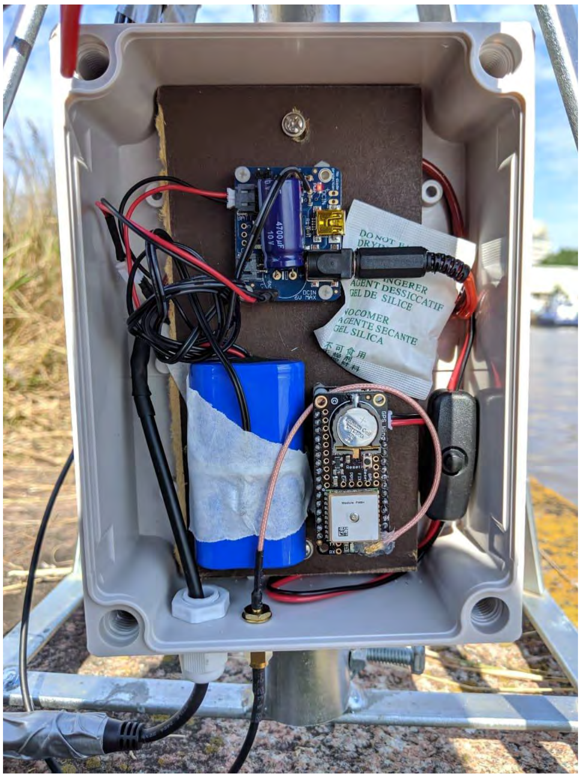
Build tutorial for MPHW, an open-source sensor for SNR-based GPS/GNSS Reflectometry (GNSS-R)



This guide was created on June 06, 2019.

Contributors:
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- Manuella Fagundes
- Felipe Geremia-Nievinski

(Portions and images reused from Adafruit tutorials, by Lady Ada and others.)

Updates:
- 28 June 2022: corrected several download links; removed DEBUG option (automatic now); emphasized selection of the board type in the IDE; added board revival instructions.
- 28 Oct 2021: appendix with design of power supply system.
- 01 Jul 2021: card ejection, reset button.
- 16 Feb 2021: enclosure hole for the antenna, outdoors testing, site guidelines.
- 26 Feb 2020: miscellaneous.

Table of Contents

0. List of materials

You can use this link to a bill of materials with all the necessary items:
https://www.adafruit.com/wishlists/469752
For convenience, we list below the items in the Adafruit shopping cart;
other shops can be used for some of the items.

1) 1x - 2.1mm female/male barrel jack extension cable - 1.5m / 5 ft
https://www.adafruit.com/product/327

2) 1x - 3.5 / 1.3mm or 3.8 / 1.1mm to 5.5 / 2.1mm DC Jack Adapter Cable
https://www.adafruit.com/product/2788

3) 1x - GPS Antenna - External Active Antenna - 3-5V 28dB 5 Meter SMA
https://www.adafruit.com/product/960

4) 1x - CR1220 12mm Diameter - 3V Lithium Coin Cell Battery - CR1220
https://www.adafruit.com/product/380

5) 1x - SMA to uFL/u.FL/IPX/IPEX RF Adapter Cable
https://www.adafruit.com/product/851

6) 1x - Header Kit for Feather - 12-pin and 16-pin Female Header Set
https://www.adafruit.com/product/2886

7) 1x - Adafruit Ultimate GPS FeatherWing

https://www.adafruit.com/product/3133

8) 1x - Adafruit Feather 32u4 Adalogger

https://www.adafruit.com/product/2795

9) 1x - Lithium Ion Battery Pack - 3.7V 4400mAh

https://www.adafruit.com/product/354

10) 1x - 10K Precision Epoxy Thermistor - 3950 NTC

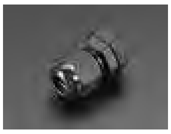
https://www.adafruit.com/product/372

11) 1x - Waterproof DC Power Cable Set - 5.5/2.1mm [optional]

https://www.adafruit.com/product/743

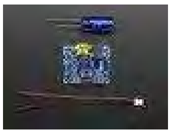
12) 1x - Cable Gland PG-9 size - 0.158" to 0.252" Cable Diameter - PG-9 [optional]

https://www.adafruit.com/product/761



13) 1x - USB / DC / Solar Lithium Ion/Polymer charger - v2

https://www.adafruit.com/product/390



14) 1x - Huge 6V 6W Solar panel - 6.0 Watt

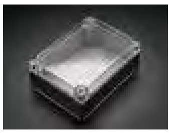
https://www.adafruit.com/product/1525

15) 1x - Through-Hole Resistors - 2.2K ohm 5% 1/4W - Pack of 25
https://www.adafruit.com/product/2782

16) 1x - Cable Gland PG-7 size - 0.118" to 0.169" Cable Diameter - PG-7
https://www.adafruit.com/product/762

17) 1x - 2.1mm to 2.5mm DC Barrel Plug Adapter
https://www.adafruit.com/product/2897

18) 1x - Large Plastic Project Enclosure - Weatherproof with Clear Top
https://www.adafruit.com/product/905



19) JST 2-pin Extension Cable with On/Off Switch - JST PH2
https://www.adafruit.com/product/3064

20) SD/MicroSD Memory Card (8 GB SDHC)
https://www.adafruit.com/product/1294

21) White Nylon Screw and Stand-off Set – M2.5 Thread [optional]
https://www.adafruit.com/product/3658

22) USB cable - A/MiniB - 3ft [optional]
https://www.adafruit.com/product/260

1. Setup the Arduino firmware

You'll need:
- Adafruit Feather 32u4 Adalogger : item 8
- SD card with file system fat32 : item 20

1.1 - Download and install the Arduino IDE

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

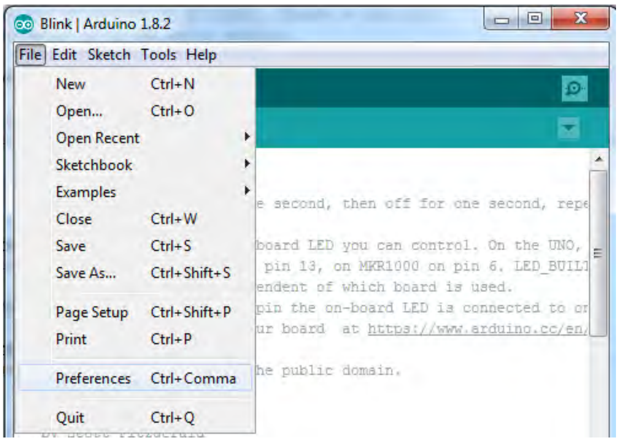
1.2 - Install Adafruit drivers for the IDE

Below we show a summary of the detailed steps in this link:

https://learn.adafruit.com/adafruit-feather-32u4-adalogger/setup

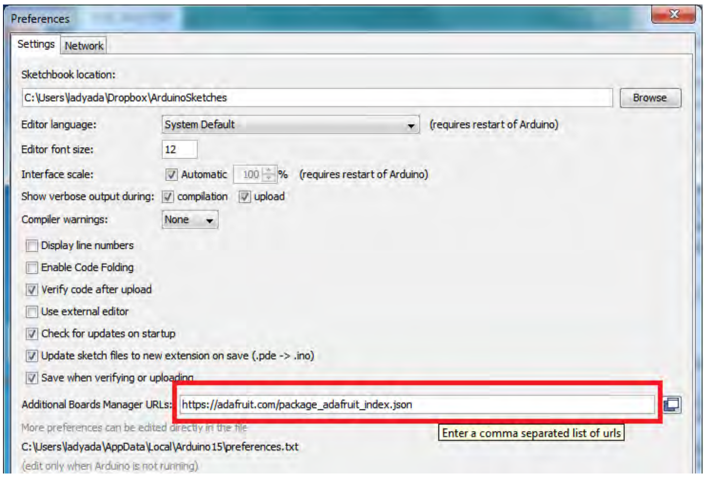
Portion reused from Adafruit tutorial:

> "After you have downloaded and installed **the latest version of Arduino IDE**, you will need to start the IDE and navigate to the **Preferences** menu. You can access it from the **File** menu in *Windows* or *Linux*, or the **Arduino** menu on *OS X*.



```
e second, then off for one second, repe

board LED you can control. On the UNO,
 pin 13, on MKR1000 on pin 6. LED_BUILT
endent of which board is used.
pin the on-board LED is connected to on
ur board  at https://www.arduino.cc/en/

he public domain.
```

A dialog will pop up just like the one shown beside.



Preferences

Settings | Network

Sketchbook location: C:\Users\ladyada\Dropbox\ArduinoSketches [Browse]

Editor language: System Default (requires restart of Arduino)

Editor font size: 12

Interface scale: ☑ Automatic 100 % (requires restart of Arduino)

Show verbose output during: ☑ compilation ☑ upload

Compiler warnings: None

☐ Display line numbers

☐ Enable Code Folding

☑ Verify code after upload

☐ Use external editor

☑ Check for updates on startup

☑ Update sketch files to new extension on save (.pde -> .ino)

☑ Save when verifying or uploading

Additional Boards Manager URLs: https://adafruit.com/package_adafruit_index.json

Enter a comma separated list of urls

More preferences can be edited directly in the file

C:\Users\ladyada\AppData\Local\Arduino15\preferences.txt

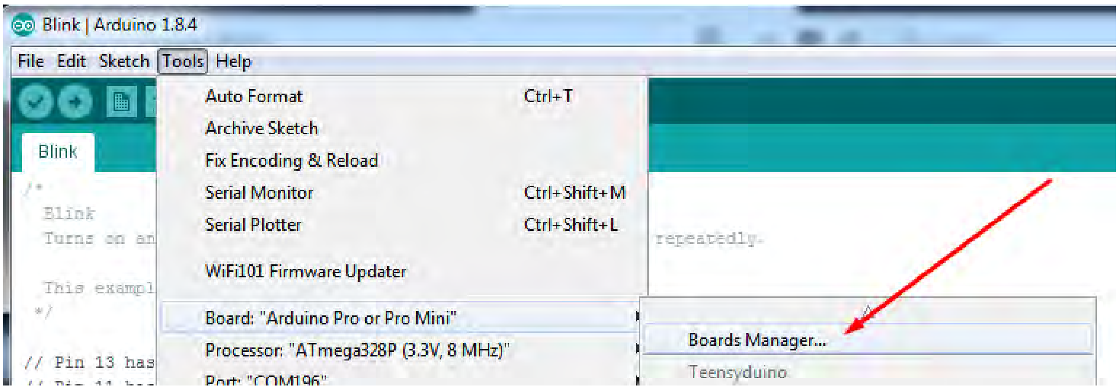
(edit only when Arduino is not running)

We will be adding a URL to the new **Additional Boards Manager URLs** option. The list of URLs is comma separated, and *you will only have to add each URL once.* New Adafruit boards and updates to existing boards will automatically be picked up by the Board Manager each time it is opened. The URLs point to index files that the Board Manager uses to build the list of available & installed boards.

Insert this link in the Arduino IDE preferences:

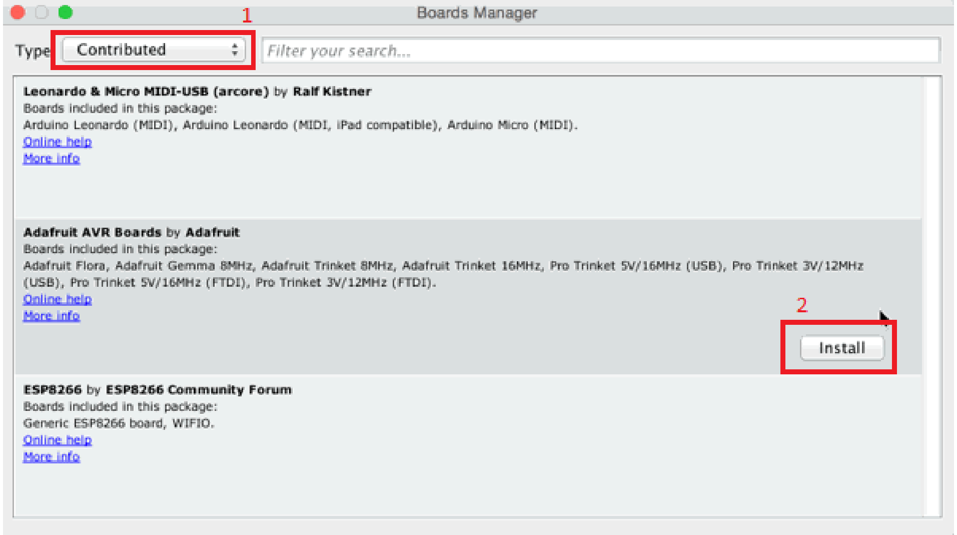
https://adafruit.github.io/arduino-board-index/package_adafruit_index.json
Click “Ok” button to save.

Now that you have added the appropriate URLs to the Arduino IDE preferences, you can open the **Boards Manager** by navigating to the **Tools->Board** menu.



```
/*
  Blink
  Turns on an
  This exampl
*/
// Pin 13 has
```

Once the Board Manager opens, click on the category drop down menu on the top left hand side of the window and select **Contributed**. You will then be able to select and install the boards supplied by the URLs added to the preferences. In the example below, we are installing support for ***Adafruit AVR Boards***, but the same applies to all boards installed with the Board Manager.



Leonardo & Micro MIDI-USB (arcore) by **Ralf Kistner**
Boards included in this package:
Arduino Leonardo (MIDI), Arduino Leonardo (MIDI, iPad compatible), Arduino Micro (MIDI).
Online help
More info

Adafruit AVR Boards by **Adafruit**
Boards included in this package:
Adafruit Flora, Adafruit Gemma 8MHz, Adafruit Trinket 8MHz, Adafruit Trinket 16MHz, Pro Trinket 5V/16MHz (USB), Pro Trinket 3V/12MHz (USB), Pro Trinket 5V/16MHz (FTDI), Pro Trinket 3V/12MHz (FTDI).
Online help
More info

ESP8266 by **ESP8266 Community Forum**
Boards included in this package:
Generic ESP8266 board, WIFIO.
Online help
More info

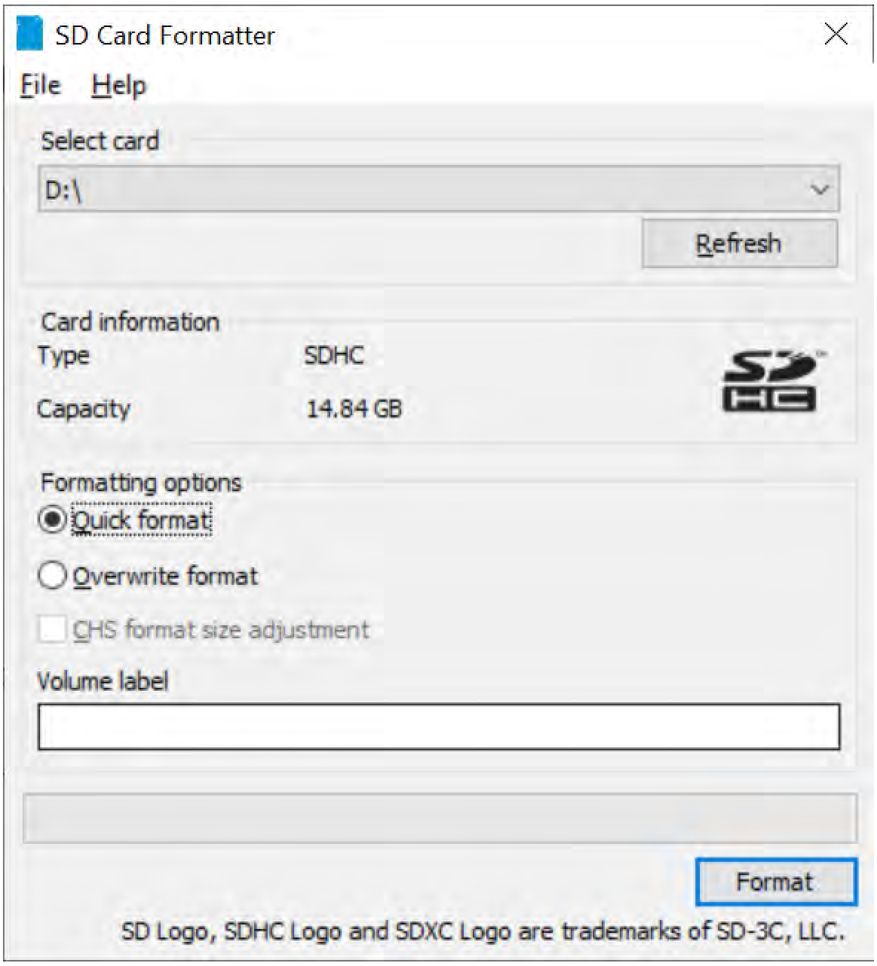
Next, **quit and reopen the Arduino IDE** to ensure that all of the boards are properly installed.

1.3 - Install Adafruit drivers for Windows

Download and run the installer:
https://github.com/adafruit/Adafruit_Windows_Drivers/releases
More details at:
https://learn.adafruit.com/adafruit-feather-32u4-adalogger/using-with-arduino-ide#install-drivers-windows-7-only-2854751

1.4 - Format the SD card to file system FAT32

We recommend to use this software to format the SD card:
https://www.sdcard.org/downloads/formatter/



Select card
D:\

Card information
Type SDHC
Capacity 14.84 GB

Formatting options
● Quick format
○ Overwrite format
□ CHS format size adjustment

Volume label

SD Logo, SDHC Logo and SDXC Logo are trademarks of SD-3C, LLC.

1.5 - Upload the Arduino sketch

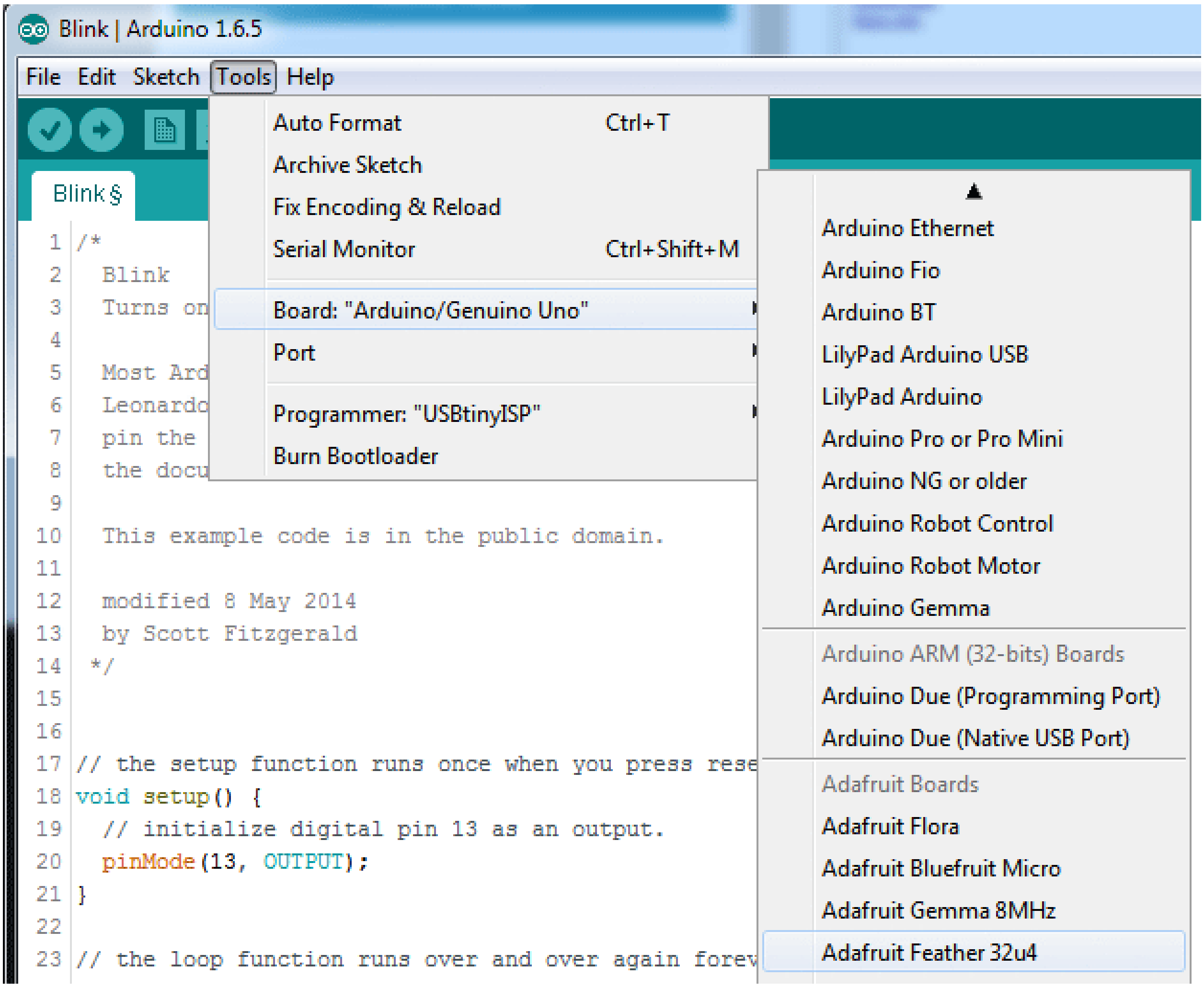
0) Preliminaries

0.1) Download the source code in this link:
https://github.com/fgnievinski/mphw/releases

0.2) Open file ardu.ino in the Arduino IDE.

0.3) Plug in the Feather 32u4 to the computer using a USB cable. Wait for it to be recognized by the operating system (it just takes a few seconds).

0.4) Select the board type in the Tools->Board menu:

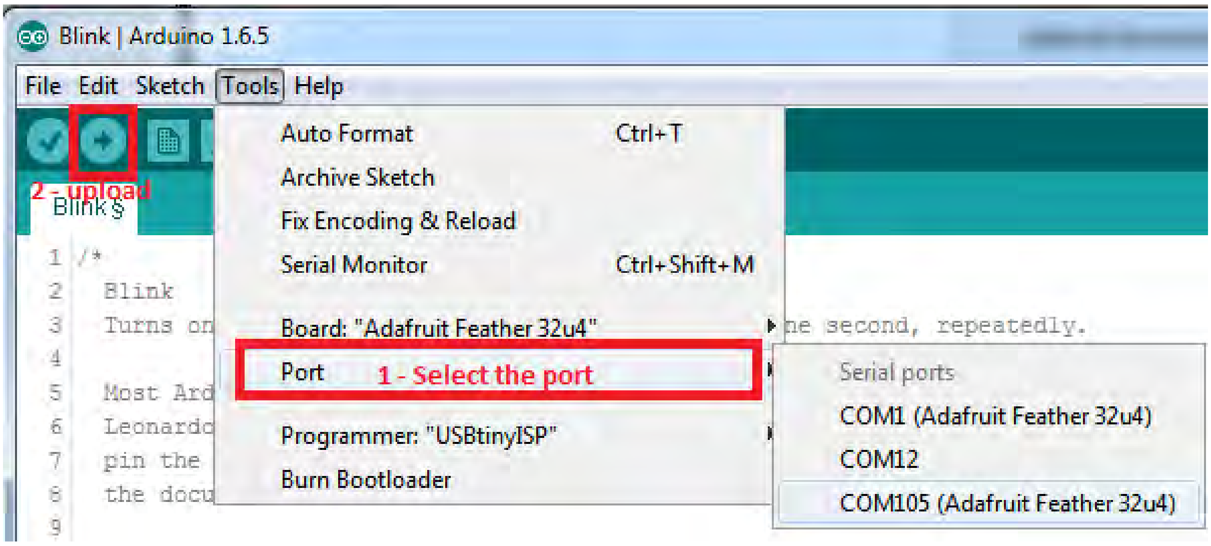


```
/*
  Blink
  Turns on

  Most Ard
  Leonardo
  pin the
  the docu

  This example code is in the public domain.

  modified 8 May 2014
  by Scott Fitzgerald
 */


// the setup function runs once when you press rese
void setup() {
  // initialize digital pin 13 as an output.
  pinMode(13, OUTPUT);
}

// the loop function runs over and over again forev
```

1) Select the serial COM port from the dropdown menu -- it'll even be 'indicated' as Feather 32u4.

2) Finally, upload the firmware, which makes the Arduino system run. Simply click on the Upload button (right-arrow icon) and wait (it may take a while to finish).

Note: in case the serial port list is empty, try to revive the board by “double-click during upload”: https://learn.adafruit.com/adafruit-feather-32u4-adalogger/faq#faq-2704880



```
/*
  Blink
  Turns on                                        ne second, repeatedly.

  Most Ard
  Leonardo
  pin the
  the docu

```

1.6 - Source code options

The following are a few options in the source code that the user may wish to modify.

File naming mode: you can change how often the system will save the data, creating a file per day or per hour. Search for the declaration of the variable `fileDuration` in the source code and set it to 'H' to save by hour or 'D' to save by day. See section 7.2.2 for more details.

Battery update interval: you can monitor the battery voltage while the system is running. Find the declaration "BATTERY_UPDATE_INTERVAL" in the source code to choose the interval (in milliseconds).

GPS update interval: defines how often the GPS data will be updated (in milliseconds); defined in GPS_UPDATE_INTERVAL.

1.7 - Update the GPS firmware (optional)

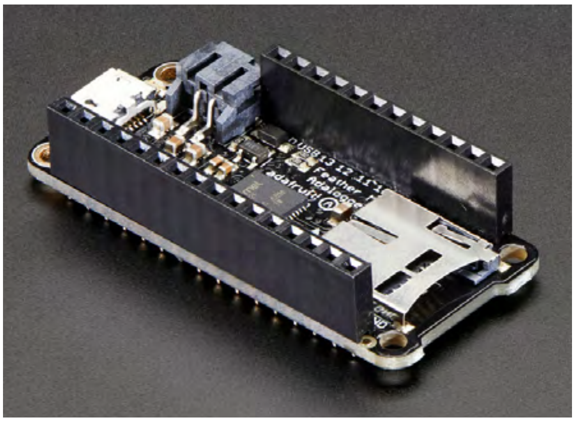
The GPS module (on the featherwing shield) has its own firmware, independent from the Arduino firmware as installed above. The GPS factory default firmware outputs SNR values as integer numbers, i.e., with 1-dB numerical resolution. Other GPS firmware versions may offer greater resolution, outputting SNR as decimal values. This section serves just a reminder in case you have access to such a GPS firmware.

2. Connecting the electronics

2.1 - Connecting the Arduino and GPS shield

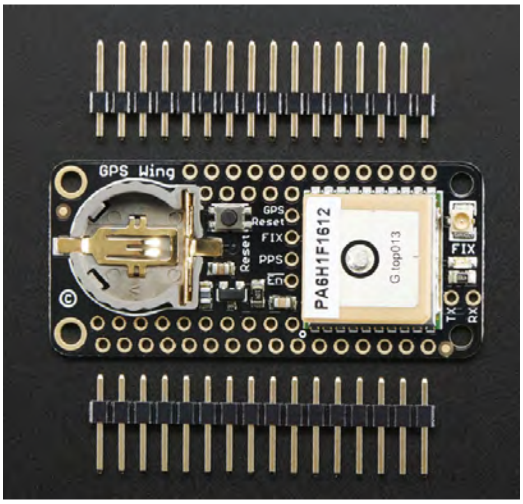
You'll need:
- Adafruit Feather 32u4 Adalogger : item 8
- Header Kit for Feather - 12-pin and 16-pin Female Header Set : item 6
- Adafruit Ultimate GPS FeatherWing : 7

Solder the "Header Kit for Feather - 12-pin and 16-pin Female Header Set" on the Feather as below.

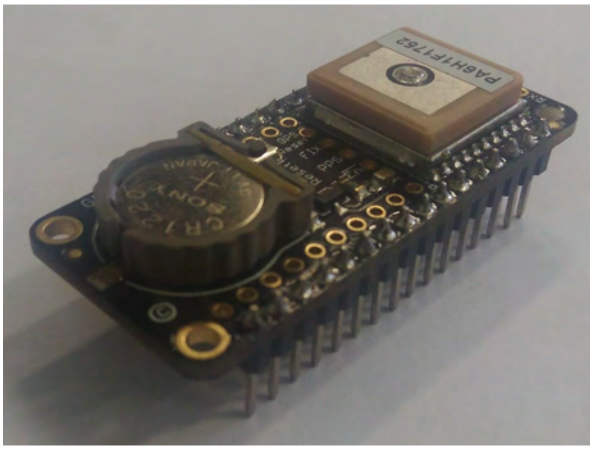


Check "Soldering on Female Header" at this link for detailed instructions:
https://cdn-learn.adafruit.com/downloads/pdf/adafruit-feather-32u4-adalogger.pdf?timestamp=1557404503#__WKANCHOR_g

Prepare the GPS module to attach on the Adafruit Feather soldering the male headers:

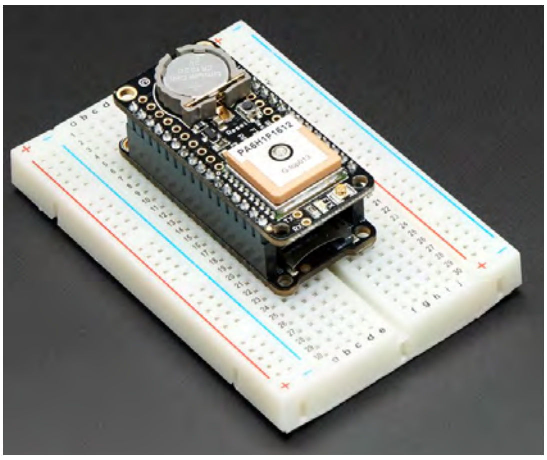


Make sure to solder the pins with the longer part facing down

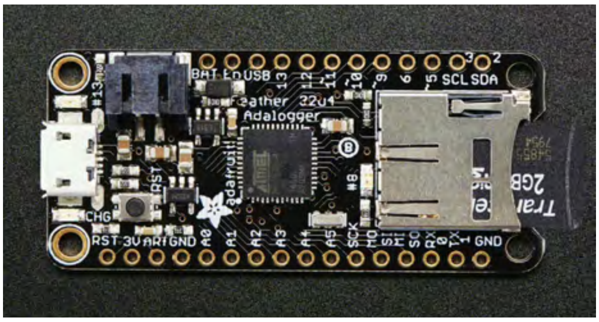


Check “Adafruit Ultimate GPS featherwing” for details:
https://learn.adafruit.com/adafruit-ultimate-gps-featherwing?view=all

Finally, we can connect the boards pressing down
(note: the protoboard in white is not necessary):



Insert the SD card into the slot on the Adafruit Feather Adalogger:



2.2 - Preparing the solar power supply system

You’ll need:
- USB / DC / Solar Lithium Ion/Polymer charger - v2 : item 13

- Huge 6V 6W Solar panel - 6.0 Watt : item 14
- Lithium Ion Battery Pack - 3.7V 4400mAh : item 9
- 10K Precision Epoxy Thermistor - 3950 NTC : item 10
- JST 2-pin Extension Cable with On/Off Switch - JST PH2 : item 19

2.2.1 - Installing the capacitor

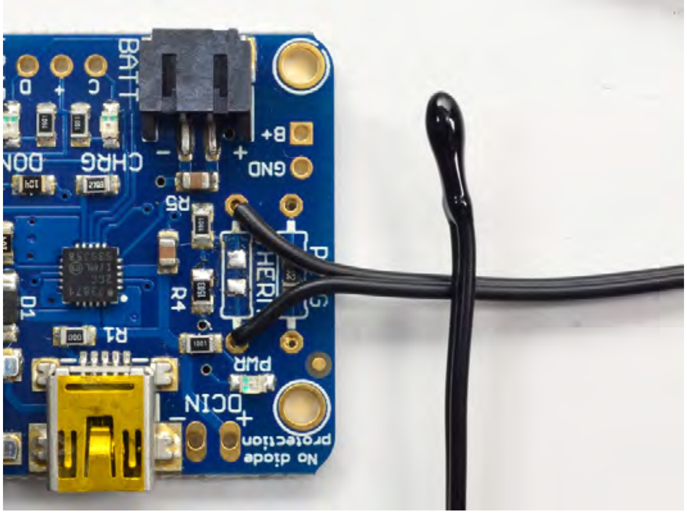
The first thing to do before starting to charge with a solar panel, is to install the large capacitor on the USB / DC / Solar Lithium Ion/Polymer charger. Watch out to check the polarity of the capacitor, make sure the positive lead of the capacitor goes into the pad marked with a plus sign (**+**)!

Follow these steps to prepare the capacitor for the solar charger:
https://learn.adafruit.com/usb-dc-and-solar-lipoly-charger/solar-charger-preparation

2.2.2 - Adding temperature sensing

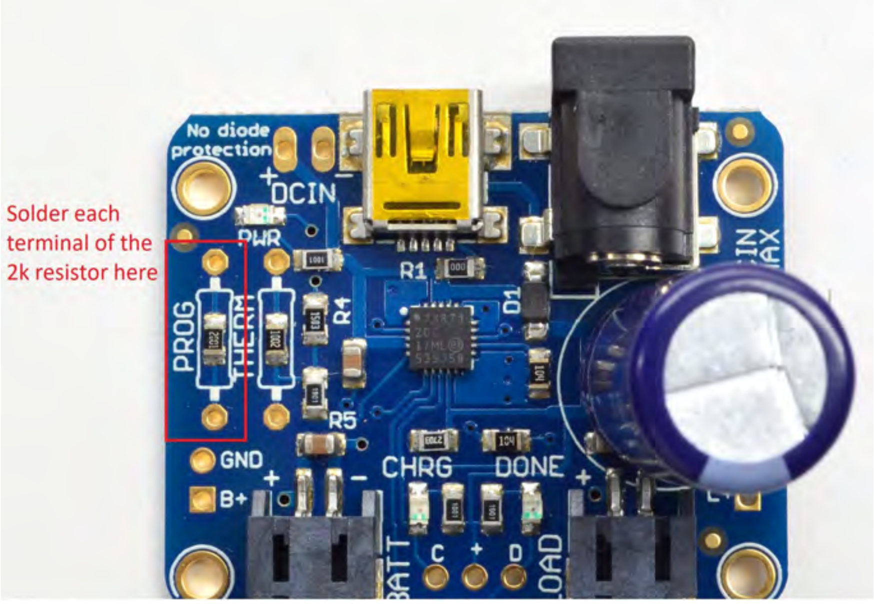
Portion reused from Adafruit tutorial:

> “Remove the 10K surface mount resistor from the **THERM** pads (or cut the trace going to it) and solder in a 10K NTC thermistor. Test out the system by trying to charge while you place the thermistor in a freezer or against some ice, as well as in a cup of > 50°C hot water. The charger should stop charging the battery. Once you are sure it is working, attach the sensing element (the epoxy bulb in this case) so it is resting against the battery.”

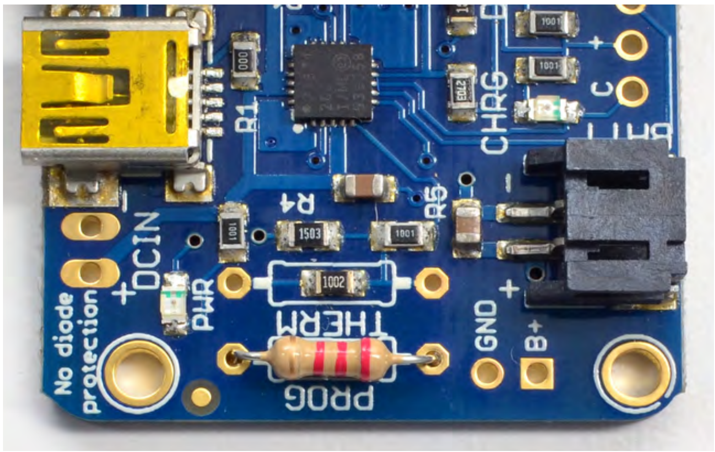


2.2.3 - Adjusting the maximum charging current

For the recommended battery (4400mAh capacity), solder a 2k-ohm resistor over the existing one in the PROG pads (or remove the existing one and solder a 1k-ohm resistor):



After doing that, you'll have a thing like this:



For details, please refer to:
https://learn.adafruit.com/usb-dc-and-solar-lipoly-charger?view=all#adjusting-the-max-charge-current-5-20

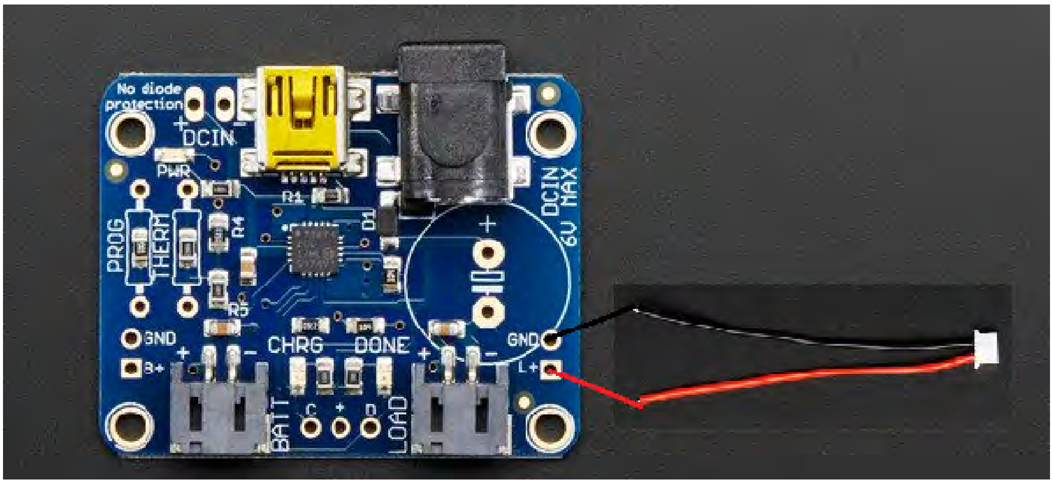
Portion reused from Adafruit tutorial:

> "**CAUTION**: This modification is indicated only for batteries bigger than 2000mAh!
> The USB/Solar charger comes with a preset rate of 500mA which will work for USB ports, USB wall adapters and solar panels up to 3 Watts. If you have a project that uses a larger

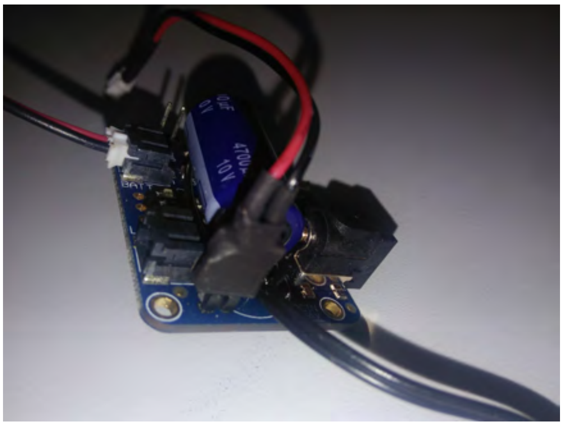
panel, or perhaps some other sort of setup, you can easily adjust the current by soldering a resistor into the **PROG** pads.”

2.2.4 - Preparing the Arduino power plug

You can solder the black and the red wires here to connect the Feather:
we recommend applying some silicone glue to avoid breaking the wires



As an alternative, we’ve soldered a pair of male pins to the board and soldered a pair of female plugs to the wires, using heat-shrink tubing for protection:



2.2.5 - Pre-charging the battery

We recommend fully charging the battery in the office, using a USB cable (with miniB connector). Otherwise, the system might run out of power in the first few days, in case you have bad luck to start with several rainy days.

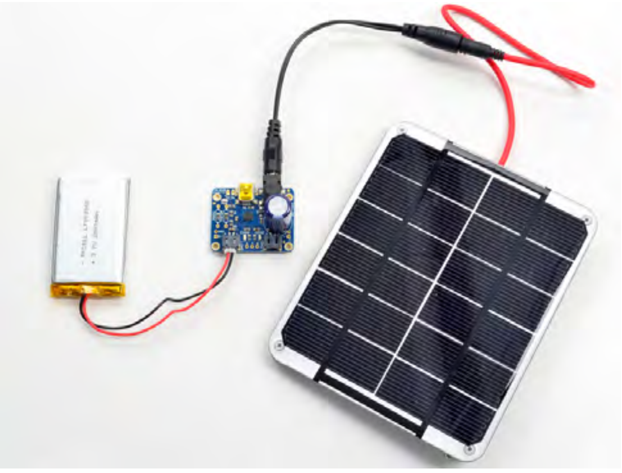
2.3 - Putting it all together

You'll need:
- SMA to uFL/u.FL/IPX/IPEX RF Adapter Cable : item 5
- 2.1mm female/male barrel jack extension cable - 1.5m / 5 ft : item 1
- 3.5 / 1.3mm or 3.8 / 1.1mm to 5.5 / 2.1mm DC Jack Adapter Cable : item 2
- all items prepared before

2.3.1 - Connecting the power supply

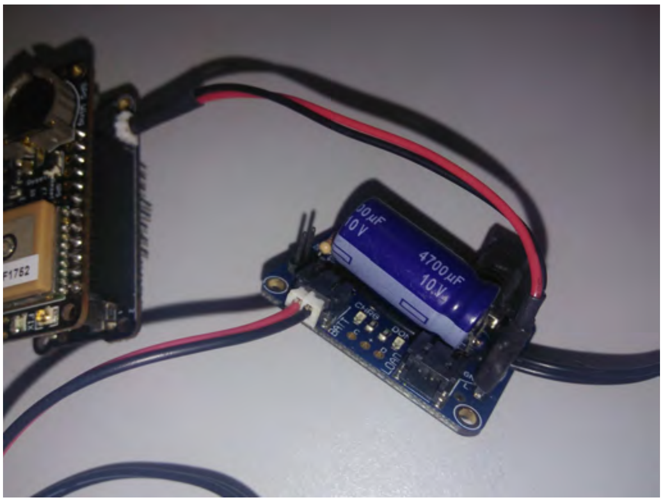
2.3.1.1 - Connecting the charger, solar panel, and battery

Use the jack adapter cable to connect the solar panel to the charges.
Use the jack extension cable (not shown) for making the cable longer.
Then connect the battery; once you've done that, you'll have something like this:

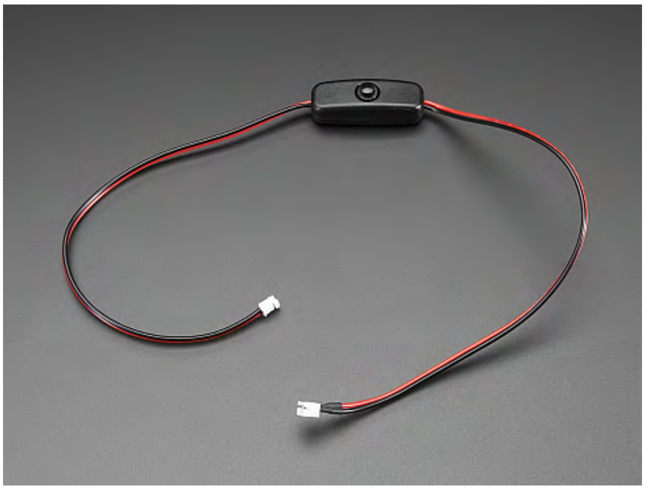


2.3.1.1 - Connecting the power supply to the Arduino

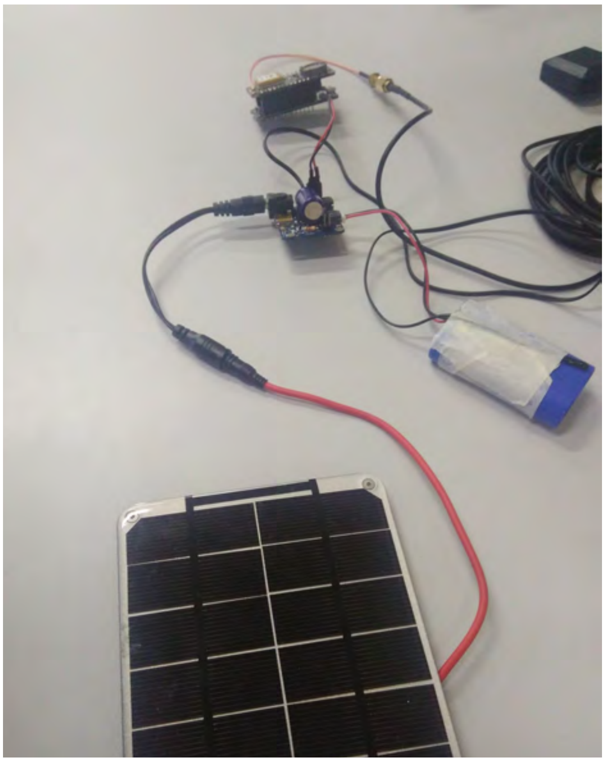
Connect the black and red wire on the Adafruit Arduino:



You may also use the extension cable with On/Off switch:

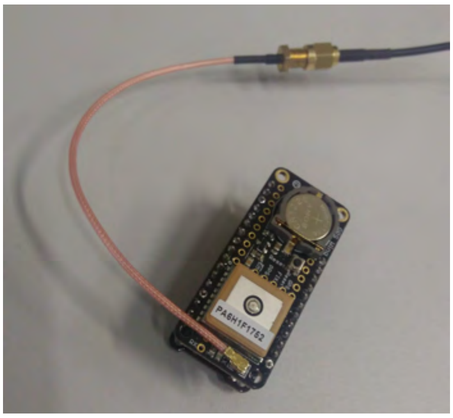


Once you’ve done that, you’ll have something like this:

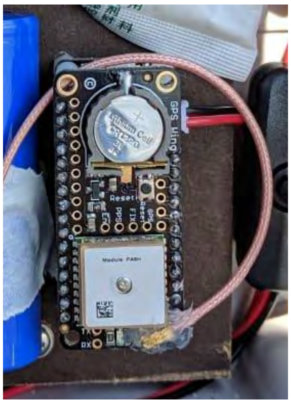


2.3.2 - Connecting the antenna

Use the adapter cable (SMA to uFI) to connect the GPS shield to the antena.



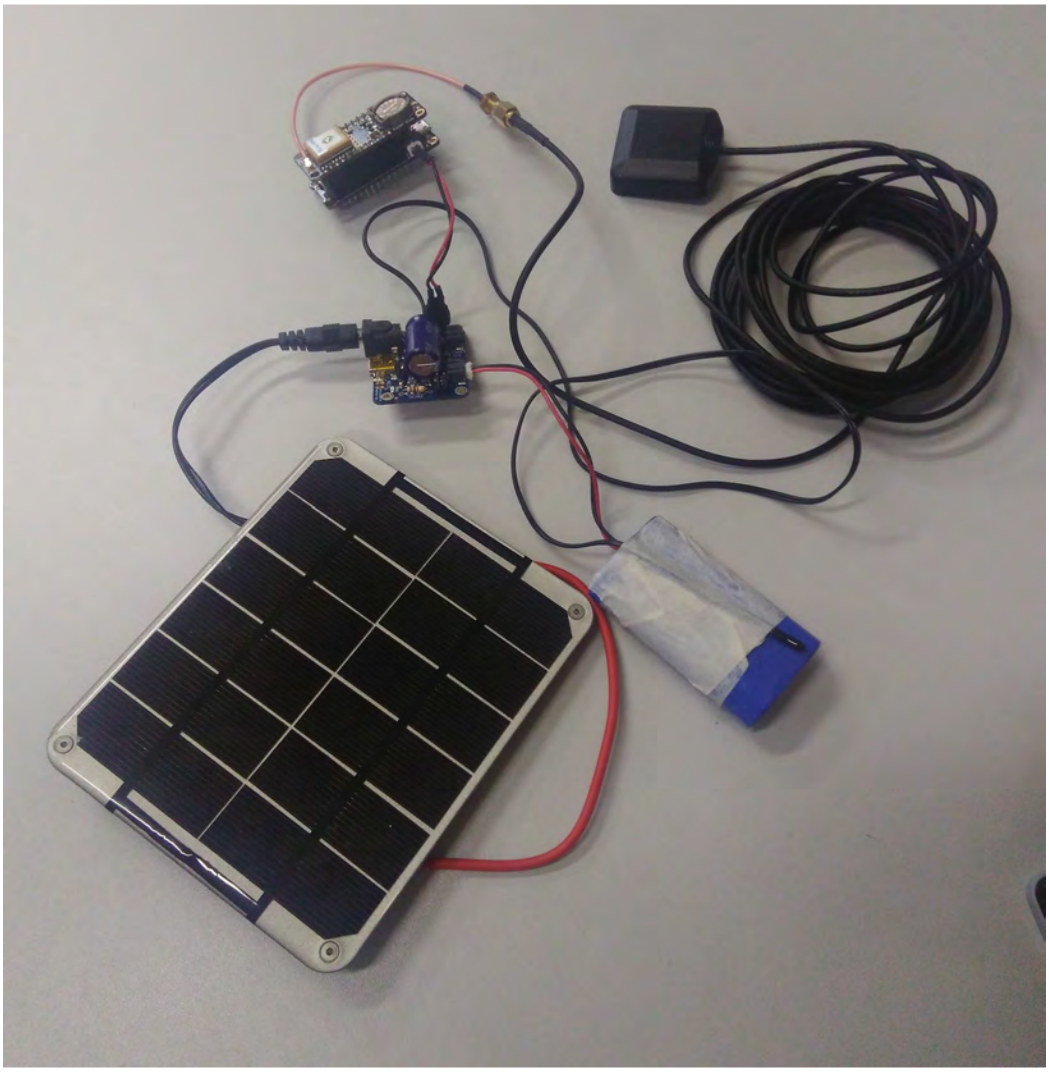
We recommend to put some silicone glue on the connection to avoid disconnecting by mechanical stresses:



(See also section 3 for mechanical fastening of the larger antenna pigtail cable connector.)

2.3.3 - First look

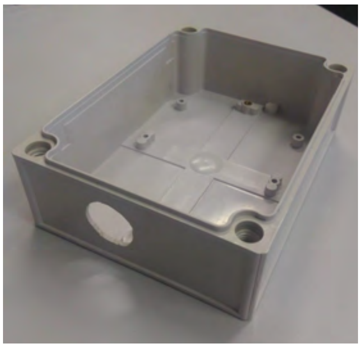
This is a look of our system outside the box:

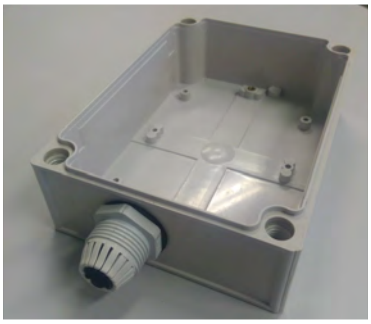


3. Preparing the enclosure

You'll need:
- Cable Gland PG-7 size - 0.118" to 0.169" Cable Diameter - PG-7 : item 16
- Large Plastic Project Enclosure - Weatherproof with Clear Top : item 18
- Waterproof DC Power Cable Set - 5.5/2.1mm [optional] : item 11
- Cable Gland PG-9 size - 0.158" to 0.252" Cable Diameter - PG-9 [optional] : item 12
- White Nylon Screw and Stand-off Set – M2.5 Thread [optional] : item 21
- SMA to uFL/u.FL/IPX/IPEX RF Adapter Cable : item 5

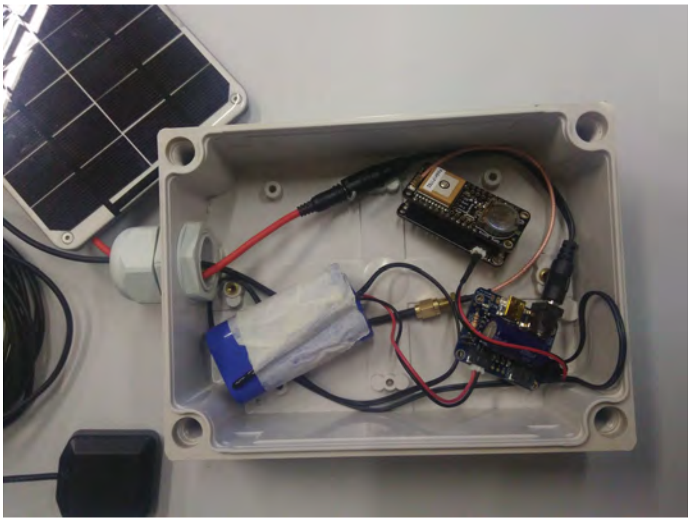
First of all you need to make a hole on the bottom side of the weatherproof box to pass the wiring through. You can use a drill or something alike to do this.





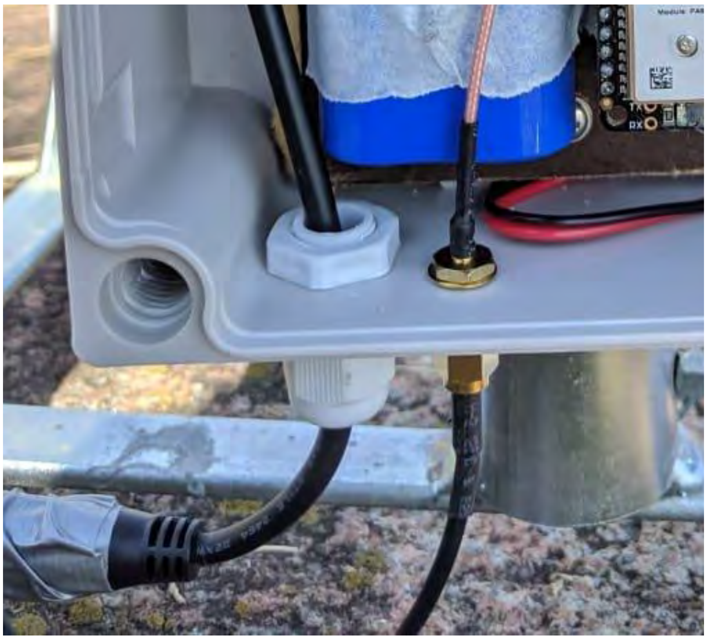
Then you install the cable gland.

Now you have to put all this inside the box, using the cable gland to pass the cables:



Optionally, use items 11 and 12 for a safer enclosure.

For the antenna cable, we recommend drilling a second smaller hole and screwing in the pigtail adapter cable (item 5). The larger coaxial connector (SMA female) should fit in tight in the enclosure's hole. Then fasten the nut, which goes on the enclosure's outside. Finally, screw in the antenna's own cable (SMA male connector). This setup will make the mechanical connection sturdier. See also comment in section 2.3.2 about silicone on the pigtail's smaller connector.

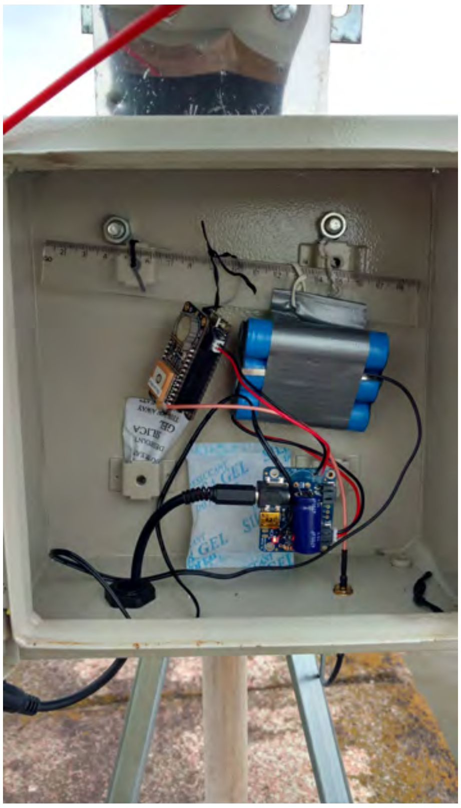


4. Mounting it outdoors

You'll need:
- solar panel support
- stick or mast
- silver tape
- U support
- base (bi-pod, quadri-pod)

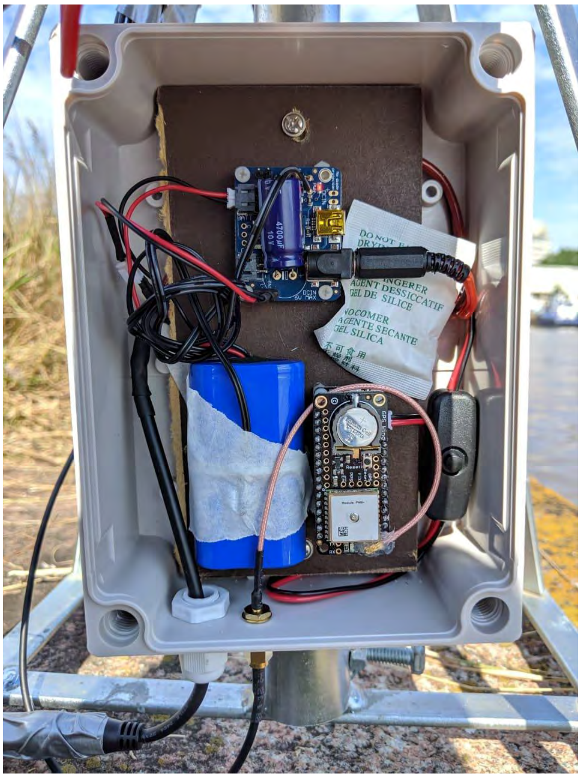
4.1 Basic precautions

Outdoors there is the risk of rain and humidity. So you need to suspend the elements as shown below. Add some packets of silica gel to absorb moisture.



As you can see, even if water enters the enclosure it would not affect the electronics. (This picture is of another enclosure version of our system.)

For a more professional setup, our suggestion is to use stand-off pins: https://www.adafruit.com/product/3658



4.2 Preparing the mast and base

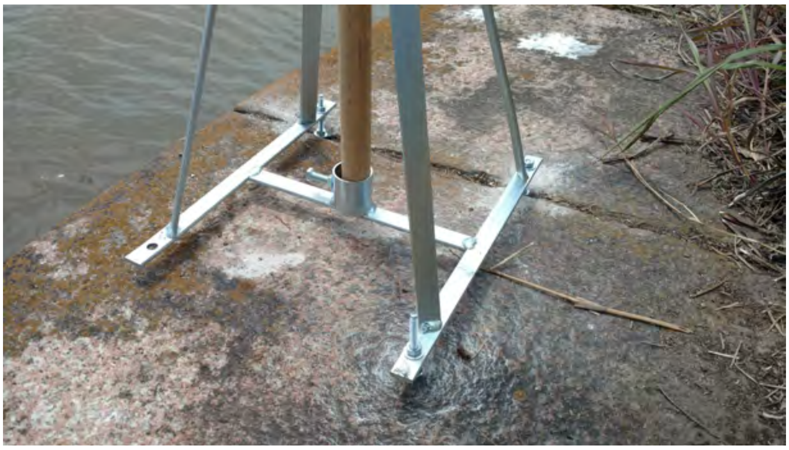
Fix the antenna on the top of a mast. Make sure to have some slack on the antenna cable -- coaxial cables should not have sharp bends!

Setup the base:

Use anchor bolts to the ground for stability.

The base anchor bolts are reinforced by inserting sealant into the hole, such as this:

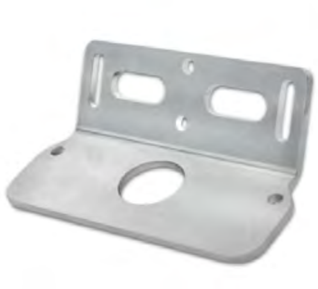
Use extra pairs of nuts to level the base.



4.3 Solar panel support

You have two options of a solar panel support: buy one or make your own.

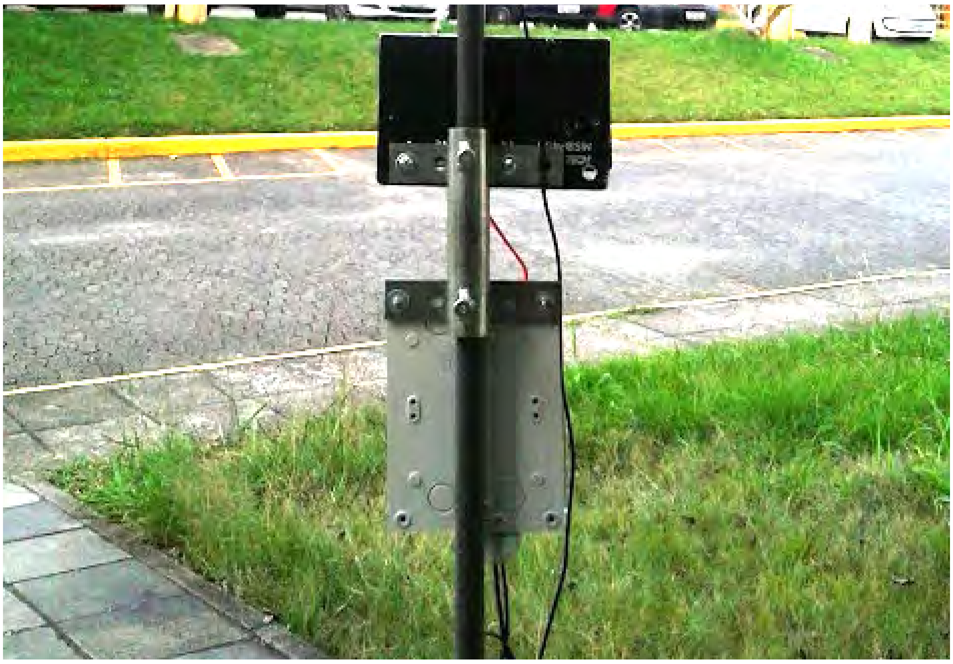
This is a model that you can buy at https://www.voltaicsystems.com/small-bracket



Alternatively you can simply bend a metal sheet and drill holes as shown below:

4.4 Fixing the enclosure on the mast

To fix the enclosure on the mast you can use a support for TV antenna, which you can find in hardware stores. The support has holes in which you can insert bolts and nuts to hold the components.



4.5 Adjusting the solar panel orientation

The sun incidence varies according to your position on Earth. You need to check the best orientation of the solar panel.

Adjusting tilt (vertical angle):
Check this link to ensure the correct angle https://www.solarpaneltilt.com/

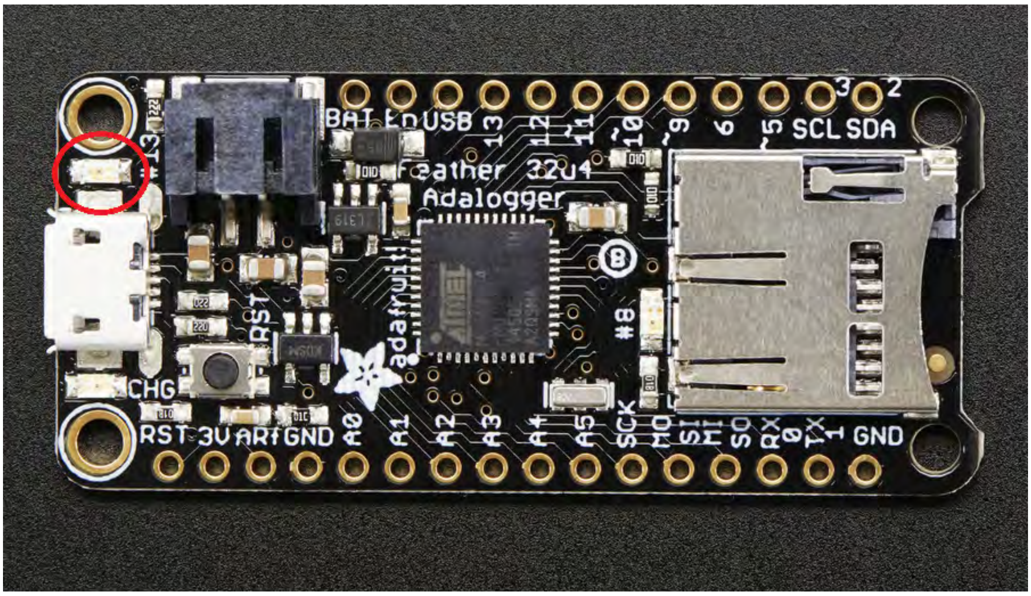
Adjusting azimuth (horizontal angle):
Face the equator, opposite from the nearest geographical pole (for example, face north in the southern hemisphere).

You're all done -- congratulations! :-)

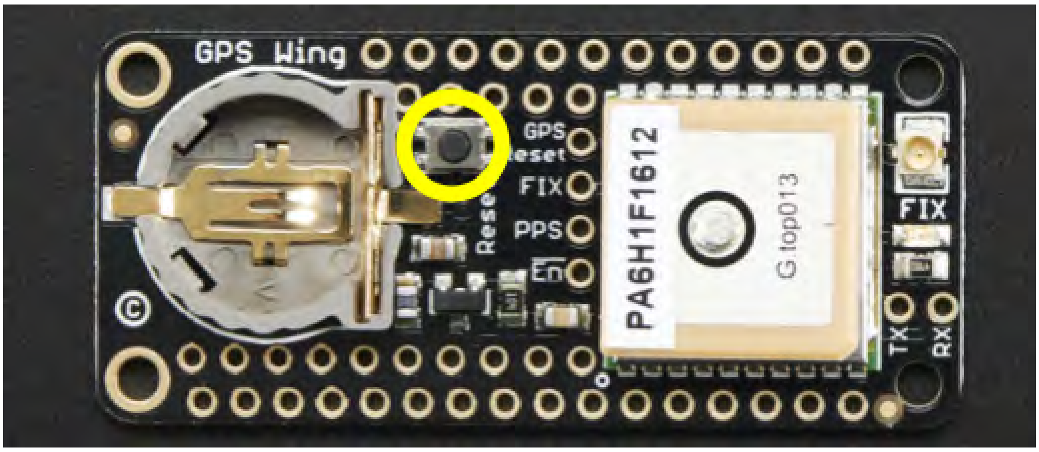
5. Checks

5.1 Activity LEDs

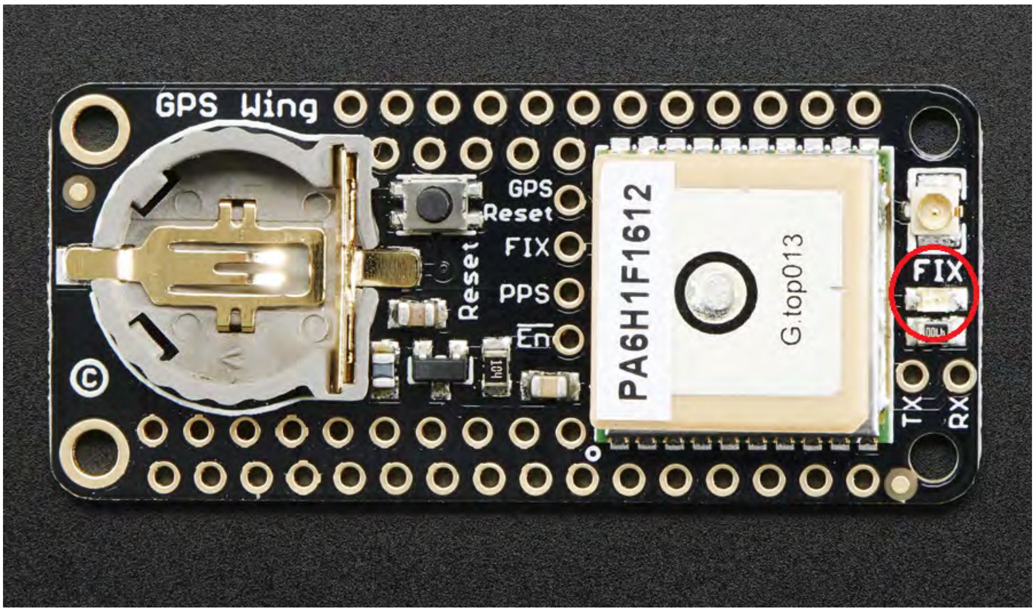
There is a red LED on the Arduino feather, close to the USB port. It will blink every time data is written to the SD card (normally once per second):



Sometimes it is necessary to use the reset button if power has been interrupted:



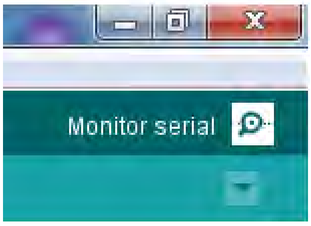
There is another red LED in the GPS shield, near the antenna plug. It will blink once per second while searching for satellites. When it has found at least four satellites, it will stop blinking. If that LED does not stop blinking after about one minute, you will need to put the antenna in a better place for improved visibility to the satellites (near a window, for example). Make sure the antenna cables are connected correctly.



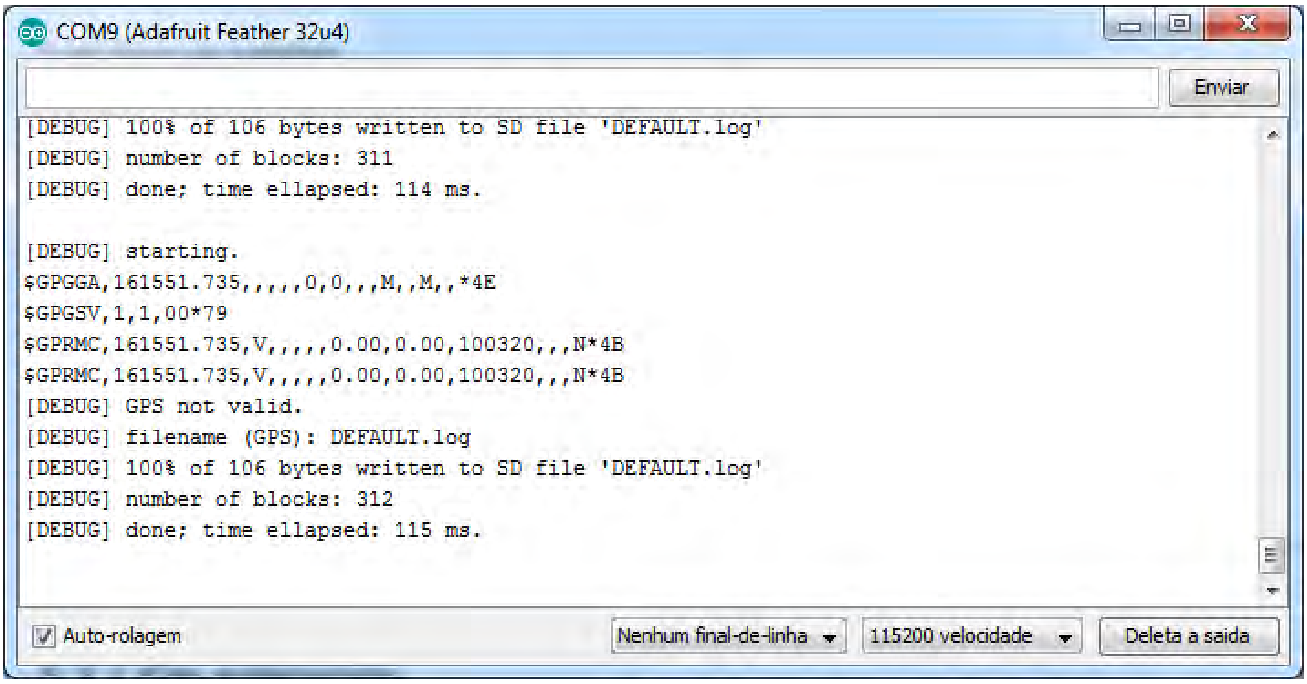
5.2 PC Serial

If you plug the Arduino to the PC via USB, you can use the Arduino IDE’s Serial Monitor to inspect debug message output.

Just plug in the Arduino to the PC, reset the Arduino, and then open the Serial Monitor by clicking in the top-right corner:



It will display the following window:



```
[DEBUG] 100% of 106 bytes written to SD file 'DEFAULT.log'
[DEBUG] number of blocks: 311
[DEBUG] done; time ellapsed: 114 ms.

[DEBUG] starting.
$GPGGA,161551.735,,,,,0,0,,,M,,M,,*4E
$GPGSV,1,1,00*79
$GPRMC,161551.735,V,,,,,0.00,0.00,100320,,,N*4B
$GPRMC,161551.735,V,,,,,0.00,0.00,100320,,,N*4B
[DEBUG] GPS not valid.
[DEBUG] filename (GPS): DEFAULT.log
[DEBUG] 100% of 106 bytes written to SD file 'DEFAULT.log'
[DEBUG] number of blocks: 312
[DEBUG] done; time ellapsed: 115 ms.
```

5.3 Outdoors testing

Before deployment in the intended location, which might be difficult to access, we recommend running a test outdoors in a more convenient location for a few days, such as a backyard or rooftop.

Also please go over the following site guidelines:

> Geremia-Nievinski, F.; Hobiger, T. (2019) "Site guidelines for multi-purpose GNSS reflectometry stations", Zenodo. https://doi.org/10.5281/zenodo.3660744

5.4 Data files

Please power off the system before removing the SD card!

To eject the SD card, push lightly to release, only then it can be pulled out normally.

Finally, plug the SD card to a reader in the PC to copy the files.

The data files compress greatly (10/1 ratio).

5.4.1 File extensions

There will be two types of data files, with extensions BAT and LOG.

LOG files

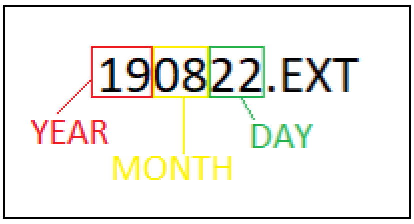
Contains the NMEA sentences. This is the main data output by the system.

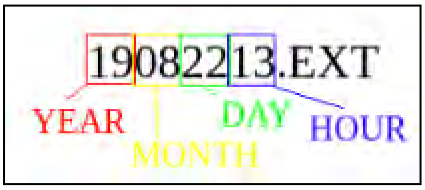
BAT files

Contains the battery voltage measurement. It can be used to monitor the battery state.

5.4.2 File names

As said in section 1.6, the user has two options to organize the data files: by day or by hour. Accordingly, the file names will follow this template:





The system will automatically create a new file for each day or hour (according to the user choice) while the system is running.

5.4.3 File contents

The file contents are ASCII text, for example:

190909.BAT:

```
190909000015 3.98
190909000116 3.99
190909000217 3.98
190909000318 3.99
190909000418 3.99
190909000519 3.99
190909000619 3.99
190909000720 3.98
190909000821 3.99
190909000921 3.98
190909001022 3.99
```

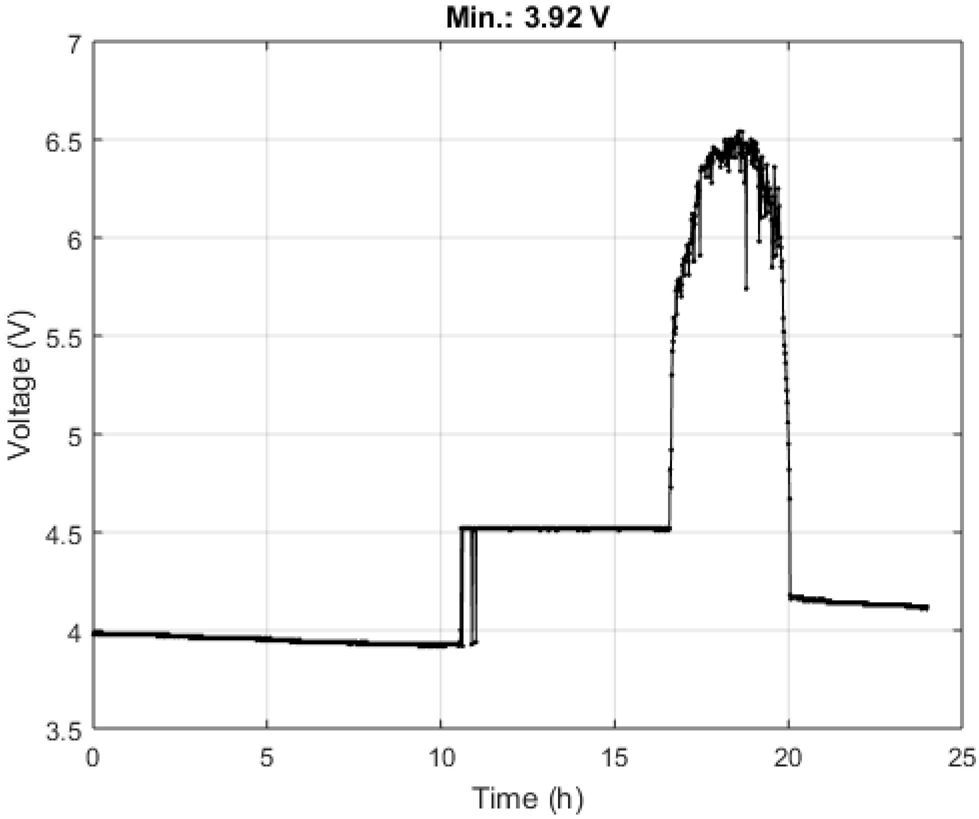
190110.LOG:

```
$GPGGA,000000.000,3001.2761,S,05113.2831,W,1,10,0.92,4.8,M,4.5,M,,*5A
```

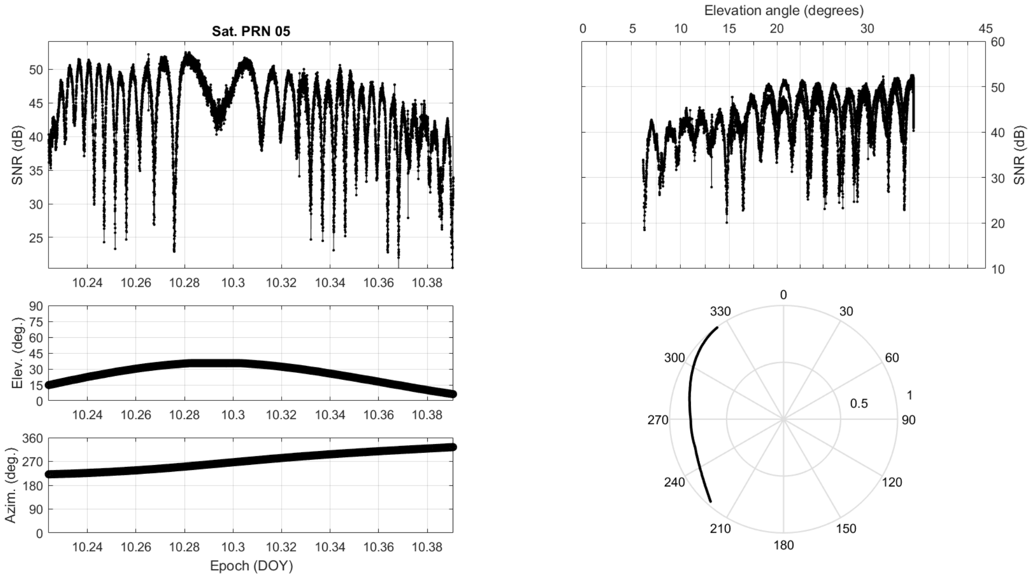
```
$GPGSV,3,1,12,18,81,354,48.0,01,64,224,49.4,11,61,286,47.1,22,53,210,45.5*70
$GPGSV,3,2,12,31,46,082,46.5,14,37,140,45.5,03,36,231,38.1,32,19,135,43.1*72
$GPGSV,3,3,12,08,18,336,42.9,17,07,222,49.5,27,03,359,43.7,10,02,088,*6D
$GPRMC,000000.000,A,3001.2761,S,05113.2831,W,0.00,350.26,100119,,,A*65

$GPGGA,000001.000,3001.2761,S,05113.2831,W,1,10,0.92,4.8,M,4.5,M,,*5B
$GPGSV,3,1,12,18,81,354,48.1,01,64,224,49.6,11,61,286,46.1,22,53,210,47.4*71
$GPGSV,3,2,12,31,46,082,46.4,14,37,140,45.3,03,36,231,36.9,32,19,135,42.6*75
$GPGSV,3,3,12,08,18,336,43.7,17,07,222,49.4,27,03,359,43.4,10,02,088,*60
$GPRMC,000001.000,A,3001.2761,S,05113.2831,W,0.01,350.26,100119,,,A*65
```

They can be loaded and plotted in Matlab:

https://github.com/fgnievinski/mphw/tree/master/code/matlab/battery



https://github.com/fgnievinski/mphw/tree/master/code/matlab/demo



Sat. PRN 05
SNR (dB)
50
45
40
35
30
25
10.24
10.26
10.28
10.3
10.32
10.34
10.36
10.38
Elev. (deg.)
90
75
60
45
30
15
0
Azim. (deg.)
360
270
180
90
0
Epoch (DOY)
Elevation angle (degrees)
0
5
10
15
20
30
45
60
50
40
30
20
10
SNR (dB)
0
30
60
1
0.5
90
120
150
180
210
240
270
300
330

A. Energy supply system

The circuit selected is designed for 3.3-volt input and has a built-in voltage regulator. The average current consumption was measured to be 82.4 mA for 1 Hz data logging rate. The product of voltage and current resulted in power consumption of 271.9 mW or 6.5 Wh per day. The battery duration was specified as 36 h, for autonomy during days with no sunshine. Multiplying that duration by the current consumption results in 2966.4 mAh or ~3 Ah battery capacity. Considering the options commercially available, we chose a 4400 mAh battery. We selected a 6-watt solar panel, which outputs 930 mA (well below the battery maximum charging rate), because it would recharge the battery in 4.7 h; this time fits in the assumed daily insolation period (average 5 hours of sun per day, depending on season and latitude).

We tested the energy supply system as designed above on the laboratory roof for two weeks, during which the sensor operated uninterruptedly. Finally, the system was deployed for field operation and the circuit voltage was recorded every minute for almost one year, as shown in Figure A1. During sunny days, the voltage reached up to 6.5 V (reduced internally to 3.3 V by the regulator); in that case, the charger feeds the output of the panel directly to the circuit load, while recharging the batteries in parallel. After sunset, voltage starts typically at 4.2 V (for a fully charged battery) and slowly decreases as the energy is depleted. The batteries continue to feed the load after sunrise, while the panel output voltage remains below 4.5 V, which is the minimum operating voltage for the particular recharger used. The time gap between successive battery readings (not shown) normally is 1 min, except for six periods of interruptions, lasting for several minutes. We have confirmed they corresponded to site visits during which we performed maintenance on the sensor.

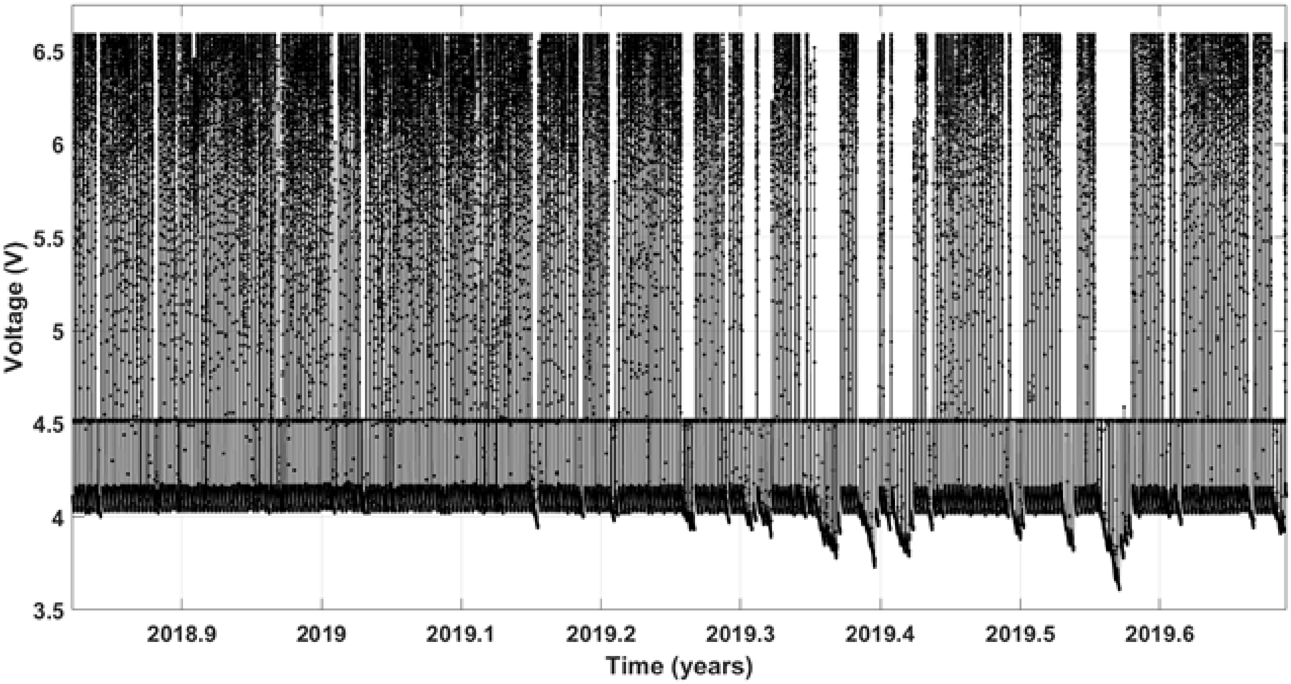


Fig. A1 Voltage versus time.