Liquid Crystal Polarimeter

User Manual

Revision 2.10

Printed in Colorado, USA

Contents

Quick Start Guide

Requires a computer running Microsoft® Windows® XP service pack 3 or later.

1) Place the included CD in the CD-ROM drive. The CD autorun menu should launch. Click on the "Install PolarVIEW…" button. If the autorun menu doesn't launch, run setup.exe in the installer directory on the CD.

2) Before the Polarimeter controller is powered on or connected to a PC via USB, the USB driver must first be installed. The installer is located in the USB drivers directory on the CD, or the "Install USB Driver" menu option in the CD menu may be selected. There are separate installers for 32 bit and 64 bit drivers.

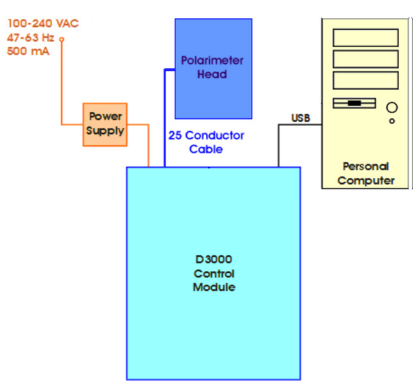
3) Plug the included USB cable into the appropriate connector on the D3000 control module. Plug the other end into an available USB port on the COMPUTER.

4) Carefully connect the optics head to the control module using the included 25-pin cable with the printing on the connector facing up.

5) Plug the power supply cable into the power connector on the D3000 control module, then connect the power supply to a properly grounded outlet.

6) Turn on the Polarimeter controller. The POWER light will illuminate and the STATUS light will blink during initialization; after initialization, the STATUS light will turn off. The POWER light remains illuminated until the power is turned off.

7) Start the PolarVIEW 3000 software by clicking Start ➔ Programs ➔ Meadowlark Optics ➔ PolarVIEW 3000.



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1. Stokes Polarimetry Using LCVRs

Analysis of polarized light is important in many applications and Meadowlark Optics' Liquid Crystal Variable Retarders are electrically tunable waveplates, which can be used for such analyses. The typical polarimeter uses electric motors and spinning waveplates that can induce noise into sensitive measurements. The Meadowlark Optics Polarimeter, being a solid-state device, has no motors and does not produce any vibration.

1.1 Stokes Polarimetry

The Stokes parameters comprise a four-component vector that completely characterizes the polarization of light. The components of the Stokes vector are simple combinations of the intensities of linear and circular polarization components of the light:

$$\mathbf{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

where:

S_0 = total light intensity

S_1 = intensity difference between horizontal and vertical linearly polarized components (horizontal – vertical)

S_2 = intensity difference between linearly polarized components oriented at ±45° (+45 – (-45))

S_3 = intensity difference between right and left circular components (right – left)

The unit for each Stokes vector component is Watts/meter^2.

The notion of ellipticity and handedness of polarization is important. Figure 1 shows how a quarter-wave retarder can be used to convert linear polarization into circular polarization. In both the left- and right-hand cases, a linear state is incident upon a quarter-wave retarder with the fast axis oriented at +45°, however the orientation of the input linear state is changed from Vertical to Horizontal. In each case, the linear state is rendered as two components, one parallel and the other perpendicular to the fast axis of the retarder. The top-most drawings in Figure 1 show how the retarder introduces a phase delay by retarding the component perpendicular to the fast axis. The lower-most drawings in Figure 1 show precession of the vector as light propagates from the retarder. In Figure 1a, vertical polarized light is converted to left-hand circular polarization, and in Figure 1b, horizontal polarized light is converted to right-hand circular polarization.

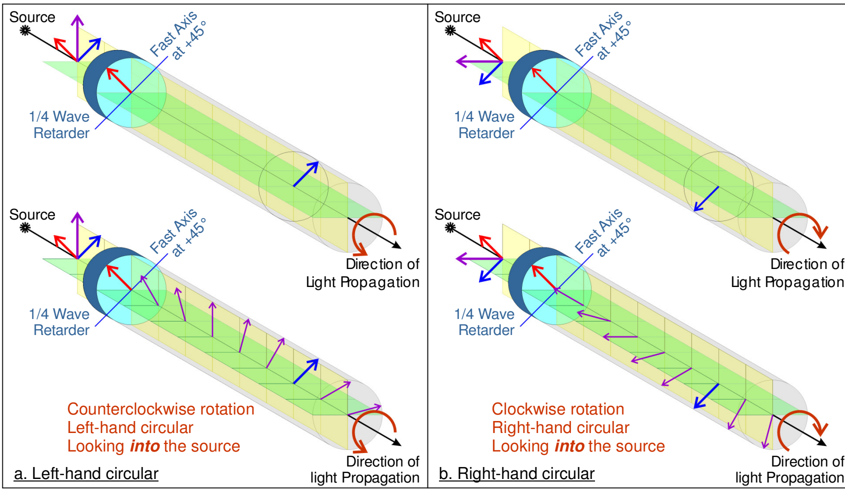

Figure 1. Left and right circular polarization states

Note the orientation of the input linear polarization (Purple arrow)

Notice also that angles (*e.g.* the orientation of the retarder's fast axis) and rotational directions (clockwise and counterclockwise) are from the perspective ***looking toward the source***.

The next three examples describe how one or two LCVRs can be combined with a beam-splitting polarizer to measure each of the Stokes parameters.

1.2 Measuring the S_1-component of the Stokes Vector

The S_1-component can be measured with a single LCVR. This component is defined as the intensity difference between the horizontal and vertical linear polarization components of the input beam. An LCVR is placed with its optic axis at +45° to a beam splitting polarizer as shown in Figure 2. The LCVR is switched between zero and half wave. In the zero-wave state the polarization state of the input beam is unchanged. In the half-wave state the LCVR rotates the vertical component into the horizontal direction and vice versa.

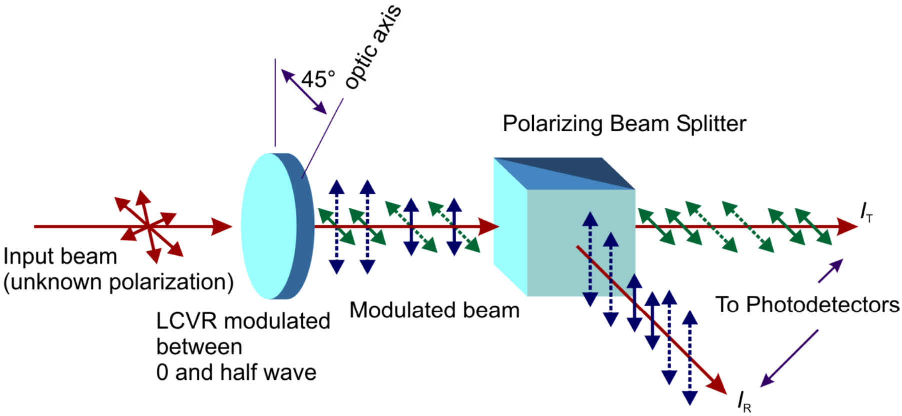

Figure 2. Measurement of the S_1-component of the Stokes vector.

The S_1-component can be calculated from:

$$S_1 = \frac{1}{2}\left[\frac{I_T(0) - I_T(\lambda/2)}{I_T(0) + I_T(\lambda/2)} - \frac{I_R(0) - I_R(\lambda/2)}{I_R(0) + I_R(\lambda/2)}\right]$$

Note that S_1 has been normalized to the total intensity. With this normalization the S_0-component should always equal unity. The first term is the S_1 parameter measured using the detector in the transmitted arm of the polarizer and the second term results from the detector in the reflected arm. The accuracy can be improved by adding a clean-up polarizer in the reflected arm. It is also assumed that the intensities are not read until the LCVR has settled between transitions (10 ms-30 ms).

1.3 Measuring the S_3-component of the Stokes vector

The S_3-component describes the circular polarization of the incoming light beam. In Figure 2, we resolved the input beam into two orthogonal linear polarization components in the horizontal and vertical directions. Here, we think of the input beam as being comprised of orthogonal circular polarizations as in Figure 3. In this case the LCVR is modulated between positive quarter wave ($\lambda/4$) and negative quarter wave ($-\lambda/4$) (actually $+3\lambda/4$). The two orthogonal circular components are then transformed into linear components in the horizontal and vertical directions. Similar to the S_1 calculation, the S_3-component is calculated using:

$$S_3 = \frac{1}{2}\left[\frac{I_T(\lambda/4) - I_T(-\lambda/4)}{I_T(\lambda/4) + I_T(-\lambda/4)} - \frac{I_R(\lambda/4) - I_R(\lambda/4)}{I_R(\lambda/4) + I_R(\lambda/4)}\right]$$

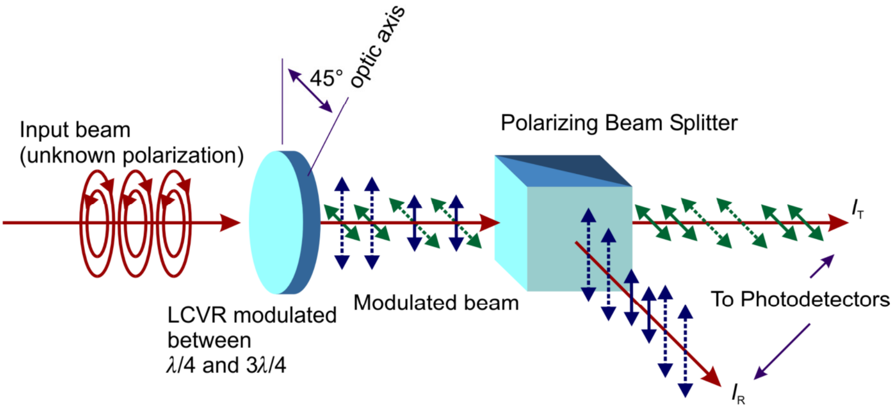

Figure 3. Measurement of the S_3-component of the Stokes vector.

1.4 Measuring the S_2-component of the Stokes vector

The third component of the Stokes vector requires two LCVRs for its measurement. We imagine the input light to be decomposed into orthogonal linear polarizations oriented along directions ±45° to the vertical. The first LCVR is adjusted to a quarter wave and left there for the duration of the measurement. This transforms the input linear components into right- and left-hand circular polarized components. The remainder of the measurement, and the final calculation, is then equivalent to that of the S_3 measurement procedure.

A complete Stokes polarimeter requires two LCVRs. During the measurement of the S_2 and S_3 components the first LCVR is held to zero retardance. It is then tuned to a quarter wave of retardance for the measurement of the S_2 component.

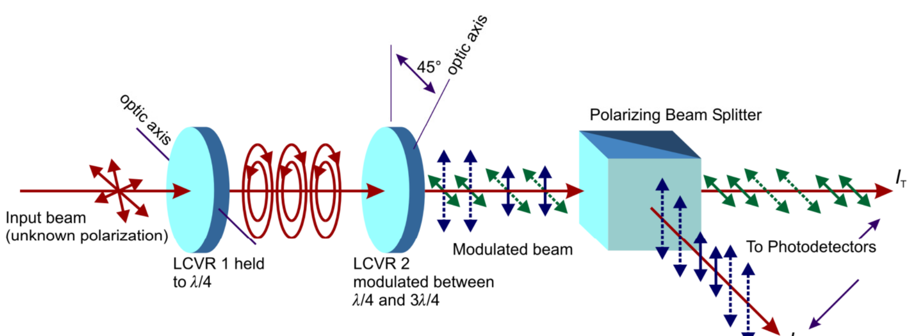

Figure 4. Measurement of the S_2-component of the Stokes vector.

1.5 Parameters calculated from Stokes vector components

The degree of polarization (DOP) is given by

$$DOP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

The degree of linear polarization (DOLP) is given by

$$DOLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}$$

The degree of circular polarization (DOCP) is given by

$$DOCP = \frac{S_3}{S_0}$$

Polarization is often rendered as an ellipse, where the ellipticity is a measure of the linearity/circularity; an ellipticity of 0 indicates linearly polarized light and an ellipticity of 1 indicates circularly polarized light. The angle of the major axis is the angle of the linear-most state, i.e., as the ellipticity approaches zero, the polarization ellipse collapses to a straight line at the angle of the linear state. The ellipticity is given by

$$e = \frac{S_3}{1 + \sqrt{S_1^2 + S_2^2}}$$

the angle of the major axis is given by

$$angle = \frac{1}{2}\arctan\left(\frac{S_2}{S_1}\right)$$

1.6 Summary

It should be noted that, while the Stokes vector is valid for "white" light, the wavelength sensitivity of the LCVR limits the bandwidth of light that can accurately be tested. For example, when an LCVR is tuned to 1/4 waves at λ_0, it will have the value 1/4 λ/λ_0 at the wavelength λ. The usable optical bandwidth depends on the required accuracy of the measurement.

1.7 References

1. T. Baur, D.E. Elmore, R.H. Lee, C.W. Querfeld, and S.R. Rogers, "Stokes II - A New Polarimeter for Solar Observations," Solar Physics , 70, 395 (1981).
2. T. Baur, "Optical Polarimeters for Solar Research," Opt. Eng. 20, 2 (1981).
3. D.S. Kliger, J.W. Lewis, and C.E. Randall, "Polarized Light in Optics and Spectroscopy, (Academic press, San Diego., California, 1990).
4. W.A. Shurcliff, "Polarized Light: Production and Use", (Harvard University Press, Cambridge, Mass., 1966).
5. D. Clarke, J.F. Grainger, "Polarized Light and Optical Measurement", (Pergamon Press, Oxford, 1971). Chapter 4 gives an excellent treatment of polarimetry.
6. M. Born, E. Wolf, "Principles of Optics", (Pergamon Press, Oxford, 1980).

2. Hardware Setup and Configuration

2.1 Laboratory and system requirements for the D3000

- 100-240 VAC, 47-63 Hz 500 mA utility power.
- A COMPUTER with an available USB port.
- Minimum COMPUTER requirements to run the PolarVIEW 3000 Liquid Crystal Polarimeter software are an 866-MHz Pentium® III processor, 256 MB RAM, 350 MB hard drive space, 800x600 pixel, 16-bit color or better graphics display, a CD-ROM, and Microsoft® Windows® XP / Vista / 7. (32 or 64 bit versions are supported)
- Recommended COMPUTER specifications are a 1-GHz Pentium® III processor, 512 MB RAM, 350 MB hard drive space, 1024x768 pixel, 16-bit color graphics, a CD-ROM and Microsoft® Windows® XP, Vista or 7.
- Optical posts and hardware for mounting the optical head. The optical head has three 8-32 tapped holes for mounting.
- The following is required for calibration
    - A quarter-wave retarder mounted with its fast axis at +45°
    - A linear polarizer that can be rotated to give horizontal, vertical, and ±45° linear polarized light
- A laser is recommended for alignment, calibration, and diagnostic purposes. A Helium-Neon or other visible laser is suggested to facilitate alignment and configuration of IR polarimeters.

2.2 Setup procedure for the D3000

1. Unpack components and cables from shipping container. Verify the shipment included:
    - D3000 controller unit (1 unit)
    - Polarimeter optical head unit (1 unit)

- +12V power supply and power cable (1 unit with +12V cable and 1 AC power cable)
- USB cable (1)
- Optics head cable, 25-pin (1)
- PolarVIEW 3000 software CD (1)
- User's manual (1 printed copy)
- Poly carrying/storage case (1)

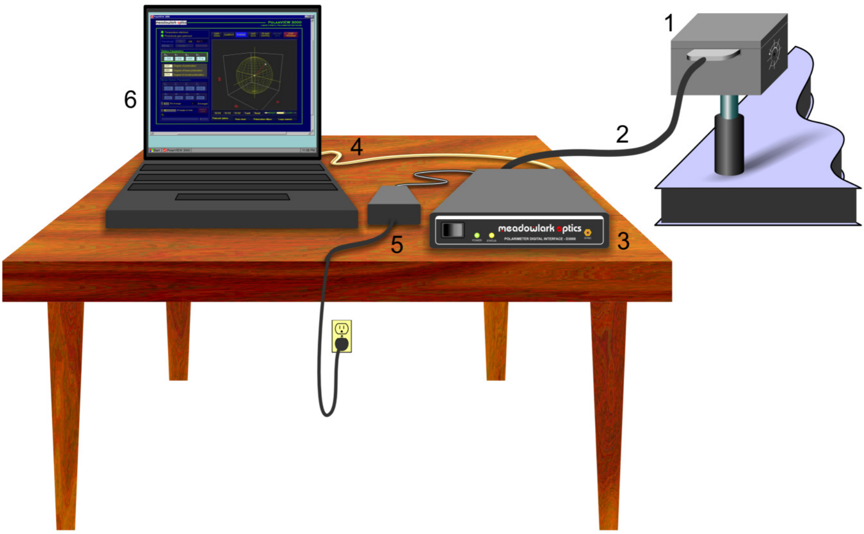

Figure 5. Polarimeter Components. (1) Polarimeter optical head, (2) Optical head cable, (3) D3000 Controller, (4) COMPUTER interface cable (USB), (5) Power supply, (6) COMPUTER running PolarVIEW 3000.

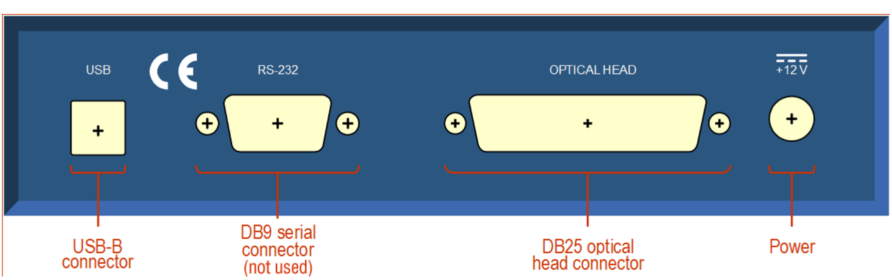

Figure 6. D3000 connector panel

2. Hardware configuration of the D3000 control module:
   - Position the polarimeter optical head on an optics table or breadboard. The optical head has three 8-32 tapped holes for mounting to standard optics hardware. The optical head should be aligned with the aperture normal to the optical axis..
   - Connect the 25-pin optical head cable to the optical head. The optical head connector is keyed to disallow improper insertion. Connect the other end of the optical head connector to the D3000 control module.
   - Connect the +12VDC supply to the D3000 control module. Plug the power supply into a properly grounded AC outlet.
   - Attach the USB cable to the USB connector on the rear of the D3000 control module, and connect the other end to an available USB port on a COMPUTER (the RS-232 connector is used only for programming the D3000 controller at the factory).

3. Before power is turned on to the polarimeter install the appropriate USB driver. This may be done either through the CD menu or by going to the USB drivers directory on the CD. There are two installers for Windows® XP, Vista and 7, one for 32 bit and one for 64 bit Windows - be sure to choose the appropriate driver for your system.

4. Turn on the front panel switch and observe the LEDs. The green power LED remains illuminated as long as the unit is powered on. The yellow status LED flashes a test pattern, then remains off until PolarVIEW 3000 is started.

5. The first time the D3000 is powered on, Windows® will detect a new USB device and will automatically use the driver installed in step 3. Please note: if the driver was not installed prior to connecting USB, the USB cable must be disconnected from the PC and the driver installed. Then, reconnect the USB cable.

6. Install the PolarVIEW 3000 software:
   - Place the PolarVIEW 3000 CD in the CD-ROM.
   - Double-click the setup.exe icon in the Installer folder and follow the on-screen instructions to install PolarVIEW 3000.
   - Upon completion there will be a Meadowlark Optics program group under Start|Programs, containing three icons: PolarVIEW 3000, the PolarVIEW 3000 User's manual (requires Adobe® Acrobat® Reader), and the PolarVIEW revision history (ASCII text).
   - If it becomes necessary to uninstall PolarVIEW 3000, repeat the two previous steps (executing setup.exe on a system on which PolarVIEW 3000 is already installed will uninstall the software).

3. Using PolarVIEW 3000

Operation of the polarimeter using PolarVIEW 3000 is detailed here. Meadowlark Optics recommends the following configuration for familiarization with the polarimeter: Output from a laser (or other monochromatic light source) at a calibration wavelength should be directed into the polarimeter aperture. A polarizer and a retarder should be available to produce convenient and predictable states of polarization (this is the configuration used in the calibration procedure described in section 5.2).

3.1 Startup Procedure

- If the D3000 control module is not already powered on, turn on the front panel switch and observe the LEDs. Verify the LEDs function as described in Section 2.2.
- The optical head includes a temperature control circuit that maintains the temperature of the liquid crystal variable retarders. Meadowlark Optics recommends waiting 5-10 minutes for the optical head temperature to stabilize.
- Start PolarVIEW 3000 by clicking the Windows® Start button|Programs|Meadowlark Optics|PolarVIEW 3000.
- The user interface will immediately appear as shown in Figure 7. If there is an error detecting the USB device (the D3000 power is not on, cables are not fully inserted into connectors or USB drivers are not installed) a dialog box will appear. After correcting the problem click the "OK" button to connect to USB.

3.2 PolarVIEW 3000 User Interface

PolarVIEW 3000 is a user-friendly interface, Figure 7, which displays polarization data and allows the user to perform various operations. In addition to the controls and indicators described in the following sections, clicking the Meadowlark Optics logo displays software and firmware version.

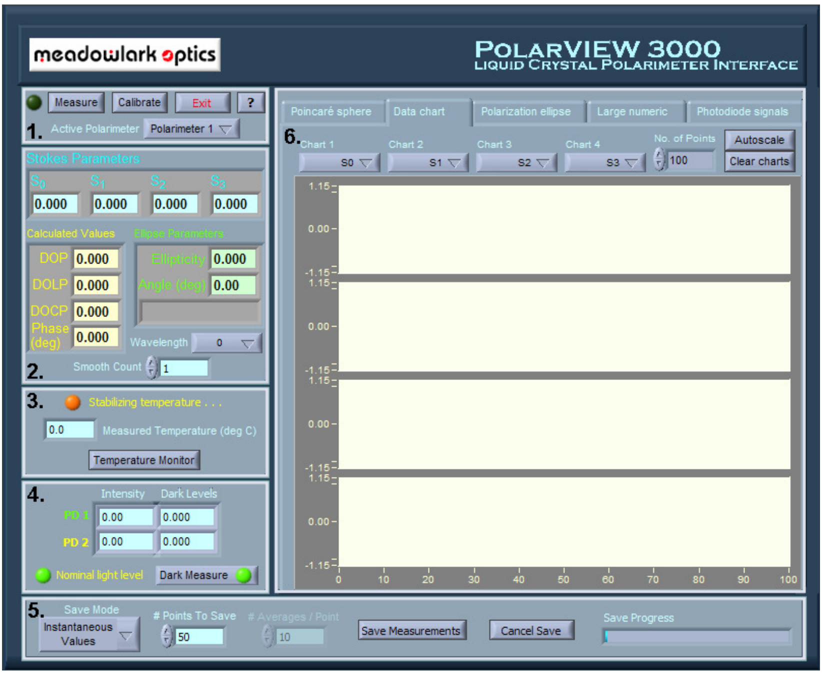

Figure 7. PolarVIEW 3000 Main Screen

(1) Main functions (2) Polarization data display

(3) Temperature information (4) Light levels (5) Save function (6) Display region

3.2.1 Main Functions

- **MEASURE -** Begins or pauses polarization measurements.
- **CALIBRATE -** Displays wavelength calibration screen (section 3.3).
- **EXIT -** Exits PolarVIEW 3000.
- **? -** Displays help.
- **ACTIVE POLARIMETER** - Allows switching between multiple polarimeters connected to the same computer.

3.2.2 Polarization Data Display

- **STOKES PARAMETERS -** Displays the four Stokes parameters.
- **CALCULATED VALUES -** Displays the degree of polarization (DOP), degree of linear polarization (DOLP), degree of circular polarization (DOCP), and phase. See large numeric tab for formulae used to calculate these values.
- **ELLIPSE PARAMETERS -** Displays the ellipticity and angle.
- **WAVELENGTH -** Selects the wavelength for which the polarimeter will be used.
- **SMOOTH -** Applies a smoothing function to the displayed polarization data (a value of 1 produces no smoothing, increasing the value increases the smoothing effect).

3.2.3 Temperature Information

- **TEMPERATURE STATUS LED** - Glows orange to indicate the optical head temperature has not stabilized; green when the optical head temperature is within tolerance and has stabilized. The user should be aware that while the LED is orange, any measurements would not be accurate.
- **MEASURED TEMPERATURE** - Optical head temperature, in °**C**.
- **TEMPERATURE MONITOR** - Displays the temperature screen (section 3.4).

3.2.4 Light Levels

- **INTENSITY** - Indicates the maximum intensity of light incident on each photo detector in the optical head. A value of 0.00 indicates no light is incident on the photo detector and a value of 1.00 is the level at which the photo detector saturates.
- **DARK LEVELS** - Indicates the dark level correction values for each photo detector.
- **LIGHT LEVEL LED -** Glows orange if either too little or too much light is incident on the photo detectors; glows green if the light level is in the proper range.
- **DARK MEASURE -** Performs dark level correction measurement. The LED glows orange if no dark level measurement has been performed and green if a dark level measurement has been performed.

3.2.5 Save Function

- **SAVE MODE** - Selects the save mode; instantaneous mode saves all polarization measurements to the specified text file, averaged mode saves averaged polarization measurements to the specified text file.
- **# POINTS TO SAVE** - Specifies the number of polarization measurements to be saved to the specified text file. Note: This number can be changed while a save operation is in progress.

- **# AVERAGES / POINT -** When in averaged mode, specifies the number of polarization measurements to be averaged before each averaged value is written to the specified text file. This control is inactive when instantaneous mode is selected.
- **SAVE MEASUREMENTS -** Initiates the save process. When clicked, the user is prompted for the polarization parameters to be saved and the name of the text file in which to save the data. Note: All save controls, with the exception of # POINTS TO SAVE, become inactive if measurements are paused during a save operation. When measurements are resumed the save operation resumes.
- **CANCEL SAVE -** Cancels a save operation that is in progress.
- **SAVE PROGRESS -** Indicates the progress of the save operation.

3.2.6 Display Region

The display region shows one of five displays that are selectable by clicking the tabs above the display area. Display formats are shown in Figures 8 - 12:

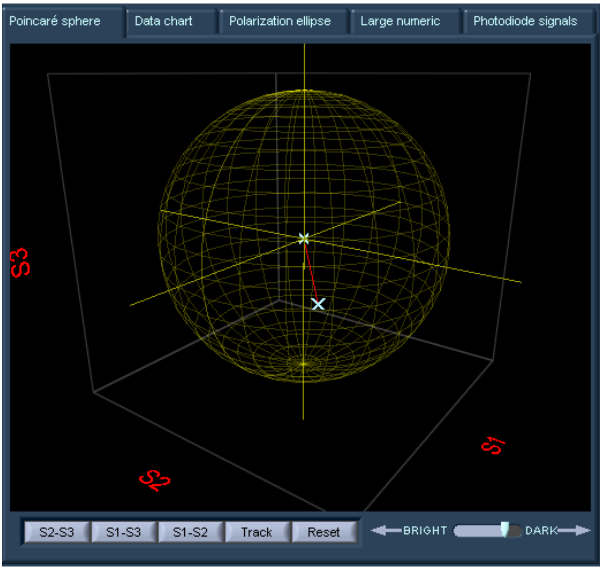

Figure 8: Poincaré Sphere

The Poincaré sphere is used to visualize the SOP of light and the transformation of the SOP produced by the polarization components, for example, polarizers, depolarizers and optical retarders. The polarization state is represented by a vector pointing from the origin to a point location in the sphere of unity radius, characterized by the set of coordinates, (S_1, S_2, S_3). For completely polarized light (DOP=1), this point will lie on the surface of the sphere. For completely unpolarized light (DOP=0), the vector will collapse to a point at the origin. The north and south poles correspond to right-hand [(S_1, S_2, S_3)=(0, 0, 1)] and left-hand [(S_1, S_2, S_3)=(0, 0, ◎1)] circular polarization, respectively. The ellipticity of the polarization decreases as the equator is approached and the equator corresponds to linearly polarized light. The (S_1, S_2, S_3) = (1, 0, 0) and (◎1, 0, 0) locations on the sphere correspond, respectively, to horizontal and vertical polarization, whereas (S_1, S_2, S_3)=(0, 1, 0) and (0, ◎1, 0) correspond to +45° and ◎45° polarization direction angle, respectively. Notice that orthogonal polarizations are always on opposite ends of the sphere. The Poincaré Sphere view offers the option of selecting a projection into the equatorial plane S_1-S_2, or into the longitudinal planes S_1-S_3 or S_2-S_3. It also allows rotation of the sphere (by clicking and dragging on the graphic) and to track a polarization state path on the sphere (TRACK button). To erase the track and return to normal mode press RESET.

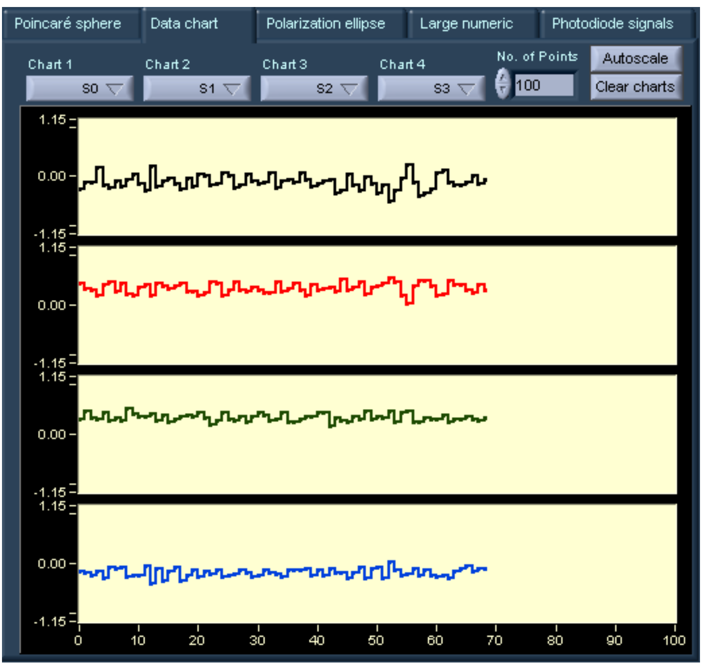

Figure 9: Data Chart

Displays four charts which provide data corresponding to a parameter selected via the pull down menu associated with the chart. Data is plotted in a left to right fashion, when the data reaches the right side of the chart the charts are cleared and plotting resumes on the left side (the charts can be cleared at any time by clicking the CLEAR CHARTS button). The number of points plotted on each sweep is user selectable via the "NO. OF POINTS" parameter. Two Y-axis scaling options exist; clicking the AUTOSCALE button initiates auto-scale of all four charts, or the user may double click on any Y axis limit and manually change the value.

Figure 10: Polarization Ellipse

Displays the polarization state as derived from the Stokes parameters. An elliptical polarization is characterized by its ellipticity and the orientation of the major axis of the ellipse, which are both displayed next to the polarization ellipse plot. The handedness (right or left) is also indicated.

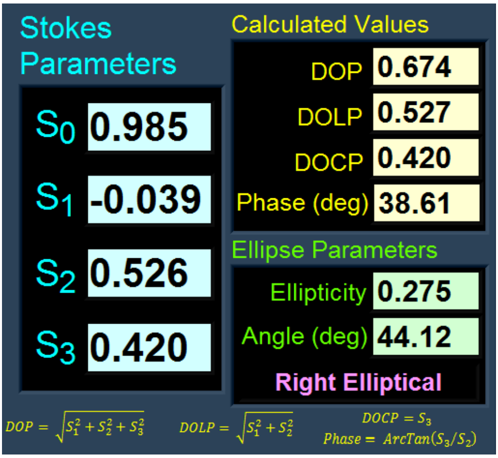

Figure 11: Large Numeric

Mimics the Stokes parameters displayed on the left side of the main screen in a larger format for easier viewing at a distance or where computer screen monitors are used at higher resolutions and also displays phase, (ArcTan (S_3/S_2)).

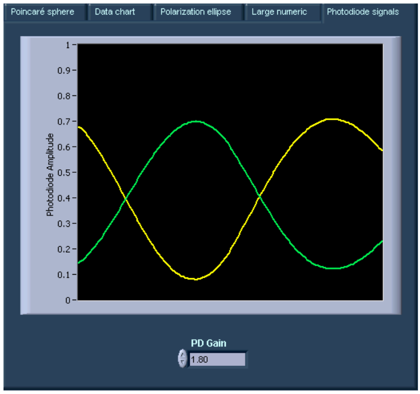

Figure 12: Photodiode signals

Graphically displays the photodiode signals; the Y-axis is scaled from 0.00 (no light) to 1.00 (saturation). The photodetector gain can be changed to account for intensities of light incident on the photodetectors. The gain is wavelength specific and is stored in the optical head; whenever a new wavelength is selected, the appropriate gain is retrieved from the optical head.

3.3 Wavelength Calibration Screen

The wavelength calibration screen, Figure 13, is displayed by clicking the CALIBRATE button on the main screen. This screen is used to calibrate the polarimeter for selected wavelengths and to make changes to the wavelength values that are stored in the optical head.

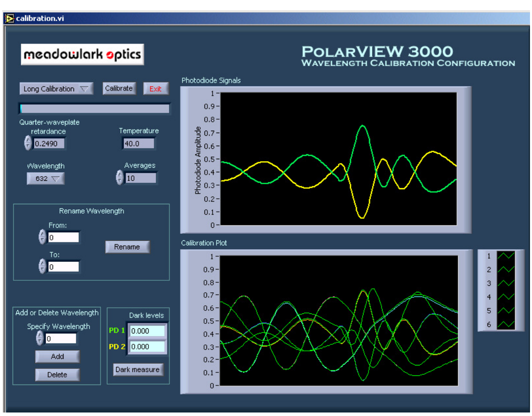

Figure 13. PolarVIEW 3000 Wavelength Calibration Screen

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3.3.1 Calibration Functions

- **LONG CALIBRATION -** Allows the user to select either the short or the long calibration process.
- **CALIBRATE -** Initiates the calibration process described in section 5.2 (the progress bar under the CALIBRATE button shows the progress of each calibration step as it is performed).
- **EXIT -** Exits the wavelength calibration screen.
- **QUARTER WAVEPLATE RETARDANCE -** Allows the user to select the *exact* retardance of the quarter waveplate retarder used in the calibration process.
- **TEMPERATURE -** Displays the current optical head temperature.
- **WAVELENGTH -** Selects the wavelength for which the polarimeter will be used.
- **AVERAGES -** Allows the user to select the number of polarization measurements that will be averaged in each step of the calibration process.
- **RENAME WAVELENGTH FIELD -** Allows the user to rename a wavelength stored in the optical head by specifying the "from" and "to" wavelengths, then clicking the RENAME button.
- **ADD OR DELETE WAVELENGTH FIELD -** Allows the user to add a wavelength to or delete a wavelength from the wavelength values stored in the optical head by specifying the wavelength, then clicking the ADD or DELETE button. *Note:* Do not attempt to rename a wavelength by deleting the wavelength, then adding the new one. A wavelength that is added to the list does not necessarily take the position of the last wavelength that was deleted.
- **DARK LEVELS** - Indicates the dark level correction values for each photodetector.
- **DARK MEASURE -** Performs a dark level correction measurement.
- **PHOTODIODE SIGNALS -** Graphically displays the two photodiode signals (refer to Figure 12 and related text).
- **CALIBRATION PLOT -** Graphically displays the photodiode signals captured during the calibration process. A good calibration is indicated by six distinct green curves shown on the display when calibration is complete. If either there are not six distinct green curves, or any of the curves are red, the calibration process should be repeated.

3.4 Temperature Screen

The PolarVIEW 3000 temperature screen, pictured in Figure 14, is displayed by clicking the TEMPERATURE MONITOR button on the main screen. This screen graphically displays the optical head temperature and also displays the temperature in a large, easy to read digital format.

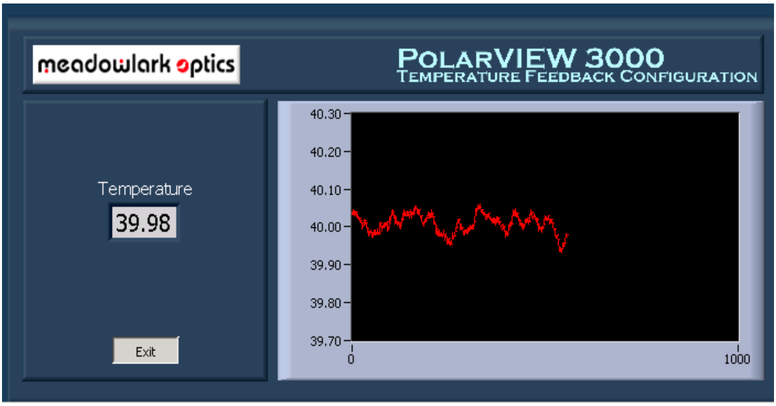


Figure 14. PolarVIEW 3000 Temperature Screen

3.4.1 Temperature Functions

- **TEMPERATURE** Displays the temperature in digital format.
- **EXIT** Exits the temperature screen.

4. Measurement Practices

4.1 Getting ready for measurements

Before taking measurements with the polarimeter it is important to perform the following steps to ensure the instrument functions properly. These instructions assume that the polarimeter is properly calibrated. If after following the instructions below the measurements are still out of specification, please recalibrate the polarimeter for the desired wavelength (refer to section 5.2).

4.2 Temperature control

Upon startup, the optical head warms to the preset calibration temperature (typically ~40°C). Verify that the optical head has reached temperature and stabilized by observing the temperature status LED on the PolarVIEW 3000 main screen. It may take a few minutes for the temperature to reach the preset value. Measurements are possible while the temperature is stabilizing but accuracy will be adversely affected until the optical head temperature stabilizes.

4.3 Dark signal reading

Ambient light incident on the photodetectors and non-zero dark current produced by the photodetectors contribute to measurement error. To correct for these error sources click the DARK MEASURE button on either the main or wavelength calibration screen. A pop-up window will prompt the user to block the beam. Block it as far away from the optical head aperture as convenient and click OK. On the following window, click to record the measured dark signal or repeat the measurement.

4.4 Photodiode gain control

Photodiode output signals will vary depending on the intensity of light incident on the photodiodes. The photodiode gain must be set so that "low light" and "saturation" conditions do not exist. To set the gain value, go to the main screen and click the 'Photodiode signals' tab. Select a value that produces plotted signals that max out at about 0.7 or 0.8 on the Y axis (refer to Figure 12 and related text). The gain should be adjusted every time the external light source varies.

4.5 Wavelength selection

The SOP measurement is wavelength dependent. The wavelength selection control reads the wavelengths stored in the optical head and allows the user to select the desired wavelength.

4.6 Start measurement and warm-up period

To start measuring, click the MEASURE button on the main screen. (Note: Verify the temperature stabilized LED is glowing green to ensure maximum accuracy).

4.7 Smoothing

PolarVIEW 3000 offers a smoothing function that reduces jitter on the displayed polarization data. This function is especially useful for noisy signals where the polarization state fluctuates. Enter the smoothing value via the smoothing control on the main screen (a value of 1 produces no smoothing, increasing the value increases the smoothing effect).

4.8 Sampling and recording to a file

Polarization measurement values may be saved to a text file by clicking the SAVE MEASUREMENTS button on the main screen. After clicking the button, dialog boxes will prompt for the parameters to be saved and the file in which to store data. If an existing filename is entered, new data will be appended to the existing file. In instantaneous mode if smoothing is active, smoothed polarization values are written to the data file. In averaged mode smoothed values are averaged and then written to the file (see section 3.2.5).

Data files generated by PolarVIEW 3000 are tab-delimited ASCII text format, and are readily compatible with common spreadsheet and analysis software. When *Save Measurements* is activated, data is written to an output file in the following format:

time	S_0	S_1	S_2	S_3	DOP	DOLP	DOCP	Phase	e	eta	temp

Where

time = elapsed time in HH:MM:SS.msec since the save was started.
S_0, S_1, S_2, S_3 = the four Stokes parameters.
DOP = Degree of Polarization.
DOLP = Degree of Linear Polarization.
DOCP = Degree of Circular Polarization.
Phase = Phase of light. (ArcTan (S_3/S_2)).
e = Polarization ellipticity (0=linear, 1=circular).
eta = Angle of the polarization ellipse major axis (±90°).
temp = Temperature of polarimeter optics head.

Note: This example assumes all parameters were selected to be saved. Different combinations can be selected via the *Save Measurements* dialog box.

5. Laboratory Considerations

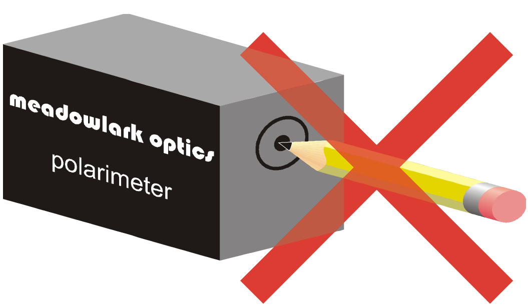
5.1 Optical alignment

It is important to properly align the polarimeter optical head. A misaligned optical head results in insufficient light on the photodetectors causing a weak signal. Furthermore, the distance light travels through a birefringent medium determines the amount of retardance. Therefore angular misalignment of the optical head changes angle of incidence of light on the LC retarders, thereby changing the path length through the liquid crystal. This causes error in the detected ellipticity. While proper alignment is important, it is not difficult to achieve. The configuration of the aperture on the front of the optical head facilitates alignment; light that is sufficiently off-axis to cause an error in the retardance measurement will not land on the photodetectors. The most straightforward alignment method is:

- Position the optical head roughly so that the light to be measured is normal to the aperture.
- Start PolarVIEW 3000, click the ‘Photodiode signals’ button on the main screen and observe the photodiode signals plotted on the screen.
- Adjust the fine positioning of the optical head until the photodiode signals are maximized.
- Tighten the mounting apparatus to secure the optical head.

If a more rigorous alignment is desired, the following technique is offered:

- Make sure the beam to be measured is collimated.
- Pick a surface plane (normal to the beam) within the laser beam path.
- Measure the approximate diameter of the laser beam at this plane. Place the polarimeter at a distance from this plane of at least 60 times the measured diameter.
- Remove the front aperture from the polarimeter by inserting a narrow object, such as a pen or small screwdriver, into one of the lateral holes and turn the aperture counterclockwise to unscrew it. ***Do not insert any objects in the center hole of the aperture***.



- With the aperture removed, locate the strongest retro-reflected beam.
- Rotate and position the polarimeter so that the reflected beam overlaps the incident beam.
- Be aware that some lasers will not be polarization stable if a portion of the beam is precisely retro-reflected back into the output coupler. If polarization or power variations are noticed, slightly misalign the beam to avoid optical feedback.
- Tighten the mounting fixtures and reinsert the front aperture, making sure you don't lose your alignment.

5.2. Calibration

The polarimeter comes pre-calibrated at up to twelve wavelengths. Due to changes in environmental conditions and laboratory configurations, recalibration by the user upon delivery and frequently thereafter is recommended. A basic knowledge of polarization optics is helpful for the calibration process.

The calibration procedure requires providing the polarimeter with six input standard States of Polarization (SOP), those being horizontal, vertical, +45°, -45°, right-hand circular (RHC) and left-hand circular (LHC). Calibration is a function of the PolarVIEW 3000 software; the six standard states of polarization will be requested as the procedural steps are completed. The following procedure describes how to produce these states using a linear polarizer and a quarter-wave retarder, as shown in Figure 15. Meadowlark Optics now offers a calibration device that consists of a linear polarizer and a quarter-wave retarder, both in holders that kinematically mount to a platform to produce desired states of polarization with trivial effort. Please contact Meadowlark Optics for more information.

Two calibration options exist; a short calibration and a long calibration. The short calibration consists of six steps while the long calibration consists of 10 steps. Either calibration procedure will give sterling results, however, for the user that desires maximum accuracy the long calibration procedure is intended to give slightly better results. For either option, best results will be obtained if the photodiode gain is set to produce photodiode curves that max out at about 0.7 or 0.8.

Referring to the diagram in Figure 15, the polarizer (with the quarter-wave retarder removed) produces linear polarization states. The angle of the linear state is determined by the rotational orientation of the polarizer. Therefore, the polarizer in Figure 15 should be mounted such that it can be rotated precisely (within ~5 arc minutes) to the desired angles. Using the quarter-wave retarder with the polarizer produces circular states. The retarder must be positioned such that its fast axis is at 45°. Figure 16 shows the angular orientation of the polarizer and quarter-wave retarder for each calibration step in the short calibration process. The long calibration process repeats steps 1, 2, 5 and 6 using the opposite face of the linear polarizer.

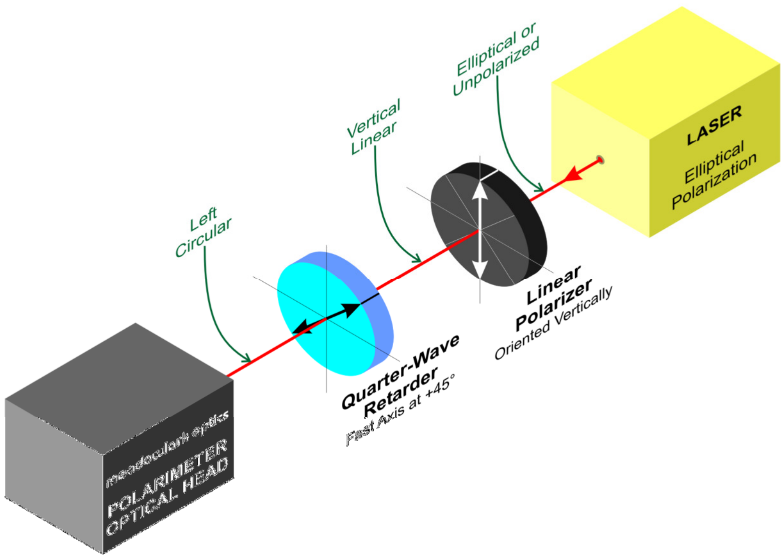


Figure 15. Optics for Polarimeter Calibration. The linear polarizer is rotated during the calibration procedure; the quarter-wave retarder is removed for the first four steps.

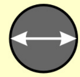
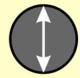
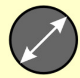
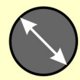
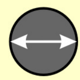
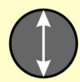
Calibration Sequence	Stokes Vector	SOP Description	Polarizer Orientation	Waveplate Orientation
Step 1	(1, 1, 0, 0)	Horizontal		*Removed*
Step 2	(1, −1, 0, 0)	Vertical		*Removed*
Step 3	(1, 0, 1, 0)	+45°		*Removed*
Step 4	(1, 0, −1, 0)	−45°		*Removed*
Step 5	(1, 0, 0, 1)	Right Circular		
Step 6	(1, 0, 0, −1)	Left Circular		

Figure 16. Polarization States for Short Calibration. Note that the rotational orientation of the polarizer and waveplate are from the perspective looking *toward the light source.*

It is not necessary that the waveplate used for calibration be exactly a quarter-wave as long the precise retardance at the calibration wavelength is known. However, it should be noted that calibration is optimized when a quarter-wave retardance is available. The source is a laser that produces an arbitrary nonlinear (i.e., elliptical) state. Elliptically polarized light is desirable because placement of a polarizer in a beam that is linearly polarized can result in a severely diminished signal if the polarization axis is perpendicular to the polarization state of the source light.

If a laser that produces linearly polarized light is used, a retarder should be placed at the laser's output aperture to produce an elliptical state. Once you have an approximately circularly polarized laser beam, you can then mount the calibration optics in front of the polarimeter. Mount the polarizer to a rotation stage with at least 5 arc-minutes angular resolution. Align the polarizer to your horizontal reference (typically the optical table) and take note of the corresponding angular value on the rotation mount. Mount the quarter wave-plate following the polarizer (between the polarizer and the polarimeter) on a similar, but removable, rotation mount. (A kinematic mount is recommended for mounting the wave-plate.) Carefully align the wave-plate axis to be at 45^o with respect to the polarizer axis when this latter is aligned to the horizontal reference. (At this position the polarizer-wave-plate set will consist of an optical isolator. Thus, one reliable way to set or verify this 45^o alignment between the wave-plate and the polarizer is by placing a retro-reflecting mirror behind the wave-plate and picking up the reflected beam, after it crosses the polarizer, with a beam-splitter and directing it to a detector. Rotate the wave plate: the intensity of the retro-reflected light will be a minimum when the plate is at 45^o degrees to the polarizer.) Once the wave-plate is aligned, lock it to that angular position as it won't need to be rotated during calibration.

To start the calibration process, ensure the polarimeter is aligned as described above. Perform a dark signal measurement by covering the beam as far away from the polarimeter as convenient, then clicking the DARK MEASURE button. Follow the prompts to record the dark value. Ensure the appropriate wavelength is selected and the quarter wave-plate retardance is set to the correct value. Set the number of measurements to be averaged for each calibration SOP to the desired value and select the calibration procedure to be performed. Initiate the calibration process by clicking the CALIBRATE button. Follow the instructions detailed for each calibration step, paying careful attention to the diagrams and the FACE A/FACE B orientation of the polarizer (polarizer faces will be clearly marked if the polarizer was purchased from Meadowlark Optics as part of a calibration set).

When the calibration process is complete the calibration plot should display six distinct green curves. If any curves are red the maximum amplitude of that curve was either too high or too low and the photodiode gain should be adjusted before recalibrating. If there are less than six distinct curves then very likely one or more of the calibration steps was not performed properly and the user should recalibrate. The user may then choose to save the calibration data or cancel without saving. Measurements may then be resumed by clicking the EXIT button to return to the main screen.

6. User Development with LabVIEW™ VI's Provided by Meadowlark Optics, Inc.

Several VI's are included in a library file on the PixelDRIVE 3000 CD. They can be found in <drive letter>:\LabVIEW\ directory. LabVIEW™ VI's that interface with the D3128 are:

- Meadowlark Polarimeter User Example.VI
- Meadowlark Polarimeter User VI's.LLB
    - Meadowlark Polarimetry Output.VI
    - Meadowlark Initialize Polarimeter.VI
    - Meadowlark Read Polarimeter.VI
    - Meadowlark Shutdown Polarimeter.VI
    - Various helper VI's

The user development directory includes a LabVIEW™ library file containing fundamental VI's and examples that implement them in rudimentary programs that read polarimetry data out of the polarimeter. The LabVIEW™ back panel of the polarimeter example VI has been made accessible to our customers to facilitate independent development. Developers are encouraged to open and examine the example VI diagram screen. Please note that the LabVIEW™ development suite (version 6.1 or greater) from National Instruments is required to use the included VI's, and Meadowlark Optics, Inc. does not provide this development package with PolarVIEW 3000. It is assumed that the customer has experience programming in LabVIEW™ and understands good programming practices. Meadowlark Optics, Inc. cannot offer customer support for LabVIEW™ application development. If a developed or modified LabVIEW™ application is to be distributed in any way, please contact Meadowlark Optics for licensing and copyright details.

7. General Specifications

Maximum absolute Degree Of Polarization error:	< 1%
Wavelength Range for Calibration Accuracy:	± 3 nm
Measurement Frequency:	10Hz (USB interface)
Resolution:	0.001 of a Stokes Parameter
Maximum Operating Temperature:	35°C
Optical Head Dimensions (inches):	2.83 × 1.75 × 1.75
Minimum Optical Power to maintain accuracy:	10 μW
(*Sensitivity can be increased by special request)*	
Driver Power Requirements:	115V/220V (±10%) 5 W Max.

Appendix A: Frequently Asked Questions

Q: Why is the controller not working?
A: Check that the power supply is plugged in, front panel switch is on and the green power light is steady. Check the status of the USB interface under Windows® Device Manager. Occasionally it helps to reboot the controller; turn off the controller, wait a few seconds, then turn it back on.

Q: I started the PolarVIEW 3000 software and then turned on the D3000 controller, now the software is behaving erratically. What is happening?
A: The D3000 controller must be turned on and have completed its power-on self-test *before* starting the PolarVIEW 3000 software.

Q: How do I uninstall the PolarVIEW 3000 software?
A: Use the Add/Remove Programs option in the Windows® control panel.

Q: Are there Apple, Linux, OS/2, or UNIX versions of PolarVIEW 3000? Can I use PolarVIEW 3000 on a COMPUTER running MS-DOS®, Windows® 3.1, Windows® 95, Windows® 98, or Windows® NT?
A: No. PolarVIEW 3000 runs under the 98SE, ME, 2000, and XP versions of Microsoft® Windows® only.

Q: What is the purpose of the SYNC connector on the front panel?
A: A pulse is produced on the SYNC connector each time the D3000 controller has finished gathering a set of photodetector samples. This signal can be used to synchronize external devices to the D3000.

Q: What is the default optical head temperature value?
A: The optical head temperature will be maintained at ~40°C.

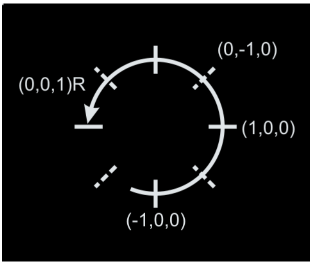
Q: Why does the front panel status LED blink when running PolarVIEW 3000?
A: The front panel status LED blinks to indicate that polarization data is being transferred from the D3000 controller to PolarVIEW 3000.

Q: Is there any significance to the blink rate?
A: In a normally operating system the front panel status LED should blink at 10 Hz.

Q: Why might the front panel status LED blink in an erratic fashion?
A: If polarization data is not being transferred at a 10 Hz rate it will be reflected by the blink rate of the front panel status LED. Normal causes would be a slow COMPUTER, excessive network activity or applications (*e.g.,* anti-virus software) running on the COMPUTER that require excessive processor bandwidth.

Q: Is it a problem if the polarimeter is running at less than 10 Hz?
A: No. PolarVIEW 3000 still displays accurate data but the update rate will be less than 10Hz.

Q: What are the markings around the aperture of the Polarimeter Optical Head?
A: The markings are the Stokes vector designation for the associated polarization state. Due to space constraints, the first element of the vector description, which is always 1, is not shown.



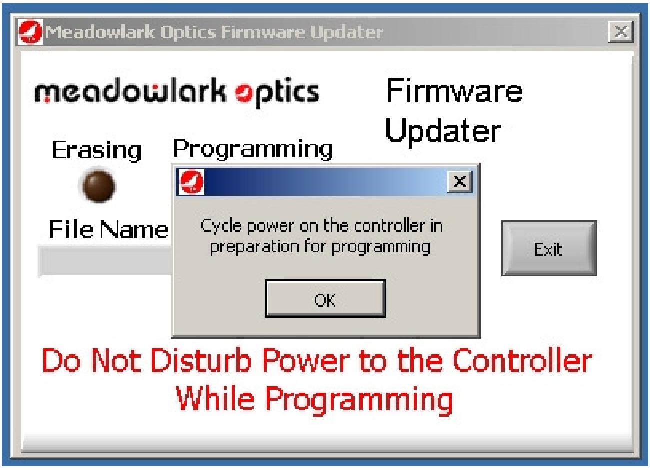
Appendix B: Firmware Updater

The D3000 internal firmware can be reprogrammed by the user when new versions are released by Meadowlark Optics. Update is accomplished by using the firmware updater program included on the PolarVIEW CD. In order to use the firmware updater program the D3000 must be powered on and connected to an available USB port on the host computer.

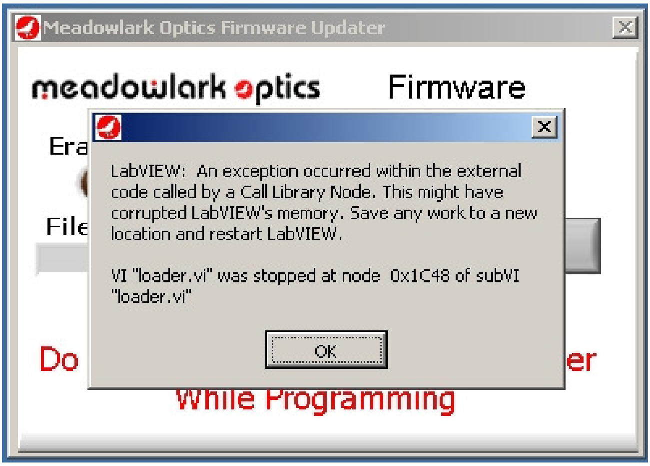
Perform the following steps to reprogram the D3000 firmware:

1. Install the firmware updater software on a COMPUTER running Microsoft® Windows® (98SE or later). Place the included CD in the CD-ROM drive, open the "Firmware updater" folder and double-click "setup.exe".

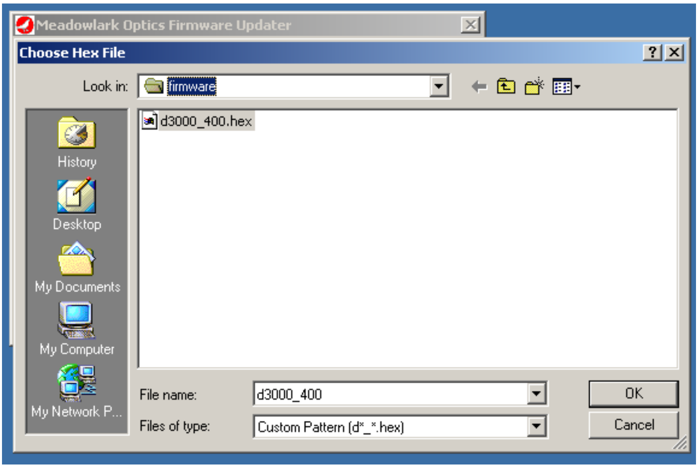
2. Start the firmware updater software by clicking Start|Programs|Meadowlark Optics/Firmware updater. The following screen will appear:



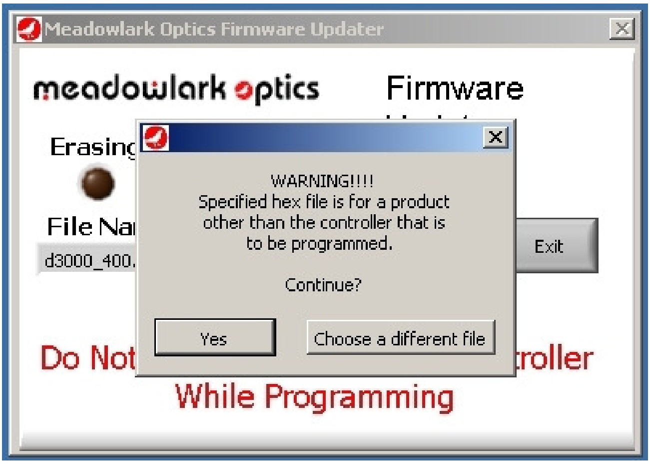
3. Cycle power on the D3000 controller to ensure the USB connection is properly made. Wait until the front panel status LED is done flashing before clicking OK. If the power is not cycled or the OK button is clicked before the front panel status LED is done flashing, the following error will be displayed. If this error appears, close the firmware updater program and re-run it.



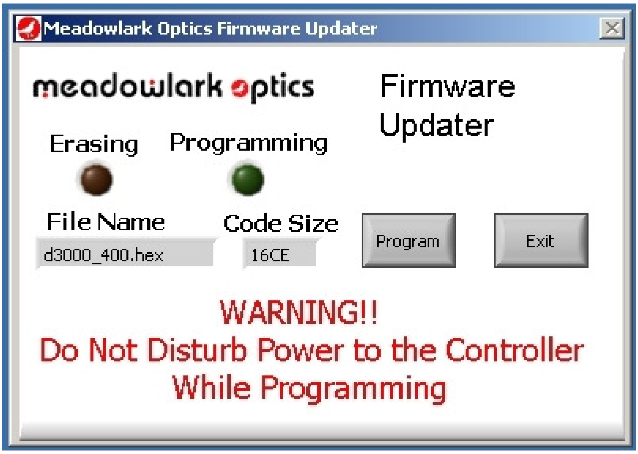
4. The following screen will appear after the USB connection is made.

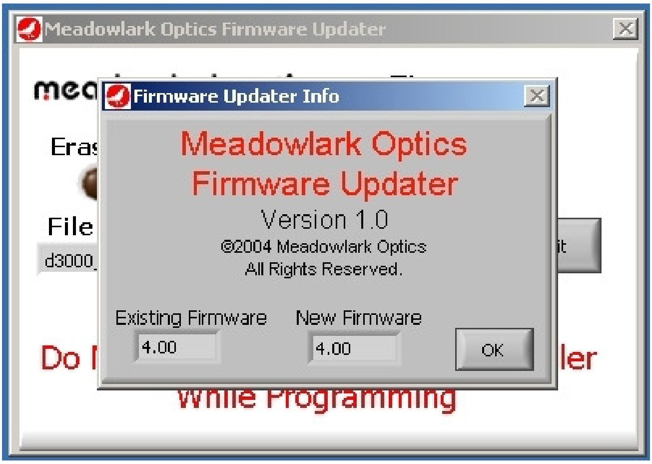


5. Choose the new hex file and click "OK". The program will check if the new firmware file is valid for the D3000, if not, the following error screen will appear. At this point the user may elect to choose a different file or go ahead and program the D3000 with the chosen file. *Extreme caution should be exercised when deciding whether to program the D3000 with a file that may not be compatible*. If there are questions about choosing the appropriate file please contact Meadowlark Optics at 303-833-4333.

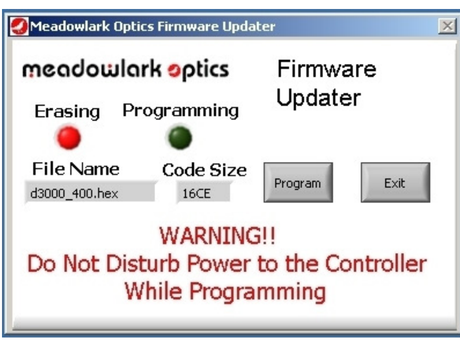


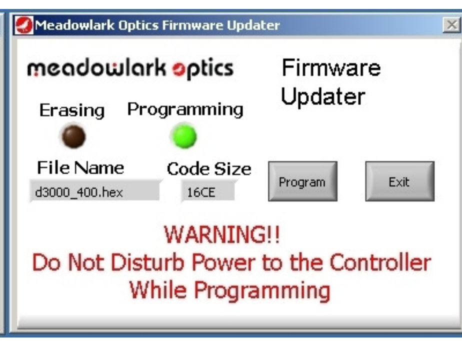
6. After the hex file is loaded and passes the validity tests, the ready screen appears as below (Code Size shows the size of the firmware code and is present only for troubleshooting). Click the Program button to reprogram the D3000 firmware. If a final check is desired before reprogramming firmware the Meadowlark Optics logo may be clicked to display a screen (shown below) showing the old and new firmware versions.



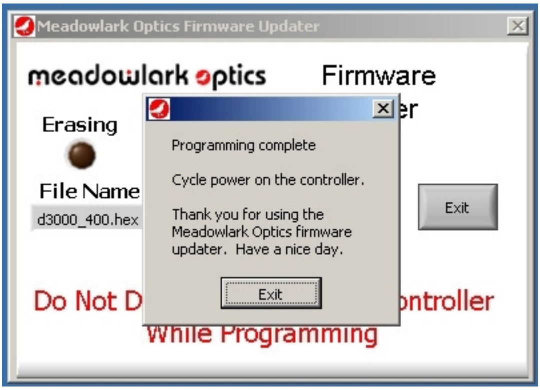


7. As the firmware is being erased and reprogrammed the status will be displayed as shown below. *DO NOT* disturb power to the D3000 while it is erasing or reprogramming, if memory is corrupted it will be required to return the unit to Meadowlark Optics for reprogramming.





8. After programming is complete the following screen appears. When the controller power is cycled the status light should flash a pattern corresponding to the version number of the new firmware. The new firmware version may also be determined by clicking the Meadowlark Optics logo in the upper left corner of PolarVIEW.



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10. Force Majeure

If performance hereunder (other than payment) is interfered with by any condition beyond a party's reasonable control, including any Act of God, the affected party shall be excused from such performance to the extent of such condition. However, if a force majeure detrimentally affects a party's performance of a material obligation hereunder for 14 days or more, the other party can terminate this Agreement.

11. Mediation, Arbitration

The parties shall endeavor to resolve any dispute by mediation in Boulder, CO under the CPR Mediation Procedure. If the parties have not resolved this matter within 45 days from the selection of a mediator, the parties shall settle any controversy arising out of this Agreement) by arbitration to be held in Boulder, Colorado, in accordance with the rules of the American Arbitration Association. A single arbitrator shall be agree upon by the parties, or, if the parties cannot agree upon an arbitrator within thirty (30) days, then the parties agree that a single arbitrator shall be appointed by the American Arbitration Association. The arbitrator will apply the substantive law of the State of Colorado. The arbitrator may award attorney's fees and costs as part of the award. The award of the arbitrator shall be binding and may be entered as a judgment in any court of competent jurisdiction.

12. Notices

Any notice under this Agreement will be in writing and delivered by personal delivery, overnight courier, confirmed facsimile, confirmed e-mail, or certified or registered mail, return receipt requested, and will be deemed given upon personal delivery, 1 day after deposit with an overnight courier, 5 days after deposit in the mail, or upon confirmation of receipt of facsimile or email. Notices will be sent to a party at its address set forth at the end of this Agreement, or such other address as a party may specify in writing pursuant to this Section.

13. Entire Agreement; Amendment; Waiver

This Agreement sets forth the entire understanding and agreement of the parties, and supersedes any and all oral or written agreements or understandings between the parties, as to the subject matter of the Agreement. This Agreement may be changed only by a writing signed by both parties. The waiver of a breach of any provision of this Agreement will not operate or be interpreted as a waiver of any other or subsequent breach.

14. Severability; Headings

If any provision herein is held to be invalid or unenforceable for any reason, the remaining provisions will continue in full force without being impaired or invalidated in any way. The parties agree to replace any invalid provision with a valid provision that most closely approximates the intent and economic effect of the invalid provision. Headings are for reference purposes only and in no way define, limit, construe or describe the scope or extent of such section.

15. Governing Law

This Agreement will be governed and construed in accordance with the laws of the State of Colorado without giving effect to conflict of laws principles. Both parties submit to personal jurisdiction in Colorado.

Trademarks

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