

EC150, IRGASON, or EC155: Which CO₂ and H₂O Eddy-Covariance System Is Best for My Application?

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Introduction

The eddy-covariance (EC) 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 EC technique requires the measurement of vertical wind speed and a scalar of interest, such as CO₂ or H₂O. Ideally these measurements would have low noise and high frequency response, and they would be colocated and synchronized. Wind velocity is typically measured with a three-dimensional ultrasonic anemometer, such as Campbell Scientific's CSAT3. CO₂ and H₂O are typically measured with an infrared gas analyzer, commonly abbreviated to IRGA, of which there are two basic types: open path and closed path. Campbell Scientific manufactures three different IRGAs: two open path, the EC150 and the IRGASON; and one closed path, the EC155. All are designed specifically for EC flux measurements.

As each of these analyzers has distinct advantages and disadvantages, this paper gives a general overview and comparison of the three. Discussed are parameters such as frequency response, power requirements, user involvement for maintenance and calibration, and a general comparison of cost for each system.

Infrared Gas Analyzers

Open-path

Open-path IRGAs measure the amount of CO₂ and H₂O in the atmosphere by measuring the absorption of an infrared beam that is propagated through the atmosphere from a source to a detector. Campbell Scientific manufactures two open-path IRGAs, the EC150 and the IRGASON. While the IRGA itself is the same in either, the EC150 is designed to be used with the CSAT3A sonic anemometer head, while the IRGASON combines the IRGA with the sonic anemometer as a single unit.

EC150

The EC150 is a good example of an open-path IRGA. Paired with a CSAT3A sonic anemometer head as shown in Figure 1, it provides the basic measurements required for CO₂ and H₂O eddy covariance. The wind and CO₂/H₂O measurements have low noise and good frequency response. While measurements are synchronized in this configuration, they are not exactly colocated.

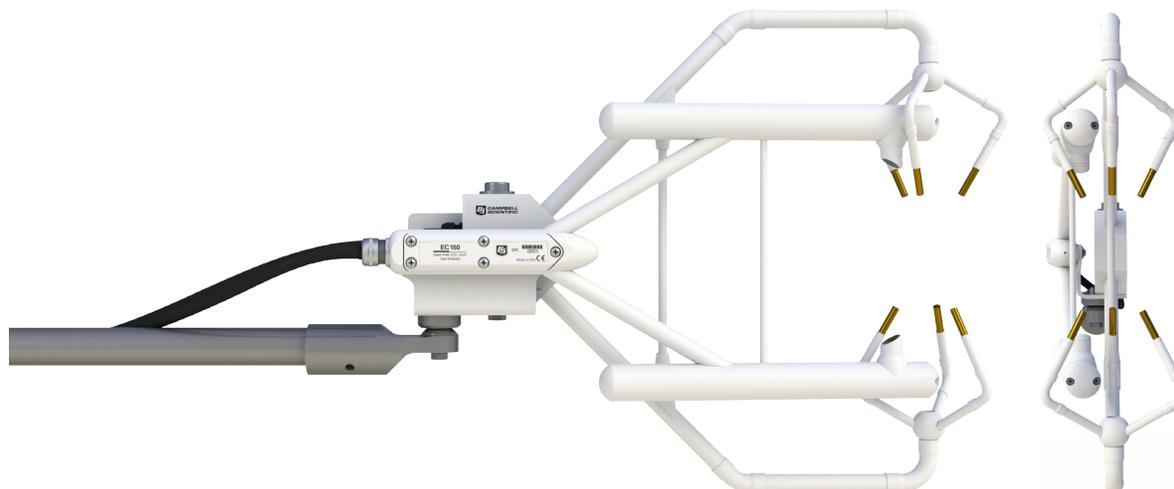


Figure 1. EC150 open-path CO₂/H₂O gas analyzer with CSAT3A sonic anemometer head

¹<http://fluxnet.ornl.gov/>. Accessed 10/22/2012

IRGASON

An advanced-generation EC sensor, the IRGASON, fully integrates the IRGA with a sonic anemometer head. CO₂, H₂O, and wind measurements are truly colocated. This integrated approach also avoids duplication of support structure that would disturb natural wind flow and introduce small error into the wind measurements.



Figure 2. IRGASON integrated open-path CO₂/H₂O gas analyzer and 3D sonic anemometer

Closed-path

Closed-path IRGAs measure the CO₂ and H₂O within an enclosed sample cell. They require a sample pump to pull the air sample through the sample cell.

EC155

Campbell Scientific's EC155 closed-path analyzer is shown below with a CSAT3A sonic anemometer head. These are the primary sensors in the CPEC200, a complete closed-path EC system that includes a sample pump, datalogger, and an optional valve module that facilitates automatic, on-line zero and span.

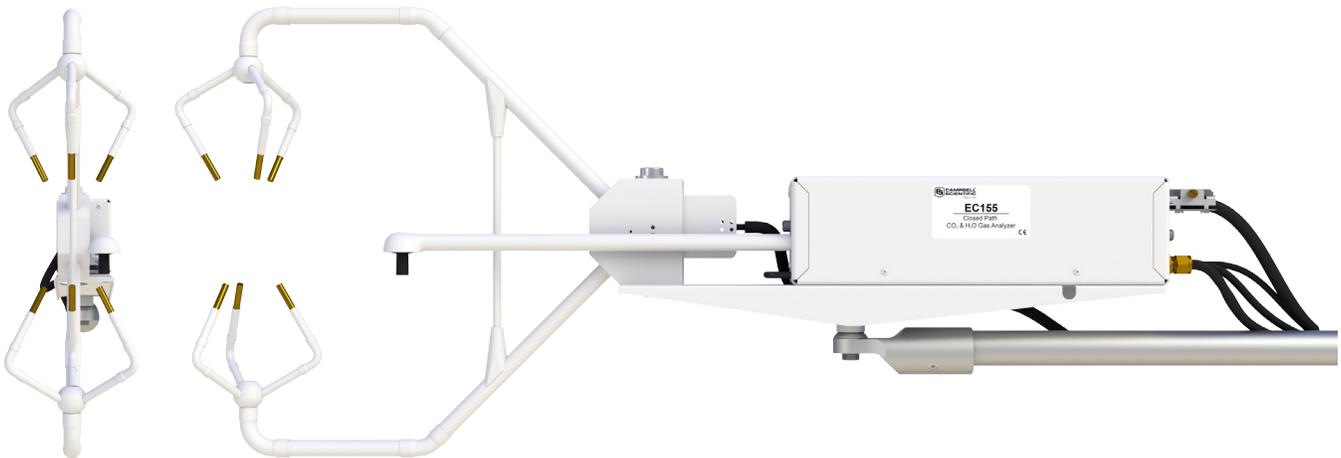


Figure 3. EC155 closed-path CO₂/H₂O gas analyzer with CSAT3A sonic anemometer head

Key Specifications

Each type of IRGA has its own advantages and limitations. The following sections provide discussion of key differences between the three instruments to help inform decisions for the best instrumentation for specific applications.

Power

Closed-path systems generally require more power than open-path systems as they require a pump to move the air sample through the IRGA. The IRGA and sonic anemometer of all Campbell Scientific systems require the same power, 5W, for these two components alone. Additional components, such as the datalogger and data storage device bring the total power required for an open-path system to approximately 6W. Although the CPEC200 closed-path system requires additional power for the sample pump, the system's total power consumption of 12W is still comparable to traditional open-path IRGAs which have been used for many years at remote field sites with solar power. Solar power for a closed-path system will be more expensive than for an open-path system as discussed in the following section.

System Cost

EC systems using closed-path IRGAs are generally more expensive than comparable open-path systems. This section compares the cost of comparable open-path (EC150 and IRGASON) and closed-path (CPEC200) systems.

In this cost trade analysis, a set of typical complete systems was defined, including a datalogger, tripod and crossarm, zero/span equipment, and solar power systems. All Campbell Scientific systems can be customized for a given application. The company's technical support can determine the final cost of a custom system. The cost of an IRGASON with its integrated sonic anemometer is similar to the cost of an EC150 with CSAT3A. The primary difference in cost being that the combined sensor head requires one shipping case, while the EC150 and CSAT3A each require their own shipping case. Although shipping cases are optional, they are recommended. In this cost trade, we assume shipping cases for all sensor heads. Consequently, the IRGASON system cost is slightly lower (1%) than the EC150 system. The remaining cost estimate will compare the EC150 (open-path EC system) to the CPEC200 (closed-path EC system) and is presented graphically in Figure 4.

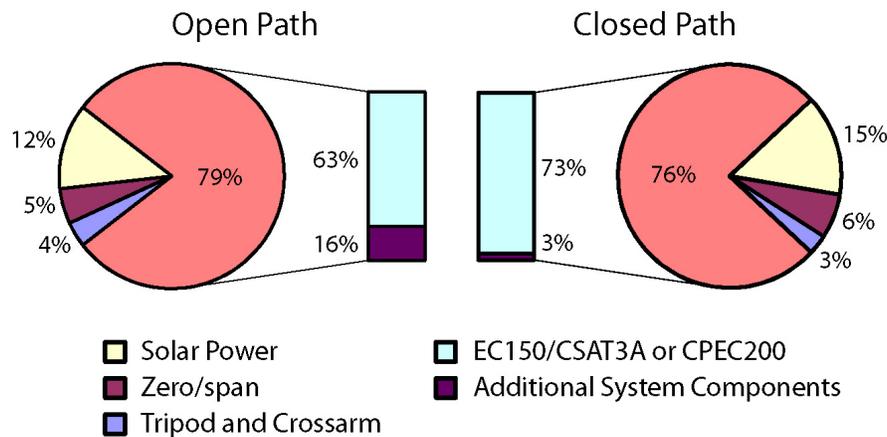


Figure 4. Comparison of component-level costs of open-path versus closed-path eddy covariance systems

The primary sensors of the open-path system, the EC150 with CSAT3A, are 63% of the total system cost. Figure 4 shows that this cost, combined with additional system components, equals 79% of total system cost. In this example, the additional system components include a datalogger, storage module, cables, etc., and have been combined for easier comparison to the CPEC200. The rest of the system (zero/span, tripod and crossarm, and a solar power system) account for the remaining 21% of total system cost.

The total cost of the closed-path EC system is 24% higher than the open-path EC system. The total for the CPEC200 and additional system components is 76% of the total system cost, only slightly lower than the 79% for the open-path EC system. In the closed-path system, however, only 3% of system cost is attributed to additional system components compared to 16% for the open-path system. This cost difference is attributed to the greater integration of system components in the CPEC200, which includes the datalogger, storage module, and enclosure in the base system. These components are sold separately in the open-path system.

Comparing just the sensors and additional system components, the closed-path system cost is 19% higher than the open-path system. This cost difference reflects the additional components required for the closed-path analyzer; primarily the sample cell, intake assembly, and sample pump. It also includes additional cost to fully assemble and test the components in the system enclosure, which is performed before shipping. In the open-path system, this basic assembly is performed by the user.

The higher cost of solar power for the closed-path EC system is due to higher power consumption of closed-path EC systems. Most of the increased power consumption is for the pump, but the heated intake assembly requires an additional 0.7 W. If AC mains power is available, the cost for power becomes insignificant in either closed- or open-path systems.

The cost required to zero and span the open-path EC system is significant at 5% of the total system. Cost includes a zero/span shroud and lab stand, as well as the user-supplied cylinders of zero and CO₂ span gas, with regulators, a flow meter, and needle valve. For situations in which a user has multiple units, only one zero/span setup is required and can be shared among units, reducing this cost. Note that the cost of a dewpoint generator to provide H₂O span capability is not included in the zero/span cost.

The zero/span cost for the closed-path EC system includes the zero and span cylinders and regulators and a three-valve module installed in the CPEC200 system. This cost is assumed to apply to each closed-path EC system to take advantage of the ability to perform zero and CO₂ span automatically.

The cost analysis shows that zero/span is more expensive for the closed-path system; however, a strictly cost-based comparison is not an accurate reflection of capabilities by system. The increased cost for the CPEC allows for automated zero/span.

The CPEC200 can be ordered without the valve module, in which case zero/span of the EC155 must be performed manually, similar to the open-path IRGAs. For this comparison scenario (manual zero/span), the cost of zero/span is less for the closed-path. This is because the open-path zero/span requires the customer to buy a zero/span shroud and lab stand. The closed-path does not require these additional components as the sample cell is always included.

The cost of the tripod and crossarm are the same in either system. The lower percentage of cost attributable to mounting structures for the closed-path system is simply a result of the higher total system cost.

Installation

Installation is similar in all three systems. All include the sensors mounted at the end of a crossarm, the EC100 electronics module mounted within 3 m of the sensors, and an enclosure that holds the datalogger mounted at the base of the tripod or tower. In all configurations a power cable and an SDM communications cable are required to connect the datalogger to the EC100.

Open-path: EC150 vs. IRGASON

The IRGASON installation is a bit simpler than the EC150 because the IRGA and sonic anemometer are manufactured as a single unit. However, it is possible to preassemble the EC150 IRGA and sonic anemometer head onto the mounting bracket before attaching it to the CM250 leveling mount. The EC150 with CSAT3A attached is heavier than the IRGASON; 3.7 kg (8.2 lb) compared to 2.8 kg (6.2 lb). Cable installation is the same for the two open-path systems.

Open-path vs. Closed-path

Installation of the EC155 IRGA and CSAT3A is very similar to the EC150 in that a separate IRGA and sonic anemometer head are mounted on a common mounting bracket attached to a CM250 leveling mount on the end of a crossarm. This configuration has an additional cable for the sample cell.

The CPEC200 system enclosure comes fully assembled, wired, and tested, making installation simpler than the open-path system. The CPEC200 has one additional enclosure for the pump module which requires a tube to connect the IRGA to the pump module.

Maintenance

For all three analyzers, basic maintenance includes cleaning the windows when they become dirty, although the process is slightly different for each. The EC155 sensor head is easily removed from the sample cell by the thumbscrews to expose the windows for cleaning. In the open-path systems, windows are always exposed. The filter of the EC155 air inlet must be replaced periodically while the open-path IRGAs have wicks around the windows that may need to be replaced occasionally. The frequency with which cleaning is required is highly dependent on local conditions. In general, the open-path may have a longer interval between cleaning the windows. However, a dirty precipitation event can change the expected frequency with which the analyzer must be maintained. The closed-path analyzer's filter may plug quickly in high-pollen environments or if there is a dust storm.

All three systems use chemicals to scrub CO₂ and H₂O from the inside of the analyzer that would otherwise build up over time as a result of gradual diffusion of these constituents through the O-rings. These scrub chemicals will need to be replaced annually to prevent the calibration drift that will eventually result in large measurement error. The scrub chemicals are easily replaced using prefilled bottles available from Campbell Scientific.

Zero/Span

Zero/span for the open-path IRGA requires installing a calibration shroud. This can be performed on site if the system is easily accessible. In many cases it may be preferable to remove the IRGA and EC100 electronics from the tower for a laboratory zero/span. As analyzers are quite stable, this is typically done infrequently.

Users may also return IRGAs to Campbell Scientific for zero/span, which may be the best option for users with a single system, or those who have no experience with the zero/span procedure. For users with multiple systems, it is generally preferable and more economical to have zero/span capability.

Zero/span for the closed-path IRGA may be done manually, much like for the open-path IRGAs. The closed-path does not require a zero/span shroud, making it more convenient and slightly less expensive than for the open-path.

As the closed-path IRGA of the CPEC200 shares most of the critical components with the open-path, its long-term stability is similar to the open-path analyzers. However, the closed-path design allows easy on-line zero and CO₂ span. Note that H₂O span requires a laboratory dewpoint generator and therefore cannot be automated. The zero and CO₂ span can be checked and set periodically, from once per day to every flux averaging period. This online zero/span provides better accuracy and gives quick feedback if a problem develops. Configuring the CPEC200 for online zero/span requires user-supplied cylinders of zero and CO₂ span with regulators. The valve module is typically ordered factory-installed. Online zero/span requires tubing connections from each cylinder to the valve module and from the valve module to the IRGA. These tubes can be ordered pre-swaged or the user may provide tubing.

Synchronization and Colocation

Ideally the wind velocity and the $\text{CO}_2/\text{H}_2\text{O}$ would be measured at the same time (synchronized) and at the same location (colocated). Synchronization and colocation are related because a spatial separation leads to a time delay as the wind carries a parcel of air from the sonic anemometer to the IRGA. All three systems are synchronized as the EC100 electronics control the measurement of both the IRGA and the sonic anemometer. Only the IRGASON, however, is colocated.

As described earlier, the IRGASON achieves this ideal by integrating the sonic anemometer and the IRGA into a single EC sensor. The EC150 and the CPEC200 have a small spatial separation between the sonic path and the IRGA, resulting in two disadvantages that should be considered. First, there is a lag between the time a parcel of air is measured by the sonic anemometer and the IRGA. Second, the separation introduces an error in the flux.

The lag time arises when the wind carries a parcel of air past both the sonic anemometer and the IRGA. Depending on the wind direction, the lag may be positive or negative. The EC150 IRGA path is 6.0 cm (2.4 in) from the sonic anemometer path. If the horizontal wind speed is $1 \text{ m}\cdot\text{s}^{-1}$ along the line from sonic to IRGA, a parcel of air takes approximately 17 ms to travel from the sonic anemometer to the IRGA. If the wind blows in the opposite direction, the lag time will be -17 ms . Even at this very low wind speed, the lag time between measurements taken by the sonic anemometer and IRGA is small compared to the typical sample interval (100 ms), meaning there is no need to adjust the lag time for each averaging period.

The CPEC200's IRGA sample intake is 15.6 cm (6.1 in) from the sonic anemometer. At $1 \text{ m}\cdot\text{s}^{-1}$, the lag is 64 ms. The CPEC200 has an additional lag time due to the time required for an air sample to travel from the intake to the middle of the sample cell. At the nominal 7 LPM pumping speed, this lag is 68 ms. Combined with the wind lag, the total lag time is $68 \pm 64 \text{ ms}$, or 4 to 132 ms. In most cases, aligning the sonic anemometer data with the IRGA data requires a one-sample lag time (100 ms). In conditions when wind direction causes the air sample to reach the IRGA intake significantly before the sonic path, a zero-sample lag time would be closer to the actual lag time. These data are generally discarded because the wind measurements are disturbed by passing by the tower or other mounting structure, the body of the IRGA, and the CSAT3A mounting block. There may be an additional delay for H_2O because of adsorption/desorption on the surfaces of the intake tube and sample cell, particularly in conditions of relatively high humidity. For these reasons it is necessary to calculate appropriate CO_2 and H_2O lag times for the closed-path IRGA.

The spatial separation of the sonic anemometer and the IRGA causes a small attenuation of the measured flux, which is dependent on the distance between the sonic anemometer path and the IRGA optical path in the EC150, or in the intake of the EC155. The flux attenuation also depends on the wind direction, the measurement height, and atmospheric stability. Horst and Lenschow² studied this effect with an array of CSAT3s and found that the flux loss is greater for crosswind separation than streamwise separation. It is also greater for low measurement height and stable atmospheric conditions, which shift the energy in the cospectrum to higher frequencies. Their model for the flux attenuation is evaluated below, for the IRGASON, EC150, and EC155, at a range of measurement height and for unstable atmospheric conditions.

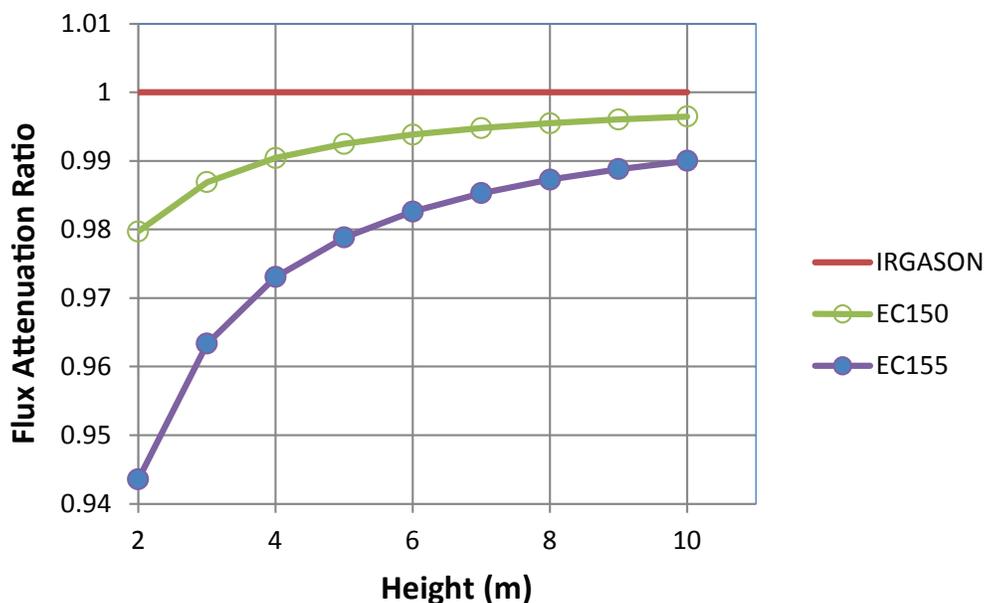


Figure 5. Crosswind separation flux attenuation ratios for unstable atmosphere

²Horst, T.W. and D.H. Lenschow, 2009. "Attenuation of scalar fluxes measured with spatially-displaced sensors," *Boundary-Layer Meteorology*, **130**, pp. 275-300. DOI 10.1007/s10546-008-9348-0

Because the sonic anemometer path and the IRGA path are colocated, the IRGASON has no flux loss (curve is identically one). The EC150, with its very small separation of 6.0 cm (2.4 in) requires a 2% flux correction at low measurement height (2.0 m, or 6.6 ft), and the EC155, with its larger separation of 15.6 cm (6.1 in) requires almost 6% correction at 2.0 m measurement height. The flux attenuation is smaller if the wind direction is along the line between sonic anemometer and the IRGA (streamwise separation), but it is larger for stable atmospheric conditions.

Flow Distortion

Wind velocity is difficult to measure without disturbing the wind. Sonic anemometers, such as the CSAT3A, determine wind velocity by measuring time of flight of an ultrasonic sound wave between a pair of transducers. The ultrasonic signal itself does not disturb the wind, but the transducers and their support structure cause distortion of the wind flow even though they are not directly in the actual measurement path. This effect can be minimized by using small transducers and an aerodynamic support structure. Additional flow distortion is caused by placing an IRGA near the sonic path. This leads to a design challenge: the IRGA should be very close to the sonic path to minimize errors due to spatial separation but should not disturb the wind as it passes through the sonic path. The EC150's aerodynamic design allows it to be placed 6.0 cm (2.4 in) from the sonic path with minimal flow distortion. The IRGASON design eliminates much of the support structure for the sonic transducers, reducing flow distortion with fully colocated sonic and IRGA measurements. The CPEC200 achieves very low flow distortion by placing the IRGA itself farther away from the sonic path. Only the small, aerodynamic intake assembly is placed near the sonic path.

Frequency Response

Open-path systems generally have better frequency response than closed-path systems, although the frequency response is limited by path averaging. Path averaging is a function of the IRGA path length, the wind speed, and the incident angle of the wind.³ Path length for both the EC150 and the IRGASON is 15.37 cm (6.05 in). Assuming the wind is perpendicular to the IRGA path, the theoretical frequency response for 1, 2, and 5 m·s⁻¹ wind speed, is shown modeled in Figure 6.³ Note that, although the frequency response of the open-path IRGA degrades at low wind speeds, the frequency content of the flux shifts downward at low wind speeds. Therefore open-path IRGAs will generally always have sufficiently good frequency response to measure the flux.

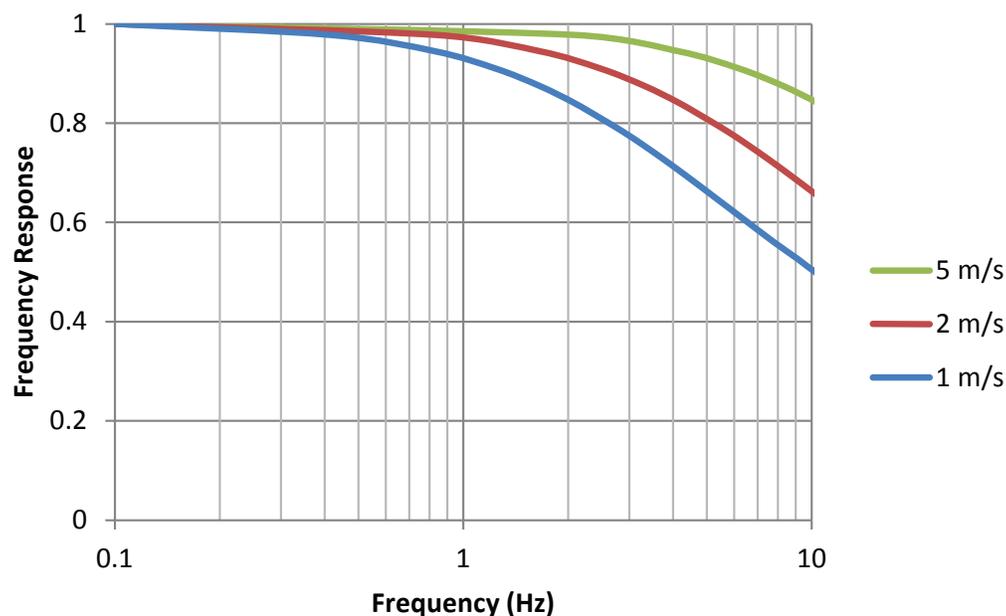


Figure 6. Theoretical frequency response of EC150 and IRGASON for 1, 2, and 5 m·s⁻¹ wind speed

The analog to path averaging for a closed-path IRGA is sample cell residence time. The frequency response of closed-path analyzers can also be degraded by mixing within system components such as the intake tube. Traditional closed-path systems often have a bandwidth on the order of 1 Hz for CO₂. The frequency response for H₂O has been shown to be further degraded by interaction of the water vapor with surfaces such as the tube wall even for short sample tubes.⁴

³Silverman, B.A. 1968. "The effect of spatial averaging on spectrum estimation," *J. Applied Meteorology*, **7**, pp. 168 – 172.

⁴Fratini, 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.

The CPEC200 was designed to give good frequency response with low power. It was tested in the laboratory by injecting an impulse of high-concentration CO₂ into the sample air stream.⁵ The EC155 frequency response is shown in Figure 7 (green triangles), along with two comparison curves. The red line is the theoretical curve for the open-path (EC150 and IRGASON) at 1 m·s⁻¹ wind speed. 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 IRGAs will be better than the EC155 for most wind conditions (above approximately 2 m·s⁻¹).

The black line in Figure 7 compares the EC155 to traditional closed-path IRGAs. Fratini et al. determined a CO₂ frequency response bandwidth of 1.1 Hz in a closed-path system with a short sampling tube (1.0 m, 3.3 ft) and 0.95 Hz for systems with somewhat longer tubes (4.0 m, 13.1 ft). The black line in Figure 7 models these traditional closed-path systems with a 50 ms sample cell residence time and a mixing time constant of 0.14 s, which gives a bandwidth of 1 Hz. The CPEC200 frequency response is much better than that of the traditional closed-path system.

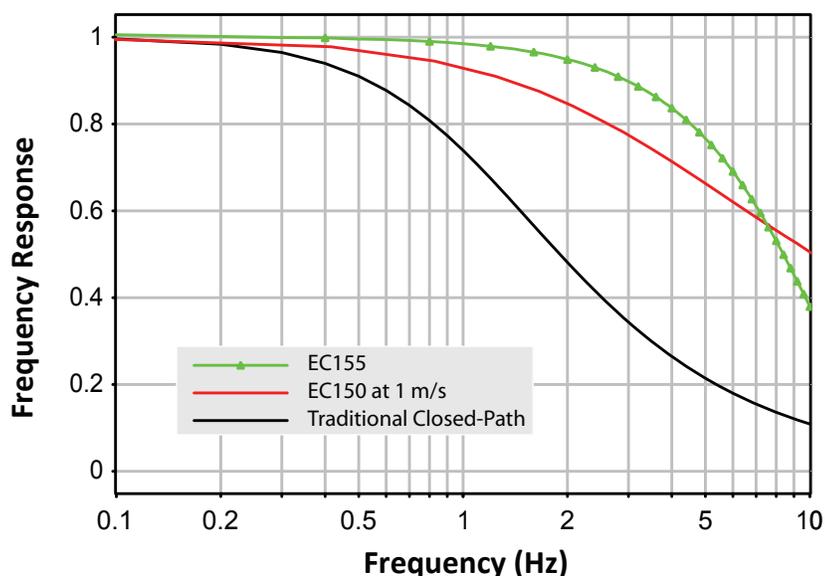


Figure 7. Frequency response of EC155 compared to traditional closed-path IRGA (black line) and open-path IRGA at low wind speed (red line)

WPL Corrections

Open-path IRGAs such as the IRGASON and the EC150 measure the density of CO₂ and H₂O in the measurement path. In open-path systems, fluctuations in temperature will cause fluctuations in CO₂ and H₂O density, as temperature affects the density of air. Therefore a sensible heat flux will cause an open-path EC system to measure an apparent CO₂ and H₂O flux. Similarly, because a latent heat (water vapor) flux causes the air to be diluted with H₂O, a latent heat flux gives rise to an apparent CO₂ flux. These effects are well known and gave rise to the Webb, Pearman, Leuning (WPL) corrections.⁶ This correction can be significant for open-path EC systems.

Closed-path IRGAs do not require WPL corrections. The temperature fluctuations are dampened in the intake tube as the air sample is brought to the temperature of the sample cell. The water vapor is measured and accounted for on a point-by-point basis, allowing the closed-path IRGA to report CO₂ and H₂O as mixing ratios, or moles of CO₂ or H₂O per mole of dry air.

Rain Performance

Precipitation can block the infrared beam of an open-path IRGA by falling through the measurement path or by accumulating on the windows. Measurements from sonic anemometers are also affected. The EC150 and IRGASON have angled windows and a wick to help shed liquid precipitation and an internal heater to help prevent an accumulation of precipitation on the window.

Closed-path IRGAs are less susceptible to precipitation than open-path IRGAs. The EC155 in the CPEC200 has a heated intake assembly with a rain diverter to prevent precipitation from entering the sample cell.

⁵Sargent, S. 2012. "Quantifying Frequency Response of a Low-power, Closed-path CO₂ and H₂O Eddy-covariance System." http://s.campbellsci.com/documents/us/technical-papers/cpec200_%20freqresp.pdf. Accessed 2/16/2013.

⁶Webb, E.K., Pearman, G.I., and Leuning, R. 1980, "Correction of Flux Measurement for Density Effects due to Heat and Water Vapor Transfer", *Quart. J. Roy. Meteor. Soc.*, **106**, 85-100.

Summary

All three Campbell Scientific EC systems require very low power. The CPEC200 power requirement is similar to traditional open-path systems, while the open-path EC150 and IRGASON are approximately half this power usage. All three are well suited to remote sites with no access to AC mains power, but an open-path system may be preferred for sites with severe power limitations.

The two open-path systems are similar in overall cost, although the IRGASON is slightly less expensive because it requires one less carrying case. The CPEC200 is 24% more expensive than the open-path (EC150) system. The additional cost of the CPEC200 is largely attributed to hardware that is integrated in the closed-path design, such as the intake assembly, sample cell assembly, and the sample pump. The CPEC200 also ships more fully assembled (datalogger and enclosure), and it provides additional capability (automatic zero/span) than comparable open-path systems. The higher power requirement for the CPEC200 makes powering it with a solar system more expensive.

All three systems are easy to install and installation costs will generally not be a significant factor in choosing one system over another. The closed-path system requires slightly more maintenance, but this difference will not be significant for most applications.

The closed-path IRGA shares most of the critical components with the open-path, so its long-term stability is similar to open-path analyzers. For systems that will have zero and span checked infrequently, any of the systems will work well. However, only the closed-path design allows automatic online zero and CO₂ span.

The IRGASON provides truly synchronous, colocated measurements of wind velocity, CO₂, and H₂O, so there is no need to correct for lag time or spectral attenuation caused by sensor separation. The integration of the sonic anemometer with the IRGA reduces flow distortion. The EC150/CSAT3A has separate IRGA and sonic anemometer, which are synchronized but have some separation. This separation is small enough that generally there will be no need to account for the lag time or spectral attenuation from sensor separation. The CPEC200 has a very low-profile intake for minimal flow distortion. Sensor separation in the CPEC200 is larger than with the open-path sensors, but as in the open-path sensors, the variation in lag time and spectral attenuation due to sensor separation is small, and may be ignored for higher measurement heights.

The frequency response of the open-path systems is limited only by path averaging. Their flux loss due to high-frequency attenuation is negligible. Traditional closed-path systems generally have had poor frequency response, with a typical bandwidth on the order of 1 Hz. The CPEC200 achieves a frequency response bandwidth of 5.8 Hz at very low power because of its small sample-cell volume (5.9 ml). This excellent frequency response enables the CPEC200 to be used even in demanding sites such as those with a low measurement height.