Absolute ranging using frequency combs

W. C. Swann, I. Coddington, N. R. Newbury
National Institute of Standards and Technology, 325 Broadway M.S. 815 Boulder, CO 80305
Author contact: swann@nist.gov, phone 303.497.7381, fax 303.497.3387

Abstract: We present a technique for measuring absolute range that uses two mismatched frequency combs to measure distance over 1.5 m range with 10 nm level statistical uncertainty.
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Frequency combs can provide a very broadband output with very low timing jitter and are therefore ideal sources for precision ranging. Frequency combs have already played an important role in a number of ranging demonstrations.[1-6] Here we describe a coherent laser RADAR (LIDAR) system that uses dual, mismatched frequency combs to measure absolute distance.[7, 8] The system can be though of as either a massively parallel multiwavelength interferometer, very similar to previous dual comb spectroscopy work,[9-12] or as a coherent linear optical sampling setup, where an LO is used to interrogate the returning pulse stream from a signal laser[13-15].

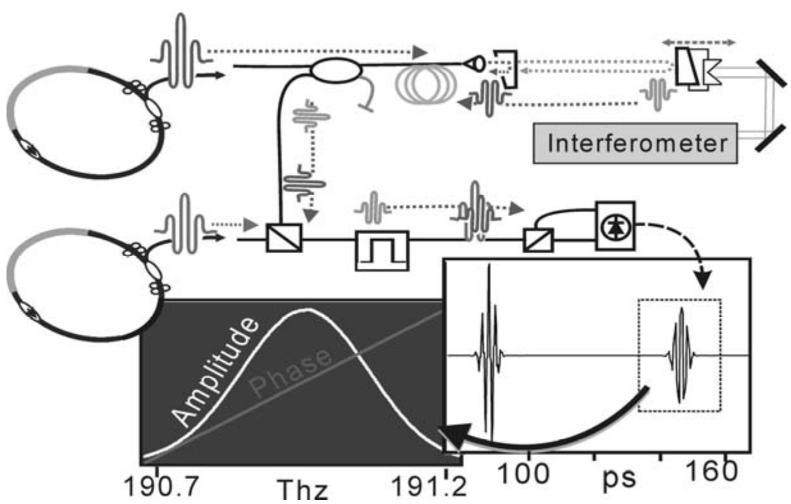

Figure 1: Schematic of the two-comb setup for measuring absolute distance between two reflectors. The upper comb signal pulse train (red) passes through a 50 % splitter, is collimated into a free beam, and is partially reflected from a stationary (reference) and also a moving mirror. (It is the distance between these two reflections that is measured.) These retro-reflected pulses pass back through the splitter and are combined with the pulse train from the lower (blue) LO comb. The comb repetition rates differ by 5 kHz, and sampling occurs when a LO pulse overlaps a signal pulse. The combined pulse trains pass through a 3 nm wide bandpass filter that broadens the pulses, resulting in better overlap. A conventional distance meter (having a corner cube on the moving mirror's back side) provides truth data. The inset shows the balanced detector output, with the x-axis rescaled to show optical delay time. The interferograms are generated as the signal and LO pulses walk through each other. Processing the interferograms as described in the text relies on the spectral amplitude and phase of the signal pulses.

Figure 1 shows a schematic of the setup. The concept is perhaps most easily considered in the time domain where it can be viewed as a "time-of-flight" measurement. In this view, one source outputs a stream of pulses that reflect off the target, while the second local oscillator source provides a precise linear time gate for measuring the return time of the first source [8]. The experimental setup is demonstrated in figure 1. The combs used in this experiment are generated by a pair of femtosecond fiber ring lasers operating at repetition rates (f_r) of 100,021 kHz and 100,016 kHz and spanning from ~1520 to 1575 nm. As in ref [12], we force a high degree of coherence between the combs by phase locking a tooth from each comb to a cavity stabilized cw laser at 1550 nm and a tooth from each comb to a second stabilized cw laser at 1535 nm. (The linewidth of these lasers is a few hertz here, but in practice need only be narrow enough to provide sufficient coherence length for the measurement). The signal laser passes through a 50:50 splitter (functioning as a circulator), optionally through a 1 km optical fiber delay line, and is launched into an air space path. It passes through a static reference plane, i.e., glass plate, which reflects ~ 4 %, and then through a target plane on a movable cart, which also reflects ~ 4 %. The position of the movable target is monitored by a standard fringe counting-interferometric distance meter. The reflected beams are then combined with the LO on a polarizing beam splitter, optically filtered to a 3 nm FWHM bandwidth, and measured with a balanced detector. The detected heterodyne signal is digitized at 14 bits synchronously with the local oscillator. The total detected signal power per reflection is ~0.4 μW or 4 fJ per pulse. Raw data for a target and reference plane separated by 2 cm are shown in the insert in figure 1.

Rather than fitting the time domain pulse of Figure 1, we take advantage of the system's phase stability to very precise measure the relative pulse arrival time by selecting (through time-gating) the pulse of interest and Fourier transforming it to find the spectral phase versus frequency, as illustrated in Figure 1. Specifically this allows one to isolate effects from dispersion and limits systematic effects related to fitting an improper pulse shape. The time gating limits systematic shifts by allowing us to collect the reference and target pulses on the same measurement path as well as suppressing spurious reflections. We subtract the spectral phase of the reference plane, and the difference is fit to a line whose slope yields the time delay and whose intercept (calculated at the carrier frequency) yields the carrier phase. A coarse "pulse-based" measurement of the distance is obtained by multiplying the measured time delay by $v_{group}/2$, where the group velocity v_{group} is calculated at the carrier frequency and measured atmospheric conditions. A fine "carrier-phase-based" measurement of the distance is obtained by multiplying the carrier phase by $\lambda_{air}/(2\pi)$ and adding some integer number of optical wavelength λ_{air}.

We will present results demonstrating that this system can reach an uncertainty of 3 μm in 200 microseconds, averaging down with ultimate uncertainties below 3 nm at 0.5 seconds. This approach to length metrology should find uses in large-scale manufacturing[16] and in future formation-flying of satellites for space-based instruments.[17, 18]

References

[1] K. Minoshima and H. Matsumoto, "High-accuracy measurement of 240-m distance in an optical tunnel by use of a compact femtosecond laser," Appl. Opt. **39**, 5512-5517 (2000)

[2] W. C. Swann and N. R. Newbury, "Frequency-resolved coherent lidar using a femtosecond fiber laser," Opt. Lett. **31**, 826-828 (2006)

[3] K.-N. Joo and S.-W. Kim, "Absolute distance measurement by dispersive interferometry using a femotsecond pulse laser," Opt. Exp. **14**, 5954-5960 (2006)

[4] J. Jonghan, *et al.*, "Absolute length calibration of gauge blocks using optical comb of a femtosecond pulse laser," Optics Express **14** (2006)

[5] Y. Salvade, *et al.*, "High-accuracy absolute distance measurement using frequency comb referenced multiwavelength source," Applied Optics **47**, 2715-2720 (2008)

[6] N. Schuhler, *et al.*, "Frequency-comb-referenced two-wavelength source for absolute distance measurement," Optics Letters **31**, 3101-3103 (2006)

[7] I. Coddington, *et al.*, submitted (2008)

[8] N. R. Newbury, *et al.*, " Lidar with femtosecond fiber-laser frequency combs," in *Proceedings of Coherent Laser Radar Conference*, 2007)

[9] A. Schliesser, *et al.*, "Frequency-comb infrared spectrometer for rapid, remote chemical sensing," Opt. Express **13**, 9029-9038 (2005)

[10] S. Schiller, "Spectrometry with frequency combs," Opt. Lett. **27**, 766-768 (2002)

[11] T. Yasui, *et al.*, "Terahertz frequency comb by multifrequency-heterodyning photoconductive detection for high-accuracy, high-resolution terahertz spectroscopy," Appl. Phys. Lett. **88**, 241104-1 - 241104-3 (2006)

[12] I. Coddington, *et al.*, "Coherent Multiheterodyne Spectroscopy Using Stabilized Optical Frequency Combs," Phys. Rev. Lett. **100**, 103902-013906 (2008)

[13] C. Dorrer, *et al.*, "Linear Optical Sampling," Photonics Technology Letters **15**, 1746-1748 (2003)

[14] C. Dorrer, "High-Speed Measurements for Optical Telecommunication Systems," IEEE Journal of Quantum Electronics **12**, 843-858 (2006)

[15] P. A. Williams, *et al.*, "Vector signal characterization of high-speed optical components by use of linear optical sampling with milliradian resolution," Phot. Tech. Lett. **accepted for publication** (2008)

[16] W. T. Estler, *et al.*, "Large-scale metrology - An update," Cirp Annals-Manufacturing Technology **51**, 587-609 (2002)

[17] M. Fridlund, "Future space missions to search for terrestrial planets," Space Science Reviews **135**, 355-369 (2008)

[18] N. White, "X-ray astronomy - Imaging black holes," Nature **407**, 146-147 (2000)