GreenFeed Standard Calibrations, CO_2 Recoveries, and Auto-Recoveries

The following pages lay out the math behind standard calibrations and CO_2 recoveries, as well as the Auto-Recovery which replaces the calibration-recovery process in new units. The examples will only include the standard gases included in GreenFeed.

Standard Calibration

One purpose of performing a standard calibration is to find the factor used in converting the raw sensor voltage values to ppm for each gas measured by GreenFeed. First, a gas with 0 ppm of methane and carbon dioxide is introduced into the sensor box of GreenFeed and the raw voltage value of the response is recorded. Then another gas with known methane and carbon dioxide concentrations is introduced into the sensor box and the response is recorded. This calibration procedure is referred to as a two-point calibration. The calibration factor is then found by using the equation,

$$F_{\text{gas}} = \frac{\text{spanPPM - zeroPPM}}{\text{spanRAW - zeroRAW}}$$

Example:

A standard calibration is performed on a GreenFeed unit with a zero and span tank. Below are the span and zero gas concentrations found in the tanks as well as a visual representation of the raw voltage responses measured by GreenFeed.

Analytical Results - Zero Tank

	Req. Conc	Act. Conc
Oxygen	20.00 %	19.90 %
Nitrogen	Balance	

Analytical Results - Span Tank

	Req. Conc	Act. Conc
Hydrogen	10.00 ppm	10.00 ppm
Methane	500.0 ppm	506.0 ppm
Carbon Dioxide	5000 ppm	5002 ppm
Oxygen	21.00 %	21.01 %
Nitrogen	Balance	

Table 1: Tank Concentration Values

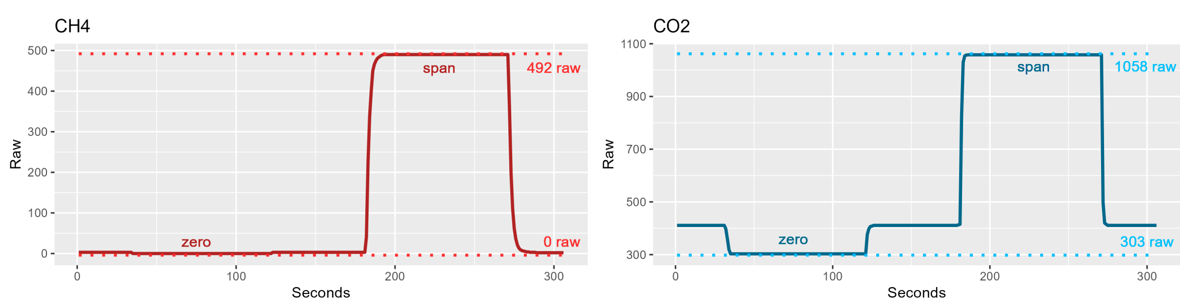

Figure 1: Standard Calibration

From this standard calibration,

$$\begin{aligned}
F_{\mathrm{CH_4}} &= \frac{506\text{ ppm} - 0\text{ ppm}}{492\text{ raw} - 0\text{ raw}} \\
&= 1.028\ \frac{\text{ppm}}{\text{raw}} \\
F_{\mathrm{CO_2}} &= \frac{5002\text{ ppm} - 0\text{ ppm}}{1058\text{ raw} - 303\text{ raw}} \\
&= 6.625\ \frac{\text{ppm}}{\text{raw}}
\end{aligned}$$

CO_2 Recovery

The CO_2 recovery compares the total amount of CO_2 released into GreenFeed to the amount of CO_2 measured by GreenFeed. First a cylinder of CO_2 is weighed, then some CO_2 is released from the cylinder into GreenFeed, and finally the cylinder is re-weighed. This process is repeated at least three times. Because the number of grams of CO_2 released into GreenFeed and the number of seconds of each release is known, the Mass Flow Rate equation can be used to find the flow factor needed to convert the raw voltage values given by the Air Velocity Transmitter to liters per second. Using the Mass Flow Rate equation,

$$\dot{m} = \rho \cdot V \cdot A,$$

where ρ is the density or concentration; V is the cross sectional velocity of the air pulled through GreenFeed; and A is the cross sectional area of the GreenFeed pipe,
and by summing the mass flow at each second of the release period, the total mass flow is calculated,

$$\begin{aligned}
\Delta m\,(\text{g}) = &\left[F_{\mathrm{CO_2}}\left(\frac{\text{ppm}}{\text{raw}}\right) \cdot \left(\frac{1\%}{10,000\text{ ppm}}\right) \cdot 1000\left(\frac{\text{L}}{\text{m}^3}\right) \cdot \rho_{\mathrm{CO_2}}\left(\frac{\text{g}}{\text{L}}\right) \cdot \sum_{i=1}^{t_{\text{r}}(\text{s})}\Big((R_i - B_i)\,(\text{raw})\Big)\right] \\
&\cdot \left[F_{\text{F}}\left(\frac{\text{m/s}}{\text{raw}}\right) \cdot \sum_{i=1}^{t_r(\text{s})}\left(FR_i\,(\text{raw}) \cdot \frac{273.15}{273.15 + T_i}\left(\frac{{}^\circ C}{{}^\circ C}\right)\right)\right] \cdot \left[A\left(\text{m}^2\right)\right]
\end{aligned}$$

and flow factor is solved for,

$$\begin{aligned}
F_{\text{F}}\left(\frac{\text{m/s}}{\text{raw}}\right) = \Delta m\,(\text{g}) \Big/ &\left[\rho_{\mathrm{CO_2}}\left(\frac{\text{g}}{\text{L}}\right) \cdot A\left(\text{m}^2\right) \cdot 1000\left(\frac{\text{L}}{\text{m}^3}\right) \cdot F_{\mathrm{CO_2}}\left(\frac{\text{ppm}}{\text{raw}}\right) \cdot \left(\frac{1\%}{10,000\text{ ppm}}\right)\right. \\
&\left.\cdot \sum_{i=1}^{t_r(\text{s})}\left(FR_i\,(\text{raw}) \cdot (R_i - B_i)\,(\text{raw}) \cdot \frac{273.15}{273.15 + T_i}\left(\frac{{}^\circ C}{{}^\circ C}\right)\right)\right]
\end{aligned}$$

where Δm is the total mass of CO_2 released into GreenFeed; $\rho_{\mathrm{CO_2}}$ is the density of CO_2 at standard temperature and pressure; A is cross sectional area of the GreenFeed pipe (0.0080073 m^2 for GreenFeed, 0.00447 m^2 for small animal GreenFeed); t_r is the number of seconds of the release; FR_i is the raw airflow at each second of the release; R_i is the raw CO_2 value at each second of the release; B_i is the raw interpolated baseline value at each second of the release; T_i is the temperature at each second of the release.

Example continued:

On the same unit, a CO_2 recovery is performed with a tank that contains only CO_2. The table below contains the times of each release as well as the mass of the tank.

Start Time	Stop Time	Time Diff	Start Mass	Stop Mass	Mass Diff
11:29:42	11:33:41	239 s	2375.4 g	2342.3 g	33.1 g
11:36:21	11:40:21	240 s	2342.3 g	2310.4 g	31.9 g
11:49:47	11:53:35	228 s	2279.8 g	2251.4 g	28.4 g
11:56:28	12:00:25	237 s	2251.4 g	2221.3 g	27.1 g

Table 2: CO_2 Recovery Values

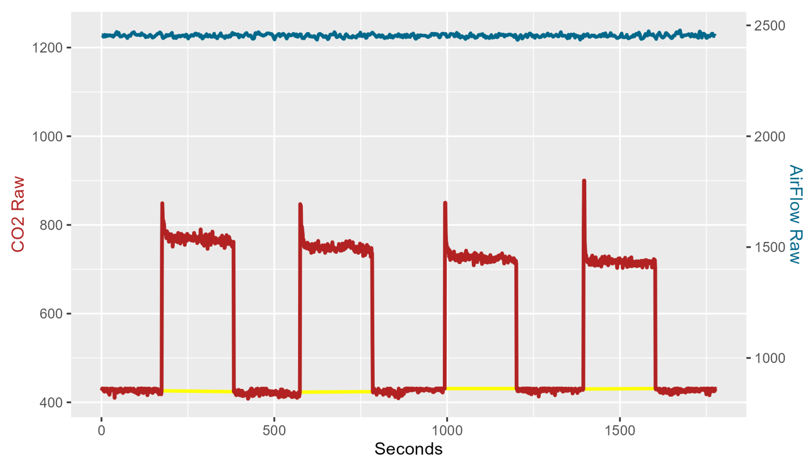

Figure 2: CO_2 Recovery

The flow factor is found using the table, along with other known values,

$$F_{\mathrm{F}} = 120.5\mathrm{g} \Bigg/ \left[1.96 \ \frac{\mathrm{g}}{\mathrm{L}} \cdot 0.0080073 \ \mathrm{m}^2 \cdot 1000 \ \frac{\mathrm{L}}{\mathrm{m}^3} \cdot 6.625 \ \frac{\mathrm{ppm}}{\mathrm{raw}} \cdot \frac{1\%}{10,000 \ \mathrm{ppm}} \cdot \sum_{i=1}^{944 \ \mathrm{s}} \left(FR_i \, (\mathrm{raw}) \cdot (R_i - B_i) \, (\mathrm{raw}) \cdot \frac{273.15 \ ^\circ C}{273.15 \ ^\circ C + T_i \ ^\circ C} \right) \right]$$

$$F_{\mathrm{F}} = 0.00192308 \ \frac{\mathrm{m/s}}{\mathrm{raw}}$$

Auto-Recovery

The auto-recovery was designed to simplify and automate the calibration-recovery process. The auto-recovery compares the actual mass flow rate that is injected into GreenFeed with the calculated mass flow rate that is measured by GreenFeed.

During an auto-recovery, a gas tank with known concentrations of CO_2 and CH_4 is connected to the gas mass flow controller which accurately controls the rate at which gas is released. The flow controller injects the gas into GreenFeed at 10 sL/min. GreenFeed simultaneously pulls ambient air in around 40 L/s.

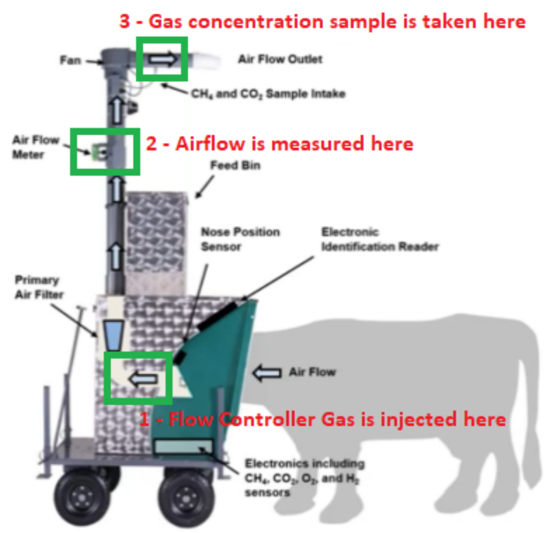

Figure 3: Auto-recovery path through GreenFeed

The ambient air and gas injected from the flow controller travels up the pipe where the Air Velocity Transmitter measures the airflow. The air then travels past the fan where a sample is taken and the gas sensors measure the concentration of each gas present in the sample. GreenFeed outputs the airflow and gas concentration measurements as raw voltage values.

Because the gas injection rate of the flow controller and the concentrations of each gas in the tank are known, the airflow and concentration sensors can be calibrated.

To find the factor with which to convert the raw voltage values from the sensors, some known values need to be gathered. The following is known,

1. the flow rate of the flow controller, set to 10 sL/min, or $0.16\overline{6}$ sL/sec
2. the concentrations of the gases in the tank
3. the density of the gases in the tank

From there, the Gas Flow Rate is found, which is the number of standard liters of each constituent gas being injected into GreenFeed per minute. The equation is,

$$Q_{\text{gas}}\left(\frac{\text{sL}}{\text{min}}\right) = \textit{conc}\,(\text{ppm}) \cdot Q\left(\frac{\text{sL}}{\text{min}}\right) \cdot \left(\frac{1\%}{10,000\ \text{ppm}}\right)$$

Then, the Flow Meter Mass Flow Rate is calculated, which is Gas Flow Rate at standard temperature and pressure in grams per day, with the equation,

$$\dot{m}_{\text{FM,gas}}\left(\frac{\text{g}}{\text{day}}\right) = Q_{\text{gas}}\left(\frac{\text{sL}}{\text{min}}\right) \cdot \rho_{\text{gas}}\left(\frac{\text{g}}{\text{L}}\right) \cdot 24\left(\frac{\text{hr}}{\text{day}}\right) \cdot 60\left(\frac{\text{min}}{\text{hr}}\right)$$

This value is used in the Mass Flow Rate equation to find the conversion factor from raw sensor values to grams per day of each gas. The following values are known,

1. average temperature during the auto-recovery, T_{avg}, in degrees Celsius
2. average airflow during the auto-recovery, FR_{avg}, in raw sensor value
3. flow offset for small animal GreenFeed units, *offset*, in raw sensor value
4. difference in response and baseline values of the auto-recovery, *diff*, in raw sensor value
5. area of pipe, A, in meters squared

Putting these values into the equation for Mass Flow Rate,

$$\begin{aligned}
\dot{m}_{\text{gas}} &= \rho \cdot V \cdot A \\
\dot{m}_{\text{gas}}\left(\frac{\text{g}}{\text{day}}\right) &= \left[\textit{diff}\,(\text{raw}) \cdot F_{\text{gas}}\left(\frac{\text{ppm}}{\text{raw}}\right) \cdot \left(\frac{1\%}{10,000\ \text{ppm}}\right) \cdot 1000\left(\frac{\text{L}}{\text{m}^3}\right) \cdot \rho_{\text{gas}}\left(\frac{\text{g}}{\text{L}}\right)\right] \\
&\quad \cdot \left[F_{\text{F}}\left(\frac{\text{m/s}}{\text{raw}}\right) \cdot (FR_{\text{avg}} - \textit{offset})\,(\text{raw}) \cdot \frac{273.15}{273.15 + T_{\text{avg}}}\left(\frac{^\circ C}{^\circ C}\right) \cdot 86,400\left(\frac{\text{s}}{\text{day}}\right)\right] \cdot \left[A\left(\text{m}^2\right)\right]
\end{aligned}$$

However, since when performing an auto-recovery, F_{gas} or F_{F} are not known, they are combined into a new variable for each gas called $F_{\text{AR,gas}}$,

$$\begin{aligned}
F_{\text{AR,gas}} = F_{\text{gas}} \cdot F_{\text{F}}\left(\frac{\text{ppm}}{\text{raw}} \cdot \frac{\text{m/s}}{\text{raw}}\right) &= \dot{m}_{\text{gas}}\left(\frac{\text{g}}{\text{day}}\right) \Big/ \left[\textit{diff}\,(\text{raw}) \cdot \left(\frac{1\%}{10,000\ \text{ppm}}\right) \cdot 1000\left(\frac{\text{L}}{\text{m}^3}\right) \cdot \rho_{\text{gas}}\left(\frac{\text{g}}{\text{L}}\right)\right. \\
&\quad \left. \cdot (FR_{\text{avg}} - \textit{offset})\,(\text{raw}) \cdot \frac{273.15}{273.15 + T_{\text{avg}}}\left(\frac{^\circ C}{^\circ C}\right) \cdot 86,400\left(\frac{\text{s}}{\text{day}}\right) \cdot A\left(\text{m}^2\right)\right]
\end{aligned}$$

Note that raw gas values and raw airflow values cannot be combined.

Example continued:

Before performing the auto-recovery, the Flow Meter Mass Flow Rate is found using the gas concentration values in the auto-recovery tank. The table below contains the concentration values.

Analytical Results		
	Req. Conc	Act. Conc
Hydrogen	0.04 %	0.04 %
Methane	3.5 %	3.498 %
Carbon Dioxide	11.5 %	11.5 %
Nitrogen	Balance	

Table 3: Auto-Recovery Tank Concentration Values

Finding Gas Flow Rate first,

$$\begin{aligned}
Q_{\mathrm{CH_4}} &= 34980 \text{ ppm} \cdot 10 \, \frac{\text{sL}}{\text{min}} \cdot \frac{1\%}{10,000 \text{ ppm}} \\
&= 0.3498 \, \frac{\text{sL}}{\text{min}} \\
Q_{\mathrm{CO_2}} &= 115000 \text{ ppm} \cdot 10 \, \frac{\text{sL}}{\text{min}} \cdot \frac{1\%}{10,000 \text{ ppm}} \\
&= 1.1500 \, \frac{\text{sL}}{\text{min}}
\end{aligned}$$

Then plugging that into the Flow Meter Mass Flow Rate equation,

$$\begin{aligned}
\dot{m}_{\mathrm{FM,CH_4}} &= 0.3498 \, \frac{\text{sL}}{\text{min}} \cdot 0.7168 \, \frac{\text{g}}{\text{L}} \cdot 24 \, \frac{\text{hr}}{\text{day}} \cdot 60 \, \frac{\text{min}}{\text{hr}} \\
&= 361.06 \, \frac{\text{g}}{\text{day}} \\
\dot{m}_{\mathrm{FM,CO_2}} &= 1.1500 \, \frac{\text{sL}}{\text{min}} \cdot 1.96 \, \frac{\text{g}}{\text{L}} \cdot 24 \, \frac{\text{hr}}{\text{day}} \cdot 60 \, \frac{\text{min}}{\text{hr}} \\
&= 3245.76 \, \frac{\text{g}}{\text{day}}
\end{aligned}$$

Now that the Flow Meter Mass Flow Rate has been found, the auto-recovery is performed and the auto-recovery factor for each gas is solved for. Below is a table and graph of the raw voltage responses measured by GreenFeed.

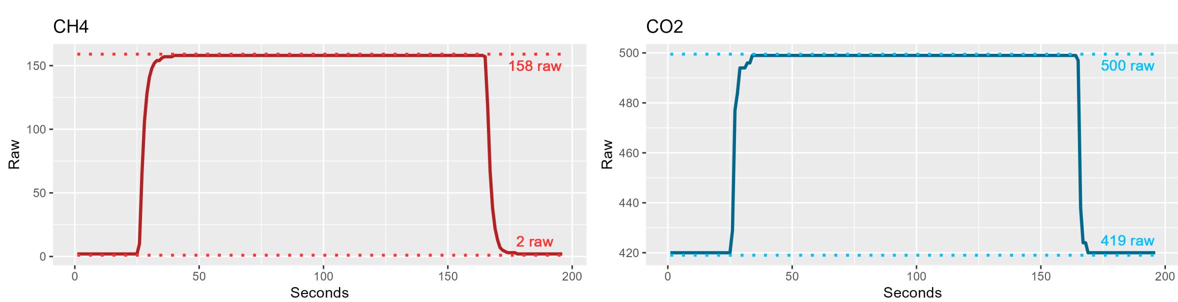

Figure 4: Auto-Recovery GreenFeed Gas Responses

Gas	Baseline	Response	Difference	Air Flow
CH_4	2 raw	158 raw	156 raw	2467 raw
CO_2	419 raw	500 raw	81 raw	2467 raw

Table 4: Auto-Recovery Values

For this auto-recovery,

$$
\begin{aligned}
F_{\mathrm{AR,CH_4}} &= 361.06\ \frac{\mathrm{g}}{\mathrm{day}} \Bigg/ \Bigg[156\ \mathrm{raw} \cdot \frac{1\%}{10,000\ \mathrm{ppm}} \cdot 1000\ \frac{\mathrm{L}}{\mathrm{m}^3} \cdot 0.7168\ \frac{\mathrm{g}}{\mathrm{L}} \cdot (2467\ \mathrm{raw} - 0\ \mathrm{raw}) \\
&\qquad \cdot \frac{273.15\ ^\circ C}{273.15\ ^\circ C + 19.8\ ^\circ C} \cdot 86,400\ \frac{\mathrm{s}}{\mathrm{day}} \cdot 0.0080073\ \mathrm{m}^2 \Bigg] \\
&= 0.00202888\ \frac{\mathrm{ppm}}{\mathrm{raw}} \cdot \frac{\mathrm{m/s}}{\mathrm{raw}} \\
F_{\mathrm{AR,CO_2}} &= 3245.76\ \frac{\mathrm{g}}{\mathrm{day}} \Bigg/ \Bigg[81\ \mathrm{raw} \cdot \frac{1\%}{10,000\ \mathrm{ppm}} \cdot 1000\ \frac{\mathrm{L}}{\mathrm{m}^3} \cdot 1.96\ \frac{\mathrm{g}}{\mathrm{L}} \cdot (2467\ \mathrm{raw} - 0\ \mathrm{raw}) \\
&\qquad \cdot \frac{273.15\ ^\circ C}{273.15\ ^\circ C + 19.8\ ^\circ C} \cdot 86,400\ \frac{\mathrm{s}}{\mathrm{day}} \cdot 0.0080073\ \mathrm{m}^2 \Bigg] \\
&= 0.01284618\ \frac{\mathrm{ppm}}{\mathrm{raw}} \cdot \frac{\mathrm{m/s}}{\mathrm{raw}}
\end{aligned}
$$

Comparing the auto-recovery to the standard calibration-recovery process, the auto-recovery factor for each gas is mathematically equivalent to the $F_{\mathrm{gas}} \cdot F_{\mathrm{F}}$ value.

Calculated From	Coefficient	CH_4	CO_2
Standard Calibration	F_{gas}	1.028	6.625
CO_2 Recovery	F_{F}	0.00192308	0.00192308
	$F_{\mathrm{gas}} \cdot F_{\mathrm{F}}$	0.00197780	0.01274074
Auto-Recovery	$F_{\mathrm{AR,gas}}$	0.00202888	0.01284618
Ratio	$F_{\mathrm{AR,gas}}$ / $F_{\mathrm{gas}} \cdot F_{\mathrm{F}}$	102.58	100.83

Table 5: Auto-recovery, Calibration-Recovery Factor Ratio

Summary

In conclusion, there are two values measured by sensors in GreenFeed that need calibration factors in order to be converted from raw voltage values to readable units - ppm of each gas and L/s of air flowing through the pipe. The standard calibration and CO_2 recovery are the original methods of finding the conversion factors for these values. The auto-recovery is the new, but equivalent, method. Although the way in which the factors are found differ between the two methods, the result is the same.

Method of Calibration	**Coefficient Being Calculated**	**Method of Calculation**
Standard Calibration	Gas Coefficients (F_{gas})	Concentration sensor responses to gases
CO_2 Recovery	Airflow Coefficient (F_{F})	Comparing total mass injected vs. Mass captured by system
Auto-Recovery	Gas and Airflow Coefficients ($F_{\text{AR,gas}}$)	Comparing mass injection rate vs. Mass capture rate

Table 6: Calibration Methods Summary