_2 - z_1}{n + 1/2}$$

Because changes in the length of the reference arm are directly related to changes in the probe laser frequency, it is possible to utilize the comb spectrum as a ‘ruler’ to detect changes in the arm length. The heterodyne output from mixing the probe laser with the comb spectrum shows a beat frequency which rises and falls as the probe laser wavelength moves relative to the stable comb teeth. In **Figure 8** a probe laser is mixed with a comb exhibiting an 80 MHz repetition rate, allowing the frequency drift of the probe laser to be easily measured. Raw (top) and adjusted (bottom) measurements shows the received heterodyne signal as the probe laser drifts across the comb spectrum. The low pass filtered heterodyne increases in frequency from time t = 0s to time t = 300s as the probe moves away from the closest comb tooth. Continuing in the same direction, the heterodyne measurement drops from 40 MHz toward 0 MHz as the next higher comb tooth becomes the nearest reference frequency. Adjusting for the sign of the slope as necessary allows

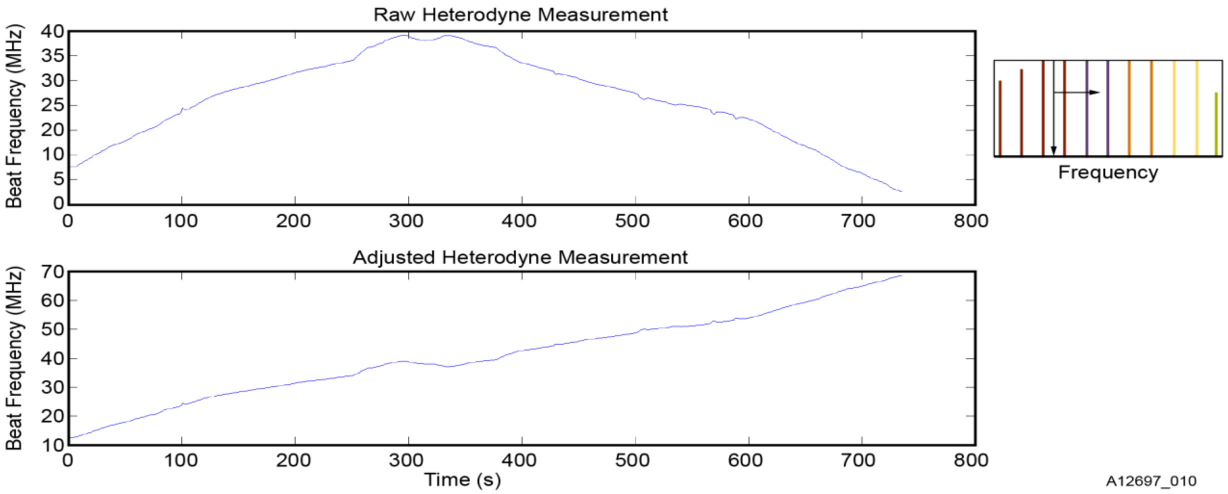

Figure 8: Demonstration of probe frequency moving across comb spectrum

one to continue this type of measurement for arbitrary excursions within the comb's octave bandwidth [10]. Given the stable, phase coherent broadband output of the frequency comb, the change in probe laser wavelength can be accurately tracked over large displacements without sacrificing accuracy or precision. Implementation of the frequency comb enables the measurement range of high precision techniques to be greatly expanded.

For a nominal optical path difference (OPD) of 100 cm and using our comb in a coarsely locked configuration an OPD change of 10pm leads to a frequency change of approximately 20 kHz. As shown in **Figure 9**: Ideal signal (blue) and frequency comb noise (red) from 10pm displacement., frequency comb noise in its coarse locked configuration leads to frequency error of approximately 1 kHz and measurement error on the order of 1 pm. Ongoing improvements for the comb's locking scheme should improve comb stability by approximately a factor of five, and implementation of a high stability optical lock will improve comb stability by several orders of magnitude, resulting in subhertz level tooth control [8]. The optical lock, while necessary for other high precision measurements, is unnecessary in the current application as high displacement precision can be obtained using the current locking scheme.

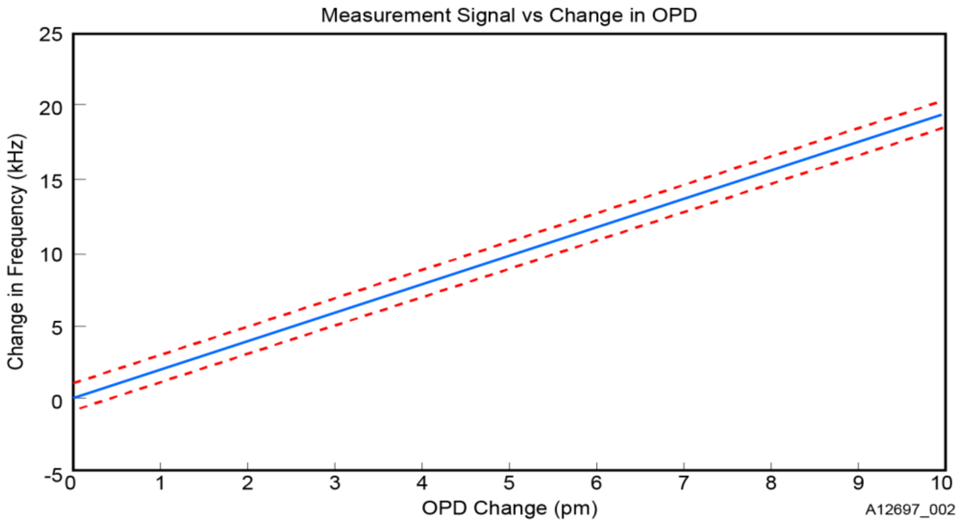

Figure 9: Ideal signal (blue) and frequency comb noise (red) from 10pm displacement.

We anticipate being able to decrease overall system error to the level necessary for measurements on the order of a single picometer, while utilizing the comb's broadband nature to achieve unambiguous displacement measurements into the micron scale and beyond.

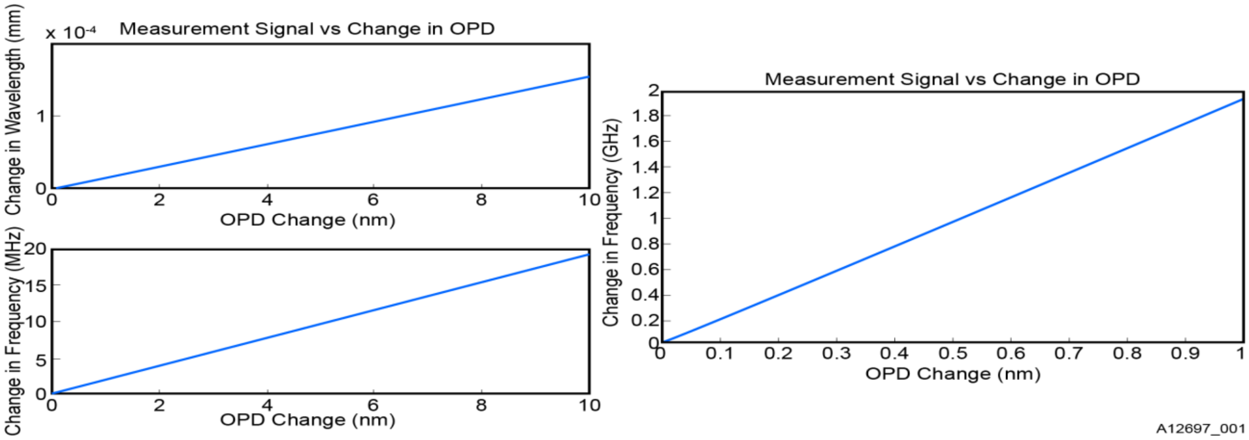

Figure 10: Idealized measurement signals for varying displacements

HIGH PRECISION LONG DISTANCE RANGING

Precision ranging applications often require measurement over greater ranges than the above picometer metrology scheme allows. One approach to measuring absolute distance utilizes two frequency comb sources to take nanometer scale absolute distance measurements at ranges on the order of a kilometer. Demonstrations of this measurement, utilizing Linear Optical Sampling (LOS) techniques taken from coherent multi-heterodyne spectroscopy, have realized 5nm precision with 60ms integration times [13, 5].

As demonstrated in a laboratory by NIST, two types of measurements are made in parallel to achieve this result. By transmitting comb light in the form of a femtosecond soliton from the source to the target, a very precise time of flight measurement can be made. This time of flight measurement provides micron scale accuracy and can be used to track rapidly moving objects. Implementation of digital processing and simple algorithms allow targets with velocities on the order of 1 km/s or less relative to the source platform to be tracked without sacrificing measurement accuracy [5].

For slower moving objects, it is possible to “hand off” time of flight measurements to interferometric ones exhibiting three orders of magnitude higher precision.

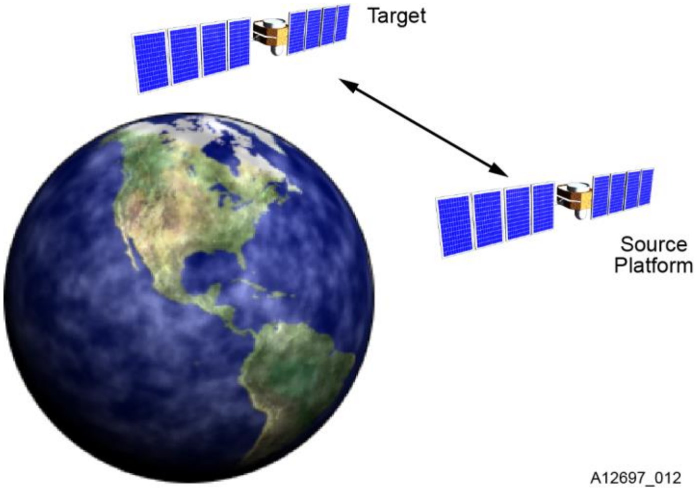

Figure 11: Target and source platforms

In order to carry out the high precision interferometric measurement, solitons from two frequency combs exhibiting slightly different repetition rates are heterodyned together. As shown in **Figure 12**, one comb serves as a local oscillator (LO), while the other serves as the probe which is sent from the source platform to a fixed reference plane and then the target platform.

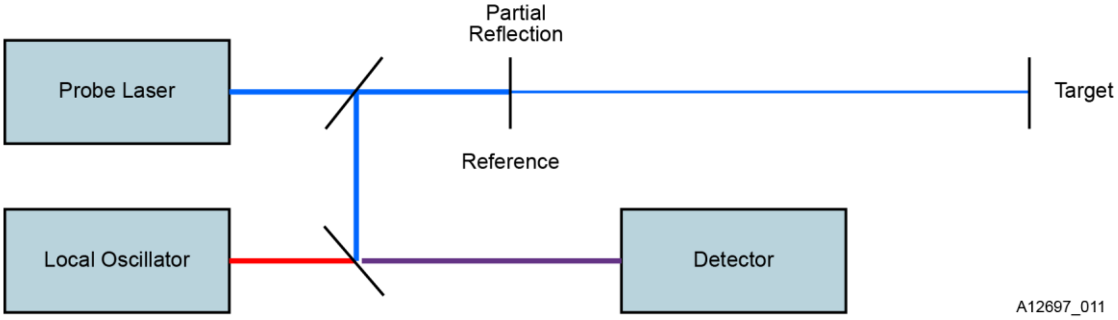

Figure 12: Schematic showing basic measurement configuration

The interferometric ranging technique builds an interferogram by cross correlating the probe laser’s return pulses with the LO pulses, relying on the slight difference in repetition rate of the two frequency combs to provide the necessary temporal scanning effect. The distance between the target plane and reference plane is calculated using established Fourier processing techniques [5].

The accuracy of these measurements is limited by the stability of the frequency combs. For the above discussed measurements, a radio-frequency lock with a wander of ~30 kHz was used to stabilize the frequency comb. By implementing a self-referenced comb with an ultra-stable optical reference such as an optical atomic clock, it should be possible to improve the fractional accuracy of these measurements by several orders of magnitude, greatly increasing both measurement resolution and operational distances [5].

ULTRA-PRECISE TIME TRANSFER

Another significant future application of frequency combs in space is ultra-precision time transfer. While techniques for frequency comparison between two distant optical oscillators have been established using frequency combs, the problem of direct time comparison remained a more significant challenge [14, 15]. Recent laboratory experiments, however, have demonstrated the ability to synchronize optical frequency clocks down to the femtosecond level across multi-kilometer link distances [15].

Despite their name, optical atomic clocks are typically used as frequency standards rather than time standards, and comparison between two clocks is through their respective frequency ratios. Implementation of optically stabilized, self-referenced frequency combs, A and B, at each end of the link allows two local time scales, t_A and t_B to be established [15]. Pulse output of the each comb serves as the “ticking” of each clock. Direct comparison of the signals through traditional two-way time transfer techniques results in pico-second timing jitter, so a technique based on linear optical sampling (LOS) is implemented in order to lock the two local time scales together [15].

Introducing a third frequency comb at a different repetition rate from the combs that are to be synchronized allows a direct link to be established between t_A and t_B. Cross correlation of the link comb with each comb A and comb B, shown in **Figure 13**, generates interferograms from which it is possible to directly calculate an error signal representing clock drift between the two local frames. Direct control over the repetition rate of each frequency comb provides a feedback mechanism with which to close the loop, locking t_A to t_B. Details of the theory, experimental design, as well as results demonstrating multi-day femtosecond scale clock synchronization across multiple kilometer path lengths, in air, can be found in the paper submitted by NIST to the American Physical Society [15].

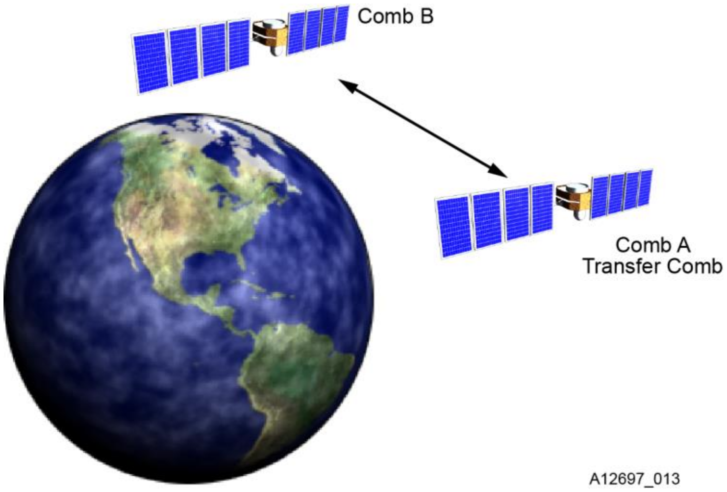

Figure 13: Clock frames and comb locations

CONCLUSION

The recent application of frequency comb based solutions to traditional aerospace measurements, such as those described here, has led to significant improvement in both the precision and accuracy with which those measurements can be made. Such breakthroughs as the frequency comb represent viable paths toward solutions for identified technology gaps standing in the way of future mission architectures [7]. It is the goal of the ongoing development of ultra-stable technologies at Ball Aerospace to enable future systems to meet increasingly challenging mission requirements, establishing new capabilities for customers in the space and tactical arenas.

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