InstESRE Pyranometer

With Arduino and ADS1115

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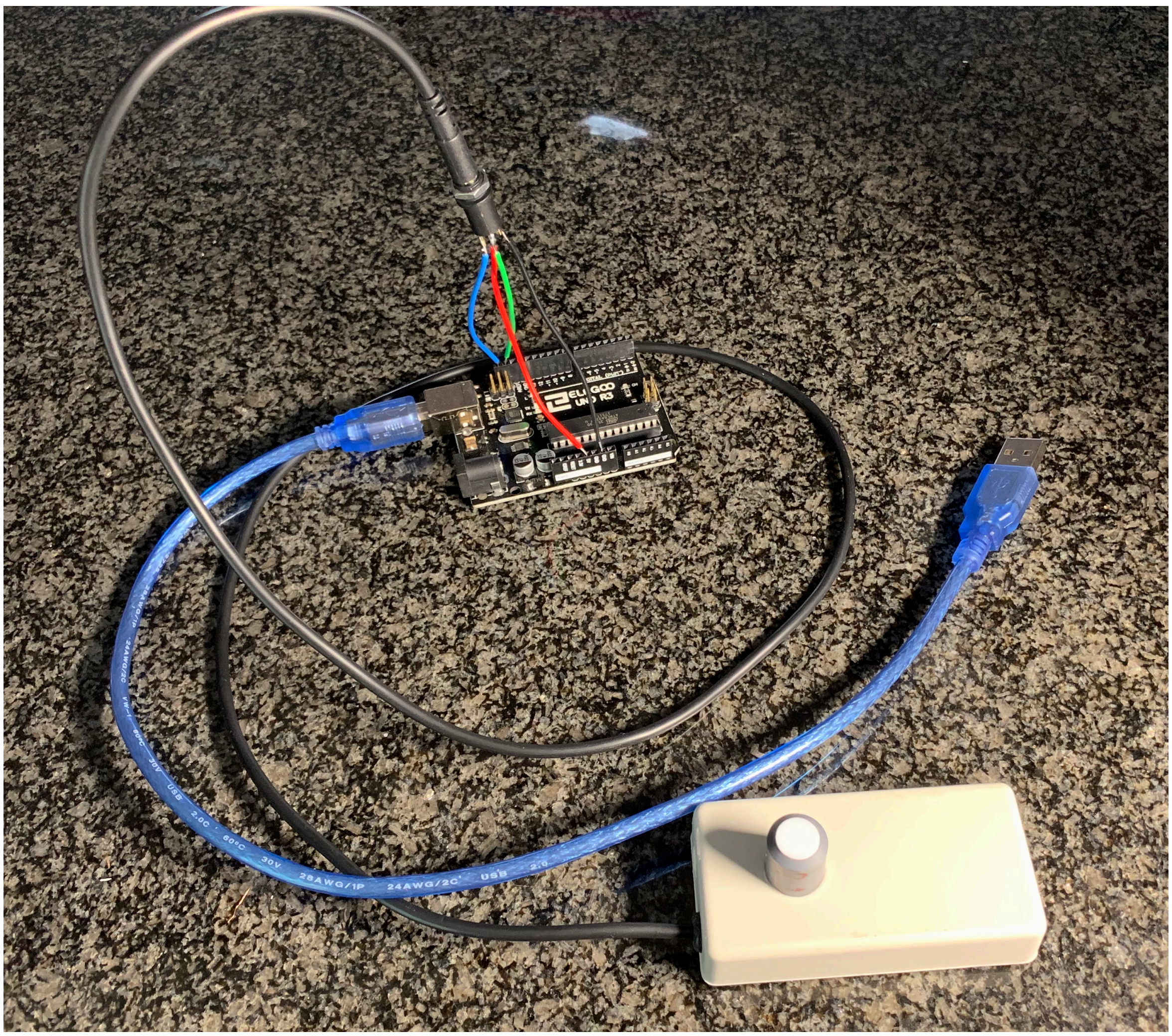

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1 Introduction

This document describes a modified version of the pyranometer kit offered by Dr. David Brooks of the Institute for Earth Science Research and Education (InstESRE):

http://www.instesre.org/construction/pyranometer/pyranometer.htm

The IV Swinger 2 IV curve tracer supports this pyranometer design as an optional sensor, and that was the motivation for the modifications. However, since other users of the InstESRE pyranometer may find it useful, this document describes the design independently from the IV Swinger 2 project.

1.1 Modifications to the InstESRE Pyranometer

The following modifications are made to the standard InstESRE pyranometer to support its use with an Arduino and to compensate for temperature dependence of the photodiode:

- Addition of an ADS1115 analog-to-digital converter (ADC)
- (Optional) addition of an internal TMP36 sensor

The InstESRE pyranometer is designed to interface with a data logger. The pyranometer outputs a voltage that is proportional to the irradiance, and the data logger performs the analog-to-digital conversion. To interface with an Arduino, the analog inputs could be used. However, the Arduino's internal ADC is only 8 bits, which is not enough resolution. Instead, we use a 16-bit ADS1115 ADC breakout board from Adafruit (or equivalent clone).

The photodiode used in the pyranometer (PDB-C139) has a known temperature dependence. By adding a TMP36 temperature sensor, which can also be read by the ADS1115, it is possible to perform temperature compensation in the software, resulting in more accurate irradiance measurements across a wide range of temperatures. It has been determined empirically that the temperature error is about 1/4 of a percent per ˚C. For example, if the pyranometer is calibrated at 25˚C, it will read about 6% too low at 60˚C without the temperature compensation. This is a pretty small error, and not necessarily worth worrying about. This feature is optional, but only adds about $2 to the cost.

1.2 Connections

Figure 1 below shows the electrical connections between all of the components of the modified InstESRE pyranometer and between the pyranometer and the Arduino.

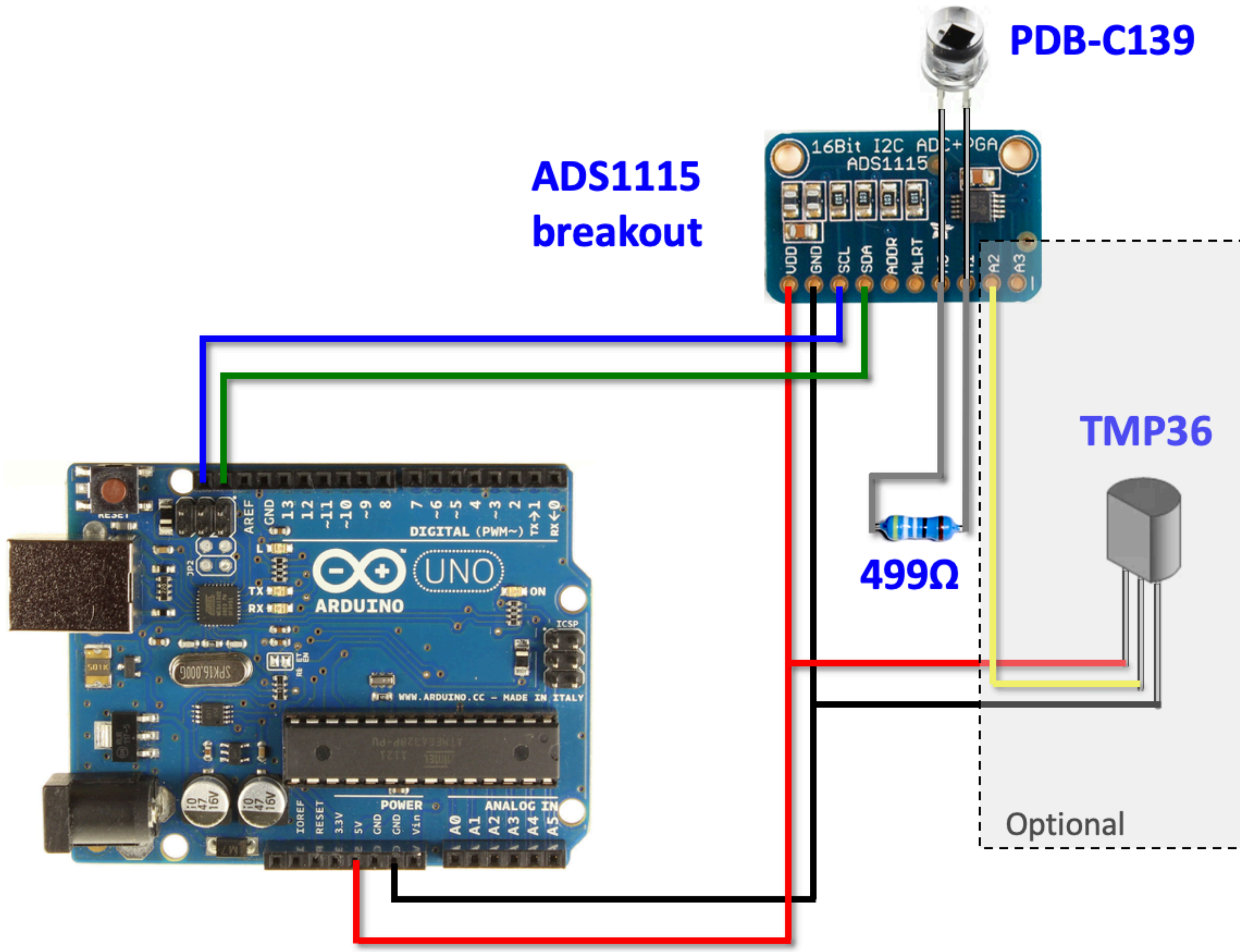


Figure 1: Pyranometer connections

The PDB-C139 photodiode is connected between the A0 and A1 pins of the ADS1115 breakout board as is the 499Ω load resistor[1]. The voltage between A0 and A1 is measured as a differential voltage, meaning that it can be positive or negative. For this reason, it is not important which direction the PDB-C139 is connected; the software takes the absolute value of the voltage reading, so positive or negative are both ok. Having said that, if it is connected as shown in the picture with the shorter cathode (-) lead connected to A0 and the longer anode (+) lead connected to A1, the readings will be positive.

The communication between the ADS1115 and the Arduino uses the two-wire I2C protocol; these are the blue and green wires in Figure 1. There is a limit to the length that the SCL and SDA wires can be without loss of communication. It is also important that they are the same length as each other. My experience is that up to 20 feet (6 meters) of standard 4-wire headphone extension cable works solidly, and 24 feet (7 meters) fails solidly. This allows the ADS1115 breakout board to be physically contained in the same enclosure as the pyranometer. For longer distances, it would be necessary for the ADS1115 board to be on the Arduino end, with two (long) wires connected to the photodiode and resistor in the pyranometer enclosure

The optional TMP36 temperature sensor must be located very close to the PDB-C139 photodiode, since it is the temperature of the photodiode that is being measured. The TMP36 needs power and ground.

[1] The InstESRE web page says 470Ω, but the current kits have 499Ω resistors.

The voltage of the middle pin indicates the temperature reading, and that is connected to the A2 pin of the ADS1115 board. This is read in single-ended (as opposed to differential) mode by the Arduino software. Note that if the ADS1115 board is placed inside the pyranometer enclosure, the power (red), ground (black), and temperature (yellow) wires are all very short. However, if the ADS1115 board is placed at the Arduino end, three (long) wires are required to support the TMP36 in addition to the two wires to the PDB-C139 (total of 5 long wires). In this case, the TMP36 datasheet recommends adding a 750Ω resistor in series with the middle (Vout) pin.

2 Building the Modified InstESRE Pyranometer

2.1 Ordering the InstESRE kit

Building the InstESRE pyranometer is possible without ordering the kit from InstESRE. But there are two parts that require tools that most people don't have: 1) the Teflon/PTFE diffuser disk needs to be punched out from a sheet with an "arch punch", and 2) the real killer is that the PVC tube that holds the sensor needs to be precision machined with a lathe. Given the very reasonable price that Dr. Brooks charges for the kit, it doesn't make sense to try to build it without the kit.

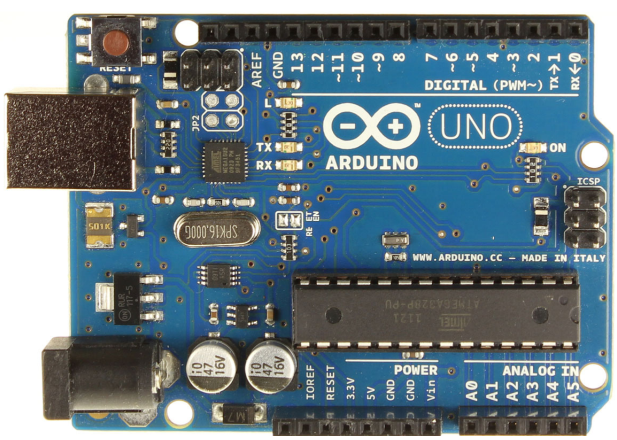
You need to contact Dr. Brooks at brooksdr@instesre.org to place your order. Payment is via PayPal. The order form for the kit can be downloaded from: http://www.instesre.org/Aerosols/order_form.pdf The standard kit (Item 3. Pyranometer kit) comes with a data logger cable. You can tell Dr. Brooks that you don't need the cable.

2.2 Buying Other Parts

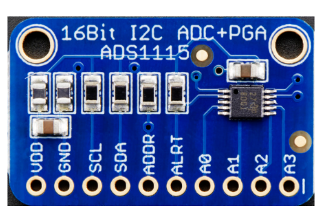
The rest of this section assumes that a cable of 20 feet or less is long enough for your needs. If not, see Section 1.2 above, but you will have to figure out the details yourself.

The parts you will need that are not included in the kit are:

- Arduino UNO R3. Other Arduino models should work too. Clones are available on Amazon for around $10.



- ADS1115 breakout board. May be purchased from Adafruit or many other sellers on Amazon and eBay. It is $15 from Adafruit, but as little as $2 on eBay (from China). As long as it looks like this, it should work:

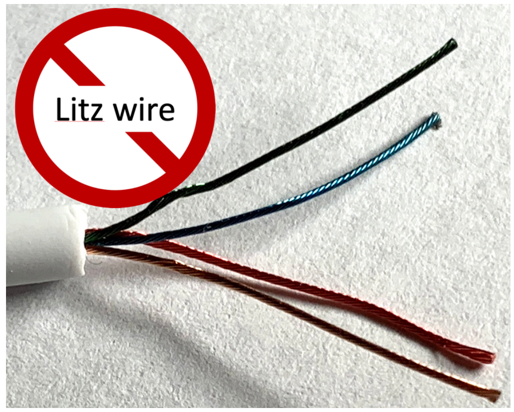


- TMP36 temperature sensor (optional). May be purchased on Amazon, eBay, Digi-Key, and elsewhere.

- 4-wire headset extension cable(s) with 3.5mm TRRS plug. The other end of the cable will be removed and the four individual wires soldered onto the ADS1115 board. I recommend using a short (1 meter or less) cable for this. Then you can use one or more additional cables to extend the length up to a combined 20 feet / 6 meters.

NOTE: Some higher quality headphone extension cables use “litz wire” for the conductors. This makes it a lot more difficult to solder when you cut off the female end because you have to burn off the insulation in order to solder it (there are YouTube videos). Litz wire is great for audio[2], but is not necessary at all for our usage and makes life much more difficult.

[2] At least some people think so



Unfortunately, you can't necessarily tell from a product description what kind of wire is inside the cable. But the cheaper it is, the less likely it is litz wire. In this case, cheaper is better!

- 4-conductor 3.5mm female panel mount jack, solder type:

- Hookup wire (red, black, blue, green)
- TMP36 temperature sensor

Note that the 3.5mm plug and jack are only necessary if you want to be able to plug and unplug the pyranometer to and from an enclosure containing the Arduino. If you don't need or want that ability, then you can use any 4-wire cable such as Cat3 landline telephone wire.

2.3 Assembly Instructions

This section contains the step-by-step instructions for assembling the modified InstESRE pyranometer. Several of these are copied from Dr. Brooks' instructions. It is recommended, however, that you use the following "Instructable" to guide you through the assembly and testing:

https://www.instructables.com/id/ADS1115-InstESRE-Pyranometer

The Instructable has photos of every step. You may want to print out this section of this document to use as a checklist.

- `Prepare enclosure:`
    - `Insert the grommet into the hole at end of the case. Use a small blunt object such as a small screwdriver. Be careful not to cut the grommet. (The grommet is the soft rubber O-shaped item.)`

____

- Spread a small amount of superglue around the inside of the larger of the two holes in the top of the case. Insert the bubble level from the inside of the case. Make sure the bubble level's shoulder seats firmly against the top of the case. Set the case aside, upside down, to let the glue dry for several minutes. [**NOTE: the bubble level is not needed for the IV Swinger 2 application, and it is not shown in the Instructable photos.]**

  ____

- Prepare photodiode and diffuser:
  - Make sure the PDB-C139 photodiode leads are straight and parallel to each other, making adjustments if necessary.

    ____

  - Insert PDB-C139 photodiode into the LED holder. It should snap into place. **Do NOT use any superglue.**

    ____

  - With the PDB-C139 photodiode leads pointing up and with the longer lead to the left and the shorter to the right, VERY SLIGHTLY bend both leads away from you.

    ____

  - Insert the photodiode assembly into the housing tube from the top. Again, **do NOT use any superglue.** Make sure the top of the diode is clean and dust free.

    ____

  - Pick up the Teflon diffuser disk with a paper towel or tissue and rub both surfaces gently to remove any dust or debris that might be there. Snap the disk into its recess at the top of the housing tube. **Do NOT use any superglue.** If it is a very loose fit, you will have to use some superglue LATER, but NOT YET.

    ____

  - Flip the assembly upside down (leads pointing up, longer one to the left). Make sure the diffuser disk didn't fall out. Use 4 pieces of tape to hold it down on a hard, smooth work surface. The tape should be below the machined rim of the tube. Wrap one more piece of tape around the tube.

____

- Add TMP36 (optional):

  - Insert the TMP36 into the hole on the near side of the photodiode leads, with the flat side of the TMP36 toward the leads, and the rounded side towards the wall of the tube. Press it down by the ends of its leads. It should fit nicely with minimal deflection of the photodiode leads.

    ____

  - Remove the TMP36, apply superglue to its top, flat side, and rounded side and promptly insert it back into the hole in the same position. Use only enough glue so it should stick to the LED holder, diode leads, and inside of the tube, but don't use so much that it could possibly <u>flow</u> around the photodiode. Make sure to press it into the hole quickly, so the glue doesn't grab it before it is all the way in.

    ____

  - Adjust the two photodiode leads and the three TMP36 leads so they are all pointing as straight up as possible

    ____

- Glue sensor tube to case:

  - Apply some superglue to the machined rim of the tube and then promptly lower the case over that, so the tube is glued into the hole in the case. The long dimension of the case should be in line with the rows of leads coming through the hole and the end hole with the grommet should be to your right. Make sure the tube is fully seated in the hole.

    ____

  - Use some tape to hold the case in position so that it is level and the tube is perpendicular to it.

    ____

- Add ADS1115 board:

  - Apply a blob of superglue to the back of the ADS1115 board right in the middle. Quickly, but carefully, lower the ADS1115 board down with the longer photodiode lead coming through hole A0 and the shorter one coming through hole A1. The three TMP36 leads will be along the edge of the ADS1115 board and may deflect slightly. Adjust the position of the ADS1115 board so the A0 and A1 holes are centered over the tube hole and hold the board in place for about a minute so it sticks to the case.

    ____

  - **Leave this untouched for a couple hours so the glue will be sure to have dried. Do not proceed with the following steps until then.**

    ____

- Add load resistor:

  - Cut both leads of the resistor to 1 cm. Bend 2mm on the end of each lead at a right angle and insert those 2mm ends into holes A0 and A1 of the ADS1115 board, alongside the photodiode leads. The reason for the 2mm length is so there's no possibility that the ends can touch the TMP36 leads or the other photodiode lead underneath the board.

    ____

  - Solder the resistor and photodiode leads to holes A0 and A1.

    ____

  - Trim the photodiode leads.

    ____

- Solder TMP36 middle lead to A2 (optional):

  - Gently bend the two outer TMP36 leads away from the edge of the ADS1115 board.

    ____

- With long-nosed pliers, carefully bend the middle TMP36 lead toward the A2 hole and solder it to the hole. You may need a small piece of stripped hookup wire in the hole to solder to if the lead isn't quite long enough to actually go into the hole. Make sure this lead is not making contact with the A1 solder joint or photodiode lead stub.

  ____

- Prepare cable:
  - Untape the whole assembly from the work surface

    ____

  - Shake it to make sure the Teflon diffuser disk doesn't fall out. If it does, set the disk aside for now.

    ____

  - Cut the female end off of the cable. Push the cut end through the grommet into the case and pull it through. Don't worry about pulling it too far, you will be able to pull it back out later. Use a drop of dish soap if it is difficult to push through.

    ____

  - Cut away the outer cable sheathing on the cut end to expose the four wires inside, being careful not to damage the insulation on the inner wires. Cut away at least 2 cm of the sheathing.

    ____

  - Strip 8 mm of the insulation from the inner four wires and twist the ends of each.

    ____

  - “Tin” the twisted ends by heating with the soldering iron and applying some solder to the strands.

    ____

- Use a digital multimeter (DMM) to determine the connectivity between the inner wires and the four parts of the 3.5mm plug on the other end of the cable. Write down the colors:

  Color:

  Tip: ____________________ [+5V]

  Ring 1: ____________________ [SCL]

  Ring 2: ____________________ [SDA]

  Sleeve: ____________________ [GND]

  NOTE: these colors will almost certainly NOT match the colors in Figure 1, so this is very important.

  ____

- Pull the cable back out through the rubber grommet until the insulation of the inner wires just reaches the VDD hole of ADS1115 board.

  ____

- Solder cable wires and hookup wire to ADS1115:
  - Cut the following lengths of hookup wire (only needed for TMP36):
    - Black, 2.5cm
    - Red, 2.5cm

    Strip 6mm from each end of each.

    ____

  - Solder the cable wire that is connected to the plug Tip (+5V) to the VDD hole, along with one end of the 2.5cm red wire.

    ____

  - Solder the cable wire that is connected to the plug Sleeve (GND) to the GND hole, along with one end of the 2.5cm black wire.

    ____

- Solder the cable wire that is connected to the plug Ring 1 (SCL) to the SCL hole.

  ____

- Solder the cable wire that is connected to the plug Ring 2 (SDA) to the SDA hole.

  ____

- Solder TMP36 power/ground leads (optional):
  - Solder the other end of the 2.5cm black wire (from the GND hole) to the TMP36 lead on the right. Make sure it doesn't contact the middle lead.

    ____

  - Solder the other end of the 2.5cm red wire (from the VDD hole) to the TMP36 lead on the left. Make sure it doesn't contact the middle lead.

    ____

- Cut and solder wires to jack:
  - Cut four hookup wires. Make them long enough for whatever enclosure you'll be putting the Arduino in (9cm for IV Swinger 2):
    - Black: __________
    - Red: __________
    - Blue: __________
    - Green: __________

    Strip 1cm from the end of each.

    ____

  - Insert the cable plug into the 3.5mm jack.

    ____

- Use the DMM to determine which solder connection on the back of the 3.5mm jack is connected to the **VDD** hole on the ADS1115 board.

  Twist the **RED** wire to that solder connection on the jack.

  ____

- Use the DMM to determine which solder connection on the back of the 3.5mm jack is connected to the **GND** hole on the ADS1115 board.

  Twist the **BLACK** wire to that solder connection on the jack.

  ____

- Use the DMM to determine which solder connection on the back of the 3.5mm jack is connected to the **SCL** hole on the ADS1115 board.

  Twist the **BLUE** wire to that solder connection on the jack.

  ____

- Use the DMM to determine which solder connection on the back of the 3.5mm jack is connected to the **SDA** hole on the ADS1115 board.

  Twist the **GREEN** wire to that solder connection on the jack.

  ____

- Use DMM to confirm the connections. Test continuity from the end of the hookup wire to the ADS1115 hole. At the same time, test that there is NO CONTINUITY to the other three.

  - Red to VDD: __________
  - Black to GND: __________
  - Blue to SCL: __________
  - Green to SDA: __________

- Solder all four hookup wires to the 3.5mm jack

  ____

- Final assembly:
  - Put the cable tie around the cable and use pliers to pull it tight right next to the grommet on the inside of the case. Trim.

    ____

  - Screw the cover to the case.

    ____

  - Use the small piece of fine abrasive paper included with the kit and gently abrade the surface of the Teflon with a circular motion, just enough to remove the "shine" from the disk.

    ____

  - If the Teflon diffuser disk did not snap tightly into its recess, use a TINY amount of superglue around the recess to hold it in. Make sure not to get any glue on the photodetector! A toothpick can be useful to apply the superglue, but move quickly. Use a small clamp to hold it in while the glue dries.

    ____

  - Connect to Arduino:

    Connect the four wires from the back of the 3.5mm jack to the Arduino as shown in Figure 1 above.

    ______

3 Running Tests

3.1 Install Arduino Application

On the computer that will be connected to the pyranometer, download and install the Arduino application (IDE) from:

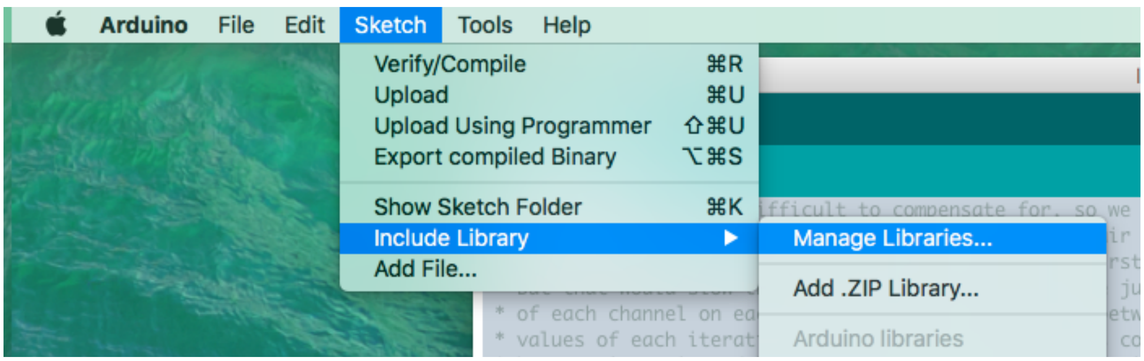
https://www.arduino.cc/en/Main/Software

3.2 Install Adafruit ADS1X15 Arduino Library

The following Arduino library must be installed:

- Adafruit ADS1X15

To do this from the Arduino IDE, use Sketch->Include Library->Manage Libraries…



Search for "Adafruit". Click on the one with the name "Adafruit ADS1X15" and then click on the Install button.

3.3 Run Generic ADS1X15 Test

- Connect the Arduino to a computer with the USB cable.
- 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/Test_ADS1X15/master/Test_ADS1X15.ino

- Right-click and use "Save As" to save Test_ADS1X15.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 Test_ADS1X15.ino sketch using:

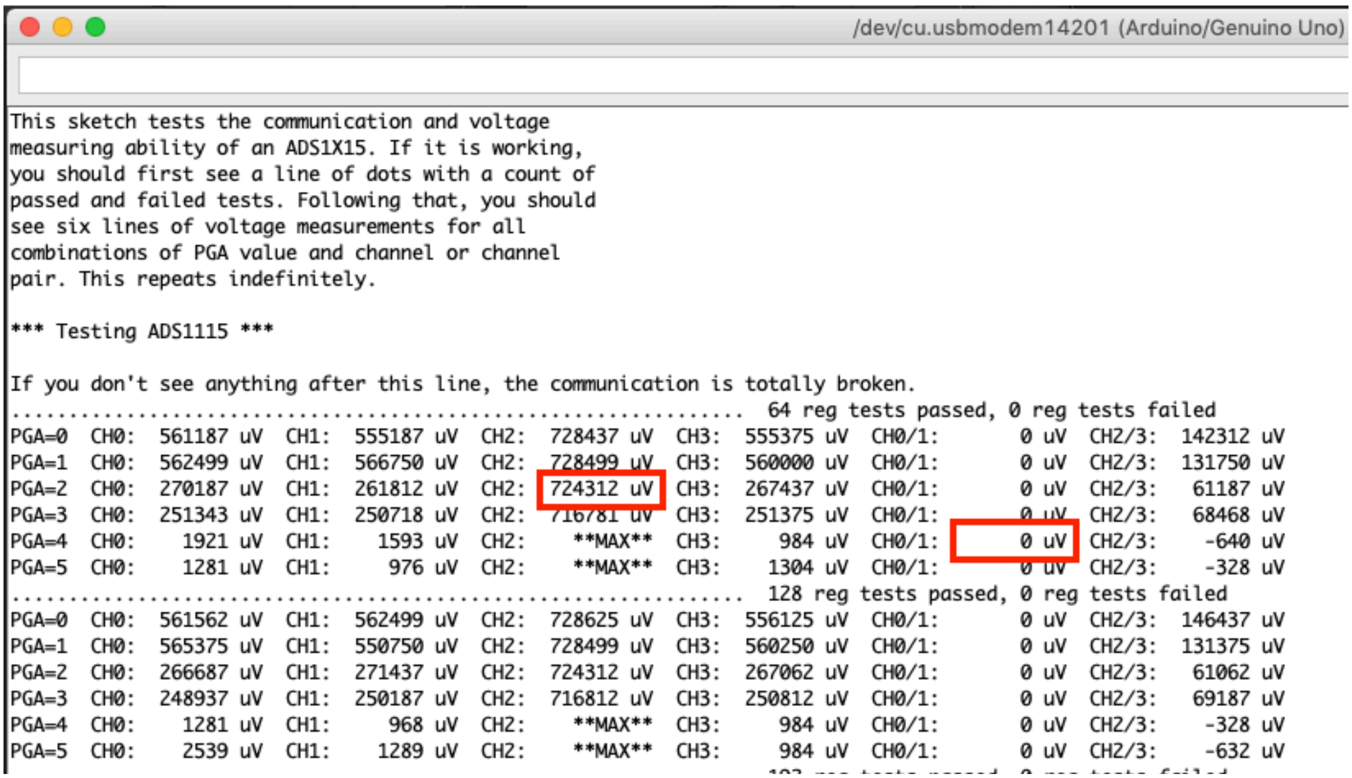
  File->Open

  The Arduino application will inform you that Test_ADS1X15.ino must be in a folder named Test_ADS1X15 and it will offer to do that for you. Accept its kind offer.

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

- Open the serial monitor (Tools->Serial Monitor) and set the baud to 57600

- Reload the sketch. The output should be similar to Figure 2 below:



```
/dev/cu.usbmodem14201 (Arduino/Genuino Uno)

This sketch tests the communication and voltage
measuring ability of an ADS1X15. If it is working,
you should first see a line of dots with a count of
passed and failed tests. Following that, you should
see six lines of voltage measurements for all
combinations of PGA value and channel or channel
pair. This repeats indefinitely.

*** Testing ADS1115 ***

If you don't see anything after this line, the communication is totally broken.
................................................................ 64 reg tests passed, 0 reg tests failed
PGA=0  CH0:  561187 uV  CH1:  555187 uV  CH2:  728437 uV  CH3:  555375 uV  CH0/1:       0 uV  CH2/3:  142312 uV
PGA=1  CH0:  562499 uV  CH1:  566750 uV  CH2:  728499 uV  CH3:  560000 uV  CH0/1:       0 uV  CH2/3:  131750 uV
PGA=2  CH0:  270187 uV  CH1:  261812 uV  CH2:  724312 uV  CH3:  267437 uV  CH0/1:       0 uV  CH2/3:   61187 uV
PGA=3  CH0:  251343 uV  CH1:  250718 uV  CH2:  716781 uV  CH3:  251375 uV  CH0/1:       0 uV  CH2/3:   68468 uV
PGA=4  CH0:    1921 uV  CH1:    1593 uV  CH2:    **MAX**  CH3:     984 uV  CH0/1:       0 uV  CH2/3:    -640 uV
PGA=5  CH0:    1281 uV  CH1:     976 uV  CH2:    **MAX**  CH3:    1304 uV  CH0/1:       0 uV  CH2/3:    -328 uV
................................................................ 128 reg tests passed, 0 reg tests failed
PGA=0  CH0:  561562 uV  CH1:  562499 uV  CH2:  728625 uV  CH3:  556125 uV  CH0/1:       0 uV  CH2/3:  146437 uV
PGA=1  CH0:  565375 uV  CH1:  550750 uV  CH2:  728499 uV  CH3:  560250 uV  CH0/1:       0 uV  CH2/3:  131375 uV
PGA=2  CH0:  266687 uV  CH1:  271437 uV  CH2:  724312 uV  CH3:  267062 uV  CH0/1:       0 uV  CH2/3:   61062 uV
PGA=3  CH0:  248937 uV  CH1:  250187 uV  CH2:  716812 uV  CH3:  250812 uV  CH0/1:       0 uV  CH2/3:   69187 uV
PGA=4  CH0:    1281 uV  CH1:     968 uV  CH2:    **MAX**  CH3:     984 uV  CH0/1:       0 uV  CH2/3:    -328 uV
PGA=5  CH0:    2539 uV  CH1:    1289 uV  CH2:    **MAX**  CH3:     984 uV  CH0/1:       0 uV  CH2/3:    -632 uV
```

Figure 2: Test_ADS1X15 Output

If this test does not run, it could be because your cable is too long or because you have made a mistake in the wiring/soldering. The only signals that are needed for this test to run are: VDD, GND, SCL, and SDA. It is also possible, but highly unlikely that the ADS1115 board is bad. If you have exhausted other possibilities, DO NOT disassemble everything. Just de-solder the cable wires from the ADS1115 and connect them to a different ADS1115 board. Only if that passes this test should you actually try replacing it.

The test must run without errors in order for you to continue.

In addition to performing register writes and reads, the test also prints out voltage measurements (in microvolts). This is a generic test, so most of these are not meaningful. The only ones that are relevant for the pyranometer are:

```
PGA = 2,    A2 (single-ended)
```

```
PGA = 4, A0/A1 (differential)
```

These are highlighted in Figure 2 above. A2 is the TMP36 voltage, which can be translated to the temperature in ˚C as follows:

```
˚C = ((A2 µV / 1000) - 500) / 10
```

For example, the A2 voltage is 724312 µV in Figure 2:

```
˚C = ((724312 / 1000) - 500) / 10 = 22.4 ˚C
```

A0/A1 is the voltage across the photodiode load resistor. With the Teflon diffuser in place the voltage should be 0 µV if you cover the detector with your finger. If you shine the "flashlight" from a cell phone directly into it, you should see this voltage go up to at least 200000 µV.

3.4 Run ADS1115_Pyranometer_Test

Following the same process for loading the Test_ADS1X15Arduino sketch in Section 3.3 above, load and run the following sketch:

https://raw.githubusercontent.com/csatt/ADS1115_InstESRE_Pyranometer/master/Arduino/Test_ADS1115_Pyranometer/Test_ADS1115_Pyranometer.ino

https://raw.githubusercontent.com/csatt/ADS1115_InstESRE_Pyranometer/master/Arduino/Test_ADS1115_Pyranometer/Test_ADS1115_Pyranometer.ino

With the "flashlight" from a cell phone shining directly into it, the output should look something like what is shown in Figure 3 below.

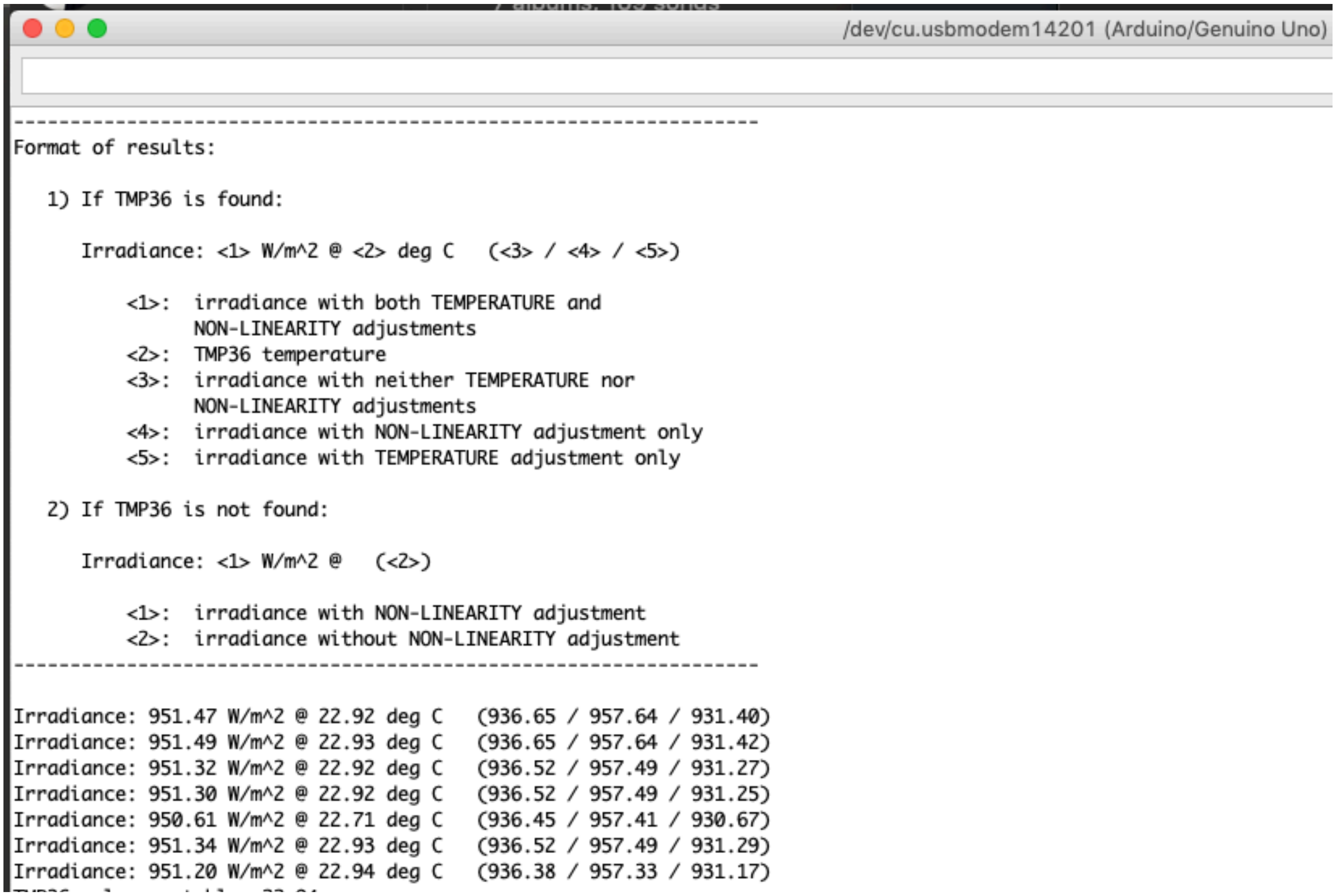


Figure 3: Test_ADS1115_Pyranometer Output

This Arduino sketch can be modified as desired, or used as a basis for other projects.

See Section 4.2.2 below for a description of the temperature and non-linearity adjustments.

4 Calibration

The irradiance values measured by the pyranometer will be very inaccurate until it is calibrated.

NOTE: IV Swinger 2 users should follow the calibration instructions in the "IV Swinger 2: Optional Environmental Sensors" document.

4.1 Reference Pyranometer

To perform an accurate calibration, you will need access to a reference pyranometer. The best reference pyranometer is a thermopile-based "true" pyranometer. These are very expensive, and you probably do not have access to one. The next best is a commercial silicon sensor pyranometer such as the Kipp & Zonen SP-Lite (which Dr. Brooks uses for calibration). If you can rent or borrow either of these types of reference pyranometer, you will be able to accurately calibrate your pyranometer.

4.2 Performing the Calibration

4.2.1 PYRANO_CAL

The Test_ADS1115_Pyranometer.ino sketch has a constant PYRANO_CAL that is the value in W/m^2 per millivolt measured across the load resistor. Its correct value is going to be different for each pyranometer due to differences in the photodiodes and load resistors.

To perform a calibration, use the reference pyranometer to measure the irradiance at the same time as the test is running. The reference pyranometer and the InstESRE pyranometer must both be pointed directly at the sun. It must be a very clear sunny day. Note the irradiance values of both pyranometers at exactly the same time and scale the value of PYRANO_CAL accordingly. Reload the sketch with the new value and confirm that the irradiance values are the same. If not, repeat the process.

4.2.2 Other calibration constants

The Test_ADS1115_Pyranometer.ino sketch has the following additional calibration constants:

- **PHOTODIODE_NOMINAL_DEG_C**

  This is used for the temperature compensation. It is the temperature at which no compensation is applied. Default is 25˚C.

- **PHOTODIODE_PCT_PER_DEG_C**

  This is the percentage that the measured irradiance value is scaled up for each ˚C above PHOTODIODE_NOMINAL_DEG_C (or scaled down for each ˚C below PHOTODIODE_NOMINAL_DEG_C). Setting this constant to 0 turns this adjustment off.

- **PHOTODIODE_NOMINAL_MV**

  This is used for an adjustment for an empirically observed error in the photodiode sensitivity, where it reads slightly low at higher irradiances and slightly high at lower irradiances. Its value is in millivolts, and represents the measured voltage across the load resistor for which the reading is "just right".

- **PHOTODIODE_ADJ_PPM**

  This is the parts-per-million that the irradiance is adjusted up for load resistor voltages that are higher than PHOTODIODE_NOMINAL_MV and down for load resistor voltages that are lower than PHOTODIODE_NOMINAL_MV. Setting this constant to 0 turns this adjustment off.