# LAI-2200C
## Plant Canopy Analyzer
**Instruction Manual**

LI-COR

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## Plant Canopy Analyzer
## Instruction Manual

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| LAI-2200C/ LAI-2200TC植物冠层分析仪<br>LAI-2200C/LAI-2200TC Plant Canopy Analyzer | | | | | | |
|---|---|---|---|---|---|---|
| 部件名称<br>Part Name | 有毒有害物质或元素<br>Toxic and Hazardous Substances or Elements | | | | | |
| | 铅<br>(Pb) | 汞<br>(Hg) | 镉<br>(Cd) | 六价铬<br>(Cr(VI)) | 多溴联苯<br>(PBB) | 多溴二苯醚<br>(PBDE) |
| 印刷电路板<br>(PCBs) | X | O | O | O | O | O |
| 光学<br>(Optics) | X | O | O | O | O | O |
| 电缆和电线<br>(Cables and Wires) | X | O | O | O | O | O |
| 金属部件<br>(Metal Parts) | X | O | O | O | O | O |
| 塑料零件<br>(Plastic Parts) | O | O | O | O | O | O |
| 电池<br>(Batteries) | O | O | O | O | O | O |

本表格依据 SJ/T 11364 的规定编制

O = 表示该有害物质在该部件所有均质材料中的含量均在 GB/T 26572规定的限量要求以下 (indicates that the content of the toxic and hazardous substance in all the Homogeneous Materials of the part is below the concentration limit requirement as described in GB/T 26572).

X = 表示该有害物质至少在该部件的某一均质材料中的含量超出 GB/T 26572规定的限量要求 (indicates that the content of the toxic and hazardous substance in at least one Homogeneous Material of the part exceeds the concentration limit requirement as described in GB/T 26572).



Doc. #53-15990-A
June 22, 2016

This device complies with part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

# Printing History

New editions of this manual will include all updates. An update addendum may be used between editions to provide up-to-date information. Revisions are indicated by the revision number. Minor updates, which do not alter the meaning of the content, will be incorporated without affecting the revision number.

| Version Number | Publication Date | Changes |
|---|---|---|
| 1 | May 2014 | First Edition |
| 2 | September 2014 | Second Edition; Added GPS specifications; Revised *Protocol Suggestions for Direct Sun* on page 5-30 |
| 3 | December 2014 | Third Edition; Added *Procedure 2.14 - Measuring Leaf Transmittance and Reflectance* on page 8-33; Updated *Required Inputs for the Scattering Model* on page 10-13 |
| 4 | November 2015 | Fourth edition; Added troubleshooting instructions for reinserting dislodged SD memory card. |

Build Date: Thursday, April 13, 2017

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# Welcome…

…and thank you for your purchase of the LAI-2200C Plant Canopy Analyzer. The LAI-2200C is the successor to the LAI-2000 and LAI-2200, which LI-COR Biosciences produced and sold for over 20 years. At LI-COR Biosciences, it is our passion to provide scientific instruments of exceptional quality, and we hope that the LAI-2200C performs exceptionally for you. We welcome your comments and suggestions. Feel free to contact us at any time.

> **Note:** The LAI-2200C is based on the LAI-2200, with the addition of a Global Positioning System (GPS). The LAI-2200 can be equipped with the 2200CLEAR upgrade kit, giving it the same functionality as the LAI-2200C.

# About this Manual:

This manual should serve as a guide to understanding the proper operation, abilities, and limitations of this instrument.

Operators new to the instrument are encouraged to read the theory sections and become acquainted with the body of published literature that cites data collected with the LAI-2000 and LAI-2200. Operators familiar with the LAI-2200 could jump to the new scattering correction feature for direct sunlight conditions (*Sun* on page 5-6) and the new integrated GPS system (*Global Positioning System* on page 3-24). The menu-level contents can help you find explanations of various instrument functions.

Familiar with the LAI-2000? See *LAI-2000 vs. LAI-2200C* on page D-1 for a brief comparison with the LAI-2200C.

# Getting Started

The LAI-2200C calculates Leaf Area Index (LAI) and other canopy attributes from light measurements made with a "fish-eye" optical sensor (148° field-of-view). Measurements made above and below the canopy are used to calculate canopy light interception at five zenith angles, from which LAI is computed using a model of radiative transfer in vegetative canopies.

The LAI-2200C (or LAI-2200 equipped with the 2200CLEAR upgrade kit) includes a built-in GPS module (*Global Positioning System* on page 3-24).

## What's What

If you have just taken delivery of your LAI-2200C, check the packaging list and verify the contents of the shipment. The following components should be included:

### LAI-2270C Control Unit

The LAI-2270C Control Unit (console) is used to configure instrument settings, store recorded data, and compute results. An internal GPS module supplies location data. The LAI-2270C is shipped with 4 "AA" alkaline batteries, which can provide up to 90 hours

of operation. An internal lithium backup battery maintains the clock when the main batteries are removed. Refer *Control Unit* on page 2-1 for a complete description.

## LAI-2250 Optical Sensor

The LAI-2250 Optical Sensor (wand) is the data collection component of the LAI-2200C. It is shipped with two "AA" alkaline batteries, which can provide over 140 hours of typical operation. A protective cap is provided to cover the bulkhead connector. Refer to *Optical Sensor* on page 2-5 for a complete description.



The optical sensor contains high precision optical components, including lenses, optical filters, and light sensors. It should be treated like an expensive camera lens and protected from impacts and intense vibration. See *Maintenance* on page 2-8 for complete care instructions.

## View Caps

Five view restricting caps (part number 9920-005) are provided with the LAI-2200C. The view restricting caps serve to limit the azimuthal field of view of the optical sensor in circumstances in which it is necessary or desirable to block part of the view. The solid cap (part number 6520-020) should be used to protect the lens when it is not in use. The white diffuser cap (part number 6522-117)

is used for collecting the ancillary data for applying scattering corrections when operating in direct sunlight (See *Sun* on page 5-6). The drilled cap (cap with the small hole drilled in the middle) is used for collecting leaf transmittance and reflectance properties (see *Procedure 2.14 - Measuring Leaf Transmittance and Reflectance* on page 8-33).



| Cap | 10° | 45° | 90° | 180° | 270° | Diffuser |
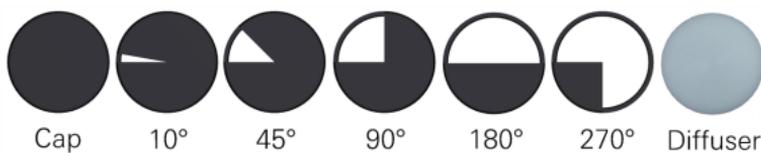
## Sensor Cables

One 6-pin cable (part number 9922-127) with bulkhead connectors is provided with each optical sensor. It is used to connect the optical sensor to the control unit.

## Data Cable

A USB Type A to USB Type Mini-B cable (part number 392-07872) is provided to transfer data between the LAI-2200C and a computer.

## FV2200 Software

File Viewer 2200 (FV2200) is the software package for processing data from the LAI-2200C on your computer. It is available for Windows®, Mac OSX®, and Linux. Download the latest version using the following link: www.licor.com/2200C-software.

FV2200 includes data analysis, charting, GPS mapping, and support for the scattering correction for measurements made in direct sunlight (see *Data Analysis with FV2200* on page 7-1).

## Accessories

In addition, the LAI-2200C includes the accessories listed below.

### Bubble Levels

Two bubble levels are provided with each optical sensor. The bottom level (part number 610-03047) attaches to the underside of the optical sensor for use in situations in which the sensor is held over the operator's head. The top level (part number 610-03048) attaches to the top of the optical sensor.

Both levels look similar. The top level, however, has the manufacturer's name printed on the bottom, whereas the bottom level does not. The top level also has the circle printed on the glass, whereas the bottom level has the circle printed on the white background.

### Lens Cleaning Kit

The Lens Cleaning Kit (part number 610-03100) includes cleaning solution and lens cleaning cloth.

### Carrying Carabiner

A carabiner (part number 610-10456) is included to allow hands-free transportation of the control unit. The clip attaches to the base of the control unit with a ring. It can be attached to the user's belt loop.

### Calibration Sheet

The calibration sheet indicates the angular response of your LAI-2250 and its response in an isotropic environment. It is a good idea to store the calibration sheet in a safe location. If it is lost, contact LI-COR Biosciences for the calibration information for your instrument.

## Instruction Manual

The Instruction Manual (part number 984-14112) contains basic operating and maintenance information for the LAI-2200C.

## Accessory Kits

Two accessory kits are provided, one for the control unit (part number 9922-107), and one for each optical sensor (part number 9922-108). They include frequently replaced components.

# Theory of Operation

Leaf Area Index is one-sided leaf surface area per ground surface area. Because the LAI-2200C is sensitive to all light-blocking objects in its view, the term foliage area index is more appropriate. In scientific literature, the terms effective Plant Area Index (PAI$_{eff}$) (Garrigues et al. 2008), Vegetation Area Index (VAI) (Fassnacht et al. 1994), and others have been used to refer to indirect LAI measurements that may include non-leafy vegetation. We use the term LAI throughout this manual, except when discussing measurements of isolated plants, in which case we use the term Foliage Density. For more on this, see *LAI or Foliage Density?* on page 6-12.

## Basic Theory

The amount of foliage in a vegetative canopy can be deduced from measurements of how quickly radiation is attenuated as it passes through the canopy. By measuring this attenuation at several angles from the zenith, foliage orientation information can also be obtained. The LAI-2200C measures the attenuation of diffuse sky radiation at five zenith angles simultaneously. The LAI-2250

Optical Sensor projects the image of its nearly hemispheric view onto five detectors arranged in concentric rings.

If the sensor is level and viewing the sky, detector 1 will measure the brightness straight overhead, while detector 5 will measure the brightness of a ring centered at the 68° zenith angle (22° above the horizon), subtending 13°.

A normal measurement with the LAI-2200C consists of a minimum of ten numbers: five of the numbers are the signals from the five detectors when the optical sensor was above the vegetation, and the remaining five are the readings made with the sensor below the vegetation. For both readings, the sensor is looking up at the sky. Five values of canopy transmittance are calculated from these readings by dividing corresponding pairs. For example, if detector 1 reads 50 (units not important) above the canopy and 5 below, then the transmittance at that angle (centered at 7°) is 5/50 = 0.10. From transmittances at all five zenith angles, the LAI-2200C calculates foliage amount (leaf area index, LAI) and foliage orientation (mean foliage tilt angle, MTA). In practice, a number of below-canopy readings are usually made to improve the spatial average.
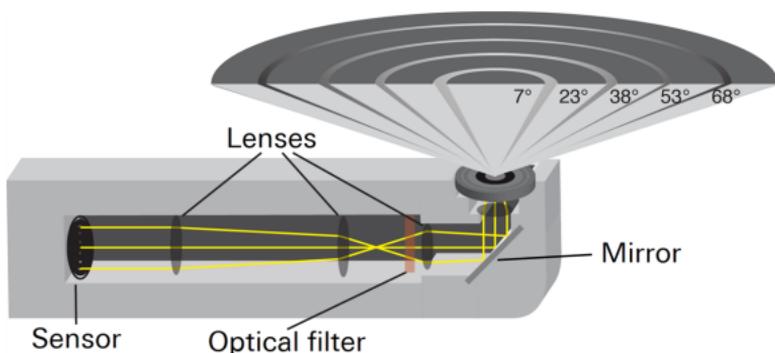
## Assumptions

There are some basic assumptions that must be met in order to make accurate calculations of foliage density and orientation. The extent to which these assumptions are violated will affect the accuracy of measurements and subsequent calculations. The four major assumptions, in approximate order of importance, are:

1  The foliage is black. It is assumed that below-canopy readings do not include any light that is reflected or transmitted by foliage. An optical filter in the LAI-2250 Optical Sensor rejects any radiation >490 nm. Foliage typically reflects and transmits little radiation in this portion of the spectrum, which helps minimize violations of this assumption.

> **Note:** The file viewer software FV2200 version 2.0 and above removes this assumption when you apply the scattering corrections to your data. See *Scattering Correction* on page 10-11.

2  The foliage is randomly distributed within certain foliage-containing envelopes. These envelopes might be parallel tubes (as in row crops), a single ellipsoid (an isolated bush), an infinite box (turf grass), or an infinite box with holes (deciduous forest with gaps).

3  The foliage elements are small compared to the area of view of each ring. The approximate guideline is this: the distance between the sensor and the nearest leaf above it should be at least four times the width of the leaf. This relationship is described in more detail later in the manual.

4  The foliage has random azimuthal orientations. That is, it does not matter how the foliage is inclined, as long as

all the leaves are not facing in the same compass direction. The importance of this assumption is reduced when measurements are made in a wide range of compass directions or without a view-restricting cap.

No real plant canopy conforms exactly to these assumptions. Foliage is never random, but is often clumped along stems and branches, and certainly is not black. Many species exhibit heliotropism, which violates the azimuthal randomness assumption. The practical compromises that must be made are often not serious, however. Many canopies can be considered random, and living foliage does have relatively low transmittance and reflectance of light below 490 nm. Offsetting errors may be common, such as when leaves are grouped along stems (increasing light transmittance), but arranged to minimize overlap (decreasing transmittance).

Some canopies violate these assumptions to an extent that requires consideration. Measurements of conifer canopies, with their high degree of organization, or senescent crops, with thin reflective leaves, might have large absolute errors. The LAI-2200C is very sensitive to small relative differences. In some cases, it might be necessary to calibrate the instrument with direct measurements in order to achieve high absolute accuracy.

# Section 2.
# Introduction to the Instrument

This section describes the physical characteristics of the instrument, the keypad interface, basic software navigation, initial setup, and instrument care.

## Control Unit

The control unit (console) houseing is constructed of durable ABS plastic with a rubber seal between the two halves. The rubber seal also serves as a shock cushion to protect the instrument from impacts.

## Display

The display is a 128 x 64 LCD graphics display. It shows alphanumeric characters. To adjust the display contrast hold the minus (-) key and press the up or down arrow keys.

USB Port

Light Sensor Connectors     LAI-2250 Optical Sensor Connectors

# Keypad

The LAI-2200C features a 22-button tactile response keypad. The upper block of 9 keys are used to navigate through menus, select menu options, and log data. Basic functions of the upper 9 keys are described in the following chart:

| | |
|---|---|
| MENU | Press the **Menu** button to go to the Main Menu; or when in Logging Mode, to go to the Log Adjust menu. |
| EXIT | The **Exit** button returns to the main screen unless an input or toggle field is active. In these cases it returns to the previous screen. |
| OK | The **OK** button selects the highlighted menu field or implements a setting after changes have been made. |
| START STOP | The **Start/Stop** button is used to initiate or terminate a logging sequence. |
| LOG | When in Log mode, the **Log** button records a reading (or two if two wands are attached). |
| ▲ ▼ | The **Up** arrow and **Down** arrow buttons are used to navigate through menu options and increment or decrement values in some fields. |
| ► ◄ | The **Right** arrow and **Left** arrow buttons advance to the next or previous menu sublevel when on a menu screen. If a toggle field is active they toggle the setting. They also are space and backspace keys in alphanumeric fields. |
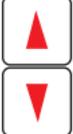
The lower block of 12 keys are used to enter alphanumeric characters. Each key is used to enter the letters and numbers indicated by the label on the key. Keys 1–9 can also

be used to log global positioning system (GPS) coordinates when GPS is active and a file is open in the LAI-2200C (or LAI-2200 equipped with GPS). The 22nd key is the power on/off key at the top left of the keypad.

When entering alphanumeric characters with the keypad, each button cycles through a loop of characters and stops looping when a different button is pressed or after 1 second has passed without a button press. Some fields can only accept numeric or alphabetic characters. The right arrow key is used to enter spaces and the left arrow key functions as a backspace key in alphanumeric fields.

## Cable Connections

USB (Universal Serial Bus), light sensor, and optical sensor connections are on the top and bottom of the LAI-2200C console.

### Optical Sensor Cable Connections

The 6-pin bulkhead connectors (labeled X and Y) are used to attach optical sensors (wands). The control unit will automatically detect an attached wand. Wands can be attached or removed while the instrument is powered on.

To attach: Align the red dots and press straight in.



Red dots
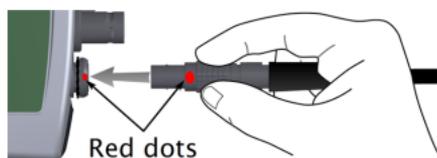
To release: Grasp the collar and pull straight out.
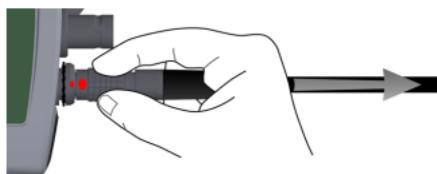
## Light Sensor Cable Connections

Two BNC (Bayonet-Neill-Concelman) bulkhead con-
nectors are available to attach LI-COR Quantum Sensors.
They are labeled "1" and "2" on the front of the control
unit and identified as Port 1 and Port 2 by the control
unit.

BNC Light Sensor Connectors
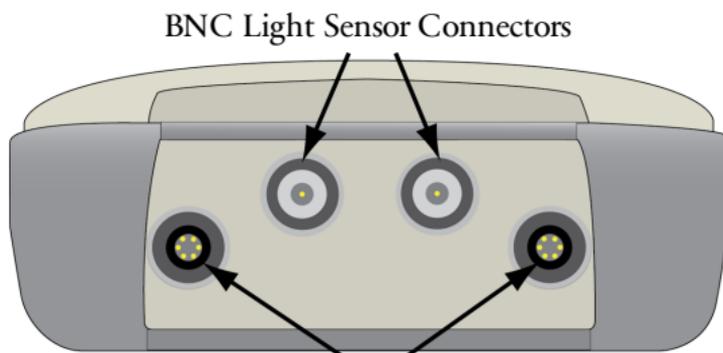


LAI-2250 Optical Sensor (wand) connectors X and Y

## Data Cable Connection

A Mini USB port is available for communicating with a
computer (*Connecting to a Computer* on page 3-23). When
connected with a USB cable, the computer will identify
the LAI-2270C (the control unit) as a mass storage device.

Mini USB Port
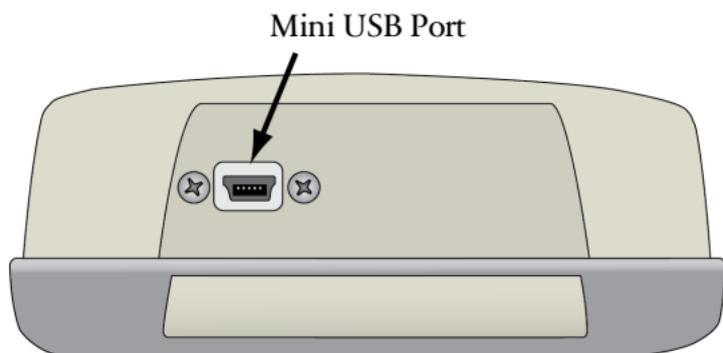
## Memory

The control unit is equipped with 128 MB of non-volatile flash memory. The instrument stores data on an internal Secure Digital (SD) card, which should provide sufficient memory for intensive data collection (enough storage for over 1.5 million records).

The format for the SD card is FAT16. Do not modify the card in any way when connected to a computer, and never remove or replace the card unless it is with a card purchased from LI-COR Biosciences (part number 616-10387). If you need to use a user-supplied SD card for any reason, contact LI-COR for formatting instructions.

## Optical Sensor

The optical sensor (wand) is constructed with a durable aluminum enclosure, which protects the electronic and optical components. It can be mounted to a camera tripod or raising pole using one of the ¼"-20 tripod mounting holes. It can be used independently of the control unit for data collection. When the wand is attached to a console, it is powered with the console batteries – it does not require its own batteries. Otherwise, it requires two "AA" batteries.

**Caution:** Batteries must be inserted with the positive poles (+) toward the cap.

## Keypad

The optical sensor keypad includes two buttons that are used to log data, switch between **A** and **B** readings, and power on/off the optical sensor. The **LOG** button on the wand functions the same as the log button on the console – if the console is in logging mode (see *Logging Mode* on page 3-12), the **LOG** button will log a record to the open file.

**Power** LED: On/Off Indicator
**LOG** LED: Logging Indicator
Above LED: Above/Below Indicator

**A/B|Power** Button: Toggle Above and Below; Optical Sensor Power

**LOG** Button
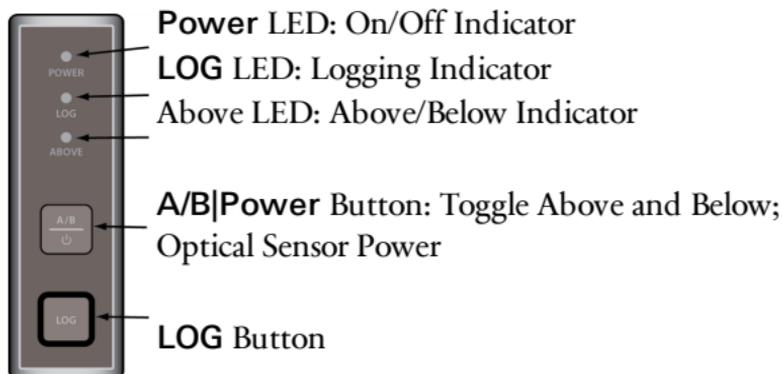
Optical sensors will turn on when the control unit is turned on (if the wand and control unit are attached), when the optical sensor cable is connected to a powered-on control unit, or when the optical sensor power button is pressed (when disconnected from the control unit). To turn the optical sensor off, press and hold the **A/B|Power** button for 2 seconds. To switch between **A** and **B** readings press and release the **A/B|Power** button.

## Indicator LEDs

Three light emitting diodes (LED) indicate the state of the optical sensor. The **POWER** LED is illuminated when the sensor is turned on. The **LOG** LED illuminates when data are being recorded. When the **LOG** button is pressed, the **LOG** LED lights up for the duration of the reading and

turns off when the log is complete. The optical sensor's **LOG** LED will flash every 2.5 seconds or 1 second as part of automatic, unattended logging (see *Logging Configurations* on page 3-15). The **ABOVE** LED indicates whether the next reading from this sensor will be labeled **A** (LED is on) or **B** (LED is off). Pressing the **A/B|Power** button switches between **A** and **B** readings.

## Features

The optical sensor has 1 megabyte (MB) non-volatile flash memory that is used when operated in unattended mode (for about 25,000 records). The optical sensor will indicate that its memory is full by flashing all three LEDs simultaneously. When the optical sensor batteries are low (<2V), the green **POWER** LED will turn red. The optical sensor will shut off automatically when the battery voltage is below 1.8 V.

Optical sensors do not require batteries when they are used in attached mode - they use power from the control unit. Be aware, however, that if a data cable is removed during a data transfer between the wand and console, the files may be damaged or lost. The control unit display indicates when data transfer is taking place with an on-screen indicator (see *Logging Mode* on page 3-12). Be sure to wait until data transfer is complete before disconnecting the data cable.

# Maintenance

The LAI-2200C is designed for low maintenance, and generally it should require little servicing beyond keeping it clean and replacing the batteries.

## Control Unit

The control unit battery compartment is on the back of the instrument. To open the battery compartment, remove the two screws that secure the battery cover with a #1 cross-head (Philips) screwdriver. The control unit requires 4 "AA" batteries. Be sure to observe proper polarity when changing batteries. Replace the batteries and reattach the cover.

## Optical Sensor

The optical sensor uses 2 "AA" batteries, which are in the handle of the optical sensor. To remove the optical sensor batteries, use a coin or large flat-tipped screwdriver to turn the battery cap counter clockwise about ¼ turn. When inserting new batteries, insert the negative (-) pole into the battery holder first. The positive (+) pole on the second battery makes contact with the black cap (part number 345-10735).

If the instrument is to be stored for a long period of time, remove the batteries to prevent damage that may result from battery leakage and corrosion.

## Calibration

There are two parts to the factory calibration. One is done at a range of angles in collimated light, and is used to center the detector and verify the angular response. The other is done in isotropic conditions (an integrating sphere) and

provides calibration factors that are used to match each ring's output to each other, but not to any absolute standard. This inter-ring calibration has no effect on LAI determination, but would be important if you were to use the sensor to map angular distributions of diffuse radiation.

Recalibration of the optical sensor is not necessary, as long as the optics within the sensor remain in place. The detectors may have long-term electrical drift, but this will not affect LAI determinations.

Instructions for entering calibration multipliers are in *Calibration and Match Values* on page 3-4. The procedure for matching two sensors is separate from calibration and is described in *Matching Sensors* on page 3-10.

## Cleaning

The optical sensor lens should be kept free of dust, dirt, and deposits when collecting data. To help keep the lens clean, leave the opaque lens cap in place when the instrument is not in use.

The front lens of the optical sensor can be cleaned with distilled water or the Lens Cleaning Kit included with the instrument.

**Note:** Be very careful not to scratch the $MgF_2$ coating on the lens. Avoid cleaning the lens with paper products, and never wipe the lens while it is dry. Damage to the lens is not covered under the warranty.

The instrument display and keypads can be cleaned with a moistened non-abrasive cloth when necessary.

## Storage

When storing the LAI-2200C for a long period of time, remove the "AA" batteries, replace the bulkhead connector caps, and attach the lens cap.

## Replacing the Internal Battery

The following steps describe how to replace the internal lithium battery. The battery should last up to 7 years. Always use a BR1225 watch battery (part number 442-08614).

1 Using a #1 cross-head (Phillips) screwdriver, loosen the four screws that secure the top and bottom of the control unit. The four screws are located in the corners of the back of the control unit, under the gray protective

rubber. Nudge the rubber out of the way of the screws.

2  Gently separate the two halves.

3  The battery is in a round coin-cell battery holder. Lift the silver tab slightly and slide the battery out. It may be necessary to lift the battery slightly with the blade of a standard screwdriver.



4  Slide the new battery into the holder with the positive (+) terminal facing up.

5  Join the top and bottom halves of the control unit. Be sure the rubber seal is seated properly.

6  Gently tighten the four screws that hold the two halves of the case together. Be very careful not to over tighten the screws, as they may strip the plastic. If a torque screwdriver is available, torque the screws to 4 in.-lbs.

# Updates and Other News

The FV2200 software application can notify you of software updates and other LAI-2200C related developments if the computer that is running the application has Internet access. Each time it is launched, FV2200 checks to see if there are any notifications that it has not already told you about, and if so, shows them to you. You can view the latest notifications at any time by clicking **Help > Latest LAI-2200 News**. This notification summary has links that will take your web browser to the appropriate locations.

You can also select **Help > Check for Software updates > Show Wand and Console Information** to view the latest versions of FV2200, console, and wand software, and, if you choose, download them from the FV2200 application.

## Instrument Firmware

There are two firmware components in the LAI-2200C – the console firmware and the wand firmware. Any updates will be available for download from FV2200 **Help > Check for Software updates > Show Wand and Console Information**. The following procedures describe how to update the firmware.

### Console Firmware

1 Acquire a console firmware file. It will have a name similar to "lai01.img". Download using FV2200 **Help > Check for Software updates > Show Wand and Console Information**. The file will be saved to your downloads directory.

2 Attach the LAI-2200C console to a computer using the USB connection. After the LAI-2200C has been

recognized by the computer, copy the new firmware file to the LAI-2200C mass storage device root directory.

3 Next, "eject" the disk, then disconnect the LAI-2200C from your computer. Power on the control unit and go to **MENU > Firmware > Console > Upgrade**. Select the new firmware file and press **OK**. The new firmware will take several minutes to install, and a **Complete OK** message will be displayed when it is finished. Press **OK** when the firmware update is complete.

Optical Sensor Firmware

**Note:** When using multiple wands, be sure they all have the same firmware version.

1 Acquire an optical sensor firmware file from FV2200 by clicking **Help > Check for Software updates > Show Wand and Console Information** and saving the file to your downloads directory. It will have a name similar to "wand01.bin". Subsequent versions will have a larger number.

2 Copy the file to the Console memory as in step 2 in the previous example.

**Note:** Wand firmware can only be updated through port X. The firmware version can be checked through port X or Y, but updates can only be delivered to wands connected to the X terminal.

3 Disconnect the LAI-2200C from the computer. Connect the wand to port X, turn on the console, and go to **MENU > Firmware > Console > Upgrade**. Select the new file and press **OK**. The update will take several seconds to complete.

# Section 3.

# Using the LAI-2200C

This section introduces the basics of the LAI-2200C, including configuration options, usage considerations, and a guide for making basic measurements. It is recommended that users who are unfamiliar with the LAI-2200C follow the example measurements and become thoroughly acquainted with the practical considerations (in the next two chapters) before attempting real measurements with the LAI-2200C.

## Power ON and OFF

To power on the LAI-2270C Control Unit (console), press the power button. It is below the left side of the display.

If not attached already, attach an optical sensor (wand) to the X or Y port using the cable (part number 9922-127). The optical sensor should turn on when the control unit is turned on (if the cable is attached), when connected to a powered up control unit, or when the optical sensor power button is pressed.

To turn off the control unit, press the power button. To turn off the optical sensor, press and hold the power button for 2 seconds. The control unit features a user-settable auto-off timer that will shut off the instrument automatically. The auto-off timer can be set for 5-60 minutes. The optical sensor automatically shuts off in 30 minutes if

no button is pressed (unless configured for automatic logging or connected to a control unit).

## Console Auto-off Timer

To set the auto-off timer on the Control Unit (console), press the **MENU** button, select **Console Setup**, then **Auto-off Timer**. Set the timer as desired and press **OK** to save the settings.

## Monitor Mode Navigation

When the LAI-2200C is turned on, Monitor Mode (right) will be displayed. Observe the variables called X1, X2, Y1, and Y2. These are values from rings 1 and 2 from the X and Y

```
X1: 634.0710
X2: 727.1623
Y1: 0.0000
Y2: 0.0000
```

sensors. Each row of the Monitor Mode screen can be set to display any one of the values in *Table 3-1* on the facing page.

Table 3-1. Variables that can be displayed in Monitor Mode.

| X1,...,X5 | Readings for Wand X, rings 1-5 |
|---|---|
| Y1,...,Y5 | Readings for Wand Y, rings 1-5 |
| gLAT: | Latitude |
| gLNG: | Longitude |
| gALT: | Altitude |
| gSAT: | Number of Satellites used |
| gHDOP: | Horizontal Dilution of Precision |
| gUTC: | UTC time (YYYY/MM/DD, HH:MM:SS) |
| T: | Time (HH:MM:SS) |
| D: | Date (YYYY/MM/DD) |
| BATT: | Battery Voltage |
| 1: | Readings for Light Sensor 1 |
| 2: | Readings for Light Sensor 2 |

To change variables on the display, press the up or down arrow to select a field. The active field will be highlighted for about 1 second. Press the right or left arrow button to scroll through available variables.

```
X1: 634.0710
X2: 727.1623
Batt: 5.80
T: 03:24:48
```

## Basic Menu Navigation

Basic navigation through menus is accomplished with the upper block of 9 keys. When viewing a menu (press the **MENU** button to view the Main

```
Main Menu
  Wand Setup
  Log Setup
  Data
  Console Setup
  Firmware
```

Menu, shown at right), the selected menu level will be highlighted. Press **OK** or the Right Arrow to select the highlighted menu option, press the Left Arrow key to go back a menu level or toggle field settings, and press **EXIT** once to return to the Main Menu or twice to return to Monitor Mode.

# Setting the Clock

Be sure to set the clock on both the console and optical sensors. The console clock can be set manually (*Procedure 1.1 - Setting the Console Clock Manually* on page 8-17) or by using the time information from the GPS (*Procedure 1.2 - Setting the Console Clock from GPS* on page 8-18). Once the clock is set, you can synchronize an optical sensor to the console (*Procedure 1.4 - Synchronizing Wand and Console Clock* on page 8-19).

> **Note:** If using two optical sensors, the clocks in both must be synchronized in order to match data in time.

# Calibration and Match Values

Every wand has two sets of 5-number calibration values: the "permanent" set (accessible via **MENU > Wand Setup > Cal Values**) and the "working" set (**MENU > Wand Setup > Match Values**). The match values are always used when the wand is making measurements, while the cal values (which are printed on each wand's calibration sheet) are there to serve as built-in reset values. For more details on wand calibrations, see *Wand Calibrations* on page 5-32.

The simplest thing to do with the match values is to reset them to the calibration values (see *Procedure 1.5 - Resetting*

*Wand to Factory Calibration* on page 8-20), and then leave them alone. With the factory calibration values in place, the ring values of the wand will all read the same when in an isotropic environment, allowing the sky brightness distribution to be measured, which is an important step when doing scattering corrections. The calibration does not ensure that two wands will read the same absolute brightnesses, however, so when two wands are used to obtain data for computing LAI (one wand above the canopy, one below), then an adjustment needs to be made. Further details are in *Multiple-Sensor Operation Revisited* on page 5-21.

# Overview of Configurations

The settings described in *Wand Setup* below affect the selected wand and are stored on the wand. Those described in *Log Setup* on the next page affect the global template and will be applied to any new file that is created on the control unit. Settings that affect how LAI is computed are stored as part of each file. The procedure for changing the settings of a file (post processing data) is described for the console in *Data Management on the Console* on page 3-20 or with FV2200 in chapter *Data Analysis with FV2200* on page 7-1.

## Wand Setup

Certain pieces of information are stored on each optical sensor. You may wish to change or view these settings. They are described below. In order to access these settings, one or more wands must be connected, and you must select a wand.

**Set Name:** You can name each wand (up to 8 alphanumeric characters). The name is stored on the wand

and can be viewed when the wand is connected to a console.

**Clock:** Set the wand time by synchronizing with the console clock or entering the time manually.

**Cal Values:** View/Edit the five back-up calibration values. These values are shown on the wand's calibration sheet.

**Match Values:** Access the five working cal values: **view/set values** to directly edit or reset them, and **calculate values** for matching two wands.

**Auto Log:** The control panel for setting up automatic logging for wand.

## Log Setup

Basic parameters can be set prior to collecting data. For most applications the default settings will work fine, but the preferred settings will vary depending on the application. Most of the following settings can be changed for a file after data has been collected as well. The following items are in the **Main Menu > Log Setup** menu:

**Transcomp:** Defines how transmittance is computed (including which readings (**A** or **B**) are used for above-canopy readings, how they are used, and what the instrument does with transmittances >1.0). These settings are described in detail in the table below. Normally, **A** readings are above canopy, and **B** readings are below. The software can also be set to determine which is above and which is below by comparing the readings (ring by ring) of successive **A**/**B** pairs or records until it finds a pair for which every ring of one is consistently higher than the corresponding ring of the other. The ID of the higher record, whether **A** or **B**, is assumed to be the above record ID through the rest of the file.

| Transcomp Setting | Description |
|---|---|
| Define Above | |
| A | (Default) A records are Above, B are Below |
| B | B records are Above, A are Below |
| Compare | Find which is Above and which is Below |
| Determine Above | |
| Previous | (Default) Use the previous Above record |
| Interpolate | Interpolate between the nearest (time) Above readings |
| Closest | Use the closest in time Above record |
| Bad Readings (when a Below record has values that exceed those of a corresponding Above record) | |
| Skip | (Default) Skip that record |
| Clip | Force the transmittance (Below/Above) to be 1.0 for that ring |

**Prompts:** Two prompts can be defined, and responses can be entered during data collection for each file.

**Obs Remarks:** An observation remark can be entered for each data record. This remark is edited in the log setup menu, and can be changed for individual records by pressing the Menu key while in Logging Mode.

**Angles:** This provides access to the angle values associated with each ring. There is no need to change these values.

**Distances:** The distance vector consists of five values used in calculation of contact numbers for the five rings of the optical sensor. Use the default values unless you are measuring an isolated crown of a plant. Refer to *The DISTS Vector* on page 6-14 for more information.

**Masks:** The mask determines which rings are used (default = all) to compute LAI. Data from rings that are ignored are still measured and recorded, however, so

nothing is lost even if a data file is generated with all rings ignored.

**Controlled Sequence:** A sequence of **A** and **B** readings can be defined.

**Console AutoLog:** Activate and set up automatic logging with wand(s) attached to the console.

**PAR Sensors:** Activate, name, and enter the calibration multipliers for LI-COR Biosciences Light Sensors here.

**GPS:** Activate the global positioning system and choose settings for when GPS data are recorded.

## Console Setup

The Console Setup menu (**Main Menu > Console Setup**) provides some basic setup options:

**Set Time:** Set the instrument time, as described in *Setting the Clock* on page 3-4.

**Auto Off Timer:** Set the duration that the control unit will remain powered on after no buttons have been pressed (5-60 minutes, increments of 5 minutes).

**Beeper:** Turns the console beeper on or off.

## Attached vs. Autonomous Configuration

In this section you'll find an overview of the ways that you can use the wand to collect data: attached to the console or autonomously (detached from the console).

### Attached Configuration

This is the configuration used when an optical sensor is attached to the control unit. The main advantage of having the sensor attached to the console is real-time display of measured or computed values. When in log mode, pressing the wand or console **LOG** button adds data to the file on the console, not the wand, and LAI calculations are updated for that file. In the console autolog

configuration, logging occurs at set intervals without pressing the **LOG** button (see *Logging Configurations* on page 3-15).

## Autonomous Configuration

This is useful for logging above canopy readings well away from the console, for later import to the console. Data can be logged manually (press **LOG**) or automatically (*Logging Configurations* on page 3-15) on an unattended wand, and later transferred to the console and merged with below-canopy readings. Note that you can also use a wand by itself to make complete one-sensor readings of a canopy: Just label above and below readings appropriately using the **A/B** button, transfer the result to a file, and recompute that file. However, since records stored on a wand accumulate in one big file, this method is not convenient for generating multiple LAI files, unless you keep careful track of starting and stopping times, so you'll know how to parse the file later.

## Operating Modes: One and Two Sensor Modes

You can collect data with one or two wands, as described below.

### One Sensor Mode

The simplest operating mode is to use one sensor for above and below readings. A sequence of readings can be pre-defined if attached to a console (see *Logging Configurations* on page 3-15), or determined "on-the-fly" by using the **A/B** key on the wand keypad. The basic procedure for using this mode is described in *Operation: One Sensor, One Control Unit* on page 3-18.

## Two Sensor Mode

Two-sensor mode simply means that there are two (or more) sensors involved in collecting data. There are some possible combinations here:

A. **One sensor detached**. This is the usual configuration. The detached sensor can stay in an adequate clearing and automatically log above canopy records. Later, the logged readings are transferred to a file in the control unit, and selected records (those closest in time to the recorded below canopy records) will need to be imported from there to the below canopy files.

B. **Both sensors attached to a control unit**. This configuration has limited usefulness, since the sensors can't be very far apart. However, in a short canopy with very changeable sky conditions, this can be a reasonable approach, provided there is an extra person (or a tripod) to hold the above sensor. This method does put both **A** and **B** records in the same file, so later import is not needed.

C. **More than two sensors, or mixed sensors**. In a large experiment, there might be several LAI-2200Cs and/or some older LAI-2000 units in use simultaneously. Typically, one sensor would still be doing the **A** readings, while all the others are collecting **B** data. FV2200 is then used to combine **A** and **B** readings.

## Matching Sensors

When using two or more optical sensors, they need to be matched so that they read the same thing under the same conditions. This can be done by console matching or FV2200 matching. The recommended method is FV2200

matching. This involves collecting data from both sensors that can later be used to adjust one set of readings in post processing using the FV2200 Software package. There are multiple ways to do this, and they are discussed in *Multiple-Sensor Operation Revisited* on page 5-21.

Console matching, desribed in *Procedure 2.1 - Making Two Wands Match - Console Matching* on page 8-24, is the required method when both optical sensors are attached to the console while logging (only possible with short canopies). Console matching cannot be used with light scattering correction.

## Setting Prompts

There are two prompts for storing additional information with each data file. Each prompt can be defined so that it requests a specific type of information, such as "What" and "Where". For the "What" prompt, you might enter a habitat type, and for the "Where" prompt, you could enter the location. After they are defined, you can enter up to 8 alphanumeric characters in each of the prompt fields when you create a new data file. To set prompts:

1  Press the **Menu** button, then go to **Log Setup** and select **Prompt**.

2  Enter the desired prompts in the **Prompt1** and **Prompt2** fields. If you wish, you can enter default responses, or leave the **Resp1** and **Resp2** fields blank. Either way, you will be able to enter responses in the **Resp1** and **Resp2** fields when you create a new data file.

## Creating Data Files

An LAI measurement is made by collecting above and below readings in a file. Follow the steps below to create a new file:

1 With the instrument on, press the **START|STOP** button.

2 Select **New File** and enter a file name (a maximum of 8 characters or numbers). File names are automatically generated based on the previous entry, incremented by one digit.

3 **View/Edit Prompts**, and/or press **OK**.

 The LAI-2200C is now in Logging Mode (below). Log **A** and **B** readings.

4 Press **START|STOP** (or **EXIT**) to save the file and quit.

## Logging Mode

After a new file is created (see above), the console will enter Logging Mode, which is used to log data to the open file. In Logging Mode, the display will show four lines of data. The Status indicator line is always displayed, along with three of the following fields:

| A:#B:# | # A readings, # B readings |
|--------|----------------------------|
| T: | Time (HH:MM:SS) |
| D: | Date (YYYY/MM/DD) |
| BATT | Battery Voltage |
| 1 or 2 | Readings for Light Sensor 1 or 2 |
| X1,...,X5 | Readings for Wand X, rings 1-5 |
| Y1,...,Y5 | Readings for Wand Y, rings 1-5 |
| gLAT: | Latitude |
| gLNG: | Longitude |
| gALT: | Altitude |
| gSAT: | Number of Satellites used |
| gHDOP: | Horizontal Dilution of Precision |
| gUTC: | UTC time (YYYY/MM/DD, HH:MM:SS) |
| SEQ: | Off or AB (to indicate controlled sequence) |
| LAI: | Current Leaf Area Index |
| SEL: | Standard Error LAI |
| MTA: | Mean Tilt Angle |
| SEM: | Standard Error MTA |

Use the arrow keys to change what is displayed in the other fields. These changes are saved automatically.

Status Indicator: READY when waiting for data, WAIT when processing data.

Optical Sensor Status: indicates which sensors are connected and whether the sensor is set for an Above or Below reading. Here, a wand is connected to the X terminal and it is set to log an Above reading.

```
READY  X:A Y:-
A: 0 B: 0
LAI: 0.00
SEL: 0.00
```

# of B readings

Leaf Area Index calculated from the current data.

# of A readings

Standard Error of LAI.

You can also enter the "Log Setup" menu from the logging menu (press the **MENU** key while in Logging Mode). Any changes made here will only be reflected in the current file, except changes to light sensors, which will be retained even after exiting Logging Mode.

## Computations During Logging

While logging data, the LAI-2200C provides real time updates of some computed quantities, such as LAI. These computations are always done with a **Transcomp** setting of "xPx". That is, the middle setting (**Determine Above: Previous, Interpolate**, or **Closest in time**) is always P (Previous), regardless of what you have selected. This is out of necessity, because there is no way to interpolate or choose the closest "Above" reading before all the "Above" readings have been made. When you are done logging and close the file, if the file needs to be recomputed because of this mismatch, (or for other reasons, such as

logging to an existing file), you will be prompted with
**Compute file?**. If you respond with **OK**, the file is recom-
puted and stored. If you decline the recomputation, the
file is stored without being recomputed. It can be recom-
puted at a later time.

# Logging Configurations

This section includes basic procedures for logging LAI
data using various configurations.

## Manual Sequence with Sensor Unattached

A manual sequence is the simplest way to collect data with
the LAI-2200C.

Follow these steps to manually log LAI data with the
optical sensor unattached:

1 Disconnect the wand from the console and power it on
   by pressing the **A/B|Power** button.
2 Select Above or Below with the **A/B|Power** button.
3 Position the sensor and press **LOG** to record a data
   value. Each record will be tagged with an **A** or **B**,
   depending on settings.

The records must be moved to the control unit for view-
ing and processing. *Procedure 2.13 - Moving Wand Data to
the Console* on page 8-33.

## Manual Sequence with Sensor Attached

Follow these steps to manually log LAI data with the optical sensor attached to the control unit:

1  Go to **MENU > Log Setup > Controlled Sequence > Use = No**
2  Create a new file (see *Procedure 2.2 - Opening a New Data File* on page 8-25).
3  Select Above or Below with the **A/B|Power** button.
4  Position the sensor and press **LOG** to record a data value. Each record will be tagged with an **A** or **B**, depending on settings.

## Controlled Sequence

If a wand is attached to a console, then a controlled sequence is an option. Specify beforehand what sequence you want, (for example, ABBBB with 3 repetitions), and the console will automatically label logged records accordingly. The **ABOVE** LED on the wand (and the SEQ lines on the console) will indicate the next required reading type. Follow *Procedure 2.4 - Setting up a Controlled Logging Sequence* on page 8-26 to set up a sequence.

## Automatic Logging (Wand)

This configuration option allows you to set up an optical sensor to log data at specified intervals, *whether or not the wand is attached to a console*. Automatic logging can be configured to record data values at intervals from 5 seconds to 3600 seconds (60 minutes) in 5 second intervals. You can also specify the start and end time and date for automatic logging. Automatically logged data can be treated as **A** or **B** readings. Data points can be manually logged during auto-logging by pressing the Log button.

To configure a wand for automatic logging, see *Procedure 2.7 - Automatic Logging - Wand* on page 8-28.

## Automatic logging (Console)

A console can also be made to log automatically (*Procedure 2.8 - Automatic Logging - Console* on page 8-29). Automatic logging can be enabled/disabled whether a file is open or not, but the only time it actually occurs is while a file is open. When a console autolog occurs, all attached sensors (wands and light sensors) are logged, and (if enabled) a G0 GPS record.

## Transferring Wand Data

Data are stored in a wand under these conditions:

- Data logged because of automatic logging (attached or unattached)
- Log button pressed while wand unattached (Manual sequence with sensor unattached).

Wand data can be moved to the console and put in a new file or import to an existing file.*Procedure 2.13 - Moving Wand Data to the Console* on page 8-33.

# Connecting Quantum Sensors

The light sensor connectors (1 and 2) on the LAI-2200C accept LI-COR Biosciences Quantum sensors (LI-190R or LI-191R). Quantum sensors measure Photosynthetically Active Radiation (PAR). The light sensor connectors are configured to measure the signal (microamps) normally provided by LI-COR Biosciences light sensors.

Follow *Procedure 1.10 - Enabling a Quantum Sensor* on page 8-23 to enable a quantum sensor channel.

# Making Basic Measurements

Now that you've become familiar with the operating principles of the LAI-2200C and the instrument accessories, it is a good idea to make a few sample measurements. Be sure to review the practical considerations in *Dealing with Sky Conditions* on page 5-1 and *Canopy Types* on page 6-1 prior to collecting actual data because the use of improper measurement techniques will result in poor data quality.

## Operation: One Sensor, One Control Unit

To try out a basic measurement, you will need one LAI-2270C Control Unit, and one LAI-2250 Optical Sensor, then follow *Example 1 - One Sensor Measurement without scattering correction* on page 8-1. You can do this in an actual canopy, of course, or simulate the canopy in the following manner:

1 Go somewhere with a good view of the sky, and use a 90 degree view cap when making **A** (above canopy) readings. Keep the sun out of the view.

2 Simulate **B** (below canopy) readings by aiming the sensor in the same direction as the above reading, but substituting a 45 degree view cap instead.

This will theoretically give you gap fractions of 0.5 for each ring, which will result in a leaf area index (LAI) of about 0.86 and a mean tilt angle (MTA) of 39 degrees (with default settings, and a uniform sky - see *Figure 5-1* on page 5-4).

Once you have gotten familiar with a basic measurement, you will want to add scattering corrections. These are described in *Dealing with Scattering* on page 5-6. To try out a basic measurement with scattering corrections, you

will need an actual canopy. Follow *Example 2 - One Sensor Measurement with Scattering Correction* on page 8-3.

## Operation: Two Sensors, One Control Unit

To try out basic two sensor operation (*Example 3 - Two Sensor Measurement without scattering correction* on page 8-4) you will need one LAI-2270C Control Unit, and two LAI-2250 Optical Sensors. The first decision to be made involves how you wish to deal with matching the sensors. The approaches are described in *Three Methods for FV2200 Matching* on page 5-22. You may also choose to completely ignore the matching issue while you get familiar with two sensor operation. In that case, you will be following the steps for "Match Method 1" as you follow Example 3, since that one allows you to completely ignore all matching while collecting field data.

When you are ready to do actual measurements with two sensors, follow the instructions under *Procedure 1.8 - Build a Match File for Two Sensors (Match Method 1)* on page 8-21. We recommend that you do "Match Method 1" and make a match file for your two sensors. Once that is done, the only time you would then deal with matching is when you import and adjust **A** records using FV2200 during post-processing (*Procedure 3.6 - Interpolating A Records - FV2200* on page 8-39).

Scattering correction on data collected with two sensors requires a bit more planning and field work, and you have several options. See the discussion in *Protocol Suggestions for Direct Sun* on page 5-30.

# Importing A Readings from Separate Files (Console)

When **A** readings are collected autonomously, they need to be imported by the file that holds the **B** readings before LAI can be computed. This can be done on the control unit (described below) or with the FV2200 software see (*Procedure 3.8 - Import A and Adjust A Records - FV2200* on page 8-40).

---

**Note:** Importing on the console is not recommended if the files are large, or if the two sensors have not been matched

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1 If it hasn't been done already, transfer the records from the wand to the console: Go to **MENU > Data > Wand > Download > select wand**. Choose **Create new file** and name the file.

2 Go to **MENU > Data > Console** and select the file that is to receive the imported records. Select the file that has the **B** readings.

3 Select **Edit** from the menu, then select **Import Observations**.

4 Choose to import **A** records.

5 Press **OK** and the file will be recomputed using the imported records.

6 LAI values will recompute automatically and can be viewed at **MENU > Data > Console > select file > View Header**.

## Data Management on the Console

In the following section, you'll learn about ways you can manage data and files on the console.

## File Quick View

To view a summary of a file, navigate to **Menu > Data > Console > select data file > Quick View**. The file header is presented:

**Quick View:**

    File Name – The name of the file
    Date and Time – Date file was created
    Response1 and 2 – Responses to prompts 1 and 2
    LAI – Leaf Area Index for the file
    SEL – Standard Error LAI
    ACF – Apparent Clumping Factor
    MTA – Mean Tilt Angle
    SEM – Standard Error MTA
    DIFN – Diffuse Non-interceptance
    SMP – Sample Size
    gLAT – Average Latitude
    gLNG – Average Longitude
    gALT – Average Altitude
    gHDOP – Average Horizontal Dilution of Precision
    gNUMF – Average number of satellites found

## Viewing Data on the Console

To view data in a file, go to **MENU > Data > Console > select data file > View**. The following options are presented:

**View Header:**

    File Name – The name of the file
    Date and Time – Date file was created
    Response1 and 2 – Responses to prompts 1 and 2
    LAI – Leaf Area Index for the file
    SEL – Standard Error LAI
    ACF – Apparent Clumping Factor
    MTA – Mean Tilt Angle
    SEM – Standard Error MTA

DIFN – Diffuse Non-interceptance
SMP – Sample Size
gLAT – Average Latitude
gLNG – Average Longitude
gALT – Average Altitude
gHDOP – Average Horizontal Dilution of Precision
gNUMF – Average number of satellites found

**View ANGLES/MASKS:**

Displays angles and masks used for each ring.

**View CNTCT#/STDDEV:**

Displays contact number and Standard Deviation for
each ring in the current file.

**View AVGTRANS/GAPS:**

Shows average transmittance and gap fraction for the
current file.

**View DISTS/ACFS:**

Shows the distance vector (path lengths) and apparent
clumping factor for each ring.

**View Observations:**

Shows values for individual readings. Use the left and
right arrow keys to navigate through the list.

## Reprocessing Data on the Console

A set of basic data processing features are available on the
LAI-2200C Control Unit. Refer to *Data Analysis with
FV2200* on page 7-1 for advanced data processing with the
FV2200 software. To edit data that are stored on the con-
trol unit, go to **MENU > Data > Console > select data
file >Edit:**

**Edit Angles** to change the angles (normally, the default
values should be used).

**Edit Mask** to apply a mask to one or more rings. Masked rings are ignored when LAI is computed. The data for masked rings is retained in the file.

**Edit Distances** to change the default distances. This is useful for measuring isolated canopies (see *Example 7 - Isolated Tree* on page 8-9 for an example).

**Edit Transcomp** to change how transmittance is computed. See *Log Setup* on page 3-6 for a detailed explanation.

**Import Observations** to import **A** records from another file to the current file. This command imports all **A** records or just the ones that are closest in time to the existing **B** records in the target file.

**Strip Observations** to delete all **A** or **B** observations from a file.

## Additional Data Management Features

Three data management options, in addition to those mentioned above, are available at **MENU > Data > Console Data > select data file.** These include:

**Recompute** to recalculate LAI and other variables.
**Delete** to permanently remove the selected file.
**Rename** to rename the file.

# Connecting to a Computer

The LAI-2200C has a USB connection that can be used to transfer data to a computer.

Plug the USB cable into a USB port on your computer and the LAI-2270C Control Unit. The LAI-2200C is recognized as a USB mass storage device when it is attached to a computer (PC, Mac, Linux platforms are supported). *The LAI-2270C will not be recognized if it is in Logging Mode or a*

*menu, so be sure to enter the Monitor Mode by pressing EXIT, or just turn off the control unit.*

When it appears on your desktop, the name of the LAI-2200C will be LAI unless it has been renamed. Inside the LAI directory, you will find a folder named Data, and inside Data you will find your logged data files.

These files can be manipulated in the normal ways: you can rename them, copy them to your computer (drag-and-drop or cut-and-paste), delete them, and open them with an application (FV2200, a spread sheet, etc.). You can also create other directories on LAI, and move any sort of file to them, but only files within the Data folder will be accessible to the console's software.

In the root directory of LAI, you may see some files with .bin and .img extensions. The .bin and .img files hold copies of the firmware for the console and wand. Updating console or wand firmware involves downloading new files using the FV2200 "Check for Software updates" (**Help > Check for Software updates > Show Wand and Console Information**), putting them in the root directory of LAI, and then telling the console to do the update (see *Instrument Firmware* on page 2-12.

To disconnect the console from the computer, eject it before unplugging it—just as you would with any USB storage device.

# Global Positioning System

A Global Positioning System (GPS) is integrated into the console of the LAI-2200C (or the LAI-2200 with the 2200CLEAR upgrade kit). When GPS is active, real-time location data can be viewed in monitor mode. The

FV2200 computer software uses GPS data for scattering corrections and mapping.

## Configuring GPS

In addition to displaying Latitude, Longitude, Coordinated Universal Time (UTC), and other GPS data in real time, the control unit can be configured to log GPS data in three ways: averages in the file header, associated with measurement records, or with GPS tagging.

- **In the file header:** When there are **G** records (GPS records) present in a file, averages are included in the file header (". File with GPS records as viewed on a computer with FV2200." on the next page).
- **With measurement records:** When an Above and/or Below record is logged, GPS data for that same place and time are logged in the same file, next to the associated measurement record. The record identifier for these GPS records will be **G0** (*Figure 3-1* on the next page).
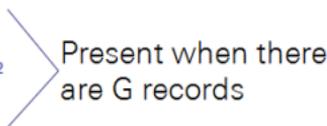
*Figure 3-1. File with GPS records as viewed on a computer with FV2200.*

- **GPS Tagging:** If GPS is active (step 2 below) and a file is open, you can log a GPS record by itself. Simply press a numeric key (1–9) on the console. The **G** record identifier will be **G1–G9**, depending on the key that was pressed. This allows you to mark areas in your plot (the corners, for example) while making measurements, without logging spurious sensor readings (*Figure 3-2* on the facing page).
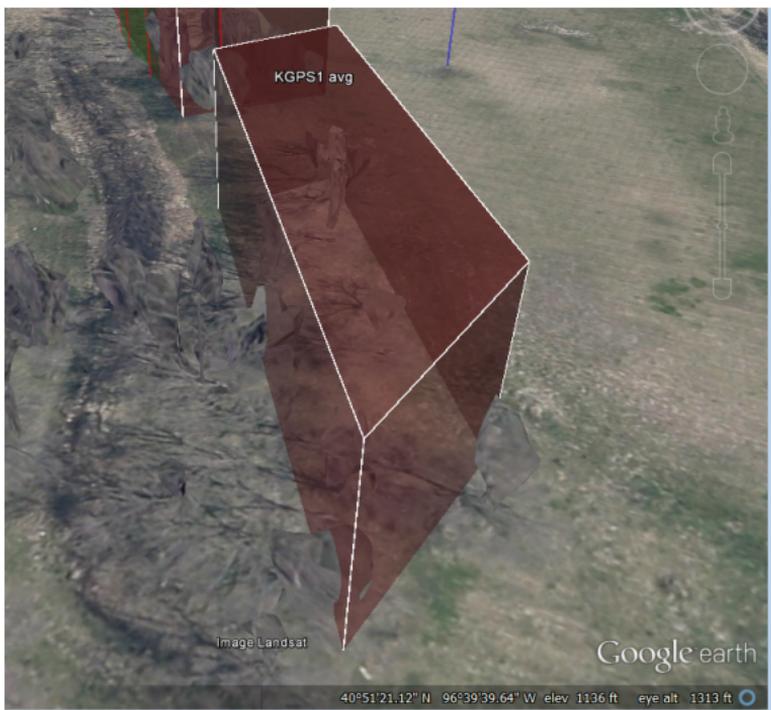
*Figure 3-2. Plot marked by GPS Tagging. At each corner of the plot, the "1" key was pressed while a file was open to log a GPS record. A different numeric key could be used to mark other plots in the same file.*

Use these steps to activate and configure the GPS:

1   On the console, go to **MENU > Log Setup**. Select **GPS** (bottom of list).

2   Press the right arrow key to select **Active–On**. GPS data will now be displayed on the console in monitor mode. Press **OK** to finish, or go to step 3 to enable GPS logging.

3   Press the down arrow key, then the left arrow key to select **Log GPS–Yes**.

4   Press the down arrow and then select **When–A, B,** or **Any**. Press **OK**. GPS data will now be recorded with

every Above reading, every Below reading, or with any reading.

## GPS Fix Quality

HDOP, one of the variables in **G** records, stands for "Horizontal Dilution of Precision". It is a measure of the geometric quality of the configuration of satellites in the sky. The lower the number, the better the configuration and the better the fix quality. If all satellites are grouped close together, the triangulation gets worse, and HDOP goes up. An HDOP under 2 is very good. If HDOP is above 5, the GPS may not be seeing enough satellites in the right configuration for a good fix.

## Mapping

The map tool in FV2200 allows the export of location data as a .kml file for Google Earth, with several choices including a 3D representation of LAI along a path (see *Make a GPS Plot* on page 7-6).

# About Data Files

In this section we describe the files that are created by the LAI-2200C. Files generated by the LAI-2200C are text based and consist of four basic parts: Header, Statistics, Sensor Information, and Observations (see *Figure 3-3* on the facing page).

*Figure 3-3. Data file as viewed on a computer.*

# Header

The header is a group of fields at the top of the file. It includes the file name, console firmware version, time stamp indicating when the file was created, and user remarks. The remaining part of the header contains the result of LAI calculations: leaf area index (LAI), standard error LAI (SEL), apparent clumping factor (ACF), diffuse non-interceptance (DIFN), mean tilt angle (MTA), standard error MTA (SEM), and the number of pairs of Above and Below observations that were included in the calculations (SMP). If GPS logging is enabled, average latitude (GpsLat), longitude (GpsLong), altitude (GpsAlt), number of satellites used (GpsNum), horizontal dilution

of precision (GpsHDOP), and coordinated universal time (GpsUTC) are visible in the header.

## Statistics

The statistics group contains 8 groups of 5 numbers: MASK indicates which rings were included in calculations (1 indicates the ring is included, 0 indicates omission). ANGLES are the midangles of the field of view for each of the 5 rings. CNTCT# are the mean contact frequencies (the logarithm of the gap fraction divided by the path length), STDEV are the standard errors of the contact frequencies, DISTS are the path lengths, and GAPS are the gap fractions. ACFS is the apparent clumping factor for each ring, and AVGTRANS is the average transmittance for each ring in the file. Chapter 10 "Theory" on page 10-1 (Theory) discusses how these quantities, as well as those in the header, are computed.

## Sensor Information

This field indicates which sensors were used to record the data and the name of the wand used. The five values to the right are matching values for each ring in the sensor. If quantum sensors are connected to port 1 or 2, the light sensor name and calibration information is in this field as well.

## Observations

The Observations each have a label (**A** or **B** indicating above or below the canopy), a sequential number, a time stamp, and the readings from the five rings of the detector. In this example, the first four samples (**B** readings 2 through 5) use **A** reading 1 as a reference. The next four samples (**B** readings 7 through 10) use the **A** reading

6 as a reference. If enabled, GPS observations are labeled
**G**. Light sensor observations are labeled 1 or 2.

## What do the Results Mean?

**LAI** is the answer to the question "How much foliage?".
Although LAI nominally means "leaf area index", please
remember that the LAI-2200C is measuring all light-
blocking objects, so "foliage area index" is more appro-
priate. LAI is dimensionless, but it can be thought of as
{$m^2$ one-sided foliage area/$m^2$ ground area}. However, if
the Model is not Horizontal (that is, if the DISTS values
have been changed to reflect measurements of an isol-
ated plant instead of an "infinitely" horizontal canopy),
then the LAI value is foliage density (foliage area in
$m^2$/canopy volume in $m^3$). See*Computing LAI* on
page 7-8.

**SEL** is Standard Error of LAI ($L_{se}$).

**ACF** is Apparent Clumping Factor. It is equivalent to the
apparent clumping index $\Omega_{app}$ defined by Ryu, et al
(2010). One of the assumptions the LAI-2200C makes is
that foliage positioning is random - if not for the entire
canopy, at least for parts of it. For example, consider a
widely spaced row crop: The randomness assumption is
clearly wrong when considering the entire field, but is
much better when considering just one row. Lang and
Xiang (1986) showed that in cases like this, if multiple
transmittance measurements are made so that each con-
tains either mostly row or mostly gap in its view, they
can be combined by averaging the natural logarithms
of the transmittances to give the correct leaf area index.
For this reason, the LAI-2200C combines multiple trans-
mittance readings by averaging the natural logarithms
of the transmittances when computing LAI. The ACF
value is

$$ACF = \frac{LAI_{\log(avg(T))}}{LAI_{avg(\log(T))}} \qquad \text{3-1}$$

where $LAI_{\log(avg(T))}$ is the leaf area index computed by taking the log of the averaged transmittances, and $LAI_{avg(\log(T))}$ is that reported by the LAI-2200C (computed by averaging the logs of the transmittances). Note that the simple averaged transmittances for each ring are reported in the statistics block of the file, after the label AVGTRANS, while the log-averaged transmittances are reported after the label GAPS. Ring by ring values of ACF are shown after the labels ACFS.

The purpose of ACF is to provide a way to "undo" the avg(log(T)) protocol used by the LAI-2200C to combine readings. Why would you want to do that? If, for example, you had an independently determined clumping factor $\Omega$ (determined, for example, from a gap size distribution measurement) for a canopy that you wished to apply to the LAI-2200C results, you would need to do this to compute a true LAI (*Ftrue*)

$$Ftrue = \frac{LAI \times ACF}{\Omega} \qquad \text{3-2}$$

LAI $\times$ ACF undoes the clumping factor compensation inherent in how the LAI-2200C works, and allows the independently determined clumping factor $\Omega$ to be applied.

**MTA** answers "How is the foliage oriented?". If all the foliage were horizontal, then the correct MTA would be 0°; if all were vertical, MTA would be 90°. This information may not be of particular interest to everyone, but it is wise to make sure the numbers seem at least reasonable. Typically, MTA will range from the 30s to the 60s, but an unexpected MTA value can indicate

something wrong with the measurement or the DISTS values.

**SEM** is Standard Error MTA.

**DIFN** is calculated by integrating gap fraction (GAPS) to yield a value that indicates the fraction of sky that is not blocked by foliage. This value ranges from 0 (no sky visible to the sensor) to 1 (no foliage visible to the sensor). DIFN is in essence a single value representation of canopy structure, as it combines LAI and MTA into one number. However, DIFN does not depend on the same assumptions that go into LAI and MTA, but only depends on the assumption of no scattering by the foliage. Of all the values computed by the LAI-2200C, DIFN comes the closest to being an indicator of "canopy light absorption". However, canopy absorption involves not only canopy structure (DIFN), but also the foliage spectral properties in the wavelength range of interest (for example, the photosynthetically active 400 to 700 nm region) for the foliage and the surface beneath the canopy, and the location of the sun. Therefore, in terms of canopy absorptance, DIFN is merely an indicator of the absorption of diffuse, short wave (<490 nm) radiation.

**SMP** is the sample size (total number of below canopy readings).

Section 4.

# Measurement Guidelines

This section includes practical considerations for data collection procedures and guidelines for collecting data under a variety of conditions.

## Guidelines for Getting Good Data

Collecting reliable data with the LAI-2200C depends on having a protocol that is appropriate for the canopy of interest and suitable for the measurement conditions. For any **A** or **B** readings that are used as a pair, the view cap must be the same size, the optical sensor (wand) must view the same part of the sky, and the view cap must cover the same part of the sensor (this only applies if the same sensor is used for both **A** and **B** readings). These and other considerations are discussed below.

## Where to Measure?

### **A** Readings

In general, **A** readings should be made as closely as possible to **B** readings, both in time and space; however, under certain conditions and with the appropriate protocol, this is not essential to acquiring good data.

In some situations, especially in forest canopies, it may be impossible or impractical to record **A** readings near the **B** readings. In these situations, it is best to use two optical

sensors (see *Operation: Two Sensors, One Control Unit* on page 3-19), with one sensor positioned above the canopy or in a clearing, logging data automatically. Additional suggestions are in *Canopy Types* on page 6-1.

## **B** Readings

It is best to consider a sampling protocol that is designed for the canopy type that is being measured. The best protocol for measuring a short homogeneous canopy (such as a grassland) may not be the best protocol for measuring a row crop (and it certainly will not be the best protocol for measuring a tall heterogeneous canopy). Guidelines for measuring specific canopy types are presented in *Canopy Types* on page 6-1.

One approach to collecting **B** readings is to make measurements equally spaced along one or more transects under the canopy. Alternatively, measurements can be made at randomly chosen locations in the study area, though practical considerations periodically make this difficult. Predetermined sample locations may violate the guidelines for usage and require adjustments to the sample location in order to collect valid data. For example, avoid making measurements with a leaf immediately above the sensor, because one leaf may block the entire view of the center rings. At the larger zenith angles, when foliage is beside the sensor rather than above it, an individual leaf blocks much less of the view. The section called *Foliage Size* on page 4-8, provides detailed guidelines for minimum distances and the theoretical justifications. Refer to Ross (1981) for guidelines used for fisheye photography.

## How Many B Readings?

When determining the proper number of **B** readings, first consider the ground area over which the computed LAI is to be valid: An entire field? Part of a field? A small plot? Second, what fraction of this area does one **B** reading represent? As a rule of thumb, consider each **B** reading to represent a sample of the canopy that is cylindrical (or some fraction of a cylinder if a view cap is used) with a radius roughly equal to the canopy height (the potential view of the sensor is larger than this, but the effective range is reduced by foliage). Thus,

$$A = f\pi H^2 \qquad\qquad 4\text{-}1$$

where $A$ is the ground area represented by the sample, $f$ is the view fraction (0.75, 0.5, 0.25, or 0.125 for the 270°, 180°, 90°, and 45° view caps respectively), and $H$ is canopy height. For example, one **B** reading with no view cap ($f$=1) in a canopy 5.0 m on a side and 1.0 m tall is a sampling of approximately 3 m$^2$, or 12% of the total ground area. If that same canopy were only 0.2 m tall, then one **B** reading would represent only 0.5% of the ground area. Thus, canopy height is a very important consideration.

Another consideration is the variability of the density of the foliage in the plot. A homogenous canopy would require fewer **B** readings than a heterogeneous one. *Table 4-1* on the next page provides guidelines for determining the proper number of **B** readings. See *Derivation of Formulae for Determining # of B Readings* on page 10-14 for the derivation.

This simple procedure is used to determine the number of **B** readings necessary for 95% confidence that the true LAI mean is within ±10% of the measured LAI.

1 Make an LAI reading based on 6 **B** readings. Be sure to include both the thinnest and densest parts of the canopy.

2 Divide the Standard Error of LAI by LAI (SEL/LAI)

3 Use *Table 4-1* below to determine the number of **B** readings.

Table 4-1. Guidelines for determining the appropriate number of B readings.

| SEL/LAI | #B Readings | SEL/LAI | #B Readings |
|---------|-------------|---------|-------------|
| 0.01 | 2 | 0.06 | 11 |
| 0.02 | 3 | 0.07 | 13 |
| 0.03 | 5 | 0.08 | 16 |
| 0.04 | 6 | 0.09 | 19 |
| 0.05 | 8 | 0.1 | 23 |

## Using View Caps

Use the 270° view cap to hide the operator from the sensor any time measurements will be made with the operator potentially in the field of view. No view cap is needed if the operator is very careful to block exactly the same portion of the sensor's field of view for both **A** and **B** measurements, but it is simpler to use the view cap.

In general, any object that is common to both the **A** and **B** readings will not affect the LAI computation. Thus, one could measure the LAI of grass beneath a tree if the **A** and **B** readings are in close proximity so that the tree occupies the same portion of the sensor's view for both **A** and **B** readings.

Here is a summary of reasons to use a view cap:

1 To remove the sun from the sensor's view
2 To remove the operator from the sensor's view
3 When sky brightness is very non-uniform
4 When there are significant gaps or clumps in the canopy
5 To reduce the required plot size
6 To reduce the required clearing size for above-canopy readings in a forest

There are times when it is preferable to use the 180° or 270° field of view instead of a narrow one:

1 To avoid loss of signal near twilight or under very dense canopies
2 If the goal of the measurement is $L_e$ (effective LAI), not $L$ (true LAI).

Be very careful that the **A** and **B** sets of readings are made with the sensor(s) viewing the same region of sky without rotating the view cap on the sensor. This is because there are usually slight azimuthal variations in the sensitivity of the optical sensor's detector, especially on the outer ring.

When using the view cap to block the sun, it is good practice to shade the entire lens from the sun, to prevent light reflected from the surrounding view cap structure from influencing the readings. Usually it is only the 5$^{th}$ ring that responds to such reflections.

## Measuring on Slopes

When making measurements on sloping terrain, there are a couple of strategies that can be employed. One method is to hold the optical sensor parallel to the ground rather

than level. Make sure that all associated **A** and **B** readings are made with the sensor tilted at the same inclination and pointed in the same compass direction.
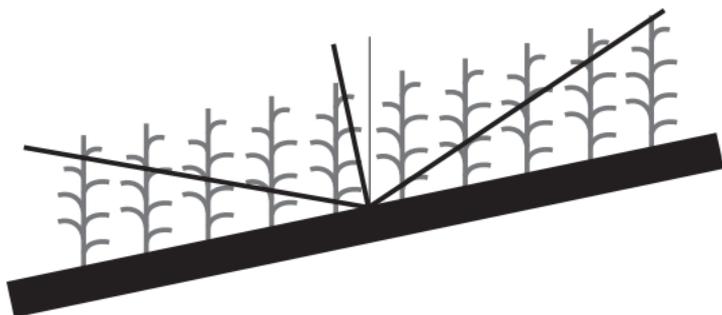


*Figure 4-1. Tilt the sensor to match the slope.*

One way to ensure that the sensor is held at the same inclination for each reading is to mount the bubble level on the handle rather than the sensor. Fix the hinge at an angle that permits the handle to be held level while the sensor is held at the desired inclination. Mark the two pieces at the hinge so that this angle can be reset easily (see *Figure 4-2* below).
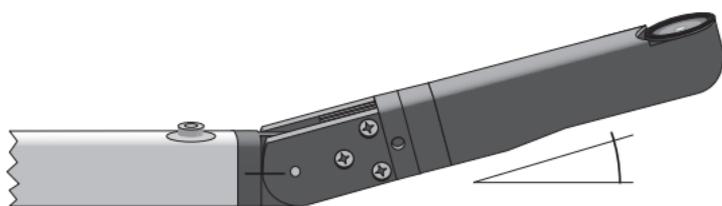


*Figure 4-2. Level the handle, tilt the sensor to match the slope, and mark across the hinge.*

If it is impossible to incline the "above" and "below" sensors at the same angle when measuring on a slope, the effects can be minimized by using a 45° view cap, and orienting the sensor for **B** readings along the contour (looking neither uphill nor downhill). The **A** readings need to be taken at the same compass direction as the **B** readings.

Another way to minimize the effects of the slope is to mask out the outer two or three rings in the analysis, either before (*Procedure 2.10 - Excluding Rings from Analysis - Console* on page 8-31 or after (*Procedure 3.5 - Excluding Rings from Analysis - FV2200* on page 8-39) data collection.

Sloping ground has some implications for scattering corrections if you are measuring with the sensor parallel to the ground (first method). This is discussed in *K Records and Sloping Terrain* on page 5-10.

## Bad Readings

Theoretically, **B** readings should always have lower values than **A** readings. In very sparse foliage they will be very close, and in large gaps where no foliage is seen by the sensor, they will be identical. But that is only in theory.

As a practical matter, a **B** reading may exceed the value of its **A** reading for any of the following reasons:

1 Changing sky conditions
2 Normal measurement variation
3 Operator error (**A** and **B** out of sequence)
4 Making **B** readings in sunlit foliage

A **B** reading is "bad" if one or more of the rings has a value that exceeds its associated **A** reading, so that the transmittance for that ring is greater than 1.0. If this is due to operator error or changing sky conditions, it would be good for the operator to be alerted so that the measurement can be started over. But if a reading is bad simply because of sparse foliage and normal fluctuations, it would be nice for the console (control unit) to overlook the slight discrepancy and proceed using a value of 1.0 for the transmittance(s) of the offending ring(s).

To determine this setting, go to **MENU > Log Setup > Transcomp >** and scroll down to **Bad Readings**. Select one of the settings described below (press **OK** to save the setting).

**Skip:** When a transmittance greater than 1.0 is found, that **B** reading is ignored in the calculation. The offending record is still stored in the file, however. You will know that a bad reading occurred if the number of **B** readings is larger than the sample size in Logging Mode (see *Logging Mode* on page 3-12). **Skip** should be used in cases where **A** and **B** readings are not expected to be very close.

**Clip:** If a transmittance greater than 1.0 is encountered, it is considered to be simply 1.0. Note that this does not change any stored values. This mode is useful when measuring in canopies where **B** readings are likely to be made under little or no foliage.

## Foliage Size

As a general rule, the distance between the sensor and the nearest leaf above it should be at least four times the width of the leaf. When a view cap is used this distance should be increased, but when more **B** readings are taken the distance can be decreased.

Table 4-2 provides guidelines for determining the minimum distance from the sensor as a function of foliage element size and zenith angle. To determine how close a particular leaf size can be to the sensor, find the column for the view cap being used in *Table 4-2* on the facing page. Divide the values by the number of **B** readings to be made and multiply the results by the leaf width (cm).

Table 4-2. Distance Factors.

| Distance Factors | | | | | | |
|---|---|---|---|---|---|---|
| | | Sensor Field of View: | | | | |
| Ring | Angle (°) | 360° | 270° | 180° | 90° | 45° |
| 1 | 7 | 10 | 20 | 30 | 50 | 100 |
| 2 | 22 | 4 | 5 | 8 | 20 | 30 |
| 3 | 38 | 3 | 3 | 5 | 10 | 20 |
| 4 | 52 | 2 | 3 | 4 | 8 | 15 |
| 5 | 68 | 2 | 2 | 3 | 7 | 14 |

The formula for determining whether a leaf is too close to the sensor is:

$$\textbf{minimum distance} = \left( \frac{d \times w}{B} \right) \qquad \text{4-2}$$

where $d$ is the distance factor from *Table 4-2* above, $B$ is the number of **B** readings, and $w$ is the leaf width (cm).

For example, with no view cap and only one **B** reading, a 5 cm leaf should be 50 cm ($(10/1) \times 5$) away at 7°, 20 cm ($(4/1) \times 5$) away at 22°, and 10 cm ($(2/1) \times 5$) away at 68°.

## Derivation of equation 4-2

One of the LAI-2200C assumptions (*Assumptions* on page 1-7) is that the foliage elements are small compared to the sensor field of view. Lang and Xiang (1986) derived a formula for the error as a function of foliage area and sample area: If R is the ratio of sample area (the region over which gap frequency determinations are made) to the area of an individual leaf, then the factor (E) by which the gap frequency is in error is

$$E = -R \ln \left(1 - \frac{1}{R}\right) \qquad \text{4-3}$$

We apply this analysis to an LAI-2250 sensor by considering the sample "area" to be the distance around a particular ring's view at a distance from the sensor that corresponds to the closest foliage. For example, the view of ring #2 is centered at 22°. If the closest foliage at 22° is 50 cm from the sensor, then the sample size for that ring (assuming the full 360° view) is $(2\pi)50(\sin(22))=118$cm. If the leaf width is 5 cm, then R in equation 4-3 is $118/5 = 24$, and the error is 1.02 or 2%.

*Table 4-2* on the previous page (Distance Factors) is for an error (E) less than 5%, requiring the ratio of view circumference to leaf width (R in equation 4-3) to be at least 10.6.

Section 5.

# Dealing with Sky Conditions

This section includes guidelines for collecting data under various sky conditions. The LAI-2200C can be operated in a range of daytime sky conditions, with appropriate adjustments in measurement and/or post-processing protocol.

**Best Sky Conditions:** Clear, blue sky (at least in the part of the sky viewed by the sensor) with the sun below the horizon (twilight) or blocked by a convenient cloud.

**Good Sky Conditions:** Clear blue sky (or a few high thin clouds) during sunlight hours. Interpolating above readings over time works well under these stable conditions, making tall canopies such as forests easy to measure with a single sensor. Direct sunlight greatly increases scattering errors, but this can be mitigated with scattering corrections. See *Sun* on page 5-6.

**Other Sky Conditions:** Most other sky conditions (such as broken or non-uniform clouds) can be problematic, and need to be handled carefully. You will need to minimize time differences between above and below readings, and carefully align above and below readings to view the same section of the sky. See *Clouds* below.

## Clouds

A very uniform overcast can be good, but scattered or non-uniform clouds represent the largest challenge for

making measurements. The ideal LAI measurement involves above and below canopy readings that see exactly the same sky at exactly the same time. In practice, the sky brightness is always changing with time and/or view direction, and hence does cause variability (random errors) in the computed LAI, even without any canopy considerations.

Cloudless blue sky is by far the easiest case to deal with. It is stable, and small variations in view direction have little effect on a sensor's reading. A sunlit cloud, however, can be many times brighter than the blue sky surrounding it, so slight variations in view direction can have significant effects if such a cloud extends across a particular ring's view boundary. It is impossible to get exactly the same view multiple times if the optical sensor (wand) is moved between each one, so variations in the readings are unavoidable. It is equally impossible to get two separate sensors to have exactly the same view, since there are very slight variations in the angular response of each sensor. This section presents strategies for dealing with these challenges.

## Sky Variability Tests

It is easy to quantify a set of sky conditions in terms of the potential error in LAI that it can produce. One method of doing this is to make a series of **A** readings of the sky. For example, mount a wand on a tripod and let it log an **A** reading every 10 seconds for 10 or 15 minutes. The FV2200 software has a sky test (*Procedure 4.1 - Sky Variability Test* on page 8-46) that will select all combinations of pairs of those readings, up to some specified maximum time separation, compute apparent LAI for each pair, then plot LAI as a function of time separation.

*Figure 5-1* on the next page illustrates the results for four condition: A) Cloudless, midday. B) Cirrus. C) Broken cumulus, fairly windy. D) Heavy, non-uniform overcast. Each condition was measured with **A** readings logged every 10 seconds over about 30 minutes using a 45 degree view cap.

These examples illustrate the advantage of clear blue sky, with LAI error of < .01 for **A** readings taken up to 5 minutes apart. On the other extreme, rapidly changing clouds dictate readings as close together as possible.
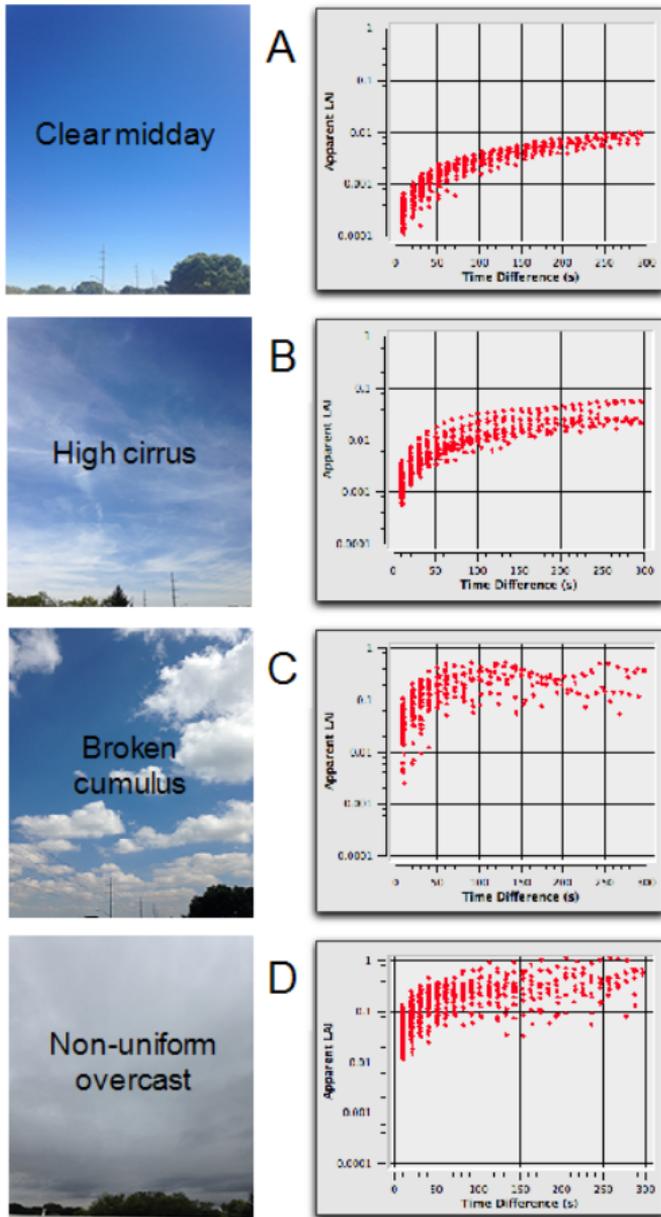
*Figure 5-1. FV2200 Sky Variability Test.*

## Sky Variability and Canopy Variability

There is another aspect of variable sky brightness that will further increase the variability of LAI in a measurement, and that is the canopy itself. The parts of a canopy that block the brighter part (e.g. cloud) of a sensor's view will be weighted more heavily than those that block the darker part of the view (e.g. blue sky).

## Dealing with Clouds

The two ways to deal with the variability that clouds introduce are to 1) minimize the time between **A** and **B** readings, and 2) increase the number of **B** readings that you might otherwise take.

### Timing

When there are clouds, the time between **A** and **B** readings in a short canopy can be minimized simply by taking an **A** reading before every **B** reading. In a tall canopy, that will not be practical with only one sensor. In two sensor mode, the time can be minimized by making the **A** readings more frequently. File sizes can be kept manageable by a simple trick: Set the **A** unit to log infrequently, say every 30 seconds. Once it starts logging, note what part of the minute (on the below unit's clock) that the **A** unit logging takes place, and then only log **B** readings as close as possible to those times. For example, if the **A** unit is logging at 10 seconds and 40 seconds of each minute, then try to log **B** readings within a few seconds of those times. (Operational aside: autologging on an LAI-2200C wand is relative to the start time only if you enable autologging prior to that start time. Otherwise, it is relative to when you enable autologging. That's why it is simpler to just wait and see what the timing actually is after it starts

logging. It also saves you from having to synchronize clocks.)

### Increase B Readings

With clouds in the sky, everywhere you would normally take one **B** reading, take several in quick succession, moving (view and position) just a little bit between each one.

In summary, clouds can be a problem in that they can introduce potentially large uncertainties into an LAI measurement unless you take steps to minimize the effect. By contrast, clear blue sky is easy to deal with. It, however, brings with it another problem: direct sunlight.

# Sun

Measurements can be made in direct sunlight, if a) the sun is always in the portion of the wand's view that is masked by a view cap when making measurements, and b) the measurements are corrected for scattering. While clouds can cause random errors, scattering represents a systematic error. Fortunately, scattering can be dealt with by a few extra sky measure-ments at the time of data collection, care in how measurements are made, and some simple post-processing steps.

## Dealing with Scattering

One of the traditional underlying assumptions of the LAI-2000 and LAI-2200C has been that foliage absorbs all the radiation in the waveband seen by the sensor (320-490



nm). Starting with version 2.0, FV2200 allows this assumption to be set aside and provides a mechanism (Kobayashi et al., 2013), for correcting measurements for the radiation reflected and transmitted by the foliage. You should apply

this correction for data taken in direct sun, since that's when the scattering errors are the highest, but you can also correct data taken when the sun is obscured, adjusting for the actual foliage scattering properties in your canopy, rather than assuming reflectance and transmittance are both 0.

## K Records

The scattering corrections require that a few extra sky radiation measurements be taken in the field, in addition to measurements – or assumptions – of foliage reflectance and transmittance. This sky brightness data will ultimately – once the file is processed by FV2200 – be contained in what we call a **K** record (**K** is for sky). In order to make a **K** record, you typically need a sequence of four **A** records, hereafter termed a **4A** sequence.

### The 4A Sequence

The first two **A** readings in the **4A** sequence use the white diffuser cap (part number 6522-117). Follow these steps to make a **4A** sequence:

1  Diffuser cap in the sun. With your back to the sun, and the sun shining on the diffuser cap, level the sensor, and take the first **A** reading.

**2** Diffuser cap shaded. Rotate just a bit to shade the diffuser cap with the shadow of your head, and take the second **A** reading. If the sun is too high to shade the diffuser with your head, hold the sensor with one hand and reach up and out with the other to shade the diffuser. You want the entire diffuser completely shaded, but not much more than that.



**3** No cap, shaded. For the third **A** reading, remove the diffuser and either shade the sensor with your head, or put a 270° view cap in place. This reading needs to have the sun blocked, but retain as wide a view of the sky as possible.



**4** Normal **A** reading. Use the same view cap and view direction you are using for the associated **B** readings.
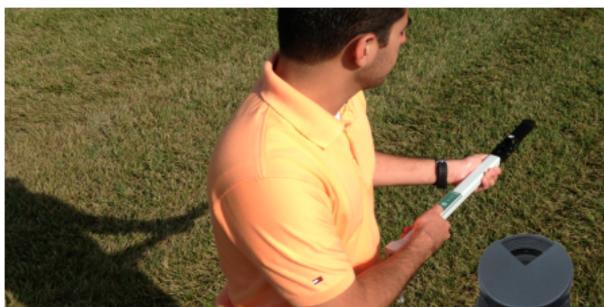
Same view cap and view direction as
the associated B readings.

Ultimately, each LAI-2200C file that is to be scatter-corrected will need to have at least one **K** record in it. This does not necessarily mean that when you are collecting data in the field, you need to do a **4A** sequence in every file. **K** records can be copied (by FV2200) into other files that need them, so you can perform a **4A** sequence somewhere in a data file (beginning, middle, end, it doesn't matter when), or as part of a below-canopy file if you are in two-sensor mode, or accumulate a series of them into their own separate file. It is a simple matter with FV2200 to turn **4A** sequences into **K** records, then copy them to whatever files need them. When FV2200 copies **K** records, it does so based on time, and uses the closest ones available in source files to the **B** records in the destination file.

A complete example of using **K** records is given in *Example 2 - One Sensor Measurement with Scattering Correction* on page 8-3, and a "guided tour" in *A Scattering Correction Example* on the next page.

## How Many K Records Needed

Sky conditions will determine how often **K** records (i.e. **4A** sequences) are needed. The determining factor is how fast the fraction of beam is changing. The simplest case (as

always) is clear blue sky. During the middle of the day, one **K** record per hour would be fine. The worst case is fast-moving scattered or broken clouds, with the sun coming and going. The choice in those conditions might come down to only taking data (**A**, **B**, and **4A** sequences) when the sun is between clouds, or only taking data (**A** and **B**) when the sun is obscured behind clouds (you know the fraction of beam is 0 then, so you so don't need **K** records), or waiting for a better day.

Another consideration is if your measurement involves multiple view directions. In principle, you should have a **K** record for each view direction used. However, *if your view azimuths are symmetric about the solar azimuth* (e.g. sun is South, and your views are East and West), then you would not need multiple **K** records unless there were distinctly differing cloud formations in those two directions.

### K Records and Sloping Terrain

In steeply sloping terrain, we recommend keeping the sensor parallel to the ground for **A** and **B** readings. See*Measuring on Slopes* on page 4-5. This has some implications for **K** records: The first two readings of a **4A** sequence (with the white diffuser) should always be made with the sensor level. The last two readings (wide sky and normal **A**) should be made with the sensor parallel to the ground. Terrain slope information can then be included with the other scattering inputs (see the FV2200 User's Guide under the FV2200 "Help" menu), so the solar angles can be adjusted appropriately.

# A Scattering Correction Example

We present an example of making a single sensor measurement complete with scattering correction. The steps to

do an example like this are summarized in *Example 2 - One Sensor Measurement with Scattering Correction* on page 8-3. Here, however, we have a specific data file that is included in the sample data files built in to FV2200. This will let you follow along on data already taken for you.

For this example we measured a site using 8 **B** records, and a starting and ending **A** record. (Final **A** records are only useful when you have interpolation enabled; we'll do that when we are done). Thus, the measurement sequence without scattering corrections would be ABBBBBBBBA. Because we are doing scattering corrections, we need to replace at least one of the **A** readings with a **4A** sequence; we'll replace the first, leaving us with a measurement sequence that is AAAABBBBBBBBA. Those first 4 readings are done as shown in *K Records* on page 5-7.

You can load this data file into FV2200. Select Files > Samples > ScatterExample.txt. The state of the file is like it just came from the field. The **4A** sequence is there, but hasn't yet been turned into a **K** record.
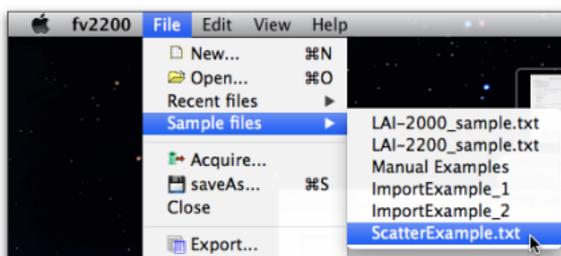


1   You will want to add a variable named **ScattCorr** to the list of displayed items in the main view of FV2200, if it is not there already (Click the **Display** button, then the **Header** tab, and drag **ScattCorr** from the

list on the left to the list on the right). This field indicates if the scattering correction is being done on a particular file, and if so, how big its effect. It will be **none** with no scattering correction, **off** if the scattering inputs are there but the scattering correction is turned off, or a numeric value if the scattering correction is on. The numeric value will be the increase in LAI due to the scattering correction.
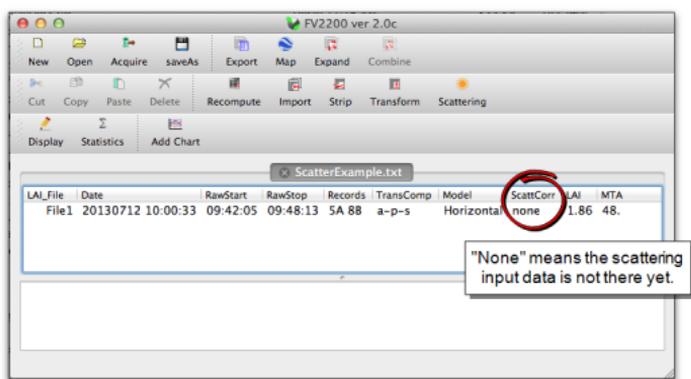


If you wish to view the data records, double click the **File1** entry, and select the **Current** tab.
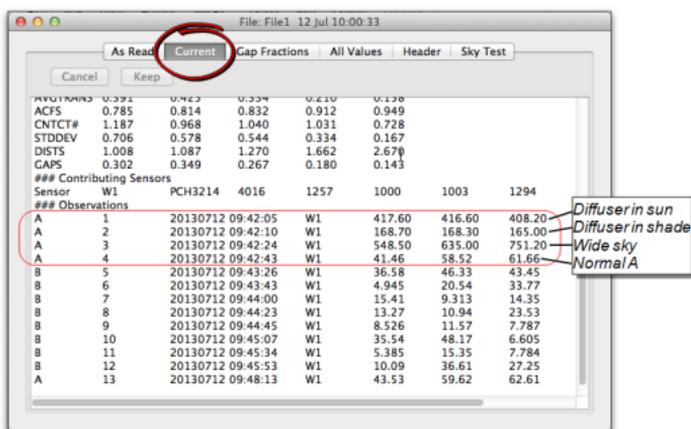
**2** Click the Scattering Tool icon to open the Scattering Correction Tool, then click the **K Records** tab. Set the values as shown.
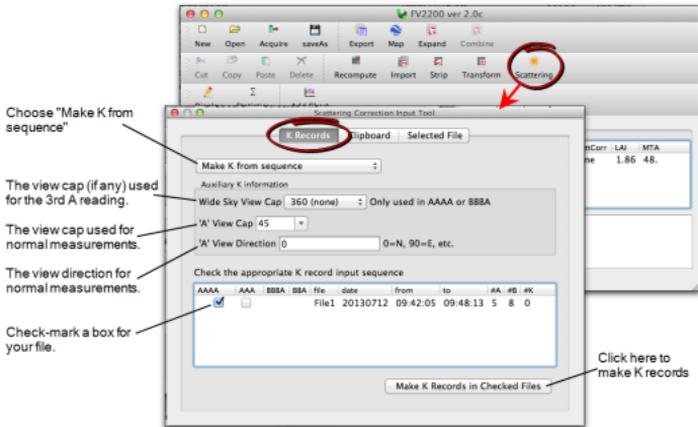


Once the **K** records are made, the "Records" field in the main view will show the change (Added 1 **K**, 'removed' 3 **A**s).

3   Click the Clipboard tab in the Scattering Correction
    Input tool, and fill in the fields as shown. For inform-
    ation on obtaining scattering properties, see *Required
    Inputs for the Scattering Model* on page 10-13.
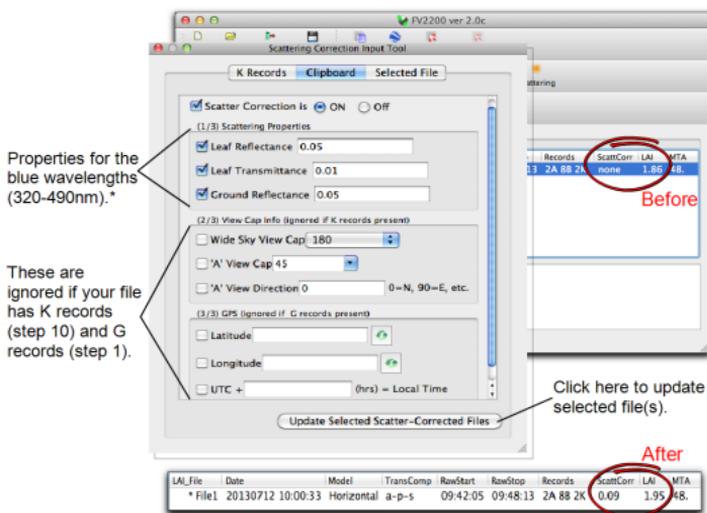


The file is now corrected for scattering, and the LAI
increased from 1.86 to 1.95.
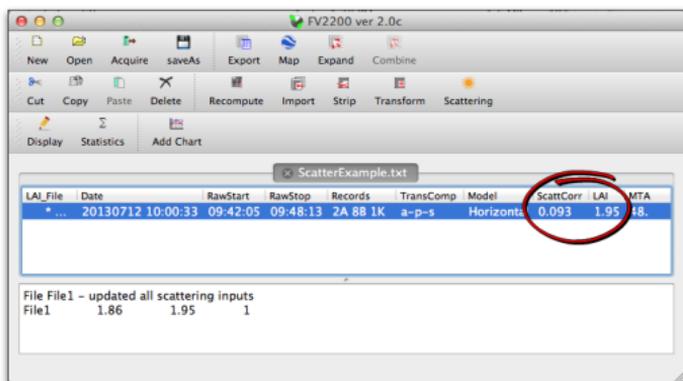


4   One final step would be to enable interpolation of the
    **A** readings, since we have that final **A** record in the
    file. If you do that, following *Procedure 3.6 -*

*Interpolating A Records - FV2200* on page 8-39, you will find that the LAI for this file changes from 1.95 to 1.94.

When the scattering correction is applied (as evidenced by the "ScattCorr" variable having a numeric value), all computed values (LAI, MTA, GAPS, etc.) reflect the scattering correction. The value of "ScattCorr" itself is the difference in leaf area index (actually, it's the difference in the parameter EllipLAI, the leaf area index based on the inversion scheme of Norman and Campbell (1989) using the ellipsoidal representation of leaf angle. This is the computation used internally when iterating through the scattering correction model).

## Other Ways to Make K Records

**4A** sequences are not the only way to make a **K** record.

### 3A Sequence

In settings where you cannot get a bigger unobstructed view of the sky than is used for the normal **A** reading, you can forego the wide sky view (the 3rd **A** of a **4A** sequence). FV2200 will use the last **A** reading in the sequence for both the wide and narrow views. This of course makes the assumption that the brightness distribution in the direction of your **A** readings is the same as for the entire sky.

### 1A + Assumption

If your LAI data was collected with the sun obscured by cloud, or below the horizon, then you already know the fraction of beam is 0. If you are also willing to make the assumption that the sky brightness distribution in the direction of your measurement is the same as for the rest of

the sky, then you can forego **3A** or **4A** sequences entirely; FV2200 will let you build **K** records based on the normal **A** readings in the file and your assumption of the fraction beam value. This is also useful for correcting old data for the effects of actual foliage reflectance and transmittance.

## Embedded Bs

Consider the following situation: You are in multi-sensor operation mode, with one sensor devoted to **A** readings, and other sensor(s) doing **B** readings. You need to get **K** records from the **A** sensor, since that's the only one with a suitable clearing. Suppose further that the **A** unit is just a wand that is automatically logging **A** records at regular intervals, so there's no chance of interrupting autologging and putting **4A** sequences into a separate file. Can you get **K** records in this situation? You can if there is enough time between autologs (probably at least 30 seconds) to do a few simple steps. When it is time to get another **K** record, follow *Procedure 2.12 - Getting K Records on an Above Sensor* on page 8-32. You are essentially doing a **4A** or **3A** sequence, but labeling all but the last as **B** records.

You will end up with a file filled with **A** records, with occasional **2B** or **3B** sequences. The **A** record that immediately follows each **2B** or **3B** sequence will also be used to make the **K** record. Thus, a sequence of BBBA is just like a **4A** sequence, and a BBA is just like a **3A** sequence.

Again, this technique is only for above files that are otherwise full of **A** records.

> **Note:** This method will not work with the LAI-2000.

## Model Limitations for Scattering Corrections

The scattering correction is based on a simple model, and how well it works in any particular circumstance depends on how well those circumstances conform to the assumptions of the model. A very fundamental assumption of the model is that the canopy is one dimensional (vertical), with foliage that can be clumped. The sun is above the canopy looking down, and the LAI sensor is below the canopy looking up. The model canopy is a good approximation to a fairly uniform, full cover actual canopy. But how about other settings?

Here is a key factor in how well the model will predict scattering errors: *The model will fail when the relation between gap fraction at any particular view angle and the sunlit leaf area that is visible in that view angle differs from what would be predicted in a horizontal canopy* (*Figure 5-2* on the next page).

## Measurement
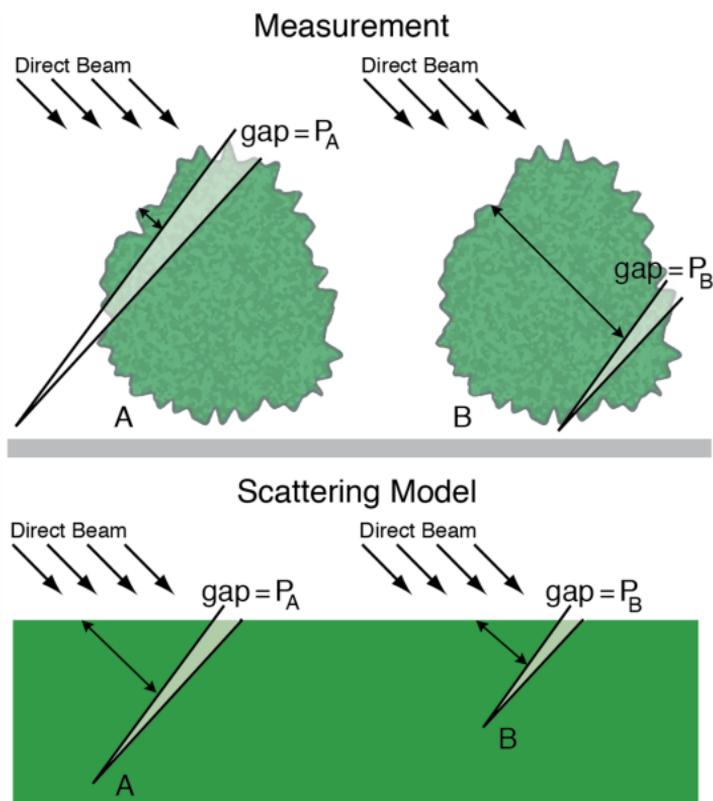


## Scattering Model



*Figure 5-2. Representation of how the scattering model can fail in an isolated canopy setting. Measurements **A** and **B** have gap fractions $P_A$ and $P_B$ for a particular ring. In the bottom part of the illustration, these are mapped to an idealized canopy in a layer with the same gap fraction at that view angle. The problem in case **A** is that the measured sunlit area (and thus scattered radiation) is much larger than the model would predict. This is seen by comparing the relative path lengths of sunlight through the canopy to get to the ring's view in the measurement vs. the scattering model (i.e. $S_A < S'_A$). In case **B**, the measured sunlit area is much smaller then the model would predict. since $S_B > S'_B$.*

Another way to look at the problem presented by case A in *Figure 5-2* above is that unlike in the model (sun above,

viewer below), the viewer and the sun are now effectively on the same side of the canopy. And the lower the sun is in the sky, the more the measurement will be dominated by sunlit leaf area, which the model cannot begin to predict, since it assumes the viewer is on the opposite side of the canopy.

*Figure 5-3* on the next page illustrates the problem and offers a clue about how to reduce the problem. If we can choose a view direction that minimizes the differences between the view path lengths through the canopy (they determine gap fraction) and the direct beam path lengths through the canopy that determine sunlit leaf area, then we might minimize the model's errors. If having the sensor look directly away from the sun, as in *Figure 5-2* on the previous page, maximizes the problem, it suggests that viewing more toward the sun (the sun can't be in the sensor's view, of course) might reduce the problem.

This suggests the following measurement guideline for canopies with significant gaps: As much as possible, keep the sun in front of you, not behind you (*Figure 5-3* on the next page).
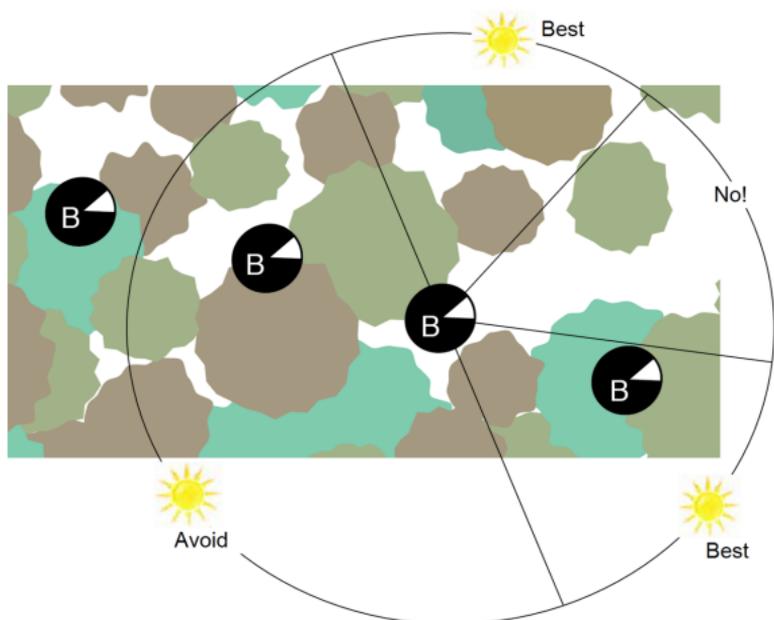
*Figure 5-3. Measurement direction with direct sun. In gapped or isolated canopies, if you are measuring with the sun out and doing scattering correction, try to keep the sun to the side or a bit in front. Avoid having the sun behind you, especially if it is lower in the sky.*

## Testing the Model

Since no canopy fits the model, it is a good idea to test your measurement protocol (and scattering correction inputs) for each situation. A simple way to do this is to pick a representative transect or plot and measure it (at identical locations) when the sun is obscured, such as at twilight, and compare those results with the scatter-corrected results. Actually, you can scatter-correct both, but the data set with the sun obscured will have an FBeam value of 0. It's best to do this sort of comparison under clear blue sky, as clouds introduce their own variability (see *Sky Variability Tests* on page 5-2).

# Multiple-Sensor Operation Revisited

Scattering corrections have some implications for multi-sensor operations, so read this section even if you think you are familiar with multi-sensor operation.

When two or more sensors are used to collect LAI data (e.g. one sensor collects above canopy **A** records, the other below canopy **B** records), two things have to happen to produce final LAI values:

1  **Combining**: The **A** records and **B** records have to be combined into one file. Normally, some of the **A** records are inserted into the **B** file based on times of the **B** records.

2  **Matching**: One of the record types (**A** or **B**) must have its values adjusted to account for calibration differences between the two wands.

While it is possible to do both combining and matching entirely on an LAI-2200C console, we highly recommend that you use the FV2200 software for both of these tasks instead. Here are the reasons:

- **K** records (i.e. **4A** sequences, **3A** sequences, etc.) should be done with a wand with factory calibration factors, not one matched to another sensor. FV2200 matching allows all wands to always use their factory calibration values. This allows any wand to be used for the **K** record precursors needed to do scattering corrections.

- Console matching is done with one snapshot reading, which is dangerous when there are clouds (see *Sky Variability Tests* on page 5-2). FV2200 matching is based on as many readings as you wish to average.

- FV2200 matching is not limited to two LAI-2200C wands, like console matching is: it can be used for any number of wands, including old (LAI-2000) instrumentation.
- Collecting the data for FV2200 matching can be done anytime, not just at the time or place of data collection. This means you can collect matching data under the best sky conditions for matching (clear blue sky), and in a place with the best view of the sky (e.g. the roof of your building).
- FV2200 matching simplifies what needs to be done in the field, reducing the chances for errors.
- Once the relevant files are on your computer, FV2200 combining and matching can be done in one simple step.

## Three Methods for FV2200 Matching

There are three variations you can use to do FV2200 matching. The method you choose will depend on the circumstances.

For this discussion, we will assume that there is a sensor (the **A** unit) that is to be used for logging **A** records in a clearing, and there is one (or more) **B** unit collecting below canopy **B** records. Note that either "unit" could be a) an autonomous wand, or b) an LAI-2000 or LAI-2200C console and wand.

The three methods listed here are named for the setting in FV2200 that you would use to do the match while importing records. The FV2200 import dialog (*Figure 5-4* on the facing page) lets you specify source files (the ones with **A** records), destination files (the ones with **B** records that need corresponding **A** records), and— when needed—

match files (files that contain some or all of the information on how the sensors compare, so adjustments can be made to imported **A** records).
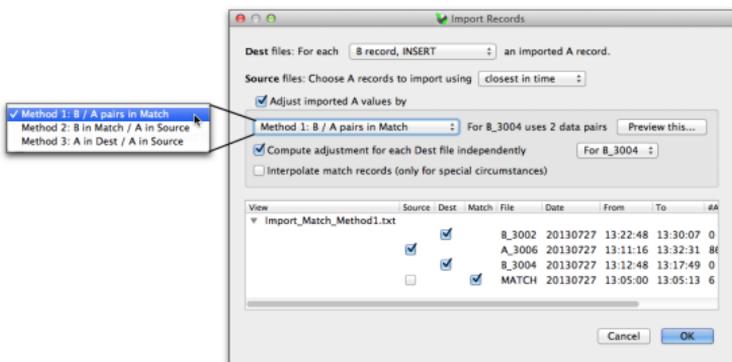


*Figure 5-4. FV2200 Import Dialog.*

## Method 1: B / A Pairs in Match

Method 1 is the recommended method for matching sensors. This method puts the match readings from both **A** and **B** units into one special file, known as a match file. This can be done before or after the measurements. If you are careful about keeping lenses cleaned, this file can be generated once and used over an extended period (weeks, months, etc.). When you have a calibration session, you might want to generate several files, one for each view cap you might use. You could name the files M45, M90, M180, for example, meaning they are for the 45, 90, and 180 degree view caps.

To make Match Method 1 file(s), follow the instructions under *Procedure 1.8 - Build a Match File for Two Sensors (Match Method 1)* on page 8-21, or *Procedure 1.9 - Build a Match File for More than Two Sensors (Match Method 1)* on page 8-22.

*Figure 5-5* on the facing page shows an example match data set for two sensors. The data reside in a file named 3213_3214_Match.txt, and contains three LAI files with match data for 3 view caps. Record types (**A** or **B**) in a match file don't matter for LAI-2200C files, since sensor serial numbers are recorded in data files and are used by FV2200 when figuring out adjustment factors when importing records.

*Procedure 3.8 - Import A and Adjust A Records - FV2200* on page 8-40 illustrates how to do match file adjustments when importing **A** records.

The main advantage of Match Method 1 is that it eliminates all matching-related field work at the time of LAI data collection. Just collect your LAI data and you're done; all the matching work has already been done. (Or will be done; your calibration session could also happen after the fact.)

The remaining two match methods involve collecting matching data at the time of regular data collection. If the sky is cloudless, then they can work as well as Method 1.
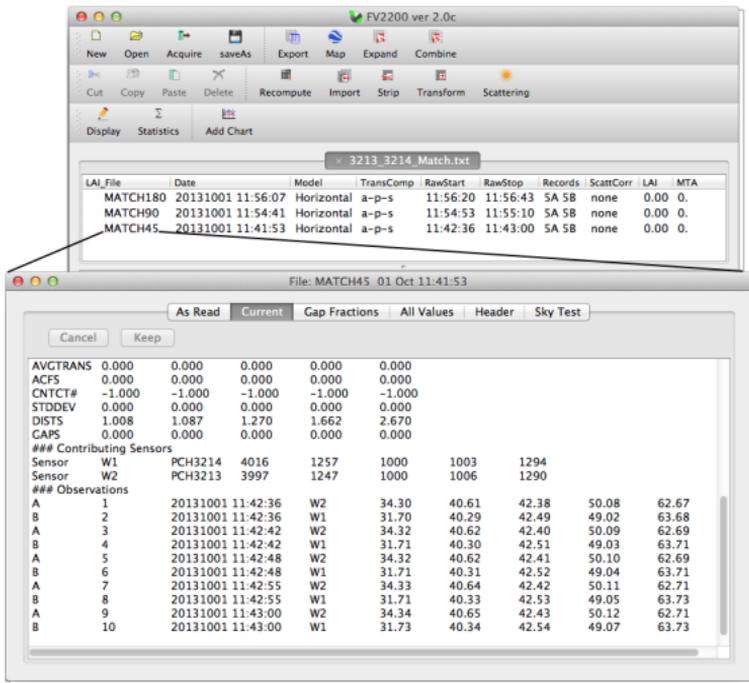
*Figure 5-5. Sample match data for two sensors, PCH3213 and PCH3214. There are three files for three view caps, and in each file several data pairs, all logged while viewing clear blue sky. Since FV2200 uses serial numbers when applying this data, it doesn't matter what record types (A or B) the sensors logged. They could be mixed (as shown), or all A, or all B. If you are doing this with LAI-2000 format files, however, then the only way to identify sensors is by record type, so the A records and B records in a match file should be made by the same sensors as did the A and B records in source and destination files. (You can convert formats, however, and avoid this constraint.)*

## Method 2: B (or A) in Match / A in Source

This method collects match data on-site, and creates a match file that contains only the below canopy sensor's match readings; the corresponding above canopy sensor's

readings are in the above canopy file. The situation in which you might use this method is illustrated below: There is a clearing in which the **A** unit will reside, and a forest or other tall canopy in which one or more **B** units will log a series of files along transects or in plots.

1   Set up the **A** sensor and start it logging in a clearing at regular intervals in the Above file.
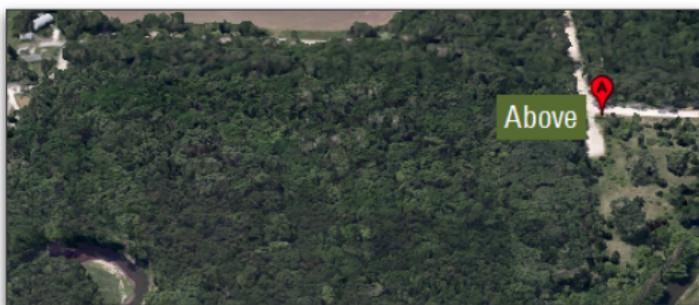


2   Before leaving the clearing, each **B** sensor makes a few matching measurements next to the **A** sensor. Log these into a file named "Match", or something to identify it as a match file.
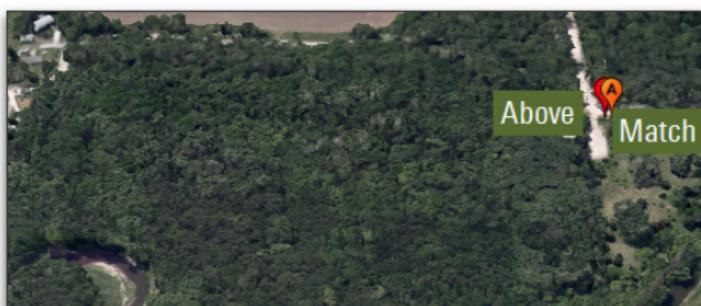
3 Each **B** unit goes off and collects multiple below can-
opy files. All have only **B** readings.
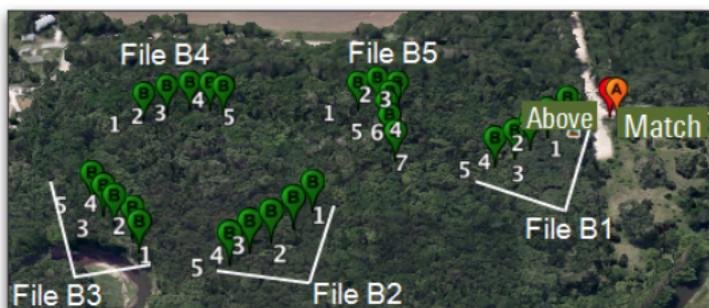


4 (Optional) Upon returning to the clearing, append a
few more readings into the Match file (or make a new
match file), before shutting down the **A** unit.

5 When importing the **A** records, use Match Method 2
to adjust the readings based on corresponding readings
between the above file and the match file.
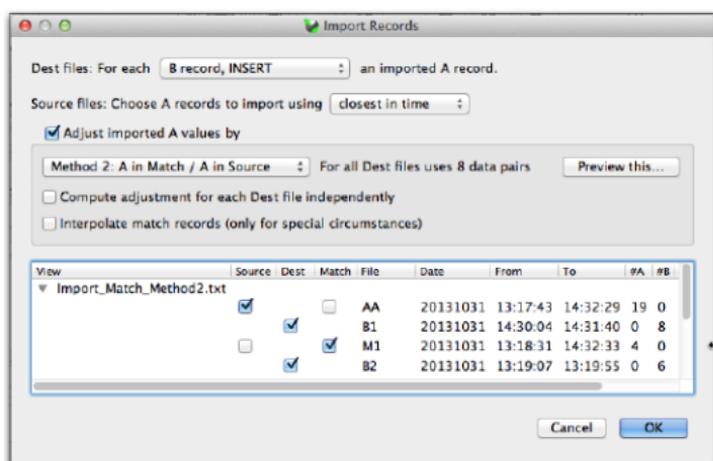


## Method 3: A in Dest / A in Source

This method collects match data on-site, but does not use
a separate match file. Instead, each **B** file contains its own
match data, in that every **B** file contains at least one **A**
record that can be used for matching. To make this work,

it must be possible for each **B** unit to get to the **A** site and take at least one **A** record for each file it creates. If that is not practical, then use Methods 1 or 2 instead.

1   Set up the **A** sensor and start it logging in a clearing at regular intervals in the Above file.



2   Begin the first **B** file with an **A** record logged alongside the Above unit. Then go do the rest of the **B** records along the transect.
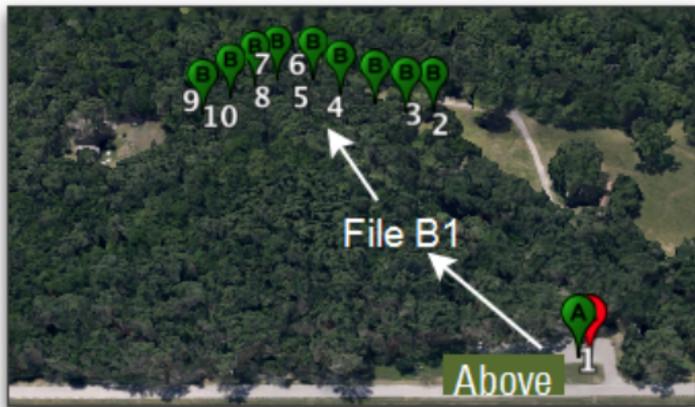


3   (optional) You can then create other below files with only **B** records if you like.

4 End the final below file with an **A** record logged beside the above unit.
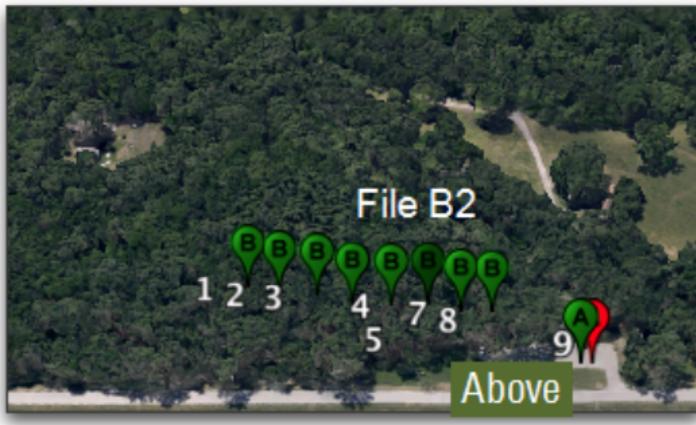


5 For the below files with an **A** record (Files B1 and B2 in this example) analyze them with Match Method 3.
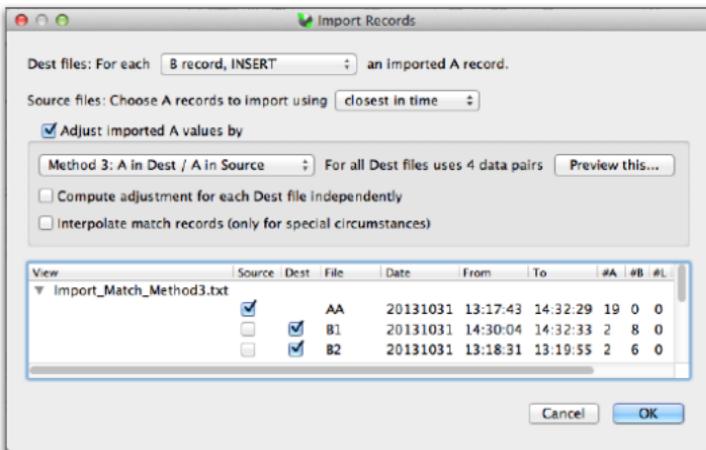


You can also combine methods 2 and 3: If you have at least one file done for method 3, you can use it (before importing **A** records) as the match file for files with only **B** records in them, using match method 2.

A potential advantage of Method 3 is that since you have an **A** record logged, you can compute an LAI estimate in

the field based on that one reading (if it is done first, or if you pick the "closest in time" option for using **A** records). That way, if disaster strikes (e.g. a bear makes off with the **A** unit), you still have some results.

The obvious disadvantage is that you need to be able to access the **A** site or a suitable clearing for each **B** file. Also, like Method 2, it forces the matching to be done at the time and place of the measurement, and that may not result in the best match unless the sky is clear.

# Protocol Suggestions for Direct Sun

This section includes some suggestions for taking measurements in direct sunlight.

## Single Sensor with Scattering Correction

- Make sure the sensor calibration is the factory default, and hasn't been modified by matching to another sensor.
- You don't need to do a **K** record for every file, unless sky conditions are very changeable. You can import **K** records from files that have them to files that need them with the FV2200 Scattering Tool. Follow *Procedure 3.10 - Importing K Records* on page 8-42.
- You can intersperse **K** record precursors and single **A** records. For example, a series of records such as AAAAB...AB...AB...AAAA would turn into KAB...AB...AB...KA.
- You might opt to keep the **K**'s in a separate file. Whenever you need to do another **K** reading, re-open that file (named **K**, for example), and append another **4A** sequence (or **3A** sequence, but be consistent) into it.

# Multiple Sensors With Scattering Correction

Scattering correction requires collecting **K** record precursors in the field. When using multiple sensors with scattering correction, make sure ALL the sensors have their factory default calibrations (*Procedure 1.5 - Resetting Wand to Factory Calibration* on page 8-20), and then follow these protocols:

## Matching Method

Use *Method 1: B / A Pairs in Match* on page 5-23 for your inter-sensor calibration scheme. Get the data for this once on a clear blue sky day, and then don't worry about it after that.

## With One Operator

If you are operating in separate sensor mode (above and below sensors), and there is only one person to do the work, then plan on doing **K** readings with the below sensor (see *K Records* on page 5-7), and putting them in a separate file. Later you can import **A** records from the above file using *Procedure 3.8 - Import A and Adjust A Records - FV2200* on page 8-40, and import **K**s from the **K** file using *Procedure 3.10 - Importing K Records* on page 8-42.

## With Multiple Operators

If there are enough people to dedicate someone to doing the **K** records, then ideally they also have a separate instrument (or just a wand) to dedicate to it as well. However, if the **A** unit needs to do double duty as the "**K** unit", one option is to do nothing but **K** records (recall that a **K** record includes a normal **A** record): Go through a **4A** or **3A** sequence as frequently as you think is needed, or as

frequently as your sanity can stand. In clear blue sky, one **K** record every 10 to 15 minutes would be plenty. However, if you think you need a higher frequency of reference **A** records than **K** records, then follow *Procedure 2.12 - Getting K Records on an Above Sensor* on page 8-32.

## Measuring Non-Uniform Canopies with Direct Sun

In a canopy with large gaps or wide rows or when measuring individual crowns, scattering corrections introduce additional constraints. *Model Limitations for Scattering Corrections* on page 5-17.

# Some Esoteric Details

This section is for those who want to know more about the nuances of indirect LAI measurements.

## Wand Calibrations

It is helpful to understand what is meant by an LAI wand calibration. Each wand receives two types of calibration at the factory. One is an angular calibration, which ensures that each ring has the proper angular response to light. This calibration is actually done a few times, with physical adjustments to the optics performed in response to each, until the response meets our criteria. This calibration should be stable for the life of the wand, and it would likely take physical damage to the wand to change it.

The other calibration that is done involves placing the wand into an integrating sphere (an isotropic environment), and results in the five ring multipliers that are stored in the wand's software. When these multipliers are applied, the wand can be used to make valid distribution

measurements of brightness, in which the output of each ring can be compared to the others. That is, under a perfectly uniform sky, all rings would read the same value. For basic LAI measurements, this calibration is not important, since each ring is ratioed with itself, so its absolute value doesn't matter. *When doing scattering corrections, measurements of sky brightness distribution are required, and thus, this calibration comes into play.*

What the ring factors do not do is ensure that two sensors will read the same under the same conditions. The relative distributions (one ring to the next) will be right, but the absolute values may well be different. This is why sensor matching is important.

## General Considerations When Matching Sensors

The following items will affect how two sensors compare:

### Size and Orientation of View Cap

The size of the view cap has a primary effect on what the wand reads. Less obvious, however, is the fact that the detector rings in the sensor typically have some small azimuthal variation in sensitivity, so how the view cap is oriented also has an effect. Therefore, when matching sensors, use the view cap that will be used for the measurements, and in the orientation (relative to the wand handle) that will be used for measurements.

### Dirt/Dust on the Lens

If you keep the lenses clean while collecting data, then match information that is also obtained under clean lens conditions will still be valid. Otherwise, you can get match data before and after a series of measurements to verify it

hasn't changed, or to interpolate match data through the time period. (This can't be done with console matching, but can be done with FV2200 matching)

## Sky Conditions

Theoretically, two perfectly leveled sensors with the same view cap aimed in exactly the same direction will see the same sky. As a practical matter, they may not be perfectly leveled nor aimed in exactly the same direction, nor have the exact same angular response. Therefore, the best sky to use when matching sensors is one that is as uniform as possible, which means blue sky with no clouds. The worst case is blue sky with some scattered clouds. If the portion of sky being viewed has a bright cloud not fully contained within a ring's view, then slight variations in view (direction or level) could make a significant difference, because the sensors will see differing amounts of that sunlit cloud, and that cloud is many times brighter than the blue sky around it. Matching sensors that are viewing clouds will build in some biases to your measurements, so avoid it.

## Detector Age

As a wand detector ages, its absolute calibration is subject to slight drift. If you match sensors even once a season, this should not be an issue.

## Temperature

Temperature represents a potential cause of drift in how sensors compare. Again, matching sensors once a season will likely take care of this as well.

## Some Scattering Correction Details

Scattering of light by foliage is greatest when the sun is behind the viewer. It is at a minimum when the sun is in front of the viewer. The simple reason for this is that the view with the sun at your back is dominated by foliage reflectance (say 0.05 for leaves, stems, and branches), while the view toward the sun is dominated by foliage transmittance (say 0.01 for leaves, and 0 for stems and branches).

You cannot make LAI measurements with the sensor oriented toward the sun, of course, but if your measurements are near the sun (keeping it blocked by the view cap), then the scattering error in the uncorrected readings could be much less than if the sensor is looking directly away from the sun's direction.

The scattering correction implemented in FV2200 takes orientation into consideration. The measurement direction and view cap information is part of the "hand entered" information specified when generating **K** records. Solar position (azimuth and zenith) is computed from UTC and your latitude and longitude. If the console is equipped with GPS, and **G** records were included in the file, then latitude, longitude, and UTC are known. Otherwise, you specify latitude and longitude of the measurement site, and its time zone (or more specifically, the hour shift between the console clock and UTC).

## Rain, Fog, and Dew

Accurate measurements can be made in wet canopies if care is taken to keep water droplets off the lens. Working in rain is also possible, but measurements will have greater uncertainty. Droplets on the lens present a concern

because they block light. A few small droplets can reduce the light seen by some rings by 10% or more. Therefore, it is important to keep the lens free of droplets by wiping it with the cloth provided in the lens cleaning kit.

Section 6.

# Canopy Types

This section includes suggested protocols and considerations for measuring LAI in various canopy types.

## Measuring Plant Canopies

### Short Homogeneous Canopies

Short homogeneous canopies are the simplest to measure. Under stable sky conditions with a 270° view cap, one **A** reading for four or more **B** readings should be sufficient. To reduce uncertainty of measurements, you can take more **B** readings.

### Small Plots

When measuring small plots, it is important to be sure that objects outside the plot do not influence measurements. From beneath a canopy, the optical sensor's potential view is conical, with a radius that is about 3 times the canopy height. The optical sensor (wand) has a view of 74° (tan (74)=3.48). However, 3 serves as a working number because of the reduced probability that foliage will be significant at the edge of the sensor's field of view.

The sensor view is about 3 times the height of the canopy.
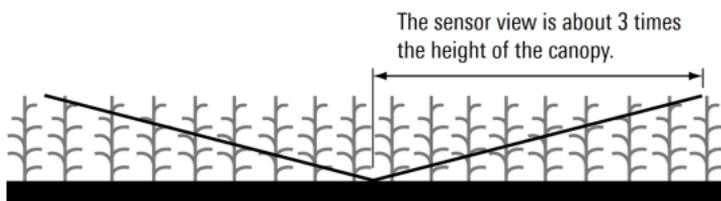
In a canopy that is 1 m high, the optical sensor should be at least 3 m from the edge in any direction that it can "see". In a plot so small that the sensor will "see" outside the plot area if measured from the middle, one could use a 90° view cap and make readings from the corners looking into the plot. Alternatively, a 180° view cap could be used if the measurements were taken near the center of the plot.
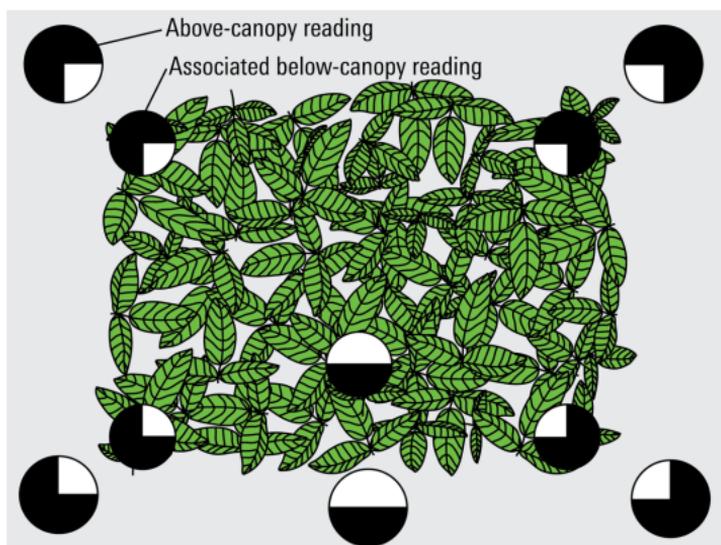


Above-canopy reading
Associated below-canopy reading

**Note:** If the sun is out, you may need a K record (e.g. a 4A sequence) for each view cap and direction you use. See *Dealing with Scattering* on page 5-6.

In dense canopies, the minimum plot size may be reduced if foliage blocks enough of the optical sensor's view. This is

easily tested by getting down on the ground and looking up at about a 30° elevation angle. If you are unable to see the edge of the plot from this vantage point, then the plot is large enough regardless of its actual dimensions.

An additional method for measuring small plots is to do the LAI computations without the outer ring. Without the outer ring, the minimum plot size decreases to 1.6 times the canopy height. The outer ring can be omitted with the Mask function prior to data collection (*Procedure 2.10 - Excluding Rings from Analysis - Console* on page 8-31), after data collection but while the file is still on the control unit (*Procedure 3.7 - Recomputing a Data File - Console* on page 8-40), or after the file has been moved to a computer (*Procedure 3.5 - Excluding Rings from Analysis - FV2200* on page 8-39).

## Row Crops

Row crops, with architecture ranging from very wide row spacing to closed canopy, can be measured accurately using the technique described here. In general, readings should be made along diagonal transects between the rows, as shown in *Figure 6-1* on the next page. Choose locations along transects so that readings are made at even intervals across the row. For example, if making 4 **B** readings per transect, make the first in the row, the second ¼ of the way between the rows, the third at mid-row, and the fourth ¾ of the way across. Measuring with a diagonal transect, rather than a perpendicular transect, improves spatial averaging.
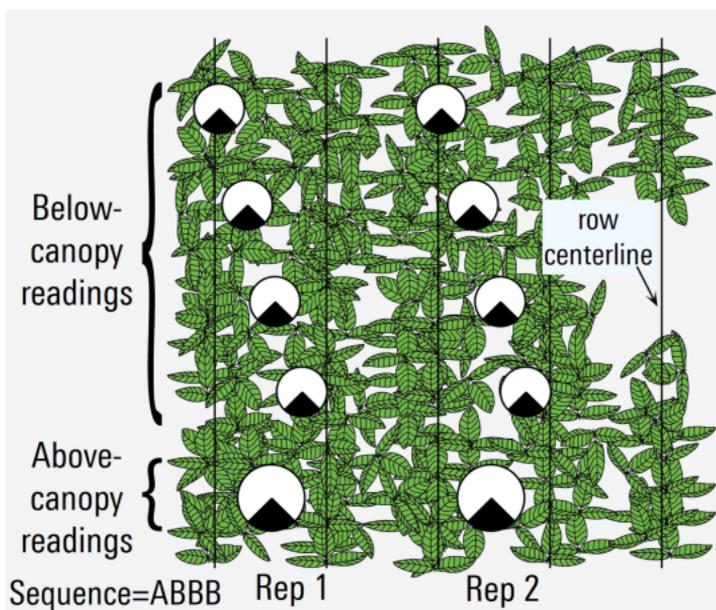
*Figure 6-1. A row crop with a homogeneous canopy (e.g., no gaps between rows) can be measured with a wide view cap.*

Be sure to make all **B** readings at the same height; if furrows and mounds cannot be smoothed, position a board along the transect and rest the sensor on it when taking readings.

If the rows have significant gaps where vegetation is lacking, perform the Canopy Gap Test (see *The Gap Test* on page 6-11) to see if these gaps merit special attention. If the Gap Test error is less than 10% (homogeneous canopy), then use as wide a field of view as possible, depending on sky conditions. If the Gap Test error is greater than 10% (heterogeneous canopy), then use the 45° view cap and double (at least) the number of diagonal transects. Measure the transects in pairs: one transect with the sensor looking along the row, and the other with the sensor looking across the row, as shown in *Figure 6-1* above.
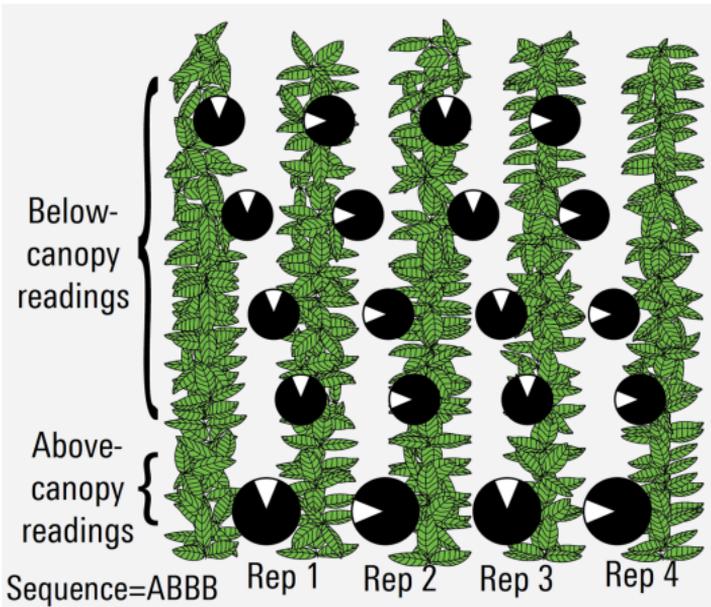
*Figure 6-2. A row crop with a heterogeneous canopy (e.g., gaps between rows) may require a narrow view cap and more repetitions.*

> **Note:** if the sun is out, you may need a K record (e.g. a 4A sequence) for each view cap and direction you use. See *Dealing with Scattering* on page 5-6 and *Measuring Non-Uniform Canopies with Direct Sun* on page 5-32 for details.

## Tall Canopies and Forests

The primary challenge to measuring very tall canopies is getting the **A** readings.

**Single Sensor:** A single sensor can be used effectively in forests when there is clear blue sky. In such conditions, you will want to do a **3A** or **4A** sequence in a suitable clearing or on a tower, then make the **B** readings under the forest canopy at your plots or along your transects.

You can then return to the clearing and do final **4A** sequence. *Example 4 - Forest Sites with One Sensor (and Control Unit)* on page 8-5 illustrates how to do this. And in fact, you can also do the same with simply a sensor by itself, following *Example 5 - Forest Sites with One Sensor (without Control Unit)* on page 8-6. This means if you happen to have a control unit and two sensors (and two people), you can use both and get your measurements done twice as fast, since you can split up the below canopy work. The above canopy data can come from just one unit, or each can get its own, letting you bypass any sensor matching.

**Two Sensors:** Refer to the discussion in *Multiple Sensors With Scattering Correction* on page 5-31.

> **Note:** If the sun is out and you are measuring a forest canopy with large gaps, choose a view direction to the side or slightly in front of the sensor's view (taking care of course to not take a reading with the sun actually in the field of view). see *Measuring Non-Uniform Canopies with Direct Sun* on page 5-32 for an illustration and discussion.

## Making **A** Readings in Forest Canopy

There are several considerations for getting **A** readings in a forest canopy.

**A** readings should be made as close as possible to the site to be measured. The maximum acceptable distance depends entirely on sky conditions. With blue sky (ignoring the sun for a moment), the two sensors could be kilometers apart and still see the same sky brightness distribution. With an overcast sky, however, the lower the

clouds, the greater the probability that two sensors some distance apart will see different skies, especially with the central rings (near the zenith). A low, heterogeneous overcast sky with quickly moving clouds is the worst case, when even 100 meters could be too great a distance between the sensors.

If making **A** readings in a clearing, be sure that the clearing is big enough. With a 180° or larger view cap, the sensor should be in the middle of a clearing with a diameter at least 7 times the height of the trees above the sensor ($2 \times \tan 74° \approx 7$).



Clearing should be 7x wider than the height of surrounding trees
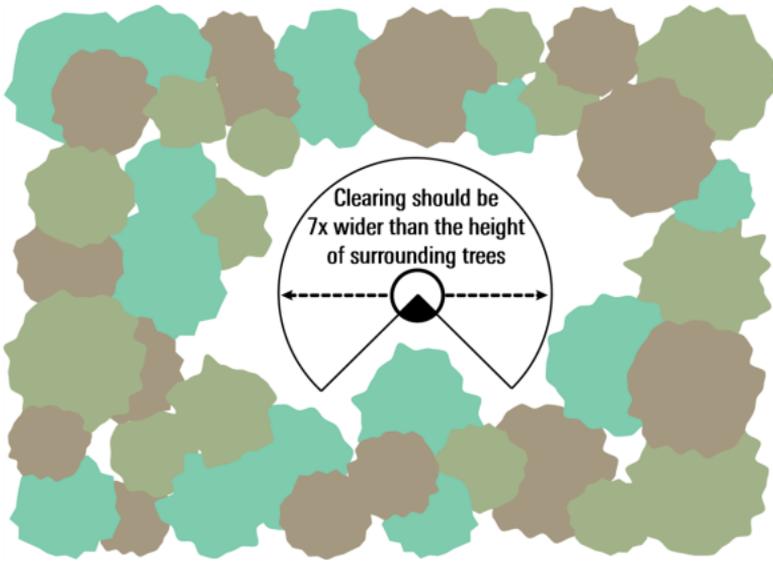
With the 90° or 45° view cap, however, a clearing half that size (diameter only 3.5 times the tree height) can be used, since the sensor can now be positioned on the edge of the clearing (looking in).
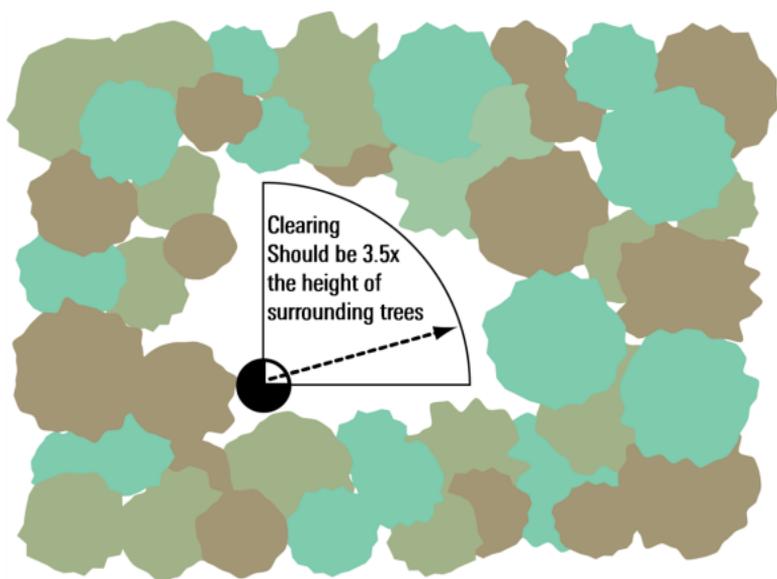
This is a common reason for using a narrow view cap in a forest. Neglecting the outer ring may be necessary if an adequately large clearing is not available. In that case, the clearing should be 1.5 times the canopy height if the 45° or 90° view cap is used. Refer to the *Small Plots* on page 6-1.

When making **A** readings for forest canopies, clearings can be made "bigger" by raising the sensor. Use the bottom level and hold the sensor over your head. The sensor can be elevated by standing on a stump, the cab of a vehicle, or by raising the sensor with a long pole, etc.

*Don't forget:* The **A** readings should be made with the same view cap (covering the same part of the optical sensor), sensor inclination (if the ground slopes), and direction of view that the **B** readings will have.

## Making K Records in a Forest Canopy

**K** records (or more precisely the precursors to them) have similar considerations as **A** records, plus a few. (If you aren't sure what **K** records are, see *K Records* on page 5-7). If the **A** unit is going to do double duty as the **K** unit, as described in *Procedure 2.12 - Getting K Records on an Above Sensor* on page 8-32, then the first and third readings of a **4A** sequence need some consideration:

The first **A** reading (sunlit diffuser) needs to be in the sun. If the site in the reference clearing where the **A** unit is located happens to be shaded, then that is a problem.

The third **A** reading is the wide sky reading. Unless your **A** site happens to be on top of a tower above the canopy, it is not likely to have an unobstructed view of the sky in all directions. You will have to choose a view cap for the third reading that is as large as will work. The worst case would be if that view is no larger than the normal **A** view, in which case you can just skip that reading, as described in *Embedded Bs* on page 5-16.

## Canopies with Large Gaps

LAI is proportional to the logarithm of the gap fraction, so the proper way to average gap fractions is to average their logarithms (Lang and Xiang, 1986). This in fact is how the LAI-2200C averages multiple **B** readings in a file. However, each **B** reading is a linear average of the light from whatever azimuthal view is visible to the sensor, as determined by the view cap. Problems can arise if the sensor sees dense foliage in one direction and little or no foliage in another direction at the time a **B** reading is recorded, because the gap in the canopy will be "over weighted", and LAI will be underestimated. A way to

avoid this problem is to use a view cap to restrict the sensor's field of view, so that dense and sparse regions of the canopy are included in separate **B** readings. The figure below illustrates how a 45° view cap helps isolate a gap near a transect.

If on the other hand, you wish to measure $L_e$ (effective LAI), then you do not want the instrument to log average. In this case, use a wide field of view (270°), and multiply your resulting LAI by ACF, the apparent clumping factor.
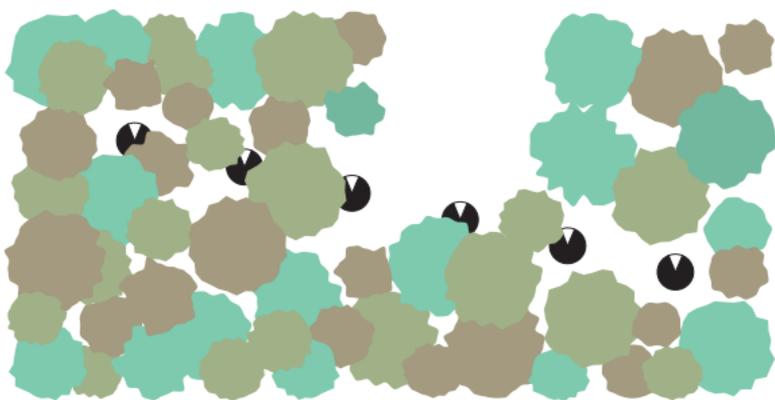


The Canopy Gap Test (see *The Gap Test* on the facing page) can be used to estimate the error of using a wide field of view in a heterogeneous canopy, when large gaps and foliage are included in the same **B** reading.

**Note:** When the sun is out and you are measuring canopies with large gaps, choose a view direction to the side of or slightly in front of the sensor's view (taking care of course to not take a reading with the sun actually in the field of view). See *Protocol Suggestions for Direct Sun* on page 5-30 for an illustration and discussion.

## Conifers

It is well known that conifer needles are not arranged in space randomly, and radiation penetration models that make that assumption will underestimate the transmittance of a conifer canopy (for example, Norman and Jarvis, 1975; Oker-Blum and Kellomaki, 1983). Since the LAI-2200C assumes random foliage positioning, it will underestimate LAI in conifer canopies.

Numerous researchers have developed sampling techniques for acquiring accurate LAI measurements in evergreen forests, including Chen (1996), Stenberg (1996), Chen et al. (1997), and Kucharik et al. (1998). A detailed sampling protocol for conifer stands is described in Law et al. (2008).

## The Gap Test

The canopy gap test is a quantitative way to estimate the error of using a wide field of view in a heterogeneous canopy. That is, a canopy with dense foliage in some areas and sparse (or no) foliage in others. The problem is that LAI is proportional to the logarithm of the gap fraction, but for any one reading, the sensor will linearly average gap fraction over its view. If the sensor's view includes both dense and sparse foliage areas, the gap fraction for that **B** record will thus be incorrectly averaged. If the dense and sparse regions are measured in separate **B** records, they will be correctly averaged.

Follow *Procedure 1.11 - The Canopy Gap Test* on page 8-23 to estimate the error from using a view cap that is too large.

# Measuring Isolated Plants

This section describes the measurement of isolated plants, for which a different protocol must be used. We begin with a discussion of LAI and foliage density.

> **Note:** It is best to avoid direct sun when making measurements of isolated canopies. If you do need to make measurements of isolated canopies in direct sun, follow the recommendations in *Isolated Canopies and Scattering Corrections* on page 6-24.

## LAI or Foliage Density?

LAI is one-sided leaf (or foliage) area per unit ground area. In a large, homogeneous plant community, LAI is a reasonable way to express the amount of vegetation. An isolated plant presents difficulties, however, because the amount of foliage over a given area of ground depends on ground position. For example, consider a single tree:

The amount of foliage above a unit of ground area at the tree's center…
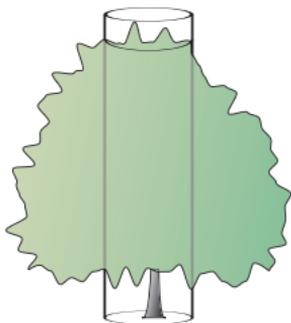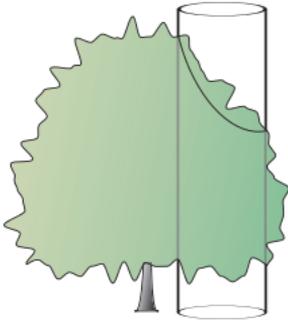
…is probably different than the amount of foliage near the tree's edge.

Also, the ground area affects the LAI measurements. For example, we might wish to express LAI based on the tree's drip line area, or based on the area associated with the tree as a member of a community, as illustrated in the over-head view below.
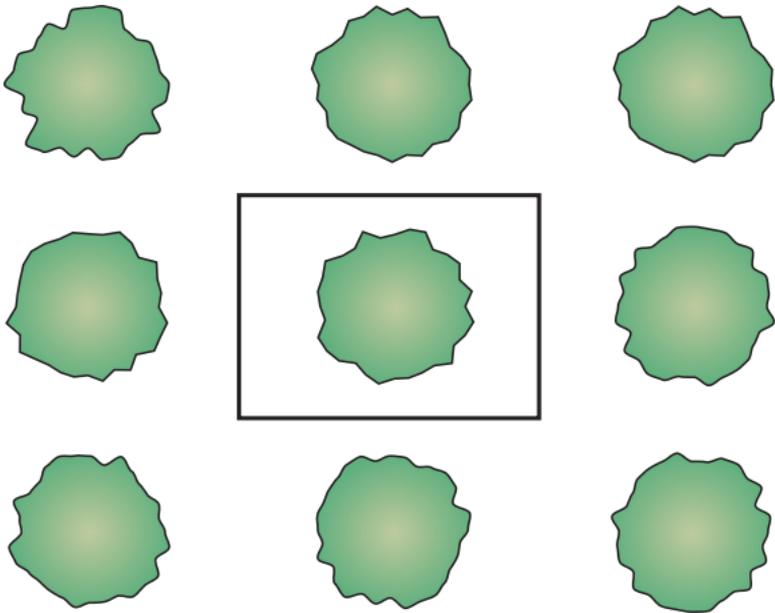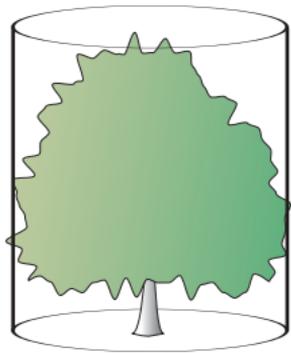
Thus, LAI for an isolated plant is ambiguous unless the size and position of the ground area is also given.

A more useful measure of foliage amount for individual plants, or clumps of plants, is that of foliage area density (or simply foliage density), which is foliage area divided by canopy volume. Foliage density has units of $m^2$ foliage area per $m^3$ canopy volume, which reduces to units of inverse length, typically $m^{-1}$. If a tree has 2 $m^2$ of foliage in a 5 $m^3$ crown, its foliage density is 0.4 $m^2/m^3$, or 0.4 $m^{-1}$.

## The DISTS Vector

*Theory* on page 10-1 describes the theory of the LAI-2200C, showing that the only theoretical difference between measuring LAI and measuring foliage density involves something called the DISTS (Distances) Vector.

The DISTS Vector is a group of 5 numbers in the control unit that are used in the computations. These numbers indicate the distances sky radiation must travel through the canopy to reach each of the 5 detector rings of the sensor. They can be viewed on the console by going to **MENU > Log Setup > Distances**. The default values in this vector are $1/\cos\theta$, where angle is the view associated with each of the five rings (7°, 23°, 38°, 53°, and 68°). When making LAI measurements, there is no need to adjust these values since $1/\cos\theta$ is sufficient regardless of canopy height.

Foliage density measurements, however, require that the DISTS vector indicate the actual mean path lengths that each ring sees through the canopy. When results are computed, the LAI value is now foliage density. The units of foliage density depend on the units used for the DISTS

values. If distances are entered in m, then the foliage density is in m$^{-1}$.

To set the DISTS vector for new data, go to **MENU > Log Setup > Distances**. To change the DISTS vector for an existing data file, go to **MENU > Data > Console Data**. Select a data file, then **Edit > Edit Dists**.

## A Simple Example

Consider a perfectly hemispherical shrub with a radius of 0.7 m. A hemisphere is the simplest because the path lengths for each ring view are identical.
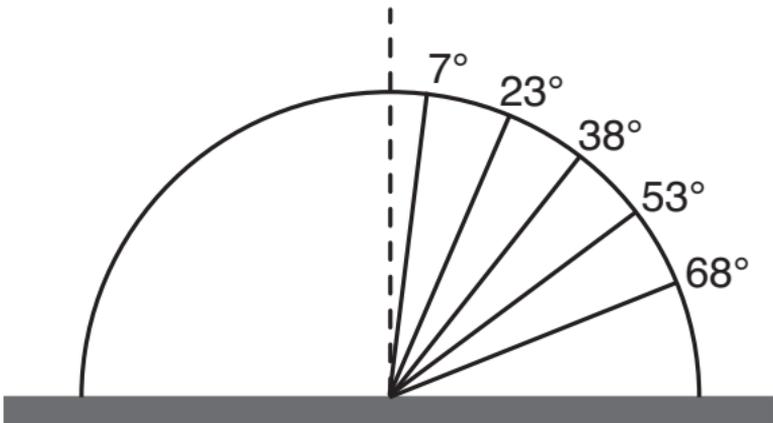


To measure the foliage density of this shrub, access the Distance vectors (**MENU > Log Setup > Distances**) and set each of the five values to 0.7. The measurement is similar to that for LAI, except that a spatial average under the shrub is now not wanted; we will take only one **B** reading, directly under the center of the plant. This example is illustrated in *Example 6 - A Simple Isolated Canopy* on page 8-8.

## Isolated Trees

**Note:** It is best to avoid direct sun when making measurements of isolated canopies. If you do need to make measurements of isolated trees in direct sun, follow the recommendations in *Isolated Canopies and Scattering Corrections* on page 6-24.

Trees are best measured using the 180° or smaller view cap, and placing the sensor next to the trunk below the crown for **B** readings. The view cap prevents the sensor from seeing the trunk of the tree. Usually, you will put the sensor above or below the largest branches in the crown because it is important to avoid having these branches dominate the sensor's view. Place the sensor just above the low branches (Method 1) or place it well beneath them out of the canopy (Method 2). Both techniques are illustrated here:
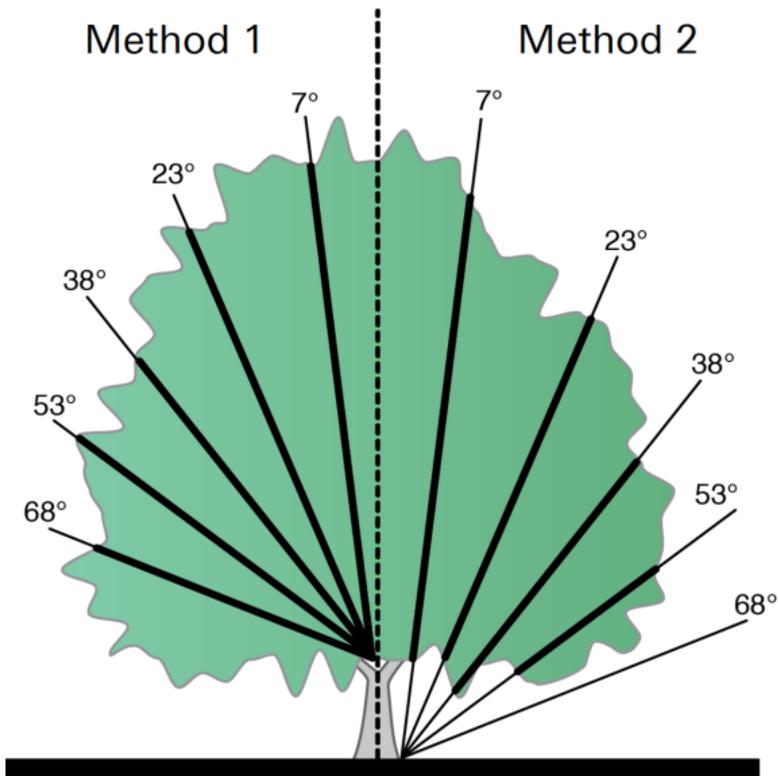
The thick segments of the diagonal lines in this figure indicate the distances each ring sees through the canopy. Note that sometimes a ring will see no foliage, as with the 68° ring in Method 2 above. A ring that sees no foliage should be masked. A 90° or 45° view cap can be used to further reduce the size of the canopy that is sampled. The view cap and view directions should be chosen to avoid including neighboring trees in the measurement.

If a tree is symmetric and well isolated, several **B** readings can be taken in different directions. The figure below illustrates measuring a tree with 4 **B** readings 90° apart, but a better average could be obtained with 12 **B** readings 30° apart, for example.

**Note:** all associated above and below readings must be viewing the same portion of the sky.
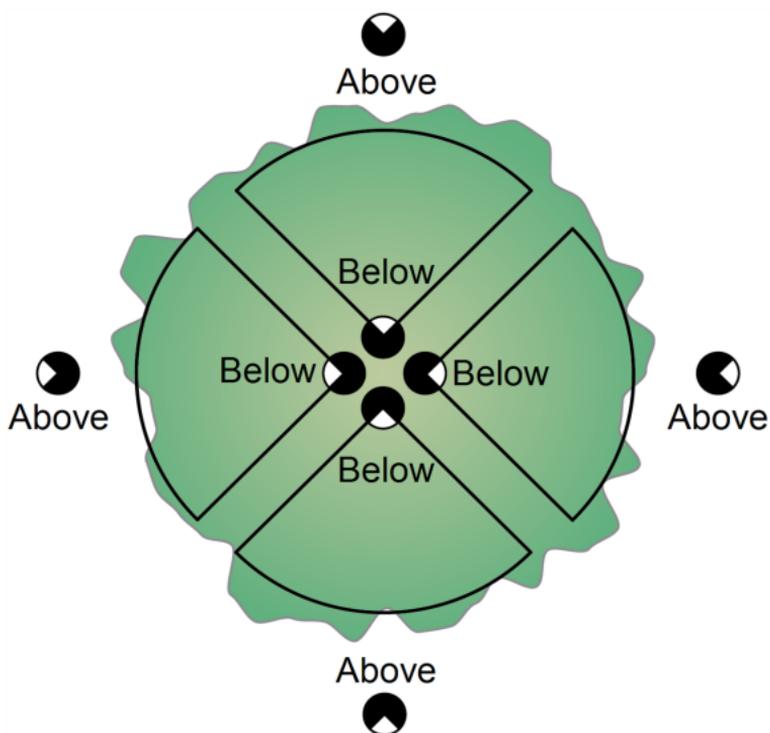
If a tree is asymmetric, then the path lengths through the tree (and thus the distance vector) will depend on azimuthal direction. Since only one distance vector is associated with a file, asymmetric trees should be measured using several files. Average foliage density is then computed by averaging the foliage densities from each of the files.
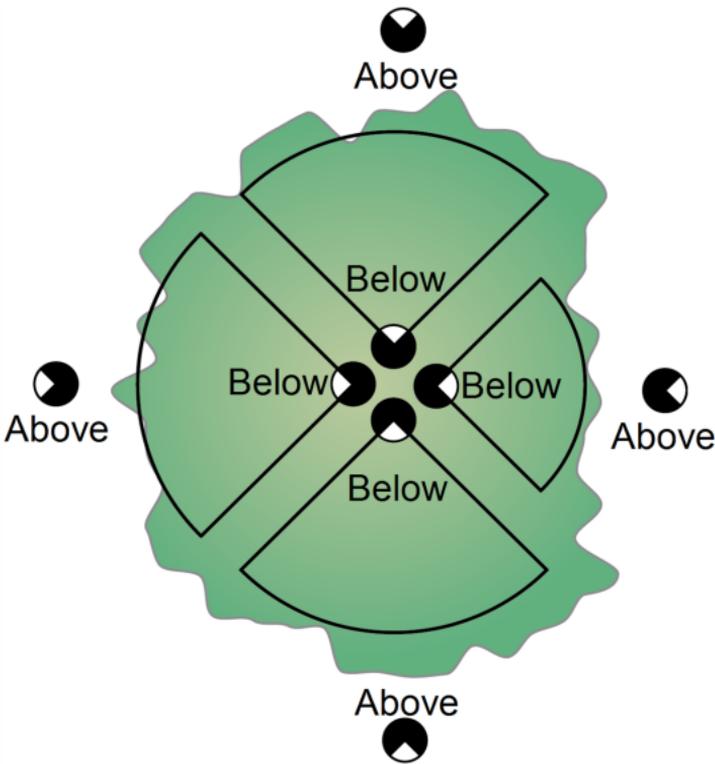
A simple method for computing path lengths and canopy volumes is provided in the FV2200 software. Use a coordinate system centered below the tree, and determine the coordinates of a sufficient number of points to describe the shape of the canopy. Alternatively, a photograph of the tree that includes a meter stick for scale can be used to obtain the tree profile.

An example of the measurements needed to describe a tree crown are shown below:



| X | Z |
|---|---|
| 1: (0.0, 0.6) |
| 2: (0.8, 0.6) |
| 3: (1.4, 0.8) |
| 4: (1.6, 1.5) |
| 5: (1.3, 2.3) |
| 6: (0.8, 2.8) |
| 7: (0.0, 3.3) |
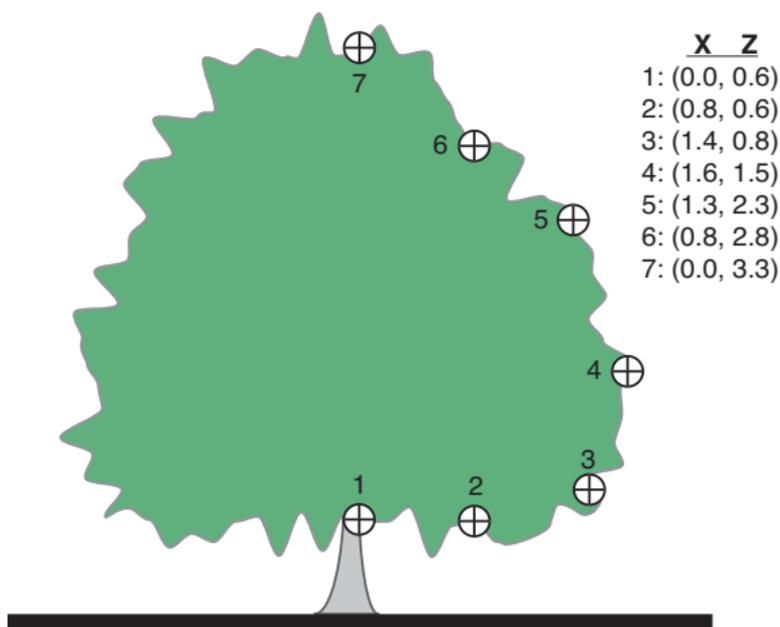
The FV2200 software can use these data to determine path lengths, neglect rings if necessary, and compute canopy volume, foliage density, or dripline LAI.

Refer to the detailed example: *Example 7 - Isolated Tree* on page 8-9.

## Isolated Rows and Hedges

The measurement of individual rows (e.g. hedges, grape vines) is possible with the LAI-2200C. Again, the data should be treated as foliage density. Here we describe two methods for measuring isolated rows or hedges.

Note: It is best to avoid direct sun when making measurements of isolated canopies. If you do need to make measurements of isolated rows or hedges in direct sun, follow the recommendations in *Isolated Canopies and Scattering Corrections* on page 6-24.

### Method 1

The measurement of isolated rows, such as a hedge or the rows in a vineyard, is similar to measuring isolated trees. With this method, the above and below measurements are taken along the length of the row.



For the below-canopy readings, place the sensor near the row center and orient the view cap so that the sensor looks away from the center. Keep it close to the lowest vegetation, but far enough away from any leaves to ensure that individual leaves do not block the view (see *Measuring Isolated Plants* on page 6-12).
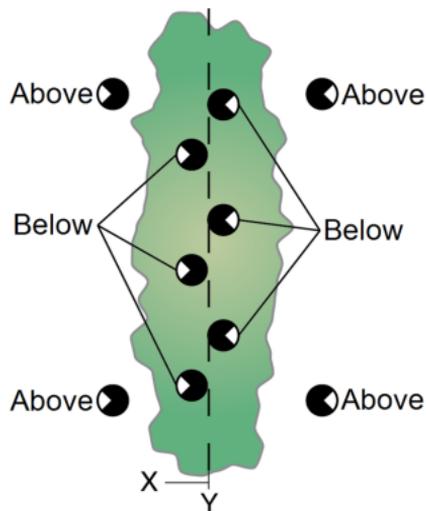
Next, characterize the canopy shape by measuring a number of X, Z coordinates. The number of coordinates required will vary, depending on the complexity of the canopy shape. If the canopy is asymmetrical, characterize each side with X, Z coordinates. Measure or estimate the row ratio for the hedge (the length Y over width X). These values are used by FV2200 software to compute the foliage density or dripline LAI.



| X | Z |
|---|---|
| 1: (0.0, | 0.5) |
| 2: (0.0, | 1.97) |
| 3: (0.31, | 1.89) |
| 4: (0.51, | 1.77) |
| 5: (0.67, | 1.55) |
| 6: (0.63, | 1.29) |
| 7: (0.54, | 1.01) |
| 8: (0.25, | 0.64) |
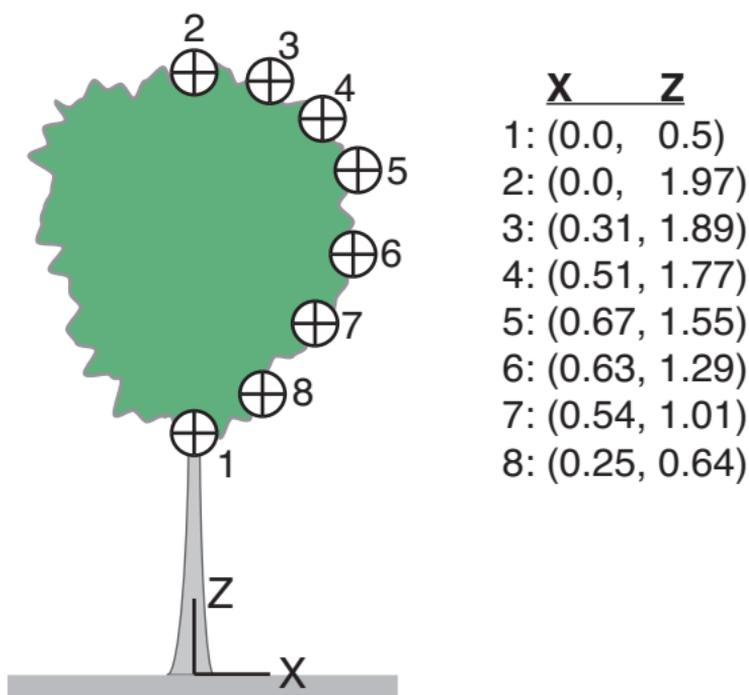
For asymmetrical canopies, LAI needs to be computed for each side of the canopy. LAI for the hedge is the average of LAI for both sides. A complete example, including sample data is presented in *Example 7 - Isolated Tree* on page 8-9.

## Method 2

A simple way to measure LAI in a hedge is to take an **A** reading viewing the sky. Take a number of **B** readings on one side of the row or the other, making sure that the sensor "sees" through the hedge, as shown below. It is useful for both symmetrical and asymmetrical canopies.

In addition to the above and below-canopy readings, measure X, Z coordinates to characterize the shape of the entire canopy, measure the distance between the sensor and the hedge center-line, (the X offset in meters), and the distance between the sensor and the bottom of the canopy, (the Z offset in meters). Measure or estimate the row ratio for the hedge (the length Y over width X). This information will be used in the FV2200 software to compute distances and LAI for the shrub. In the figure below, the sensor was held at the base of the canopy, resulting in a Z offset of 0.

Make B readings with the sensor at the base of the vegitation or below the canopy. Measure the X and Z offsets from coordinate #1. In this case, they are -0.20, 0.5.

| X | Z |
|---|---|
| 1: (0.0, 0.5) |
| 2: (-0.12, 0.75) |
| 3: (-0.18, 1.09) |
| 4: (-0.23, 1.44) |
| 5: (-0.17, 1.77) |
| 6: (0.0, 1.97) |
| 7: (0.3, 1.89) |
| 8: (0.51, 1.76) |
| 9: (0.66, 1.54) |
| 10: (0.63, 1.28) |
| 11: (0.53, 1.01) |
| 12: (0.24, 0.64) |
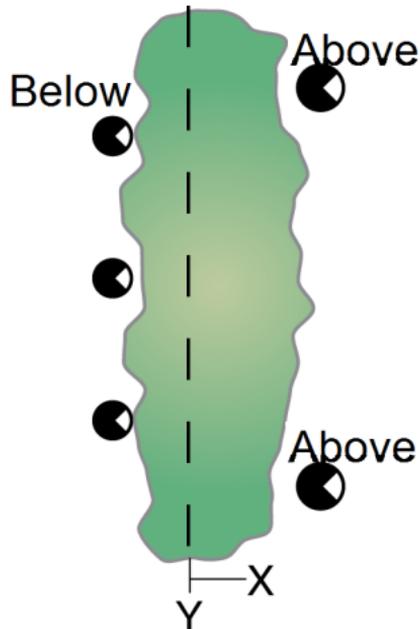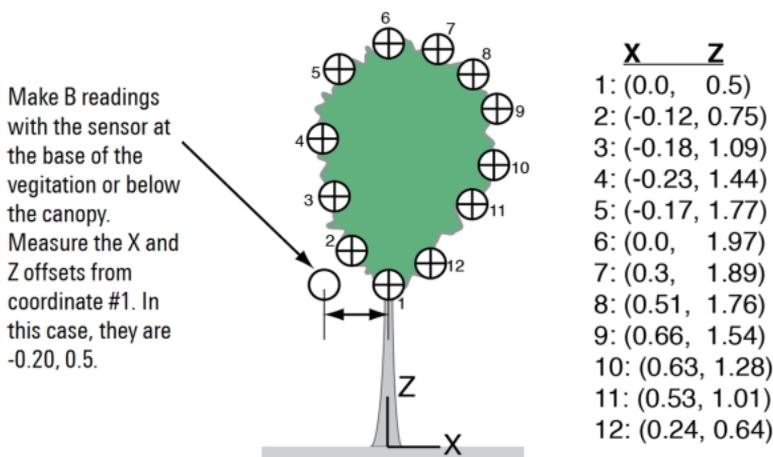
This example is illustrated in *Example 6 - A Simple Isolated Canopy* on page 8-8.

## Isolated Canopies and Scattering Corrections

The model used to do the scattering corrections in FV2200 ver. 2.0 is one-dimensional, while the geometry for an isolated canopy is clearly two or three-dimensional. That discrepancy is not a major issue for determining scattering from diffuse radiation. However, when Fbeam > 0 (i.e. when the sun is out), it can be a serious issue, since the actual path length for sunlight to reach the foliage along the path of a ring's view through the canopy is potentially much different in reality versus the model (see *Figure 5-2* on page 5-18).

Therefore, if it is possible to avoid direct sun when measuring isolated canopies (single tree, single row, etc.), then that is the best approach. If you do need to make measurements in direct sun, then the following steps should be taken to minimize the error in the scattering adjustment:

- Measure with the sun as high in the sky as possible.
- Work with the sun to the side or slightly in front of the sensor's view, while keeping the sun OUT of the sensor's field of view (see *Figure 5-3* on page 5-20)
- If you are measuring a canopy from the outside looking through (across a row, for example), have the sensor looking toward the shaded side of the canopy, not the sunlit side.

Section 7.

# Data Analysis with FV2200

FV2200 allows easy manipulation of LAI-2200C and LAI-2000 data files (hereafter referred to as LAI files). These files can be read from disk, or imported from either console type (LAI-2200C or LAI-2000). LAI files can be manipulated in any way that they can on the control unit (console), and in many other ways besides. FV2200 also supports mapping for files containing GPS records.

## Getting FV2200

FV2200 is available for Windows®, Mac OSX®, and Linux. Download to your computer using the following link: www.licor.com/2200C-software.

## Software Updates

Once FV2200 is installed, each time it is run it checks a LI-COR server for any LAI-2200C related updates since the last time it ran. If there are changes, a "Latest News" file is displayed, which will display any software updates to LAI-2200C console software, wand software, or FV2200, and provides links to the new versions. Also, once FV2200 is running, you can get this information manually in either of two ways from the Help menu. Also under the Help menu is a guide to using FV2200.

All require internet access.

Visit licor.com
Visit LAI-2200 website
View FV2200 Guide
Check for Software updates
Latest LAI-2200 news

New with version 2.
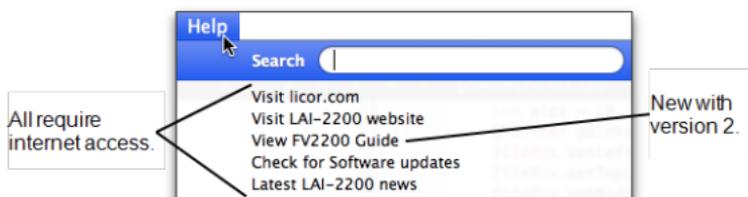
# Main Window

When the FV2200 software is launched the main window will open. From this window, you can import LAI files or open LAI files from a disk. Three tool bars are visible in the Main Window: File, Display, and Edit. Toolbars can be hidden, moved around or detached by clicking and dragging the toolbar drag handle. Hide and show toolbars using the View menu or by right-clicking on the menu bar. To resize buttons in the toolbars or change display defaults, select **File > Preferences** (or **FV2200 > Preferences** on Mac). Choose between small icons (no boxes checked), large icons, or icons with labels (small or large).

Plot Data from LAI files.

Make .kml file from GPS data.

Mask rings, interpolate, change canopy models, etc.

Import A readings.

Add scattering corrections.

Sets the displayed variables in views.

Each LAI file is one line in the view.

| LAI_File | Date | RawStart | RawStop | TransComp | Model | Records | ScattCorr | LAI | SMP |
|---|---|---|---|---|---|---|---|---|---|
| WP4 | 20131010 16:21:24 | 16:21:36 | 16:27:47 | a-p-s | Horizontal | 2A 30B 32G | none | 4.13 | 30 |
| WP3 | 20131010 16:08:39 | 16:08:46 | 16:21:05 | a-p-s | Horizontal | 3A 50B 53G | none | 3.55 | 50 |
| WP2 | 20131010 15:58:12 | 15:58:24 | 16:08:19 | a-p-s | Horizontal | 2A 25B 27G | none | 2.75 | 23 |

Created new view for file /Users/jon/Documents/LAI-2200/GPS/WildernessPark/WildernessPark.txt
3 LAI files read into view WildernessPark.txt
Created new view for file /Users/jon/Documents/ScatterExample.txt
1 LAI files read into view ScatterExample.txt

Views are created when a text file containing one or more LAI files is opened and read.

Log window, where actions are recorded.

# Basic Tasks

FV2200 can read files on your computer that have been transferred from control units (*Procedure 3.1 - Moving Data to a Computer* on page 8-37), or directly from an LAI-2270C Control Unit that is connected to your computer with a USB cable.

To open files that are saved on your computer's hard drive or the LAI-2200C console if it is attached via USB, click the **Open** icon or **File > Open** and navigate to the stored file. Double click the file to open it, or select multiple files and click **OK**.

Alternatively, you can drag the data file(s) onto the main window: The file(s) will be opened in the current view, or if there are no views, one will be created.

On Mac and Windows operating systems, you can drag and drop the data file(s) onto the FV2200 icon: on Mac, if FV2200 is not running, it will launch, create a view, and open the files in that view. If FV2200 is running, this is just like dropping the files onto the main windows. On Windows, FV2200 will launch (if it is already running, a second one is launched), a view is created, and the files opened in the view.

If multiple files were selected, click **Yes** to place them into one tab or **No** to place them in separate tabs.
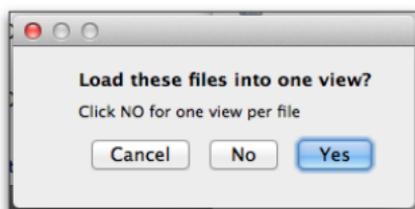
Once files have been opened, a view is created with the tab showing the source files. If you open another file or group of files, these will go into a second view. LAI files (rows of a view) can be cut, copied, and pasted from one view to another.

## View an LAI File

Double click a file in a view to open the Details window.
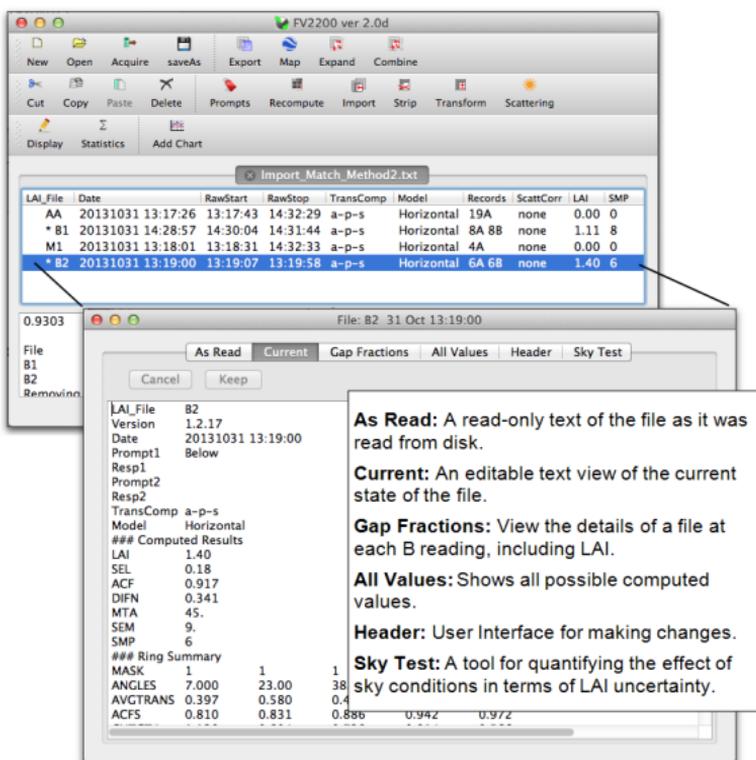


## Import A Records

When **A** and **B** records are in separate files, they must be merged to compute results. If the **A** and **B** readings were collected using two different sensors, imported **A** records may also need to be adjusted to match the **B** sensor's

calibration, if it hadn't been done already. This is discussed in *Multiple-Sensor Operation Revisited* on page 5-21. Both of these tasks—importing and (if necessary) adjusting—are accomplished using the "Import Records" dialog.

## Recompute Data Files

There are a number of reasons a file might need to be recomputed, such as adding scattering corrections, importing **A** readings, masking a ring, etc., and generally the recomputation happens automatically as part of that process. There is also a Recompute dialog box that lets you make some typical modifications (change the ring mask, change how transmittances are computed, or change the canopy model) and apply those changes to one or a group of files.

## Implementing Scattering Corrections

Scattering corrections are discussed in *Dealing with Scattering* on page 5-6. If the necessary data (the **K** record precursors) have been collected for your files, use FV2200's Scattering Tool to complete the task: generate **K** records, copy them to other files (if necessary), set the remaining inputs in the files, and recompute. The example given in *Example 4 - Forest Sites with One Sensor (and Control Unit)* on page 8-5 includes all of these steps.

## Plot Selected Data

You can plot data within an LAI file, or across multiple files. You can define a chart, then click on various LAI file (s) to update the chart for that file(s). All of this is configured using the **Add Chart** dialog.
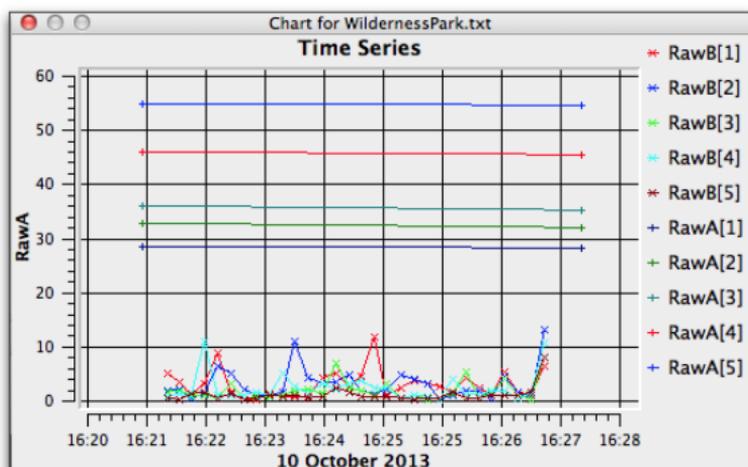


## Make a GPS Plot

LAI files that contain GPS data, either because they were logged with an LAI-2200C console with built-in GPS, or they have had GPS data added as part of the scattering correction inputs, can be used to generate .kml files, which allows selected data to be displayed on a satellite image of the area. For example, ". LAI data plotted on Google® Earth with a .kml file produced by FV2200." on the facing page shows a path of where the data points were logged (top) and a 3D image of LAI along that path (height being proportional to LAI at any given point).
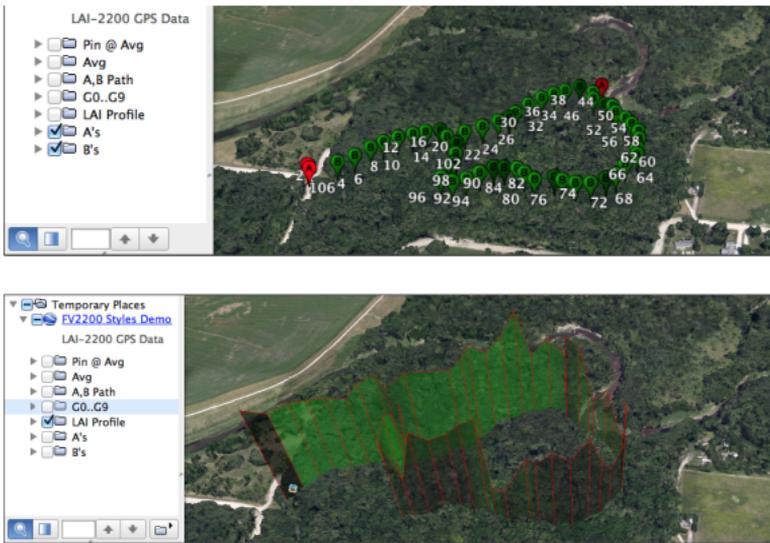
*Figure 7-1. LAI data plotted on Google® Earth with a .kml file produced by FV2200.*

## View LAI for each B Record

Often it is desired to "break apart" an LAI data file and see what the LAI was at each location for which there was a B reading. FV2200 version 2 provides this information for you without your having to do anything. To see it, double click the file to get the Details view, and click on the **Gap Fractions** tab.

# Computing LAI

FV2200 duplicates the LAI computation done in the LAI-2200C console (LAI-2000 Method), and also provides some alternatives: the Lang Method, Ellipsoidal Method, and Constrained Least Squares Method. These are described below.

There are some points to remember when interpreting these results:

1 The "L" in LAI (Leaf Area Index) is traditional, and not necessarily a fact. Anything that blocks light will be included in the result: branches, stems, animals, etc. Thus, "Foliage Area Index" is a better way to think of this.

2 LAI could be foliage area index ($m^2$ foliage/$m^2$ ground), or foliage area density ($m^2/m^3$) canopy. It is the path lengths (Dist[*]) that determine which units are appropriate. For standard path lengths (Horizontal Uniform model), LAI is foliage area index. For any other path lengths (Isolated Canopy, Measured Distances, and Isolated Canopy, Computed Distances), LAI should be interpreted as foliage density.

3 The LAI values include a correction (log average transmittances) for clumping. Thus, especially if narrow view caps were used, measured LAI is closer to $L$ (true LAI) than $L_e$ (effective LAI). If you want $L_e$, multiply LAI by ACF, the apparent clumping factor.

## LAI-2000 Method

LAI is computed from (see *Theory* on page 10-1 for the derivation):

$$L = 2 \sum_{i=1}^{5} \overline{K}_i W_i \qquad \text{7-1}$$

where $L$ is the leaf (all light blocking objects) area index (LAI), $\overline{K}_i$ is the mean contact number for the i$^{th}$ ring (CONTACT#[*]), and $W_i$ is the weighting factor for the i$^{th}$ ring (LAI_W[*]).

| LAI_File | LAI | CNTCT#[1] | CNTCT#[2] | CNTCT#[3] | CNTCT#[4] | CNTCT#[5] | LAI_Wt[1] | LAI_Wt[2] | LAI_Wt[3] | LAI_Wt[4] | LAI_Wt[5] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1.2 | 3.06 | 3.066 | 3.075 | 2.005 | 1.356 | 1.015 | 0.034 | 0.104 | 0.160 | 0.208 | 0.494 |
| *1.3 | 3.80 | 4.045 | 3.506 | 3.162 | 1.615 | 1.124 | 0.034 | 0.104 | 0.160 | 0.208 | 0.494 |
| *1.4 | 3.39 | 4.264 | 3.004 | 1.993 | 1.404 | 1.265 | 0.034 | 0.104 | 0.160 | 0.208 | 0.494 |

LAI = 2 * (K1 * W1 + K2 * W2 + K3 * W3 + K4 * W4 + K5 * W5)

The mean contact number is a function of the transmittance and the path length $S_i$ (DIST[*]). For $n$ Above/Below pairs of observations,

$$\overline{K}_i = \frac{\frac{1}{n}\sum_{i=1}^{n} -\ln\left(\frac{B_j}{A}\right)}{S_i}$$

7-2

Weighting factor $W_i$ is computed from

$$W_i = \Delta\theta_i \sin\overline{\theta}_i$$

7-3

where $\overline{\theta}_i$ is the mean zenith angle and $\Delta\theta_i$ is the ring width (radians) associated with $i^{th}$ ring. Values for $\Delta\theta_i$ are given in ". Ring widths and weighting factors." below below. The weighting factors are normalized to sum to 1.0, so when one or more rings are masked, the remaining weighting factors increase.

Table 7-1. Ring widths and weighting factors.

| Ring | Width (°) | Weighting Factor |
|---|---|---|
| 1 | 12.2 | 0.041 |
| 2 | 12.2 | 0.131 |
| 3 | 11.8 | 0.201 |
| 4 | 13.2 | 0.290 |
| 5 | 13.2 | 0.337 |

## Lang Method

A simple method of computing LAI from the slope and intercept of a plot of contact number vs. angle was proposed by Lang (1987).

$$L_{lang} = 2\,(m + b) \qquad\qquad 7\text{-}4$$

where $L_{lang}$ is leaf area index (LangLAI), $m$ is the slope and $b$ is the intercept of contact number (CNTCT#[*]) plotted as a function of angle (in radians). LangLAI can be added to views or viewed in the "All Values" tab of any data file.

## Ellipsoidal Method

Another method of inverting gap fraction data is to use an ellipsoidal-based description of leaf angle distribution. Refer to Norman and Campbell (1989), and Campbell (1986).

Variables computed with the Ellipsoidal Method include:

**EllipLAI** – LAI (or foliage density) obtained from the ellipsoidal distribution method.

**EllipMTA** – Mean Tilt Angle obtained from the ellipsoidal method.

**EllipX** – The ratio of horizontal to vertical radii of an ellipsoid whose surface area fractions describe the foliage angle distributions in the canopy.

These variables can be added to views or viewed in the "All Values" tab of any data file.

## Constrained Least Squares Method

An alternative method of inverting gap fraction data is that of constrained least squares. Refer to Norman and Campbell (1989) and Perry et al. (1988). The outputs associated with this method are listed below:

**CLS_LAI** – LAI (or foliage density) by method of the con-
strained least squares.

**CLS_c** – The smallest constraint that yields all positive
area fractions.

**CLS_LAD[*]** – foliage angle distribution. The angle
classes are 9°, 27°, 45°, 63°, and 81° (90 divided evenly
by 5). If one or more rings are masked, there will be
fewer angle classes.

**CLS_MTA** – Mean Tilt Angle based on the distribution
(S).

**CLS_Mu, CLS_Nu** – Mu, Nu of the Beta distribution
(Goel and Strebel, 1984).

# Section 8.

# Examples and Procedures

This chapter contains step-by-step instructions for most of the common operations with the LAI-2200C and FV2200.

Each Example tells how to measure LAI with a particular optical sensor (wand) configuration or canopy type. Examples 2, 4, and 5 include the scattering correction for use with direct sun conditions. When using two or more optical sensors with scattering correction, see *Multiple Sensors With Scattering Correction* on page 5-31.

Each Procedure describes a particular task on the console or in post-processing. These procedures are referenced from various locations in this manual.

## Example 1 - One Sensor Measurement without scattering correction

This step-by-step section requires one LAI-2270C Control Unit and one LAI-2250 Optical Sensor and view caps. Follow these steps:

1 Place the desired view cap on the sensor with the opening pointing away from the handle. Attach the optical sensor to the control unit (either the X or Y terminal) and turn on the control unit. Verify that the sensor is operating correctly by placing a hand over the lens and

observing that the reading drops (in Monitor Mode). Remove your hand and notice that the reading returns to normal.

2 Set prompts, if desired.

3 Open a file (*Procedure 2.2 - Opening a New Data File* on page 8-25). Enter responses to the prompts and press **OK** to save or **EXIT** to skip the prompts. Now the LAI-2200C will enter Logging Mode and is ready to record data.

4 Position the optical sensor above the canopy. Be sure it is level and that no foreign objects are in view of the sensor. Verify that the ABOVE LED is illuminated (press the **A/B** button on the wand if it is not). Press the **LOG** button on the wand or control unit to record an Above reading.

5 Press the **A/B** button (the ABOVE LED will turn off). Hold the optical sensor below the canopy(level and oriented in the same direction as the above-canopy reading was) and press the **LOG** button to record a Below reading.

6 LAI, MTA, SEL, and SEM values will be visible in Logging Mode (use the arrow keys to change what is displayed).

7 Continue making **B** readings, moving the sensor to a new location each time. Typically, the distance between **B** readings is on the order of the canopy height. You can intersperse **A** readings as necessary, if sky conditions or the view direction changes.

8 When you are finished, press the **START|STOP** button to close the file and exit Logging Mode.

# Example 2 - One Sensor Measurement with Scattering Correction

This example is of an LAI measurement that would normally be made by doing an **A** reading, followed by a series of **B** readings. Thus, our sequence (if we weren't doing scattering corrections) might be ABBBB. Because we are doing scattering corrections, we will want to replace the **A** readings with a **4A** sequence. Thus, we'll end up with a record sequence of AAAABBBB.

Preliminary steps are just like the previous example.

1 Perform a **4A** sequence (*Procedure 2.6 - Logging a 4A or 3A Sequence* on page 8-28).
2 Log the **B** readings.
3 Close the file (press **START|STOP**).
4 Transfer the file to FV2200 (*Procedure 3.1 - Moving Data to a Computer* on page 8-37).
5 Convert the **3A** or **4A** sequences to **K** records (*Procedure 3.9 - Generating K records from Sequences* on page 8-41).
6 Enter the remaining scattering inputs (step 6 of *Procedure 3.11 - Set Scattering Inputs for a Group of Files* on page 8-43).

**Note:** For more details about measurements with scattering correction, see *Protocol Suggestions for Direct Sun* on page 5-30.

**Note:** When using two or more sensors with scattering correction, see *Multiple Sensors With Scattering Correction* on page 5-31.

# Example 3 - Two Sensor Measurement without scattering correction

The Match Methods mentioned below are discussed in *Three Methods for FV2200 Matching* on page 5-22.

1 Place the desired view caps (same size) over the lenses of two optical sensors (see chapters 4 and 6). Connect the optical sensor to the control unit and turn on the control unit.

2 Synchronize clocks in both wands (*Procedure 1.4 - Synchronizing Wand and Console Clock* on page 8-19), and delete any data from the above wand (**MENU > Data > Wand > Purge**).

3 Start the Above wand autologging (*Procedure 2.7 - Automatic Logging - Wand* on page 8-28).

4 Disconnect the Above wand, and place it in an area that affords a clear view of the sky. Be sure it is level, stable, and oriented so that it views the same sky as the below canopy sensor will see.

5 Before leaving the **A** unit:
   A. If you are doing Match Method 2, create your match file now (*Procedure 2.5 - Creating a Match File for Match Method 2* on page 8-27).
   B. If you are doing Match Method 3, record your match data by opening a file and logging a few **A** readings with the sensors together. Leave the file open for the **B** records.

6 Go to the site for measuring **B** records, and record the readings. For each one, make sure it is seeing the same sky as the **A** unit.

7  (Match Method 3 only, optional) Before closing the file, return to the **A** unit, and append 1 or 2 **A** readings into the file.

8  Press **START|STOP** to close the file.

9  If you are doing Match Method 1 or 2, repeat step 6 as necessary, creating more below files. If you are doing Match Method 3, then you have to repeat steps 5 through 8 as needed.

10 When you are done, disable autologging on the above sensor (*Procedure 2.7 - Automatic Logging - Wand* on page 8-28) and download the files from the sensor to the control unit (*Procedure 2.13 - Moving Wand Data to the Console* on page 8-33).

11 Move the above and below files onto your computer (*Procedure 3.1 - Moving Data to a Computer* on page 8-37).

12 Import **A** records from the above file into the below files (*Procedure 3.8 - Import A and Adjust A Records - FV2200* on page 8-40).

> **Note:** When using two or more sensors with scattering correction, see *Multiple Sensors With Scattering Correction* on page 5-31.

# Example 4 - Forest Sites with One Sensor (and Control Unit)

This method is best suited to a clear blue day. The strategy is to start at a clearing and make **A** and **K** readings in an "above" file. Then move to the measurement site and measure each transect or plot in separate "below" files. Finally, return to the clearing and make final **A** and **K** readings.

FV2200 is used to put everything together, do the scattering corrections, and compute final results.

1  At the **A** site, open a file (*Procedure 2.2 - Opening a New Data File* on page 8-25). We'll assume the name is "above", and log a **4A** or **3A** sequence (depending on the size of the clearing) (*Procedure 2.6 - Logging a 4A or 3A Sequence* on page 8-28). Close the file.

2  Measure each transect or plot into a separate below file. Each will have any number of **B** records.

3  Return to the **A** site, and repeat step 1, open file "above" and append another **4A** sequence into it. Close the file.

4  Read all files into FV2200 (*Procedure 3.3 - Loading Data Files into FV2200* on page 8-38). They can all be in one view.

5  Generate **K** records in file "above" (*Procedure 3.9 - Generating K records from Sequences* on page 8-41).

6  Import **K** records to the below files (*Procedure 3.12 - Combining Multiple Files - FV2200* on page 8-45).

7  Import **A** records to the "below" files (*Procedure 3.8 - Import A and Adjust A Records - FV2200* on page 8-40). Enable interpolation, and don't do adjustments (since **A** and **B** are the same sensor).

8  Set the rest of the scattering inputs on the "below" files (step 6 of *Procedure 3.11 - Set Scattering Inputs for a Group of Files* on page 8-43).

# Example 5 - Forest Sites with One Sensor (without Control Unit)

The only difference between this example and the one above is that we don't have separate files; everything gets

collected by the wand and winds up in one file. Again, this is best on a clear blue day.

1   At the **A** site, log a **4A** or **3A** sequence (depending on the size of the clearing).

2   Move to measurement sites, and log **B** records. You will need to mark the start of each new 'file': you could log a fake **A** record, or cover the lens with your hand and log a record with tiny values in it. Later on, you will use these markers and eventually delete them.

3   Return to the **A** site, and repeat step 1.

4   Copy the wand data to a control unit (*Procedure 2.13 - Moving Wand Data to the Console* on page 8-33). We'll call this file 'BIG', since it is the big file from which we'll make the other files, one for each transect or plot.

5   Load 'BIG' into FV2200 (*Procedure 3.3 - Loading Data Files into FV2200* on page 8-38).

6   Generate **K** records in 'BIG' (*Procedure 3.9 - Generating K records from Sequences* on page 8-41).

7   Set the rest of the scattering inputs in 'BIG' (step 6 of *Procedure 3.11 - Set Scattering Inputs for a Group of Files* on page 8-43).

8   In the main view of FV2200, copy 'BIG' (highlight it and hit copy button (or **File > Copy**). Then paste (**File > Paste**) as many copies into that same view as you have transects or plots.

9   For each file pasted, double click it to get the detail view and do the following:

a) Click the "current" tab to view the file as text.

b) Rename the file. Change BIG to T2.

c) Set it for interpolation (change "a-p-s" to "a-i-s").

d) Remove all extraneous records for that particular file. Example: This file will be T2 (transect#2), so we can highlight and delete records 25 - 30, and 37 - 49.

e) Finally, click "Keep."

10   Click the **Keep** button.

# Example 6 - A Simple Isolated Canopy

Consider the example given in *A Simple Example* on page 6-15. In this example, the plant is a hemispherical shrub with measured path lengths of 0.7 m. Launch the FV2200 software. Click on **File > Sample files > Manual Examples.txt**. Double click on the file called **SHRUB** to view file details, then select the **As Read** tab. The data file for this shrub looks something like this:

```
...
MODEL      IsoMeasured
...
LAI        6.69
SEL        0.00
ACF        1.000
DIFN       0.092
MTA        49
SEM        2
SMP        1
MASK       1     1     1     1     1
ANGLES     7.00  23.00 38.00 53.00 68.00
AVGTRANS   0.059 0.068 0.097 0.084 0.131
ACFS       1.000 1.000 1.000 1.000 1.000
CNTCT#     4.035 3.850 3.338 3.539 2.903
STDDEV     0.000 0.000 0.000 0.000 0.000
DISTS      0.700 0.700 0.700 0.700 0.700
GAPS       0.059 0.068 0.097 0.084 0.131
...
A: 1  20090924   12:13:44 109.23 108.96 102.21 96.61 100.67
B: 2  20090924   12:14:05 6.480  7.360  9.880  8.110 13.19
```

The LAI value is foliage density. There are two ways to tell this by looking at the file. One is the **MODEL** line. "Horizontal" means the canopy model is horizontally infinite, or at least large enough that the default DISTS vectors apply. "IsoMeasured" means an isolated canopy. The other way to know this is to look at the DISTS values. Since they are not the default values (1.008, 1.086, 1.269, 1.662, and 2.669), then LAI should be interpreted as foliage density.

Click on the **Header** tab, then click **Change**. In the **Recompute** dialog, check **Change Canopy Model**, then check **Change View Cap**. Select the 90 degree cap and observe changes in the **Volume** and **Area** fields, which are used to compute Drip Line LAI (DLLAI).

# Example 7 - Isolated Tree

Below is an example of the procedure that could be used to measure LAI for an isolated plant. The steps below will

generate a file much like the example file named **TREE1** in the FV2200 software, which is accessed by going to **File > Sample files > Manual Examples**.

1 Create a new file with default **Transcomp** settings. Use a 90° view cap and take one AB pair in each of the four directions.

2 Measure the average shape of the tree's crown with several X, Z pairs of points that describe the profile, as shown below (a photo of the profile with a meter stick for scale could be used as well).

3 Measure the X and Z offsets, as shown below.



X      Z
1: (0.0, 0.6)
2: (0.8, 0.6)
3: (1.4, 0.8)
4: (1.6, 1.5)
5: (1.3, 2.3)
6: (0.8, 2.8)
7: (0.0, 3.5)

Measure the distance between the sensor and the bottom of the canopy (Z offset), 0.5 m in this case.

Place the sensor at ground level for B readings.

Measure the distance between the sensor and the centerline of the canopy (x offset), 0.05 m in this case.
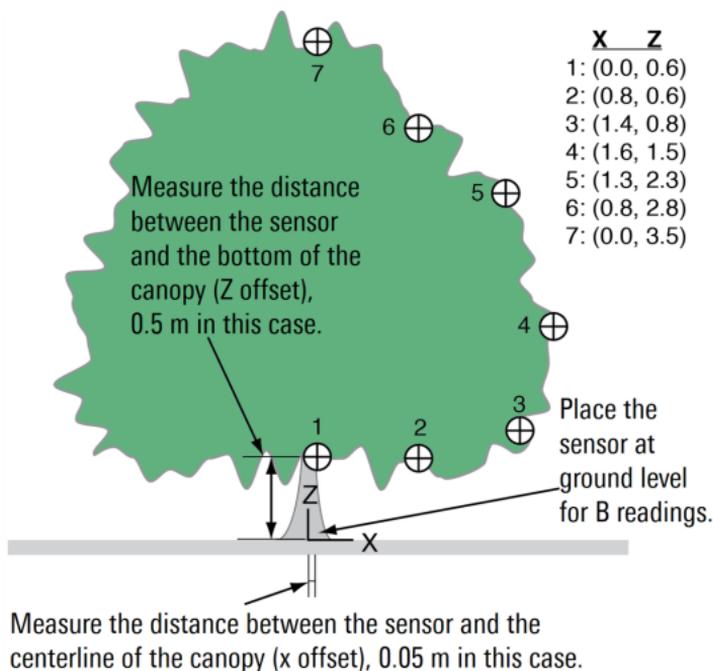
4 Open the file with the FV2200 software.

5 Select the file and click the **Recompute** button. Check the **Change Canopy Model** box.

6 Check the **Isolated Computed** box, and the **Change vertical profile** box.

7  Click the **Edit…** button and enter the X, Z coordinates to define the canopy shape. Right click on the profile to add more points. Click **OK** when finished.

8  Enter the X and Z sensor position. Observe changes in volume and area values as these fields are updated.
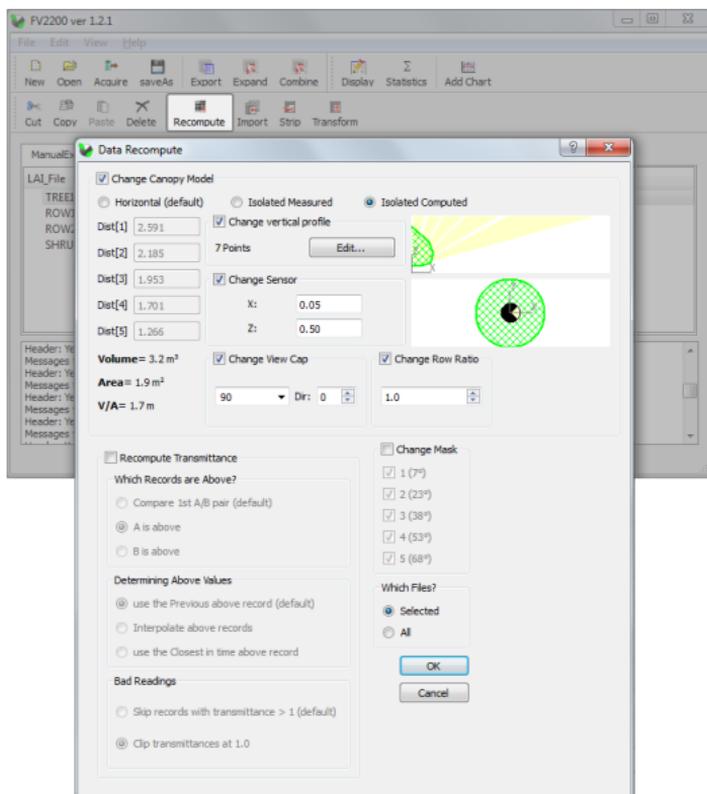


9  Click **OK** to implement the changes. The new LAI value, along with a summary of the procedure, will be visible in the log.

10  Save the file to retain any changes.

## Example 8 - Isolated Row 1

There are two approaches that can be used to measure an isolated row, such as a grape vine or hedge. The first is

described here, and the second is described for "Row 2" below.

The steps below will generate a file much like the example named ROW1 in the FV2200 software, which is opened by clicking on **File > Sample files > Manual Examples**.

1   Set the console **Transcomp** settings to **Define Above: A; Determine Above: Interpolate; Bad Readings: Clip**. Place a view cap with a 90° opening over the lens and create a new file.

2   Make an above-canopy reading, multiple below-canopy readings, and a second above-canopy reading. Make the below canopy readings with the sensor at the base of the canopy, as shown.
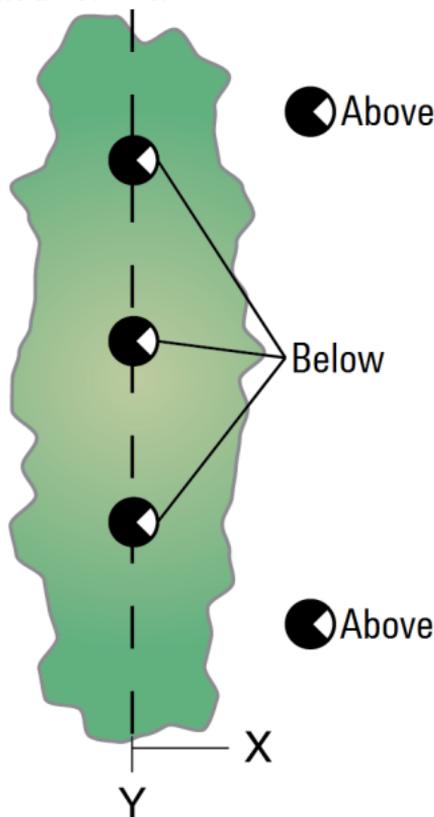


3   Measure several X, Z coordinates (meters) to characterize the vertical profile, perpendicular to the centerline of the hedge. This example uses 8 coordinates. See the following figure.

| X | Z |
|---|---|
| 1: (0.0, | 0.0) |
| 2: (0.0, | 1.47) |
| 3: (0.31, | 1.39) |
| 4: (0.51, | 1.27) |
| 5: (0.67, | 1.05) |
| 6: (0.63, | 0.79) |
| 7: (0.54, | 0.51) |
| 8: (0.25, | 0.14) |

Place the sensor at the 0,0 coordinate.
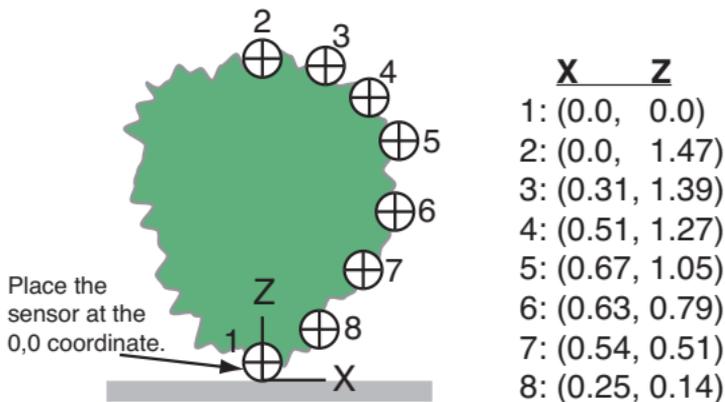
4  Measure the width (Y) and depth (X) of the hedge to compute the row ratio (Y/X), 5 in this case.

5  Open the data file in the FV2200 software.

6  Click the **Recompute** button. In the Recompute Dialog box, select **Change Mask**. Deselect ring 5 because it did not "view" any foliage.

7  Next, check the **Change Canopy Model** check box, then the **Isolated Computed** radio button. Check the **Change Vertical Profile** button, then select **Edit…**.

8  Enter the X, Z coordinates to define the shape of the hedge. Right click on the canopy profile to add more points.

9  Check the **Change Row Ratio** box and set the row ratio to 5. Click **OK**.
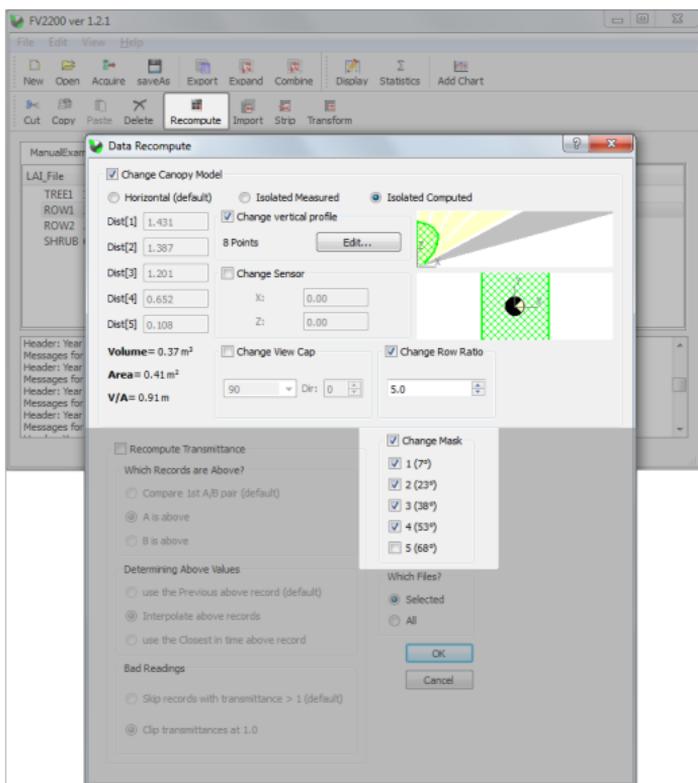
10 The new LAI values are displayed in the Log. Save the file to retain changes.

If the hedge were asymmetrical, two files would be required, one for each side of the canopy (or row 2 below could be used).

## Example 9 - Isolated Row 2

The steps below will create a file similar to the example **ROW2** in the FV2200 software, which is opened by **File > Sample files > Manual Examples**.

1 Set the console **Transcomp** settings to **Define Above: A; Determine Above: Interpolate; Bad Readings: Clip**. Place a view cap with a 90° opening

over the lens and create a new file.

2 Make an above-canopy reading, several below canopy readings, and a final above-canopy reading. Take the below-canopy readings along a line that is parallel to the centerline of the shrub, but not directly under the shrub, as shown.
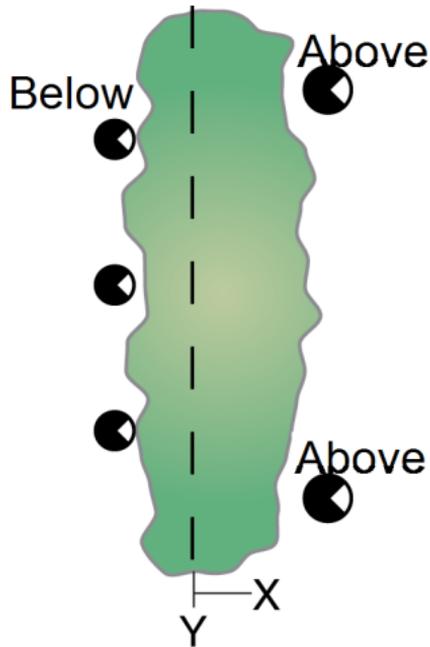


3 Measure a number of X, Z coordinates (meters) to characterize the vertical profile, perpendicular to the centerline, of the hedge. Measure the distance between where the **B** readings were taken and the centerline of the hedge (X offset), -0.20 in this case, and the distance between the vegetation and the sensor (Z offset) in meters (0.0 in this case), as shown in the following figure.

Make B readings with the sensor at the base of the vegitation or below the canopy. Measure the X and Z offsets from coordinate #1. In this case, they are -0.20, 0.0.

| X | Z |
|---|---|
| 1: (0.0, 0.0) |
| 2: (-0.12, 0.25) |
| 3: (-0.18, 0.59) |
| 4: (-0.23, 0.94) |
| 5: (-0.17, 1.27) |
| 6: (0.0, 1.47) |
| 7: (0.3, 1.39) |
| 8: (0.51, 1.56) |
| 9: (0.66, 1.04) |
| 10: (0.63, 0.78) |
| 11: (0.53, 0.51) |
| 12: (0.24, 0.14) |
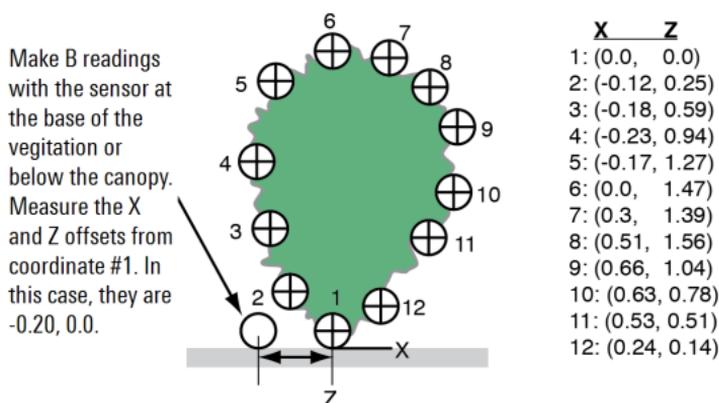
4  Measure the width (Y) and depth (X) of the hedge to compute the row ratio (Y/X).

5  Open the data file in the FV2200 software.

6  Click the **Recompute** button. In the Recompute Dialog box, check the **Change Canopy Model** check box, then the **Isolated Computed** radio button. Check the **Change vertical profile** button, then select **Edit….**

7  Enter the X, Z coordinates to define the shape of the hedge. Right click on the canopy profile to add more points.

8  Check the **Change Sensor** check box.

9  Check the **Change Row Ratio** box and set the ratio. Click **OK**.
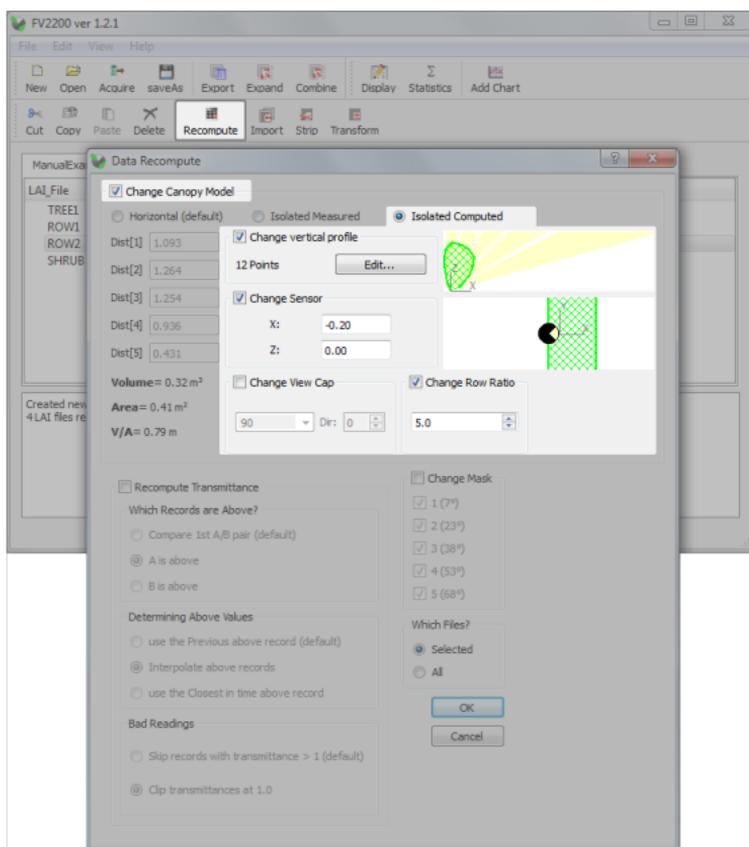
The new LAI value is shown in the Log. Save the file to retain changes.

# 1.0 Preoperation Procedures

You may need to go through some of these procedures before starting your field work.

## Procedure 1.1 - Setting the Console Clock Manually

The console clock uses 24-hour time notation (1:00 p.m. = 13:00). Follow these steps to set the clock:

1 Go to **MENU > Console Setup > Set Time** and press OK (or the Right arrow button).

2 The time field reads HH:MM YYYY/MM/DD. Use the Up and Down arrow buttons to select the correct values for each field, and use the Left and Right arrow buttons to switch between fields.

3 Press **OK** to implement the new time or EXIT to abandon changes.

## Procedure 1.2 - Setting the Console Clock from GPS

The console clock uses 24-hour time notation (1:00 p.m. = 13:00). If GPS is active and has valid data, you can choose to set the clock using GPS-generated Universal Coordinated Time (UTC). To set the clock using GPS:

1 Go to MENU > Console Setup > Set Time > Use GPS and press OK (or the Right arrow button).

2 Enter a number for UTC Offset, ± difference from UTC in hours and minutes for a particular time zone (e.g. if console is set to Central Daylight Time (USA), then this is −5).

3 Press OK to implement the new time or EXIT to abandon changes.

## Procedure 1.3 - Setting the Wand Clock Manually

The optical sensor (wand) clock can be set manually or synchronized with the control unit clock. To set the wand clock Manually:

1 Connect the wand to the control unit, go to **MENU > Wand Setup > Select wand > Clock** and press **OK** (or the Right arrow button).

2 Select Set Time

3 The time field reads HH:MM YYYY/MM/DD. Use the Up and Down arrow buttons to select the correct values for each field, and use the Left and Right arrow buttons to switch between fields.

4 The time is implemented after you select Yes. Verify the time and press **OK**.

> **Note:** If using two optical sensors, the clocks in both must be synchronized in order to match data in time. See *Procedure 1.4 - Synchronizing Wand and Console Clock* below.

## Procedure 1.4 - Synchronizing Wand and Console Clock

The optical sensor (wand) clock can be synchronized with the control unit clock.

1 Connect the wand to the control unit, go to **MENU > Wand Setup > Select wand > Clock** and press **OK** (or the Right arrow button).

2 Select Sync Time.

3 The time is implemented after you select Yes. Verify the time and press OK.

## Procedure 1.5 - Resetting Wand to Factory Calibration

1  Go to **MENU > Wand Setup > Select wand > Match Values > View/Set**.

2  Press **LOG**.

> **Note:** Factory calibration values need to be in place for sky brightness distribution to be measured, which is an important step when doing scattering corrections.

## Procedure 1.6 - Deleting Records From a Wand

To delete all records from the optical sensor memory:

1  Attach the optical sensor(s) to the console.

2  Go to **MENU > Data > Wand > Purge**.

3  Select the appropriate optical sensor.

4  Press **OK** to purge, or **EXIT** to return to the Wand Data menu.

## Procedure 1.7 - Setting Prompts

1  Press the **Menu** button, then go to **Log Setup** and select **Prompt**.

2  Enter the desired prompts in the **Prompt1** and **Prompt2** fields. If you wish, you can enter default responses, or leave the **Resp1** and **Resp2** fields blank. Either way, you will be able to enter responses in the **Resp1** and **Resp2** fields when you create a new data file.

## Procedure 1.8 - Build a Match File for Two Sensors (Match Method 1)

This is best done on a cloudless day, in a location with a clear view of the sky. If the sky is not cloudless in the area being viewed by the sensors (and you can't chose a better day), then hand-hold both optical sensors (so they move a little bit) for step 5 and log about 10 readings instead of 1 or 2.

You will want to do these steps for each size view cap that you might be using, creating a separate file for each.

1 Install the view cap to be used on each optical sensor. Each sensor should have the same view cap size with the same orientation on the lens.
2 Connect the sensors to a console.
3 Reset each sensor to its factory default calibration *Procedure 1.5 - Resetting Wand to Factory Calibration* on the previous page).
4 Open a file (*Procedure 2.2 - Opening a New Data File* on page 8-25). Give it a name to reflect that it is a match file, and include the view cap size (e.g. M45 or M90).
5 Make sure sensor are pointed in the same direction, side by side. Log 1 or 2 readings by pressing **LOG** for each reading.
6 Close the file.

LAI-2000 Note: If you do this with LAI-2000s, do not connect two sensors to a single console, but rather use a separate console for each wand, and make separate files. Then follow one of two paths:

- Convert each file to LAI-2200C format (*Procedure 3.4 - Converting LAI-2000 file to LAI-2200C* on page 8-39), being sure to specify the serial number for the sensor.
- Combine the two files into one file for that view cap size (*Procedure 3.12 - Combining Multiple Files - FV2200* on page 8-45).

Alternatively, if you wish to retain the LAI-2000 format, then when you create the two files, log **A** readings in one, and **B** readings in the other, and combine the files. Then, on subsequent data collection, be sure the sensor that logged the **A** readings is always the one used for above data.

## Procedure 1.9 - Build a Match File for More than Two Sensors (Match Method 1)

1   Build match files for pairs of sensors by following the instructions under *Procedure 1.8 - Build a Match File for Two Sensors (Match Method 1)* on the previous page. If there is an odd number of sensors, so that one cannot be attached to a console, then

  A.   Use it autonomously to log readings without a console. Be sure to clean its memory first (*Procedure 1.6 - Deleting Records From a Wand* on page 8-20).

  B.   Download the logged records by importing them into the appropriate match file (*Procedure 2.13 - Moving Wand Data to the Console* on page 8-33).

2   Combine all the match files for a given view cap size by using *Procedure 3.12 - Combining Multiple Files - FV2200* on page 8-45.

## Procedure 1.10 - Enabling a Quantum Sensor

1  Attach the quantum sensor cable to port 1 or 2, then go to **MENU > Log Setup > PAR Sensors**, select **Port 1** or **Port 2** (whichever has a quantum sensor attached), and press **OK**.

2  Set the **Enabled** field to **On**.

3  (Optional) Name the sensor. The name is used in the Contributing Sensors section of data files (see *Sensor Information* on page 3-30).

4  In the **Cal** field, enter the calibration multiplier for your light sensor. The calibration multiplier is printed on your sensor's calibration certificate. It also can be found by entering your sensor's serial number in the Calibration search box at http://www.licor.com/env/support.

5  Press **OK** to implement the changes.

Quantum sensor settings are saved to the global template and will be applied to any data file that is created.

## Procedure 1.11 - The Canopy Gap Test

The Canopy Gap Test is discussed in *The Gap Test* on page 6-11. Follow these steps to estimate the error resulting from using a view cap that is too large:

1  Use a 45° view cap.

2  Set **Transcomp** to A-P-C (Above, Previous, and Clip).

3  Make a measurement in the canopy consisting of 2 **AB** pairs. Both of the below readings should be in the same location, but one viewing the densest part of the canopy, and the other viewing the sparsest part.

(Because they are viewing different directions, you
need separate **A** readings for each **B** reading.)

Look at the value of ACF, apparent clumping factor. For
purposes of this test, interpret this as the ratio of the LAI
you would get with a wider view cap to the one you
would get with the narrower view cap. For example, an
ACF of .95 means the wider view cap would produce an
LAI that is 5% lower than that found with a narrow view
cap. An ACF of 0.8 would be 20% lower, and so on. The
lower the ACF, the more you need the narrow view cap.

# 2.0 Field Operation Procedures

Thi section includes procedures for field measurements.

## Procedure 2.1 - Making Two Wands Match - Console Matching

Here's how to make two sensors match each other prior to
collecting data. This technique will adjust the match val-
ues of one of the sensors. It should be performed with
both sensors viewing a cloudless sky.

> **Note:** This technique is only recommended if LAI data
> is to be collected with two wands attached to one con-
> sole. There are better matching methods for all other
> cases. See *Multiple-Sensor Operation Revisited* on
> page 5-21.

1  Attach the two sensors to be matched to the console,
   and turn on the control unit.

2  Place the sensors side by side so they see the same sec-
   tion of blue, cloudless sky, if at all possible. View the
   readings in Monitor mode (*Monitor Mode Navigation*

on page 3-2).

3  Set match values.

   A.  Go to MENU, select Wand Setup, select the wand
       to be used for Below readings, and press OK.
   B.  Select Match Values and press OK.
   C.  Select Calculate and press OK. The wand chosen
       in step "a" will be set to match the other wand.
       Press OK.

4  View values in Monitor Mode to confirm match.

5  To reset the original calibration values, select **View/Set
   Values** from the **Match Values** menu (**Menu >
   Wand Setup > Select wand > Match Values**).
   Press **LOG** to reset, then **OK**.

Note that when data are logged, each **A** or **B** record con-
tains an indicator (e.g. W1, W2, etc) telling what wand
took the data. In the header is a "Contributing Sensors"
section that relates the wand indicators to actual serial
numbers and match values:

```
          :
DISTS     1.008     1.087     1.270     1.662     2.670
GAPS      0.000     0.000     0.000     0.000     0.000
### Contributing Sensors
MATCH     W1        PCH2516   3978      1244      1000      1004      1289
MATCH     W2        PCH2462   3650      1044      900       904       1144
### Data
A         1         20090924 15:23:21   W1        199.228   198.956   202.214   186.611   190.670
B         2         20090924 15:23:55   W2        2.48003   2.33006   2.68008   3.11003   4.21009
B         3         20090924 15:24:02   W2        7.43006   2.60031   2.15000   3.34005   4.14001
          :
```

## Procedure 2.2 - Opening a New Data File

1  With the instrument on, press the **START|STOP** but-
   ton.

2  Select **New File** and enter a file name (a maximum of
   8 characters or numbers). File names are automatically

generated based on the previous entry, incremented by one digit.

3  **View/Edit** remarks, and/or press **OK**.

4  The LAI-2200C is now in Logging Mode. Log **A** or **B** readings.

## Procedure 2.3 - Import to an Existing Data File

1  With the instrument on and a sensor attached, press the **START|STOP** button.

2  Select **EXISTING FILE** and select a file from the list.

3  **View/Edit** remarks, and/or press **OK**.

4  The LAI-2200C is now in Logging Mode. Log **A** or **B** readings.

Hint: It is helpful to sort the list of existing files by modification date, with most recent files near the top of the list. To sort the list that way, press the **MENU** key when viewing the existing file list, and select **Reverse Date**. That sort order will remain for subsequent uses until you change it to something else.

## Procedure 2.4 - Setting up a Controlled Logging Sequence

The controlled logging sequence is discussed in *Controlled Sequence* on page 3-16.

1  Connect the optical sensor to the control unit.

2  Go to **MENU > Log Setup > Controlled Sequence** and press **OK**.

3  Set the **Use** field to **Yes**.

4  Set the number of repetitions (from 1 to 41).

5   Define the sequence. Press the number "2" button to specify an **A** reading and the "8" button to specify a **B** reading (e.g. for the sequence **ABBBB**, press 28888). The sequence can have up to 20 readings.

6   Press **OK**. The controlled sequence will be used for any new file.

7   Create a new file (*Procedure 2.2 - Opening a New Data File* on page 8-25). To view your position in the sequence, in the logging screen, use the left or right arrow key to change a field to indicate **Seq:**. This will indicate where you are in the sequence. The wand LEDs indicate which reading is next in the sequence.

The sequence can be interrupted at any time by pressing the **A/B|Power** button. For example, if the upcoming measurement is specified as an **A** reading, press the **A/B|Power** button to change the upcoming reading as a **B** reading. After logging the data point, the sequence will continue with the next specified measurement.

To deactivate the controlled sequence, set the **Use** field to **No**.

## Procedure 2.5 - Creating a Match File for Match Method 2

Match methods are discussed in *Three Methods for FV2200 Matching* on page 5-22.

Set up the **A** sensor and get it logging. Place the **B** wand beside it, open a file, and log several **A** records:

1   Press **START|STOP** button on the control unit, select **New File**, and name the file "match," or something to identify it as a match file.

2  Make sure the **B** wand is set for **A** records (the ABOVE LED should be lit).

3  Put the sensors together, being as careful as you can that they are both equally leveled and oriented. Press the **LOG** button several times to capture several **A** records.

## Procedure 2.6 - Logging a 4A or 3A Sequence

Photos and descriptions of these steps are in *K Records* on page 5-7.

1st **A** reading - white diffuser, sunlit.

2nd **A** reading - white diffuser, shaded.

3rd **A** reading - as wide a view as possible.

4th **A** reading - normal view cap, normal direction (normal = same as **B** measurement).

Note that step 3 is optional: If the largest unobstructed view of the sky is no larger that the view with the normal view cap, skip this step, and consider it a **3A** sequence.

## Procedure 2.7 - Automatic Logging - Wand

This procedure describes how to configure a wand for automatic logging. Discussion is in *Automatic Logging (Wand)* on page 3-16.

1  Attach the wand to the console. On the console, go to **MENU > Wand Setup** > **select wand** > **Auto Log** and press **OK**.

2   Select **Start Time**, and enter the desired start time and day (you can only set the start day of the current month). Press **OK.**

3   Select **Stop Time**, and enter the desired stop time and day (current month). Press **OK.**

4   Select **Frequency** and enter a multiple of 5 seconds between 5 and 3600 seconds. Press **OK** after entering the value.

5   Select the **On/Off** field, highlight **On** and press **OK.** The optical sensor can be disconnected from the control unit. If the wand is powered off, it should power up automatically at the specified start time. If these readings are "Above," be sure that the blue "Above" LED is illuminated. This will ensure that these readings are tagged with an **A** in the file.

When automatic logging is "On", the LOG LED light on the wand will blink every 2.5 seconds during the run-up to the logging start time. When it begins logging data, the LOG LED light will blink every second and the wand will beep at the beginning and end of each log.

> **Note:** In wand versions 1.19 and below, automatic logging may not start if you specify a start time that has already passed.

## Procedure 2.8 - Automatic Logging - Console

This recipe describes how to configure a console for automatic logging. Discussion is in *Automatic logging (Console)* on page 3-17.

1  Go to **MENU > Log Setup > Console AutoLog**.
2  Set the **Active** field to **On**. Press the down key to
   select **Period** and enter a multiple of 5 seconds
   between 5 and 3600 seconds. Press **OK** after entering
   the value.

When a file is open and autologging is active, the display
will show **AUTO** followed by a countdown to the next
log in seconds. All attached sensors (wands and quantum
sensors) are logged, and (if enabled) a G0 GPS record.

## Procedure 2.9 - Importing A Records - Console

When **A** readings are collected in a separate file, they need
to be imported by the file that holds the **B** readings before
LAI can be computed. This can be done on the control
unit (described below) or with the recommended method
of using the FV2200 software (*Procedure 3.8 - Import A and
Adjust A Records - FV2200* on page 8-40).

1  If it hasn't been done already, transfer the records from
   the wand to the console: Go to **MENU > Data >
   Wand Data > Download > select wand**. Choose
   **Create new file** and name the file.
2  Go to **MENU > Data > Console Data** and select the
   file that is to receive the imported records. Select the
   file that has the **B** readings.
3  Select **Edit** from the menu, then select **Import Obser-
   vations**.
4  Choose to import **A** records.
5  Press **OK** and the file will be recomputed using the
   imported records.

6  LAI values will recompute automatically and can be
   viewed in **MENU > Data > Console Data > select
   file > View Header**.

## Procedure 2.10 - Excluding Rings from Analysis - Console

The mask determines which rings are used (default = all)
to compute LAI. Data from rings that are ignored are still
measured and recorded, however, so nothing is lost even if
a data file is generated with all rings ignored.

Prior to logging:

1  Go to **MENU > Log Setup > Masks**.
2  Select **YES** for every ring to be used or **NO** for every
   ring to be ignored.
3  Press **OK** to keep the settings, **EXIT** to leave the menu
   without making changes, or **LOG** to reset to default set-
   tings.

After logging:

1  Go to **MENU > Data > Console > select data file
   > Edit > Edit Mask**.
2  Select **YES** for every ring to be used or **NO** for every
   ring to be ignored.
3  Press **OK** to keep the settings, **EXIT** to leave the menu
   without making changes, or **LOG** to reset to default set-
   tings.

Rings can also be excluded in post-processing with the
FV2200 software. Follow *Procedure 3.5 - Excluding Rings
from Analysis - FV2200* on page 8-39.

## Procedure 2.11 - Interpolating A Records - Console

The **Interpolate Transcomp** setting will choose the **A** reading that is closest in time to a given **B** reading to compute LAI.

1 Go to **MENU > Log Setup > Transcomp**.
2 Scroll down to the line below "Determine Above".
3 Use the left and right arrow keys to select **Interpolate**.
4 Press **OK** to keep the settings, **EXIT** to leave the menu without making changes, or **LOG** to reset to default settings.

## Procedure 2.12 - Getting K Records on an Above Sensor

When a wand is logging **A** records autonomously, it is possible to also use this wand for getting **K** record precursors, provided the logging interval is about 30 seconds or more. The goal is to intersperse a **2B** or **3B** sequence into the file. See *Embedded Bs* on page 5-16 for more explanation.

When it's time to get another **K** record, do this:

1 Wait for an autolog to occur.
2 Push the **A/B** button to change to **B** records.
3 Remove the view cap, and put the white diffuser in place.
4 With the sun on the diffuser, press the **LOG** button.
5 Shade the diffuser, and press the **LOG** button again.
6 (Optional wide sky view). Remove the diffuser. With the sensor shaded, or with a 270° view cap, press **LOG** again.

7  Place the normal view cap back on, and press the **A/B** button to change back to **A** records, so that the next autologged reading will be an **A**.

8  Use FV2200 to convert BBBA or BBA sequences to **K** records (*Procedure 3.9 - Generating K records from Sequences* on page 8-41).

## Procedure 2.13 - Moving Wand Data to the Console

Wand data can be moved to the console and put in a new file or import to an existing file.

1  Connect the wand to the console. On the console, go to **MENU > Data**.

2  Select **Wand Data** and then choose **Download**.

3  Select the optical sensor that has the desired data.

4  Select **New File** to create a new data file or select **Add to File** to import an existing data file.

5  If you choose **New File**, name the file (up to eight characters) and press **OK**. If you choose **Add to File**, select the file from the list and press **OK**.

It may take several seconds for the file to be transferred and for appended files to be modified. When the file is copied, it remains in the memory of the optical sensor. To delete files from the optical sensor memory, follow *Procedure 1.6 - Deleting Records From a Wand* on page 8-20.

## Procedure 2.14 - Measuring Leaf Transmittance and Reflectance

The theoretical discussion for this procedure is in *Required Inputs for the Scattering Model* on page 10-13. Leaf transmittance will be labeled *LeafTau* and leaf reflectance will

be *LeafRho*. This technique was first described in Kobayashi et al., 2013.

You will need an optical sensor (wand), the drilled cap (lens cap with a small hole in the middle), and a white diffuse reflectance standard panel (about 25 cm by 25 cm). Let *Rpanel* be the absolute reflectance of the panel. Typical *Rpanel* for a clean, halon reflectance standard is 0.99. You can use something less reflective, as long as you know its reflectance.

This procedure should be done on a clear day with the sun far enough from the zenith (overhead) so that the sensor will not shade the reflectance panel when mounted above it.

1  Attach the drilled cap (with the small hole) to the optical sensor. Attach the optical sensor to the control unit.

2  Using a ring stand or other suitable device, mount the optical sensor about 20 cm above the center of the white standard panel, viewing downward. Make sure the sensor or ring stand does not shade the panel.

3  Determine the size of the optical sensor's view by increasingly shading one corner of the white standard panel until the Ring #1 reading begins to change (*Figure 8-1* on page 8-36). This indicates how far the view extends from the center of the panel. Doing this shading on three corners instead of just one will account for any sensor tilt. Adjust the sensor's height until its view includes as much of the panel as possible without getting closer than a few centimeters from the panel's edge. All subsequent measurements should be with the sensor locked in this position.

4  Hold a leaf against the optical sensor lens cap so that the hole is completely covered by the leaf. Note the Ring #1 reading; we will refer to this value as *T*.

5  Remove the leaf, and note the Ring #1 reading again. This is *Tref*.

   *LeafTau = T / Tref*

6  Cover the reflectance standard with the type of leaves being measured. Overlap them so that all parts of the panel visible to the sensor are covered. Note the Ring #1 reading; we will refer to this value as *R*.

7  Remove the leaves and any debris and note the Ring #1 reading again. This is *Rref*.

   *LeafRho = R / Rref / Rpanel*
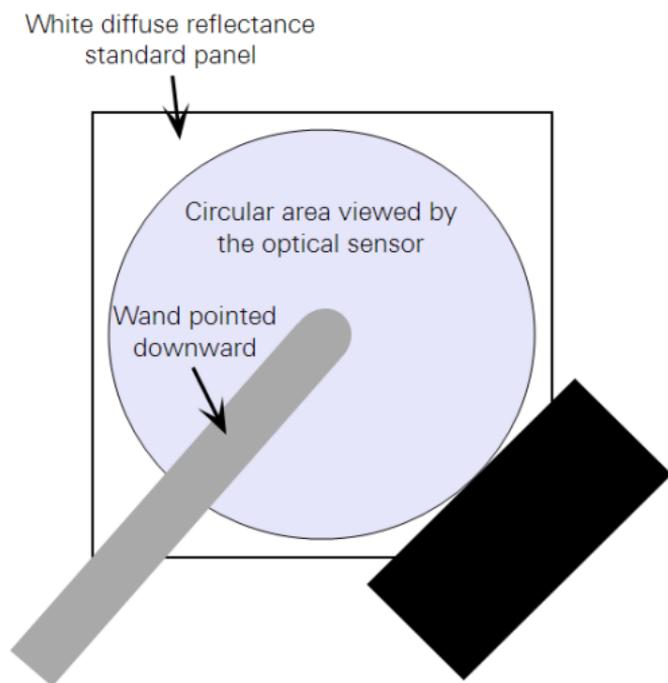
*Figure 8-1. Determining wand height for measuring leaf optical properties. Viewed from above. Shade three corners of the reflectance panel to determine the area viewed by the optical sensor. Shading of the viewed area causes the reading to change. Adjust wand height until the viewed area fills as much of the reflectance panel as possible without getting very close to the edge.*

# 3.0 Post Operation Procedures

This section describes procedures that you will follow after collecting data.

## Procedure 3.1 - Moving Data to a Computer

1  Connect the console to your computer with the USB cable. It will appear as a mass storage drive named LAI.

2  Open the data folder in the LAI drive.

3  Locate the LAI file (look for name it was given for logging), and drag or copy it to a directory on your computer.

> **Note:** The LAI-2270C Control Unit will not be recognized if it is in Logging Mode or a menu, so be sure to enter the Monitor Mode by pressing EXIT, or just turn off the control unit.

## Procedure 3.2 - LAI-2000 File Transfer - RS-232

The steps below describe how to import data from an LAI-2000 using FV2200:

1  Click the **Acquire** button to launch the Acquire Wizard. Enable the LAI-2000 radio button and click **Next**.

2  Connect the LAI-2000 to the serial port on your computer with a 9-pin RS-232 cable. On the LAI-2000, press **FCT 31** and enter the following settings: **Baudd=4800; Data bits=8; Parity=none; XON/XOFF-F=NO**.

3  Press **FCT 33** and enter the following: **Format: Standard; Print Obs: YES**.

4  Click **Next**.

5  Select the serial port that is attached to the LAI-2000 and click **Next**.

6  Choose whether you would like to route to a view (check **Add to View**), save the file, or both. You may open the files in any of the current view tabs or a new view tab, and save multiple files as one file.

7  On the LAI-2000, Press **FCT 32** and enter the page range. The incoming data will be displayed in the Wizard window, as well as routed to a view and/or saved in a file, depending on what you selected.

8  Click **Finish** and FV2200 will process the last file that was downloaded. Note that the last file received will not be processed (added to a view, or written to disk) until you click the **Finish** button.

## Procedure 3.3 - Loading Data Files into FV2200

The FV2200 software package can be used to read data files directly from the console (connected with a USB cable), or files can be dragged to the computer and read from there (*Procedure 3.1 - Moving Data to a Computer* on the previous page).

1  Launch FV2200 on your computer (see *Data Analysis with FV2200* on page 7-1).

2  Click the **Open** icon or **File > Open** and navigate to the stored file.

3  Double click the file to open it, or select multiple files and click **OK**.

Alternatively, you can drag the data file(s) onto the main window: The file(s) will be opened in the current view, or if there are no views, one will be created. On Mac and Windows operating systems, you can drag and drop the data file(s) onto the FV2200 icon.

## Procedure 3.4 - Converting LAI-2000 file to LAI-2200C

There are a couple of ways to do this. To convert a single file, you can use the **Current** tab of the Details window. The advantage of this method is that you have an opportunity to specify sensor serial numbers, which are useful when doing importing and adjusting records (*Procedure 3.8 - Import A and Adjust A Records - FV2200* on the next page). Another method of converting formats involves saving files in a view.

Details for both methods are included in the *FV2200 User Guide* on the "Help" tab of FV2200.

## Procedure 3.5 - Excluding Rings from Analysis - FV2200

Mask attributes can be changed in the FV2200 software so that selected rings are excluded.

1　In the Main Window, select the files that you wish to recompute, and click the **Recompute** button (or click **Edit > Recompute**). The **Recompute Observations** dialog box will appear. Alternatively, double-click a data file to open the File Details window, select the Header tab and click **Change…**

2　Enable the **Change Mask** box, then unselect the box beside each ring that is to be omitted.

3　Click **OK**. Changes to calculations will also be displayed in the "Log" section of the Main Window.

## Procedure 3.6 - Interpolating A Records - FV2200

There are a couple of ways to do this:

- For one or more files, use the **Recompute** tool, check the **Recompute Transmittance** box, and check the **interpolation** radio button.
- For a single file, open the Details view, click the Header tab, then click the **Change…** button in the **Canopy Model** and **Mask** box.
- Use the Details view, click the Current tab, and edit the middle item of the **Transcomp=** line to be an i, and click **Keep**.

TransComp= a-i-s

- If the file has not had **A** records imported yet, you can specify that the **A** records are to be interpolated in the Import dialog box.

## Procedure 3.7 - Recomputing a Data File - Console

1 Go to **MENU > Data > Console**.
2 Select a data file.
3 Select **Recompute** to recalculate LAI or other variables.

This can also be done with FV2200 using **Edit > Recompute**.

## Procedure 3.8 - Import A and Adjust A Records - FV2200

Detailed examples are in the FV2200 2.0 User Guide (Access in the Help menu). Here is a simplified outline:

1 Open the "above" and "below" file(s). You may elect to put them into one view.

2 If match files are involved, load them as well.

3 Open the Import dialog (**Edit > Records > Import**).

4 If imported readings are to be adjusted, click the **Adjust** box, and select the match method to be used.

5 Check the appropriate boxes in the list of files, identifying the match files(s), source, and destination.

6 Click **OK**.

# Procedure 3.9 - Generating K records from Sequences

1. Load the file into FV2200.
2. Click the Scattering tool icon.

3. Click "K Records"

4. Select "Make K from Sequence."

5. Enter measurement details.

6. Check the files according to the input sequence(s) in the file.
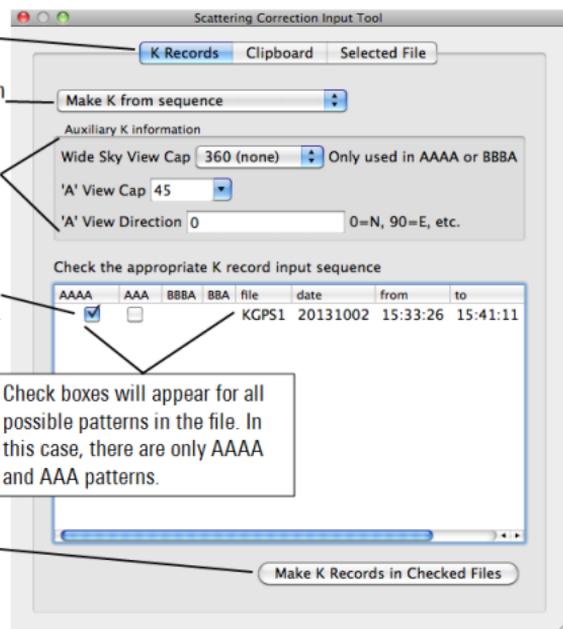
7. Click "Make K Records..."



Normally, you only check one pattern (AAAA, AAA, etc.) per file. You can get away with mixing certain patterns, however, such as AAAA and AAA, or BBBA and BBA provided the sequences do not run together. In other words, **4A** or **3A** sequences surrounded by **B** records

would be fine, or **3B** or **2B** records surrounded by **A** records would be fine. (You would not want to mix **A** sequences with **B** sequences, however). The order that FV2200 converts records in a file (if doing more than one sequence in the file) is this: **4A**, then **3A**, then **3BA**, then **2BA**. So, if you have **4A** and **3A** together, the **4As** will be done first, before the **3As**. If you do check more than one pattern for a file, you will see a warning. It won't stop you; it's just a check to see if you know what you are doing.

## Procedure 3.10 - Importing K Records

If you have **K** records, but not in the right file, or need to share **K** records among multiple files, then follow these steps (also illustrated in *Figure 8-2* on the facing page):

1  Put the source and destination files (the files that have **K** records, and the files that need them) into the same view, and make that the active view.
2  Open the Scattering tool (**Edit > Scattering**).
3  Click the **K Records** tab.
4  Set the drop-down menu to **Import K Records**.
5  In the file list, check the **Source** and **Dest** boxes as needed.
6  Click the **Import K Records** button.

FV2200 is smart about importing **K** records; it only copies the ones that are needed for any given file, based on the times of the **B** records in the destination files. It will always import at least one, and more if they are available and if the **B** record times warrant it.
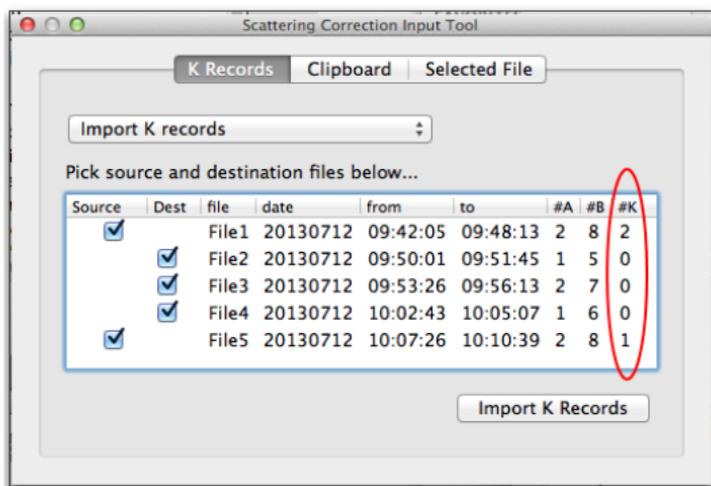
*Figure 8-2. Importing K Records. K records can be copied from files that have them to files that need them. Only the closest-in-time K records are copied.*

## Procedure 3.11 - Set Scattering Inputs for a Group of Files

Examples are in the FV2200 2.0 User Guide (Access in the Help Menu). Here is a simplified outline:

1   Put the files for which you want to do scattering correction into a common view, and make it the active one.

2   If any of the files contain **K** Record precursors (e.g. **4A** sequences), generate the **K** records (*Procedure 3.9 - Generating K records from Sequences* on page 8-41).

3   If any of the files need to import **K** records, do that next (*Procedure 3.10 - Importing K Records* on the previous page).

4   If any of the files need to import **A** records, do that next (*Procedure 3.8 - Import A and Adjust A Records - FV2200* on page 8-40).

5  If there are still files with no **K** records, you can gen-
   erate them based on assumptions:
   A.  Click the **K Record** tab in the Scattering tool
       (**Edit > Scattering**).
   B.  Set the drop-down menu to **Make K Records
       from Assumptions**.
   C.  Set the input fields, and select the Target files.
   D.  Click the **Generate** button.
6  Set remaining inputs:
   A.  In the view, highlight the file(s) that are to receive
       these inputs.
   B.  Click the **Clipboard** tab (*Figure 8-3* below) in the
       Scattering tool (**Edit > Scattering**).
   C.  Set the input values.
   D.  Click the **Update** button.
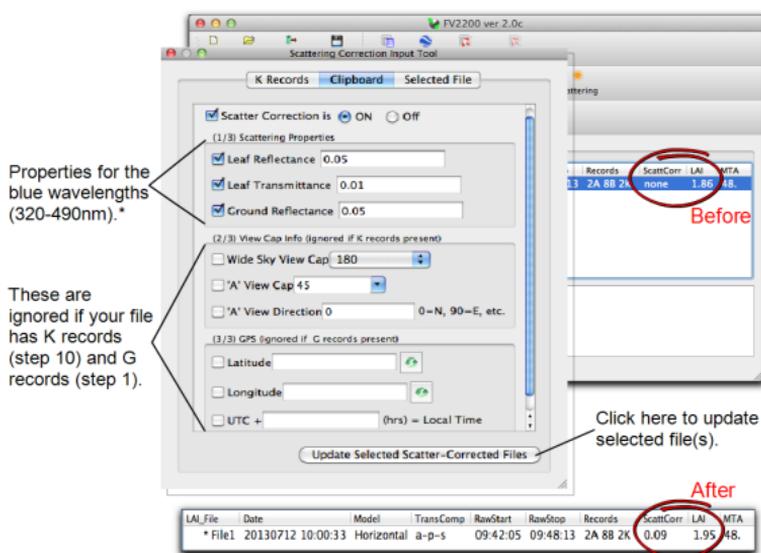


*Figure 8-3. Clipboard for scattering correction inputs. For
information on obtaining scattering properties, see Required
Inputs for the Scattering Model on page 10-13 .*

# Procedure 3.12 - Combining Multiple Files - FV2200

The Combine Files dialog (**File > Combine**) lets you pick a selection of files for which all of the data records are to be combined. The file header information of the resulting file will be based on the first file's headers in the source list.

If you need a more customized method to combine files, you can simply cut and past from the Detail View. The thing to watch if you do that, however, is the Contributing Sensor information and the Sensor ID values of each record. The Combine Files automated routine takes care of relating sensor IDs (W1, W2, etc.) to the proper sensor in a new list. For example, if one file has one Contributing Sensor, say serial # 1234, and another file has a different one (#4321), if you combine by cut-and-pasting records, all files will have sensor ID's of W1, and differences will be lost. The automated combine, however, will leave you with W1 and W2 records, with both sensors appearing in the Contributing Sensor list labeled appropriately as W1 and W2.

# Procedure 3.13 - Determining LAI for each B record - FV2200

Double click the file to get the Details view, and click on the **Gap Fractions** tab.



# 4.0 Miscellaneous Procedures

This section describes procedures that you may nned to do under special circumstances.

## Procedure 4.1 - Sky Variability Test

The sky variability test is discussed and demonstrated in *Sky Variability Tests* on page 5-2.

1  Log a file of **A** readings with a sensor mounted on a tri-pod, logging at regular intervals—perhaps 10 seconds.

2  Move the file to a computer, and load it into FV2200.

3  Double click on the file to open the Details window.

4  Click the **Sky Test** tab in the Details window.

Section 9.

# Instrument Software Reference

This section provides a description of the functions that are available through the LAI-2200C Control Unit software.

## Main Menu

### 1 Wand Setup

Select Wand X (name) or Y (name).

#### 1.1 Set Name

These fields are used to name the optical sensors. When an optical sensor is named, the name is stored in the optical sensor. For example, if an optical sensor is attached to the X port and named "PCH3102", and later attached to the Y port, it will still be called "PCH3102".

#### 1.2 Clock

##### 1.2.1 Set

The **Set** function is used to manually enter the time for the optical sensor clocks (HH:MM, YYYY/MM/DD).

### 1.2.2 Sync

The **Sync** function sets the optical sensor clock based on the control unit clock. Presents Yes/No verification.

## 1.3 Cal Values

Calibration multipliers are set from this field. Use the arrow and numeric keys to enter calibration values. Press **OK** to store the values. These values should match the calibration sheet.

## 1.4 Match Values

These functions pertain to the match values for the selected wand.

### 1.4.1 View / Set Values

**View/Set** allows you to view and/or edit the current values, or reset them to the calibration values by pressing **LOG**.

### 1.4.2 Compute Values

Two wands must be connected for this. The wand selected when entering the menu will be matched to the other. **Compute** will determine the values by measurement: You will need a second wand connected to do this, and both wands positioned and stable, viewing the same view of the sky (Don't do this indoors with artificial light, or looking out a window - tiny variations in views can cause large errors in those environments.) When you select "Yes", the match will be performed.

## 1.5 Auto Log

### 1.5.1 On/Off
### 1.5.2 Start Time
### 1.5.3 Stop Time
### 1.5.4 Frequency

**Auto Log** and the subsequent menu options are used to configure automatic logging, start time, stop time, and frequency.

# 2 Log Setup

These settings apply to new data, not existing data.

## 2.1 Transcomp

### 2.1.1 Define above:

This field defines how the sensor determines which readings are above-canopy and which are below-canopy.

**Compare:** The console will compare adjacent records to determine which type (A or B) has consistently higher values for active (non-masked) rings. That type will then be considered the above-canopy record type.

**A:** Means that readings taken while the optical sensor "Above" LED is illuminated will be considered above-canopy readings when calculating LAI.

**B:** Readings taken while the optical sensor "Above" LED is *not* illuminated will be considered below-canopy readings when calculating LAI.

### 2.1.2 Determine Above:

This field defines how the sensor uses above-canopy readings when computing LAI.

**Previous**: Uses the previous above-canopy record in the file to compute LAI.

**Interpolate**: Interpolates between two closest-in-time above-canopy records to generate each required above-canopy record. This is particularly useful when sky conditions are changing rapidly.

**Closest**: Associates each above-canopy record with the closest below-canopy record (in time) to compute LAI.

### 2.1.3 Bad Readings:

Bad readings occur when a below reading exceeds the value of a corresponding above reading (see page *Bad Readings* on page 4-7). There are two options:

**Skip**: The instrument will beep if a below reading has transmittance >1.0. It will log the below reading, but it will not use the record when computing LAI.

**Clip**: The transmittance for that ring in that record will be taken to be 1.0 when LAI is computed.

## 2.2 Prompts
**Prompt1:**
**Resp1:**
**Prompt2:**
**Resp2:**
Set prompts to prompt the user for additional information that will be recorded with each data file.

## 2.3 Obs Remarks

Remarks can be entered for each logged record. Remarks are set at this menu level or changed for individual records by entering the Log Setup menu while in logging mode. Changes to the remark are saved with each subsequent data file.

## 2.4 Angles

### 2.4.1 Sensor Angles:

1: 7.00
2: 23.00
3: 38.00
4: 53.00
5: 68.00

Angles in these fields are set to reflect the view of each ring in the sensor.

## 2.5 Distances

### 2.5.1 Distance Vectors

1: 1.008
2: 1.087
3: 1.270
4: 1.662
5: 2.670

The values are the average path length each ring sees through the canopy. By default, the values are $1/\cos \theta$. For large, flat uniform canopies, this is sufficient; canopy height does not matter. For isolated canopies, the values should represent actual path lengths in meters.

## 2.6 Masks
### 2.6.1 Use Ring
Ring1: <YES | NO>
Ring2: <YES | NO>
Ring3: <YES | NO>
Ring4: <YES | NO>
Ring5: <YES | NO>

Determines which rings are used in LAI calculations.
To exclude a ring, set its value (use ← and →) to No.
To reset (all rings to Yes), press the **LOG** button
while viewing this screen.

## 2.7 Controlled Sequence
Use: Yes|No
Reps: up to 41
Pattern:

## 2.8 Console AutoLog
Active: < On | Off >
Period: xx

The logging period can be entered in multiples of 5
seconds with a maximum of 3600 seconds (1 hour).

## 2.9 PAR Sensors
### 2.8.1 Port 1
### 2.8.2 Port 2
Enabled: < On | Off >
Name: Port 1
Cal: xxxxx

These fields are used to configure LI-COR radiation
sensors. Enable the port by selecting On, Name the
sensor, and enter the calibration multiplier for the
sensor.

## 2.10 GPS
Active: < On | Off >
Log GPS: < Yes | No >
When: < A | B | Any >

# 3 Data

## 3.1 Console Data
### 3.1.1 Select data file:

**3.1.1.1 Quick View**
Shows the file header, which includes the file name, time and date created, responses to prompts, LAI, SEL, ACF, MTA, SEM, DIFN, and SMP (sample size). This also shows GPS information if the GPS is on.

**3.1.1.2 View**
3.1.1.2.1 View Header

Shows file name, time and date created, responses to prompts, LAI, SEL, ACF, MTA, SEM, DIFN, and SMP (sample size). This also shows GPS information if the GPS is on.
3.1.1.2.2 View ANGLES/MASK

Shows angles and masks used to compute the selected data file.
3.1.1.2.3 View CNTCT #/STDDEV

Shows contact number and standard deviation computed for the selected data file.

3.1.1.2.4 View AVGTRANS/GAPS

Shows average transmittance and gap fraction computed for the selected data file.

3.1.1.2.5 View DISTS/ACFS

Shows distances and apparent clumping factors for each ring.

3.1.1.2.6 View Observations

Shows ring values for each above and below reading in the file. Use the left/right arrow keys to scroll through readings.

### 3.1.1.3 Edit

These options pertain to the selected data file only.

3.1.1.3.1 Edit Angles

Sensor Angles: Edit the angles used in computations. Press **OK** to save new settings, **EXIT** to cancel, and **LOG** to reset to default settings.

3.1.1.3.2 Edit Mask

Use Mask: Apply a mask to any ring that is not to be used in computations. Press **OK** to save the new settings, **EXIT** to cancel, and **LOG** to reset to default values.

3.1.1.3.3 Edit Distances

Distance Vectors: Change these values to alter distances used in computations. Press **OK** to save the new settings, **EXIT** to cancel, and **LOG** to reset to default values.

3.1.1.3.4 Edit Transcomp

Use this field to change how the instrument defines above-canopy readings, determines above-canopy readings, and treats bad readings. A full description is in section 2.1 above.

3.1.1.3.5 Import Observations

This function can be used to import **A** or **B** records from another file.

3.1.1.3.6 Strip Observations

This function can be used to remove all **A** or **B** records from a file.

### 3.1.1.4 Recompute

Recomputes values for the selected data file. Use if any changes have been made to the file.

### 3.1.1.5 Delete

Permanently deletes the selected file.

### 3.1.1.5 Rename

Prompts for a new file name for the selected file.

## 3.2 Wand Data

*3.2.1* Download – to transfer data from the wand to the control unit.

*3.2.2* Purge – to delete data files from the wand.

# 4 Console Setup

## 4.1 Set Time

### 4.1.1 Console Time

Prompts for time and date. Use the up and down arrow keys to set time and date, or set via GPS UTC if available.

## 4.2 Auto Off Timer

Set the duration that the control unit will remain "On" before powering off automatically. The auto off timer can be set to 5-60 minutes in increments of 5 minutes using the up/down arrow keys.

## 4.3 Beeper

Turns the instrument beeper "On/Off". Select the desired setting and press **OK**.

# 5 Firmware

## 5.1 Console

### 5.1.1 Info
### 5.1.2 Upgrade

See page *Console Firmware* on page 2-12 for details.

## 5.2 Wand

### 5.2.1 Info
### 5.2.2 Upgrade

See page *Optical Sensor Firmware* on page 2-13 for details.

Section 10.

# Theory

The LAI-2200C measures the probability of seeing the sky when looking up through a vegetative canopy in different directions. These measurements essentially contain two pieces of structural information about the canopy: 1) the amount of foliage in the canopy and 2) the foliage orientation. This section describes the details of how the LAI-2200C extracts this information from its measurements.

## Calculations

As a beam of light passes through a plant canopy, there is a certain probability that it will be intercepted by foliage. The probability of interception is proportional to the path length, foliage density (area of foliage per volume of canopy), and foliage orientation. If foliage elements are small compared to the overall canopy, and they are randomly distributed in the sensor view, then it is well known that a beam of light from zenith angle $\theta$ has a probability of $P(\theta)$ of non-interception:

$$P(\theta) = e^{-G(\theta)\mu S(\theta)}$$

10-1

where $G(\theta)$ is the fraction of foliage projected toward $\theta$, $\mu$ is foliage density (m$^2$ foliage per m$^3$ canopy volume), and $S(\theta)$ is path length (m) through the canopy at angle $\theta$. Miller (1967) gives the exact solution for $\mu$ as

$$\mu = 2 \int_0^{\pi/2} -\frac{\ln P(\theta)}{S(\theta)} \sin \theta \, d\theta \qquad \text{10-2}$$

## Foliage Density and Leaf Area Index

In a horizontally large, homogeneous canopy, path length, $S(\theta)$ is related to canopy height $h$ by

$$S(\theta) = \frac{h}{\cos \theta} \qquad \text{10-3}$$

In such a canopy, the relation between leaf area index $L$ and foliage density $\mu$ is

$$L = \mu h \qquad \text{10-4}$$

Substituting these into (10-2) yields

$$\mu = \frac{2}{h} \int_0^{\mu/2} -\ln P(\theta) \cos \theta \sin \theta \, d\theta$$

$$L = \mu h = 2 \int_0^{\pi/2} -\ln P(\theta) \cos \theta \sin \theta \, d\theta \qquad \text{10-5}$$

Thus, we can use a common formula 10-7 for computing either $L$ or $\mu$: For $L$, we use $S(\theta) = 1/\cos\theta$ (height $h$ does not matter because it cancels out of equation 10-5, and for computing $\mu$ we use actual values of $S(\theta)$. The difference between $L$ and $\mu$ is driven by $S(\theta)$.

## Clumping

When multiple observations of $P(\theta)$ are available, there are two ways they can be combined: The values of $P(\theta)$ can be averaged:

$$\mu = 2 \int_0^{\pi/2} -\frac{\ln \overline{P(\theta)}}{S(\theta)} \sin \theta \, d\theta \qquad \text{10-6}$$

or the values of $\ln P(\theta)$ averaged:

$$\mu = 2 \int_0^{\pi/2} -\frac{\overline{\ln P(\theta)}}{S(\theta)} \sin \theta d\theta \qquad \text{10-7}$$

Equation 10-7 will account for clumping (on spatial scales larger than the field of view of the sensor), but equation 10-6 is appropriate for determining effective leaf area index $L_e$, which by definition must ignore clumping.

The LAI-2200C computes both of these, and uses equation 10-7 for its reported leaf area index value $L$, and the ratio of equations 10-6 and 10-7 for computing $\Omega_{app}$, the apparent clumping factor (Ryu et al. 2010).

$$\Omega_{app} = \frac{2 \int_0^{\pi/2} -\frac{\ln \overline{P(\theta)}}{S(\theta)} \sin \theta d\theta}{2 \int_0^{\pi/2} -\frac{\overline{\ln P(\theta)}}{S(\theta)} \sin \theta d\theta} \qquad \text{10-8}$$

Effective leaf area index, $L_e$, can be computed by

$$L_e = L\Omega_{app} \qquad \text{10-9}$$

## Foliage Orientation

Once $L$ or μ is determined from equation 10-1, equation 10-2 can be solved for the orientation function $G(\theta)$.

$$G(\theta) = \frac{-\ln P(\theta)}{\mu S(\theta)} \qquad \text{10-10}$$

*Figure 10-1* on the next page shows the theoretical values of $G(\theta)$ for an ideal canopy whose foliage is random both in position and azimuthal orientation, but inclined at a

fixed angle. Curves for ten different foliage inclination angles are shown.
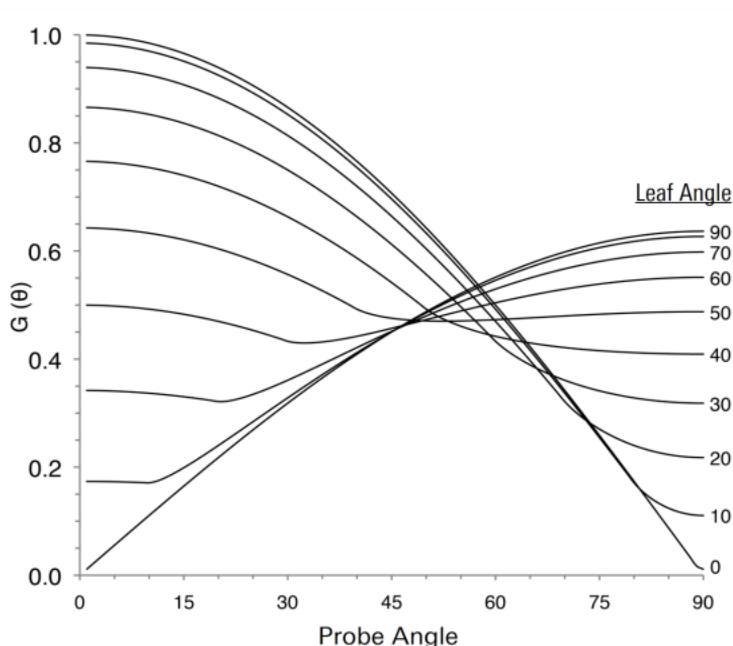


*Figure 10-1. Idealized relationship between projected foliage area and direction for various foliage inclination angles, after Warren Wilson (1959).*

The (rad$^{-1}$) LAI-2200C calculates foliage mean tilt angle $\alpha_f$ after the manner of Lang (1986), using an empirical polynomial relating inclination angle to the slopes of the idealized curves between 25° and 65° (data in *Table 10-1* on the facing page, plot in *Figure 10-2* on the facing page).

Table 10-1.

| MTA (degrees) | Slope | MTA (degrees) | Slope |
|---|---|---|---|
| 1 | -0.6964 | 50 | -0.1547 |
| 10 | -0.6859 | 60 | 0.1180 |
| 20 | -0.6546 | 70 | 0.3164 |
| 30 | -0.5855 | 80 | 0.4131 |
| 40 | -0.4105 | 89 | 0.4431 |
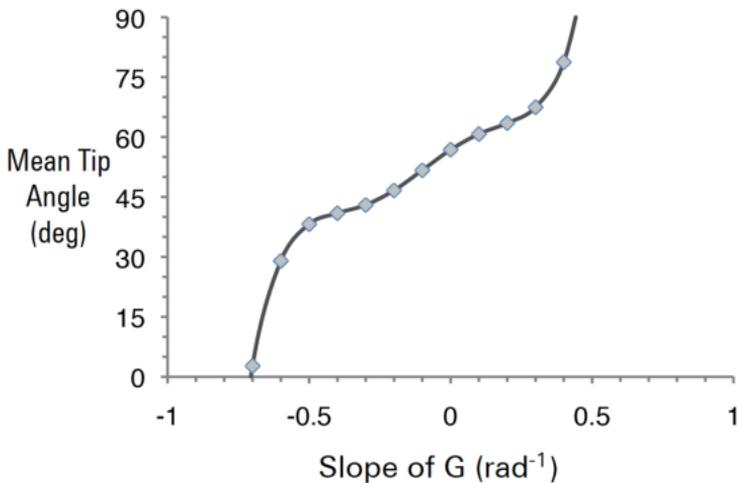


*Figure 10-2. Plot of equation 10-22, which relates slope of the foliage orientation function to average inclination angle. 0° leaf angle is horizontal, and 90° is vertical.*

## Implementation Algorithms

In this section, the subscript $i$ refers to optical sensor rings ($i$=1…5), and the subscript $j$ refers to observational pairs ($j$=1…N$_{obs}$). $B_{ij}$ is the $j^{th}$ below-canopy observation, $i^{th}$ ring, and $A_{ij}$ is its corresponding above canopy reading.

## AVGTRANS

The average probability of light penetration into the canopy is computed by

$$\overline{P(\theta_i)} = \frac{1}{N_{obs}} \sum_{j=1}^{N_{obs}} \frac{B_{ij}}{A_{ij}} \qquad \text{10-11}$$

The 5 values of $\overline{P(\theta_i)}$ are labeled AVGTRANS in the LAI-2200C data file.

## GAPS

The probability of light penetration based on averaging the logarithms of transmittance for the $i^{th}$ ring is computed from

$$G_i = e^{\left(\overline{\ln P(\theta_i)}\right)} = e^{\left(\frac{1}{N_{obs}} \sum_{j=1}^{N_{obs}} \ln \frac{B_{ij}}{A_{ij}}\right)} \qquad \text{10-12}$$

The values of $G_i$ are labeled GAPS in the data file.

## LAI and CNTCT#

The leaf area index $L$ for the file, labeled LAI, is computed from

$$L = 2 \int_0^{\pi/2} -\frac{\overline{\ln P(\theta)}}{S(\theta)} \sin\theta d\theta = 2 \sum_{i=1}^{5} \overline{K_i} W_i \qquad \text{10-13}$$

where

$$\overline{K}_i = \frac{1}{N_{obs}} \sum_{j=1}^{N_{obs}} \frac{-\ln\left(\frac{B_{ij}}{A_{ij}}\right)}{S_i} \qquad \text{10-14}$$

and

$$W_i = \sin\theta_i d\theta_i$$

10-15

$K_i$ is sometimes called the contact number, and is reported with the label CNTCT# in the data file. For further explanation of $W_i$, see Weighting Factors, below.

## ACF and ACFS

An apparent clumping factor for each ring, labeled ACFS in the LAI-2200C data file, is computed from

$$\Omega_i = \frac{\ln\overline{P(\theta_i)}}{\overline{\ln P(\theta_i)}} = \frac{\ln\left(\frac{1}{N_{obs}}\sum_{j=1}^{N_{obs}}\left(\frac{B_{ij}}{A_{ij}}\right)\right)}{\frac{1}{N_{obs}}\left(\sum_{j=1}^{N_{obs}}\ln\left(\frac{B_{ij}}{A_{ij}}\right)\right)}$$

10-16

A total apparent clumping factor, $\Omega_{app}$, labeled ACF in the data file, is computed from

$$\Omega_{app} = \frac{2\int_0^{\pi/2}-\frac{\ln\overline{P(\theta)}}{S(\theta)}\sin\theta d\theta}{2\int_0^{\pi/2}-\frac{\overline{\ln P(\theta)}}{S(\theta)}\sin\theta d\theta} = \frac{2\sum_{i=1}^{5}-\frac{\ln\overline{P(\theta_i)}}{S_i}W_i}{2\sum_{i=1}^{5}\overline{K_i}W_i}$$

10-17

## SEL and STDDEV

Standard error $L_{se}$ of the leaf area index value is reported as SEL, and is computed from

$$L_{se} = \sqrt{\frac{\frac{1}{N_{obs}}\sum_{j=1}^{N_{obs}}L_j^2 - L^2}{N_{obs}}}$$

10-18

where $L_j$ is the leaf area index calculated for an individual A/B pair

$$L_j = 2 \sum_{i=1}^{5} K_{ij} W_i \qquad \text{10-19}$$

where $K_{ij}$ is the contact value for the pair.

$$K_{ij} = \frac{-\ln\left(\frac{B_{ij}}{A_{ij}}\right)}{S_i} \qquad \text{10-20}$$

The standard deviation $K_{\sigma i}$ of the contact numbers is reported as STDEV, and computed from

$$K_{\sigma i} = \sqrt{\frac{1}{N_{obs} - 1} \sum_{j=1}^{N_{obs}} \left(K_{ij} - \overline{K}_i\right)^2} \qquad \text{10-21}$$

## MTA

Mean Tilt Angle $\alpha_f$ is the average inclination of the foliage in degrees from the horizontal (0=flat, 90=vertical), and is computed from a 5$^{th}$ order polynomial $\alpha(m)$:

$$\alpha(m) = a_0 + (a_1 + (a_2 + (a_3 + (a_4 + a_5 m)\, m)\, m)\, m)\, m \qquad \text{10-22}$$

where

$a_0$=56.81964
$a_1$=46.84833
$a_2$=-64.62133
$a_3$=-158.69141
$a_4$=522.06260
$a_5$=1008.14931

The value of $\alpha(m)$ is constrained so that $0 \leq \alpha(m) \leq 90$. The independent variable $m$ is the slope of the mean contact numbers ($K$) plotted against ring angle $\theta$ in radians.

$$\overline{\alpha}_f = \alpha \left( \frac{m}{L} \right)$$  10-23

## SEM

Standard error of the mean tilt angle is estimated from

$$\alpha_{se} = \left| \overline{\alpha}_f - \alpha \left( \frac{m \pm m_{se}}{L} \right) \right|$$  10-24

where $m_{se}$ is the standard error of the slope $m$. When $m > 0$, we use ($m-m_{se}$); otherwise, we use ($m+m_{se}$).

## DIFN

Diffuse non-interceptance $D$ is the fraction of sky radiation that will penetrate the canopy, averaged over the hemisphere (Norman and Welles, 1983). Note: this is computed from $\overline{\ln P(\theta)}$ not $\ln \overline{P(\theta)}$.

$$D = \frac{\displaystyle\int_0^{\pi/2} G(\theta) \sin\theta \cos\theta d\theta}{\displaystyle\int_0^{\pi/2} \sin\theta \cos\theta d\theta} = 2\sum_{i=1}^{5} \overline{G_i} W'_i$$  10-25

where

$$W'_i = \sin\theta_i \cos\theta_i d\theta_i$$  10-26

This value is reported as DIFN in the data file. FV2200 makes a related computation ($D_{sky}$, labeled DIFN_SKY), that is weighted by sky brightness distribution based on the A readings.

$$D_{sky} = \frac{\int_0^{\pi/2} A\left(\theta\right) G\left(\theta\right) \sin\theta \cos\theta d\theta}{\int_0^{\pi/2} A\left(\theta\right) \sin\theta \cos\theta d\theta} = \frac{\sum_{i=1}^{5} \overline{A_i} G_i W'_i}{\sum_{i=1}^{5} \overline{A_i} W'_i} \qquad \text{10-27}$$

where $\overline{A_i}$ is the average of the $N_A$ above canopy readings in the file.

$$\overline{A_i} = \frac{1}{N_A} \sum_{j=1}^{N_A} A_{ij} \qquad \text{10-28}$$

## Weighting Factors

The weighting factors for LAI and DIFN work out to be (when no rings are masked):

| $\theta i$ | $d\theta i$ | Wi $\sin\theta d\theta$ | W'i $\sin\theta\cos\theta d\theta$ |
|---|---|---|---|
| 7 | 12.2 | 0.041 | 0.033 |
| 23 | 12.2 | 0.131 | 0.097 |
| 38 | 11.8 | 0.201 | 0.127 |
| 53 | 13.2 | 0.290 | 0.141 |
| 68 | 13.2 | 0.337 | 0.102 |

When a ring is masked (excluded from the computations), its weighting value is set to 0. This will increase the weighting of the remaining rings, since their sum must be

$$\sum_{i=1}^{5} W_i = \int_0^{\pi/2} \sin\theta d\theta = 1 \qquad \text{10-29}$$

and

$$\sum_{i=1}^{5} W'_i = \int_{0}^{\pi/2} \sin\theta \cos\theta d\theta = 0.5 \qquad \text{10-30}$$

The values of $W_i$ are available on the FV2200 as the LAI_wt, and the values of $W'_i$ are shown as DIFN_wt.

## Alternative Methods

Gap fractions have been measured using fisheye photographs (Anderson, 1971; Bonhomme and Chartier 1972), by traversing a sunward-pointed sensor beneath the canopy (reviewed by Ross, 1981; Lang et al. 1985; Perry et al. 1988), by linear light sensors (Walker et al. 1988), and by pushing metal probes through the canopy (Warren Wilson, 1959).

See Norman and Campbell (1989), Welles (1990), Welles and Cohen (1996), Gower et al. (1999), Machado and Reich (1999), de Jesus et al. (2001), Mussche et al. (2001), Breda (2003) Hyer and Goertz (2004), Keane et al. (2005), Garrigues et al. (2008) for additional reviews and comparisons.

Mathematical techniques for deducing foliage density and angle distribution from measurements of gap fraction (or contact frequency) have been presented by many authors, including Warren Wilson (1959), Miller (1963, 1967), Philip (1965), Ross (1981), Anderson (1984a, 1984b), Lang (1986, 1987), Lang et al. (1985), Perry et al. (1988), and Norman and Campbell (1989).

## Scattering Correction

One of the traditional underlying assumptions of the LAI-2000 and LAI-2200C has always been that foliage

absorbs all the radiation in the waveband seen by the sensor (320-490 nm). Starting with version 2.0, FV2200 allows this assumption to be set aside, and provides a model (Kobayashi et al, 2013) for correcting measurements for the radiation reflected and transmitted by the foliage.

## How Scattering Correction Works

The algorithm that FV2200 uses for correcting for scattering goes something like this:

1 Compute gap fractions. From the measured gap fractions, calculate a first guess of leaf area index (LAI) and leaf angle distribution (LAD).

2 Predict the scattering effect on gap fractions. Run the Kobayashi model to predict the error that an LAI-2200C would make in a canopy based on LAI, LAD, and the other scattering correction inputs (leaf properties, sky brightness distribution, etc.). The model is a one-dimensional, multi-layer model, having foliage properties that you have specified. Foliage orientation, clumping, and total LAI is based on Step 1.

The model propagates beam and diffuse radiation through the layers, and predicts fractional irradiances on sunlit and shaded leaves in each layer. It then predicts the view that the LAI sensor, and the bottom of the canopy, has of the sunlit and shaded foliage throughout the model, and the resulting radiation errors each ring of a **B** reading would have.

3 Subtract the scattering effect from gap fractions. The gap fractions are then adjusted to remove the predicted scattering effects.

4 The adjusted gap fractions are used to compute a new LAI and LAD. If they have not changed, the process is

done. Otherwise, it's back to step 2 with the adjusted gap fractions.

This process usually takes 4 or 5 iterations.

## Required Inputs for the Scattering Model

The scattering model uses the following inputs:

- **LeafRho:** Average foliage reflectance in the blue (230-490 nm waveband).
- **LeafTau:** Average foliage transmittance in the blue.
- **SoilRho:** Surface reflectance beneath the canopy in the blue.
- **SolarZen:** Solar zenith angle (0° = overhead, 90° = on horizon).
- **SolarAzm:** Solar azimuth angle (0° = North, 90° = East, etc.).
- **SkyViewCap:** The azimuthal view size of WideSky values (e.g. 270°).
- **AViewCap:** The azimuthal view size of ASky values (e.g. 45°).
- **AViewAzm:** The azimuthal direction of ASky values (0° = N, 90° = East, etc.).
- **FBeam:** The fraction of the total incident radiation from the sky that is direct beam, in the blue.
- **WideSky:** The 5 ring values of sky brightness using the SkyViewCap.
- **ASky:** The 5 ring values of sky brightness using the ASky Cap.

### Scattering Properties

The three values for average vegetative reflectance, transmittance, and the surface beneath the canopy (**LeafRho**, **LeafTau**, and **SoilRho**) should be for the 320-490 nm

(blue) waveband. The values could come from spectroradiometric measurements integrated over this waveband, or from a radiometer sensitive in that waveband.

Kobayashi et. al. present a technique for using the LAI-2x00 optical sensor (wand) and a reference panel to determine leaf reflectance (**LeafRho**) and transmittance (**LeafTau**) values. To use this method, follow *Procedure 2.14 - Measuring Leaf Transmittance and Reflectance* on page 8-33. A lens cap with a small hole at the center (1.27 mm in diameter) was attached to the optical sensor. They also used a white halon diffuse reflectance standard panel (25 cm x 25 cm and 99% reflectivity).

## Sky Brightness Properties

Both **WideSky** and **ASky** have the following constraints:

- They need to be made with an unobstructed view of the sky.
- They should be made with the same wand.
- The wands making the measurements should be using the factory calibration values. This is the calibration that relates one ring to another. With this calibration, all of the sensor's rings will read the same in a purely isotropic environment. This (**WideSky** and **ASky**) is the one time in LAI-2200C processing that the rings of the sensor are NOT treated independently, and the factory isotropic calibration is needed.

# Derivation of Formulae for Determining # of B Readings

The guideline presented in Chapter 4 for determining the number of **B** readings (*How Many B Readings?* on

page 4-3) comes from the following analysis:

$$M = m \pm t(n)E$$

<div align="right">10-31</div>

where $M$ is the true mean of a population, $m$ is the mean of a sample of that population, $t(n)$ is the value of the t distribution (ignoring sign) for a 5% probability, and $E$ is the standard error of $m$. We rewrite equation 10-31 in terms of an acceptable uncertainty $\delta$:

$$\frac{M}{m} = 1 \pm \delta$$

<div align="right">10-32</div>

Since standard error E is standard deviation D divided by the square root of the number of samples n, we can express $\delta$ as:

$$\delta = \frac{t(n)D}{m\sqrt{n}}$$

<div align="right">10-33</div>

To solve equation 10-33 for sample size $n$, we find a functional relationship for $t(n)$ by fitting a curve to the form

$$t(n) = \frac{1}{a+bn} + c$$

<div align="right">10-34</div>

and find $a$ = -0.11528, $b$ = 0.060798, and $c$ = 2.9817. Substituting equation 10-34 into 10-33 and solving for $n$ yields

$$n = \frac{-B + \sqrt{B2 - 4bC}}{2b}$$

<div align="right">10-35</div>

where

$$B = a - bc\left(\frac{D}{m\delta}\right)^2 \text{ and } C = -(1 + ac)\left(\frac{D}{m\delta}\right)^2.$$

As a practical matter, the term $D/(m\delta)$ can be determined by a "trial measurement" with the LAI-2200C using some number of **B** readings. These readings should be a fair representation of the diversity of the foliage density. Given *LAI*, *SEL*, and *SMP*, the $D/(m\delta)$ term can be computed from

$$\frac{D}{m\delta} = \frac{(SEL)\sqrt{(SMP)}}{(LAI)\delta}$$

10-36

*Table 10-2* below, from equation 10-35, predicts the number of samples necessary for a 95% confidence that a sampled mean is within some error $\delta$ of a population mean.

Table 10-2.

| $D/(m\delta)$ | $n$ | $D/(m\delta)$ | $n$ | $D/(m\delta)$ | $n$ |
|---|---|---|---|---|---|
| 0.2 | 2 | 1.2 | 8 | 2.2 | 19 |
| 0.4 | 3 | 1.4 | 10 | 2.4 | 22 |
| 0.6 | 4 | 1.6 | 12 | 2.6 | 25 |
| 0.8 | 5 | 1.8 | 14 | 2.8 | 28 |
| 1.0 | 7 | 2.0 | 16 | 3.0 | 30 |

*Table 4-1* on page 4-4 is in terms of SEL and LAI, rather than D and m, and is based on a sample of 6 (SMP) with $\delta = 0.1$.

# Appendix A.

# Troubleshooting

**Console will not power up:**

This could be one of three things: low batteries, a locked processor (try removing the batteries for a few seconds), or a short in a wand (try disconnecting all sensors).

**Can't match sensors (Console Match *Procedure 2.1 - Making Two Wands Match - Console Matching* on page 8-24):**

Be sure both sensors see the same diffuse view. Also, be sure that both wand match values are set to their default values before performing a match. If the match values are not set to their defaults there is a chance that the match will fail. If you are still unable to match the sensors after restoring the default values, reset the match values to those given on the calibration sheet with the sensor. Then perform the match again.

If the sensors see direct sunlight or artificial light, then the match procedure is futile.

**Instrument will not turn off:**

The LAI-2200C will not power off if a data file is open or if it is reading data from the internal memory. Wait a few moments for the data transfer to finish and close any open data files, then try again. If the control unit continues to

be unresponsive, press and hold the power button for 5 seconds. Open data files may be lost. If the LAI-2200C continues to be unresponsive, remove the "AA" batteries for a moment. Replace the batteries. Stored data will not be at risk, but open data files may be lost.

**Instrument (wand or console) locks up:**

For both the wand and console, remove and re-install the batteries.

**Wand not recognized or does not respond to light:**

Disconnect then reconnect the wand. After a few seconds, the control unit should begin displaying values associated with the wand.

**LAI=0**

Check the raw readings on the console or using FV2200. Are there both **A** and **B** records in the file? Do the relative magnitudes of the **A** and **B** records seem correct? Check the number of samples used. If it is 0, then the unit threw out all the **A** and **B** pairs because of bad readings. Set the Transcomp settings to APC and recompute the file.

**Questionable MTA results:**

This may indicate a problem, or be due to the method used by the control unit to compute MTA. Check the DISTS values. If they do not reflect the canopy being measured (isolated canopy or large area), MTA and LAI will be incorrect. Also, the method used by the control unit has the drawback of losing resolution near the extremes of 0° (horizontal leaves) and 90° (vertical leaves). Refer to *Foliage Orientation* on page 10-3 for a plot of the polynomial used. Note that slight changes in slope (the

independent variable) make a big difference at the extremes of MTA. It is not uncommon in a canopy of relatively horizontal foliage for the control unit to give MTA values from 0° to 20° or even 30° from one measurement to the next. If more accurate MTA's are needed, use the FV2200 software to compute a mean tilt angle with the Constrained Least Squares technique.

**Data will not read to memory or transfer to a computer:**

In rare cases, such as after a fall, the SD memory card can slip out of place. Follow these steps to check the SD card and put it back in place if needed:

1 Power off the instrument and remove the AA batteries, if installed (instructions*Maintenance* on page 2-8).

2 Open the instrument case. If the SD card (see *Figure A-1* below) is touching the side of the case, it is disconnected. Continue to step 3 to put it back in place. If there is a gap between the SD card and the instrument case, then the SD card is *not* out of place. In that case, contact LI-COR technical support for assistance.
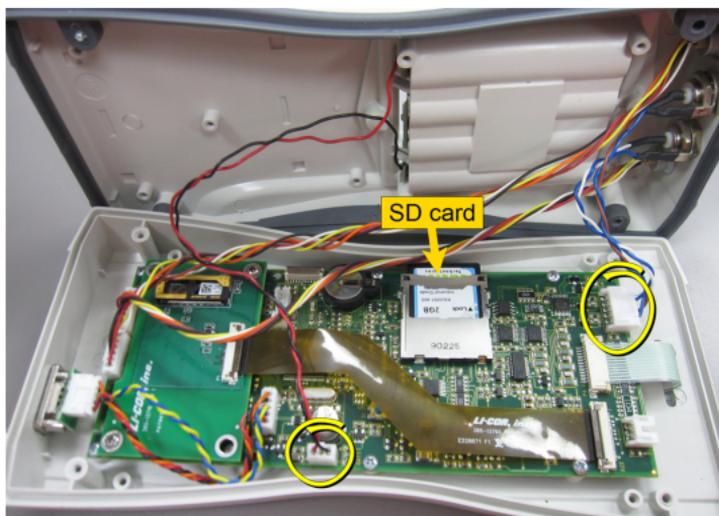


*Figure A-1. Light sensor and power cable connectors are circled.*

3 Disconnect the light sensor and power cable connectors (circled above) from the main PC board.

4  Using a small Phillips screwdriver, remove the six
   screws (see arrows below) that attach the main PC
   board to the instrument case.
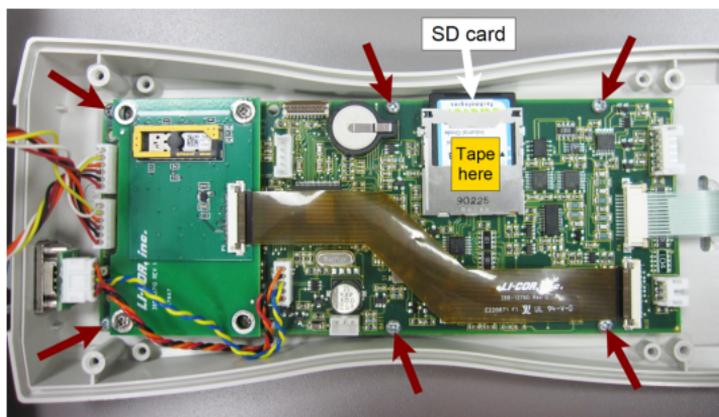


*Figure A-2. Arrows point to the six screws that need to be
removed.*

5  Lift the main PC board slightly above the edge of the
   instrument case, and push the SD card firmly into the
   slot. It will "click" into place when properly inserted.

6  Reinstall the main PC board, replacing the six screws.
   There should now be a small gap between the SD card
   and the side of the insrument case. To help prevent the
   SD card from coming loose again, you can place a small
   piece of tape over the SD card and its metal card slot, as
   indicated in figure 11-2.

7  Reconnect the light sensor and power cable connectors
   to the main PC board.

8  Reassemble the case.

9  Reinstall the AA batteries and battery cover.

If you continue to have difficulty transferring data or read-
ing to memory, please call LI-COR technical support or
email envsupport@licor.com for assistance.

# Appendix B.

# Specifications

## LAI-2270C Control Unit

***Sensor Inputs:*** 2 bulkhead connectors (6-pin) for LAI-2250 Optical Sensors. 2 BNC bulkhead connectors for LI-COR Quantum Sensors.

***Data Storage Capacity:*** 128 MB of FAT16 memory.

***Keypad:*** 22 button tactile response keypad. 10 key numeric keypad with full alphabetic capabilities with 9 function/control keys.

***Display:*** 128x64 graphics LCD display.

Communications: USB (as mass storage device)

***Global Positioning System (GPS RADIONOVA® RF Antenna Module):*** Horizontal position accuracy: 2.5 m CEP (50% Circular Error Probability, Open-Sky, 24hr Static, good view of the sky). Maximum position update rate: 1 Hz. GPS receiver sensitivity, autonomous acquisition: -148dBm. Time to first fix (TTFF), hot start: 1 second. TTFF, warm start: 6s (typical). TTFF, cold start (with good view of the sky): 37 seconds at 90% probability.

***Clock:*** Year, Month, Day, Hour, Minute, Second. Accuracy of ±3 minutes per month.

***Power Requirements:*** 4 "AA" batteries (alkaline, NiMH, or lithium).

***Battery Life:*** 90 hours with 4 "AA" alkaline batteries without optical sensor attached and without GPS enabled. 60 hours with 4 "AA" alkaline batteries with

one optical sensor attached and without GPS enabled. 40 hours with 4 "AA" alkaline batteries without optical sensor attached and with GPS enabled.

*Low Battery Warning:* Display indicates when battery power is <15%.

*Size:* 20.9 x 9.8 x 3.5 cm (8.2" x 3.9" x 1.4").

*Weight:* 0.454 kg (1.0 lb) with batteries.

# LAI-2250 Optical Sensor

*Sensor Inputs:* 1 6-pin bulkhead connector for control unit interface.

*Memory:* 1 MB flash memory for record storage; 1KB EEPROM for calibration and configuration storage.

*Keypad:* 2 button, tactile response keypad.

*Clock:* Year, Month, Day, Hour, Minute, Second. ± 3 minutes per month. Can be synced with control unit clock when joined with a data cable.

*Power Requirements:* 2 "AA" batteries (alkaline, NiMH, lithium).

*Battery Life:* 180 hours of typical operation (with 2 alkaline batteries).

*Optics:* 1.00° maximum decentering error as measured from center of mass of ring. 0.50° maximum magnification error as measured from the center of mass of ring 4.

*Wavelength Range:* ≈320-490 nm

Nominal Angular Coverage:

Ring1: 0.0-12.3°
Ring 2: 16.7-28.6°
Ring 3: 32.4-43.4°
Ring 4: 47.3-58.1°
Ring 5: 62.3-74.1°

*Lens Coating:* MgF2 for improved transmission at oblique angles (external and internal lenses).

*View Caps:* Provide azimuthal masking of view into quadrants of 0°, 10°, 45°, 90°, 180°, and 270°.

*Diffuser Cap:* Used to cover the lens when measuring sky radiation properties for scattering corrections.

*Size:* 63.8 L x 2.9 W x 2.9 D cm (25.1" x 1.125" x 1.125") (Endcap: 4.4 W x 5.1 D cm; 1.75" x 2.0").

*Drilled Cap*: Used to measure leaf optical properties.

*Weight:* 0.845 kg (1.86 lbs) with batteries.

# LAI-2200C General

*Operating Temperature Range:* -20 to 50° C (-4 to 122° F).

*Humidity Range:* 0 to 95% RH, non-condensing conditions.

*Storage Temperature Range:* -40 to 65° C (-40 to 149° F).

# Appendix C.
# Part Numbers

The following is a partial list of parts available from LI-COR Biosciences.

Contact sales (envsales@licor.com), call 1-800-447-3576 (US & Canada), 1-402-467-3576 (international), or order the parts from the LI-COR Biosciences eCommerce website (go to http://www.licor.com/env/ and click on "Order").

| Description | Part # |
|---|---|
| LAI-2270C Control Unit | LAI-2270C |
| LAI-2250 Plant Canopy Sensor | LAI-2250 |
| Optical Sensor Cable | 9922-127 |
| View Restrictor Cap Set | 9920-005 |
| Lens Cap | 6520-020 |
| Diffuser Cap | 6522-117 |
| View Restricting Cap 90° Opening | 6520-021 |
| View Restricting Cap 180° Opening | 6520-022 |
| View Restricting Cap 45° Opening | 6520-023 |
| View Restricting Cap 270° Opening | 6520-029 |
| View Restricting Cap 10° Opening | 6520-030 |
| GPS Board | 9922-135 |
| GPS Flex Cable | 388-13760 |
| 3 V Lithium Battery BR1225 | 442-08614 |
| Optical Sensor Battery Compartment Cap | 345-10735 |
| Storage Case | 9922-125 |

# Appendix D.
# LAI-2000 vs. LAI-2200C

1.0 Operational

1.1 The LAI-2200C uses menus instead of Fct codes. Access the menu by pressing the Menu key. The full structure is given in *Instrument Software Reference* on page 9-1. Changes are shown below, along with the equivalent Fct codes that the LAI-2000 used.

Main Menu
    Wand Setup
        <user picks wand>
        Set Name
        Clock
        Cal Values "**Fct 01 XCal or Fct 02 YCal**"
        Match Values "**Fct 03 Vectors**"
        Auto Log "**Fct 11 Set Op Mode**" for remote above logging.
    Log Setup
        Transcomp "**Fct 16 Bad Reading**", plus other new options.
        Prompts "**Fct 12 Set Prompts**"
        Angles "**Fct 07 Set Angles**"
        Distances "**Fct 06 Set Dists**"
        Masks
        Control Sequence "**Fct 11 Set Op Mode**"
        PAR Sensors "**Fct 08 1,2 Channels**"
        Data
    Wand Data
        Download
        Purge

Console Data
<user picks file>
   View "**Fct 27 View**"
   View Header
   View Ang/Dst
   View Cntct#/StdDev
   View Ang/Gap Frac
   View Observations
Edit "**Fct 25 Edit**"
   Edit Angles
   Edit Mask
   Edit Distances
   Edit Transcomp
   Import Observations
   Strip Observations
Recompute "**Fct 26 Recompute**"
Delete
Rename
Console Setup
   Set Time "**Fct 05 Set Clock**"
   Upgrade Firmware
   Auto Off Timer
   Beeper

1.2 Optical Sensors (Wands) are Smart.

1.2.1. The console can detect when one is attached, and which port it is attached to.

1.2.2. The wands carry their own identity and calibration information with them.

1.2.3. The wands can log data without being attached to a console. Here's the thing to remember: If a wand is attached to the console, and a log file is open, pressing the LOG key on the console or on the wand will add a record to the file in the console. Otherwise, pressing LOG will add a record to the memory of the wand. Also, automatic logging can be set up for a wand (define start time, stop time, and frequency). Any

autologged data always goes the wand memory. To get records out of a wand, attach it to a console, and go to **MENU > Data > Wand > Download**. You can put the data into a new file, or append it to an existing file.

1.3 Less Dependence on Operating Mode. The LAI-2000 had a list of operating modes to choose from (1 Sensor X, 1 Sensor Y, etc.). These have essentially gone away. To illustrate this, we show below how to do the most common of the former modes using the LAI-2200C:

A) 1 Sensor X or Y:

Power on.

Attach a wand.

Press Start/Stop. Name the file.

Use the A/B button on the wand to select if the next reading is A or B.

Log readings.

Press Start/Stop to close the file.

If you want to do a predetermined sequence ( ↑↓↓↓ etc.), you can set that up with **MENU > Log Setup > Control Sequence**.

B) Remote Below, and Remote Above:

Power ON

Attach Both Sensors.

Match one to the other (**MENU > Wand Setup > (pick one to adjust) > Match Values**)

Setup autolog. (**MENU > Wand Setup > (pick the A wand) > Auto Log**)

Detach and deploy the A wand.

Collect B file(s) with the console and remaining wand.

Retrieve the A data. Reattach the **A** wand, and go to **MENU > Data > Wand > Download**, and name a new file.

Merge the A and B readings. Go to **MENU > Data > Console > (pick a B file) > Edit > Import**

**Observations**, and select the **A** file. Repeat for remaining **B** files.

2.0 Computational

2.1 Weighting Factors. Both instruments compute LAI by applying weighting factors to the contact values computed for each ring ("Weighting Factors" on page 10-10). The LAI-2000 assigned ring data to the entire interval between 0 and $\pi/2$, while the LAI-2200C only uses the discrete bands actually viewed by the rings. Refer to *Weighting Factors* on page 10-10 for LAI-2200C weighting factors.

2.2 Ignoring rings. The LAI-2200C allows rings to be ignored in the computation of LAI. To set this for new data files: **MENU > Log Setup > Masks**. To change this on an existing data file: **MENU > Data > Console > (pick a file) > Edit > Edit Mask**

2.3 ACF. The LAI-2200C computes a new value, Apparent Clumping Factor (ACF), which is a value 1 (no clumping) or less (clumping). The LAI-2200C reports an ACF value for each ring (the log of the average transmittance divided by the average of the logs of the transmittances), and a weighted average for all the rings. This is discussed further on page *Implementation Algorithms* on page 10-5.

# Appendix E.

# References

Anderson, M. C., 1971. Radiation and crop structure. In: Z. Sestak, J. Catsky and P. G. Jarvis (eds), Plant Photosynthetic Production: Manual of Methods. W. Junk, the Hague, pp 412-466.

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Appendix F.

# Warranty

Each LI-COR, Inc. instrument is warranted by LI-COR, Inc. to be free from defects in material and workmanship; however, LI-COR, Inc.'s sole obligation under this warranty shall be to repair or replace any part of the instrument which LI-COR, Inc.'s examination discloses to have been defective in material or workmanship without charge and only under the following conditions, which are:

1 The defects are called to the attention of LI-COR, Inc. in Lincoln, Nebraska, in writing within one year after the shipping date of the instrument.

2 The instrument has not been maintained, repaired or altered by anyone who was not approved by LI-COR, Inc.

3 The instrument was used in the normal, proper and ordinary manner and has not been abused, altered, misused, neglected, involved in an accident or damaged by act of God or other casualty.

4 The purchaser, whether it is a DISTRIBUTOR or direct customer of LI-COR or a DISTRIBUTOR'S customer, packs and ships or delivers the instrument to LI-COR, Inc. at LI-COR Inc.'s factory in Lincoln, Nebraska, U.S.A. within 30 days after LI-COR, Inc. has received written notice of the defect. Unless other arrangements have been made in writing, transportation to LI-COR,

Inc. (by air unless otherwise authorized by LI-COR, Inc.) is at customer expense.

5  No-charge repair parts may be sent at LI-COR, Inc.'s sole discretion to the purchaser for installation by purchaser.

6  LI-COR, Inc.'s liability is limited to repair or replace any part of the instrument without charge if LI-COR, Inc.'s examination disclosed that part to have been defective in material or workmanship.

**There are no warranties, express or implied, including but not limited to any implied warranty of merchantability of fitness for a particular purpose on underwater cables or on expendables such as batteries, lamps, thermocouples, and calibrations.**

**Other than the obligation of LI-COR, Inc. expressly set forth herein, LI-COR, Inc. disclaims all warranties of merchantability or fitness for a particular purpose. The foregoing constitutes LI-COR, Inc.'s sole obligation and liability with respect to damages resulting from the use or performance of the instrument and in no event shall LI-COR, Inc. or its representatives be liable for damages beyond the price paid for the instrument, or for direct, incidental or consequential damages.**

The laws of some locations may not allow the exclusion or limitation on implied warranties or on incidental or consequential damaged, so the limitations herein may not apply directly. This warranty gives you specific legal rights, and you may already have other rights which vary from state to state. All warranties that apply, whether included by this contract or by law, are limited to the time period of this warranty which is a twelve-month period

commencing from the date the instrument is shipped to a user who is a customer or eighteen months from the date of shipment to LI-COR, Inc.'s authorized distributor, whichever is earlier.

This warranty supersedes all warranties for products purchased prior to June 1, 1984, unless this warranty is later superseded. To the extent not superseded by the terms of any extended warranty, the terms and conditions of LI-COR's Warranty still apply.

DISTRIBUTOR or the DISTRIBUTOR's customers may ship the instruments directly to LI-COR if they are unable to repair the instrument themselves even though the DISTRIBUTOR has been approved for making such repairs and has agreed with the customer to make such repairs as covered by this limited warranty.

Further information concerning this warranty may be obtained by writing or telephoning Warranty manager at LI-COR, Inc.

Appendix G.

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