Quantifying Frequency Response of a Low-power, Closed-path CO_2 and H_2O Eddy-covariance System

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Introduction

The eddy-covariance technique is widely used to quantify the exchange of heat, carbon dioxide, water vapor, and other trace gases between Earth's surface and the atmosphere.[1] These data provide the information required to analyze carbon storage properties of various ecosystems, create accurate gas exchange budgets, and compare emissions characteristics between various land use such as agricultural lands, forestlands, sagebrush steppe, or urban plots and landfills.

The eddy-covariance technique requires the measurement of vertical wind speed and a scalar of interest, such as CO_2 or H_2O. Ideally, these measurements would have low noise and high frequency response and would be colocated and synchronized. Wind velocity is typically measured with a three-dimensional ultrasonic anemometer, such as Campbell Scientific's CSAT3. CO_2 and H_2O are typically measured with an infrared gas analyzer, commonly abbreviated to IRGA, of which there are two basic types: open path and closed path, each with their own set of advantages and disadvantages.

The accuracy of eddy-covariance flux measurements is critically dependent on the analyzer's frequency response. While closed-path analyzers offer improved performance in humid or actively precipitating conditions and also give the option of automatic zero and span, their frequency response is generally worse than open-path analyzers due to the residence time in the sample cell and mixing along intake tubes and within the sample cell. H_2O frequency response can suffer additional losses due to interaction with the surface of the intake tube and sample cell. The traditional approach to maintain good frequency response in a closed-path system is to use a high sample-flow rate or reduce the pressure in the sample cell, or a combination of both. This approach requires a relatively high-power pump making it difficult to operate without close access to AC mains power, which limits use in remote locations.

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[1] http://fluxnet.ornl.gov/ Accessed 10/11/2012

Campbell Scientific's CPEC200 closed-path, eddy-covariance system combines all of the advantages of a closed-path system yet achieves good frequency response with low power consumption. The CPEC200 consists of the EC155 closed-path CO_2/H_2O gas analyzer, a CSAT3A three-dimensional sonic anemometer sensor head, a CR3000 datalogger that stores both raw and processed data, a low-power sample pump, and an optional valve module that allows automated zero and span. Various options for storing and exchanging data are available for monitoring and downloading data.

The EC155 provides excellent frequency response at low power by using a very small sample cell volume of 5.9 ml. It has a sample cell residence time of 50 ms at the nominal 7 LPM flow. Traditional closed-path analyzers, which use a larger sample volume, require higher flow rates to achieve this residence time. High flow rate requires a larger pump that consumes more power. The very small sample cell of the EC155 allows the CPEC200 to achieve a total system power of 12 W, comparable to traditional open-path IRGAs.

This paper characterizes the frequency response of the EC155 using a novel laboratory technique. This technique can be used to accurately and precisely characterize the frequency response of a closed-path analyzer, a sample tube, or other components (such as filters) that are used in the sample path. The technique described involves injecting an impulse of dry CO_2 at the system inlet, measuring the impulse response, and then Fourier transforming and normalizing to give the frequency response. The response is compared to a simple model that includes a term representing ideal plug flow through the sample cell and an exponential mixing term.

Background

Closed-path IRGAs, such as the EC155, measure CO_2 and H_2O within an enclosed sample cell. They require a sample pump to pull the air sample through the sample cell. The EC155 closed-path analyzer is shown in Figure 1 with a CSAT3A sonic anemometer.

Figure 1. EC155 closed-path infrared gas analyzer

Closed-path IRGAs can lose frequency response due to mixing in the intake tube that brings the air sample to the analyzer.[2] These losses can be worse for H_2O due to interaction of vapor with the wall of the sample tube.[3] Losses due to sample tube interaction can be mitigated by using relatively short sample tubes[4] or by using a very short, heated intake tube with a small inner diameter.

Frequency response of eddy-covariance analyzers is typically characterized by comparing spectra from the sonic anemometer's virtual temperature and the scalar of interest. This technique has the advantage that it gives a complete characterization of a system as it is being used in the field. It is, however, subject to ambient conditions. Wind speed and direction, cloud cover, temperature, humidity, and time of day can all determine both the ambient conditions as well as the input signal (fluctuations in temperature, vertical wind, CO_2, and H_2O). Given this, the typical approach requires sampling for an extended duration, typically a season or a year, and then binning the data or selection of a "golden day" having the desired conditions. This becomes impractical for studies that aim to compare aspects of the test setup such as intake tube length or diameter, sample flow rate, tubing material, filter design, or ambient conditions such as temperature and humidity.

Theory

The frequency response of a system is defined as the ratio of its output to its input and given as a function of frequency. In an ideal system the value would be 1.0 at all frequencies. In a real system, fluctuations in CO_2 or H_2O tend to be dampened by mixing or by path averaging. The frequency response quantifies this loss of high-frequency information.

The frequency response of the EC155 was tested in the laboratory by injecting an impulse of high-concentration CO_2 into the sample air stream. This CO_2 "puff" approximates a delta function; a spike which has zero width. A delta function has equal energy at all frequencies. Therefore, its Fourier transform is flat making it an ideal input for testing the frequency response of a system. The frequency response is the output as a function of frequency divided by the input spectrum. In practice, it is not possible to generate an impulse with zero width. However, if the pulse is narrow compared to the response of the system, it provides a good measurement of frequency response.

In an ideal analyzer, there is no mixing within the sample cell as the air flows through the cell. The following scenario describes this ideal situation. When a concentration impulse enters the sample cell it changes the total number of CO_2 molecules in the path, changing the measured concentration. As this puff of CO_2 travels down the sample cell, the measured CO_2 concentration remains constant. When the impulse exits the sample cell the concentration falls quickly to the background level. The time series will be a rectangle function with a height related to the amount of CO_2 in the impulse and duration equal to the travel time.

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[2] Massman, W J. 1991. "The Attenuation of Concentration Fluctuations in Turbulent Flow through a Tube," *Journal of Geophysical Research*, **96**, D8, pp. 15,269 – 15,273.

[3] Runkle, B.R.K., Wille, C., Gažoviˇc, M., and Kutzback, L. 2012. "Attenuation Correction Procedures for Water Vapour Fluxes from Closed-Path Eddy-Covariance Systems," *Boundary-Layer Meteorology*, **142**, pp. 401 – 423.

[4] Fratini, G., Ibrom, A., Arriga, N., Burba, G., and Papale, D. 2012. "Relative humidity effects on water vapour fluxes measured with closed-path eddy-covariance systems with short sampling lines," *Agricultural and Forest Meteorology*, **165,** pp. 53 -63.

These are represented below as the ideal situation in which there is only one parameter; the residence time in the sample cell. The residence time is:

$$\tau = V / F$$

where: τ = residence time
V = sample cell volume (5.9 ml)
F = volumetric flow (7 LPM)

Converting the units gives the sample cell residence time, 50 ms.

At the other extreme, the sample cell can be modeled as a perfect mixing volume. For this case it is assumed that as air enters the sample cell it is instantly mixed throughout the entire volume of the sample cell. For this case the concentration is described as an exponential function of time:

$$C(t) = e^{(-t/\tau)}$$

where: *C(t)* is the concentration as a function of time
e is Euler's number
τ is the mixing time constant

The mixing time constant τ is defined by the sample cell residence time as given above. The time series for these two cases are shown in Figure 2 with the no-mixing case in green and the complete-mixing case in red. The Fourier transform of these two time series shows the frequency response of the two extreme scenarios. The complete-mixing case has significantly lower response from below 1.0 Hz to above 15.0 Hz. This indicates that mixing in the sample cell degrades the measurement of fluctuations through the range of frequencies that transport flux.

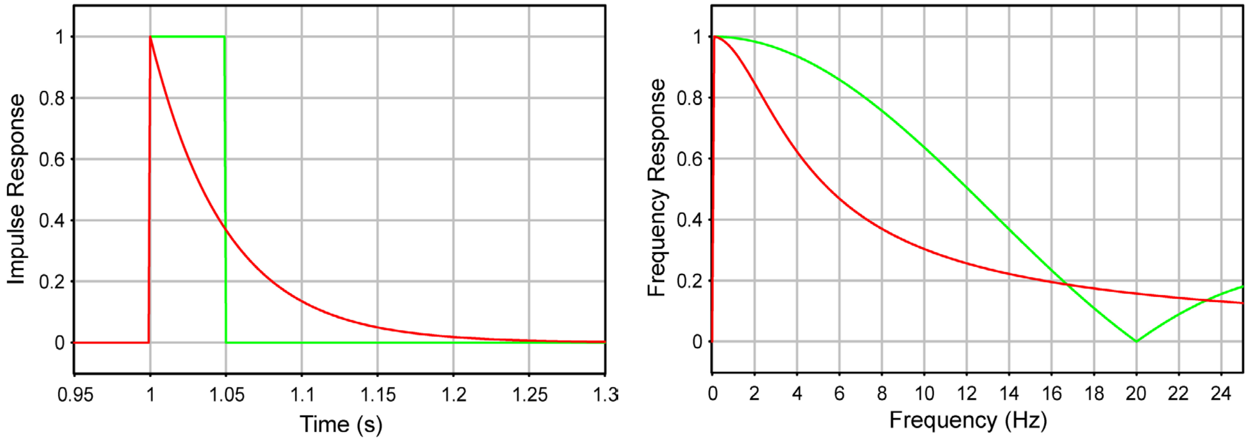

Figure 2. Theoretical impulse responses (left panel) and frequency responses (right panel) for no mixing (green) and complete mixing (red)

These two cases represent the bounds for the frequency response of a real sample cell. A physical system will not be described perfectly by either extreme. Assuming a cylindrical geometry, the aspect ratio of a volume determines how it behaves. A long narrow sample cell, for example, will tend to have little mixing, particularly if the Reynolds number is high enough for turbulent flow. A sample cell of roughly equal diameter to length will approach the complete mixing model.

The length of the EC155 sample cell is 11.77 cm (4.63 in), 14.8 times the diameter of 0.80 cm (0.313 in). Given these dimensions, flow in the EC155 is not likely to approach the complete mixing scenario. However, the Reynolds number for the nominal flow (7 LPM) is 900 to 1200, which is well below the threshold for turbulent flow, so there is likely to be significant mixing as the an air sample travels down its length.

The no-mixing and complete-mixing models can be combined to give a more realistic model for the behavior of a sample cell. The proposed empirical model is a convolution of the two cases. This model has two parameters: the (no mixing) travel time and the mixing-time constant. Figure 3 shows the model evaluated for a mixing-time constant from 0 to 50 ms, with a travel time of 50 ms in all cases.

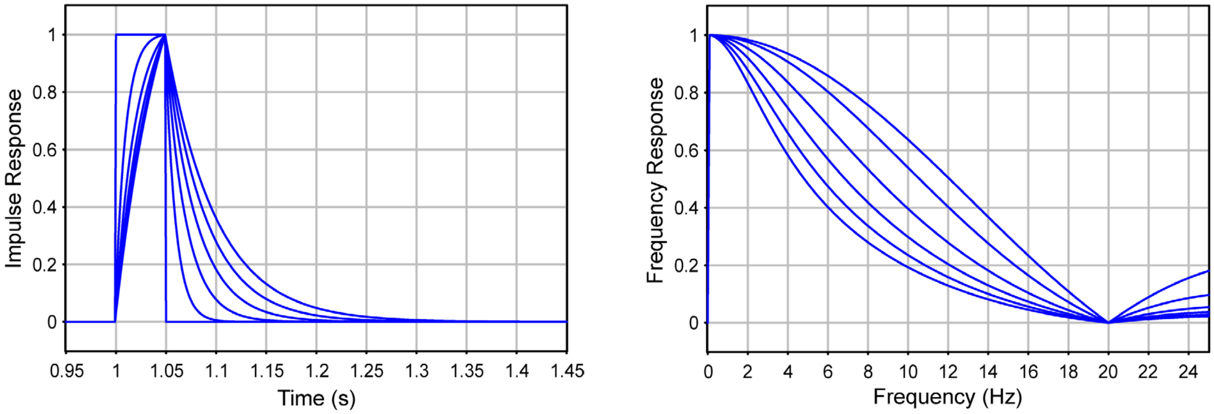

Figure 3. Modeled time series (left panel) and spectrum (right panel) for mixing time constants 0 to 50 ms

A commonly used figure of merit for a system's frequency response is the half-power bandwidth, also known as the cutoff frequency. This is the frequency at which the power spectrum falls to 0.5. The frequency response is an amplitude spectrum, not a power spectrum, so the bandwidth is defined as the frequency where the response falls to the square root of 0.5 or 0.707. The bandwidths for the modeled cases are listed in Table 1.

Table 1. Mixing time and corresponding bandwidth used for modeling

Mixing time constant (ms)	Bandwidth (Hz)
0	8.9
10	7.5
20	5.7
30	4.4
40	3.6
50	3.0

A comparison of the mixing time constant to the travel time gives a useful figure of merit for an analyzer sample cell. A small mixing-time constant compared to the residence time indicates little mixing, and the performance will approach the ideal. A mixing-time constant that approaches the residence time indicates relatively poor frequency response.

Methods

Frequency response testing was accomplished by using a standard EC155 closed-path gas analyzer with a surrogate intake tube that allowed pulse injection. The surrogate tube was a straight length of the same stainless steel tubing 0.58 m (23.0 in) long, with 2.7 mm (0.105 in) inner diameter as is used in the normal EC155 intake assembly. The EC155 intake assembly is heated and insulated with a rain diverter and filter at the inlet. The surrogate intake was unheated.

The air sample collected in these experiments consisted of ambient room air pulled through a 200 L mixing volume. The surrogate intake tube was connected to the mixing volume by a short piece of plastic tubing (Bevaline IV, 0.250 in OD, 0.125 in ID). This plastic tubing was slipped over the end of the stainless steel tubing. The valve for the pulse injection was inserted through the wall of the plastic tubing just upstream of the stainless steel tube inlet. The flow was controlled at 7 LPM which is nominal for the CPEC200 system. The sample cell pressure was 84.1 kPa; 3.3 kPa below ambient, also typical of normal operation.

The CO_2 pulse was injected with a fast-acting solenoid valve (VHS micro-dispense valve, The Lee Co., Westbrook, CT) driven with a spike-and-hold driver, (part number IECX0501350AA, The Lee Co.) The valve is rated for an actuation time of 0.25 ms. The spike-and-hold driver holds the valve open for a time that is adjustable from 0.1 to 5.0 ms. An experiment to test the procedure found no difference from adjusting the valve-open time over its full range. In every case, the valve was sufficiently fast to have no noticeable effect on the measured frequency response even at very high flow rates (data not shown). The VHS valve was configured with a 0.0075-in ID orifice. The pulse consisted of 1.5% CO_2 in compressed air. The configuration described above is shown in Figure 4.

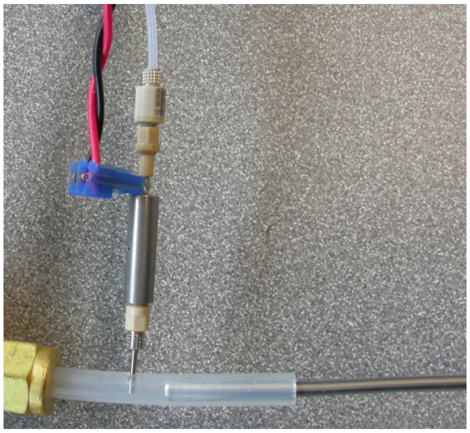

Figure 4. Experimental configuration for injecting CO_2 pulses

A CR3000 datalogger collected data from the EC155 at 50 Hz and triggered the injection valve every 10 s. Multiple pulses were collected to evaluate repeatability of the technique and to provide averaging for noise reduction.

Results

The ambient room air contained approximately 800 ppm CO_2 and 14.5 ppt H_2O. Each pulse raised the measured CO_2 concentration by approximately 150 ppm. This is 1/100 of the actual concentration (1.5%, or 15,000 ppm) that was injected. This inferred a volume injected of approximately 60 µl (1/100 of the sample cell volume). The H_2O pulse was approximately –0.14 ppt. This is approximately 1/100 of the ambient concentration, consistent with an injection volume of approximately 60 µl.

As the ambient CO_2 concentration and humidity changed throughout the experiment period, the background concentrations were calculated as moving averages over 10 s (the pulse-injection period). This background was subtracted from the measurements. A total of 449 pulses were extracted and overlaid, as shown in Figure 5.

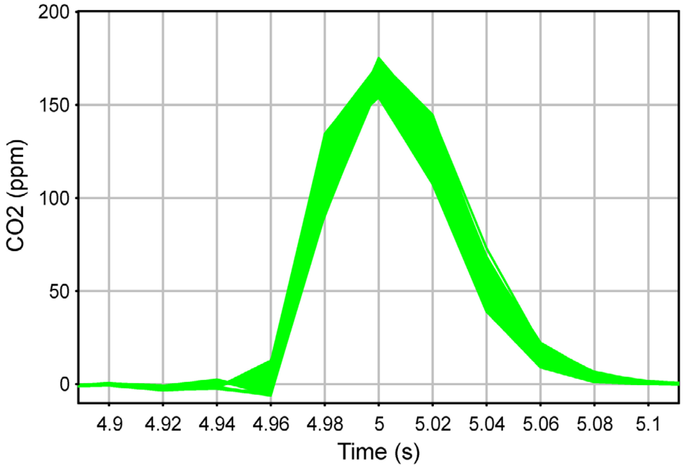

Figure 5. Measured CO_2 time series (449 scans overlayed)

Variation among the scans is caused by timing jitter between the EC155, which is measuring at 150 Hz, and the datalogger, which samples at 50 Hz. The high signal-to-noise ratio for the CO_2 pulses allowed a comparison of the spectrum of a single scan to the ensemble average of all 449 scans. No significant difference was observed, indicating the averaging of multiple pulses of slightly different phase did not affect the result (data not shown). This gave confidence that the H_2O pulses could be averaged to achieve a reasonable precision. The ensemble average pulses for CO_2 and H_2O are shown in Figure 6.

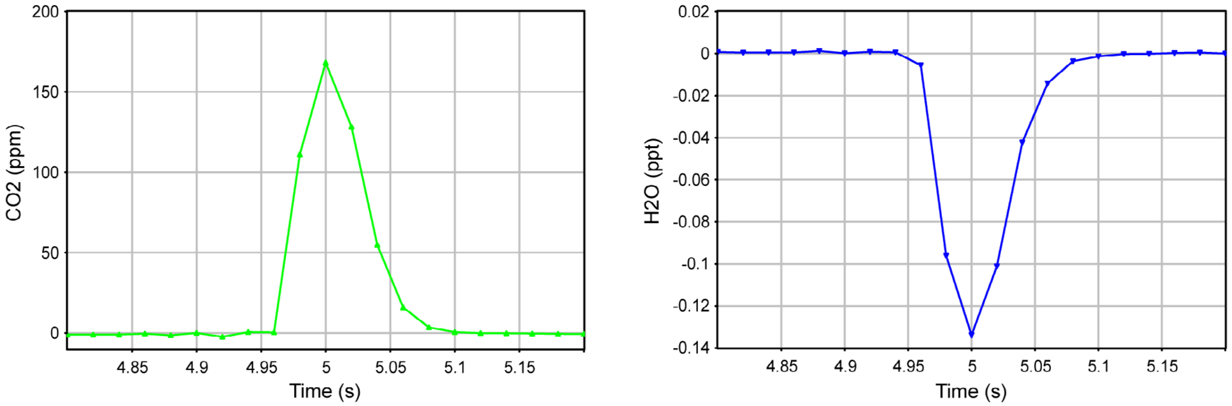

Figure 6. Ensemble average for CO_2 (left panel) and H_2O (right panel) time series

In Figure 7 the H_2O pulse is inverted, and both have been normalized to their peak, to allow a comparison. The two curves are nearly identical, indicating no increased lag or mixing due to the interaction of H_2O with the surfaces of the intake tube or sample cell.

The frequency response was calculated from these averaged, normalized impulse responses by normalizing the Fourier transform of each to a value of 1.0 at low frequency (0.1 to 0.5 Hz). The resulting spectra are shown in Figure 7.

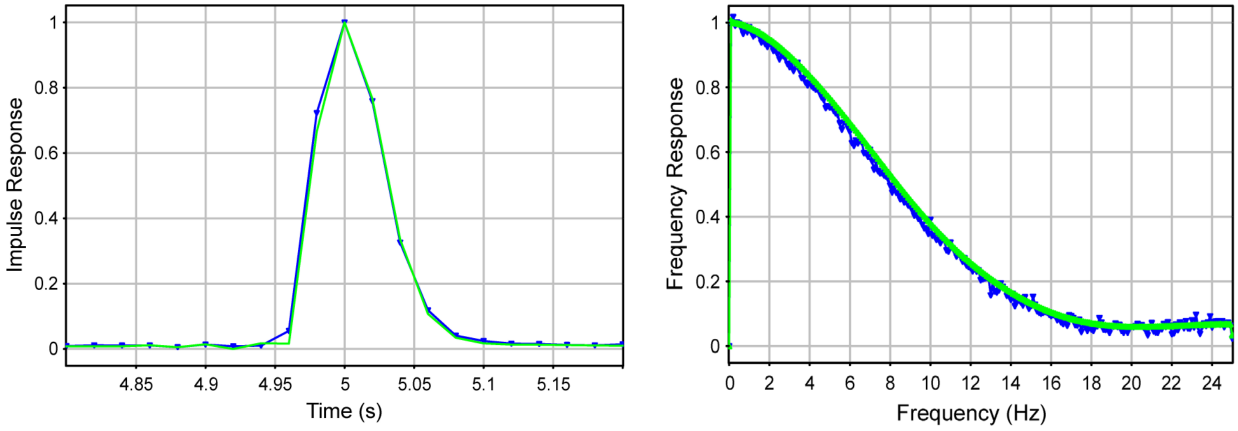

Figure 7. CO_2 (green) and H_2O (blue) time series overlayed (left panel) and frequency responses (right panel)

The CO_2, shown in green, and H_2O, shown in blue, are nearly identical, as expected from the similar impulse responses. The H_2O clearly has more noise than CO_2, and may be slightly lower than CO_2 from 2 to 10 Hz. The frequency response beyond 18 Hz is relatively flat at approximately 0.06. This indicates the 50 Hz sample rate was not fast enough to strictly satisfy the Nyquist criterion. This upper frequency range may be contaminated by response aliased from above 25 Hz. This aliased response, however, is not likely to extend all the way down to the useful spectral range below 10 or 15 Hz. This indicates the 50 Hz sampling was fast enough to adequately measure the frequency response of the EC155.

The CO_2 frequency response was compared to the theoretical models from Figure 3. These models assumed the nominal travel time of 50 ms and mixing-time constants from 0 to 50 ms. Figure 8 (left panel) shows this comparison. The measured frequency response (green) lies nearly on top of the theoretical model for 20 ms mixing. A slightly better fit is obtained by adjusting the model parameters to 54 ms travel time and 18 ms mixing-time constant, as shown in the right panel of Figure 8.

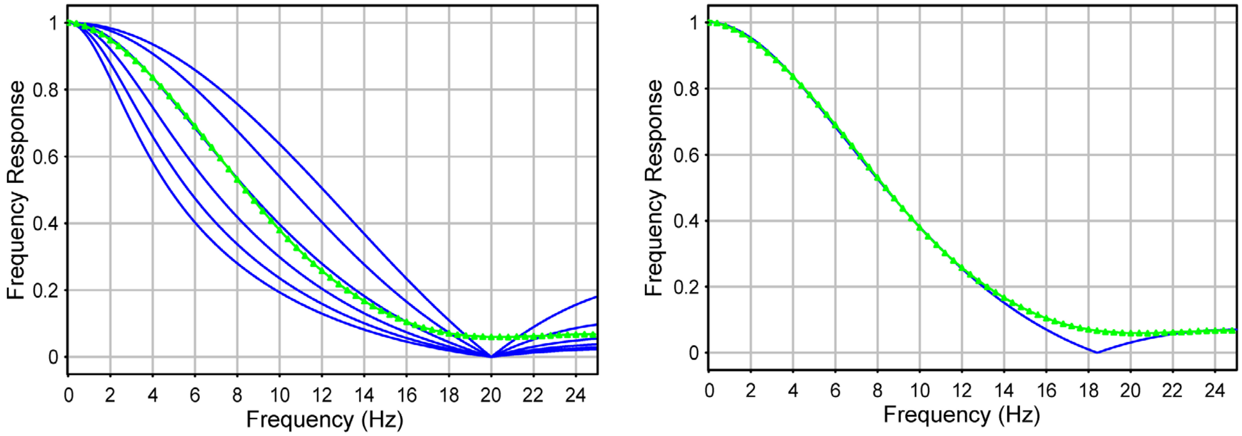

Figure 8. CO_2 frequency response compared to theoretical models (left panel) and empirical model (right panel)

The EC155 frequency response is shown in Figure 9 with a logarithmic x-axis. For comparison, Figure 9 also shows the theoretical frequency response for an open-path analyzer at a low wind speed of 1 m s^{-1} (red line). This model accounts for averaging along the IRGA optical path[5] (15.37 cm assumed, corresponding to the EC150). As shown in Figure 9, the measured EC155 frequency response is actually better than the model for the open-path analyzer. However, the open-path frequency response improves with higher wind speed. The EC155 does not depend on wind speed, so the frequency response of the open-path IRGA will be better than the EC155 for most wind conditions.

The black line in Figure 9 compares the EC155 to traditional closed-path IRGAs. Fratini et al determined a CO_2 frequency response bandwidth of 1.1 Hz for in a closed-path system with a short (1.0 m) sampling tube and 0.95 Hz for systems with somewhat longer (4.0 m) tubes. Each system showed H_2O frequency response that was substantially worse, especially at high relative humidity.[4]

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[5] Silverman, Bernard A. 1968. "The effect of spatial averaging on spectrum estimation," *Journal of Applied Meteorology*, **7**, pp. 168-172.

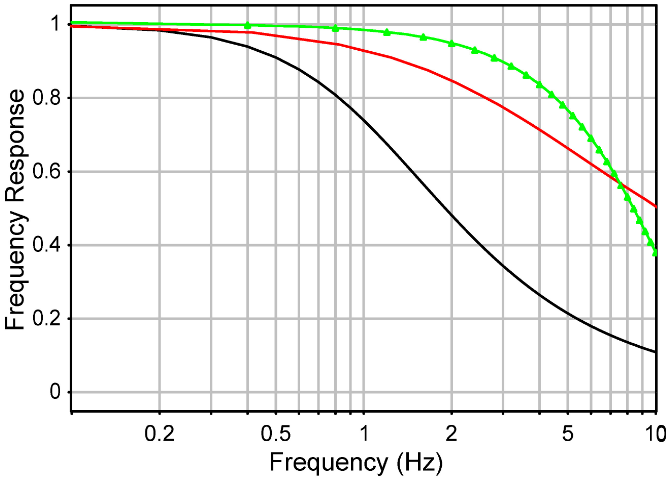

Figure 9. Frequency response of EC155 compared to traditional closed-path IRGA (black line) and open-path IRGA at low wind speed (red line)

Summary

The frequency response of the EC155 was measured with a novel pulse-injection technique. Excellent frequency responses were obtained for both CO_2 and H_2O at 5.8 Hz half-power bandwidth and showed remarkable agreement with each other. The results also showed a strong correlation between that of the modeled sample-cell residence time of 54 ms and the expected time of 50 ms. The modeled exponential mixing time constant of 18 ms is much shorter than the measured residence time, indicating that little mixing occurred in the intake tube or the sample cell.

The EC155 frequency response is much better than traditional closed-path IRGAs, and is comparable to that of open-path IRGAs at low wind speeds. This excellent frequency response, even at a lower power, is possible in part because of the location of the analyzer relative to the sonic path. This close proximity allows a short (0.6 m) intake tube that reduces mixing within the intake tube. The sample cell volume is only 5.9 ml to minimize the residence time of the sample; for example 50 ms at 7 LPM sample flow. A key design parameter of the system was to lower the pressure drop so that the power required to operate the pump is significantly reduced.

Traditionally, the frequency response of H_2O exhibits losses due to the interactions with the surface of the intake tube and the sample cell. With the small sample cell volume and short intake tube of the EC155, however, the frequency response of H_2O is preserved and shows strong agreement with that of CO_2.