# Using the LI-870 $CO_2/H_2O$ Analyzer


LI-COR®

# Using the LI-870

## $CO_2/H_2O$ Analyzer

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## Printing History



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## Notes on Safety

This LI-COR product has been designed to be safe when operated in the manner described in this manual. The safety of this product cannot be assured if the product is used in any other way than is specified in this manual. The product is intended to be used by qualified personnel. Read this entire manual before using the product.

| Equipment markings: | |
|---|---|
|  | The product is marked with this symbol when it is necessary for you to refer to the manual or accompanying documents in order to protect against injury or damage to the product. |
|  | The product is marked with this symbol when a hazardous voltage may be present. |
|  | The product is marked with this symbol if a Chassis Ground connection is required. |
|  | The product is marked with this symbol to indicate that a direct current (DC) power supply is required. |
| **WARNING** | Warnings must be followed carefully to avoid bodily injury. |
| **CAUTION** | Cautions must be observed to avoid damage to your equipment. |
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| **Note** | Notes contain important information and useful tips on the operation of your equipment. |

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## California Proposition 65 Warning

**WARNING:** This product contains chemicals known to the State of California to cause cancer and birth defects or other reproductive harm.

## Federal Communications Commission Radio Interference Statement

**WARNING:** This equipment generates, uses, and can radiate radio frequency energy and if not installed in accordance with the instruction manual, may cause interference to radio communications. It has been tested and found to comply with the limits for a Class A computing device pursuant to Subpart J of Part 15 of FCC rules, which are designed to provide a reasonable protection against such interference when operated in a commercial environment. Operation of this equipment in a residential area is likely to cause interference in which case the user, at his own expense, will be required to take whatever measures may be required to correct the interference.

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This symbol indicates that the product is to be collected separately from unsorted municipal waste. The following applies to users in European countries: This product is designated for separate collection at an appropriate collection point. Do not dispose of as household waste. For more information, contact your local distributor or the local authorities in charge of waste management.

# Contents

## Section 1. Overview of the LI-870



## Section 2. Using the LI-870



## Section 3. Troubleshooting



## Section 4. Maintenance



## Appendix A. Specifications

## Appendix B. Equations summary

## Standard Terms and Conditions

# Section 1.
# Overview of the LI-870

The LI-870 is a $CO_2/H_2O$ Gas Analyzer that is designed for use with the Smart Chamber and LI-8250 Multiplexer in soil gas flux systems. This document provides basic operating instructions for the LI-870. Refer to the Smart Chamber and LI-8250 manuals for additional information.

## What's what

If you have just taken delivery of your LI-870, check your packing list to ensure the following items have been included.

### LI-870 $CO_2/H_2O$ Analyzer

**Part number: 870-01**

The LI-870 is a portable gas analyzer designed for use with the Smart Chamber or LI-8250 Multiplexer for soil $CO_2$ flux measurements.

The LI-870 measures $CO_2$ in air at concentrations from 0 to 20,000 ppm using non-dispersive infrared gas analysis technology. This technology is well-established in other LI-COR products, including the widely-published LI-8100A Automated Soil $CO_2$ Flux System, LI-830 and LI-850 $CO_2$ and $CO_2/H_2O$ Gas Analyzers, and LI-COR eddy covariance analyzers. Water vapor measurements are used in corrections to report $CO_2$ concentrations with high accuracy. Power to the LI-870 is supplied from the Smart Chamber or LI-8250 Multiplexer. The LI-870, in turn, provides $CO_2$ data to the Smart Chamber or LI-8250 Multiplexer for storage and processing.

## LI-870 cable and tube assembly

Part number: 9982-010

A 1.2 meter cable and tubing assembly is included with the LI-870 to connect the LI-870 with the Smart Chamber or LI-8250 Multiplexer. This assembly includes:

- Sealed USB-A to USB-B cable (part number 392-17654).
- Sealed 2.5 × 5 mm IP68 power cable (part number 9982-008).
- Two lengths 1.2 meter 1/4" Bev-A-Line® tubing (part number 222-01824) with quick-connect fittings (part numbers 300-07124 (male) and 300-07125 (female)).

The assembly components are zip tied in plastic conduit.

## Shoulder strap

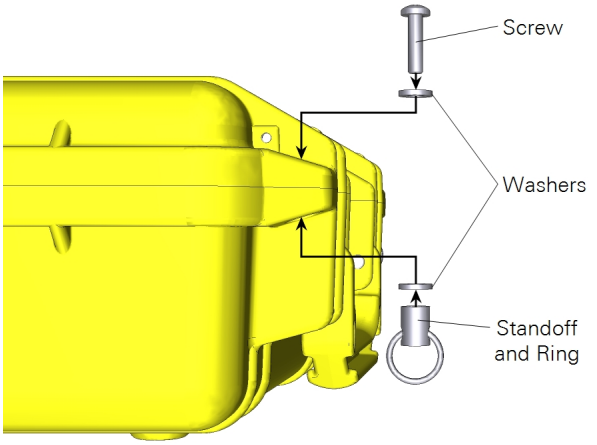
Part number: 604-18146

The shoulder strap is to carry the LI-870.

## Split ring assembly

Part number: 9882-019

The LI-870 ships with a split ring and standoff assembled for attaching the shoulder strap. The rings are attached near the clasps of the case. Each assembly consists of a machined standoff (part number 9882-019), screw (part number 122-07715), split ring (part number 610-10353), and two washers (part number 167-00154).




## Spares kit

**Part number: 9982-020**

A spares kit is shipped with the LI-870 and contains the following.

| Description | Quantity | Part Number |
|---|---|---|
| 1/4" Bev-A-Line® IV Plastic Tubing (12 meters) | 1 | 8150-250[a] |
| 1/4" Quick-connect Straight Union | 2 | 300-03123 |
| Quick Connect Plug 0.165 with Hose Barb (Male) | 1 | 300-07124 |
| Quick Connect Plug 0.165 with Hose Barb (Female) | 1 | 300-07125 |
| Optical Bench Cleaning Kit | 1 | 9980-066 |
| USB-A to USB-B, Unsealed, 2 meter | 1 | 392-06652 |

# Software

The LI-870 can be calibrated using the LI-830/LI-850 user interface software, which is available from the LI-COR support site at licor.com/830-850-support. Select software, and find the installer appropriate for your operating system. This software is available for both Windows® and macOS® operating systems and is used to calibrate your LI-870 and view live data.

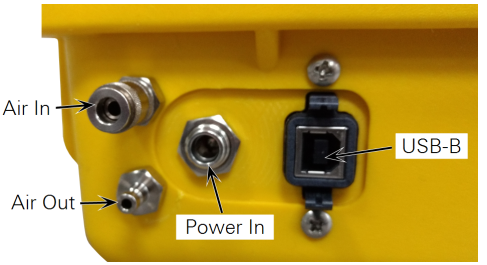
[a]Additional tubing can be repurchased as a 15 meter roll.

# Section 2.
# Using the LI-870

The basic operation of the LI-870 involves connecting the USB data cable, connecting the tubing, and connecting the power cable between the LI-870 and Smart Chamber or LI-8250 Multiplexer, as described here.

## Connecting the cable assembly

Connecting the LI-870 to the Smart Chamber or LI-8250 Multiplexer is simple, only requiring a few steps.

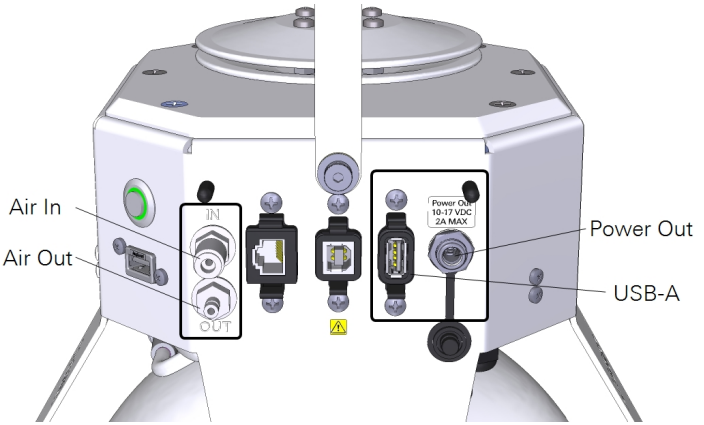


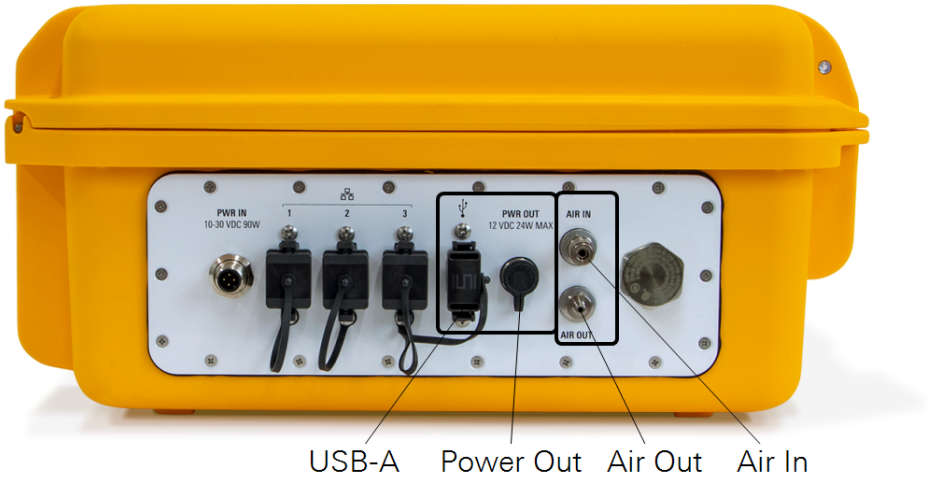

First, attach each end of the cable assembly to the LI-870. The USB-B end of the USB-A to USB-B cable is attached to the LI-870, while the USB-A end is attached to the Smart Chamber or LI-8250.

> **Note:** Only use the supplied USB-A to USB-B cable from the LI-870 to cable assembly (part number 9982-010).

Next, attach the cable assembly to the Smart Chamber or LI-8250. Connect the steel quick connect fittings for the air tubing, and thread the power cable on to the power-in and power-out connectors on each panel. Tighten snugly to ensure a water-

tight seal. Follow the detailed instructions in the Smart Chamber or LI-8250 instruction manual for additional details.



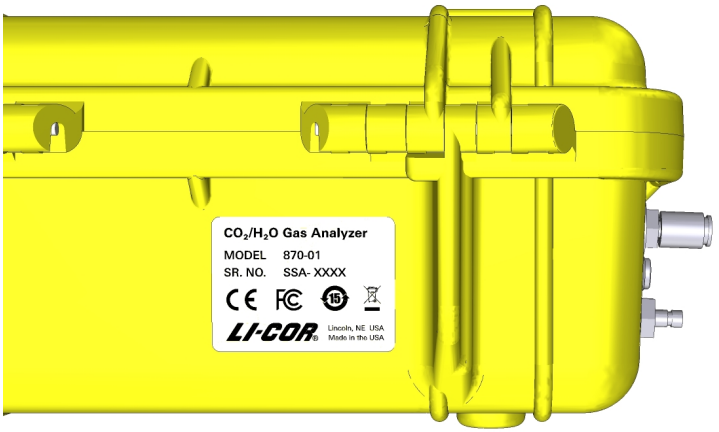
***Warning:*** *The power output is 10-17 VDC ⎓ with a center positive pin ⊖—⊙—⊕. The output has a 2 amp maximum and is designed to only power the LI-870 $CO_2/H_2O$ Analyzer Accessory. Only use the power cable supplied with the LI-870 cable assembly (P/N 9982-010), and do not attempt to power any other devices with the Smart Chamber or LI-8250. Drawing a current in excess of 2 amps will trip the self-resetting breaker. If you trip the self-resetting breaker, you will need to wait for a few minutes before attempting to re-power the LI-870.*

# Powering the analyzer and making measurements

After connecting the power cable, you should power on your Smart Chamber or LI-8250 and launch the user interface software. Power to the LI-870 is supplied directly from the Smart Chamber or LI-8250.

## Identifying the LI-870 serial number

In the **Settings** page of the Smart Chamber or LI-8250 interface, you will need to connect to your LI-870 using the serial number. The label is on the bottom of the case.

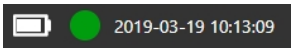



## Warm up time

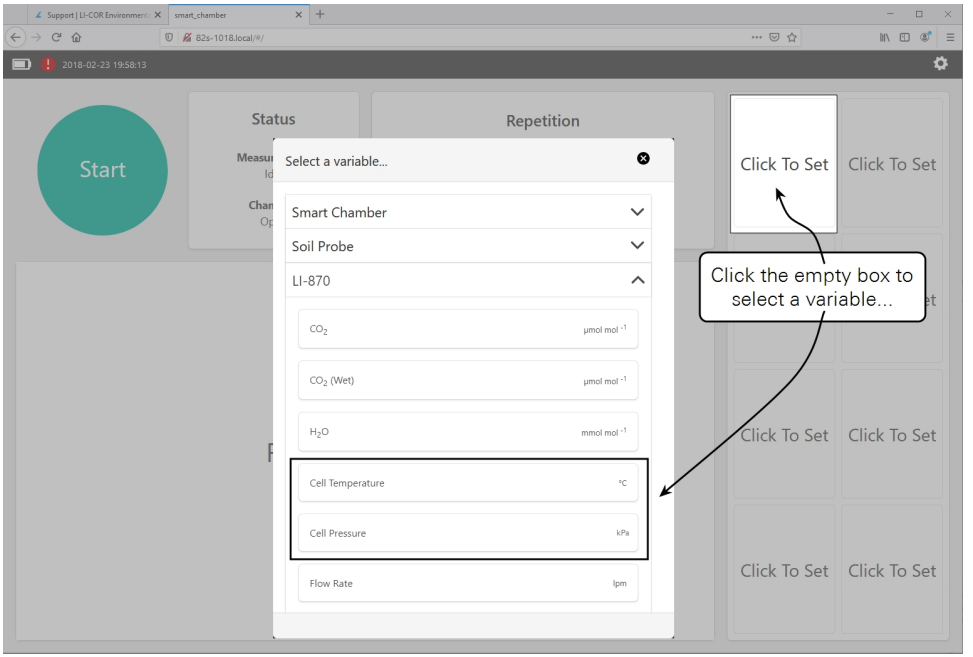
The LI-870 will boot up as soon as power is supplied from the chamber. The optical bench should be allowed to warm up prior to taking measurements. The LI-870

optical bench is temperature- and pressure-controlled, so a sudden influx of ambient air into an optical bench that has not been allowed to warm up and stabilize will likely produce noisy data. For this reason, it is critical that your analyzer is allowed to warm up prior to taking measurements. In most cases, 10 to 15 minutes of warm up time will allow the optical bench to stabilize, but warmup time depends largely on ambient temperature.

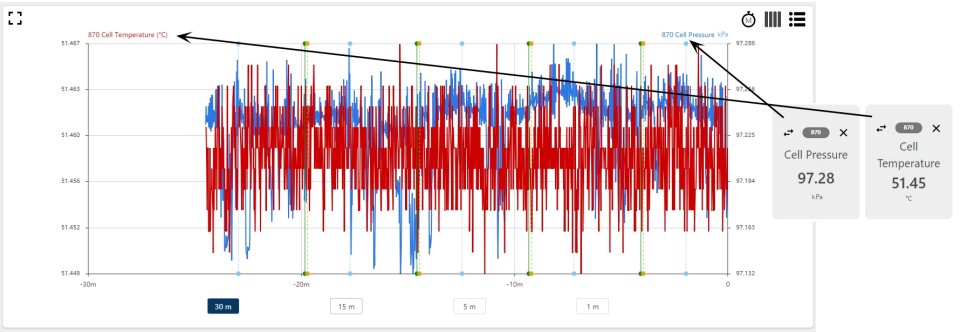
In the Smart Chamber and LI-8250 interface, you can see when your LI-870 optical bench has stabilized when the dot in the upper-left portion of any screen by the time stamp is green. If the bench is not stabilized, this dot will be red.




You can also visualize the optical bench temperature and pressure from the **Home Page** of the Smart Chamber or LI-8250 interface to assess whether they have stabilized. After connecting to the Smart Chamber or LI-8250, from the **Home Page**, select **Click to Set**. In the **Select a variable**... window that opens, open the LI-870 list, and you can select **Cell Temperature** and **Cell Pressure**.



These variables will now be in the grid on the **Home Page.** Click them again to graph the values live.




The axes auto-scale, so pay close attention to the axis labels to assess stability. In the example graph above, the bench temperature, for example, is stabilized within roughly ± 0.1 °C from the median value/middle of the graph. Once the values have stabilized like this, you can begin taking measurements following the instructions in the Smart Chamber or LI-8250 manual.

# Storing the LI-870

The post-purge function of the Smart Chamber is designed to allow for ambient air to flush $CO_2$- and water vapor-rich air from the cable assembly tubing and analyzer after each measurement. When you are performing your last measurement(s) of the season, or when you return to the lab or desk after taking your last measurements, you should perform a measurement or two with the Smart Chamber to allow dry ambient air to flow through your chamber. This will help to remove humidity before storage.

**Note:** For more information on post-purge, consult the Smart Chamber manual or find resources online at licor.com/env/support.

The LI-870 should be stored in non-condensing conditions. If the instrument is stored in high humidity or moderate humidity for a long time while powered off, some optical components may temporarily become saturated with humidity. If this occurs, the instrument may need to run for several days before readings return to normal. If possible, store the instrument in an air conditioned environment.

# Section 3.
# Troubleshooting

In this section, we describe how to identify some potential problems with the LI-870 and how to resolve them. If you can't find a solution here, if you need further assistance performing maintenance, or if you have other questions, contact your local distributor or LI-COR technical support for more help.

## Smart Chamber or LI-8250 software not recognizing LI-870

Power is supplied from the Smart Chamber or LI-8250, and assuming your connection is completed correctly, the gas analyzer is always powered on when the Smart Chamber or LI-8250 is powered on. The Smart Chamber or LI-8250 will automatically recognize your device with no further steps needed. Simply expand the **LI-870** drop-down in the **Connections** menu of the **Measurement Settings** page of the Smart Chamber or LI-8250 software, select your instrument serial number, and press **Update.**

If you open the drop-down menu and your instrument does not appear,

- Is your power cable fully connected to both devices? Make sure the cable is fully inserted and the threaded nut is snugly fastened.
- Is your USB cable fully connected to both devices? Ensure that the connectors on both sealed cables are clipped to the prongs on each device.

If your cables are fully connected but you still cannot identify your device, you can open your device to see if power is being supplied. Next to the connection panel inside the case, a red LED light will be blinking if power is being supplied.

**Note:** Do not open the LI-870 enclosure in the field. This can cause the temperature and pressure of the optics to become destabilized. More importantly, this can allow dust and debris into your analyzer. If possible, you should confirm whether your analyzer is working properly and troubleshoot any issues before taking it out to the field.

If your Smart Chamber or LI-8250 is on and your cables are properly connected, the light should be blinking. If it is not blinking, something could be wrong with your power cable, the chamber power-out connector, analyzer power-in connector, or other electronics inside the case. Check for dust and debris in the connectors and for damage to the cable itself. For power-related issues, it is recommended that you call LI-COR technical support for further instructions.

If the light is blinking but you still cannot identify your device through the Smart Chamber or LI-8250 software, check your USB cable for damage. Is there dust or debris in the cable heads or the connectors? Try refreshing the interface software, clearing your browser cache, and rebooting your Smart Chamber or LI-8250. If you still cannot connect, contact LI-COR technical support.

## Unable to Zero or Span the Instrument

Is there dirt in the optics? If the optical cell becomes contaminated, the instrument will drift in either the zero or span. See *Cleaning the optical bench* on page 4-1 for details on cleaning your optical bench.

## Instrument Reports -50 ppm $CO_2$ or Measurements Jump Around

If the instrument measures -50 ppm or the measurements are going between negative and positive values, or just simply not making any sense, the optical source may have failed or be in the midst of failure. Contact technical support for additional troubleshooting help.

# Section 4.
# Maintenance

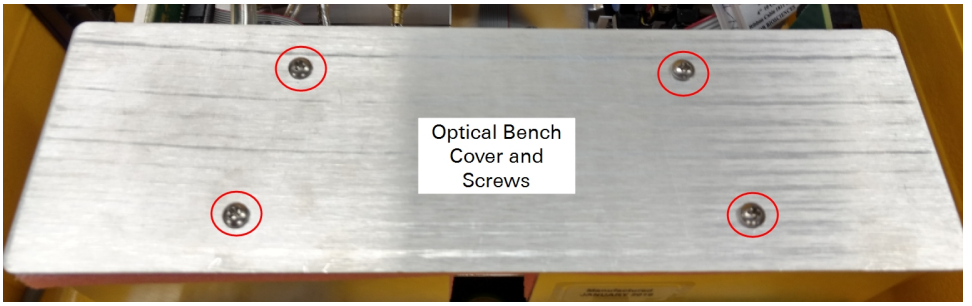
## Cleaning the optical bench

The LI-870 optical bench can be removed and cleaned with just a few steps if necessary. Generally speaking, you shouldn't undertake this procedure unless you've ruled out other potential problems. While the process itself is not difficult, you will have to set the instrument zero and span after reassembling the optical bench.

An optical bench cleaning kit (part number 9980-066) is included with your LI-870 spares kit. You will also need a small Phillips screwdriver. Follow these steps to remove and clean your optical bench and replace the O-rings. Note that the images included in this section were taken from a prototype LI-870. The wiring and plumbing in your instrument may appear slightly different.

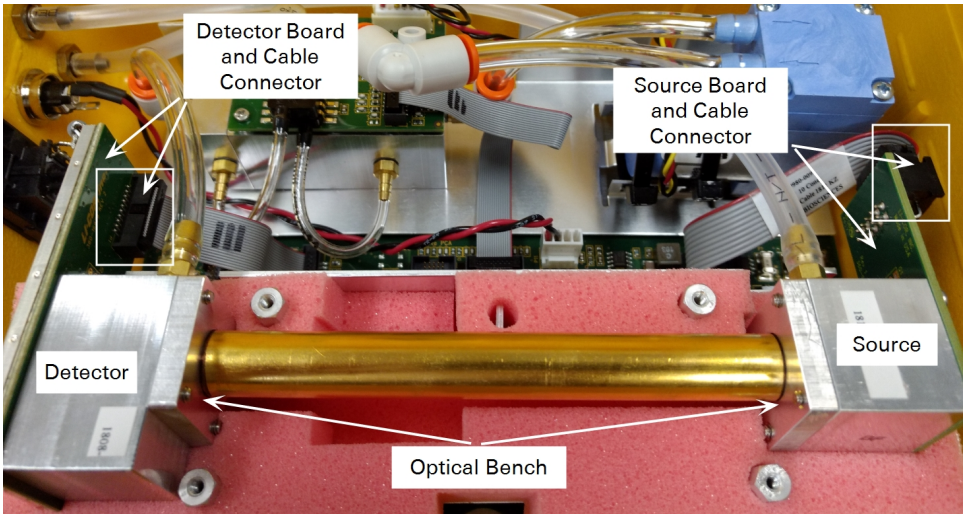
**Warning:** *Be sure that you are properly grounded to avoid electrostatic discharge that can damage the electronics. Use an anti-static wrist strap, electrostatic discharge grounding mat, or occasionally touch bare metal that has a clear path to ground, such as an unpainted computer case.*

1. Unplug your instrument from the Smart Chamber or LI-8250. If you've been operating the instrument recently, you should allow the optical bench to cool down to room temperature.
2. Open the analyzer and remove the plate covering the optical bench.

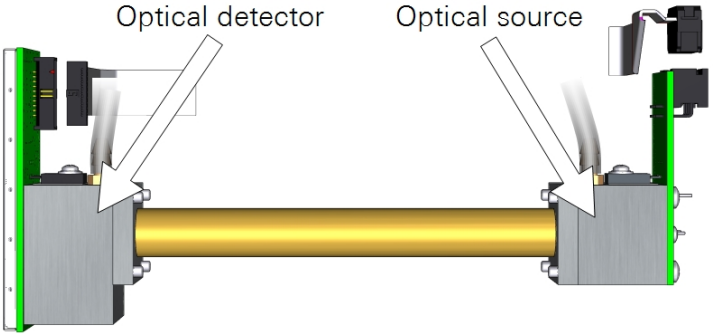



The bench cover is held in place by four screws. Remove these screws, remove the plate and foam, and set aside. The insulated optical bench will now be visible.

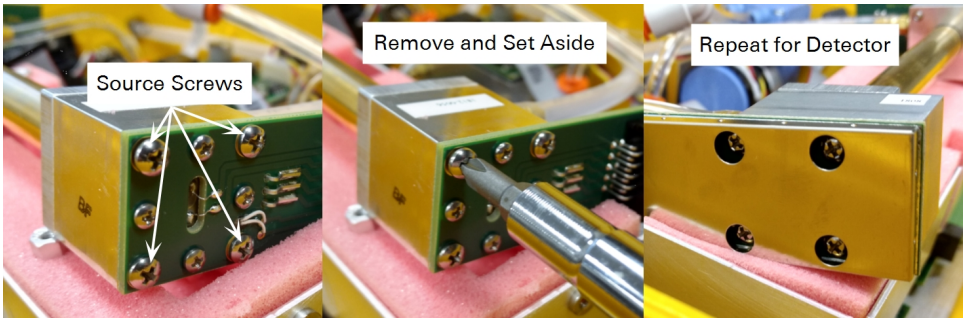
3 Gently lift the optical bench out of the insulating foam and remove the cable connectors from the source and detector circuit boards.




4 Gently grasp the plugs and pull them free.

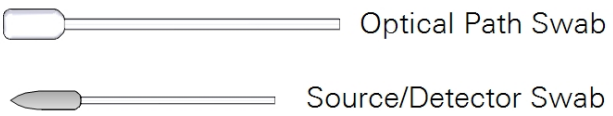



5 Remove the screws that secure the source and detector (4 each), then separate the source and detector housings (with circuit boards attached) from the optical path.




6 Clean the optical bench, source, and detector.

7 Retrieve an optical path swab from the accessories kit.



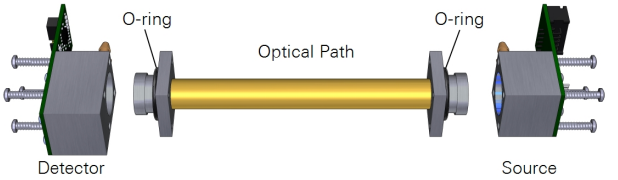

Dip one end into a 50:50 ethanol:water mixture (mild dish washing soap and water will work too) and carefully swab both ends of the optical path. Then, dip a Source/Detector swab into the solution and then swab around the source and detector to remove any residue.

**Warning**: *Do not use abrasive cleansers. Abrasive cleaners can irreparably damage the gold plating on the optical path, source, or detector.*

8 Inspect the hose barbs and tubing.

If the tubes are dirty or damaged, cut a new length of tubing from the extra tubing included in your spares kit, and replace them. Carefully remove them from the hose barbs. If the tubes are in good condition and clean, you may be able to reuse them. If the hose barbs are dirty, remove them and clean them with rubbing alcohol or soapy water. Use caution and do not scratch the hose barbs because scratches may cause leaks.

9 Inspect the O-Rings.




Four O-rings are included in the Optical Bench Cleaning Kit (part number 9980-066), and additional O-rings can be purchased from LI-COR. Replace them if they are smashed flat or damaged in any way.

10 Let the optical components dry and reassemble the optical bench.

Attach the source and detector. The orientation of the optical path cylinder is unimportant — either end can be inserted into the source and detector housing. Tighten each of the screws snugly.

11 Place the optical bench back into the foam, re-insert the cable connectors to the source and detector, and screw the cover plate back to complete the re-assembly.

12 Perform a zero and span calibration (see *User calibration* on page 4-6 for instructions).

# Connecting to LI-870 for calibration

Though the primary interface for the LI-870 is through the Smart Chamber or LI-8250 software, you may also connect your LI-870 to the LI-COR LI-830/850 software to view data and for user calibration.

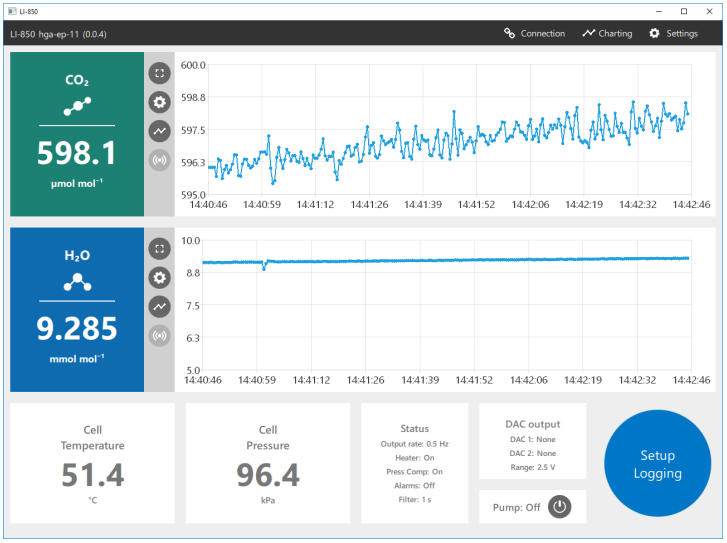
After downloading and installing the software from the LI-COR support site (licor.com/env/support), launch the software. It should display **No Analyzer Connected**.

**Note:** You must connect the power cable from a powered-on Smart Chamber or LI-8250 to power to analyzer when using the software.

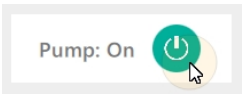
Connect your analyzer to your computer using the USB-B to USB-A cable included with your purchase. You may see a notification that says **Setting up device**, or something similar. After the automatic device setup is complete, go back to the software, and click **Connect**. In the box that opens, expand the **Connect to** drop-down menu, and you will see your device.

**Important:** The LI-830/850 software will recognize your LI-870 as an LI-850. This is normal. Go ahead and click **Update**, and you will connect to your LI-870.

After connecting, the software presents you with live data and graphs.




Here you can see important diagnostic information like **Cell Temperature** and **Cell Pressure**. You can also turn the pump on by clicking the power button next to **Pump**: in the bottom-right of the software.



The software offers a variety of other features you may choose to explore. A more thorough explanation of the software is available at the LI-COR support site. However, for LI-870 soil applications, you will likely only the use the software for instrument calibration.

# User calibration

If the instrument is not measuring as expected, or if you have disassembled the optical bench for any reason, you should check the zero and span settings and set them if necessary. The zero and span are an offset and slope. The zero value ensures that the instrument shows zero when the gas has a zero concentration. A change in the zero will affect every measurement. The span setting ensures a correct measurement at a known non-zero concentration. A change in the span affects higher concentration measurements more than lower ones. The recommended order of operation for user calibration is

1. Set the $H_2O$ zero.
2. Set the $CO_2$ zero.
3. Set the $H_2O$ span.
4. Set the $CO_2$ span.

For user calibration, additional tubing (part number 222-01824) and quick connects (part numbers 300-07124 (male) and 300-07125 (female)) are included with your spares kit.

## Setting the $H_2O$ zero and spans

The water vapor span can be set with a dew point generator such as the LI-610. The procedure is the same as setting the $CO_2$ zero and spans, only this uses known concentrations of water vapor rather than $CO_2$.

**Caution:** Setting the zero and span incorrectly for either $CO_2$ or $H_2O$ will adversely impact the performance of your instrument. If you do not have the proper equipment to span the analyzer, it is best to leave it alone.

## Setting the $CO_2$ zero

Always perform the zero first. To set the zero, you'll need either a tank of dry air that is free of $CO_2$ or a $CO_2$ scrubbing chemical such as wet soda lime and a desiccant such as Drierite.

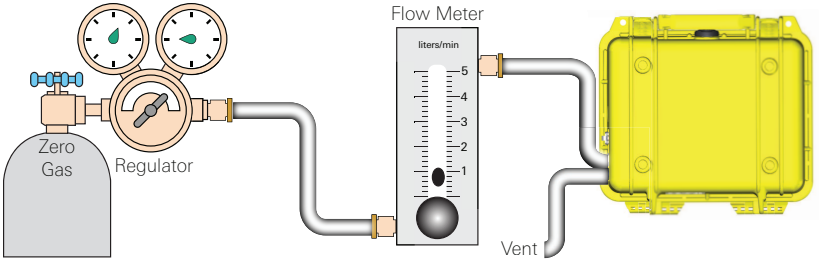
1 Plumb the zero-gas tank or scrubber to the air inlet.

Be sure to use an air filter to prevent contaminants from entering the optical path.

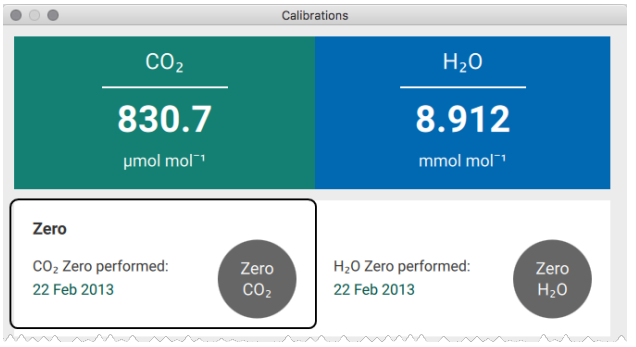
- If using tank air, the pressure of the tank is sufficient to flow the gas through the analyzer. Allow at least 0.75 liters per minute to flow through the cell (no more than 1.0 lpm).
- If using a scrubbing chemical, use a pump to draw air through the analyzer.

2 Install a 10 to 20 cm length of tubing to the air outlet.

This vent prevents ambient air from diffusing upstream into the optical cell.



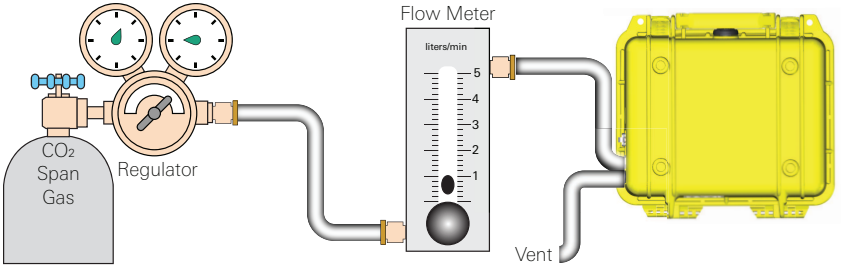

3 When the $CO_2$ concentration has stabilized, click the **Zero $CO_2$** button.



## Setting the primary $CO_2$ span

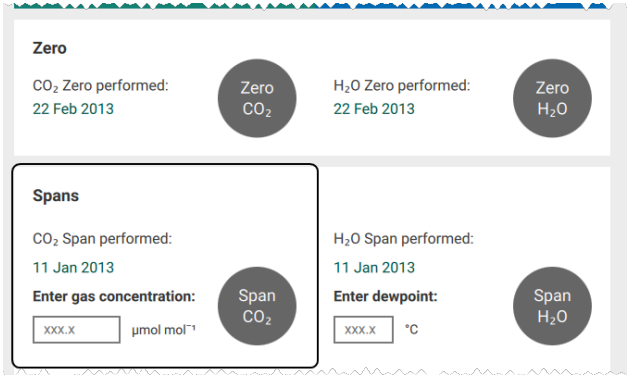
When choosing a span gas, we recommend a gas concentration that is close to - but still slightly above - the upper limit of what you expect to measure. For example, if you are measuring near-ambient levels, choose a span gas that is near 400 ppm $CO_2$ (as opposed to 18,000 ppm). Similarly, if you are measuring concentrations near 15,000 ppm $CO_2$, a span gas with 100 ppm would not be ideal.

4 After zeroing, flow a gas with a known $CO_2$ concentration through the analyzer at a rate of 0.5 liters per minute.




5 Enter the $CO_2$ concentration of the span gas into the software.

6 When the $CO_2$ reading has stabilized, click **Span $CO_2$**.




## Setting the secondary $CO_2$ span

You can set a second span (using a gas that has a $CO_2$ concentration that is higher or lower than the primary span gas) to improve the precision of the analyzer. The pro-

cess is exactly the same as setting the primary span, only you'll enter a different concentration and click **Span2 $CO_2$**.

## Recovering from a bad zero or span

If your attempt to zero or span does not go as planned, you can restore the factory default zero and span settings. The information you need is provided on the calibration sheet (included with the instrument or available for download from www.licor.com/env/support/). Under **Settings > Calibrations > Advanced**, enter the factory zero and span values for your instrument.

# Appendix A.
# Specifications

## General

**Case dimensions**: 28.4 cm L × 27.9 cm W × 12.4 cm H (11.2 in × 11 in × 4.9 in)
**Weight:** 2.31 kg (5.1 lbs.)
**Measurement rate**: 1 per second (1 Hz)
**Operating temperature range:** -20 to 45 °C, without solar loading
**Relative humidity range:** 0 to 95% RH, non-condensing
**Measurement principle:** Non-dispersive infrared (NDIR)
**Operating pressure range:** 50 to 110 kPa
**Flow rate (nominal):** 0.75 liters $min^{-1}$
**Power Requirements:**

- **Input voltage:** 10-17 VDC, 2 A max
- **After warmup (without pump):** 0.33 A @ 12 VDC (4.0 W) average
- **After warmup (with pump):** 0.42 A @ 12 VDC (5.0 W) average
- **Power source**: 8200-01S Smart Chamber or LI-8250 Multiplexer

## $CO_2$ Measurements

**Measurement range:** 0 to 20,000 ppm
**Accuracy:** Within 1.5% of reading

## $H_2O$ Measurements

**Measurement range:** 0 to 60 mmol $mol^{-1}$
**Accuracy:** Within 1.5% of reading

# Appendix B.
# Equations summary

The LI-870 computes $CO_2$ concentrations using an equation of the form

$$c = f(\alpha'')(T + 273.15) \quad \text{B-1}$$

where $c$ is concentration, $f()$ is the calibration function, $\alpha$" is the absorptance, $g(\alpha,P)$ is the pressure correction, $S(\alpha)$ is the span, and $T$ is the temperature (°C) of the gas in the cell, typically 51.5 °C. Absorptance is computed from

$$\alpha'' = \alpha' g(\alpha', P) \quad \text{B-2}$$

$\alpha$' is a span corrected absorptance, and g($\alpha$',$P$) is the pressure correction.

$$\alpha' = \alpha S(\alpha) \quad \text{B-3}$$

$S(\alpha)$ is the span function, and raw absorptance $\alpha$ is computed from

$$\alpha = \left(1 - \frac{V}{V_o} Z\right) \quad \text{B-4}$$

where $V$ and $V_o$ are the raw detector sample and reference readings, and $Z$ is the zeroing parameter.

Span is a linear function of absorptance.

$$S(\alpha) = S_o + S_1 \alpha \quad \text{B-5}$$

# $H_2O$ Equations

Absorptance $\alpha_\omega$ for water vapor is computed from

$$\alpha_w = \left(1 - \frac{V_w}{V_{wo}} Z_w\right) \qquad \text{B-6}$$

$$\alpha'_w = \alpha_w S_w\,(\alpha_w)$$

$$\alpha''_w = \alpha' g_w\,(\alpha'_w, P)$$

where $V_W$ and $V_{WO}$ are the sample and reference raw detector readings, and $Z_W$ is the zero parameter. The pressure correction for water vapor is an empirical function $g_W()$ of absorptance and pressure $P$:

$$g_w(\alpha'_w, P) = \frac{P_o}{P\left(1+0.8\alpha'_w\left(\frac{P_o}{P}-1\right)\right)} \qquad \text{B-7}$$

The value of $P_O$ is 99 kPa. When the pressure correction is not enabled, $g_W()$ is simply 1.0. Water vapor concentration $W$ (mmol $mol^{-1}$) is computed from

$$W = f_w\,(\alpha''_w)\,(T + 273.15) \qquad \text{B-8}$$

where $f_W(x)$ is a third order polynomial whose coefficients are given on the calibration sheet.

$$f_w\,(x) = a_{w1}x + a_{w2}x^2 + a_{w3}x^3 \qquad \text{B-9}$$

# $CO_2$ Equations

The measurement of $CO_2$ is a bit more complicated than for $H_2O$ because of the influence of water vapor. There is a slight direct cross sensitivity in the $CO_2$ signal to $H_2O$. This is measured at the factory and accounted for in the computation of absorptance (equation B-10). There is also a band broadening effect that is accounted for in the computation of concentration (equation B-14).

$CO_2$ absorptance $\alpha c$ is computed from

$$\alpha_c = \left(1 - \left(\frac{V_c}{V_{co}} + X_{wc}\left(1 - \frac{V_w}{V_{wo}} Z_w\right)\right) Z_c\right) \qquad \text{B-10}$$

$$\alpha'_c = \alpha_c S_c(\alpha_w)$$

$$\alpha''_c = \alpha'_c g_c(\alpha'_c, P)$$

where $V_c$ and $V_{co}$ are the raw detector signals for sample and reference, $Z_c$ is the $CO_2$ zero parameter, and $X_{wc}$ is a cross sensitivity parameter for the effect of water vapor on $CO_2$. Its value is reported on the calibration sheet as **XS=**.

The empirical pressure correction function $g_c()$ depends on $CO_2$ absorptance and pressure:

When $P = P_o$, $g_c() = 1$.

When $P < P_o$

$$g_c(\alpha_c, P) = X$$

$$X = \frac{1}{A + B\left(\frac{1}{z-\alpha_c} - \frac{1}{z}\right)} + 1$$

$$A = \frac{1}{a(p-1)} \qquad \text{B-11}$$

$$B = \frac{1}{\frac{1}{b+cp} + d}$$

$$p = \frac{P_0}{P}$$

where $a$ = 1.10158, $b$ = -6.1217E-3, $c$ = -0.266278, $d$ = 3.69895, and $z$ is the asymptotic value of absorptance, obtained from the calibration coefficients (equation B-15).

$$z = a_{c1} + a_{c3} \qquad \text{B-12}$$

When $P > P_o$

$$g_c(\alpha_c, P) = \frac{1}{X}$$

$$P = \frac{P}{P_0} \qquad \text{B-13}$$

where $X$, $A$, and $B$ are computed as in equation B-11. $CO_2$ concentration $C$ (µmol $mol^{-1}$) is computed from

$$C = f_c\left(\frac{\alpha''_c}{\psi(W)}\right)\psi(W)\,(T + 273.15) \qquad \text{B-14}$$

where $f_c(x)$ is a function whose inverse is a double rectangular hyperbola, and whose coefficients (*a1*…*a4*) are given on the calibration sheet.

$$f_c^{-1}(C) = \frac{a_{c1}C}{a_{c2}+C} + \frac{a_{c3}C}{a_{c4}+C} \qquad \text{B-15}$$

Solving equation B-15 for $C$ yields the calibration function

$$f_c\left(x\right) = \frac{\left(a_2a_3+a_1a_4\right)-\left(a_2+a_4\right)x-\sqrt{(a_2-a_4)^2x^2+Dx+(a_2a_3+a_1a_4)^2}}{2(x-a_1-a_3)} \qquad \text{B-16}$$

Where

$$D = 2\,(a_2 - a_4)\,(a_1a_4 - a_2a_3) \qquad \text{B-17}$$

$\psi(W)$ accounts for band broadening by water vapor.

$$\psi(W) = 1 + (h(\alpha'_c) - 1)\,\frac{W}{1000} \qquad \text{B-18}$$

The band broadening coefficient $h(\alpha'_c)$ has been determined to be 1.45 for the instrument for $CO_2$ concentrations near ambient. At higher concentrations, the value decreases. We capture this behavior with an empirical relationship (equation B-19).

$$h(\alpha'_c) = \frac{1}{(0.64b_w-0.64)e^{-3\left(\frac{z}{\alpha'_c}-1\right)}+\frac{1}{b_w}} \qquad \text{B-19}$$

Where $z$ is from equation B-12, and $b_w$ is the low concentration band broadening coefficient: 1.45. This is the value shown on the calibration sheet as *BB* = 1.45. The typical relationship between $h(\alpha'_c)$ and $CO_2$ concentration is shown in *Figure B-1* on the facing page. ('Typical' because the exact relationship depends on the relationship between absorptance and $CO_2$, which is the calibration curve.)

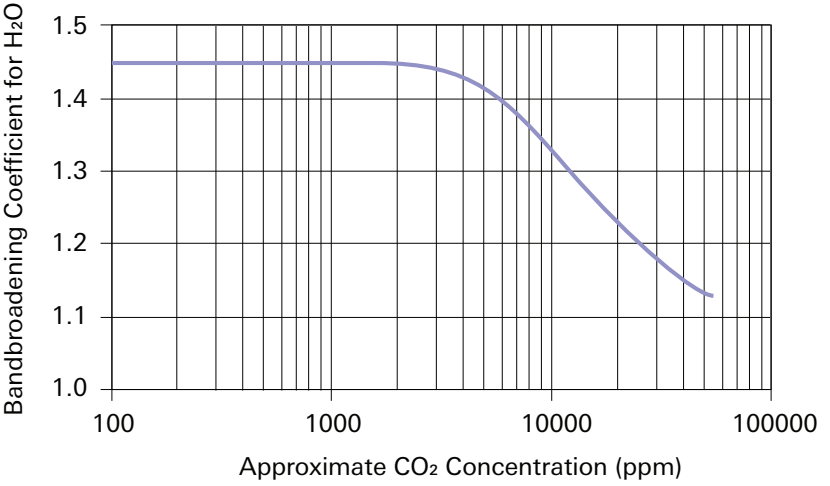



*Figure B-1. The typical relationship between* $h(\alpha'_c)$ *and* $CO_2$ *concentration.*

**Note:** We formulated equation B-19 with $0.64b_w - 0.64$ instead of the simple equivalent (0.29) because this allows band broadening corrections to be turned off by setting $b_w$ to 1. When $b_w$ =1, $h(\alpha_c)$ = 1 everywhere. Also, to avoid computational problems (underflows, overflows, and division by zero) we constrain the argument $\alpha_c$ when computing $h(\alpha_c)$ to be $0.1 < \alpha_c \leq z$. $\alpha_c$ - 0.1 is typically equivalent to about 600 ppm.

# Calibration Equations

The following equations describe the implementation of zero and span calibrations.

## Zeroing $H_2O$

When the command for zeroing water is received, the LI-870 computes the water zero from equation B-20, where $\overline{V}_w$ and $\overline{V}_{wo}$ are averaged for 5 seconds.

$$Z_w = \frac{\overline{V}_{wo}}{\overline{V}_w} \qquad \text{B-20}$$

## Zeroing $CO_2$

When the command for zeroing $CO_2$ is received, the instrument computes the $CO_2$ zero term from equation B-21, where $\overline{V}_c$, $\overline{V}_{co}$, $\overline{V}_w$, and $\overline{V}_{wo}$ are averaged for 5 seconds.

$$Z_c = \frac{1}{\left(\frac{\overline{V}_c}{\overline{V}_{co}} + X_{wc}\left(1 - \frac{\overline{V}_w}{\overline{V}_{wo}} Z_w\right)\right)} \quad \text{B-21}$$

## Spanning $H_2O$

When the command for setting the span for $H_2O$ is received, along with the target concentration $W_T$, from the target concentration, the target absoprtance $\alpha_T$ is computed from

$$\alpha_{wT} = f_w^{-1}\left(\frac{W_T}{T+273.15}\right) \quad \text{B-22}$$

LI-870 computes $S_{w0}$ from equation B-23 , where $\overline{\alpha}_w$ is averaged over five seconds.

$$S_{w0} = \frac{\beta_w}{\overline{\alpha}_w} - S_{w1}\overline{\alpha}_w \quad \text{B-23}$$

where

$$\beta_w = \frac{\alpha_{wT}}{g_w(\alpha_{wT}, P)} \quad \text{B-24}$$

The instrument retains the following values, which are used for subsequent secondary spans:

$$\alpha_{w1} = \overline{\alpha}_w \quad \text{B-25}$$

$$\beta_{w1} = \beta_w$$

## Secondary Span $H_2O$

When the secondary span command for $H_2O$ is received, the instrument computes new values for both $S_{w0}$ and $S_{w1}$. First, it measures a new $\overline{\alpha}_w$ and computes a new $\beta_w$ from equation B-24. Then, it uses these plus the retained values ($\alpha_{w1}$ and $\beta_{w1}$ from the previous normal span) to compute

$$S_{w1} = \frac{\frac{\beta_w}{\overline{\alpha}_w} - \frac{\beta_{w1}}{\alpha_{w1}}}{\overline{\alpha}_w - \alpha_{w1}} \quad \text{B-26}$$

Given the new span slope $S_{w1}$, it updates the span offset $S_{w0}$ by equation B-23.

## Spanning $CO_2$

When the command for setting the $CO_2$ span is received, along with the target concentration $C_T$, the instrument computes $S_{c0}$ from equation B-28, where $\overline{\alpha}_c$ and $\overline{W}$ are averaged for 5 seconds.

$$\alpha_{cT} = f_c^{-1}\left(\frac{C_T}{(T+273.15)\psi(\overline{W})}\right) \quad \text{B-27}$$

$$S_{c0} = \frac{\beta_c}{\overline{\alpha}_c} - S_{c1}\overline{\alpha}_c \quad \text{B-28}$$

where

$$\beta_c = \frac{\alpha_{cT}\psi(\overline{W})}{g_c(\alpha_{cT}, P)} \quad \text{B-29}$$

Note that

$$\psi(\overline{W}) = 1 + (h(\alpha_{cT}) - 1)\frac{\overline{W}}{1000}$$

$$= \left(1 + \left(\frac{1}{(0.64b_w - 0.64)e^{-3\left(\frac{z}{\alpha_{cT}} - 1\right)} + \frac{1}{b_e}} - 1\right)\frac{\overline{W}}{1000}\right) \quad \text{B-30}$$

We need $\alpha cT$ to compute $\psi(\overline{W})$, but $\alpha cT$ depends on $\psi(\overline{W})$. We resolve this by using an approximation (equation B-31) instead when computing equation B-30

$$\alpha_{cT} \approx f_c^{-1}\left(\frac{C_T}{(T+273.15)}\right) \quad \text{B-31}$$

The instrument retains the following values, which are used for subsequent secondary spans, if necessary:

$$\alpha_{c1} = \overline{\alpha}_c \quad \text{B-32}$$

$$\beta_{c1} = \beta_c \quad \text{B-33}$$

## Secondary Span $CO_2$

When the secondary span command for $CO_2$ is received, the instrument computes new values for both $S_{c0}$ and $S_{c1}$. First, it measures a new $\overline{\alpha}_c$ and computes a new $\beta_c$ from equation B-29. Then it uses these, plus the retained values ($\alpha_{c1}$ and $\beta_{c1}$ from the previous normal span) to compute

$$S_{c1} = \frac{\frac{\beta_c}{\overline{\alpha}_c} - \frac{\beta_{c1}}{\alpha_{c1}}}{\overline{\alpha}_c - \alpha_{c1}} \qquad \text{B-34}$$

Given the new span slope $S_{c1}$, it updates the span offset $S_{c0}$ by equation B-28.

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9. Title/Risk of Loss. All domestic shipments are made FOB per Uniform Commercial Code. All international shipments are made per INCOTERMS 2000 designated by LI-COR. LI-COR title to the Products and the risk of loss of or damage to the Products ordered by the Buyer will pass to Buyer at time of LI-COR delivery of Products to the carrier. The carrier shall be deemed Buyer's agent, and any claims for damages in shipment must be filed with the carrier. LI-COR is authorized to designate a carrier pursuant to LI-COR standard shipping practices unless otherwise specified in writing by Buyer.

10. Intellectual Property Rights. Title to and ownership of the documentation, and any improved, updated, modified or additional parts thereof, and all copyright, patent, trade secret, trademark and other intellectual property rights embodied in the Products, shall at all times remain the property of LI-COR or LI-COR licensors.

11. Acceptance. All sales are final and all Products shall automatically be deemed accepted upon delivery to Buyer when goods are loaded on the carrier at LI-COR premises in Lincoln, Nebraska, USA. Buyer may not return any Products to LI-COR except as provided for by LI-COR warranty or as provided herein.

12. Product Warranties. Unless otherwise specified by LI-COR:

(a) LI-COR warrants that, for a period of twelve (12) months from the date of shipment of the Products from LI-COR (the "Warranty Period"), unless otherwise specified for individual Products or extended by a Support Contract or Extended Warranty Contract, the Products sold hereunder will be free from material defects in materials and workmanship and will conform to LI-COR published specifications in effect as of the date of manufacture. LI-COR SPECIFICALLY DISCLAIMS ANY INDIRECT,SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES (INCLUDING LOSS OF USE OR LOST PROFITS) WHICH MAY RESULT FROM THE USE OF PRODUCTS PURCHASED HEREUNDER, AS FURTHER SET FORTH IN SECTION 13 OF THESE CONDITIONS OF SALE. This limited warranty extends only to Buyer as original purchaser unless otherwise agreed upon in writing by LI-COR.

(b) The foregoing warranty shall not apply if the defective Product (i) has been subjected to abuse, misuse, neglect, negligence, accident, improper testing, improper installation, improper storage, improper handling or use contrary to any instructions issued by LI-COR, (ii) has been repaired or altered by persons other than LI-COR, (iii) has not been installed, operated, repaired and maintained in accordance with the documentation or operated outside of the environmental specifications for the Product; (iv) has failed due an Act of God, including but not limited to fire, flood, tornado, earthquake, hurricane or lightning or (v) has been used with any devices, accessories or products not manufactured by or approved by LI-COR. In addition, the foregoing warranty shall not apply to Products (i) LI-COR Standard Terms and Conditions of Sale – rev. 5/15/2009 marked or identified as "sample," (ii) loaned or provided to Buyer at no cost, or (iii) which are sold "as is."

c) If during the Warranty Period: (i) LI-COR is notified promptly in writing upon discovery of any defect in the Product, including a detailed description of such alleged defect, (ii) such Product is returned, transportation charges prepaid, to LI-COR designated manufacturing facility subject to the prior approval of LI-COR with a valid Return Material Authorization ("RMA") number, and (iii) LI-COR inspections and tests determine that the Product is indeed defective and the Product has not been subjected to any of the conditions set forth above, then, as Buyer's sole remedy and LI-COR sole obligation under the foregoing warranty, LI-COR will, at LI-COR option, repair or replace without charge the defective Product. In no event will the Buyer itself nor will the Buyer allow any party other than LI-COR or a third party authorized in writing by LI-COR to perform any service on the Products.

(d) During the Warranty Period, LI-COR will provide on-site warranty repair for Odyssey® Infrared Imager, Aerius Automated Infrared Imager, Pearl® Imager and/ or 4300 DNA Analyzer Products including travel costs, repair parts, and labor to maintain the hardware in proper operating condition. At LI-COR discretion, the Buyer may be required to run certain diagnostic procedures to help determine the source of the problem before on-site warranty repair is rendered. If an on-site service call is initiated, LI-COR will dispatch a service technician to the Buyer site. On-site service will be provided 8:00 a.m. to 5:00 p.m. (Buyer local time), Monday through Friday, excluding LI-COR holidays. The cost of a repair/service call for an instrument malfunction caused by third party hardware and/or software will be billed to Buyer on a time and material basis.

(e) Any Product that has either been repaired or replaced under this warranty shall have warranty coverage (parts only) for the longer of ninety (90) days or the remaining original warranty period. Replacement parts used in the repair of Products may be new or equivalent to new.

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18. Assignment. Buyer shall not assign or transfer these Conditions or any rights or obligations under these Conditions, whether voluntary or by operation of law, without the prior written consent of LI-COR. LI-COR may assign or transfer these Conditions to any successor by way of merger, acquisition or sale of all or substantially all of the assets relating to these Conditions. LI-COR or any successor may assign all or part of the right to payments under these Conditions. Any assignment or transfer of these Conditions made in contravention of the terms hereof shall be null and void. Subject to the foregoing, these Conditions shall be binding on and inure to the benefit of the parties' respective successors and permitted assigns.

19. Entire Agreement. These Conditions of Sale take precedence over Buyer's additional or different terms and conditions, to which notice of objection is hereby given. Acceptance by Buyer is limited to LI-COR Conditions of Sale. Neither LI-COR commencement of performance nor delivery shall be deemed or construed as acceptance of Buyer's additional or different terms and conditions. These Conditions supersede all prior communications, transactions, and understandings, whether oral or written, and constitute the sole and entire agreement between the parties

pertaining to the referenced quotation or purchase order, provided that: (1) these Conditions shall not, without LI-COR prior written consent, supersede any conflicting terms of: (a) prior written agreements duly executed by LI-COR, or (b) governmental purchase orders, terms of purchase, requests for quotation or acquisition regulations relative to governmental purchasers; and (2) to the extent not in conflict with any such prior or governmental terms, these Conditions shall supplement them. No modification, addition or deletion, or waiver of any of the terms and conditions of these Conditions shall be binding on either party unless made in a non-preprinted agreement clearly understood by both parties to be a modification or waiver, and signed by a duly authorized representative of each party.

20. Entire Agreement. These Conditions of Sale take precedence over Buyer's additional or different terms and conditions, to which notice of objection is hereby given. Acceptance by Buyer is limited to LI-COR Conditions of Sale. Neither LI-COR commencement of performance nor delivery shall be deemed or construed as acceptance of Buyer's additional or different terms and conditions. These Conditions supersede all prior communications, transactions, and understandings, whether oral or written, and constitute the sole and entire agreement between the parties pertaining to the referenced quotation or purchase order, provided that: (1) these Conditions shall not, without LI-COR prior written consent, supersede any conflicting terms of: (a) prior written agreements duly executed by LI-COR, or (b) governmental purchase orders, terms of purchase, requests for quotation or acquisition regulations relative to governmental purchasers; and (2) to the extent not in conflict with any such prior or governmental terms, these Conditions shall supplement them. No modification, addition or deletion, or waiver of any of the terms and conditions of these Conditions shall be binding on either party unless made in a non-preprinted agreement clearly understood by both parties to be a modification or waiver, and signed by a duly authorized representative of each party.

21. Force Majeure. Shipping dates are approximate and may be delayed absent prompt receipt from Buyer of all necessary information. LI-COR shall not be responsible for any failure to perform or delay attributable in whole or in part to any cause beyond its reasonable control, including but not limited to Acts of God, government actions, war, civil disturbance, insurrection, sabotage, labor shortages or disputes, failure or delay in delivery by LI-COR suppliers or subcontractors, transportation difficulties, customs clearance, shortage of energy, raw materials or equipment, or Buyer's fault or negligence. In the event of any such delay the date of delivery shall, at the request of LI-COR, be deferred for a period equal to the time lost by reason of the delay.

22. Governing Law and Venue. These Conditions and performance by the parties hereunder shall be construed in accordance with the laws of the State of Nebraska, U.S.A., without regard to provisions on the conflicts of laws.

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