

Capturing and processing soil GHG fluxes using the LI-8100A

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The LI-8100A Automated Soil CO₂ Flux System is designed to measure CO₂ efflux from soils using the closed non-steady state transient approach. While CO₂ is an important gas in many contexts, it is not the only gas of interest for many research applications. By exploiting some simple hooks in the system a third party analyzer capable of measuring other trace gases can be interfaced with the LI-8100A System and our data processing software (SoilFluxPro) can be used to compute fluxes for these additional gases. In this application note we describe considerations for selecting an appropriate third party analyzer, how to integrate it into the system and the procedure used to compute fluxes of additional gases in SoilFluxPro.

Flow, volume, and pressure considerations

There are three flow loops inside a multiplexed LI-8100A System: the primary *sampling loop* between the multiplexer and chamber, the *sub-sampling loop* between the LI-8100A and the multiplexer, and the *pressure regulation loop* inside the multiplexer. Each of these loops operates at a different flow rate. The nominal flow rate through the sub-sampling loop is between 1.5 and 1.7 SLPM at near atmospheric pressure.

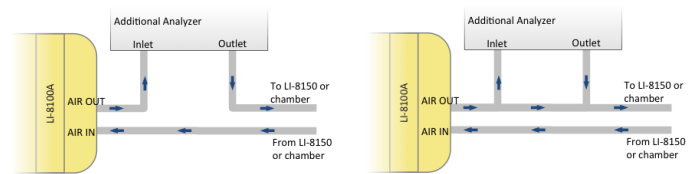


Figure 1. Plumbing schemes for connecting an additional analyzer in to the LI-8100A System. Left hand panel: series configuration. Right hand panel: parallel configuration.

In a multiplexed configuration, the sub-sampling loop is where any additional analyzer should be placed, either in series with the air outlet from the LI-8100A or in parallel to it (Figure 1). Series placement is possible when the additional analyzer does not use its own internal pump and is capable of operating at the same flow rate and pressure as the LI-8100A. Parallel placement is required when the additional analyzer operates at a different pressure or flow rate lower than the LI-8100A. In either configuration it is possible for the additional analyzer to cause a slight over-pressure on the LI-8100A's optical bench. Care should be taken to avoid creating flow restrictions in the sub-sampling loop and where these cannot be avoided it may be necessary to adjust the bias on the pressure regulation loop. To adjust the pressure regulation loop:

- 1 With all plumbing modifications and the additional analyzer in place, note the LI-8100A optical bench pressure when all flow pumps are off.
- 2 Open the LI-8150 multiplexer and remove the splash guard that covers the fuses.
- 3 Locate the blue **Pressure Adjust** potentiometer (up and to the left of the fuses, see Figure 2).
- 4 Turn on all flow pumps and look at the LI-8100A optical bench pressure.

If it is different from the pressure noted in step 1 use a small flat head screwdriver to adjust the **Pressure Adjust** potentiometer to minimize the pressure difference between when the pumps are on or off. Note that it may not be possible to bring the pressure difference to zero between when the flow pumps are on and off; within ± 0.5 kPa would be typical. If

there is some offset, the calibration procedures outlined below should be followed to ensure that the LI-8100A performs as expected.

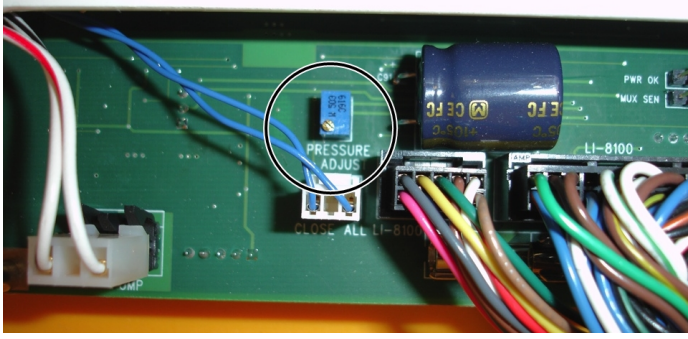


Figure 2. Pressure Adjust potentiometer.

When operating with a single chamber and standalone LI-8100A analyzer control unit, the third party analyzer should be placed on the AIR OUT line from the LI-8100A using one of the plumbing schemes described in Figure 1. The plumbing configuration follows the same guidelines when placing the additional analyzer in the sub-sampling loop of a multiplexed system. The flow rate between an LI-8100A and a single chamber, and the flow rate in the sub-sampling loop of a multiplexed system, are both nominally between 1.5 and 1.7 SLPM.

The volume of the additional analyzer will have at least two kinetic effects: 1) it brings additional air to the system, which dilutes trace gas entering the system from the soil surface and reduces the measured trace gas mole fraction rate of change (dC/dt); and 2) it creates a time delay in the onset of a monotonic concentration increase or decrease. Accurate fluxes can still be measured if the added volume is sufficiently small.

The quantitative impact of the added volume on dC/dt can be evaluated by considering the equation used to calculate flux F ($\text{mol m}^{-2}\text{s}^{-1}$, equation 1). This equation is derived based on the assumption of a single fixed volume V (m^3) with homogeneous air density ρ (mole m^{-3}). For simplicity in this discussion the effects of water corrections are neglected. This however, does not change the conclusions. Thus,

$$F = \frac{\rho V}{S} \frac{dC}{dt} \quad 1$$

where F is the flux of trace gas ($\text{mol m}^{-2}\text{s}^{-1}$), where ρ is air density (mol m^{-3}), dC/dt is the time rate of change in mole fraction of the gas being measured ($\text{mol mol}^{-1}\text{s}^{-1}$), and S (m^2) is the soil surface area over which the flux occurs. For a flux F , the trace gas mole fraction rate of change dC/dt is proportional to the total number of molecules in the system ρV .

For a well-mixed system, when an additional volume V_{added} (m^3) that contains a gas of density ρ_{added} is inserted into the system, equation 1 becomes

$$F = \frac{(\rho_{\text{system}} V_{\text{system}} + \rho_{\text{added}} V_{\text{added}})}{S} \frac{dC}{dt} \quad 2$$

Assuming V_{system} (m^3) and V_{added} each operate at uniform temperature and pressure, $\rho_{\text{system}} = P_{\text{added}} / RT_{\text{added}}$ and $\rho_{\text{added}} = P_{\text{added}} / RT_{\text{added}}$, where R is the universal gas constant ($8.314 \text{ Pa m}^3\text{K}^{-1}\text{mol}^{-1}$), and T_{system} , P_{system} and T_{added} , P_{added} are the temperature (K) and pressure (Pa) in the system and additional volume respectively. Substituting these expressions and factoring gives,

$$F = \frac{\rho_{\text{system}} \left(V_{\text{system}} + V_{\text{added}} \frac{P_{\text{added}}}{P_{\text{system}}} \frac{T_{\text{system}}}{T_{\text{added}}} \right)}{S} \frac{dC}{dt} \quad 3$$

For data processing using SoilFluxPro, an effective volume $V_{\text{effective}}$ for the addition can be defined for the added analyzer and entered into the software.

$$V_{\text{effective}} = V_{\text{added}} \frac{P_{\text{added}}}{P_{\text{system}}} \frac{T_{\text{system}}}{T_{\text{added}}} \quad 4$$

Thus, the total volume used in equation 1 becomes simply $V_{\text{system}} + V_{\text{effective}}$ and the density is ρ_{system} . The system density is computed using P_{system} from the pressure measurement in the LI-8100A optical bench, and T_{system} from the chamber air temperature. There are inherently small variations in $V_{\text{effective}}$ due to changes in T_{system} and P_{system} but these are generally small and subsequently neglected.

In cases where the volume of the addition operates at a non-uniform temperature and pressure or is not well known, $V_{\text{effective}}$ can be estimated experimentally by plumbing the third-party analyzer in a closed loop and injecting a known volume $V_{\text{injection}}$ (m^3) of pure CO_2 into the loop. The gas concentrations in the loop pre-injection C_1 (mol mol^{-1}) and post-injection C_2 (mol mol^{-1}) are defined as

$$C_1 = \frac{N_{\text{CO}_2}}{N_{\text{added}}} \quad 5$$

$$C_2 = \frac{N_{\text{CO}_2} + N_{\text{injection}}}{N_{\text{added}} + N_{\text{injection}}} \quad 6$$

where N_{CO_2} is the number of moles of CO_2 in the additional volume pre-injection, N_{added} is the total number of moles in the additional volume pre-injection, and $N_{\text{injection}}$ is the number of moles of CO_2 injected into the loop. Substituting equation 5 into 6 and rearranging to solve for N_{added} yields

$$N_{\text{added}} = \frac{N_{\text{injection}} (c_2 - 1)}{(c_1 - c_2)} \quad 7$$

where $N_{\text{added}} = \frac{P_{\text{added}} V_{\text{added}}}{RT_{\text{added}}}$ and $N_{\text{injection}} = \frac{P_{\text{injection}} V_{\text{injection}}}{RT_{\text{injection}}}$. $T_{\text{injection}}$ (K) and $P_{\text{injection}}$ (Pa) are the temperature and

pressure, respectively, of the gas injected into the closed loop. Substituting these into equation 7, and following from equation 4, yields

$$V_{\text{effective}} = \frac{P_{\text{injection}} T_{\text{system}} V_{\text{injection}} (c_2 - 1)}{P_{\text{system}} T_{\text{injection}} (c_1 - c_2)} \quad 8$$

In practice it is difficult to know $T_{\text{injection}}$ and $P_{\text{injection}}$ with great certainty. Making the assumption that $P_{\text{injection}} = P_{\text{system}}$ and $T_{\text{injection}} = T_{\text{system}}$ introduces some error in determining $V_{\text{effective}}$ experimentally, but it allows equation 8 to be simplified, eliminating the need to know temperature or pressure.

$$V_{\text{effective}} = \frac{V_{\text{injection}} (c_2 - 1)}{(c_1 - c_2)} \quad 9$$

In many cases, the impact of an added volume on flux calculations will be modest as $V_{\text{effective}}$ for many modern trace gas analyzers is small. For example, neglecting the additional volume of an analyzer with an internal volume of 325 cm³, operating at 18.75 kPa and 300.12 K would introduce an error of less than 1.5% for the nominal system volume of a multiplexed system.

By trapping air making its way around the measurement circuit, the volume of a third-party gas analyzer may also introduce an additional time delay and have other effects that can compromise the flux measurement. The magnitudes of these effects are related to the analyzer's volume V_{added} , its operating pressure and temperature, and the flow rate through it. We can qualitatively assess the kinetic consequences of adding the volume by defining a time constant for the effective volume of the added analyzer and comparing it empirically to tested cases. We define a time constant τ_{added} (s)

$$\tau_{\text{added}} = \frac{\rho_{\text{added}} V_{\text{added}}}{U_{\text{added}}} \quad 10$$

where U_{added} is the molar flow rate (moles s⁻¹) delivered to the analyzer, ρ_{added} is air density in the analyzer evaluated at the analyzer's internal temperature and pressure, and V_{added} is its actual volume.

Time constants for different analyzers or model volumes inserted into the LI-8100A sub-sampling loop are shown in Table 1. We have tested the impact of adding volumes in both series and parallel configurations, and found that accurate fluxes were observed when a volume was added having a time constant of about 7 seconds, but not 17 seconds (Table 1). Based on these results, we expect that third-party analyzers added in series or parallel with time constants less than 5 to 7 seconds may work well. We recommend fluxes made with any other configuration not shown here be validated. Validation can be straightforward if the third-party analyzer measures CO₂ as well as other gases of interest.

The configurations reported in Table 1 all affect dC/dt and introduce time delays. But for systems with appropriate time constants, accurate fluxes can be obtained by entering the appropriate volumes, adjusting the dead band to accommodate delays, and computing fluxes using SoilFluxPro.

Table 1. Time constants for different analyzers or volumes added to the LI-8100A sub-sampling loop. Temperatures and pressures pertain to conditions inside the added volumes or analyzers.

	LI-8100A	Test Analyzer	Test Volume 1	Test Volume 2
Configuration	Series	Parallel	Series	Series
Volume (cm ³)	14.5	325	200	500
P (kPa)	98	18.75	98	98
T (K)	323	300	298	298
Flow rate (SLPM)	1.7	0.8	1.7	1.7
τ_{added} (s)	0.5	4.6	7.1	17.7
Flux OK?	Yes	Yes	Yes	No

Calibration considerations

The calibration procedures outlined in the LI-8100A user manual are fine for normal operation of the instrument where optical bench pressure is not significantly altered from ambient. However, when plumbing additional volumes into the system, small pressure differences can cause offsets in the gas measurements when the standard calibration procedure is followed. These offsets tend to be small and may only be apparent when a CO₂ measurement is available at two different points in the system.

When operating with a third party analyzer plumbed into the system an alternative calibration routine can be used:

- 1 With the system plumbed for operation with the third party analyzer, turn on the flow pumps and note the optical bench pressure.
- 2 Disconnect the hose from the air inlet (AIR IN) and connect the calibration rig as described in Figure 3.
- 3 With the flow pumps on, adjust the flow rate through the rotometer such that bench pressure on the LI-8100A is as close as possible to what it was in step 1. A slight pressure difference (± 0.5 kPa) may be unavoidable and is okay. It is critical however, that flow through the rotometer exceeds the flow through the LI-8100A and that some small excess flow leaves the vent tube in the calibration rig. A flow rate of 2.0 to 2.5 LPM through the rotometer may be suitable to meet the demand of the LI-8100A pump and have a small flow out the vent.

- 4 When the gas concentration reading stabilizes, set the zero, span or span 2 using the LI-8100A interface software as described in the LI-8100A user manual.
- 5 Calibrating the third party analyzer following this same procedure may be wise as well. Check with its manufacturer for calibration details.

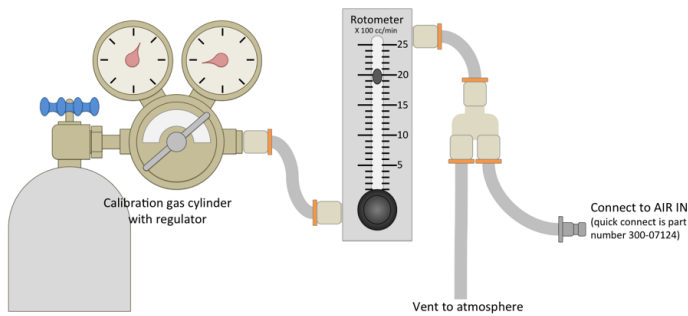


Figure 3. Calibration rig used to calibrate the LI-8100A at operating pressure.

Despite careful calibration some offsets may be seen between CO₂ and water vapor as measured by the LI-8100A and some third party analyzer plumbed in line with it. These offsets can appear due to a number of reasons, and are not necessarily important in the context of the flux measurement. For water vapor, differences during a given flux measurement may be expected due to interactions with surfaces at different points in the system that lead to a differential time response for water vapor for the two analyzers. For this reason it is important to record both the concentration of the gas of interest and water vapor from the additional analyzer, or where available, record the dry mole fraction for the gas of interest.

For CO₂, differences will occur due to an inherent time delay resulting from the additional analyzer being physically separated from the LI-8100A's analyzer; the magnitude of this delay is related to the volume, flow rate, operating pressure, and location of the additional analyzer. But differences may also occur due to drift of the LI-8100A over time or pressure induced calibration offsets as discussed previously. It should also be noted that the accuracy of the LI-8100A's analyzer is specified as 1.5% of reading.

In a closed system where fluxes are computed from a rate of change, measurement of absolute concentration may seem less important than ability of the analyzer to accurately measure a change in concentration. However, because the absorbance measured by the LI-8100A is a non-linear function of CO₂ (and water vapor) concentration over its calibration range, the absolute concentration and rate of change are interrelated, and offsets in the absolute concentration may have a small impact on the flux. In practice, this effect is small and arises because the slope of the calibration curve increases with increasing CO₂ concentration.

Data integration

Using analog signals

If available on the third party analyzer, its analog outputs can be used to integrate data on the LI-8100A resulting in a single .81x file containing the time series for multiple gas species that can be processed in SoilFluxPro. If the system includes a multiplexer these output channels can be fed into one or more of the three auxiliary inputs available for the 8100-104 or 8100-104C chambers. In software, the auxiliary inputs from a single chamber can be mapped to all ports, allowing the third party analyzer to be connected at only a single location (Figure 4). For single chamber systems, lacking a multiplexer, the outputs must be fed into one or more of the four auxiliary inputs available through the 8100-663 Auxiliary Sensor Interface regardless of the chamber used.

The auxiliary inputs available through either the chambers or the 8100-663 are measured in volts with 13 bit resolution over a 0 to 5V input range. The instrument software supports linear scaling (general purpose input), as well as a Steinhart-Hart conversion (Figure 4).

For integrating data in a multiplexed system an auxiliary input cable (part number 392-08577) is available that connects directly to the auxiliary inputs on the 8100-104 and 8100-104C chambers. This cable provides a weatherized connection at the chamber and bare leads to interface to the third party analyzer's analog outputs. One cable will be necessary for each channel in use, and due to the cable's length, the analyzer must be placed near the chamber it is connected to. A 2 m cable (392-07955) is also available that allows the additional analyzer to be attached directly to the LI-8150 in place of a chamber, allowing the LI-8150, LI-8100A and third-party analyzer to be collocated up to 15 m from the chambers. Only one of the 392-07955 cables is required to access all three of the auxiliary inputs. Pin outs for both cables are given in Table 2.

For connecting to the 8100-663 Auxiliary Sensor Interface a user supplied cable with a suitable connection to the third party analyzer on one end and bare leads on the other will be required. For details on how to connect to the auxiliary sensor interface see the LI-8100A user manual.

Using an external data file

Where analog signals are not available, it is possible to integrate a separate data file from a third party analyzer in post processing using the import feature in SoilFluxPro. This allows fluxes to be computed for data collected remotely from the LI-8100A when analog outputs are not available from the additional analyzer. It is necessary that the data to

be imported have time stamps that are reasonably synchronized with the LI-8100A; fixed offsets can be accounted for. The import routine will select or generate a data point from the import file for each record of the LI-8100A file. If there is not an exact match, it will pick the two closest values and interpolate. Thus, 1 Hz data is best, but is not required. The import routine supports native text file formats used by a number of gas analyzer manufacturers, and can be configured to match a variety of other formats. For details on how to import external files see SoilFluxPro's user manual.

Time keeping and clock synchronization between the LI-8100A and other system clocks

Importing data from a third party analyzer into the LI-8100A's .81x files through SoilFluxPro Software is done by matching time stamps between the two data sets. This requires that the two devices keep time relatively consistently between each other. In cases where an offset exists in the timestamps, a fixed offset can be applied and accounted for in SoilFluxPro during importation. This requires, however, that the offset be constant over the entire data set being processed. On short time scales it may be reasonable to assume drift is minimal and that the offset is approximately constant, with any additional small deviations accounted for in the curve fitting process. Over longer time scales, the asynchronous nature of clock drift ensures that without some intervention the offset will not be a constant value.

There is no internal mechanism in the LI-8100A that allows the instrument clock to be synchronized to a standard, or for it to act as a standard for other connected devices. In its typical application, the LI-8100A system runs independently and relies on the user to manually set its clock through its interface software before collecting data.

For users wishing to automate clock synchronization there is hope however. The LI-8100A configuration grammar supports pushing a time and date stamp to the instrument through either its serial or Ethernet interfaces. This allows a computer or microcontroller connected to the instrument to serve as an external standard for the instrument's clock. In many cases the external standard can be the third-party analyzer (more details below).

Configuration grammar

When a measurement is not active the following command can be used to set the time and date:

```
<SR><CFG><CLOCK><TIME>
{HHMMSS}</TIME><DATE>
{YYYYMMDD}</DATE></CLOCK></CFG></SR>
```

In situations where automated clock synchronization would be desirable, it is unlikely that there will be open windows where a measurement is not active (e.g., continuous sampling with a multiplexed system). Thus, before sending the command to update the clock, it will be necessary to send the following command to end the active measurement:

```
<SR><CMD><MEAS>STOP</MEAS></CMD></SR>
```

To restart the measurement, send the following:

```
<SR><CMD><MEAS>START</MEAS></CMD></SR>
```

This will restart the measurement using the settings from the active configuration. To avoid file naming errors that will prevent the measurement from restarting, select append mode when configuring and starting the initial measurement through the interface software.

All commands sent to the LI-8100A need to be followed with a line feed (ASCII 10) for the instrument to recognize them. The instrument sends an acknowledgment after receiving a valid command.

8100sync

In cases where the third-party analyzer runs a Windows operating system, clock synchronization can be done using a simple application, 8100sync, and the Windows Task Scheduler.

You can download 8100sync from the technical support website (www.licor.com/env/support) or directly at: <https://www.licor.com/documents/7sz6ddmimlskqez39wistcx1qwj56zpx>

8100Sync is a tool used to manipulate the clock on an LI-8100A running embedded software 4.0 or above, and includes some basic file management functionality. It is intended to be run from the Windows Task Scheduler at some regular interval to synchronize the LI-8100A clock to PC time. 8100Sync has been tested on Windows Vista, 7 and 10, and may be compatible other versions of Windows.

It consists of two separate executable files: 8100Sync2.0.exe and comscript.exe, and a simple configuration file. 8100Sync2.0.exe provides a graphical interface for comscript.exe with real-time status updates and an editor for the configuration file. Comscript.exe handles communication with the

LI-8100A and can be run independent of 8100Sync2.0.exe. When run independently comscript.exe provides no user feedback, but will trigger a save-only version of the configuration editor if problems are found with the configuration file. 8100Sync2.0.exe is dependent on comscript.exe and the application will automatically exit when comscript.exe is done executing; this allows either application to be used in the Task Scheduler. When the configuration editor is opened from either application, comscript.exe stops and will restart when the editor is closed.

Full details on how to use 8100Sync and how to configure the Task Scheduler can be found in the documentation included with the application.

Table 2. Pin out of cables that can be used to integrate analog signals into the LI-8100A System.

392-08577			392-07955	
Pin	Description	Color	Description	Color
1	Analog input (+)	Brown	Ground	White
2	4 mA limited, 5 VDC regulated reference output	Pink	Chamber temp. signal (+)	Brown
3	100 mA limited, 5 VDC supply	Blue	Analog ground	Green
4	Not used	Grey	Auxiliary input V4+	Yellow
5	50 mA limited unregulated output	Red	Chamber stop signal	Grey
6	30 mA limited, switched 5 VDC supply	Yellow	Auxiliary input V3+	Pink
7	Analog input (-)	Green	Chamber open and close signal	Blue
8	Ground	White	Auxiliary input V2+	Red
9	N/A	N/A	Switch 5V supply control	Orange
10	N/A	N/A	Voltage supply to chamber	Tan

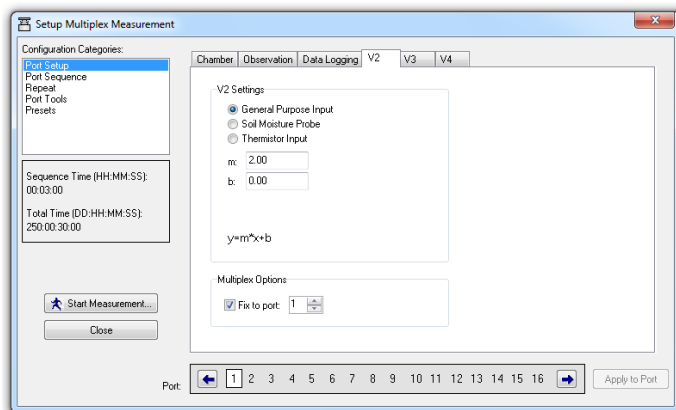


Figure 4. Analog input settings. For a linear voltage input select General Purpose Input and use the m and b coefficients to scale the raw voltage to meaningful engineering units: recorded value = $mV_{in} + b$. In multiplexed configuration use **Fix to port**: to route the analog inputs from one chamber to all the other chambers. This will ensure that the third party analyzer’s data is recorded in the correct location in the data file.

Curve fitting and computing fluxes using SoilFluxPro

To compute fluxes for additional variables included in the .81x file access the recompute dialog; This can be done for all records in a file using the **Recompute** icon at the top of the SoilFluxPro window, or for a single record by double clicking the record in the summary view and going to the **Recompute** tab in that record’s observation view. Figure 5 shows the recompute window for a single record.

In the recompute dialog, click the + under **Flux Computations** to add an additional variable for which fluxes are to be computed. Under **Gas column label**: select the variable. In the example here methane mole fraction was logged as $\mu\text{mol}/\text{mol}$ through auxiliary input V2. Check the box for **Curve Fit** and select start and stop times for the curve fit. These may need to be adjusted later. Under **Dilution correct with** select the channel where water vapor was recorded from the additional analyzer and use the scalar below it to scale the value to mol/mol . In the example, water vapor was logged on V4 as mmol/mol , so it needs to be multiplied by 0.001 to convert to mol/mol . If the third party analyzer reports dry mole fraction, then no additional dilution correction is needed. Under **Vext** input the effective volume determined following the guidelines presented under *Flow, volume, and pressure considerations*. In this case the additional analyzer has an actual volume of approximately 325 cm^3 and operates at 18.75 kPa and 300.12 K. At a chamber pressure of 100 kPa and temperature of 298.5 K the effective volume was 60.62 cm^3 .

It should be noted that in the example presented here effective volume is treated as a constant. But in practice chamber temperature and pressure are typically not constant, leading to an effective volume that may be different for each measurement. However, when the effective volume is small relative to the total system volume, the error associated with treating it as a constant may not be important. For the example presented here, changing the chamber temperature by 25 °C affects the total volume by less than 0.1% and for a 5 kPa change in chamber pressure, the effect is less than 0.04%.

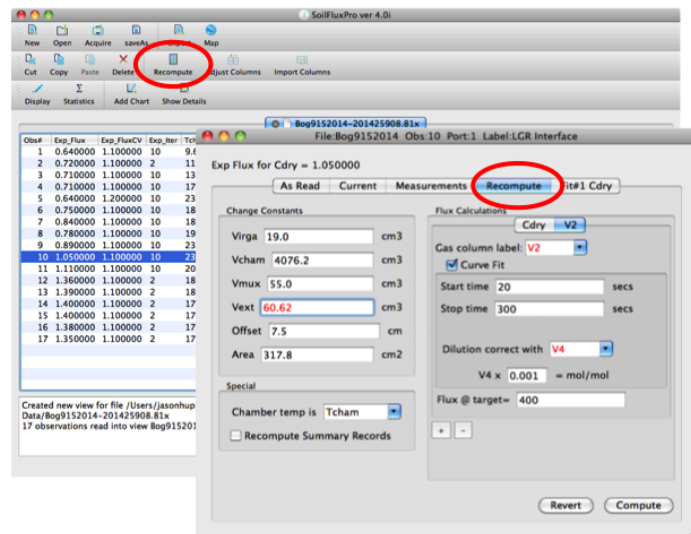


Figure 5. The recompute dialog.

Open the observation view for a record and go to the tab for the additional flux computation. In the example shown here, the tab is labeled **Fit#2 V2** (Figure 6). Use the **Guidance** tab to determine appropriate start and stop times for the curve fitting. In the example dataset, a start time between 40 and 100 seconds and a stop time of greater than 220 seconds would work (shaded areas in Figure 6). For the start time look for the initial plateau and select a time in that window. For stop time, select a time after the values level off. If the **Stop Time Analysis** curve does not level off or is very noisy, it is possible that the measurement length was too short. Once appropriate start and stop times have been determined it will be necessary to go back and recompute the data set if these times differ from the times used in the initial flux computation.

Note that for gas species with large fluxes and low resistance to diffusion in the soil, long measurement periods may lead to underestimations of the final flux due to buildup of the gas in the soil air space during the measurement. For gas species with low fluxes, such as methane, long measurement periods may be required to get enough data for a good curve fit. This means when measuring methane and

carbon dioxide together, it will often be necessary to use different stop times for the two gases in the flux computation, with the stop time for carbon dioxide occurring much before that of methane.

Once satisfied with the curve fitting and summary values, the **Export** icon at the top of the main SoilFluxPro window can be used to export the summary values. For additional details on computing additional fluxes and exporting data see the SoilFluxPro manual accessed under **Help** in the software.

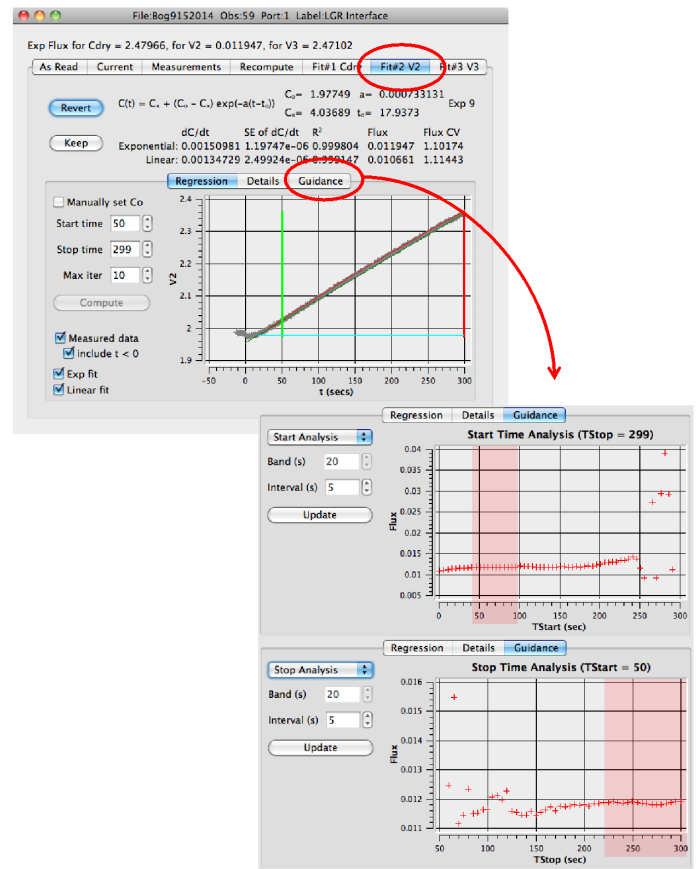


Figure 6. Viewing the curve fit for additional flux computations and using **Guidance** to select appropriate start and stop times. Windows with appropriate start and stop times are shaded in red.

Example 1: Measurements using the Los Gatos Research Ultra-Portable Greenhouse Gas Analyzer



Figure 7. A multiplexed LI-8100A System deployed with the Los Gatos Research Ultra-Portable Greenhouse Gas Analyzer (model 915-0011).

An Ultra-Portable GGA (model 915-0011) from Los Gatos Research, a member of the ABB group, was integrated into a multiplexed LI-8100A System (Figure 7) using a parallel plumbing configuration. Data from the analyzer was brought into the LI-8100A System using its analog outputs. Data collection was tested using both connection schemes described under Data Integration. Wiring for the two cable sets tested is described in Table 3.

The Ultra-Portable GGA had an actual volume of approximately 325 cm^3 and operated at 18.75 kPa and 300.12 K. Flow rate through the Ultra-Portable GGA was 0.8 SLPM. A chamber pressure of 100 kPa and temperature of 298.5 K was used to compute the effective volume for the Ultra-Portable GGA and an effective volume of 60.62 cm^3 was used for all flux computations.

Table 3. Cable connections used to integrate data from the Ultra-Portable GGA. A pre-assembled version of the Turck to DB-9 cable described here is available from LI-COR (part number 9981-188).

DB-9 connector to Ultra-Portable GGA	392-08577 wire color (three cables were used)	392-07955 wire color
CH ₄ signal (pin 1)	Brown (cable 1)	Red
CO ₂ signal (pin 2)	Brown (cable 2)	Pink
H ₂ O signal (pin 3)	Brown (cable 3)	Yellow
CH ₄ ground (pin 6)	Green (cable 1)	Green
CO ₂ ground (pin 7)	Green (cable 2)	Green
H ₂ O ground (pin 8)	Green (cable 3)	Green

Initial experiments were done in the lab to compare a known flux to the flux as determined from each analyzer's

time series data. Known fluxes were generated by injecting pure CO₂ at a constant rate through a mass-flow controller into a sealed collar below an 8100-104 chamber. Data from these experiments are presented in Table 4 and show that for an artificial flux produced by mass-flow the LI-8100A and Ultra-Portable GGA give the same and expected result.

Table 4. Comparison of known mass-flow fluxes between the LI-8100A and Ultra-Portable GGA. Fluxes are given as $\mu\text{mol m}^{-2} \text{ s}^{-1}$ plus or minus one standard deviation.

Injection Rate (SCCM)	Expected Flux	LI-8100A	Ultra-Portable GGA
0.1	2.3956± 0.0070	2.6203± 0.1295	2.6231± 0.1313
0.2	4.7339± 0.0080	4.6816± 0.1620	4.6896± 0.1575
0.4	9.3986± 0.0081	9.1713± 0.1501	9.1788± 0.1532
0.8	18.7328± 0.0079	18.1524± 0.1700	18.1577± 0.1727

The system was deployed on a mowed lawn and an artificial peat bog in Lincoln, NE to measure fluxes of carbon dioxide and methane. The two analyzers were cross calibrated prior to the laboratory experiments, but no subsequent calibration was performed prior to the field deployments. Figure 8 shows a comparison of the ranges and initial offsets in carbon dioxide concentration as reported by the two analyzers. While they showed a rather variable offset in concentration at the start of each measurement, the magnitude of change in concentration over each flux measurement was very similar for both analyzers at both sites.

Comparisons were made between the diffusive fluxes of carbon dioxide computed from these data and are presented in Figure 9. Fluxes at the lawn site were quite large during the deployment due to warm weather (mean temperature of 25.7 °C) and abundant soil moisture, and quite low at the artificial bog, presumably due to cooler temperatures (mean temperature of 19.4 °C) and low gas conductance of the saturated peat. Once fit with appropriate start and stop times for the curve fits, the carbon dioxide fluxes from both analyzers at both sites showed little difference (approximate difference of 0.3%) despite the offsets observed in the absolute concentrations as reported by the two instruments.

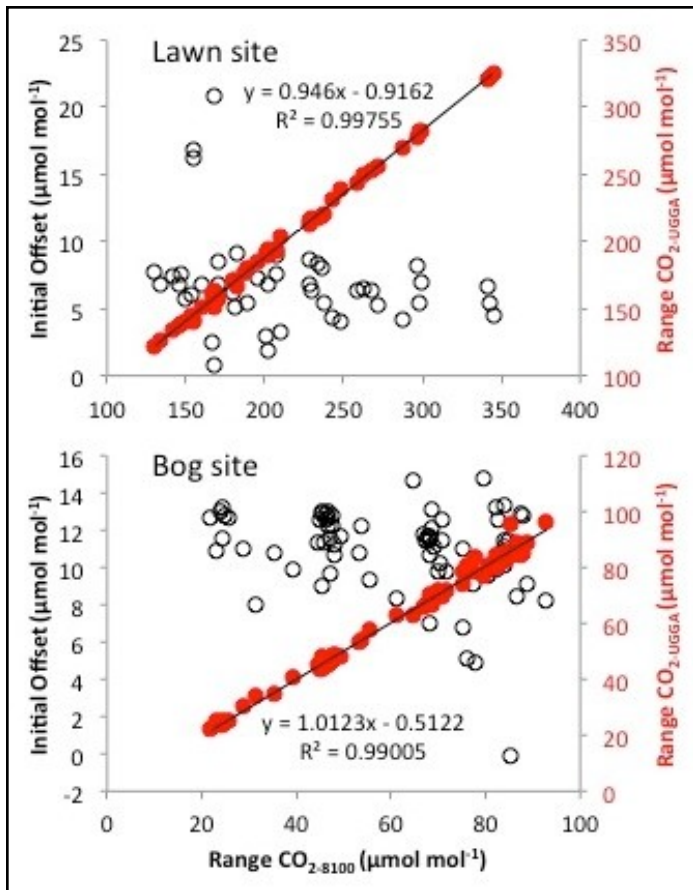


Figure 8. Range and initial offset for the flux measurements made at the lawn and artificial bog sites. The initial offset is computed as the initial carbon dioxide concentration as reported by the Ultra-Portable GGA minus the initial carbon dioxide concentration as reported by the LI-8100A.

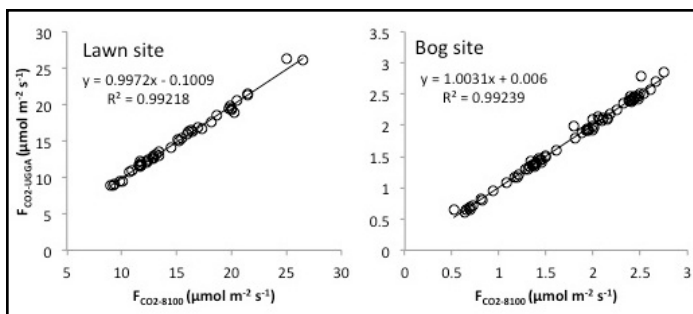


Figure 9. Comparison of exponential fluxes for carbon dioxide from the lawn and bog sites for the Ultra-Portable GGA (F_{CO_2-UGGA}) and the LI-8100A (F_{CO_2-8100}). For the lawn site the curve fits were done for the Ultra-Portable GGA using a 40 second start time and 120 second stop time. For the Ultra-Portable GGA at the bog site a 30 second start time and a 120 second stop time were used. At both sites start times for the LI-8100A were 20 seconds and stop times were 120 seconds.

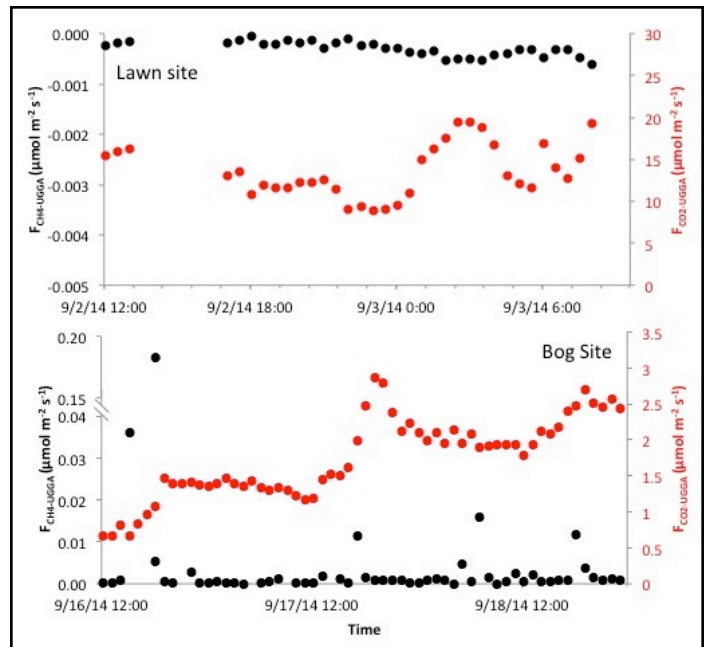


Figure 10. Fluxes for methane and carbon dioxide at the lawn and bog sites as measured by the Ultra-Portable GGA. Curve fitting for carbon dioxide is the same as described in Figure 9. For methane at the lawn site the curve fitting is the same as for carbon dioxide. At the bog site a start time of 30 seconds and a stop time of 300 seconds was used for the methane flux.

Methane fluxes at the two sites were small, but consistent with expected trends given soil conditions (Figure 10). At the lawn site a small negative flux was observed (mean of $-3.3 \times 10^{-4} \mu\text{mol m}^{-2} \text{s}^{-1}$), presumably due to methane oxidation. At the artificial bog fluxes were nominally zero for most measurements, but did show positive fluxes (maximum of $0.18 \mu\text{mol m}^{-2} \text{s}^{-1}$) in the late afternoon when the soil under the chamber was exposed to direct solar radiation.

Example 2: Measurements using the Picarro G2508 analyzer



Figure 11. A multiplexed LI-8100A System deployed with the Picarro G2508.

A five-species gas analyzer (model G2508) from Picarro, Inc. was integrated into a multiplexed LI-8100A System (Figure 11) using a parallel plumbing configuration. Data from the G2508 were logged to the analyzer's hard disk and merged with the LI-8100A's data in post processing using SoilFluxPro's import utility. 8100Sync was run on the G2508 from the Windows Task Scheduler, and used to synchronize the LI-8100A's clock to the clock of the G2508 every day at midnight. Clock synchronization was done over Ethernet using a direct connection between the LAN ports on the two instruments.

Flow through the G2508 was provided by the analyzer's vacuum pump and additional external plumbing was required to connect the two devices. While the G2508 optical bench has a specified volume of approximately 35 cm³, the additional external plumbing and pump represented a significant fraction of the total additional volume the analyzer added to the system. This complicated the computation of $V_{effective}$ as temperature and pressure were not uniform through the total volume and were only known in the optical bench. As such, $V_{effective}$ was determined for the G2508 experimentally as described in *Flow, volume, and pressure considerations*. Results are presented in Table 5.

Table 5. Effective volume as determined by injecting pure CO₂ into the G2508. Values are shown as mean plus or minus one standard error for n=3. The effective volume used for flux calculations was the mean of that determined for the three injection volumes; 62.13 cm³.

Injection Volume (μl)	Change in CO ₂ concentration (μmol mol ⁻¹)	$V_{effective}$ (cm ³)
10	161.3 ± 3.97	62.02 ± 1.55
20	311.6 ± 3.14	64.10 ± 0.65
40	662.8 ± 12.65	60.28 ± 1.13

The system was deployed on a mowed lawn and an artificial peat bog in Lincoln, NE to measure fluxes of carbon dioxide and methane. During deployment at the lawn site the two analyzers were cross calibrated by passing dry standard gases through them to ensure they were functioning correctly.

At both sites methane fluxes were relatively small and consistent with expectations based on soil conditions (Figure 12). At the lawn site predominately small negative fluxes were observed (mean of -1.8×10^{-4} μmol m⁻² s⁻¹) and were attributed to methane oxidation in the soil. Accumulation curves for methane at this site showed an oscillation in concentration across the curve (Figure 13). While similar oscillations have been observed in accumulation curves due to pressure perturbations or poor mixing in the chamber, in this case the oscillations appear to be due to the asynchronous nature of the G2508's measurements and concentration changes approaching the instrument's limit of precision (<10 ppb + 0.05% of reading, precision for raw signal). Methane was measured approximately every eight seconds by the G2508 and was up-sampled by the instrument to generate an approximately one sample per second time series. At the bog site, where fluxes were higher (mean of 1.2×10^{-2} μmol m⁻² s⁻¹) and larger changes in methane concentration were observed, similar oscillations were not evident in the accumulation curves.

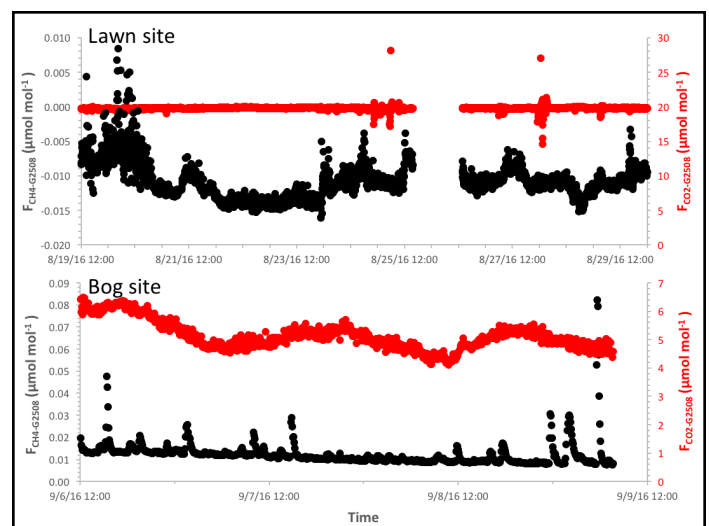


Figure 12. Methane and carbon dioxide fluxes from the lawn and bog sites as measured by the G2508. The gap on 8/26/16 was a period when other tests were being done with the system.

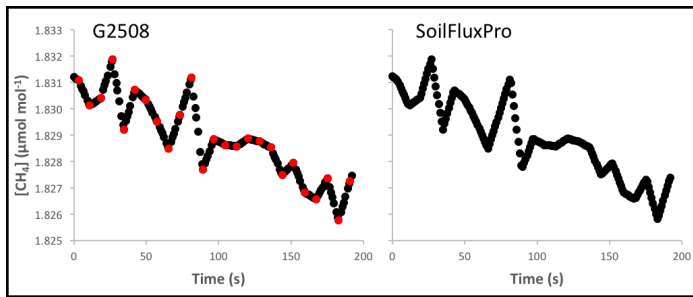


Figure 13. Example of methane concentration time series from a representative chamber measurement at the lawn site. The left panel shows measured (red) and interpolated (black) values from the G2508's output file. The right panel shows the same measurements after being imported through SoilFluxPro.

At both sites carbon dioxide fluxes were of a relatively similar magnitude; mean of $8.8 \mu\text{mol m}^{-2} \text{s}^{-1}$ at the lawn site and $5.0 \mu\text{mol m}^{-2} \text{s}^{-1}$ at the bog site as measured by the LI-8100A. A cross comparison was made between the flux of carbon dioxide computed from the LI-8100A's data and that of the G2508 (Figure 14). After careful optimization of the measurement start times, a small residual difference was observed in the fluxes computed from carbon dioxide dry mixing ratio, with fluxes computed from the G2508's data on average 2.7% larger than those computed from the LI-8100A. This offset was consistent across data from both deployments and did not appear to be due to a calibration offset between the two instruments, as they reported expected values when sampling dry standard gases during the initial cross calibration. Fluxes computed using a traditional dilution correction applied to the G2508's wet mole fraction data to get dry mixing ratio (Hupp 2011), were more similar to the LI-8100A fluxes (mean difference of 0.27% across both sites). The dilution correction used to compute dry mixing ratios on board the G2508 includes an additional spectroscopic correction not included in a traditional dilution correction (Rella 2010).

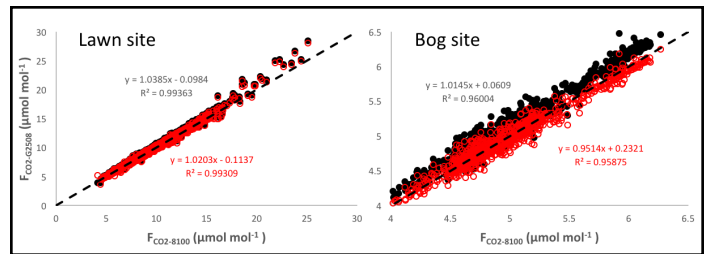


Figure 14. Comparison of exponential fluxes for carbon dioxide from the lawn and bog sites for the G2508 ($F_{\text{CO}_2\text{-G2508}}$) and the LI-8100A ($F_{\text{CO}_2\text{-8100}}$). At the lawn site start times were 50 seconds and 60 seconds for the LI-8100A and G2508 respectively. At the bog site start times were 30 seconds and 50 seconds. At both sites stop times were 180 seconds. Data in red were computed using wet mole fractions from the G2508 and a traditional dilution correction. Data in black were computed using the dry mixing ratio as reported by the G2508. Dashed lines represent a 1:1 relationship.

Example 3: Recommended integration procedures for Aerodyne, Inc. Dual-TILDAS analyzers

A Dual-TILDAS analyzer from Aerodyne, Inc. fitted with a Super Cell optical cell (2.7 L internal volume), was tested with a multiplexed LI-8100A system. While the tested analyzer, pump and optical cell configuration proved to have a time constant too long for use with the LI-8100A system. The tests provide insight and a basis for recommended integration schemes for other Dual-TILDAS instruments that should work well with the LI-8100A system.

The recommended plumbing configuration for a Dual-TILDAS analyzer connected to the LI-8100A system is shown in Figure 15 and follows the configuration used in our internal testing. The analyzer should be plumbed in parallel to the AIR OUT line from the LI-8100A as shown using the 9981-189 hose assembly, or similar user provided plumbing assembly. Flow through the analyzer needs to be provided by an independent pump cable of drawing sufficient vacuum on the analyzer's optical cell. In testing we used a Pfeiffer MVP 015-4 PK T05 064 connected to the analyzer's outlet. This pump provided a flow rate of approximately 1.0 SLPM at the analyzer's inlet, with an optical cell pressure maintained at 6.7 kPa. Cell pressure and flow should be set using inlet and outlet valves following the standard recommendations of Aerodyne Inc. Filters (recommended filter: United Filtration Systems Inc. DIF-BN60) should be included on both the analyzer's inlet and outlet to protect the optical cell from contamination and a series of solenoid valves (recommended valve: Parker 009-0294-900) may be included in the sub-sample loop to allow an auto-

background gas to be provided to the Dual-TILDAS under its own control.

It is recommended that time series data for flux measurements be logged separately on the LI-8100A and Dual-TILDAS and fluxes computed in post processing by merging the data files in SoilFluxPro. Time synchronization between the two instruments can be done over Ethernet or serial using 8100Sync configured to run in the Windows Task Scheduler onboard the Dual-TILDAS.

During testing, $V_{effective}$ and time constants were derived for the test setup following the procedures outlined in *Flow, volume, and pressure considerations*. $V_{effective}$, as determined from injections of pure CO₂, was 267.2 cm³ and that, computed using the analyzer's internal volume, was 178.2 cm³; the difference between the two presumably owing to the volume of the components in the analyzer's sub-sampling loop.

The time constant for the analyzer as computed from the measured flow rate in its sub-sample loop and its measured $V_{effective}$ was 16.3 seconds. In previous work, we have observed that time constants around this value had too large of impact on system kinetics for a closed transient measurement.

While the pump used in testing provided too low a flow rate to be useful with an analyzer fit with the Super Cell, it could be expected to work with a Dual-TILDAS fit with the standard optical cell (0.67 L internal volume). Assuming the same sub-sample loop contribution to $V_{effective}$ and the same operating pressure, at 1.0 SLPM the expected time constant for the standard cell would be approximately 8 seconds. To work with the Super cell, a flow rate of greater than 2 SLPM would be needed at the tested operating pressure (6.7 kPa) and temperature (24 °C).

While its flow rate is expected to be suitable for use with the standard optical cell, the tested pump may not be suitable depending on the gas species desired for measurements. The tested pump uses the fluoroelastomer FPM for its internal seals and diaphragms, which may interact with certain gas species. When new, the pump off-gassed all species measured by the analyzer during testing (CO, CH₄, CO₂, N₂O, C₂H₆) and had to be purged with air for several hours before it could be used for measurements. After purging the pump, no impact was observed during testing due to the FPM materials inside the pump.

For recommended pumps operating at higher flow rates and/or different internal materials contact Aerodyne Inc.

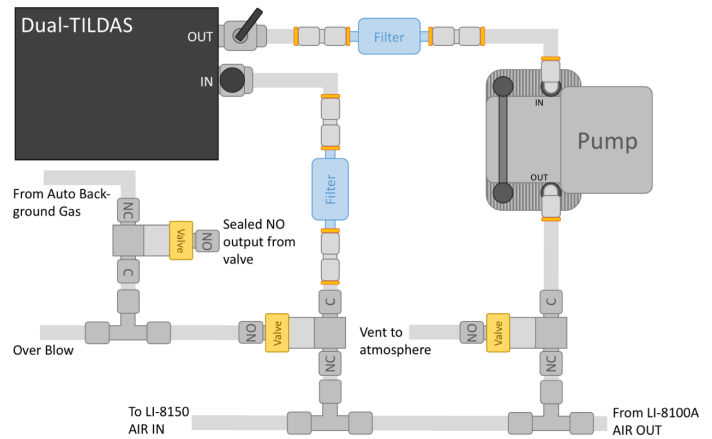


Figure 15. Recommended plumbing configuration for connecting a Dual-TILDAS analyzer to the LI-8100A system. Valves (Parker 009-0294-900) are included to allow an auto background gas to be provided to the analyzer. The valves are energized while auto backgrounding, separating the analyzer from the LI-8100A sub-sample loop. Flow of background gas needs to be higher than flow through the Dual-TILDAS such that when energized there is net flow of background gas out the port labeled **Over Blow**. Recommended filters are United Filtration Systems Inc. DIF-BN60.

References

- Hupp, J.R. 2011. The Importance of Water Vapor Measurements and Corrections. LI-COR, Inc., Application Note 129.
- Rella, C.W. 2010. Accurate Greenhouse Gas Measurements in Humid Gas Streams Using the Picarro G1301 Carbon Dioxide/Methane/Water Vapor Gas Analyzer. Picarro, Inc., White Paper.

Useful Part Numbers

Part Number	Description
8150-250	Bev-a-line tubing (15m roll)
300-07385	1/4" Quick-connect "T" fitting
300-03367	1/4" Quick-connect "Y" fitting
300-03123	1/4" Quick-connect straight union
300-07124	Male stainless steel quick-connect (connects to LI-8100A AIR IN)
300-07125	Female stainless steel quick-connect (connects to LI-8100A AIR OUT)
300-15313	Swagelok straight fitting (connects 9981-189 to Picarro G2805)
294-03334	0-2.5 LPM flow meter (rotometer)
300-08118	1/8" NPT to 1/4" Quick-connect right angle fitting (two used with rotometer)
392-08577	Auxiliary sensor input cable for 8100-104 or 8100-104C chambers
392-07955	Turck to bare leads cable, 2 m long
314-03430	Male DB-9 connector with shielded housing (used to access Ultra-Portable GGA's analog outputs)
9981-188	Pre-assembled Turck to DB-9 cable for connecting the Ultra-Portable GGA to the LI-8150.
9981-189	Pre-assembled hose assembly for plumbing additional analyzers in parallel to the LI-8100A subsampling loop.

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