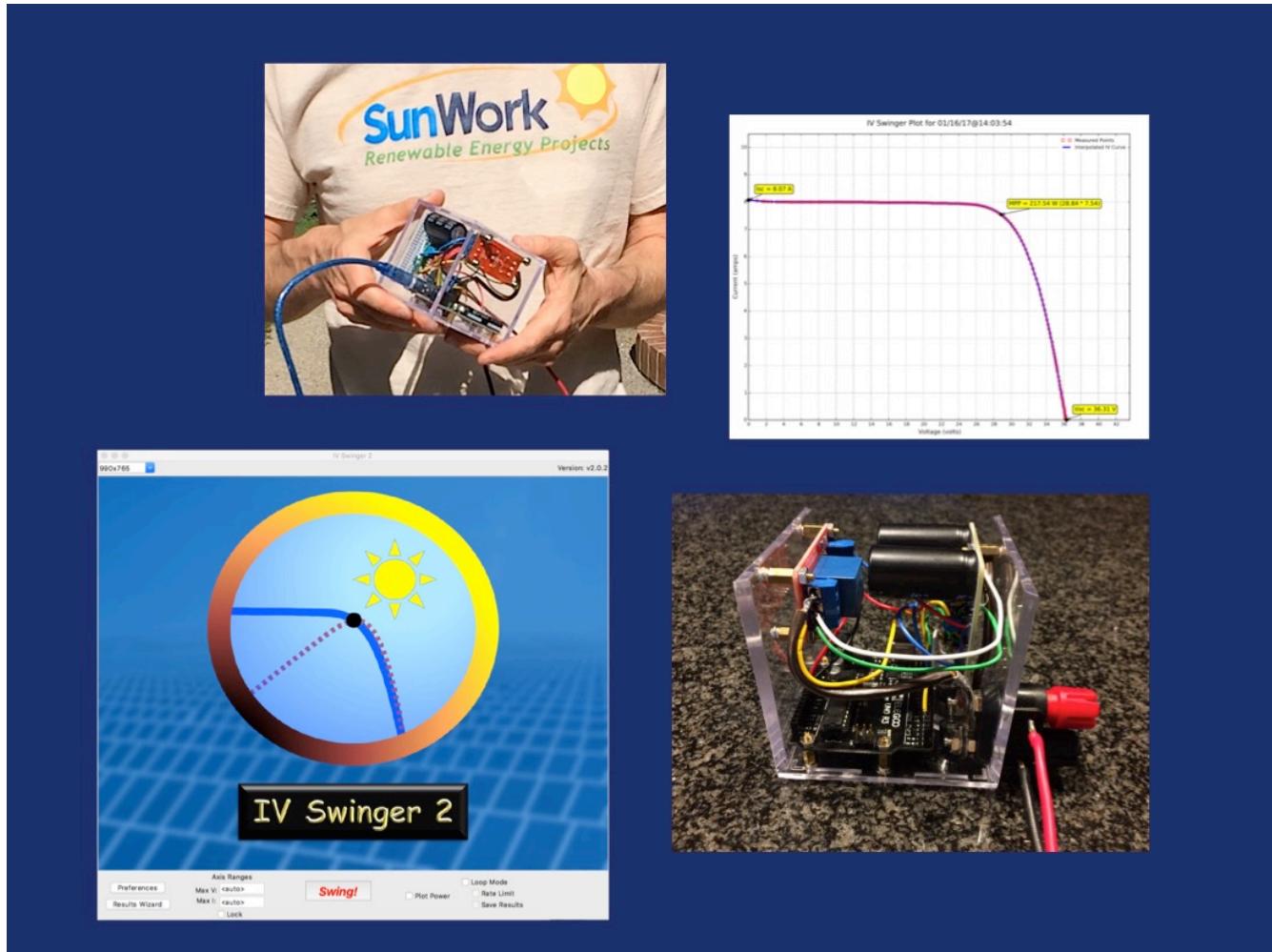


IV Swinger 2

User Guide

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Chris Satterlee



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IV Swinger and IV Swinger 2 are open source hardware and software projects.

Permission to use the hardware design is granted under the terms of the TAPR Open Hardware License Version 1.0 (May 25, 2007) - <http://www.tapr.org/OHL>

Permission to use the software is granted under the terms of the GNU General Public License v3 - <http://www.gnu.org/licenses>.

Current versions of the license files, documentation, Fritzing file (hardware description), and software can be found at:

https://github.com/csatt/IV_Swinger

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1 YouTube Demo Videos / Quick Start

1.1 YouTube Demo Videos

Part I: <https://youtu.be/WhnTWciiNNo> (7:02)

Part II: https://youtu.be/9iPq5AsuU_U (6:48)

1.2 Quick Start

1. Open the IV Swinger 2 application on your Mac or Windows laptop

Software installation instructions are on page 45. There should be a “Not connected” message below the button labeled “Swing!”

2. Connect the USB cable from the IV Swinger 2 hardware to the laptop

The “Swing!” button on your screen should change to red text and the “Not connected” message should disappear.

3. Connect the PV panel to the cables

Take care to connect the positive (+) cable from the panel to the female IV Swinger cable (RED binding post) and the negative (-) cable from the panel to the male IV Swinger cable (BLACK binding post).

4. Establish the desired PV panel conditions

i.e. angle, shading, etc. Also at this point, take any other desired measurements such as insolation and temperature.

5. Click on the “Swing!” Button

The IV curve will be displayed on the screen. Repeat as many times and as often as desired. All results are saved and can be viewed, copied, combined, modified, etc. later.

- "Plot Power" can be checked to include the power curve on the graph. This can be done after the fact too.
- "Loop Mode" can be checked to repeatedly swing IV curves. "Rate Limit" can be checked to slow down the looping rate to a specified interval. Since looping can generate a lot of data and image files, the default is to not save the results. "Save Results" can be checked to override this default.

6. Click on the “Results Wizard” Button

A dialog window will open with options to:

- View results of previous runs
- Combine multiple curves on the same plot (overlays)
- Modify the title and appearance of curves and overlays
- Copy them to a USB drive (or elsewhere)
- View the PDF

The Results Wizard does not require the hardware to be connected. In fact it can be run on results that were collected by a different computer and copied to a USB drive.

2 Introduction

Like the first-generation IV Swinger, IV Swinger 2 automates the process of tracing the IV curve of a single photovoltaic (PV) solar panel.

The IV curve is a graph of current versus voltage for various load values driven by the PV panel. A typical IV curve of an unshaded PV panel looks like this:

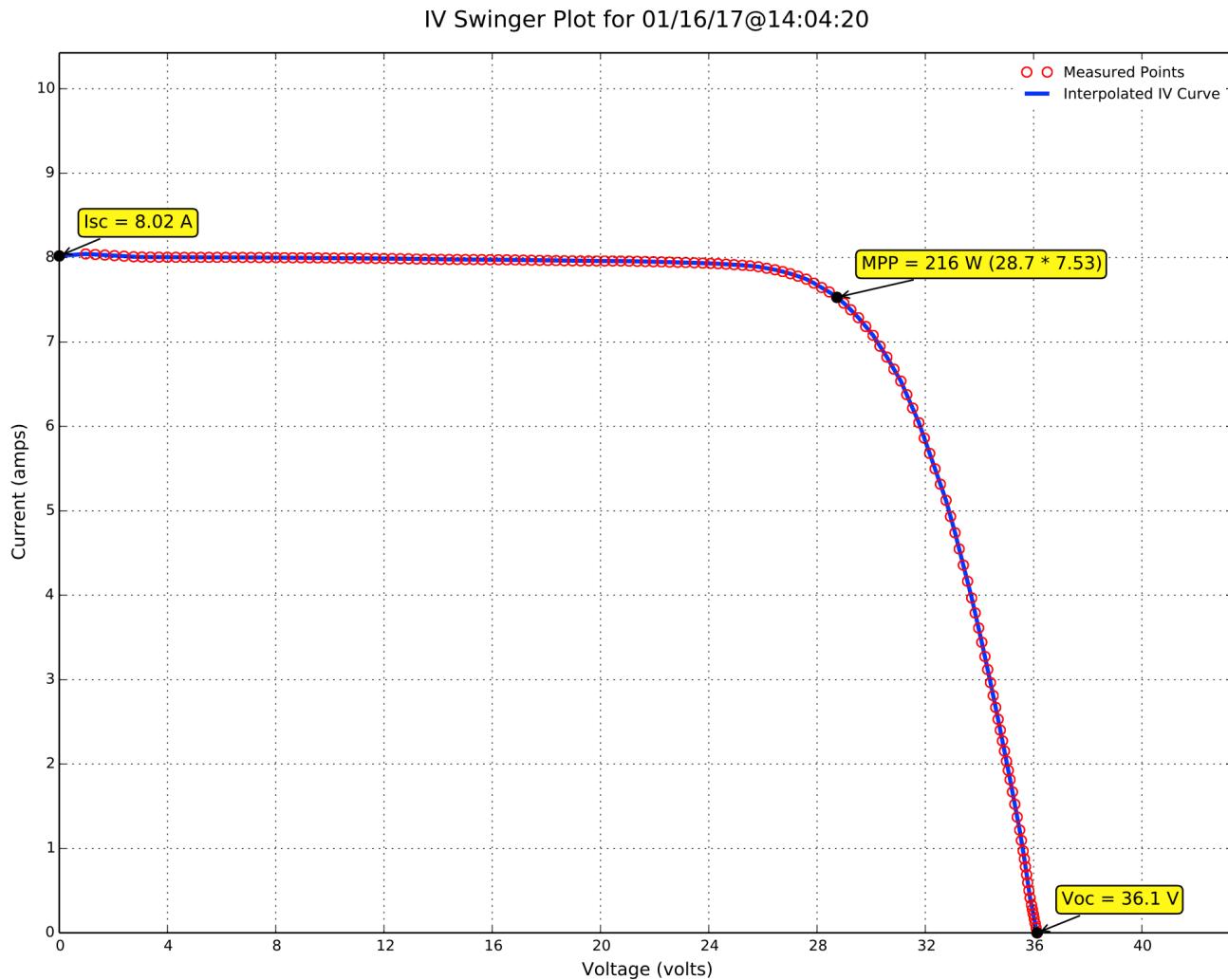


Figure 2-1: Typical IV Curve of Unshaded PV Module

At one extreme there is the short-circuit current (I_{sc}), which is the current delivered by the PV when the leads are directly connected to each other (in which case the load is 0 ohms and the voltage is 0 volts). At the other extreme is the open-circuit voltage (V_{oc}), which is the voltage across the PV terminals when there is no connection between them (in which case the load resistance is infinite and the current is 0 amps). Between these two points is a curve dependent on the load (resistance) connected between the PV terminals. As seen above, the typical IV curve is a fairly horizontal line declining slightly from I_{sc} as the voltage increases and then declining steeply when the voltage nears V_{oc} . Power is the product of current and voltage. No power is delivered when the circuit is shorted (since the voltage is 0) and no power is delivered when the circuit is open (since the current is 0). The maximum power is delivered for the load value at the “knee” of the curve. One purpose of generating an IV curve is to determine the maximum power that a given panel can generate under a given set of conditions (such as insolation and

temperature). Plotting the IV curves for different conditions including shading is an important lab exercise in courses teaching principles of photovoltaic operation

Manual generation of an IV curve is a fairly tedious (albeit educational) process. First the I_{sc} and V_{oc} values are measured with a multimeter. Then the PV panel is connected to a variable load. This can be a bank of light bulbs that may be switched into or out of the circuit. Or it can be a heavy-duty rheostat. The load value is incrementally changed, and at each point the meter is used to measure the current and voltage, which are recorded manually. Then the values are typed into a spreadsheet and plotted. Performing this process by hand at least once is a good way to get a real feel for what is going on. But it is time-consuming, subject to human error, subject to changing conditions, etc.

The IV Swinger is named for the process of “swinging out an IV curve”, which is how Gil Masters describes it in his CEE176B class at Stanford. The first generation IV Swinger uses immersion heating coils for the loads, and a Raspberry Pi single-board computer to control relays that switch the loads into and out of the circuit. It has built-in voltmeter and ammeter hardware that are read by the software at each load value. The results are written to a USB thumb drive for later viewing.

IV Swinger 2 is a completely different design. It uses a capacitor as the load. A discharged capacitor “looks” like a short circuit (zero resistance). But as it charges up, its apparent resistance increases. When it is fully charged, it “looks” like an open circuit (infinite resistance). A typical PV module in full sun will charge the capacitor up to the V_{oc} voltage in a matter of milliseconds. An Arduino UNO microcontroller board is used to control a single relay that switches between bleeding the charge from the capacitor to connecting the PV module across it. After switching the PV module into the circuit, the Arduino very quickly reads from the voltmeter and ammeter hardware repeatedly to record points on the IV curve as the capacitor charges up.

IV Swinger 2 requires a Mac or Windows laptop to be connected to it by a USB cable. The power for the Arduino and other circuitry come through the USB cable. An application program running on the laptop communicates with the Arduino via the USB cable and provides the interface to the user.

Although IV Swinger 2 is not quite as easy to relate to the manual method as the original IV Swinger, it has many advantages:

- Real time results
- Much better resolution (>100 points per curve vs. ~20)
- Much lower time to swing a curve (milliseconds vs seconds)
- Much smaller size and lower weight
- Simpler user interface
- Simpler, more reliable and repairable design
- More flexible connectivity (binding posts)
- Much lower cost to build (\$50 vs \$330)
- Much less time and effort to build

3 Visual Tour of the Hardware

3.1 USB Port

On the front of the IV Swinger 2 is a single “Type B” USB port/jack. This how the IV Swinger 2 connects to the host laptop computer both for power and communication. Note that when the USB cable is plugged into this port, the lid is “locked” onto the case and when the cable is unplugged, the lid may be removed.

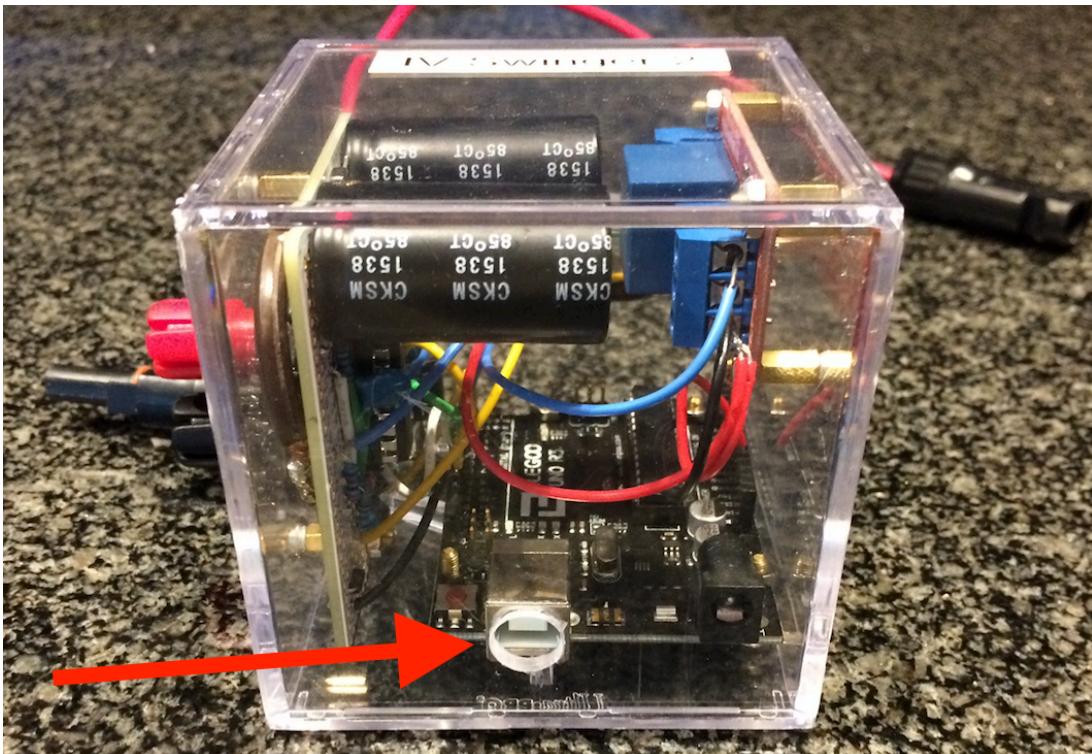


Figure 3-1: USB Port

3.2 Binding Posts / PV Connection Cables

On the lower left side, at the rear, are the RED and BLACK binding posts. The RED post connects to the positive module cable (PV+) and the BLACK post connects to the negative module cable (PV-). The PV connection cables are inserted into the holes in the binding posts at the back, and the knobs tightened down. Make sure the connection cable with the female MC4 connector is connected to the RED binding post and the cable with the male MC4 connector is connected to the BLACK binding post. The binding posts allow for the flexibility of using different length PV connection cables or even non-MC4 connections such as banana plugs, but you have to be careful to get the polarity correct.



Figure 3-2: Binding Posts and PV Cables

3.3 Innards

3.3.1 Circuit Board with Load Capacitors

The white “Perma-Proto” board on the side with the binding posts contains the following:

- 2000 μ F load capacitance (two 1000 μ F capacitors in parallel)
- Bleed resistor. Between tests, the relay connects this resistor across the capacitors to drain them of all charge.
- Analog-to-Digital Converter (ADC) for voltmeter and ammeter
- Shunt resistor (on back). This is used for the ammeter. It is a precise low-resistance (.005 Ω) resistor that is in the load circuit. The voltage across it is measured by the ADC (after amplification by the op amp circuit). Ohm’s Law is then used to calculate the measured current.
- Voltage divider circuit to scale the PV voltage down to the range supported by the ADC
- Op amp circuit to scale the voltage across the ammeter shunt resistor up to the range supported by the ADC

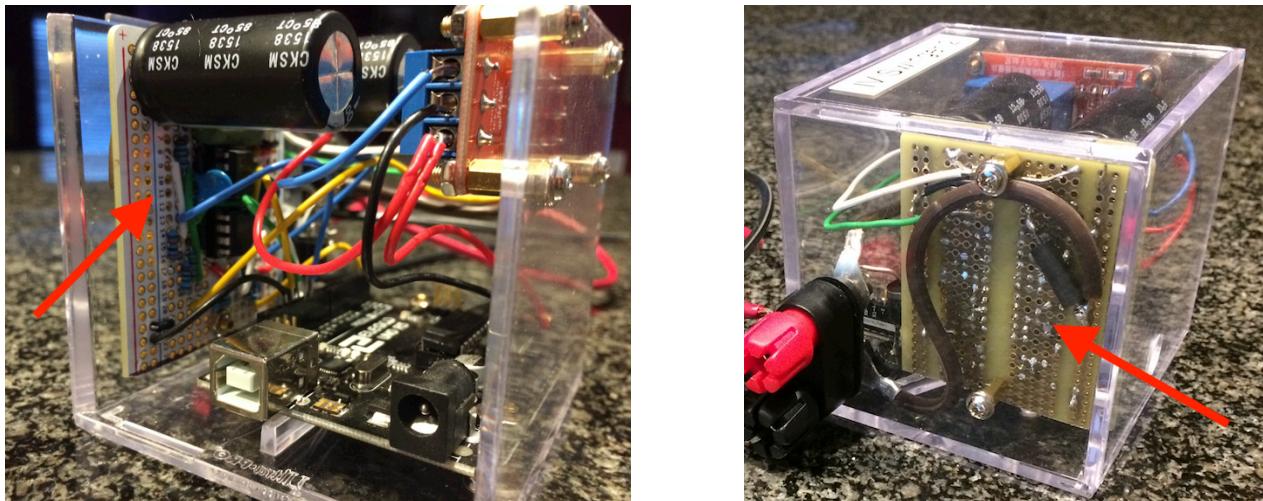


Figure 3-3: Circuit Board with Load Capacitors

3.3.2 Arduino UNO

The Arduino UNO is the board (with the USB port) mounted to the bottom of the case. This is a very inexpensive (~\$10) and ubiquitous microcontroller that is a staple of the “maker” community. It runs software that communicates with the host laptop computer over USB. When instructed by the laptop, it runs the algorithm for swinging the IV curve. This algorithm consists of activating the relay and repeatedly reading the ammeter and voltmeter values from the ADC while the capacitor charges up. When the points have all been measured, the values are uploaded to the laptop.

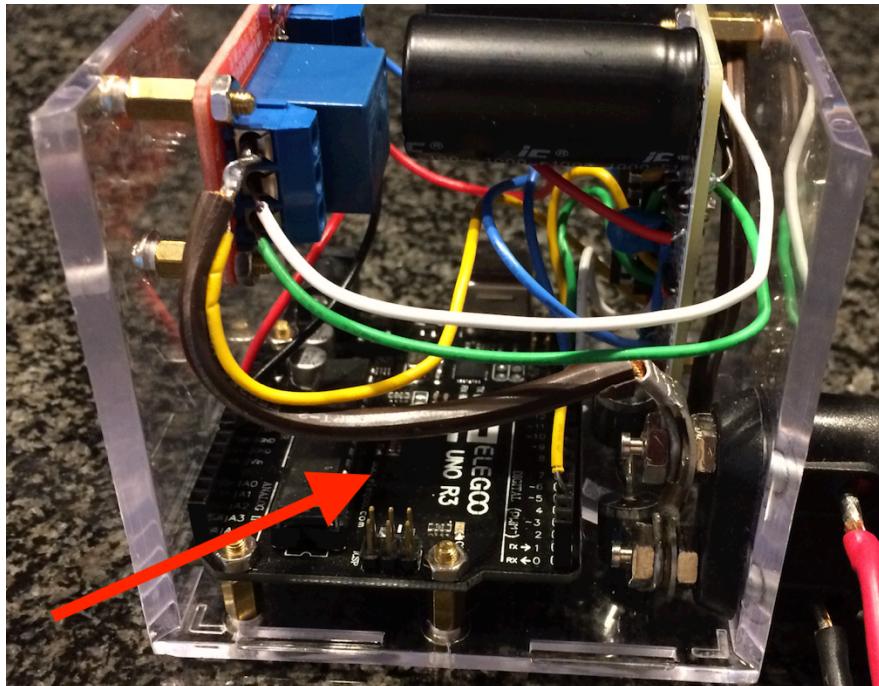


Figure 3-4: Arduino UNO

3.3.3 Relay Module

The relay is controlled by the Arduino software to switch what is across the capacitor load: the bleed resistor or the PV module. The bleed resistor is selected most of the time. The load capacitor is selected only for the brief amount of time that the IV curve is being traced. A relay is a physical switch operated by an electromagnet. You can hear it “click” when it switches. The two clicks (representing the beginning and end of the IV curve) will be very close together in most cases (“click-click”). But in low sun cases, there can be several seconds between the two clicks since the capacitor load takes a lot longer to charge up to the Voc voltage.

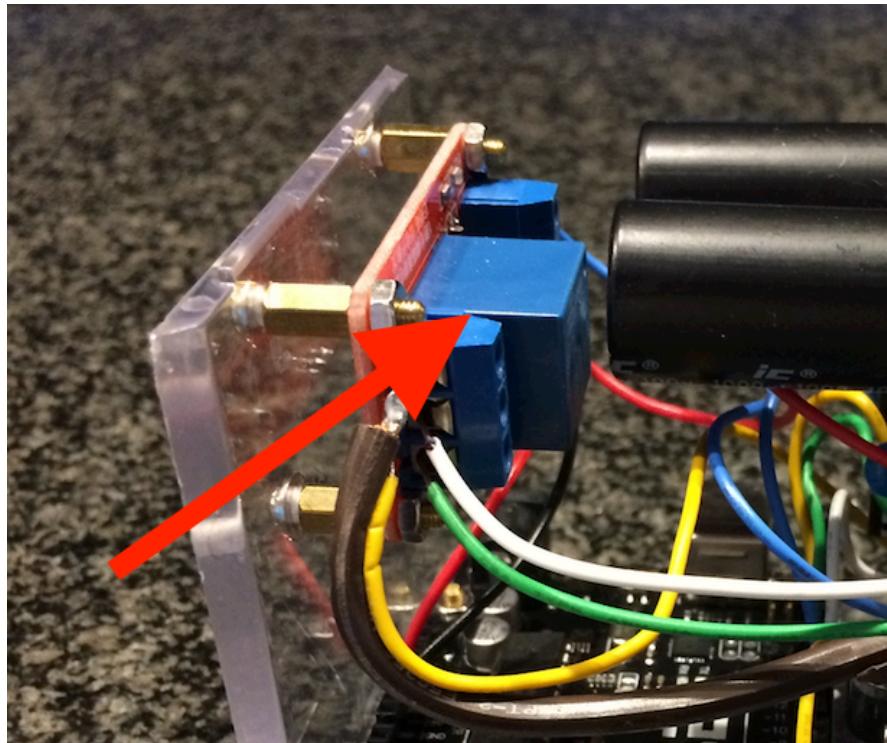
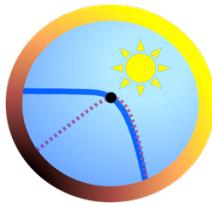


Figure 3-5: Relay Module

4 Using the IV Swinger 2 Software

The IV Swinger 2 software application runs on a Mac or Windows laptop. If it is already installed, you can recognize it from its icon:



On a Mac, the program will be in the Applications folder. On Windows, it will be in the standard place that your version of Windows keeps programs (e.g. the “Program Files (x86)” folder).

If the application is not already installed, see the *Laptop Software Installation* section on page 45 of this document.

4.1 Main Window

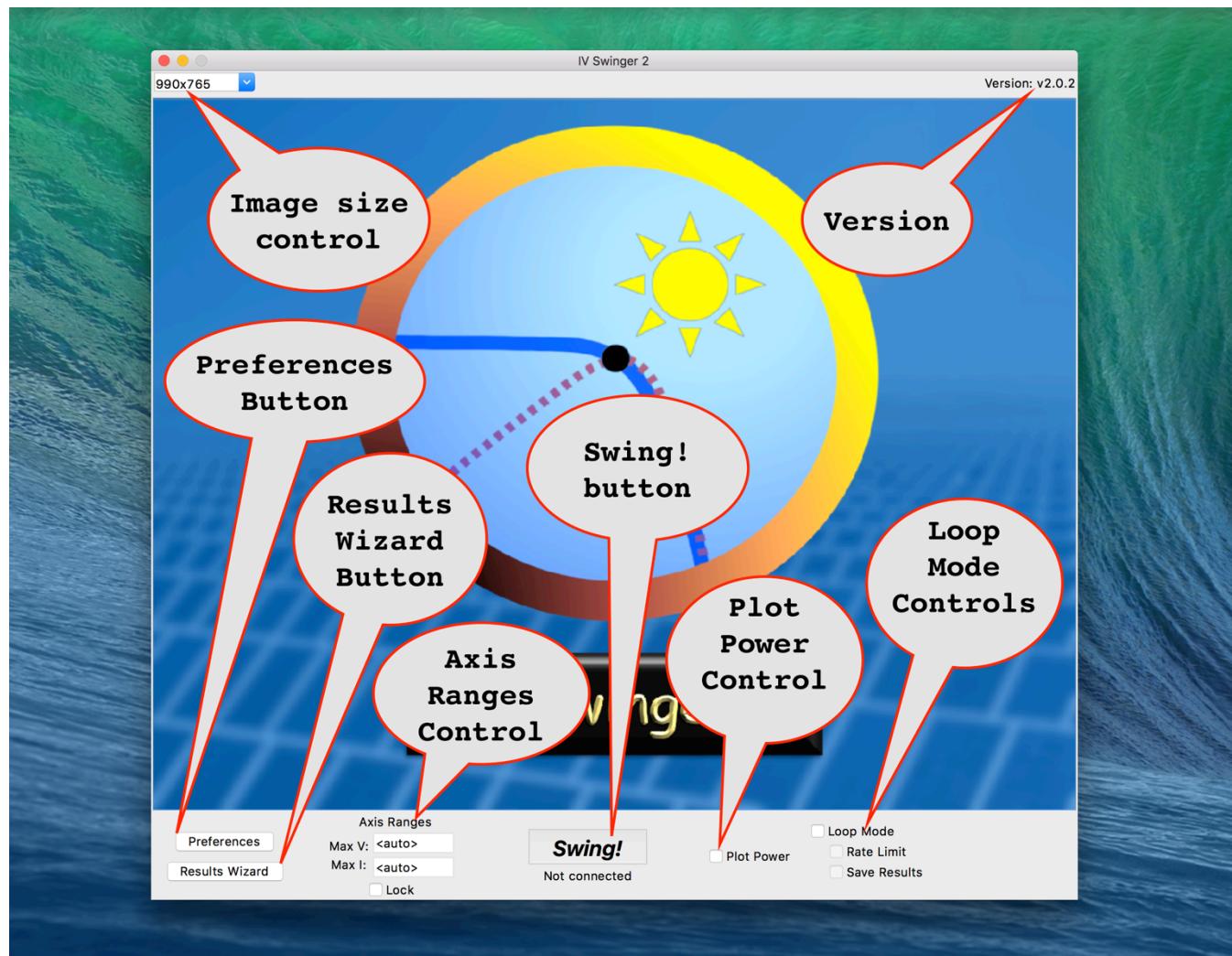


Figure 4-1: Main Window (annotated)

When the application is first opened, a “splash screen” with the logo and title is displayed. The annotated image in Figure 4-1 above is from the Mac version. The Windows version is the same other than the standard window control buttons and the fact that Windows includes the menus on the window itself¹. In order of importance, the annotated items are as follows:

4.1.1 Swing! Button

The Swing! button is used to initiate the tracing of an IV curve. Before the IV Swinger 2 hardware is connected, the button looks like this:

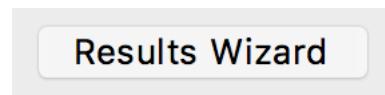


The button cannot be pressed until the hardware is connected and the button changes its appearance to this:



Pressing the button can be done either by clicking it with the mouse or by pressing the Enter key.

4.1.2 Results Wizard Button



Click this button to open the Results Wizard, which is a dialog that provides options to:

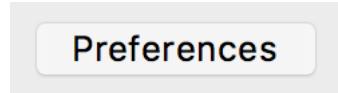
- View results of previous runs
- Combine multiple curves on the same plot (overlays)
- Modify the title and appearance of curves and overlays
- Copy them to a USB drive (or elsewhere)
- View the PDF

The Results Wizard does not require the hardware to be connected. In fact it can be run on results that were collected by a different computer and copied to a USB drive.

Detailed usage instructions are provided in the Results Wizard Dialog section on page 22.

¹ Most of the screen captures in this document are from the Mac version. There are minor differences in the “look and feel” of the Windows equivalents, but no functional differences.

4.1.3 Preferences Button



Click this button to open the Preferences Dialog, which provides options to:

- Change the appearance of the plotted graph (font size, line size, etc.)
- Change the behavior of the looping option
- Change the behavior of the low-level Arduino code

Detailed usage instructions are provided in the Preferences Dialog section on page 34.

4.1.4 Plot Power Button



Check this box to display the power curve overlaid on the IV curve.

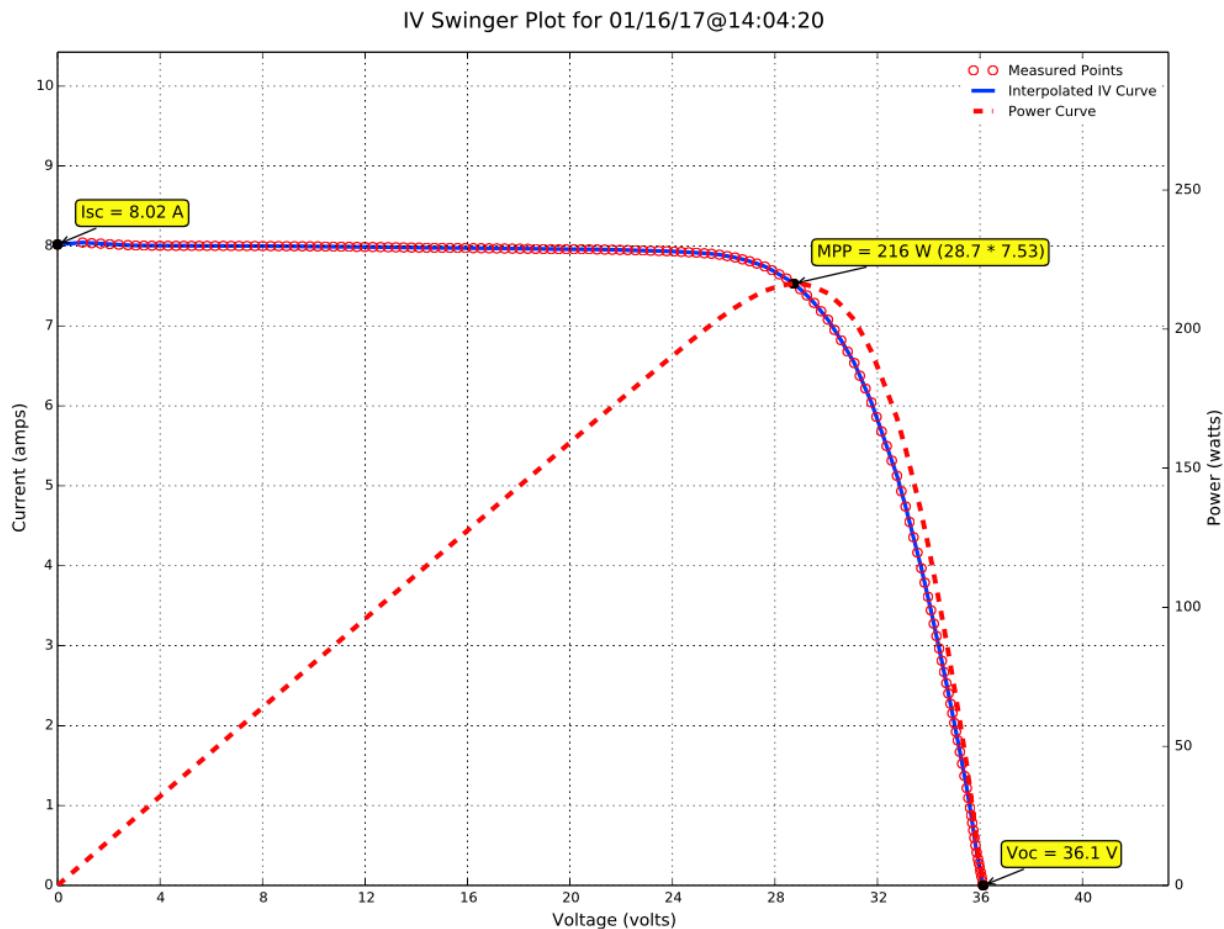
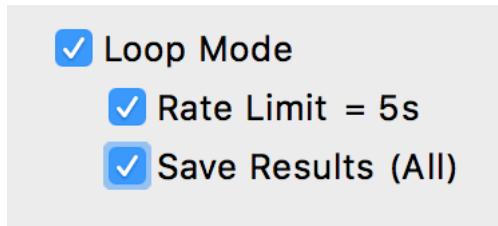


Figure 4-2: IV Curve with Power Plotted

Figure 4-2 above is an example. The graph now has a secondary vertical axis on the right indicating power in watts. This axis is scaled such that the power curve (dashed red line) intersects the IV curve at the Maximum Power Point (MPP).

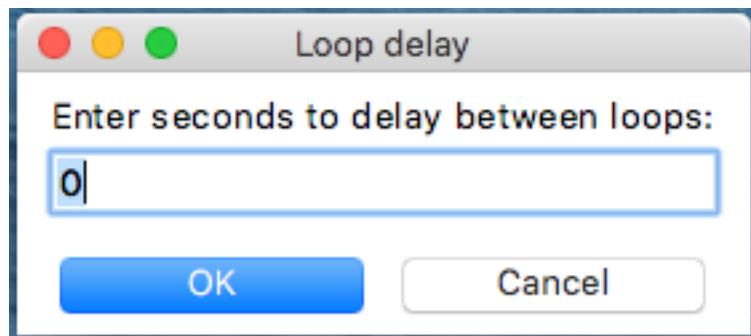
4.1.5 Loop Mode Controls



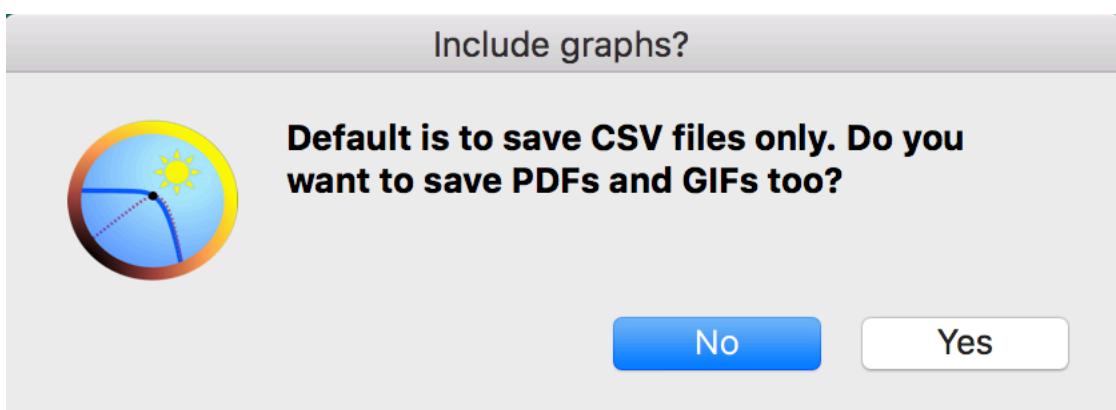
By default, pressing the Swing! button generates a single IV curve. Checking the “Loop Mode” box enables automatic repetition of the curve tracing. When this box is checked, pressing the Swing! button starts the looping. The Swing! button changes to a STOP button and the looping continues until that button is pressed.

If neither of the other two boxes are checked, a maximum of one IV curve is traced every one second and none of the results are saved. This mode can be useful to observe the effect of different types of shading in real time without cluttering your disk with all of the saved results.

If the Rate Limit box is checked, a small dialog pops up requesting the number of seconds to delay between repetitions²:



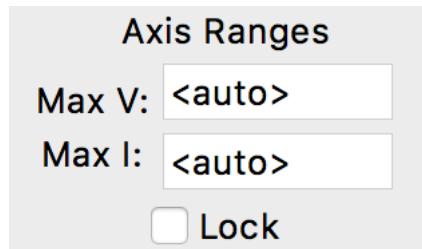
If the Save Results box is checked, the following dialog pops up:



² Older, slower laptops may not be able to keep up with the specified rate if the delay is small.

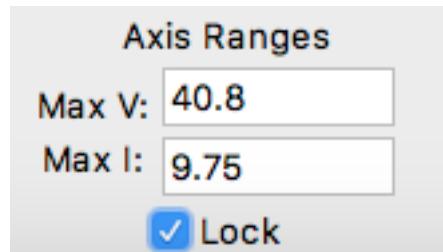
If you choose “No”, only the (very small) CSV files are saved and the graph files are not saved. However, if the Results Wizard is used to browse these results later, it will re-generate the graph files. If you choose “Yes”, the graph files will be saved too.

4.1.6 Axis Ranges Control



By default, the axis ranges are chosen automatically, i.e. the maximum voltage on the X-axis and the maximum current on the Y-axis are chosen so the displayed IV curve fits nicely on the graph. The axis range controls can be used to override this behavior.

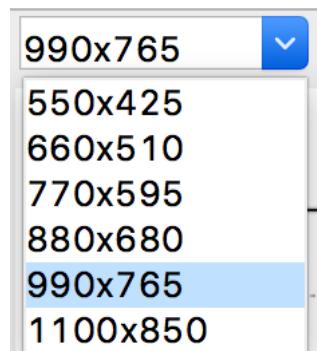
The Lock box can be checked to lock the ranges to the values of the first (or most recent) run or to values entered by the user (just type the desired value and hit Enter). If the values are changed when a plot is currently displayed, it will be redrawn using the new values.



A typical use case for this would be if you want to swing a series of IV curves and see them all at the same scale. After swinging the first one in the series, check the box and then swing the others.

Note that when Loop Mode is enabled, the Lock box is automatically checked (and grayed out). This is so all iterations of the loop are plotted at the same scale so all changes from one iteration are properly visualized relative to each other.

4.1.7 Image Size Control



The image size control in the upper left of the main window controls the size of the displayed image in pixels (width x height). If the default size isn't a good fit for your laptop screen, use this to change it. The pull down menu has several choices. You may also just type in a size, but it must be in the ratio of 11.0 x 8.5 (actually, just type in the width and the height will be calculated for you).

Note that this only affects the size of the GIF image that is used to display the graph on your laptop screen. The PDF is always the same size: 11.0" x 8.5".

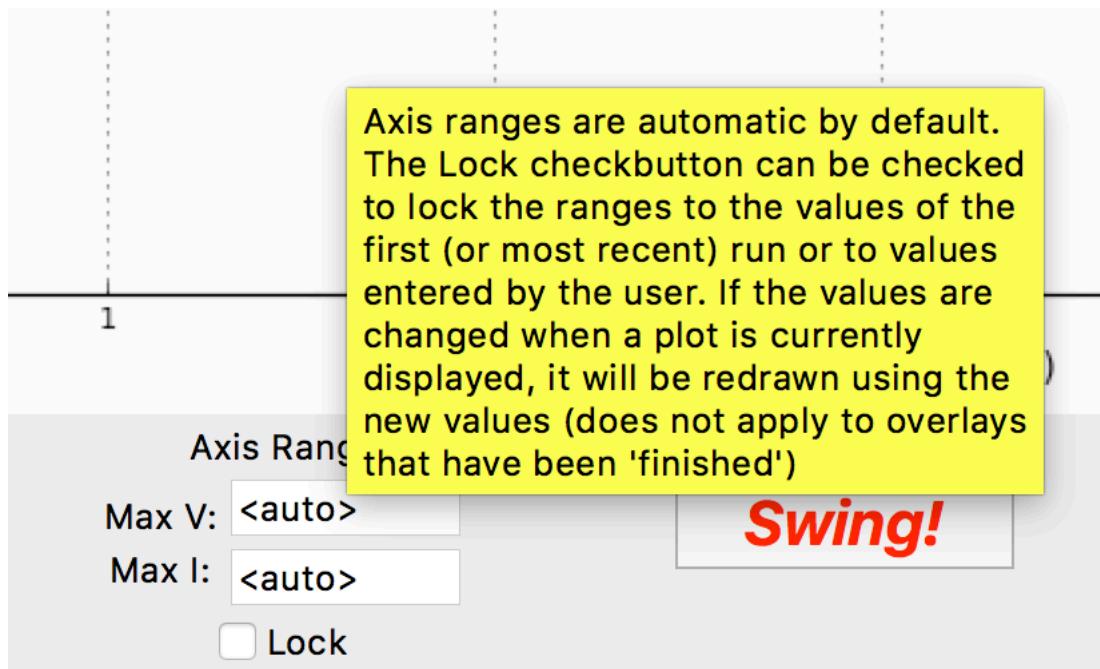
4.1.8 Version

Version: v2.0.2

The version number of the software is displayed in the upper right corner of the main window.

4.2 Tooltips

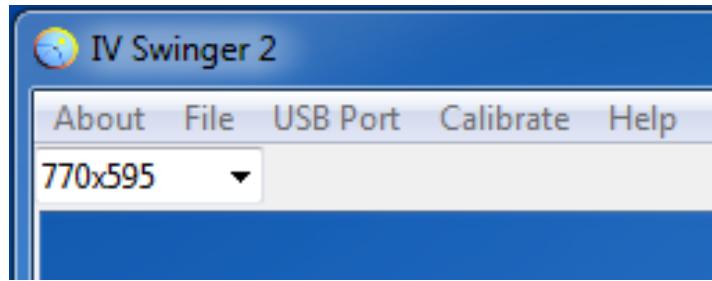
Most of the user interface tools (e.g. buttons, checkboxes, pulldowns, etc.) have "tooltips", which are little yellow pop-up help windows that appear when the mouse is hovered over the tool. For example:



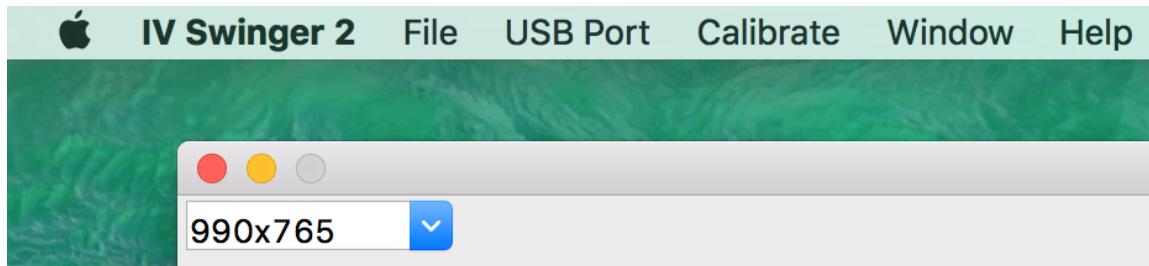
The tooltip disappears after you've had enough time to read it. But if you weren't finished, just move the mouse off and then back onto the tool and it will reappear.

4.3 Menus

As mentioned earlier, the Windows version has the menus along the top of the application window (like all Windows applications):



The Mac version puts the menus at the top of the screen when the application has focus (like all Mac applications):



Two other minor differences are that the first menu is named “About” in the Windows version and is named “IV Swinger 2” in the Mac version, and there is a “Window” menu in the Mac version. Otherwise they are identical.

4.3.1 About Menu (Windows)

This menu has only one item: “About IV Swinger 2”. This brings up a dialog with the software version number, open source license info and copyright.

4.3.2 IV Swinger 2 Menu (Mac)

This menu is the typical Mac “application” menu:

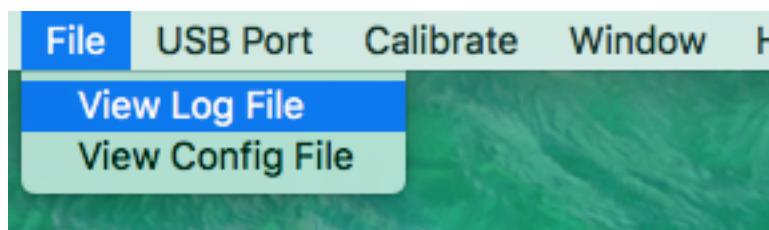


The “About IV Swinger 2” item brings up a dialog with the software version number, open source license info and copyright.

The others are standard for all Mac applications, but not necessarily useful. The Preferences item brings up the Preferences Dialog and is equivalent to pressing the Preferences button.

4.3.3 File Menu

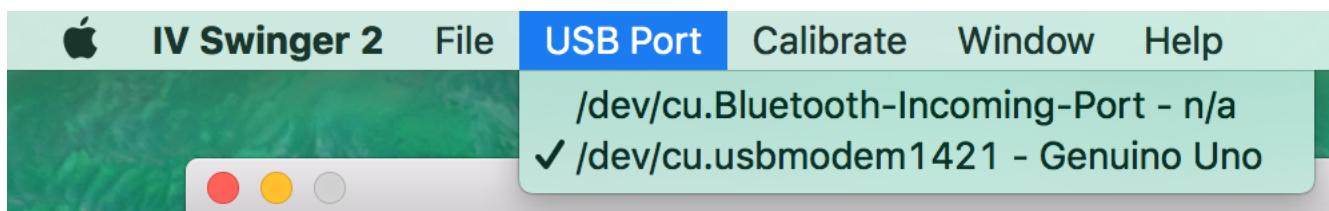
The File menu has only two items: “View Log File” and “View Config File”.



This is not likely to be useful for general users. The log file contains debug information logged by the software. The config file contains the preferences and other values that are retained between invocations of the application. A copy of the config file is also saved for each run so that the values applicable to that run are saved (and possibly modified later). When the Results Wizard is in use and a previous run is being viewed, the config file for that run is displayed when “View Config File” is selected.

4.3.4 USB Port Menu

The USB Port menu lists each USB port that is connected to a device. It can be used (if necessary) to tell the software what port the IV Swinger 2 is connected to.



Normally the software figures this out by itself and automatically selects the correct port, so you may never need to use this menu.

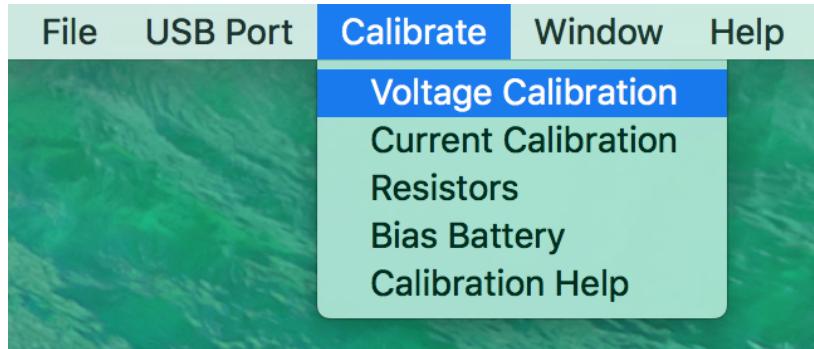
Note that if you unplug the IV Swinger 2 from one USB port and plug it into a different one while the application is running, it won’t figure that out by itself and it won’t list the new port in the menu list. In this case, just close the application and open it again.

4.3.5 Calibrate Menu

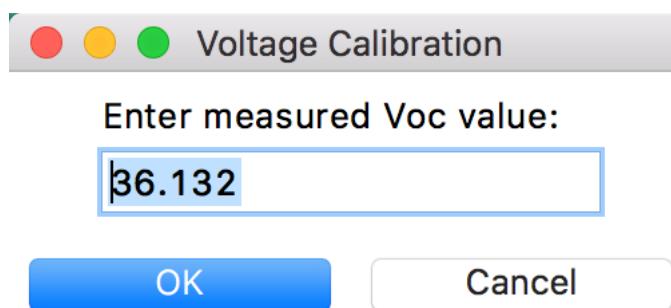
The Calibrate menu allows you to “correct” the open circuit voltage (Voc) and short circuit current (Isc) values of a given IV curve with values that are measured with a digital multimeter (DMM). The curve will be regenerated with Voc and Isc calibrated to the measured values, and future curves will be generated using the new calibration. There is also an option to specify the values of the resistors that are used in the voltmeter and ammeter circuitry in the hardware. And there is an option to calibrate a “bias battery” that may be necessary for IV Swinger 2 variants that are used with PV cells.

Note that IV Swinger 2 is not meant to be a precision instrument. Even when it is calibrated to measured values for a given IV curve, it may not be accurate for curves that have much higher or lower Voc and/or Isc values. Furthermore, the calibration may be affected by temperature and other factors. For the primary users of IV Swinger 2 (students learning about PV technology), a high degree of accuracy is not critical.

The calibration menu looks like this:



When the Voltage Calibration item is selected, the following dialog comes up:

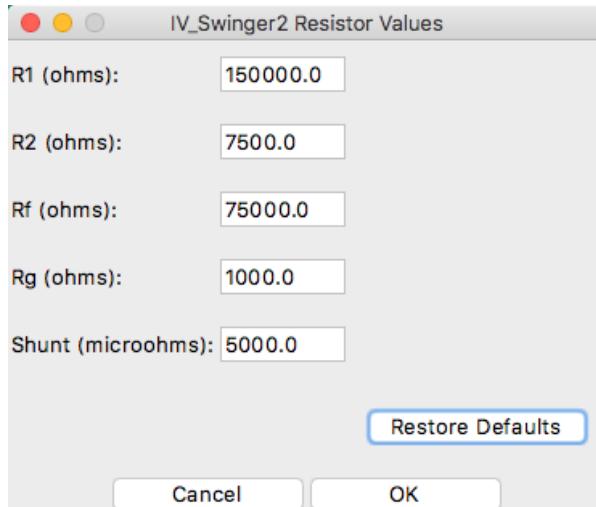


You then overtype the value with the measured value and press OK.

The Current Calibration dialog is very similar.

The Calibration Help item has detailed instructions on how to perform the calibrations with a DMM. Those instructions will not be repeated here, but are important to follow carefully.

When the “Resistors” menu entry is selected, a dialog that looks like the following comes up:



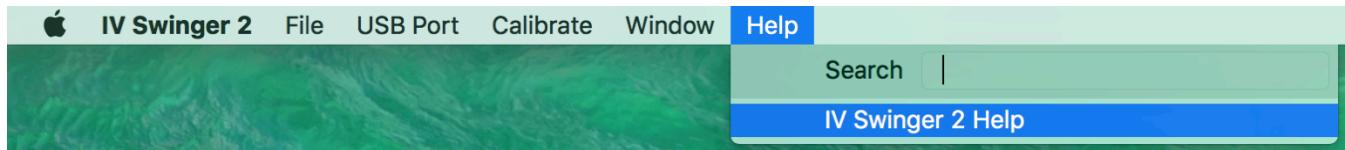
Most users will have no occasion to change these values. But if you have built an IV Swinger 2 variant that uses resistor values that are different³, this allows those values to be specified. It also allows the precise measured values for these resistors to be specified even if the hardware uses the standard values; this is of little value, however, since the voltage and current calibration compensate for differences in the resistors from their nominal values (in addition to other sources of error).

The voltage calibration, current calibration, and resistor values are all stored in non-volatile memory on the IV Swinger 2 device (Arduino EEPROM). This means that a calibrated IV Swinger 2 can be used by multiple laptops, and the results will be the same⁴.

The “Bias Battery” calibration is used only for the cell version of IV Swinger 2, which sometimes requires a bias battery in series with the PV cell. See Chapter 9 on page 47 for more information.

4.3.6 Help Menu

The Help menu currently has only one item: “IV Swinger 2 Help” which brings up a dialog with a very coarse overview of how to use the application.



³ This would be the case for a “scaled up” or “scaled down” design that is optimized for different minimum/typical/maximum Isc and Voc values.

⁴ Prior to release 2.0.3 of the application and version 1.1.0 of the Arduino sketch, the calibration was stored on the laptop.

4.4 Results Wizard Dialog

The Results Wizard dialog is shown in Figure 4-3 below. It provides the tools for viewing results of previous runs, combining multiple curves on the same plot, modifying their title and appearance, copying them to a USB drive (or elsewhere), deleting them, etc.

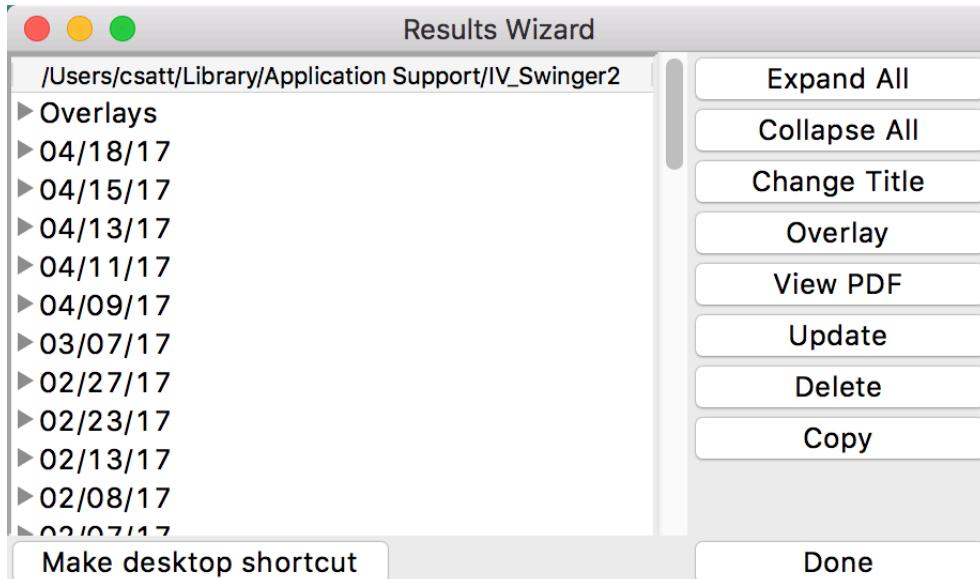


Figure 4-3: Results Wizard Dialog

4.4.1 Expanding and Collapsing Date Groups

The left hand side of the dialog is a “tree view” that groups results by the date they were captured. Each date group can be expanded or collapsed (by default all come up collapsed, as above). To expand a date group, click on the small triangle (plus sign in Windows) to its left, for example:

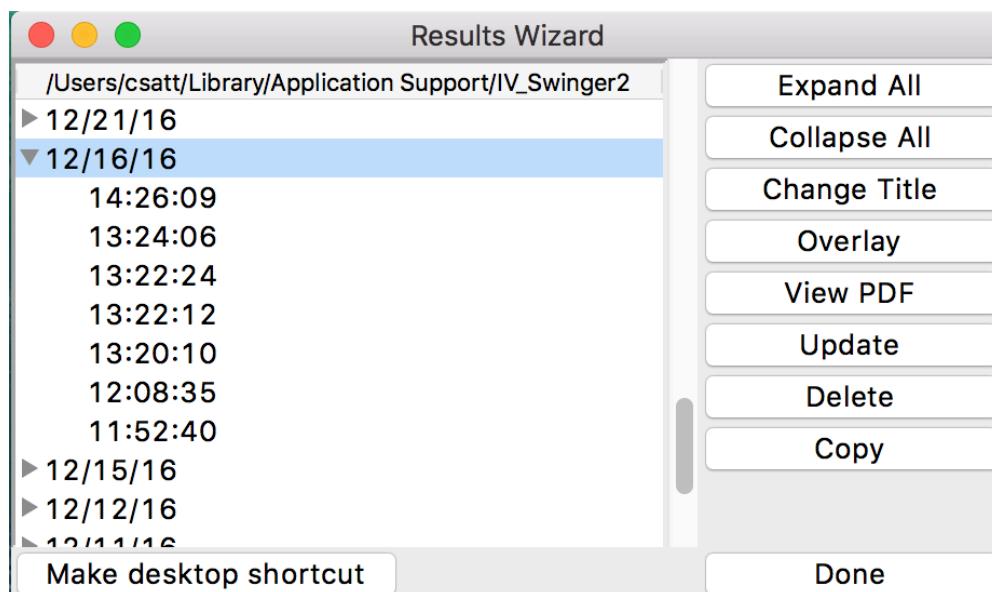


Figure 4-4: Expanding a Date Group

Within each date group are the runs that were captured on that date, labeled by the time that they were captured. Note that all runs (and date groups) are sorted from newest to oldest.

The Expand All and Collapse All buttons at the upper right expand and collapse all date groups at once.

4.4.2 Selecting Runs

Click on a single run to select it. The IV curve will be displayed in the main window:

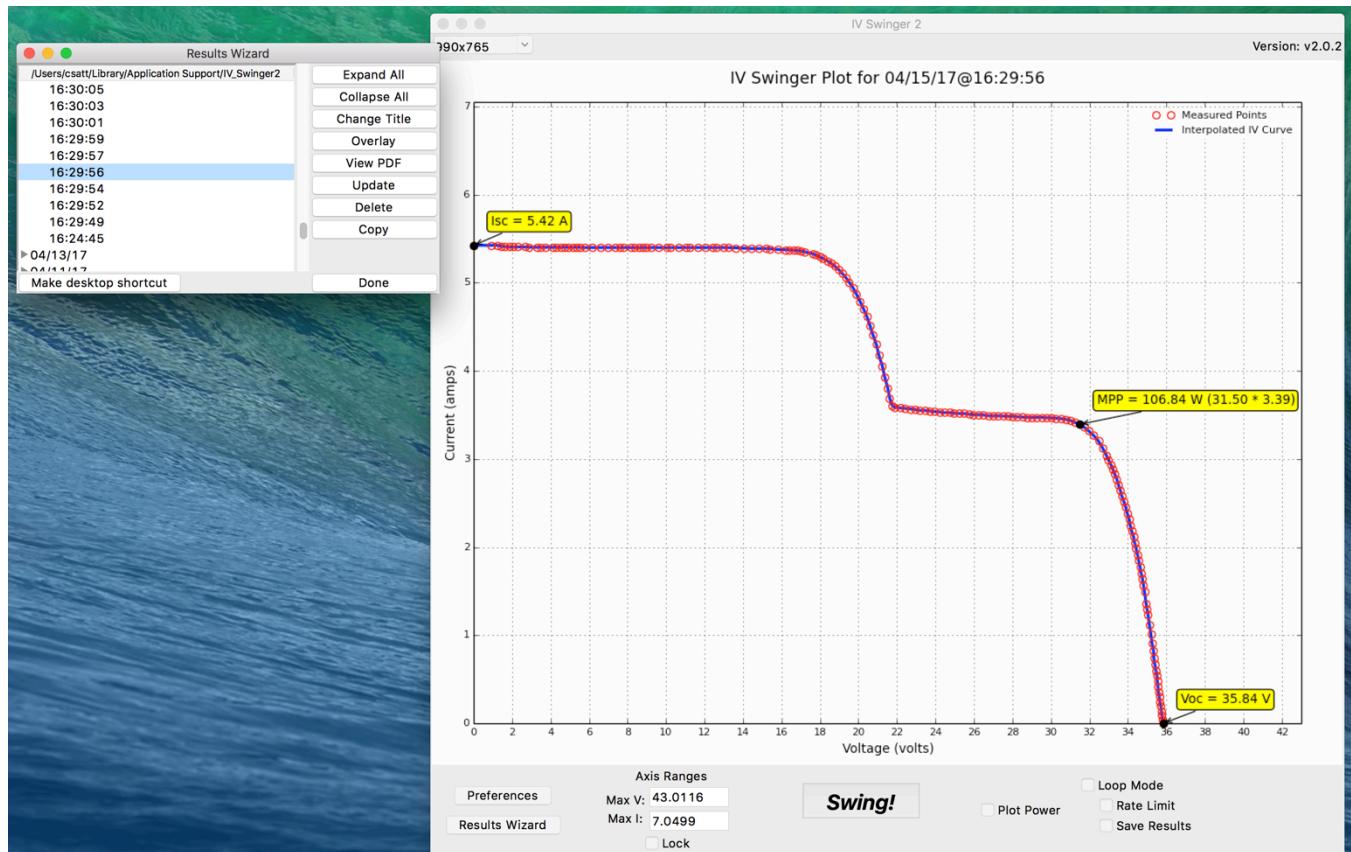


Figure 4-5: Selecting a Run

The up and down arrow keys can be used to move up and down the list. This can be very useful to quickly “flip through” the results. In fact it can be used to create a sort of “animation” if there’s a series of runs that were generated with the axes locked.

Some actions support multiple selected runs. Use “Shift-click” to select a contiguous range of runs and “Control-click” to select non-contiguous runs, just as you would in other Mac and Windows applications. Note that when multiple runs are selected, the oldest one is displayed.

4.4.3 Changing the Title

The default title at the top of each graph is “IV Swinger Plot for mm/dd/yy@hh:mm:ss”. This can be changed to something more descriptive. Select a single run and click the Change Title button. This opens a dialog where you can change the title. The new title is also listed in the tree view:

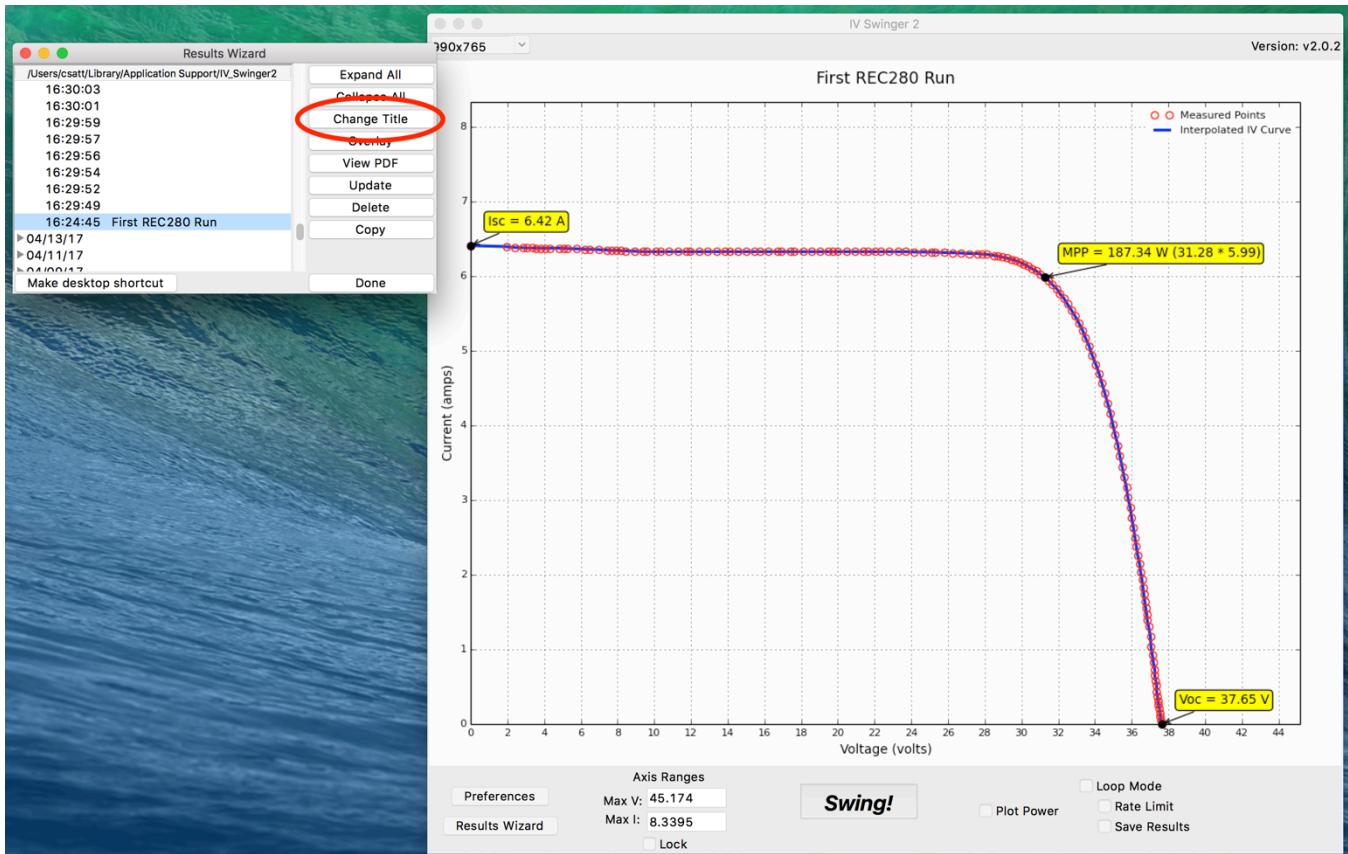


Figure 4-6: Changing the Title of a Run

4.4.4 Overlaying Multiple Runs

Combining multiple IV curves onto a single graph can be very useful for seeing their differences. The Results Wizard supports overlaying up to eight IV curves on the same graph.

The basic sequence for using this feature is:

1. Select up to 8 runs (using shift-click and/or control-click)
2. Click on the Overlay button
3. Change plotting options, if desired
4. Click the Finished button

These steps are illustrated in Figure 4-7 below. This screenshot was taken between step #3 and step #4. Notice that the dialog has now sprouted the section in the lower left corner containing a list of the overlay runs, some option check boxes, and Help, Cancel, and Finished buttons.

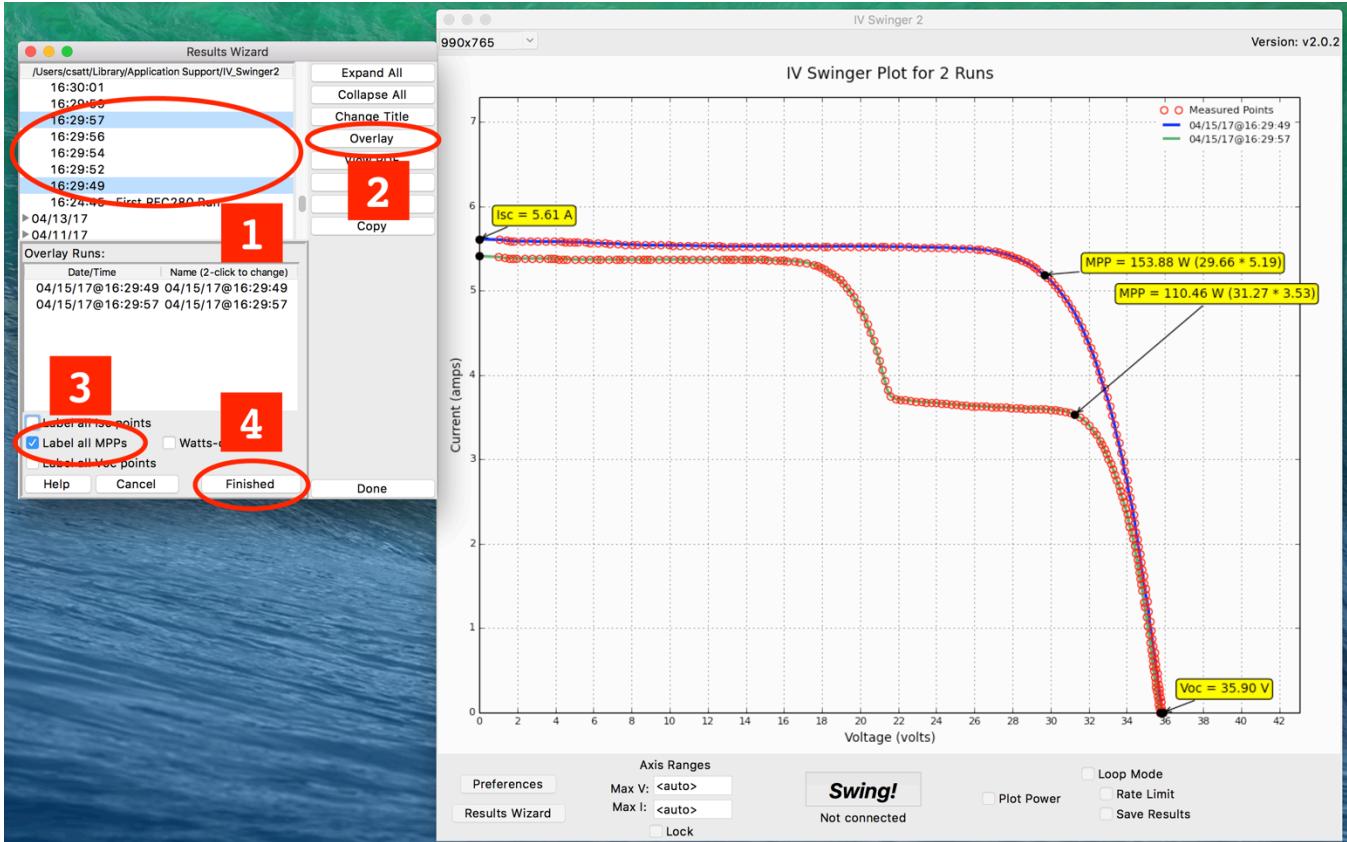


Figure 4-7: Creating an Overlay

4.4.4.1 Changing Overlay Plotting Options

The overlay example shown in Figure 4-7 shows one simple change to the plotting options made in step #3: the “Label all MPPs” box is checked. Many other changes may be made at this point (in addition to the other similar check boxes):

- The title can be changed by clicking on the Title button
- The order can be changed by dragging and dropping the runs listed in the “Overlay Runs” box (or by clicking on the Date/Time heading to sort chronologically)
- The names of the runs on the graph can be changed by double-clicking on them in the “Overlay Runs” box
- The Plot Power box (in the main window) can be checked or unchecked
- Any of the Plotting preferences in the Preferences Dialog (see section 4.5 on page 34) can be changed

4.4.4.2 Saving Overlays

When the Finished button is pressed, the overlay is saved. If the Cancel button is pressed, the overlay is discarded. The saved overlays are viewable in the “Overlays” group at the top of the tree view list in the Results Wizard.

IMPORTANT: Saved overlays are “final”. They cannot be “tweaked” later. Of course you can always recreate them from scratch.

4.4.5 Viewing the PDF

The graph shown in the main window is a GIF format image. A PDF of each graph is also generated for each run (or overlay), and this is much more suitable for printing. It is also possible to zoom into the PDF without the image becoming pixelated⁵. The View PDF button invokes the viewer that your computer is set up to use by default for PDF files (e.g. Preview on Mac and Acrobat Reader on Windows).

Once the PDF is open in the viewer, you can print it from there or do any of the other things that the viewer allows you to do (including saving it somewhere else).

4.4.6 Batch Updates

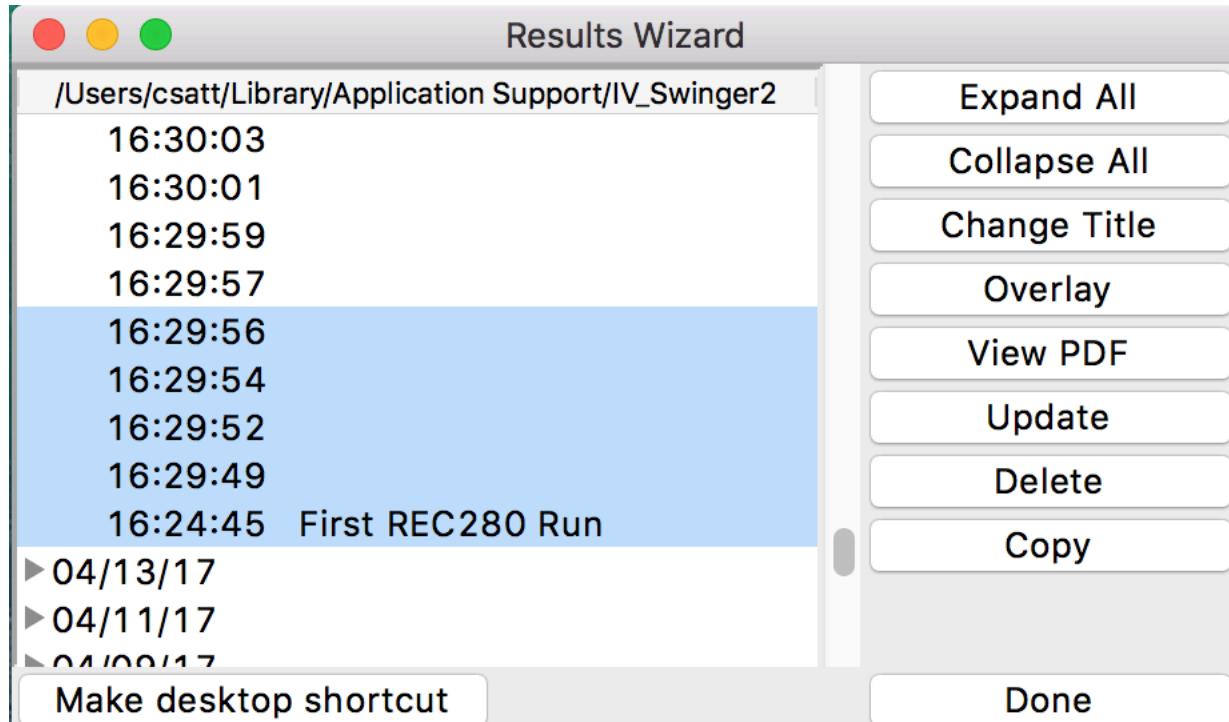
The Update button is used for updating a batch of runs to conform to the same set of plotting preferences. The sequence is as follows:

1. Select multiple runs
2. Change plotting option
3. Click Update button

The order of the first two steps is important.

For example, suppose you want to add the power curve to a batch of runs.

FIRST, you would select all of the desired runs (using shift-click and/or control-click):

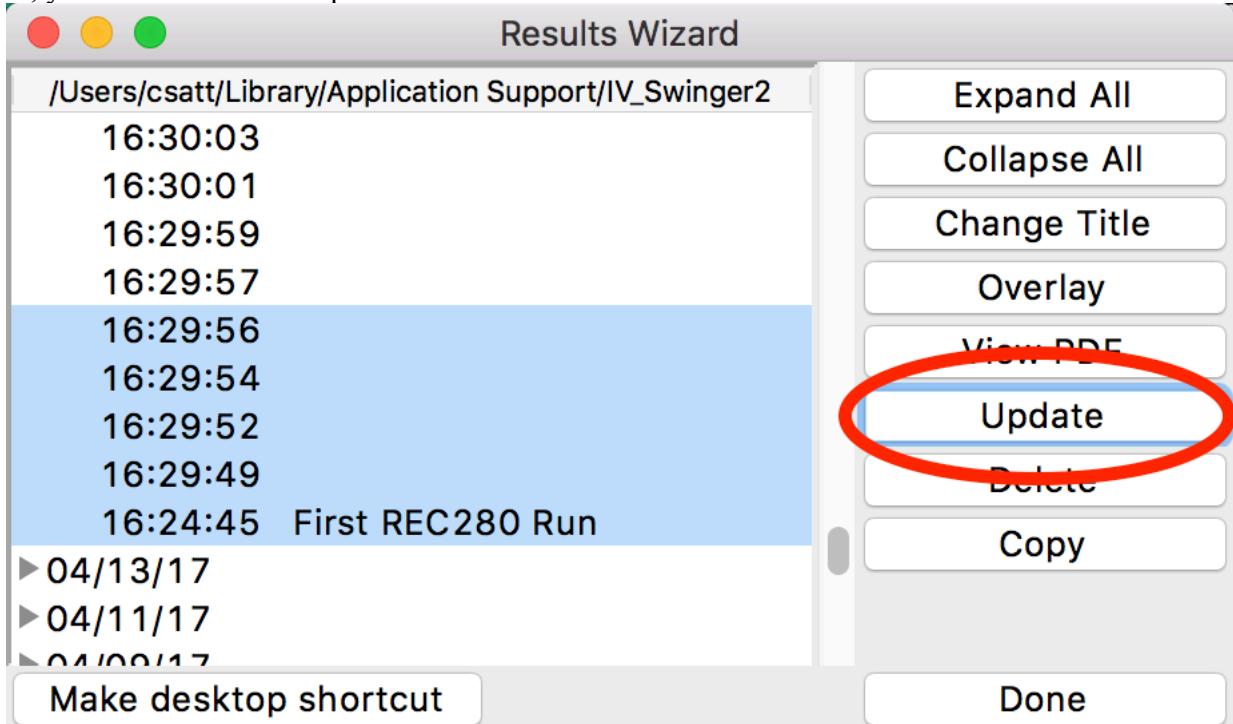


SECOND, you would check the Plot Power box:

⁵ Unfortunately, for technical reasons the PDF cannot be used in the image pane of the main window.



LAST, you would click the Update button:



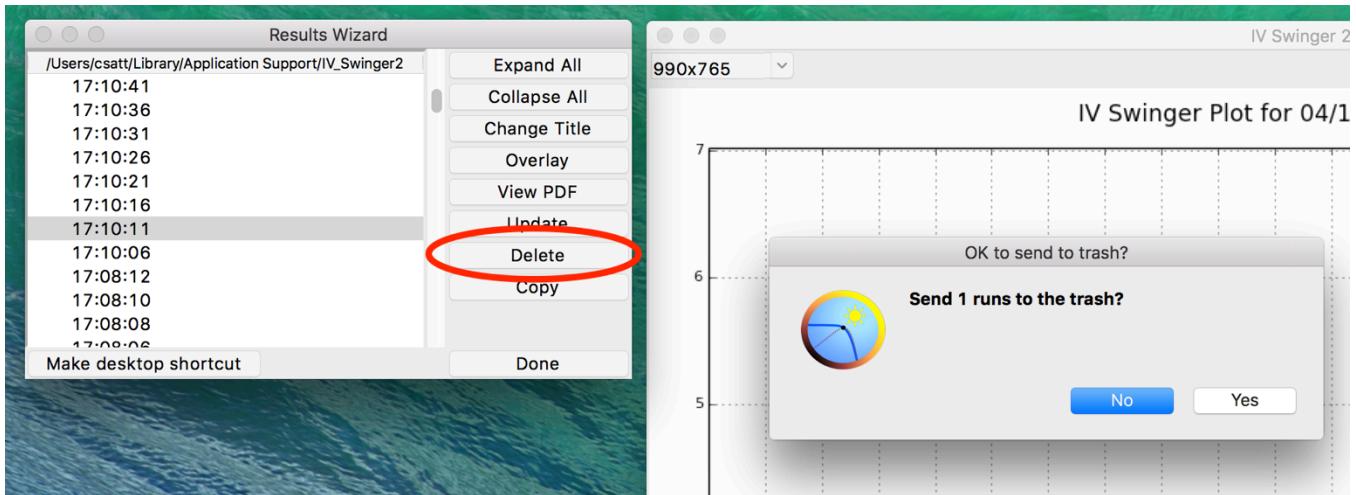
The batch update can also be used to redraw all of the selected runs using the same axis ranges. To do that, step #2 would be to check the Lock box in the Axis Ranges controls (and possibly type in the Max V and Max I values).

Similarly, the display image size can be updated for a batch of runs. To do that, step #2 would be to change the value in the Image Size control (see section 4.1.7 on page 16).

And finally, step #2 can be changing any of the Plotting preferences in the Preferences Dialog (see section 4.5 on page 34).

4.4.7 Deleting Runs

To delete runs (actually send them to the trash), select them and then click the Delete button. This will bring up a dialog asking for your OK to move it/them to the trash:

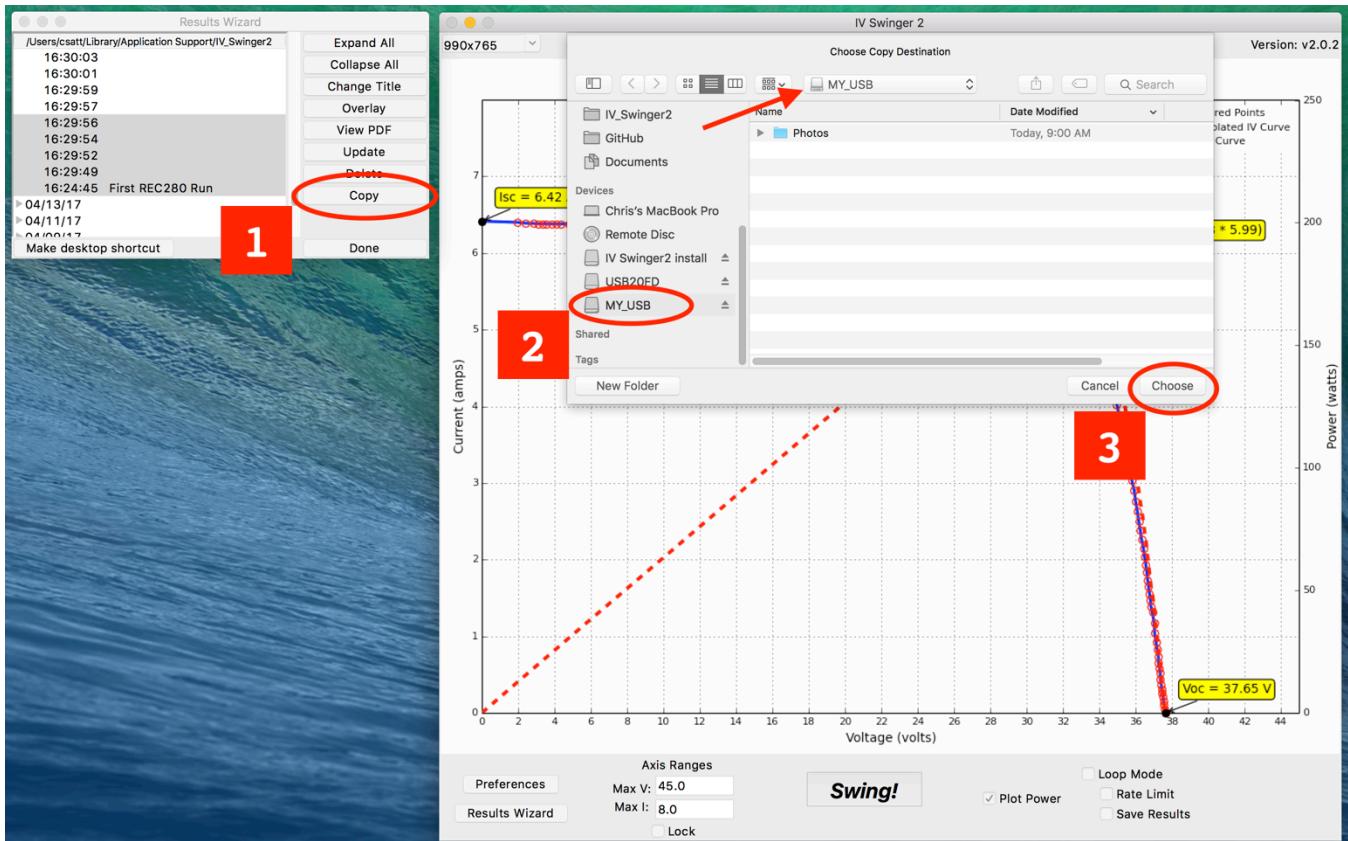


4.4.8 Copying Runs

To copy runs to a USB drive (or anywhere else), select them and then click the Copy button. This will bring up a standard Finder (Mac) or Explorer (Windows) dialog for you to select the destination for the copy. See Figure 4-8: Copying Runs to a USB Drive (Mac) and Figure 4-9: Copying Runs to a USB Drive (Windows) below for what this looks like on both platforms.

If it doesn't already exist, a folder named IV_Swinger2 will be created at the selected destination, and the selected run or runs will be copied under that folder. Each run consists of multiple files in a folder named for the date and time of the run (see section 4.6 on page 40). If the IV_Swinger2 folder already exists at the selected destination, the selected run or runs will be added to it.

Note that runs copied to a USB drive on a Mac may be viewed on a Windows machine and vice versa.



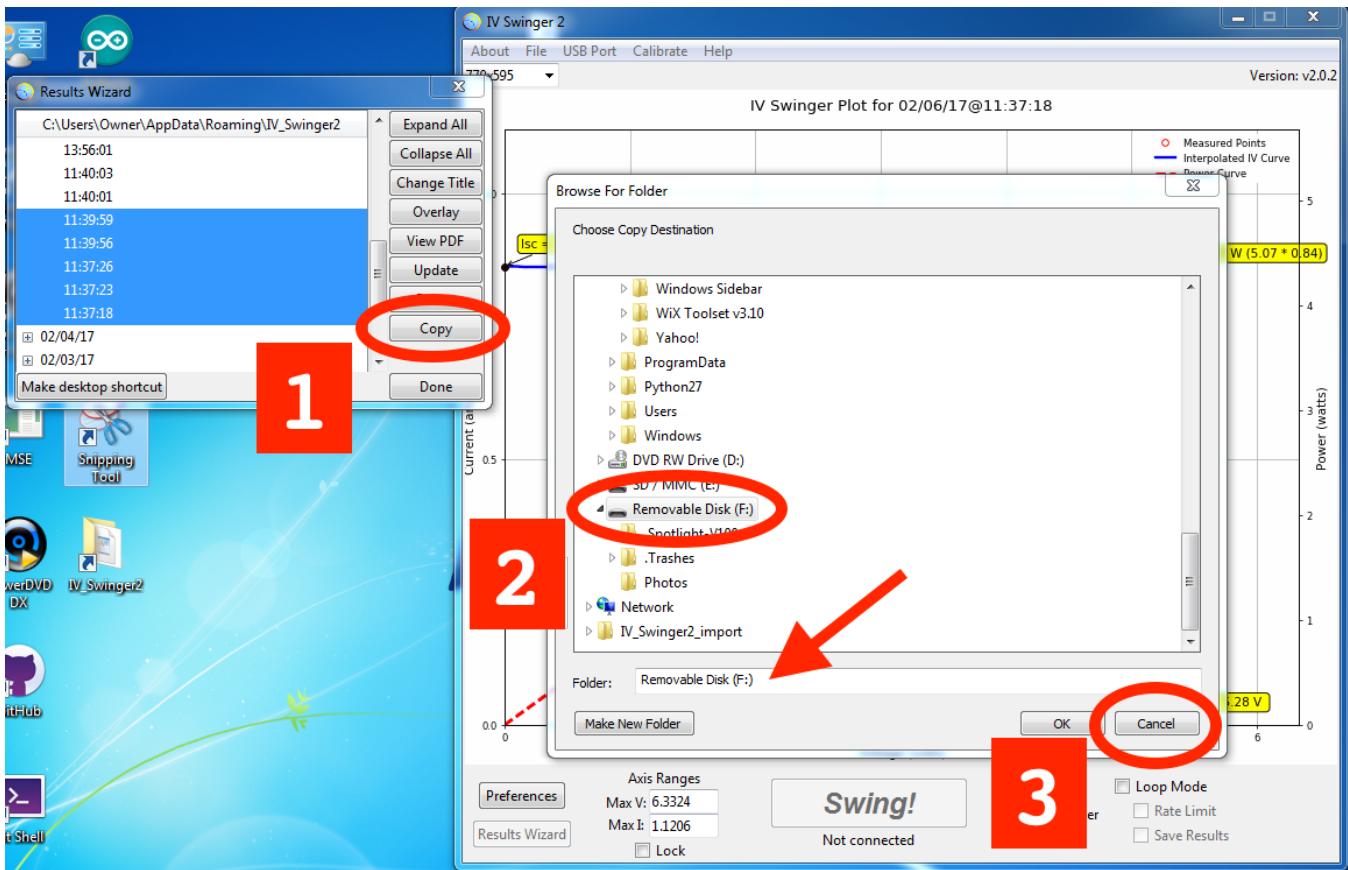


Figure 4-9: Copying Runs to a USB Drive (Windows)⁶

4.4.9 Changing Where to Look for Runs

The runs are stored in a folder named IV_Swinger2 in a standard, but somewhat difficult-to-find location on your computer. This location may be different depending on the version of MacOS or Windows that you are running. When you open the Results Wizard, this location is listed at top of the tree view pane (see Figure 4-10 below).

If you want to use the Results Wizard to browse runs on a USB drive (e.g. copied from a different computer), you can point it to that new location by clicking on the path at the top of the tree view pane. This will bring up a standard Finder (Mac) or Explorer (Windows) dialog for you to select the location of the results.

Figure 4-11 shows this process on a Mac. Windows is very similar. Figure 4-12 shows what it looks like after the path has successfully been changed to point to the USB drive.

⁶ Click OK, not Cancel!

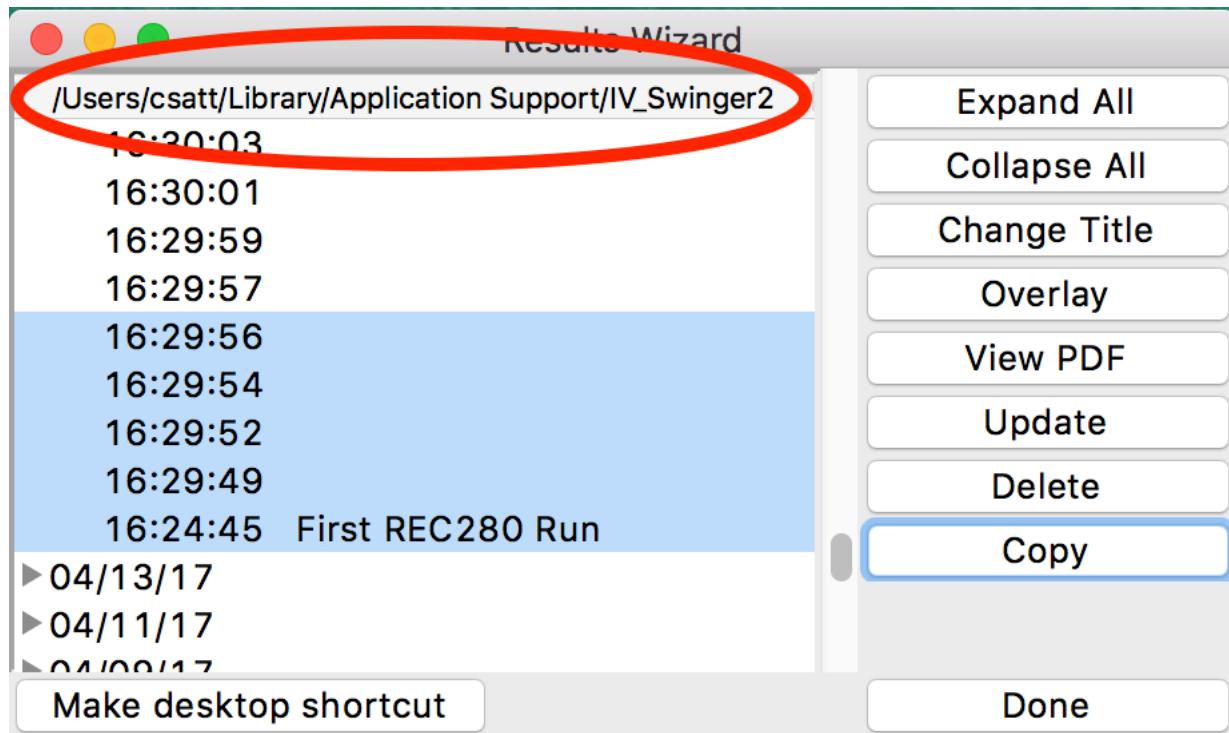


Figure 4-10: Path to Results Folder

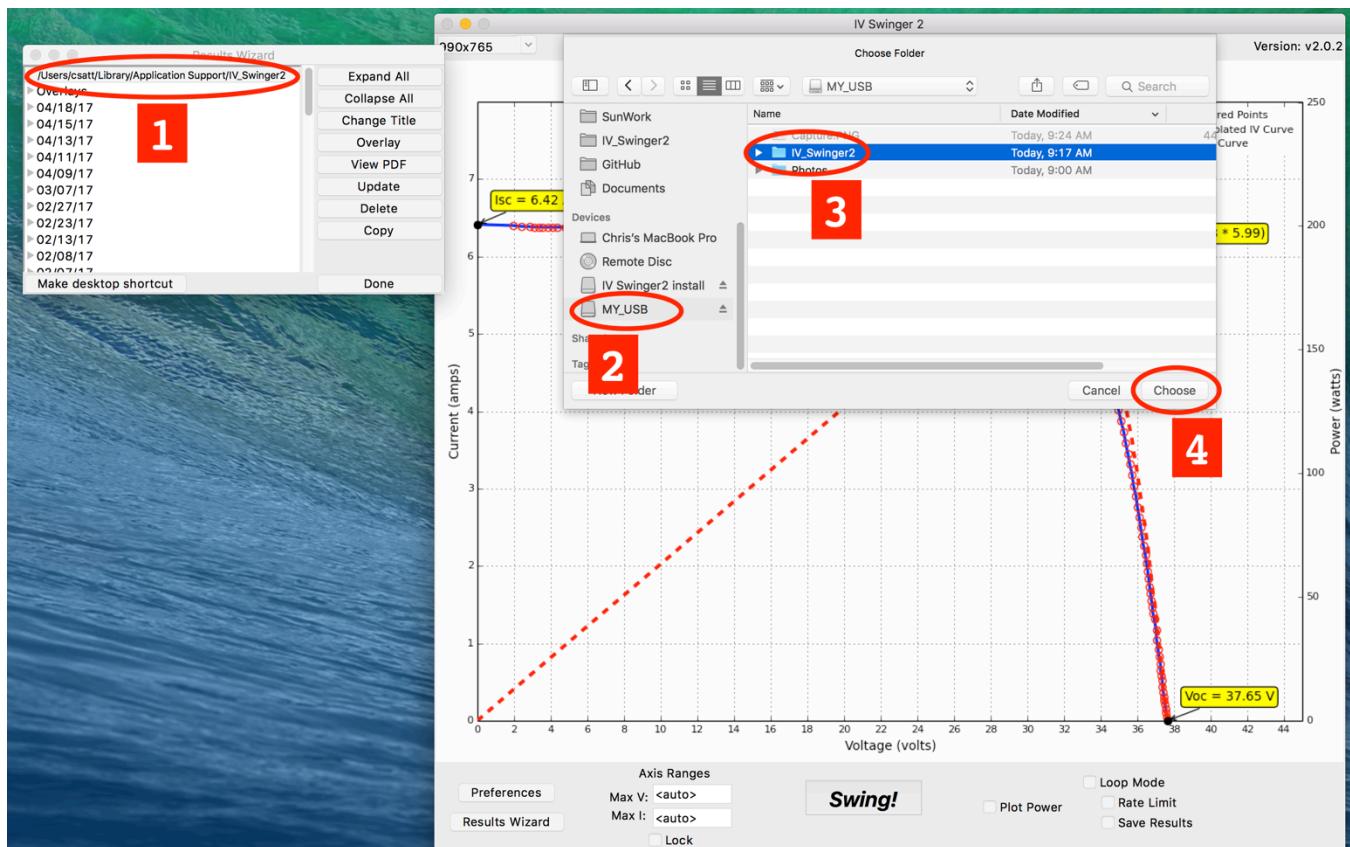


Figure 4-11: Changing the Path to a USB Drive

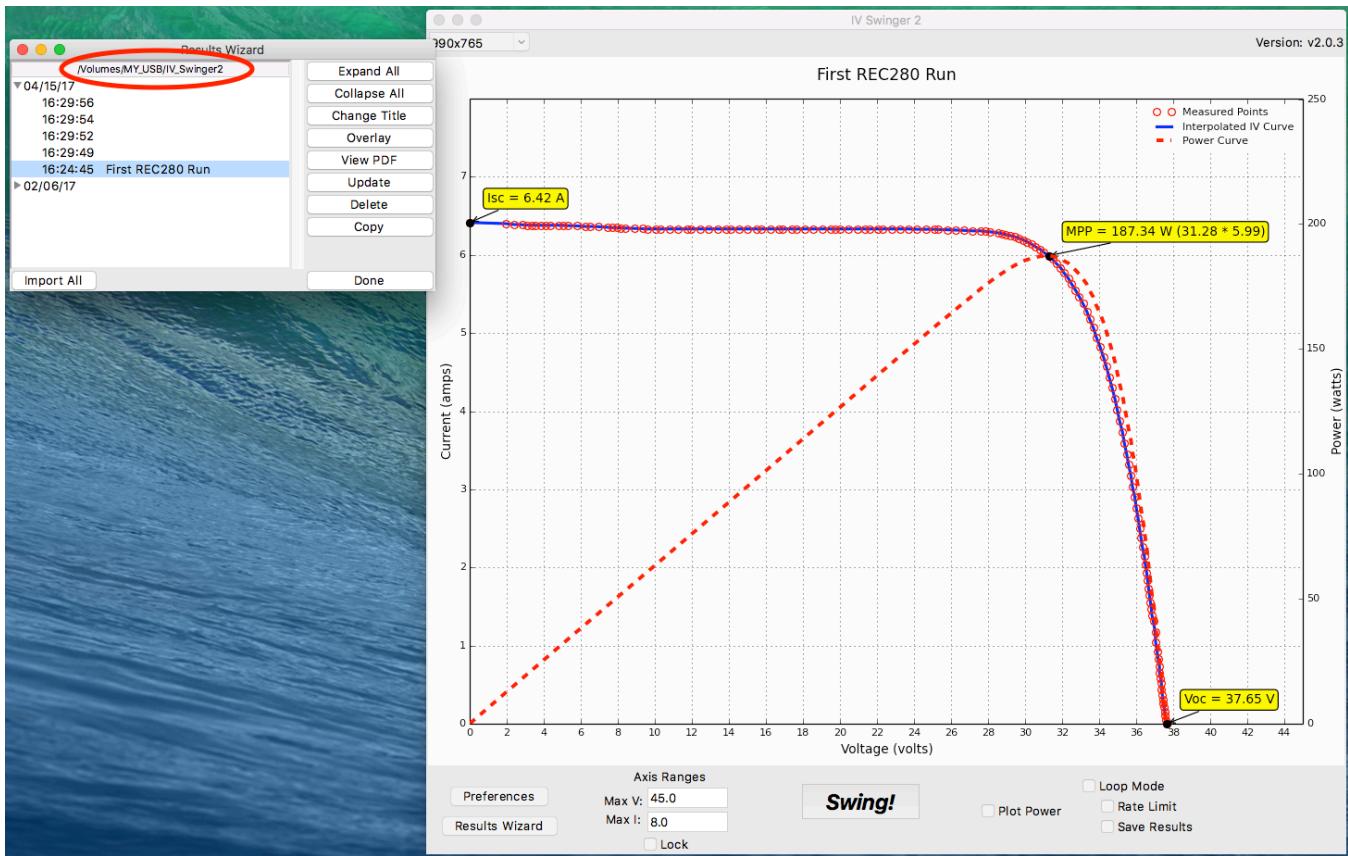


Figure 4-12: Path Successfully Changed to USB Drive

4.4.10 Creating a Desktop Shortcut to Runs Folder

The Results Wizard provides the tools necessary for most browsing, modifying, combining, printing, etc. It “hides” the details of what files are included in the results folders.

However, some users may want to directly access the raw results folders and their files. For example, you may want to open the CSV file(s) in a spreadsheet program. You might also want to know how much disk space is being used, etc. As described in the previous section, the path to the results folder is shown at the top of the Results Wizard tree view pane. But this may be a “hidden” folder that is difficult to navigate to in Finder/Explorer.

The Make Desktop Shortcut button at the bottom of the Results Wizard can be used to create a desktop shortcut to the results folder to make it easier to locate in Finder/Explorer. The shortcut will be named IV_Swinger2.

See section 4.6 on page 40 for a description of the files.

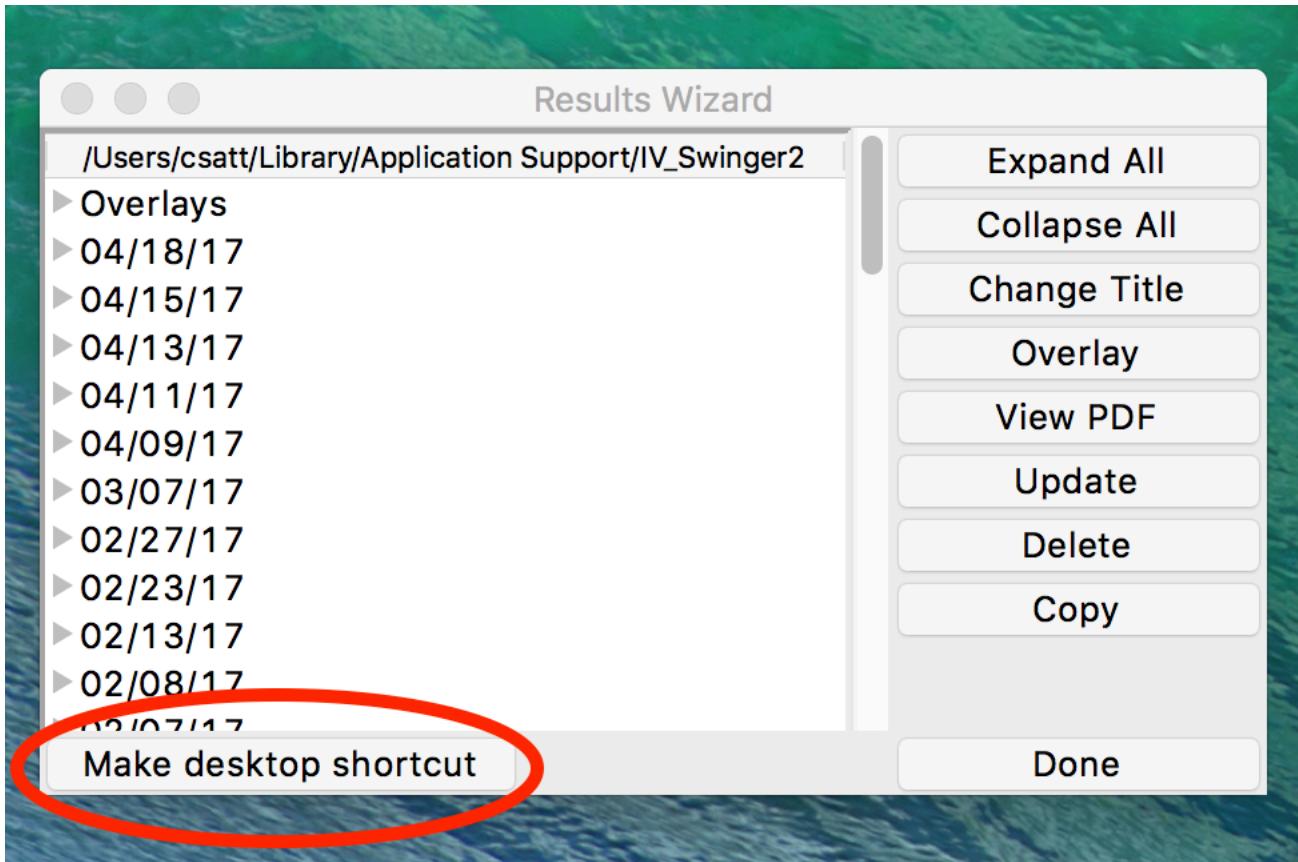


Figure 4-13: Making a Desktop Shortcut to Raw Results

4.4.11 Importing Results from a USB Drive

Section 4.4.9 above describes how to view the results on a USB drive (or elsewhere). In this case, the button in the lower left corner of the dialog changes to an “Import All” button, as shown below in Figure 4-14. Pressing this button will copy all of the results from the USB drive to the standard runs folder. If any of the same runs or overlays already exist, a dialog comes up asking whether to overwrite all of them. If you answer “no”, then the import will skip all of the duplicates and only copy the different ones. If you answer “yes” the import will overwrite all of the duplicates as well as copying the different ones.

The typical use case for this is that Person A has captured results on a laptop and wants to share them with Person B (e.g. a lab partner). The first step is for Person A to copy the results to a USB drive (see section 4.4.8 on page 28). Next, Person A gives the USB drive to Person B, who imports the results to his/her laptop and then gives the USB drive back to Person A.

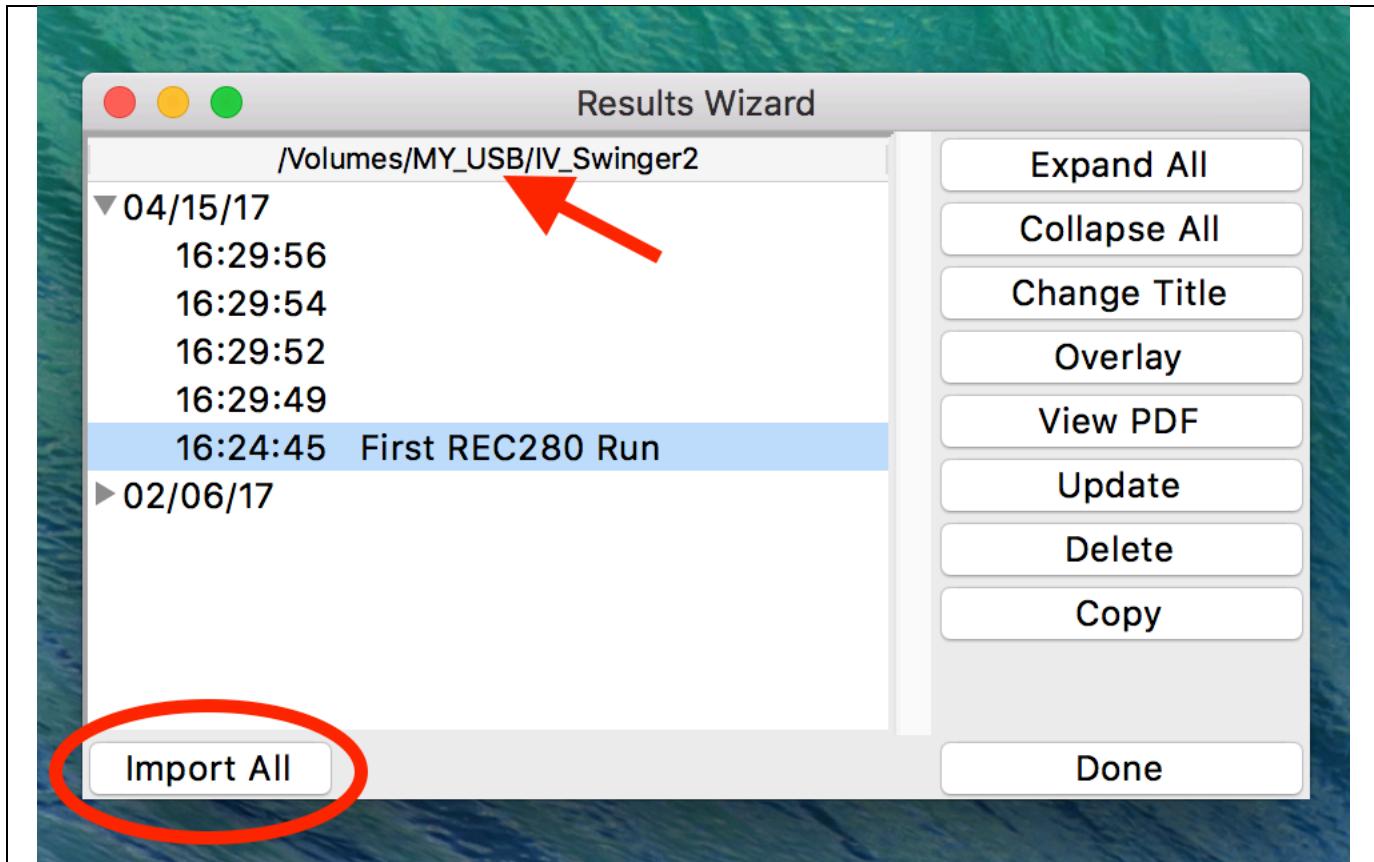


Figure 4-14: Importing Results from USB Drive

4.5 Preferences Dialog

Figure 4-15 below shows the dialog that comes up when the Preferences button is pressed. This is the Mac version but the Windows version is very similar. At the top are three “tabs”: Plotting, Looping, and Arduino. The figure shows the Plotting tab selected.

Sections 4.5.1, 4.5.2, and 4.5.3 below discuss each tab.

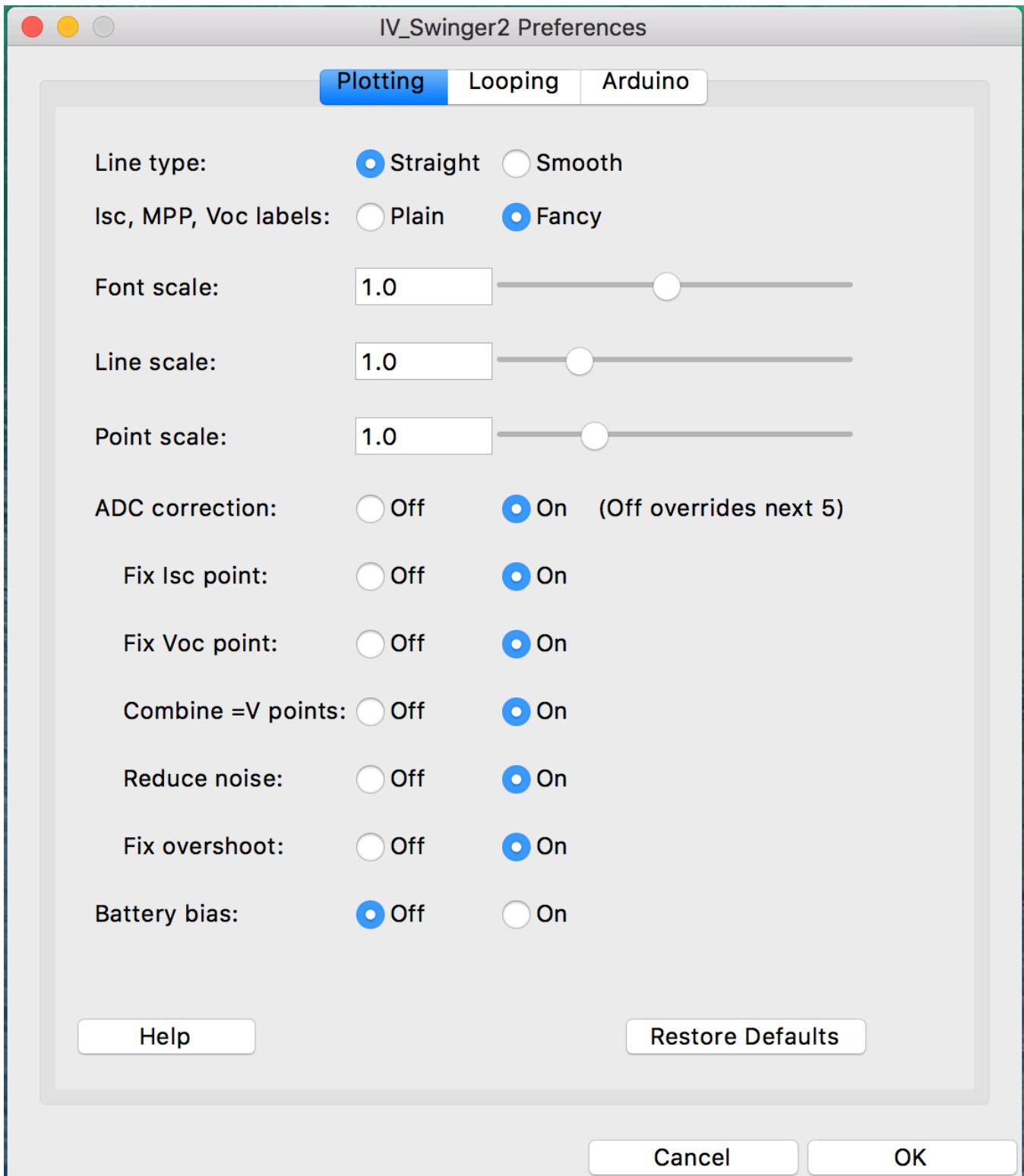


Figure 4-15: Preferences Dialog

4.5.1 Plotting Preferences Tab

Figure 4-15 above shows the Plotting tab.

The configuration options on the Plotting tab control the appearance of the IV curve plot, both on screen and in the generated PDF. Changes made to these options are applied immediately to the current plot (if there is one), so you can experiment and see the effect of your changes. Clicking OK will save the new values, and they will be used from that point forward. Clicking Cancel will revert to the previous values. Following are brief explanations of each option.

4.5.1.1 Line type

The curve interpolated between the measured points may either be "Straight" or "Smooth". The default is "Straight" because most IV Swinger 2 runs have so many points that there is virtually no advantage to a smooth curve, which takes longer to generate. When "Smooth" is selected, Catmull-Rom spline interpolation is used⁷.

4.5.1.2 Isc, MPP, Voc labels

Two styles are available for the labels: "Plain" and "Fancy". Plain labels are text only. Fancy labels are enclosed in a box with a yellow background, and there are arrows indicating the point.

4.5.1.3 Font scale, Line scale, and Point scale

The default font size, line thickness, and size of the "dots" indicating the measured points are chosen automatically based on the size/resolution of the graph. These options allow the user to scale those up or down, according to taste. The sliders can be used, or the values can be typed in manually. If Line scale is set to 0.0, the interpolated curve is not plotted. If Point scale is set to 0.0, the measured points are not plotted.

4.5.1.4 ADC correction

By default, several "corrections" are made to the raw values read by the analog to digital converter (ADC) chip to correct for noise and other effects that affect the proper rendering of the IV curve and the calculation of the maximum power. If "Off" is selected, these corrections are not performed. Note that the values written to the ADC CSV file are the uncorrected values, regardless of this setting. Also note that the calibration settings are used regardless of this setting.

Additionally, there are individual controls for each of the ADC corrections. These options are only relevant if the "ADC correction" option is "On".

4.5.1.4.1 Fix Isc point

If "ADC correction" is "On", this controls whether the first point of the curve should be modified (or even removed in some cases). This point is the Arduino code's attempt at approximating the Isc point, but its simplistic algorithm often gets it wrong. When this control is "On", the Isc point is removed if the first measured point after it has a voltage value more than 20% of the Voc voltage value (in which case implying that we know Isc is misleading). Otherwise, it is extrapolated from the beginning of the curve using a more sophisticated algorithm than the Arduino code uses.

⁷ The original IV Swinger captured only about 30 points, so this was important. The feature is still in the code.

4.5.1.4.2 Fix Voc point

If "ADC correction" is "On", this controls whether the last point of the curve should be modified. The Arduino code records the actual ADC values for both channels. Due to noise, however, the value on the channel measuring current is usually not zero. This correction simply zeros out that value.

4.5.1.4.3 Combine =V points

If "ADC correction" is "On", this controls whether consecutive points that have equal ADC values on the voltage channel will be combined to a single point using the average of the ADC values on the current channel for those points.

4.5.1.4.4 Reduce noise

If "ADC correction" is "On", this controls whether the noise reduction algorithm is applied.

4.5.1.5 Battery bias

The cell version of IV Swinger 2 may require a bias battery to be placed in series with the PV cell in order to trace the curve properly. A calibration of the bias battery must be performed before swinging a cell IV curve using the bias battery. Once that has been done, this control enables the software to "subtract" the bias such that the rendered IV curve is that of the PV cell alone.

4.5.2 Looping Preferences Tab

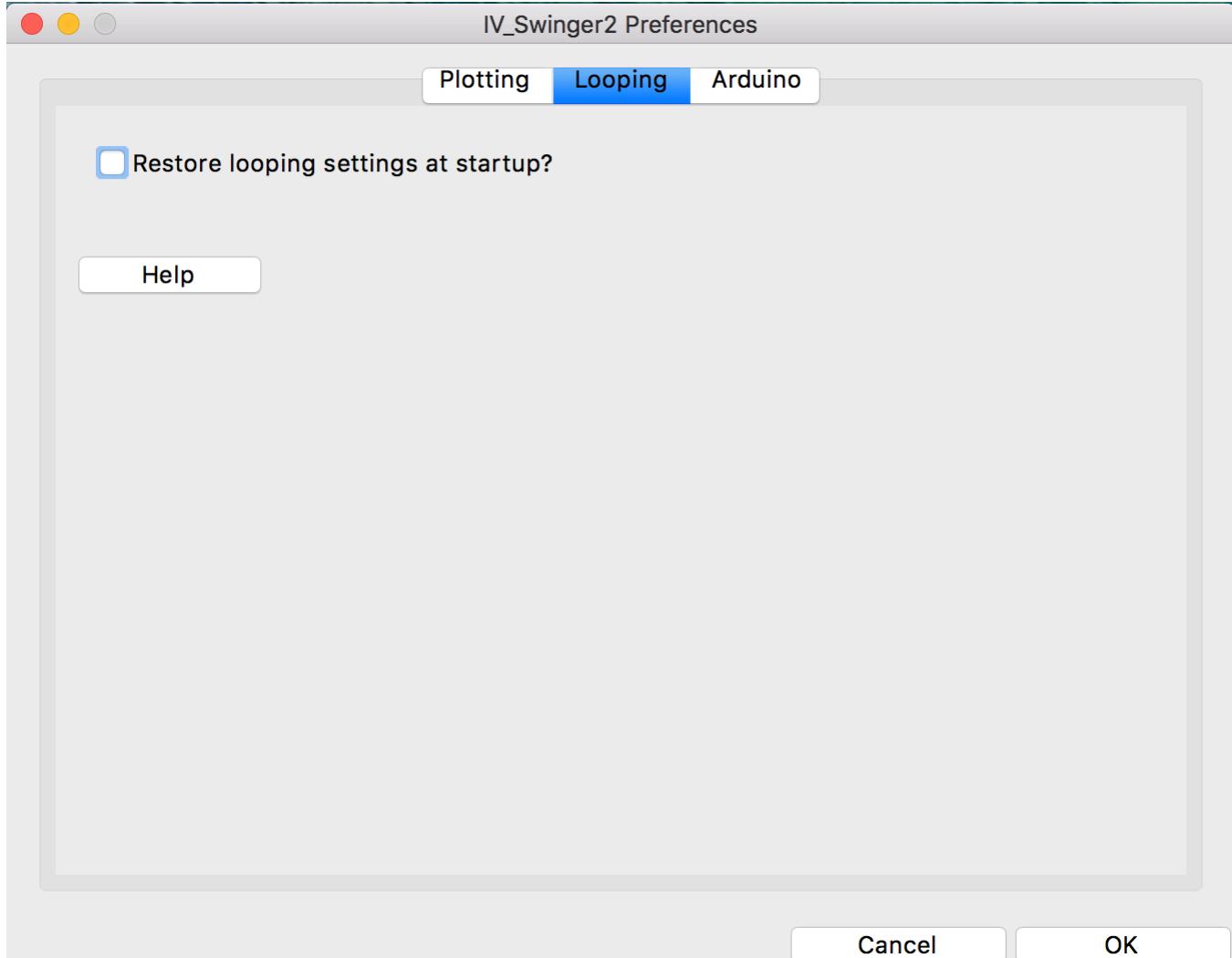


Figure 4-16: Preferences Looping Tab

There is currently only one option on the Preferences Looping tab. The main options controlling looping behavior are on the main IV Swinger 2 window to the right of the "Swing!" button (see section 4.1.5 on page 15). The lone Preferences option is to choose whether the settings on the main screen should be retained after the program is closed and restored the next time it is opened. If this box is not checked, the application always comes up with Loop Mode turned off.

4.5.3 Arduino Preferences Tab

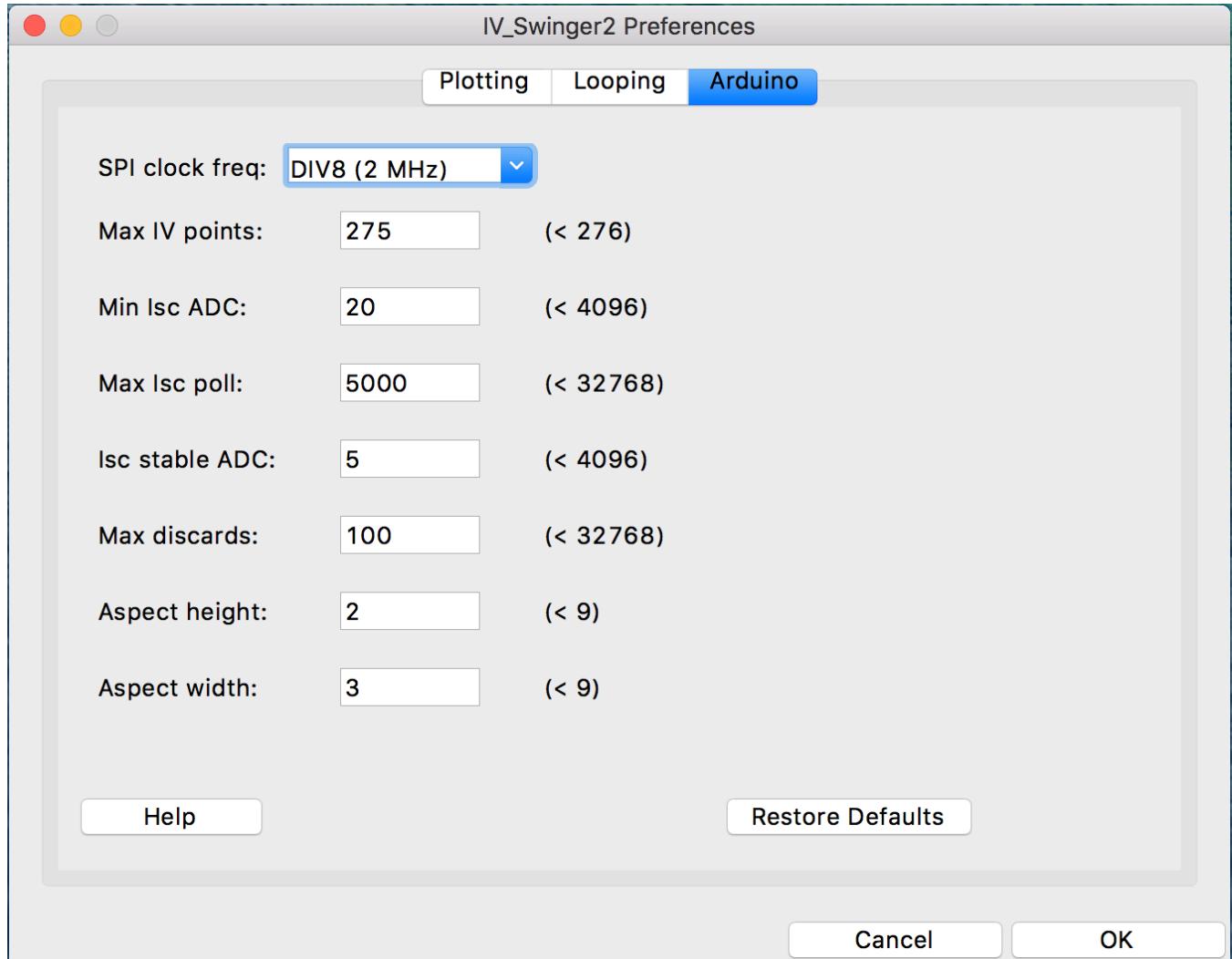


Figure 4-17: Preferences Arduino Tab

The configuration options on the Arduino tab are for advanced users who are familiar with the code that runs on the IV Swinger 2 Arduino microcontroller. Normally the default values should be used. Any changes made here are sent to the Arduino when the OK button is pressed and take effect starting with the next run. Following are very brief descriptions of each option.

4.5.3.1 SPI clock freq

Clock frequency of the SPI bus. The SPI bus is used to communicate with the MCP3202 ADC. At 5V, the MCP3202 is specified to work up to 1.8 MHz, but current parts have been shown to operate fine with faster clocks. A higher SPI clock frequency results in more closely spaced points on the IV curve. The default is 2 MHz.

4.5.3.2 Max IV points

Maximum number of I/V pairs to capture. The actual number will always be less (sometimes substantially less).

4.5.3.3 Min Isc ADC

Minimum ADC value the channel measuring current must reach before starting to poll for stable Isc.

4.5.3.4 Max Isc poll

Maximum number of loops waiting for Isc to stabilize before giving up.

4.5.3.5 Isc stable ADC

Three consecutive measurements must vary less than this amount for Isc to be considered stable.

4.5.3.6 Max discards

Maximum consecutive points that may be discarded because they are too close together before recording a point anyway.

4.5.3.7 Aspect height

Height of graph's aspect ratio (max 8). Used for "distance" calculation in the discard algorithm.

4.5.3.8 Aspect width

Width of graph's aspect ratio (max 8). Used for "distance" calculation in the discard algorithm.

4.6 Folders and Files

Most users should not need or want to access the raw folders files that are used by the IV Swinger 2 software application. For those who do, this section describes them.

The top-level folder is named IV_Swinger2 and, as described earlier, is in a standard, but somewhat difficult-to-find location on your computer. This location may be different depending on the version of MacOS or Windows that you are running. When you open the Results Wizard, this location is listed at top of the tree view pane. The “Make desktop shortcut” button can be used to make it easier to navigate to.

The IV_Swinger2 folder contains the following:

- A file named IV_Swinger2.cfg
- A folder named “Logs”
- A folder for each run named for the date and time of the run
- A folder named “Overlays” (after at least one overlay is created)

4.6.1 IV_Swinger.cfg file

This file saves all configuration values such as image size, calibration, and all of the preferences from the Preferences Dialog. These values are restored from this file the next time the application is started. It

should not be edited unless you know what you are doing. You may, however, remove it and it will be re-created (with default values) when the application starts.

4.6.2 Logs folder

This folder contains one file for each session that the application is run (possibly spanning many runs). This is not likely to be useful for general users. The log file contains debug information logged by the software.

4.6.3 Run folders and files

Each run generates its own folder with a name like 170415_16_24_45 (yymmdd hh_mm_ss).

▼ 170415_16_24_45	Today, 8:54 AM	--
IV_Swinger2.cfg	Today, 11:01 AM	612 bytes
iv_swinger2_170415_16_24_45.pdf	Today, 8:54 AM	20 KB
iv_swinger2_170415_16_24_45.gif	Today, 8:54 AM	152 KB
iv_swinger2_170415_16_24_45.csv	Yesterday, 11:09 PM	4 KB
adc_pairs_170415_16_24_45.csv	Apr 15, 2017, 4:24 PM	1 KB

Figure 4-18: Run folder contents

The files in the run folder are the following:

4.6.3.1 IV_Swinger.cfg

This is a copy of the IV_Swinger.cfg file (see section 4.6.1 above) as it existed when the run was performed OR when modifications were made using the Results Wizard.

4.6.3.2 iv_swinger2_yymmdd_hh_mm_ss.pdf

This is the PDF of the graph.

4.6.3.3 iv_swinger2_yymmdd_hh_mm_ss.gif

This is the GIF of the graph (used for the on-screen display).

4.6.3.4 iv_swinger2_yymmdd_hh_mm_ss.csv

This is the CSV file containing the voltage, current, power, and load resistance of each point on the curve. It is in exactly the same format as the original IV Swinger CSV files. It may be read into Excel or another spreadsheet program if desired. Since it is a text file, it can also be easily read by any other program that an advanced user might want to write for the purpose of analyzing the data.

4.6.3.5 adc_pairs_yymmdd_hh_mm_ss.csv

This is the CSV file that contains the raw values from the Analog to Digital Converter (ADC). These values are converted to the voltage and current values in the iv_swinger2_yymmdd_hh_mm_ss.csv file based on the resistor values in the voltmeter and ammeter circuitry and on the calibration values. They are also “corrected” to remove some other artifacts. It is unlikely that this file would be useful to the end user.

4.6.4 overlays folder

This folder contains one sub-folder for each overlay that has been created using the Results Wizard. The sub-folders are named with the same yymmdd_hh_mm_ss format as the run folders, but the time refers to the time that the overlay was created, not the time of any of its runs. There are only two files in each sub-folder. Note that these are only the image files; no information about how the overlay was constructed is saved. This is why overlays cannot be “tweaked” after they are finalized.

4.6.4.1 overlaid_yymmdd_hh_mm_ss.pdf

This is the PDF of the overlay graph.

4.6.4.2 overlaid_yymmdd_hh_mm_ss.gif

This is the GIF of the overlay graph (used for the on-screen display).

5 Known Bugs

This section describes bugs that have not yet been understood and/or fixed.

The bugs listed in previous versions of this User Guide have been identified and fixed. There are no known bugs in application version v2.1.2 and Arduino sketch version 1.3.1 (latest versions as of this writing).

6 Ratings and Limitations

1. Number of times the IV Swinger 2 can be dropped and survive: **ZERO**

IV Swinger 2 is a lot more likely to survive a drop than the original IV Swinger. But it's still an acrylic case, and there are connections that are not soldered. So still – don't drop it.

2. Maximum rated PV panel Isc: **10A**

It is not recommended to connect the IV Swinger 2 to two or more PV panels in parallel. But if you do, remember that the currents of parallel PV panels ADD, so make sure the sum of their rated Isc values is less than 10A.

3. Maximum rated PV panel Voc: **80V**

It is not recommended to connect the IV Swinger 2 to two or more PV panels in series. But if you do, remember that the voltages of series PV panels ADD, so make sure the sum of their rated Voc values is less than 80V.

4. Maximum temperature: **unknown**

This is much less likely to be an issue for IV Swinger 2 than it was for the original IV Swinger since swinging the curve doesn't generate any appreciable heat. Also, the Arduino should be able to run at a higher temperature than the Raspberry Pi.

5. Lifetime (number of IV traces until it dies): **unknown**

The IV Swinger 2 should be much longer lived than the original IV Swinger. The one relay is much less stressed when it switches. On the other hand, it is so easy and quick to swing an IV curve now (especially with loop mode) that the additional longevity may be outweighed by the number of curves attempted. Fortunately, the relay is easy and inexpensive to replace. Nothing else should wear out.

6. Number of times you can take the IV Swinger 2 to an airport and not get arrested: **ZERO**

OK, it's much less scary looking than the original. But you still might have some explaining to do.

7 Laptop Software Installation

The IV Swinger 2 application runs on either Mac or Windows

7.1 Mac

7.1.1 IV Swinger 2 application (Mac)

Requirement: MacOS version 10.10 (Yosemite) or higher

Download latest release from:

https://github.com/csatt/IV_Swinger/releases/latest

Under “Downloads” click on the link that starts with “iv_swinger2” and ends with “_mac.dmg”. Open it and follow the instructions on the screen.

7.2 Windows

7.2.1 IV Swinger 2 application (Windows)

Requirement: Windows 7 or higher

Download latest release from:

https://github.com/csatt/IV_Swinger/releases/latest

Under “Downloads” click on the link that starts with “iv_swinger2” and ends with “_win.msi”. Open it and follow the instructions on the screen.

7.2.2 Arduino driver (Windows)

This is only necessary if you are actually connecting to the IV Swinger 2 hardware. If you are just using the software to look at the results from a different computer, you don’t need this.

Download and install latest release from:

<https://www.arduino.cc/en/Main/Software> (under “Download the Arduino IDE”)

You can choose to install the whole application or only the driver. All you need is the driver (but feel free to install everything).

8 Arduino Software Installation

The Arduino software that runs on the IV Swinger 2 hardware is called a “sketch”. It is installed when the IV Swinger 2 is constructed, but newer versions with bug fixes and other improvements may become available at a later time.

The IV Swinger 2 application detects the version of the Arduino sketch when it connects. If the Arduino sketch is not up to date, a warning dialog is displayed. This dialog includes instructions for updating the sketch. These instructions are also below.

It is a goal that newer versions of the application work with older versions of the Arduino sketch and vice versa (of course without the benefit of any bug fixes or new features that require both to be updated). However, this may not be possible in all cases.

Here are the instructions for installing the latest IV Swinger 2 Arduino sketch:

- Install the Arduino application (IDE) from:

<https://www.arduino.cc/en/Main/Software>

- Open Arduino application on your computer
- Find where the Arduino software looks for sketches:

Arduino->Preferences->Sketchbook location

- Use your browser to go to:

https://raw.githubusercontent.com/csatt/IV_Swinger/master/Arduino/IV_Swinger2/IV_Swinger2.ino

- Right-click and use “Save As” to save IV_Swinger.ino to the Arduino sketchbook folder found above (make sure your browser doesn’t add an extension like .txt to the file name)
- Go back to the Arduino application and find the IV_swinger2.ino sketch using:

File->Open

The Arduino application will inform you that IV_Swinger2.ino must be in a folder named IV_Swinger2 and it will offer to do that for you. Accept its kind offer.

- Click on arrow button or select “Upload” from “Sketch” menu

9 IV Curve Tracing of PV Cells

IV Swinger 2 was designed for tracing IV curves of a full PV module (panel). It is possible, however, to modify the hardware design slightly to create versions of it that are capable of tracing IV curves of a single PV cell. This is more challenging than one might think. All silicon PV cells have a Voc around 0.7V. The cells used to construct a module have an Isc equal to the module's Isc. Some small cells have a much lower Isc. We'll refer to the former as "high power" cells and the latter as "low power" cells.

9.1 Hardware Modifications

One hardware change that is common for both high and low power cells is that the voltage divider be changed to a voltage multiplier, or at least changed to a ratio of 1:1. The latter is easier, and simply entails **changing resistor R1 to a 0Ω resistor (i.e. wire)**. This uses only 0.7V of the 5V range of the ADC, so it is not ideal resolution-wise but isn't bad.

9.1.1 High Power PV Cells

High power PV cells have an Isc value similar to a PV module. But their voltage is only 1/60 the voltage of a 60-cell module. If we used the same capacitance for the load capacitors, this would mean that the time it takes for the curve to reach the MPP would be so small that there might be only one or two points before the knee of the curve. Using **two 22000μF (6.3V) capacitors instead of two 1000μF (100V) capacitors** fixes this (and they are the same physical size).

The larger capacitors hold 22x the charge, however, so they would take 22x the time to drain through the normal 47Ω bleed resistor, Rb. This would be over 10 seconds. At the low voltage of the PV cell, the easiest fix for this is to simply **change resistor Rb to a 0Ω resistor (i.e. wire)**.

9.1.2 Low Power PV Cells

Low power PV cells may have a much lower Isc value than the standard IV Swinger 2 is designed for. In order for the ammeter resolution to be acceptable, the gain of its voltage multiplier must be increased. This is accomplished by using a higher resistance for resistor Rf. The default of 75kΩ gives a range of 0-13A. **A 2MΩ resistor for Rf** gives a range of 0-500mA⁸.

Since the time between points is inversely proportional to the current, it may not be necessary to use a higher capacitance for the load (as it is for the high power PV cells, see above). It depends on how much lower the current is. But it doesn't hurt, so for maximum flexibility, **22000μF capacitors should be used, and the bleed resistor changed to 0Ω**.

9.2 Bias Battery

As described above, high power PV cells require a larger capacitance for the load since their IV curves are very "tall and skinny".

There is another major problem, however. Even when the capacitors are fully discharged, they have a non-zero resistance. This is known as the equivalent series resistance (ESR). Furthermore, the relay

⁸ $I_{max} = V_{adc_max} / (R_{shunt} * (1 + R_f/R_g)) = 5 / (0.005 * (1 + R_f/1000)) = 1000 / (1 + R_f/1000)$

contacts, shunt resistor, and wires in the circuit all have small resistances. The sum of these resistances determines the minimum voltage that the very first measured point can possibly be, given the current (Ohm's Law). This is a negligible effect for a module since this minimum voltage is far lower than the MPP voltage. It is also not a problem for a low power PV cell since its current is low. But for a high power PV cell, the minimum voltage can be greater than the MPP voltage, making it impossible to trace an IV curve.

For example, suppose a PV cell has an I_{sc} of 8A and a V_{mp} of 0.5V. The load resistance at the MPP is only $0.5V / 8A = 0.0625\Omega = 62.5m\Omega^9$. The resistance of the relay contacts alone may be higher than that, meaning the traced IV curve would only contain points after the MPP, and that isn't useful at all.

A solution to this is to use **a bias battery in series with the PV cell**. This pushes the whole IV curve to the right, and by “subtracting out” the effect of the bias battery, the IV curve of the cell can be recovered.

CAVEAT: using a bias battery is better in theory than in practice. It is extremely sensitive to the accuracy of a calibration process that determines the voltage and internal resistance of the battery.

All batteries have an internal resistance that determines their output voltage as a function of the current they are delivering. The terminal-to-terminal voltage of a standard 1.5V battery is 1.5V only when it isn't connected to anything (open circuit). Once it has a load and is delivering current, the voltage drops. Therefore, when a battery is placed in series with the PV cell, the amount that it shifts the curve to the right is smaller at the high-current parts of the curve than it is at the low current parts. So while a 1.5V shift in the MPP voltage would be enough to quadruple the MPP load resistance (e.g. $62.5m\Omega$ to $250m\Omega$), a single 1.5V battery would not generate nearly that much of a shift at 8A.

Reasonable results have been obtained with a **2x2 arrangement of 1.5V D-cells**. Smaller batteries (e.g. AAA, AA, C) have higher internal resistances. The series arrangement puts the open circuit voltage at 3V, but doubles the internal resistance. The parallel arrangement halves that. So the 2x2 arrangement has the same internal resistance a single D-cell, but double the voltage. The voltage at 8A is about 1.8V.

9.3 Application Configuration

The IV Swinger 2 application has support for both high power and low power “cell versions”.

9.3.1 Resistor Values

The non-standard values for the R_1 and R_f resistors must be communicated to the application using the “Resistors” item on the “Calibrate” menu. For both the high power and low power variants, the R_1 resistor value should be changed to 0.0 ohms. And for the low power variant, the R_f resistor value should be changed to 2000000.0 ohms (or whatever the actual value is). When they are changed, these values are stored in the Arduino EEPROM on the IV Swinger 2.

9.3.2 Bias Battery Calibration

When a bias battery is used, a calibration process is required to determine the open circuit voltage of the battery itself as well as the internal resistance of the battery. These values are needed in order to

⁹ Compare this to a typical module with a 30V V_{mp} : $30V / 8A = 3.75\Omega$

“subtract out” the effect of the bias battery when an IV curve is swung with the battery in series with the PV cell.

It is very important to perform accurate voltage and current calibrations before performing the bias battery calibration. The current calibration must be performed with the bias battery and the PV cell in series, but with “Battery bias” set to “Off” in Preferences. The cell must be kept stationary, and the sun must be constant during the measurement. The voltage calibration should be performed with the bias battery alone (no PV cell).

After the current and voltage calibrations have been performed, the “Bias Battery” item can be selected from the Calibrate menu with the bias battery alone connected to the IV Swinger 2. Pressing the “Calibrate” button performs the calibration. The battery voltage and resistance are displayed in the dialog (and the IV curve of the battery itself is displayed in the main window). This can be repeated several times to see if the values stay constant. If they are changing a lot, the results will be poor. The quality of the results depends very strongly on the battery resistance value (slope of the battery IV curve).

9.3.3 Swinging an IV Curve with a Bias Battery

Once the bias battery calibration has been performed, the battery can be connected in series with the PV cell, and IV curves can be swung.

9.3.3.1 Applying the Battery Bias

With the default preferences, the resulting curve will be that of the battery and PV cell together. By turning “Battery bias” to “On” on the Plotting tab of Preferences, the effect of the battery is subtracted from the combined curve, leaving the curve for the PV cell.