Countering nonlinearity in digitization for precise dual-frequency comb spectroscopy.

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Abstract: In order to measure gas concentrations with sub-percent accuracy, we measure, simulate and propose solutions for removing analog to digital converter (ADC) imposed bias on the recorded interferograms in dual comb spectroscopy.

Dual-comb absorption spectroscopy (DCS) is well suited to measure precise gas concentrations [1], in part, due to the absence of optical induced distortions of the measured spectrum. However, there is still the potential for distortions in the recording of the rf interferograms. Here we examine the impact of distortions imposed by the bit-to-bit differential nonlinearity (DNL) common in ADCs in the bandwidth range of interest to DCS. We also propose a solution in the form of an additive dither signal to wash out some of these effects. The experiment is shown in Fig. 1 and consist of two frequency combs, centered at 1650 nm (pulse repetition rate = 200 MHz), used to record the spectrum from a 99.999% methane absorption cell (5.45 cm, 10 kPa). The electronic RF signal goes to a data acquisition (DAQ) device, which first uses an ADC to digitize the interferogram. We show that nonlinearity in this ADC can distort the apparent absorbance in this interferogram by >1%, which can make the ADC the dominant source of DCS bias. However, one can manipulate the electronic signal between the photodetector and DAQ to reduce this digitization error to <0.2%.

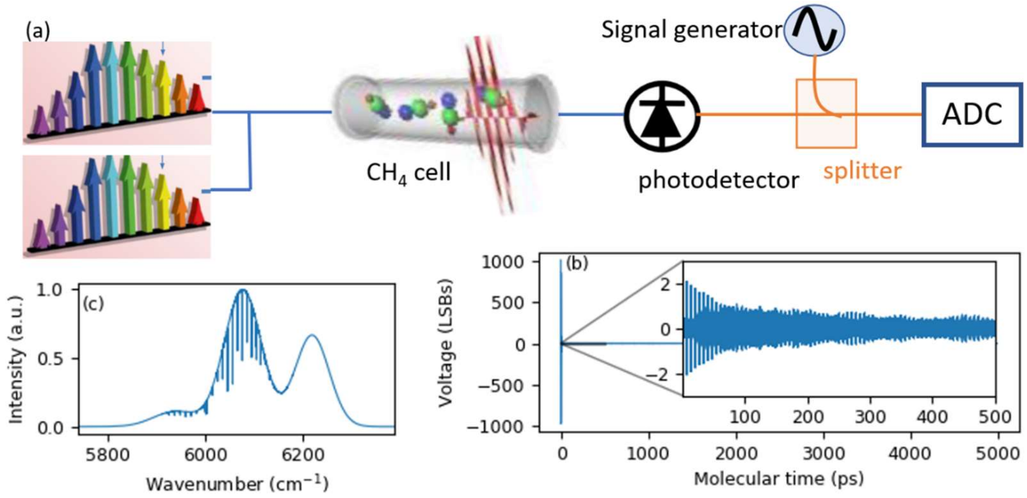

Figure 1: (a) Schematic of dual-comb spectrometer. Blue traces are optical signals, orange traces are electrical signals. A signal generator adds a sine wave dither to measured interferogram through an RF splitter. (b) Simulation of digitized interferogram without dither. Centerburst spans 2000 least significant bits (LSBs) on the ADC, and (inset) free-induction decay signal spans 4 LSBs. (c) Simulated frequency-domain methane spectrum corresponding to interferogram in (b).

ADCs can be linear over the full range but still have small scale nonlinearities that can impact small signals. The challenge in DCS, depicted in Fig. 1b, is that the raw signal consists of a large centerburst signal followed by a low-voltage free-induction decay (FID) signal containing absorption information for small molecules. The FID portion of this signal in Fig. 1b is 0.2% the amplitude of the centerburst, so it can be sensitive to these small-scale ADC distortions. To understand the DNL in our AC coupled, 200MHz, 14-bit ADC (TI ADS62P49) we record an analog-filtered sine wave and quantify the difference between the digitized signal and fitted sine wave. The digitization error is visible in Fig. 2b and shows a sawtooth pattern with typical periodicity of 16 LSBs.

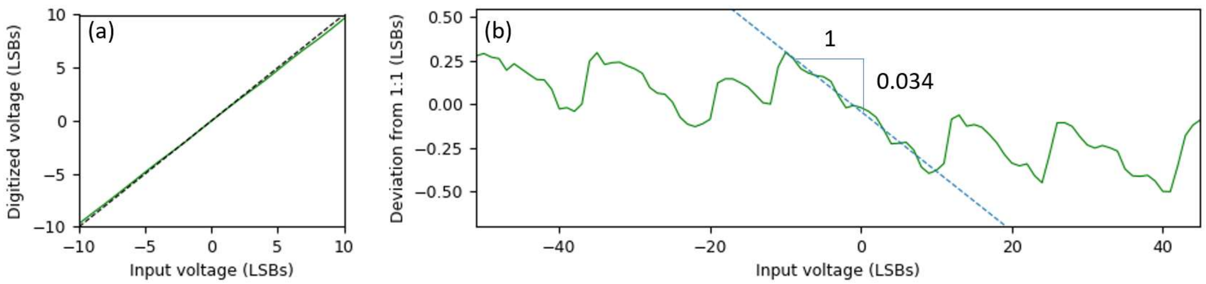

Figure 2: Measured digitization bias. (a) transfer curve from input signal to digitized output. (b) bias determined from difference between transfer curve and parity line. Bias has sawtooth structure with period 16 counts and a slope of -3.4%.

The slope of this sawtooth is -3.4% (±0.6%); therefore, an FID signal spanning less than 14 counts on the ADC should be compressed by 3.4%. However, if the electrical signal is manipulated so that the FID spans over a larger portion of the ADC bias function, then the overall FID amplitude will be less susceptible to this sawtooth nonlinearity. In order to spread this FID voltage across the ADC, we propose adding a sine wave to the interferogram.

In Fig. 3, we explore the effect of an additive sine-wave dither on the interferogram with simulation and experiment. The simulated data is a HITRAN [3] CH_4 spectrum on a Gaussian intensity spectrum. We Fourier transform this synthetic spectrum, add white noise with standard-deviation of 2 ADC counts, add a 1 MHz sine wave of different amplitudes and random phase, and then apply the ADC digitization bias from Fig. 2b. We add 5000 of these synthetic interferograms together to simulate a 25-second measurement, then fit the resulting spectrum using the cepstral fitting method [2] with a 25 ps high-pass filter.

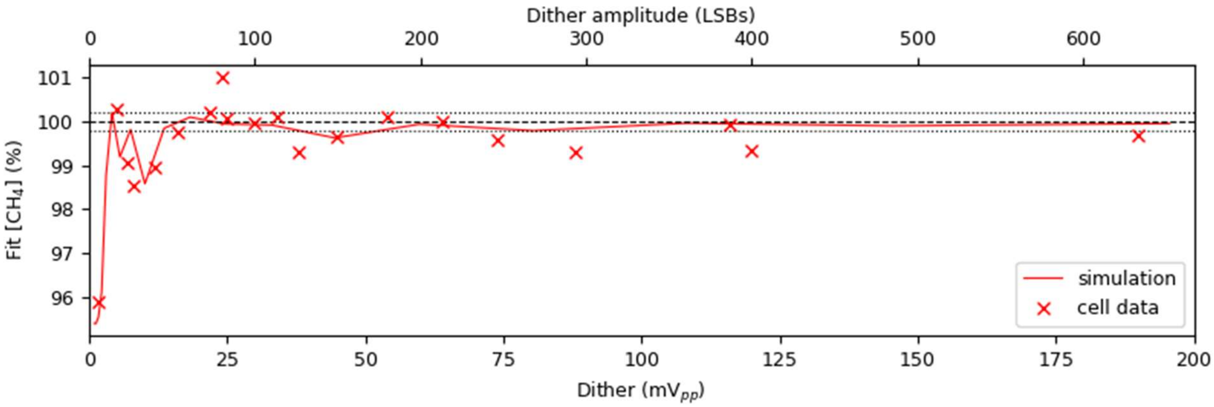

Figure 3: Adding a sine-wave dither to interferogram reduces the digitization bias. Solid trace indicates fits with simulated interferograms, and markers indicate fits of measured interferograms through a 5.45cm, 10kPa pure CH_4 cell. Sine waves with amplitude > 60mV_{pp} reduce digitization bias below 0.2% (dotted lines).

Both data and model show good agreement, suggesting that ADC bias is the primary error source in the zero-dither measurement. Nonlinearity in the ADC can produce a 4% change in the fitted concentration from dual-comb absorption spectroscopy. The effect of this negative-sawtooth digitization error in this ADC (Fig. 2b) is to reduce the apparent absorbance of the measurement. We show that by adding a 1 MHz electrical sine wave to the interferogram of sufficient amplitude, we can reduce this digitization bias to <0.2%. Other methods to reduce digitization bias, such as adding white noise, chirping the interferogram or a post gain correction, will also be explored.

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[3] I.E. Gordon, L.S. Rothman, R.J. Hargreaves et al. J. of Quant. Spectros. and Rad. Trans. **277**, 107949 (2022).