AccuPAR

PAR/LAI ceptometer

model *LP-80*

Operator's Manual
Version 1.2

Decagon Devices, Inc.

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Trademarks

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1. Introduction

Welcome to Decagon's AccuPAR model LP-80 PAR/ LAI Ceptometer. The AccuPAR measures Photosynthetically Active Radiation (PAR) in the 400-700nm waveband, and can invert these readings to give you Leaf Area Index for your plant canopy. This manual is designed to help you accomplish your research goals, and understand how to get the most out of your AccuPAR.

Customer Service and Tech Support

When contacting us via fax or email, include the following information: Your AccuPAR's serial number, your name, address, phone and fax number, and a description of your problem

Phone:

Call Monday through Friday, between 8 a.m. and 5 p.m. PST.

US and Canada (toll-free): 1-800-755-2751 .

Outside of the US and Canada: **(509) 332-2756.**

Fax:

(509) 332-5158.

E-mail:

accupar@decagon.com.

Warranty

The AccuPAR has a one year warranty on parts and labor. It is activated upon the arrival of the instrument at your location.

Seller's Liability

Seller warrants new equipment of its own manufacture against defective workmanship and materials for a period of one year from date of receipt of equipment (the results of ordinary wear and tear, neglect, misuse, accident and excessive deterioration due to corrosion from any cause are not considered to be a defect); but Seller's liability for defective parts shall in no event exceed the furnishing of replacement parts f.o.b. the factory where originally manufactured. Material and equipment covered hereby which is not manufactured by the Seller shall be covered only by the warranty of its manufacturer. Seller shall not be liable to Buyer for loss, damage, or injuries to persons (including death), or to property or things of whatsoever kind (including, but not without limitation, loss of anticipated profits), occasioned by or arising out of the installation, operation, use, misuse, nonuse, repair, or replacement of said material and equipment, or out of the use of any method or process for which the same may be employed. The use of this equipment constitutes Buyer's acceptance of the terms set forth in this warranty. There are no understandings, representations, or warranties of any kind, express, implied, statutory or otherwise, (including, but without limitation, the implied warranties of merchantability and fitness for a particular purpose), not expressly set forth herein.

Repair Instructions

If your AccuPAR needs to be sent in for service or repair, call Decagon at **(509) 332-2756** or **1-800-755-2751** (US and Canada)**.** We will ask you for your address, phone number, and serial number. For non-warranty repairs, we will also ask for a purchase order number, a repair budget, and billing address.

When shipping your instrument back to us, include a document listing the complete shipping address, name and department of the person responsible for the instrument, and (most importantly) a description of the problem. This will better help our technicians and our shipping department to quickly expedite repair on your instrument and ship it back to you.

Pack your AccuPAR carefully. Ship it back in the black carrying case, preferably inside a cardboard box. Ship to:

Decagon Devices Inc.
950 NE Nelson Court
Pullman, WA 99163

Repair Costs:

Manufacturer's defects and instruments under warranty will be repaired at no cost. For non-warranty repairs, costs for parts, labor, and shipping will be billed to you. We have a $65 minimum charge for repair that takes one hour or less. For repair over one hour the labor rate is $65/hour.

2. About the LP-80

The AccuPAR model LP-80 is a menu-driven, battery-operated linear PAR ceptometer, used to measure light interception in plant canopies, and to calculate Leaf Area Index (LAI). It consists of an integrated microprocessor-driven datalogger and probe. The probe contains 80 independent sensors, spaced 1cm apart. The photosensors measure PAR (Photosynthetically Active Radiation) in the 400-700nm waveband. The AccuPAR displays PAR in units of micromols per meter squared per second (μmol $m^{-2}s^{-1}$). The instrument is capable of hand-held or unattended measurement.

Specifications

Operating Environment:

- 0° to 50° C (32°-122° F)
- 100% relative humidity

Probe Length: 86.5 cm

Number of sensors: 80

Overall Length: 102 cm (40.25 in)

Probe Cross-Section: 19cm x 9.5cm (.75 x .375 in)

Microcontroller dimensions: 15.8 x 9.5 x 3.3cm (6.2 x 3.75 x 1.3 in.)

PAR Range: 0 to >2,500μmol $m^{-2}s^{-1}$

Resolution: 1μmol $m^{-2}s^{-1}$

Minimum Spatial resolution: 1cm

Data Storage Capacity: 1MB RAM.

Unattended logging interval: User selectable, between 1 and 60 minutes.

Instrument weight: 1.21kg (2.7 pounds)

Data retrieval: direct via RS-232

Keypad: 6-Key menu-driven.

Clock: 24-hour ±1 minute per month.

Interface Cable: RS-232 cable

Power: Four AA Alkaline cells.

External PAR sensor connector: Locking 3-pin sealed circular connector.

Overview of the LP-80

The LP-80's menu-driven interface is designed for ease of use. There are four menus to choose from: PAR/LAI sampling menu, unattended logging menu, file menu, and the setup menu. You navigate between the menus by pressing the MENU button, and select items within each menu using the up and down arrow keys, and the ENTER or ESC keys. An internal bubble level is mounted in the upper right corner of the case to allow you to keep the probe relatively level when making measurements.

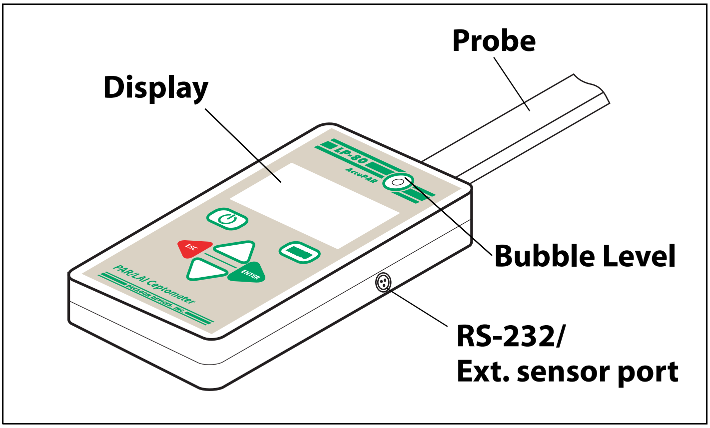
The AccuPAR can be operated in environments with temperatures from 0 to 50 °C, and in relative humidities of up to 100%. The instrument is shipped with an RS-232 interface cable to allow for downloading data to a computer, and an external PAR sensor to allow for simultaneous above and below canopy PAR measurements. The AccuPAR operates on four AA alkaline batteries.

Components of the LP-80 system

The AccuPAR and its accessories come to you in a durable foam-padded carrying case. As you open the case, you should find the following:

- AccuPAR model LP-80
- RS-232 Cable
- Operator's manual
- external PAR sensor
- #1 Phillips screwdriver

Features



Keyboard Operation

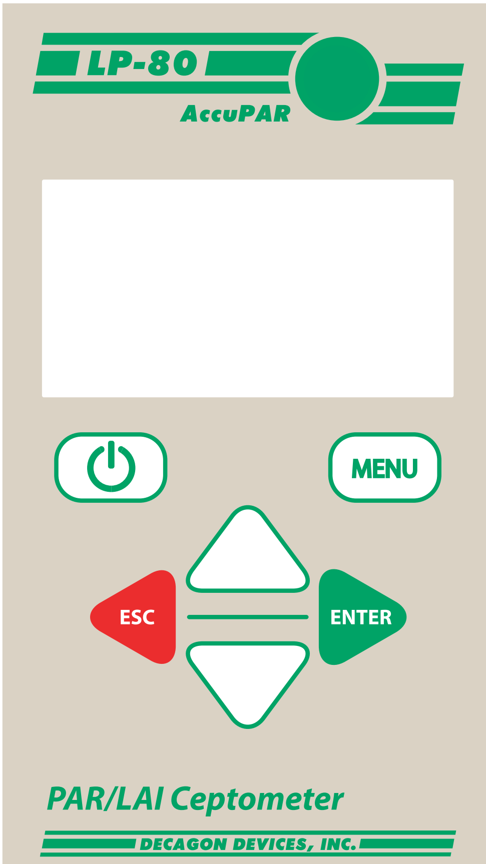


Figure 1: LP-80 Keypad

The LP-80's keypad is a 6-key panel, designed for ease of use and intuitive navigability through the operating system. Here is a brief description of the key functions:

ON/OFF Key: Located in the upper left corner, it turns the instrument on or off. The AccuPAR will turn itself off automatically after 10 minutes of inactivity.

MENU Key: Cycles between the four menus.

UP and DOWN ARROW KEYS: In PAR sampling menu, they initiate above (up arrow) and below (down arrow) canopy PAR readings. In other menus, they are used to navigate to items within those menus and to change numeric values in sub menus.

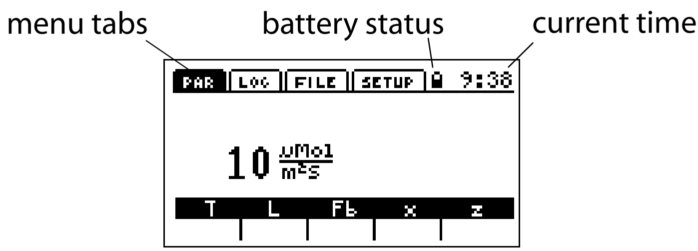
Round Green Key: The circular key in the upper right corner of the keypad (by the AccuPAR logo) also serves the same function as the Down-arrow key. It is designed as an ergonomic alternative when taking multiple below-canopy PAR samples

ESC: Discards the current PAR reading displayed in the lower half of the PAR sampling menu, backs out of FILE menu options and stores changes in SETUP menu options.

ENTER: Saves the current PAR readings in the PAR sampling menu, and selects items in other menus.

Turning on the instrument

When you first turn on the instrument, it will be in the PAR sampling menu, in which you will see real-time PAR data displayed in the center portion of the screen. If you have the external PAR sensor connected, you will also see its real-time PAR data displayed, and indicated by an above-canopy icon.



At any time, you can cycle between the four menus by pressing the MENU key. The menus are indicated by the tabs on the top of the screen, with the active menu highlighted in black. To the right of the menu tabs is the current battery status and the time. Later chapters discuss each menu in detail and how to use the features that each provides.

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3. Definitions

The AccuPAR uses several variables to calculate Leaf Area Index, and displays values for these variables on the screen as measurements are taken. This chapter will discuss these variables and their definitions. If you're not familiar with them, we recommend that you review this chapter before proceeding with measurements.

PAR

PAR (photosynthetically active radiation) is defined as the radiation in the 400 to 700 nanometer waveband. It represents the portion of the spectrum which plants use for photosynthesis. Under a plant canopy, radiation levels can vary from full sun to almost zero over the space of a few centimeters. Therefore, reliable measurement of PAR requires many samples at different locations under the canopy. The AccuPAR measures PAR either manually or in unattended logging mode. Intercepted PAR data can be used for determining important parameters of canopy structure and for the calculation of LAI. An external point sensor may be used to collect instantaneous above canopy PAR measurements when sampling under or within a canopy. You also have the option of segmenting the probe to reflect spatial changes in the plant canopy. This is useful when evaluating discontinuous and irregular canopies, or to limit the size of active sensors along the probe.

Tau (τ)

Tau is another variable in the LAI inversion equations. It is defined as the ratio of below canopy PAR measurements to the above canopy PAR value. It is measured automatically by the instrument, based upon the PAR readings you make. The current Tau value is displayed and updated in the lower left corner of the screen in the PAR menu. Further explanation of the significance of Tau is given in Chapter 9.

LAI (L)

LAI (Leaf Area Index) is defined as the area of leaves per unit area of soil surface. It is a very valuable measurement in helping to assess canopy density and biomass. The AccuPAR calculates LAI based on the above and below-canopy PAR measurements along with other variables that relate to the canopy architecture and position of the sun. These variables are the zenith angle, a fractional beam measurement value, and a leaf area distribution parameter (also known as *x*) for your particular canopy. The AccuPAR automatically calculates both the zenith angle and fractional beam reading, and requires you to input a value for x in the setup menu.

External Sensor

An external PAR sensor is provided with the AccuPAR to allow you to make simultaneous above and below canopy PAR measurements. This is useful if you want to be able to make multiple PAR measurements under the canopy in variable light conditions without having to keep moving the instrument in and out of the canopy to update the above canopy PAR reference.

Zenith Angle (z)

Zenith angle can be defined as the angle the sun makes with respect to the zenith, or the point in the sky directly overhead, vertical to where you stand. The zenith is defined as being 0° and the horizon is 90°. The zenith angle of the sun is necessary for calculation of certain canopy structure parameters, such as LAI. It is calculated by the AccuPAR based on your global position and the time of day, and is displayed in the lower right corner of the screen when taking above and below PAR measurements. To make sure this value is accurate, you must first correctly set the longitude, latitude, date, and time of day in the setup menu.

Fraction of Beam Radiation (F_b)

Fractional beam radiation is the ratio of direct beam radiation coming directly from the sun to radiation coming from all ambient sources like the atmosphere or reflected from other surfaces. A fractional beam radiation value is necessary for calculation of LAI using PAR data. The AccuPAR obtains this value by comparing the above canopy PAR measurement to the calculated value of incoming solar radiation at your location and zenith angle. The current calculated F_b is displayed and updated at the bottom of the screen in the PAR menu.

Leaf Distribution Parameter (x)

Leaf Distribution Parameter (also known as Chi, or x) refers to the distribution of leaf angles within a canopy. The parameter x is the ratio of the length of the horizontal to the vertical axis of the spheroid described by the leaf angle distribution of a canopy. It can also be measured as the ratio of the projected area of an average canopy element (a leaf, for example) on a horizontal plane to its projection on a vertical plane. The default value for x is 1.0, which assumes the canopy angle distribution to be spherical. Onions are good example of a strongly vertical crop. For onions, x would be about 0.7. On the other extreme, strawberries, a crop with a strongly horizontal nature, would have a x value of about 3.

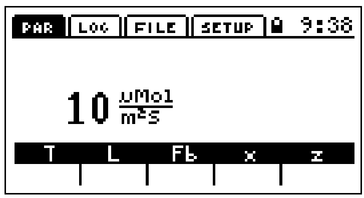
Table one gives some typical values for x. In some cases a range of values is given, indicating the variability that is to be expected for x in any canopy. Fortunately, the value of LAI computed is not strongly dependent on the value of x chosen. The AccuPAR uses a value of x=1.0 as its default.

Table 1: typical *x* values

Crop	*X*
Ryegrass	0.67 to 2.47
Maize	0.76 to 2.52
Rye	0.80 to 1.27
Wheat	0.96
Barley	1.20
Timothy	1.13
Sorghum	1.43
Lucerne	1.54
Hybrid Swede	1.29 to 1.81
Sugar Beet	1.46 to 1.88
Rape	1.92 to 2.13
Cucumber	2.17
Tobacco	1.29 to 2.22
Potato	1.70 to 2.47
Horse Bean	1.81 to 2.17
Sunflower	1.81 to 2.31
White Clover	2.47 to 3.26
Strawberry	3.03
Jerusalem Artichoke	2.16

4. PAR/LAI Menu

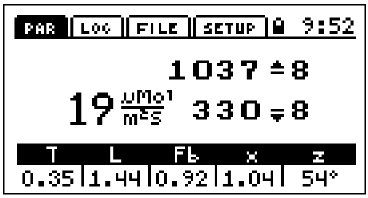
The first menu option is the PAR/LAI sampling menu, which is used for all measurements with the AccuPAR. The default screen is one similar to this:



This screen example indicates that the current real-time PAR level is 10 μmols/m^2/s (this example was taken indoors), and that no above or below PAR measurements have been taken. If the external sensor is attached, the real-time PAR value measured by the external sensor will be also displayed above the real-time probe PAR data.

Taking Measurements

To make an above-canopy PAR measurement, press the up-arrow key in this menu. The resulting value will be displayed in the upper right section of the screen. To make measurements below the canopy, press the down-arrow key or the green circular key in the upper right corner of the keypad. When at least one of both an above and below canopy measurement have been taken, other relevant data is displayed at the bottom of the screen, as shown in this example:

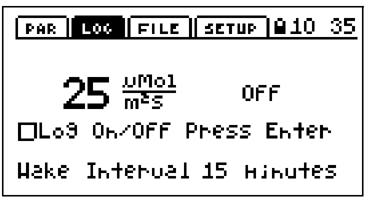


The current calculated Tau (T), LAI value (L) beam fraction (F_b), leaf distribution parameter (x) and zenith angle (z) values are updated and displayed at the bottom of the screen with each subsequent PAR measurement. If the external sensor is attached, both above and below values will be summed each time the down arrow is pressed. Pressing ENTER saves these values to memory. Pressing ESC discards the values. Both options clear the screen for new data. The values displayed at the bottom of the screen are dependent on how you have set up your instrument in the Setup menu. For a more detailed description of these variables and their definitions, please refer to chapter 3 (Definitions) or chapter 8 (Theory).

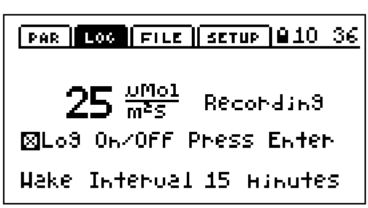
With each above or below canopy measurement, a number appears to the left of the PAR value, indicating the number of measurements taken. The displayed PAR value reflects the average of the samples taken. Therefore, in the above sample screen, eight above and below canopy measurements have been made, so the average of the eight above-canopy PAR values is 1037 µmols, while the average of the eight below-canopy value is 330 µmols

5. Log Menu

When you advance to the LOG menu, the following screen appears:



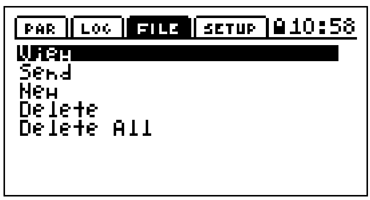
This menu allows you to put the instrument in an unattended datalogging mode. In this mode, the AccuPAR will automatically measure and store PAR data at an interval that you specify. You can select the measurement interval by pressing the up or down arrows. This will allow you to select any value between 1 and 60 minutes. In the above example, it is set to make and store a measurement every 15 minutes. To activate or deactivate the logging mode, press the Enter button. When the logging mode is enabled the screen will change to the following:



The data that is taken in this mode will be stored in the current file that is open at the time of activation. *Note: you can move from this menu to other menus while the logging mode is activated, but the instrument will not log measurements unless it is in the Log menu. Also, when the Log mode is activated, it continues to be active whether or not the AccuPAR's display is on.*

7. File Menu

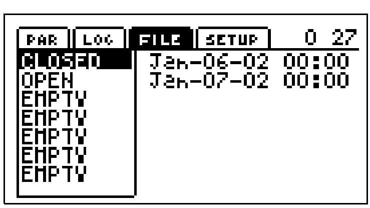
The File menu allows you configure and interact with data that you store with your AccuPAR. When you advance to this menu, the following screen appears: From this menu you can view files and



their relevant data, send the data to your computer terminal for download and analysis, create a new file, delete a specific file, or delete all files. To select one of the options in this menu, scroll to the desired item and press the ENTER key.

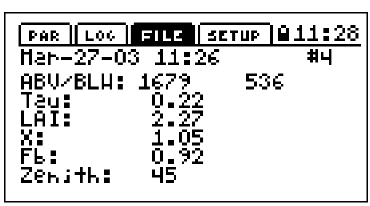
View

When you select "View" from the File menu, you will see a screen such as this one:



The list on the left shows the status of the current files: Closed, Open, or Empty. The file labeled as "Open" is the file you are currently storing data to. "Closed" files are ones that contain previously-stored data. "Empty" simply shows that there is room for other files to be created. The time and date that each file was created is displayed next to its status. In the above example, the file listed as "Open" was created Jan. 7, 2002 at the beginning of the day. Each day at 00:00, the AccuPAR will create a new file. It will then use that file as the default file for data taken that day. If you want to create a separate file, you can do so from the NEW option of the File menu.

You can scroll between different files using the up and down arrows. To view the data from a selected file, press the ENTER key while it is highlighted. The stored data will be displayed. Use the up and down arrows to scroll through the stored data. The values are shown in columns with their corresponding labels as shown..



Send

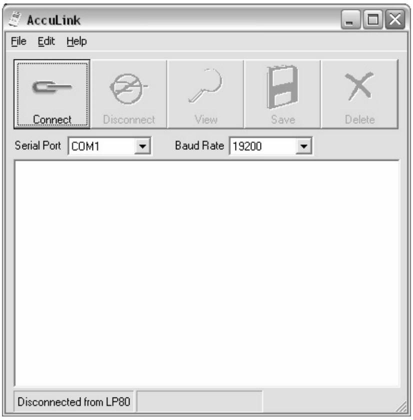
The Send option allows you to download stored data to your computer via the RS-232 cable that came with your system. You can download the data using AccuLink (free software included with your shipment), Windows Hyperterminal or any similar terminal software.

There are three options for downloading data: "**Download Summary**", "**Download Raw**", or "**Download All**". These options are chosen in the Setup menu under "Download Options." "Download Summary" displays the average above and below canopy PAR data for each measurement, with the corresponding values for Tau, LAI, Fb, etc. "Download Raw" displays the PAR values for each measurement that went into the averaged value. It also breaks down each measurement by probe segment. "Download All" displays all the raw data followed by the summary data.

Downloading using AccuLink 2.0

AccuLink is a program designed specifically for downloading data from the AccuPAR. Using AccuLink, you can either send data manually using the "Send" command, or retreive it from the utility software. To install AccuLink, double-click on the the "AccuLink2_0.exe" icon on the CD that came with your LP-80. The program will begin to install in the "Program Files" folder of your hard drive.

1. Once the software is installed, click on the AccuLink.exe to start the program. The following screen will appear:



2. Connect the RS232 from a serial port on your computer to the AccuPAR's external port.
3. Select the correct COM port from the drop-down menu and select the highest baud rate your computer can use.
4. Click on the "Connect" icon to connect to the AccuPAR. All files in the AccuPAR will be displayed on the screen.
5. To view the content of an individual file, click on a file and then click on the "View" icon. The data for that file will be displayed on screen according to how you have set the download options (e.g. Download Summary, Download Raw, etc.) in the Setup menu.
6. To save the data to a specific folder or location, click

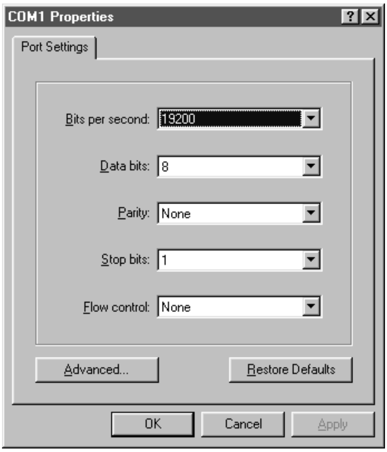
on the "Save" icon and specify a target location for the data. You can also specify the file type in the "Preferences" sub-menu of this option.

Downloading using Windows Hyperterminal

Here are the steps involved for downloading using Windows Hyperterminal, which comes with all Windows operating systems since Windows 95:

1. Open Windows Hyperterminal: From the Start menu, select Programs > Accessories > Communications > Hyperterminal. Click on the Hypertrm.exe icon.
2. At the dialog box prompt, select a name for the new connection, and an icon (if desired).
3. At the "Connect To" dialog box, select an available COM port at the bottom of the screen in the "Connect Using" box.
4. In the Communication Properties Dialog box, select the settings as shown below: 19200 Bits per second (or whatever the baud rate is set for in the AccuPAR's Setup menu), 8 Data bits, no

Parity, 1 Stop bit, and no Flow Control.



5. Once the terminal window opens, click on the File menu and select "Properties." Click on the "Settings" tab, and then click on the "ASCII Setup" button. Check the box that says "Append line feeds to incoming line ends" and then click OK.

6. To set up the terminal program to capture the data, click on the Transfer menu and select "Capture Text." Select the directory where you want to place the data text file and then click "Start."

7. Select "Send" from the AccuPAR's File menu. The list of current files will appear as in the "View" menu. Use the up and down arrows to select the file you wish to download, then press the ENTER key to send the data to your com-

puter. The data will appear on the screen.

8. To finish capturing the text, click on the "Transfer" menu again and select "Capture Text > Stop." Before closing Hyperterminal, save the session with a name you will be able to recognize. The next time you need to download, you will just need to open the Hyperterminal folder and select the name you saved.

9. You may now open the text file in a word processing program or a spreadsheet program like Microsoft Excel.

The following is an example of the data format displayed in the "Download Summary" mode. The number at the top is the AccuPAR's name for the file, followed by the word "DOWNLOAD". In this example, "DOWNLOAD" is followed by "SUM" to indicate that it is downloading the summary data rather than the raw data. The next line displays the time and date the file was created. The following lines display the data stored in the file.

```
0031A4E3
DOWNLOAD SUM
Jun-05-03 13:14
SUM,799,2102.39, 412.70,   0.19,   3.09,   1.00,   0.90,    25
SUM,799,2102.60, 411.70,   0.19,   3.00,   1.00,   0.90,    25
SUM,799,2097.80, 334.39,   0.15,   3.36,   1.00,   0.90,    25
```

The columns are in the following order: download mode (in this case, SUM for summary), minutes into the current day, average above canopy PAR value, average below canopy PAR value, Tau, LAI, Chi, Fb, and zenith angle.

The next example shows what is displayed in the "Download Raw" mode. When you download the raw data, the data for each measurement that went into the average will be displayed. In other words, the data for each "button push" will be displayed rather than their average. This fact can be seen by comparing the raw data below to the summary for the same data shown above.

Again, the number at the top of the displayed data is the AccuPAR's name for the file. In this example, "DOWNLOAD RAW" indicates that it is downloading raw data. The next line displays the time and date the file was created. The following lines display the raw data stored in the file for each PAR measurement, shown in the following order: minutes into the day, PAR value for segment 1, segment 2, etc. through segment 8, and finally the external PAR sensor value (if taken with the external sensor attached):

0031A4E3
DOWNLOAD RAW
Jun-05-03 13:14
BLW,799, 727.20, 723.29, 733.20, 748.29, 733.59, 751.40, 776.20, 782.20,2092.50
BLW,799, 540.09, 535.00, 545.70, 558.70, 542.40, 561.59, 588.90, 592.00,2102.10
BLW,799, 492.60, 486.39, 496.29, 508.29, 491.10, 509.20, 535.40, 536.90,2106.39
BLW,799, 492.60, 486.39, 496.29, 508.29, 491.10, 509.20, 535.40, 536.90,2106.39
BLW,799, 268.70, 266.89, 281.20, 290.60, 289.29, 298.70, 315.39, 315.50,2106.39
BLW,799, 268.70, 266.89, 281.20, 290.60, 289.29, 298.70, 315.39, 315.50,2106.39
BLW,799, 249.00, 248.69, 264.20, 272.70, 275.29, 281.60, 290.89, 290.20,2101.80
BLW,799, 249.69, 248.10, 262.29, 271.10, 274.10, 281.29, 291.20, 291.00,2100.19
BLW,799, 249.69, 248.10, 262.29, 271.10, 274.10, 281.29, 291.20, 291.00,2100.19
BLW,799, 294.39, 291.50, 303.29, 312.70, 306.50, 319.70, 341.10, 343.20,2105.80
BLW,799, 513.29, 512.59, 527.29, 543.50, 531.00, 554.70, 585.90, 590.79,2102.39
BLW,799, 394.60, 394.29, 409.50, 423.10, 410.79, 429.60, 457.20, 458.50,2100.69
BLW,799, 332.89, 334.10, 351.70, 366.10, 357.39, 375.50, 403.50, 405.60,2101.80
BLW,799, 404.39, 403.70, 418.89, 432.60, 419.89, 439.79, 469.60, 472.29,2101.39
BLW,799, 283.10, 283.00, 298.79, 309.29, 305.00, 318.00, 339.50, 342.00,2097.00
BLW,799, 283.10, 283.00, 298.79, 309.29, 305.00, 318.00, 339.50, 342.00,2097.00
BLW,799, 283.10, 283.00, 298.79, 309.29, 305.00, 318.00, 339.50, 342.00,2097.00
BLW,799, 283.10, 283.00, 298.79, 309.29, 305.00, 318.00, 339.50, 342.00,2097.00

New

To create a new file to store your data, press the New option from the File menu. A dialog box will appear asking if you want to create a new file. Press the ENTER key to create the file, or press ESC to escape. By default, the AccuPAR will create a new file at midnight (0:00) each day. Therefore, the data you store on that day will be allocated to that file, unless you specify otherwise.

Delete

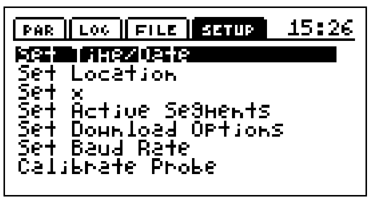
To delete a specific file, select Delete from the File menu. A dialog box will appear asking if you want to delete a file. To proceed, press the ENTER button. Scroll to the file you wish to delete and press the ENTER button again. The file will be deleted and you will be returned back to the File menu. You cannot delete the currently open file.

Delete All

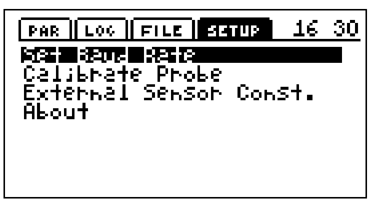
To delete all stored files, select “Delete All” from the File menu. A dialog box will appear asking if you want to delete all files. To proceed, press the ENTER button. To escape, press the ESC button. If you proceed, you will see the words “Please Wait..” while the instrument deletes the files. This may take a minute or so to complete. Once all the files have been deleted, a new file will be automatically created.

7. Setup Menu

The setup menu is where you configure and set most of the parameters that affect the functionality of your AccuPAR. When you scroll to this menu, the following screen appears:



Scrolling further down:



Use the up and down arrows to scroll among the menu items.

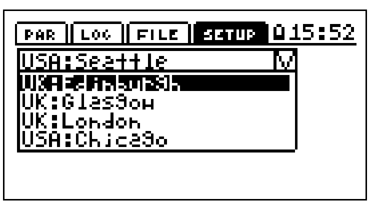
Set Time/Date:

Set your current time and date in this menu. The instrument uses the time and date provided here to calculate its zenith angle and F_b values, so make sure it is accurate. Use the up and down arrow keys to change the values of each item, and use the

ENTER key to move to the next item. At the "Daylight Savings" box, press the up arrow to check the box, or the down arrow to un-check it. Once you have set the time and date correctly, press the ESC key to exit the menu and store the result in memory.

Set Location

You will need to set the correct longitude and latitude for your location in order for your LAI calculations to be correct. This is due to the fact that zenith angle calculation is based not only on the time and date, but the longitude and latitude of the site. When you select this menu item, you will see a large scrolling menu with various countries and cities listed:



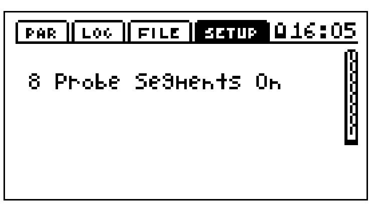
Scroll to your country using the up and down arrows, and select a city closest to your location and in your time zone by pressing the ENTER button. The longitude, latitude, and time offset settings will be displayed. Press the ENTER key to advance to the individual settings, and use the up and down arrows to change the values to correspond to your exact location. Once the values are set correctly, press the ESC button.

Set x

This menu is used to set the *x* (leaf distribution) parameter for the plant canopy you plan to measure. See the next chapter for further explanation of the *x* parameter. To change the value of the *x* parameter, use the up and down arrow keys. When the value is correct, press the ESC button.

Set Active Segments

For some measurement purposes, you may not want to use the entire length of the probe. For such applications, you can turn off sections of the probe, starting from the base and continuing down the probe to the end. When you select this menu, the following screen will appear:



This screen shows that all 8 segments are on, which is the default setting. To reduce this amount, press the up-arrow key until you reach the desired number of active segments. The icon on the right side of the screen will illustrate the active segments as you reduce or increase them. Once you have selected your desired number of segments, press the ESC button. If you have selected active segments smaller than 8, the segment icon will also appear in the PAR/LAI sampling menu to remind you that it is in segmented mode.

Set Download Options

As mentioned in the "File Menu" section of this chapter, you can select the data to be downloaded to a computer. When you select this menu, you have 3 options: Download Summary, Download Raw, and Download All. Here is a brief description of the three options:

- Download Summary: Downloads the average above and below canopy PAR values for each stored item, along with the associated Tau, LAI, x, etc. for the reading.

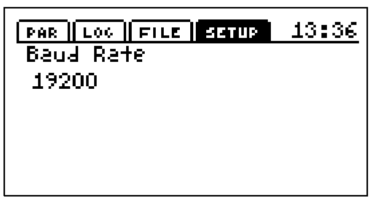
- Download Raw: Downloads the individual PAR data for each reading that went into the averaged value. For each reading, it also displays the individual readings that each of the 8 probe measurement segments measured.

- Download All: Downloads both the summary data and the Raw data for each stored reading.

For a more detailed description and illustration of these options, refer to chapter 7 (File Menu).

Set Baud Rate

This menu is also used to set up the Send menu. This allows you to select the transfer rate of your AccuPAR when it downloads data. The baud rate that you set here must match the baud rate of your computer's terminal program. Upon entering this screen you will see the following:



To change the value, press the up or down arrow key. When you get the desired value, press the ESC button and that value will be stored for future downloads.

Calibrate Probe

The AccuPAR is equipped with a calibrated external PAR sensor. As mentioned earlier, this is used for making simultaneous above and below canopy PAR measurements. It is also used to calibrate your AccuPAR's probe, ensuring that the PAR response between the external sensor and the probe are the same. When you select this option, the following screen appears:

```
PAR | LOG | FILE | SETUP   13 48
Press ESC to exit or
1. Level external sensor
2. Level probe by sensor
3. PAR > 600
4. Press ENTER
```

Typically both the external sensor and the probe are leveled. However, you can also calibrate the AccuPAR on a flat board or platform that you can prop up at an angle to get more direct light from the sun, as long as they both have the same angle.

Direction #3 means that the PAR level must be above 600µmols m^{-1} s^{-1}. Values below this will not update the calibration, so check the PAR levels before proceeding with the calibration.

When you have it ready to calibrate, move out of the probe area to minimize reflection off your body, and press the ENTER button to perform the calibration (it is important not to affect light levels on the probe through shading or reflection). The probe response will be displayed graphically. If you have no external sensor attached while performing the calibration, the calibration graph will not appear and the display will return to setup.

External Sensor Const.

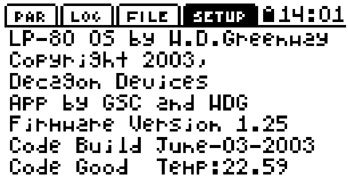
This menu option stands for "External Sensor Constant." This menu is for adjusting the calibration constant of the external sensor. Therefore, you should only adjust this value either when using a new external sensor, or after the external sensor has been re-calibrated. To check to make sure this value is correct, check the tag attached to the external sensor's cable. The value shown should correspond with the value shown in this menu. If you need to adjust the value, press the up or down arrow keys to the correct value, then press the ESC key.

As with most electronic components, the sensitivity of the external sensors drift over time and therefore periodically need re-calibration. Therefore we recommend that you have your external sensor re-calibrated. If you use it heavily each year, we suggest this be done on a yearly basis. If you only make periodic measurements, one re-calibration every 2 to 3 years should be adequate. Contact Decagon for more details about re-calibrating the external sensor.

About

The About menu shows you data about the operating system of the AccuPAR, and more importantly, the status of the operating code, i.e. if the program has been corrupted or if it is good.

Here is an example of the About screen:



The top portion describes the name of the instrument, copyright info, and version number. At the very bottom, the code status is displayed ("Good"). This indicates that the code has not been corrupted. Next to the code status, the instrument temperature is displayed. This is useful in troubleshooting the performance of the AccuPAR in hot weather, since the instrument incorporates a temperature-compensation device for the LCD screen.

8: PAR and LAI Theory

The AccuPAR is useful for a number of applications, including the measurement of average and intercepted PAR. From these measurements, LAI can be calculated and other attributes of the canopy structure can be determined.

PAR (photosynthetically active radiation)

PAR is defined as the radiation in the 400 to 700 nanometer waveband. It represents the portion of the solar spectrum which plants use for photosynthesis. Under a plant canopy, radiation levels can vary from full sun to almost zero over the space of a few centimeters. Therefore, reliable measurement of PAR requires many samples at different locations under the canopy.

Average and Intercepted PAR

Monteith (1977) observed that dry matter production of a plant canopy is directly related to the amount of photosynthetically useful radiation intercepted by the canopy. Dry matter production is modeled as the product of three terms:

$$P = efS$$
(equation 1)

where P is the amount of dry matter produced, S is the flux density of incident radiation intercepted by the crop, f is the fraction of incident radiation intercepted by the crop, and e is a conversion efficiency. Conversion efficiency and fractional interception (f) are determined by crop physiology and management.

Incident solar radiation is the only environmental factor. If f and S are monitored over the period of growth of a crop, and P is measured at harvest, e can be determined. The results of experimental treatments or the influence of genetics can be interpreted in terms of their effect on e and f.

The radiation incident on a canopy can be absorbed by the canopy, transmitted through the canopy and absorbed or reflected at the soil surface, or reflected by the canopy. In principle, only PAR absorbed by the canopy is useful in producing dry matter, so f should be the fractional absorption. If t is the fraction of incident radiation transmitted by the canopy, r is the fraction of incident radiation reflected to a sensor above the canopy, and r_s is the reflectance of the soil surface, then the absorbed radiation fraction is calculated from:

$$f = 1 - t - r + tr_s$$

(equation 2)

The last two terms are often ignored and fractional interception is approximated by:

$$f = 1 - t$$

(equation 3)

The error resulting from this approximation is usually small when t, r, and r_s are measured in the PAR waveband because most of the PAR is absorbed. The error becomes much more significant when measurements of total solar radiation are used because of large scattering coefficients of leaves for near infrared radiation.

As a first-order estimate of error, assume that

$$r = (1 - t)r_c + tr_s$$

(equation 4)

where r_c is the reflectance of the vegetation. Equation 2 becomes:

$$f = (1 - t)(1 - r_c)$$

(equation 5)

The error resulting from using equation 3 is approximately equal to r_c, which is typically less than 0.05 in the PAR waveband. Since the AccuPAR's sensors are sensitive only to radiation in the PAR waveband, equation 3 will generally be accurate for making measurements of intercepted radiation. However, measurement of the other terms needed for equation 2 is simple and will also be explained.

Sampling for Fractional Interception

The functions needed to perform these calculations are available in the PAR sampling menu of the AccuPAR. The measurements needed for fractional interception are those from which t, r, and r_s are calculated. If S is the PAR reading from an upward-facing AccuPAR above the plant canopy, R is the reflected PAR above the plant canopy (inverted AccuPAR above the crop), T is the upward-facing AccuPAR below the plant canopy, and U is the reflected PAR from the soil surface, then t, r, and r_s can be calculated from:

$$t = T/S$$

(equation 6)

$$r = R/S$$

(equation 7)

$$r_s = U/T$$

(equation 8)

Assume only *t* needs to be known. Measure *S* above the crop canopy. Level the AccuPAR above the canopy and press the up-arrow key. The reading displayed in the upper right portion of the screen is the value for *S*.

Measure *T* by placing the AccuPAR below the plant canopy, being careful to place it below all of the leaves. Try to keep the instrument level. Press the down-arrow key to make below-canopy measurements. The resulting values are displayed below the above-canopy values on the screen. Since the light below the canopy is extremely variable, several samples at different locations will be necessary for a reliable reading. The number of necessary samples can be determined by taking, for example, 10 individual readings and computing the coefficient of variation from:

$$CV = \frac{S}{\bar{T}}$$

(equation 9)

where *S* is the standard deviation of the 10 readings:

$$S = \sqrt{\frac{\Sigma(T_i - \bar{T})^2}{n-1}}$$

where *n* is the number of samples taken. The fractional error in the measurement of *T* will be *CV* divided by the square root of the number of samples.

Once you have taken the first below-canopy PAR reading, you will see the current τ value displayed in the lower left corner of the screen. With each subsequent below-canopy measurement, the τ value will be updated. After you have taken sufficient measurements, use the displayed τ value in the lower left corner for *t* (see equation 6).

This calculation would normally be generated by a computer program after the data from all of the samples have been sent to the computer. However, it is important to set up some kind of sampling scheme beforehand or keep detailed notes of sampled areas of the field plot or treatment so that they can be compared to stored readings.

To find *r*, level the AccuPAR above the canopy and press the up-arrow. Then invert the AccuPAR at a height of 1-2 meters above the crop canopy.

Leveling is not critical for this measurement since the radiation reaching the sensor is not directional. Press the down-arrow key in the PAR sampling menu. Multiple readings are typically not necessary, since *R* is not usually variable. *r* for equation 7 is shown in the T location at the bottom of the AccuPAR screen.

To find r_s, invert the AccuPAR over the soil below the canopy and take measurements at several locations. Average and store these measurements as before. This reading is the value *U*. Calculate r_s from equation 8 using *U* and *T*. A value in the range of 0.1 to 0.2 should be obtained, but it is possible that the light level below the canopy will be so low that *U* will not be accurately measured. If a value outside of the expected range is obtained, there will be negligible error in *f* by assuming $r = 0.15$. As mentioned before, evaluation of intercepted radiation normally involves the measurement of *t*.

Only measurements below the canopy have been discussed. Obviously, measurements throughout the canopy are possible. Profiles of interception with height can be useful in determining at what location most of the photosynthesis is occurring in the canopy.

Using PAR to determine Leaf Area Index

The PAR measured by the AccuPAR within a plant canopy is a combination of radiation transmitted through the canopy and radiation scattered by leaves within the canopy. A complete model of transmission and scattering is given by Norman and Jarvis (1975), but it is very complex and not suitable for inversion.

The Norman-Jarvis model was used to test and fit two simpler models which are more easily inverted. Equation 10 is a simple light scattering model suggested by Goudriaan (1988). It gives the fraction of transmitted PAR, τ (ratio of PAR measured below the canopy to PAR above the canopy), below a canopy of LAI, L, as

$$\tau = f_b \exp(-\sqrt{a}KL) + (1 - f_b)\exp(-0.87\sqrt{a}L)$$

(equation 10)

where f_b is the fraction of incident PAR which is beam, a is the leaf absorptivity in the PAR band (AccuPAR assumes 0.9 in LAI sampling routines), and K is the extinction coefficient for the canopy. The extinction coefficient can be modeled in various ways. Assuming an ellipsoidal angle distribution function (Campbell 1986), then

$$K = \frac{\sqrt{x^2 + \tan\Theta^2}}{x + 1.744(x + 1.182)^{-0.733}}$$

(equation 11)

where θ is the zenith angle of the sun and *x* is a leaf angle distribution parameter. When *x*=1, the angle distribution is spherical, and *K* simplifies to

$$K = \frac{1}{2\cos\Theta}$$

(equation 12)

John Norman suggested a different equation for predicting scattered and transmitted PAR.

$$\tau = \exp\left\{\frac{A(1 - 0.47f_b)L}{\left(1 - \frac{1}{2K}\right)f_b - 1}\right\}$$

(equation 13)

where $A = 0.283 + 0.785a - 0.159a^2$.

Both equations predict canopy PAR within a few percent of values from the complete Norman-Jarvis model. Equation 10 is slightly more accurate, but equation 13 is much easier to invert to obtain *L*. The difference in accuracy of the two equations is smaller than other uncertainties in the method, so equation 13 will be used to determine LAI. Inverting equation 13 gives the following:

$$L = \frac{\left[\left(1 - \frac{1}{2K}\right)f_b - 1\right]\ln\tau}{A(1 - 0.47f_b)}$$

(equation 14)

Applications and Examples

This section describes the method of manually collecting PAR data for the determination of LAI in a barley and pea canopy. This example has been included to show how the AccuPAR automatically calculates LAI in the field.

PAR was measured above a barley canopy of 391 μmol (μmol $m^{-2}s^{-2}$) on an overcast day. The average of several measurements below the canopy was 62 μmol. The transmission, τ, is therefore
62/391 = 0.159. Since the day was overcast, $f_b = 0$. If $a = 0.9$, then $A = 0.86$. From equation 14, $L = -ln(0.159)/0.86 = 2.14$. Because the measurement was made under overcast skies, it was not necessary to have canopy structure information or solar elevation angle. Measurements on overcast days are the simplest for LAI determination and do not

require assumptions about canopy structure.

The next example uses measurements on a sunny day. 1614 μmol was measured above a pea canopy and 80 μmol under the canopy. The fraction of PAR transmitted by the canopy was therefore $\tau = 80/1614 = 0.05$. The solar zenith angle was 30°, and the beam fraction was 0.881. The A value for equation 14 is again 0.86. "x" for the canopy is unknown, but unless leaves have obvious horizontal or vertical tendencies, a spherical distribution can be assumed and x be set equal to 1. (The AccuPAR default value for leaf distribution parameter is 1.0, which is applicable for many canopies). For a zenith angle of 30°, this gives $K = 0.577$. Substituting these values into equation 14 results in $L = 5.2$.

The AccuPAR program utilizes these same equations when the instrument is used to automatically calculate Leaf Area Index. In the AccuPAR's setup menu, you enter your local time, date, and leaf distribution parameter, and it automatically calculates zenith angle and beam fraction. It then couples these parameters with collected intercepted PAR data to determine LAI.

Extinction Coefficient and Canopy Structure

If the the elements of a canopy are randomly distributed in space, then the probability of a ray of light, or other probe, penetrating the canopy without interception can be calculated from theory. The probability of penetration without interception is equal to the sunfleck fraction, which is the beam transmission coefficient, $\tau(\theta)$, for the canopy. The parameter, θ, is the zenith angle (angle measured from the vertical) of the probe or solar beam. τ usually varies with zenith angle. The transmission coefficient for a canopy of randomly placed elements is:

$$\tau(\theta) = \exp(-KL)$$

(equation 16)

where L is the leaf area index of the canopy (area of leaves per unit area of soil surface) and K is the extinction coefficient for the canopy, which depends on the leaf angle distribution of canopy elements and the zenith angle of the probe.

A number of expressions have been proposed for K. The most useful is from Campbell (1986) where the angle distribution of canopy elements is assumed to be ellipsoidal. One can picture the angle distribution of area in a plant canopy to be similar to the angle distribution of area on the surface of oblate or prolate spheroids, or spheres. The equation for *K* is:

$$K = \frac{\sqrt{x^2 + \tan\Theta^2}}{x + 1.744(x + 1.182)^{-0.733}}$$

(equation 17)

The parameter, *x*, is the ratio of the length of the horizontal to the vertical axis of the spheroid, and can be measured as the ratio of the projected area of an average canopy element on a horizontal plane to its projection on a vertical plane.

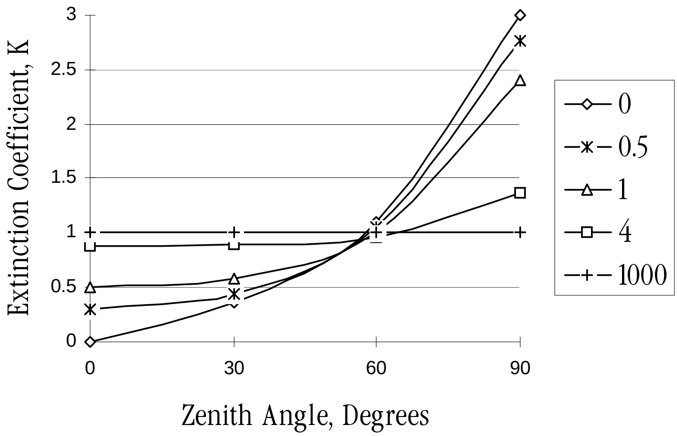


Figure 4: Extinction Coefficient vs. Zenith Angle

Figure 4 shows the extinction coefficient plotted as a function of zenith angle for various values of *x*. There are two important things to note. First, at a zenith angle of about 57°, the extinction coefficient is near unity for all canopies. When leaves are horizontal (large *x*), the extinction coefficient, *K*, is unity for all elevation angles, but as *x* decreases, *K* becomes smaller at large zenith angles and larger at small zenith angles.

Equation 16 can be used in various ways to determine the leaf area index, and also the leaf angle distribution for a canopy. The simplest application is that of Bonhomme *et al.* (1974). Since $K = 1$ for zenith angles near 57°, the inversion of equation 16 is simple and gives:

$$L = -\ln(\tau_{57})$$

(equation 18)

If a measurement is made when the zenith angle is about 57°, equation 18 can be used directly to find L.

If measurements of the transmission coefficient, τ, are made at several elevation angles, a simple method from Lang (1987) can be used. The measurements of τ are used to compute $y = \cos \Theta \ln \tau \Theta$. These are regressed on Θ (in radians), giving a slope, B and intercept, A. The leaf area index is given by:

$$L = 2(A + B)$$

(equation 19)

An approximate value for x is $x = exp(-B/0.4L)$.

Example: Readings were obtained as follows:

Table 2: Sample readings

Θ-deg	Θ-rad	τ	$-\cos\Theta \ln\tau$
35	0.61	0.21	1.28
41	0.72	0.18	1.29
55	0.96	0.10	1.32

Linear Regression gives:

$A = 1.21$
$B = 0.12$
$L = 2(1.21 + 0.12) = 2.64$
$x = \exp(-0.12 / 0.4 \text{ x } 2.64) = 0.9$

A more precise method for finding x is as follows. We would like to find values for x and L which minimize:

$$F = \sum(\ln\tau_i + K_i L)^2$$

(equation 20)

subject to the constraint, x>0, where τ_i are transmission coefficients measured at several zenith angles, Θ_i, and the K_i are the extinction coefficients for the corresponding angles.

Correction of PAR for Sun Angle

Canopy transmission (τ), measured at one zenith angle, can be used to predict transmission or radiation interception for other zenith angles. For example, a measurement might be made at Θ=32° from which cover (1 - transmission at Θ=0) is to be calculated. From equation 16:

$$\frac{\ln\tau_1}{\ln\tau_2} = \frac{K_1}{K_2} = p$$

(equation 21)

so:

$$\tau(\Theta_1) = \tau(\Theta_2)^p$$

(equation 22)

We can calculate *p* from equation 17:

$$p = \left[\frac{(x^2 + (\tan\Theta_1)^2)}{(x^2 + (\tan\Theta_2)^2)}\right]^{\frac{1}{2}}$$

(equation 23)

If $\Theta_1 = 0$,

$$p = \left[\frac{(x^2)}{(x^2 + (\tan\Theta_2)^2)}\right]^{\frac{1}{2}}$$

If *x* is not known, assume *x*=1.

Example: From the measurements in the previous example, find the canopy cover. Take Θ = 35°, τ = 0.21. The x value is 0.9.

$$p = \left[\frac{(0.9^2)}{(0.9^2(\tan 35)^2)}\right]^{\frac{1}{2}}$$

$\tau(0) = 0.21^{0.79} = 0.29$

Cover = 1 - $\tau(0)$ = 1 - 0.29 = 0.71

Intercepted radiation averaged over an entire day can be estimated from:

$$f = 1-\tau_d$$

(equation 24)

where τ_d is the transmission coefficient averaged over all elevation angles. τ_d can be calculated from:

$$-ln\tau_d = uL^v$$

(equation 25)

where u and v are functions of x which can be calculated from:

$$u = 1 - 0.33exp(-0.57x)$$

(equation 26)

$$v = 1 - 0.33exp(-0.97x)$$

(equation 27)

The next table shows typical values.

Table 3: values of *u* and *v* for equation 25

x	u	v
0.1	0.69	0.73
0.5	0.75	0.82
1.0	0.81	0.89
2.0	0.90	0.95
4.0	0.96	0.98
8.0	0.99	0.99

Combining equations 16 and 25 gives:

$$\tau_d = \tau(\Theta)^q$$

(equation 28)

where $q = uL^{v-1}/K$

Example: Calculate a value for fractional daily interception for the crop in the previous two examples.

$u = 1 - 0.33exp(-0.57 \times 0.9) = 0.80$
$v = 1 - 0.33exp(-0.97 \times 0.9) = 0.87$

$$K = \frac{(0.9^2 + (\tan 35)^2)^{\frac{1}{2}}}{0.9 + 1.774(0.9 + 1.182)^{-0.733}} = \frac{1.14}{1.94} = 0.59$$

$q = 0.80 \times 2.64^{-0.13}/0.59 = 1.2$

$\tau_d = 0.21^{1.2} = 0.15$

$f = 1 - \tau_d = 1 - 0.12 = 0.85$

LAI measurements and Non-Random Distribution

There has been much discussion concerning inversion methods to obtain leaf area index. Since all inversion methods rely on the assumption that elements of a canopy are randomly dispersed in space, errors in the measurement of leaf area index may result from a non-random arrangement of canopy elements. This is especially true for canopies with heliotropic leaves, conifer forests, row crops before canopy closure or for canopies which never close, as in desert vegetation. The degree of error in measurement is a result of the canopy's deviation from this random dispersion assumption.

In past studies, LAI has been used to relate both actual biomass area and the interception of PAR by a plant canopy. Another proposed view regarding LAI in which L, the actual biomass area, was related to a new term, L_e, which represents the actual orientation of the canopy elements relating to the interception of PAR at a given angle. *In situ* measurements of LAI using hemispherical photography were equated with this new term "effective plant area index" (L_e), which was defined as:

$$L_e = \Omega L$$

where L_e represents the actual leaf area index (equal to a harvested leaf area measurement) and Ω refers to a clumping index resulting from the non-random distribution of canopy elements.

When a canopy displays random dispersion, Ω is unity; however, when a canopy is clumped, Ω is not unity. In this equation, L_e refers to the actual canopy element orientation. For example, in a randomly dispersed canopy, L would be equal to L_e (figure 1), in an under-dispersed canopy (clumped), L would be greater than L_e (figure 2), and in an over-dispersed canopy, L would be less than L_e (figure 3). Refer to the next page for illustrations.

The purpose of this discussion is to expose you to possible errors that may occur when making LAI measurements *in situ*. When setting up an experiment, you should carefully examine the desired end result. If you are interested in the interception of PAR within a canopy, the result of the inversions given in this manual will be correct in reaching L_e. The leaf or plant area index that is calculated through inversion will be an accurate portrayal of the canopy's structure and orientation with respect to light interception. In this instance, while clumping effects within the canopy remain present, these effects do not cause error with regard to light interception and the effective area index for that situation. Alternately, if you are interested in obtaining the actual biomass represented by L in this discussion, all measurements should be performed so that the effects of clumping are minimized. Clumping effects can be minimized by segmenting the AccuPAR's probe in small groups such that the area sampled by a group is relatively random (see Lang and Yueqin, 1986). This can also be done by measuring only at certain times of day or at positions within the canopy that directly minimize the clumping effects.

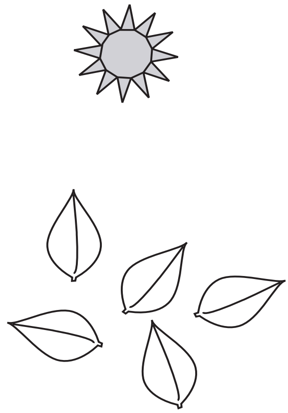


Figure 1: Randomly Dispersed
$L = L_e$

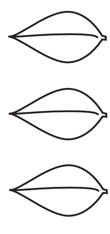


Figure 2: Underdispersed
$L > L_e$

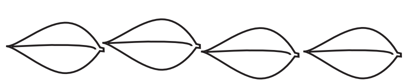


Figure 3: Overdispersed
$L < L_e$

Zenith Angle and Equation of Time

The formulas for calculating elevation angle are relatively straightforward. The zenith angle is calculated from:

$$\Psi = arccos(sin L sin D + cos L cos D cos 0.2618(t-t_o))$$

(equation 30)

where L is the latitude, D is the solar declination, t is the time, and t_0 is the time of solar noon. The earth turns at a rate of 0.2618 radians per hour, so the 0.2618 factor converts hours to radians. Time, t, is in hours (local solar time), ranging from 0 to 24. Latitude of a given site is easily found in an atlas or using a GPS system. Users in the Southern hemisphere should enter latitude as a negative number. Solar declination ranges from +0.409 radians (+23.45°) at summer solstice to
-0.409 radians (-23.45°) at winter solstice. It can be calculated from:

$$D = \arcsin[0.39785 \sin[4.869+0.0172J +0.03345 \sin(6.224+0.0172J)]]$$

(equation 31)

where J is the day of the year. Some values are given in Table 1. The time of solar noon is calculated from:

$$t_o = 12 - LC - ET$$

(equation 32)

where LC is the longitude correction and ET is the Equation of Time. LC is +4 minutes, or +1/15 hour for each degree east of the standard meridian and -1.15 hour for each degree west of the standard meridian. Standard meridians are at 0°, 15°, 30°...etc. Generally, time zones run approximately +7.5° to -7.5° on either side of a standard meridian, but this varies depending on political boundaries, so check an atlas to find both standard meridian and longitude. Typically, longitudes in the Eastern Hemisphere are given as negative values.

The Equation of Time is a 15 to 20 minute correction which depends on the day of the year. It can be calculated from:

$$ET=[-104.7\sin\phi+596.2\sin 2\phi +4.3\sin 3\phi-12.7\sin 4\phi-429.3\cos\phi-2.0\cos 2\phi+19.3\cos 3\phi]/3600$$

(equation 33)

where $\phi = (279.575 + 0.986\ J)\pi/180$. Some values for ET are given in Table 4.

Example Calculation:

Find the zenith angle for Pullman, WA at 10:45 PDT on June 30. Convert the time of observation to standard time by subtracting one hour and convert minutes to decimal hours, so t = 9.75 hours.

June 30 is J = 181.

Pullman latitude is 46.77°, or 0.816 radians, and longitude is 117.2°.

The standard meridian for Pullman is 120°.

The local meridian is 2.8° east of the standard meridian, so LC = 2.8/15 = 0.19 hours.

From Equation 33 or Table 4, ET = -0.06 hours. Equation 32 then gives t_0 = 12 - 0.19 - (-0.06) = 11.87.

Declination from Table 4 or Equation 31 is 0.4 radians.

Substituting these values into Equation 30 gives:

$$\theta = \arccos\{\sin(0.816)\, \sin(0.4) + \cos(0.816)\, \cos(0.4)\, \cos[0.2618(9.75 - 11.87)]\} = 0.61 \text{ radians, or } 34.9°.$$

Table 4: Solar Declination and Equation of Time

Date	Day of Year	D in radians	ET hour
Jan 1	1	-0.403	-0.057
Jan 10	10	-0.386	-0.123
Jan 20	20	-0.355	-0.182

Table 4: Solar Declination and Equation of Time

Date	Day of Year	D in radians	ET hour
Jan 30	30	-0.312	-0.222
Feb 9	40	-0.261	-0.238
Feb 19	50	-0.202	-0.232
Mar 1	60	-0.138	-0.208
Mar 11	70	-0.071	-0.117
Mar 21	80	-0.002	-0.122
Mar 31	90	0.067	-0.072
Apr 10	100	0.133	-0.024
Apr 20	110	0.196	0.017
Apr 30	120	0.253	0.046
May 10	130	0.304	0.060
May 20	140	0.346	0.059
May 30	150	0.378	0.043
Jun 9	160	0.399	0.015
Jun 19	170	0.409	-0.019
Jun 29	180	0.406	-0.055
Jul 9	190	0.392	-0.085
Jun 19	200	0.366	-0.103
Jun 29	210	0.331	-0.107
Aug 8	220	0.286	-0.097
Aug 18	230	0.233	-0.065
Aug 28	240	0.174	-0.022
Sep 7	250	0.111	0.031
Sep 17	260	0.045	0.089
Sep 27	270	-0.023	0.147

Table 4: Solar Declination and Equation of Time

Date	Day of Year	D in radians	ET hour
Oct 7	280	-0.091	0.201
Oct 17	290	-0.157	0.243
Oct 27	300	-0.219	0.268
Nov 6	310	-0.275	0.243
Nov 16	320	-0.324	0.255
Nov 26	330	-0.363	0.213
Dec 6	340	-0.391	0.151
Dec 16	350	-0.406	0.075
Dec 26	360	-0.408	-0.007

Automatic Calculation of Zenith Angle

The AccuPAR automatically determines zenith angle using the above equation and parameters. However, to get the accurate zenith angle for your location, you need to enter the site latitude, longitude and universal time offset in the Setup menu. Once these values are entered, the AccuPAR determines zenith angle without further input. The sun's zenith angle will then be calculated and stored at the end of each data set.

9. Measurement Tips

Above Canopy (External) Sensor

The AccuPAR is supplied with an external PAR sensor which connects to the port on the right side of the AccuPAR. The external sensor allows you to take simultaneous above and below canopy PAR readings without having to move the instrument above and below the canopy you are measuring.

For above-canopy PAR data collection, consider connecting the external point sensor to the AccuPAR. This ensures an accurate measurement of intercepted PAR, especially on days where radiation levels vary rapidly. Ideally, you can mount the sensor on a tripod and level it with a bubble level.

When it is not feasible to use an external point sensor to obtain above-canopy measurements, such as in timber or tropical crops, you have two choices:

1. Use a separate datalogger with an attached PAR sensor such as a point quantum sensor, or configure another AccuPAR to log in the unattended

mode (one reading per minute, for example) in a clearing outside the canopy. After collecting PAR data within the canopy, you can correlate the data from the two instruments after downloading it from each to a computer.

2. You can use your AccuPAR as an above-canopy reference by regularly collecting above-canopy PAR data in a large clearing within the canopy structure.

Note: For LAI data in tall canopies, use the intercepted PAR inversions and not the gap fraction theory. Intercepted PAR inversions may be found in Chapter 8.

Sample Size

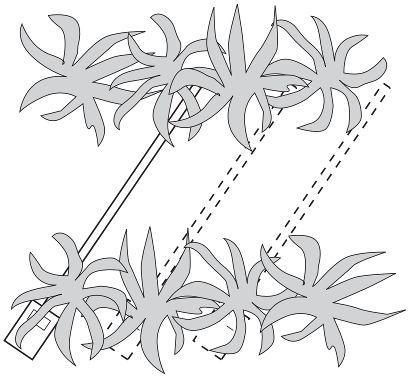
When evaluating experimental protocols for measuring average intercepted PAR and determining average LAI for a large area, make sure that a sufficient number of samples and sampling locations are used. This will reduce errors caused by canopy structure variations.

Clumping in Canopies

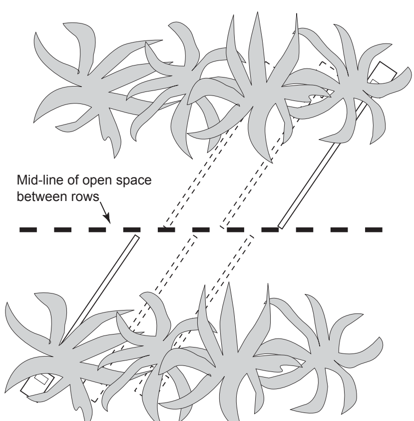
When evaluating discontinuous canopies or canopies with definite clumping, the AccuPAR can be configured such that its active sampling area is reduced, or you can download the data collected by the AccuPAR's probe segments. In this way you can gather information that better describes the changes in canopy structure with regard to location. To reduce the sampling size of the probe, refer to the "Set Active Segments" option in the setup menu (see chapter 7). To see the individual PAR readings for each of the eight probe segments, select "Download All" or "Download Raw" from the "Download options" section of the Setup menu, then download the stored data (select "Send" in the File menu).

LAI Sampling in Row Crops

One of the common uses for the AccuPAR is measuring the leaf area index of row crops. When doing so, it is important to take measurements in such a way as to give a good row-to-row representation of the entire below-canopy PAR environment both under the plants and between rows. We suggest a sampling regime such as shown below, where the probe either extends from mid-row to mid-row, or extends from mid-row to the middle of the open space between rows, depending on row width and canopy size.



Scenario 1: The two ends of the AccuPAR probe are in the middle of each row, getting a good representative sample of the entire area below and between rows.



Scenario 2: The base of the probe is in the center of the row, while the end is in the center of the open space between rows. When sampling the next row, the same orientation is maintained, giving an accurate representation of the overall area.

10. Care and Maintenance

Batteries

The AccuPAR uses four standard 1.5V alkaline batteries. These batteries are easily obtained and should last for at least 2 years before they have discharged. The battery icon in the upper right corner of the screen (next to the time) shows you the current power level of your batteries.

Replacing Batteries

If the alkaline batteries require replacement, remove the four screws on the bottom of the AccuPAR case and lift the cover carefully. The batteries are located on both sides of the circuit board. **Be sure to orient them properly**; placing them the wrong way in the battery holder can damage the AccuPAR. The battery holders indicate which direction they should be placed.

Note: Data will not be lost when the batteries are replaced. The memory and program sections of the AccuPAR are non-volatile.

After replacing the batteries, press the reset button at the top left corner of the board.

Cleaning the Probe and Controller

The white probe diffuser should always be clean to ensure accurate readings. To clean the probe, use a small amount of isopropyl alcohol and a soft cloth. Rub the surface until it is clean.

To clean the controller, use a soft cloth and water to wash heavy dirt, then use ethyl or isopropyl alcohol to finish cleaning. Make sure to only use a soft cloth when cleaning the LCD window. Tissues made from wood fiber will scratch the surface.

Re-calibration

The AccuPAR calibrates its sensors against the external sensor supplied with the instrument. Therefore, provided your external sensor's calibration is good, you simply re-calibrate the AccuPAR in the Setup menu (see chapter 9) as often as you wish. However, as is the case with all electronic components, shifts in the external sensor's sensitivity will occur over time. As a result, we recommend that you periodically send your external sensor in to Decagon's factory for re-calibration, depending on how often you use it. If you use it heavily each year, we suggest once a year. For periodic measurements, one re-calibration every 2 to 3 years should be adequate. Before sending the instrument in, contact Decagon via phone or email so we can prepare for its arrival.

General Precautions

The AccuPAR is a low maintenance instrument. There are only a few suggestions to keep in mind

- Keep the probe clean. The accuracy of readings may decline if there is any debris on the probe which prevents light from entering the sensors.
- Although the AccuPAR is splash-resistant, don't immerse the instrument in water, or leave the it in contact with rain for long periods of time.
- When transporting the AccuPAR, keep the instrument in its padded hard-sided carrying case to prevent damage.

Declaration of Conformity

Application of Council Directive:	89/336/EEC
Standards to which conformity is declared:	EN50082 : 1998 EN55022 : 1998
Manufacturer's Name:	Decagon Devices, Inc.
Manufacturer's Address:	950 NE Nelson Court Pullman, WA 99163 USA
Type of Equipment:	AccuPAR Linear PAR/LAI Ceptometer.
Model Number:	LP-80
Year of First Manufacture:	2003

This is to certify that the AccuPAR model LP-80, manufactured by Decagon Devices, Inc., a corporation based in Pullman, Washington, USA meets or exceeds the standards for CE compliance as per the Council Directives noted above. All instruments are built at the factory at Decagon and pertinent testing documentation is freely available for verification.

Appendix A: External Sensor Information

The external quantum sensor provided with the AccuPAR model LP-80 is calibrated to provide an output of approximately 0.1mV per µmol $m^{-2}s^{-1}$ This sensor offers good accuracy, however you should be aware of potential sources of error. The biggest error is often caused by small changes in the position of the sensor. The sensor must be exactly horizontal for the most accurate measurements.

Specifications

Output: approx. 0.1mV per µmol $m^{-2}s^{-1}$
Dimensions: 24 mm diameter, 27mm tall
Cable length: 2m
Range: 0 to 4000 µmol $m^{-2}s^{-1}$ (full sunlight ~ 2000)
Warranty: 1 year parts and labor.

Spectral Response

An ideal quantum sensor would give equal emphasis to all photons between 400 and 700 nm and would exclude photons above and below these wavelengths. The most accurate way to measure this radiation is with a spectroradiometer.

However, quantum sensors that approximate the ideal response with filters are accurate to within ±3% for common light sources. The spectral response of the external sensor is such that it underestimates the 400 to 500 nm wavelengths (blue light), overestimates the 550-650 nm wavelengths (yellow and orange), and has little sensitivity above 650 nm (red light). Fortunately common light sources are mixtures of colors and many spectral errors offset each other.

Cosine Response

Some of the radiation coming into a sensor at low angles is reflected, which causes the reading to be less than it should be. to partly correct for this problem, more expensive sensor are enclosed in a black cylinder with a small raised translucent disk in the top. This cosine corrected head helps to capture radiation at low angles. the Apogee sensor is flush mounted in a PVC grey body that blocks the radiation at very low angles. the small gap between the edge of the sensor and the grey body allows the correct amount of low angle radiation to be captured by the sensor. The cosine error for typical applications is less than 1%.

Temperature Response

Increasing temperature increases the output of most radiation sensors. This sensor was calibrated at 20°C

Our measurements indicate that it reads 0.6% low at 10°C and 0.8° high at 30°C. The temperature error is insignificant for most applications.

Long-term stability

The output of all radiation sensors tends to drift over time as the detector ages. The average decrease of the sensor is 1% every year. Therefore, we recommend returning the sensor for recalibration at least every 3 years.

Appendix B: Further Readings

The following is a list of references that offer more detail concerning plant canopy characteristics and research.

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