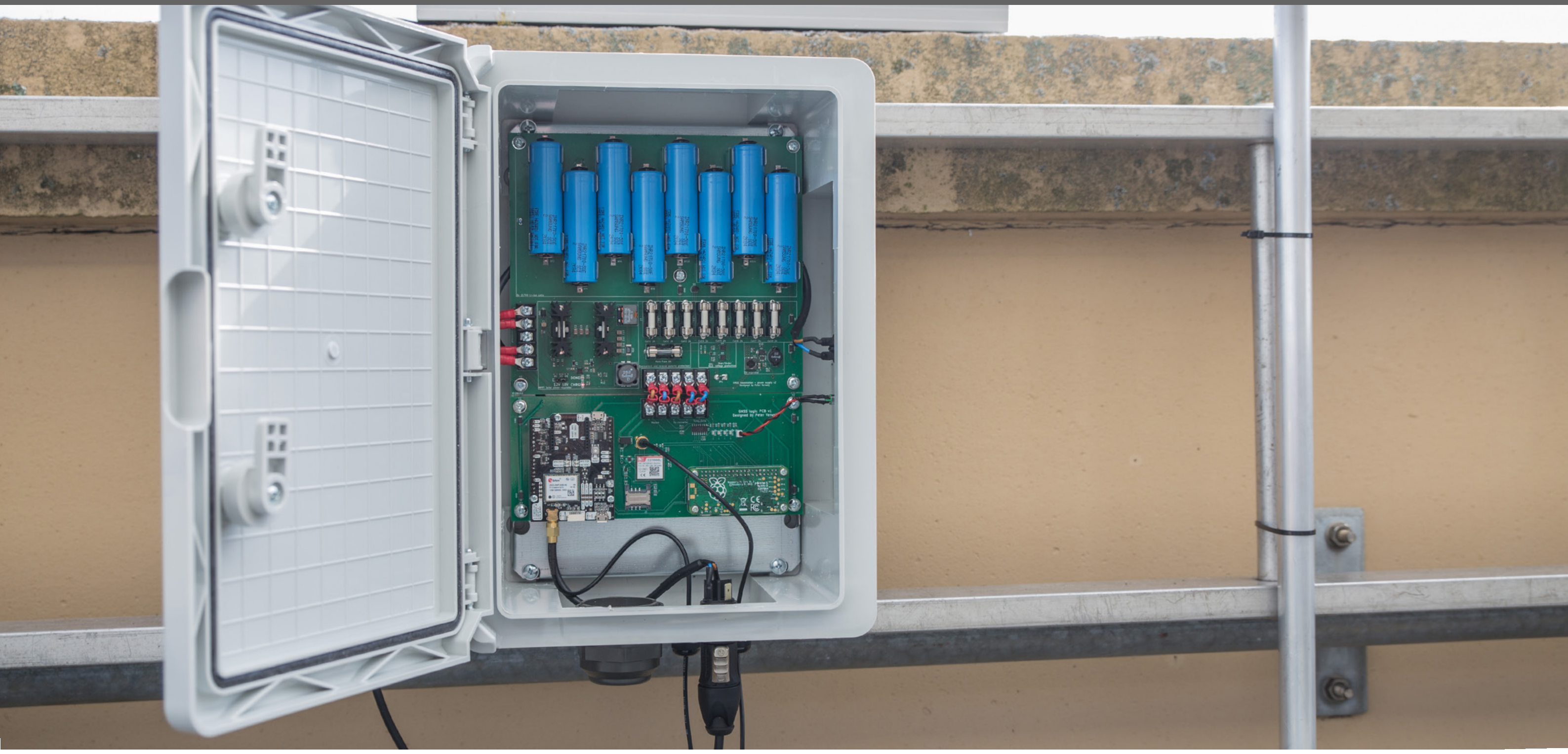
Lowcost GNSS reference station

Design choices and assembly instruction

Peter Verweij - 1 May 2021 - Version 2

Contents



Contents

The work leading to these results has received funding from the European Community's Horizon 2020 Programme (2014-2020) under grant agreement n° 776691. The opinions expressed in the document are of the authors only and no way reflect the European Commission's opinions. The European Union is not liable for any use that may be made of the information.

TWIGA

GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
MPPT	Maximum power point tracking
PCB	Printed Circuit Board
RF	Radio Frequency
SIM	Subscriber Identity Module
SMA	SubMiniature version A (Coaxial RF connector)

1. Introduction

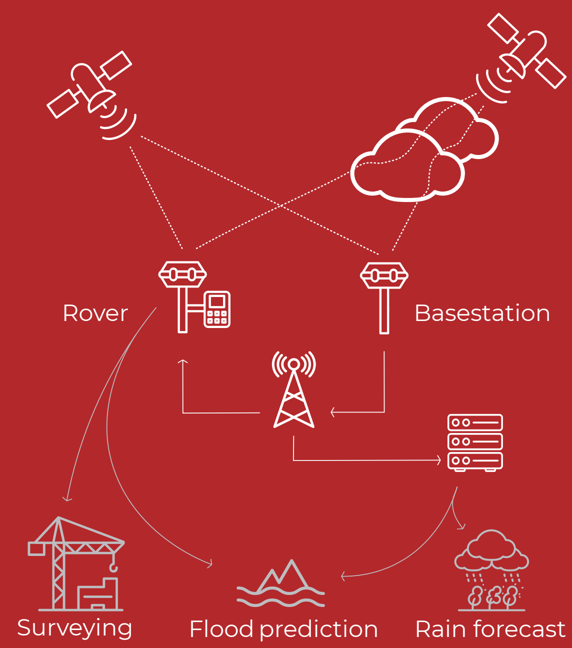
Peter Verweij has designed a BASE and ROVER device for low cost precise positioning during his graduation for the master Integrated Product Design of the faculty Industrial design. In the Months after his graduation, a follow up project was carried out to refine the BASE design.

1.1. Target

The target of this project is to build a lowcost GNSS reference station.

The proposed system for centimeter accuracy positioning (figure 1.2) is a differential GPS system. It uses dual frequency receivers which can largely eliminate the ionospheric error by comparing the travel speed of two waves with a different wavelength through the ionosphere. A reference (base) station is used to correct for other positioning errors, such as the troposphere. This base station is situated at a known location. By measuring its own known location, the base station can define the current present error.

The positioning data is uploaded to a server. From that location the data can be used for surveying and research purposes.
Research towards better rain forecast models, together with affordable survey equipment can improve the ability to predict flooding.



1.2. System and use case overview

1.2. Previous design

The previous GNSS reference station was portable and could easily be transported. However the 3D printing and separate PCB's made the device hard to reproduce. Also the watertightness of the 3D printed parts was questionable.

A similar design should be made which overcomes these issues. Most base stations will be used stationary. Portability is still usefull but not the main target of this project anymore.

1.1. BASE2 design

2. Design choices

In this chapter the system structure and design choices are noted down.

2.1. Basic system description

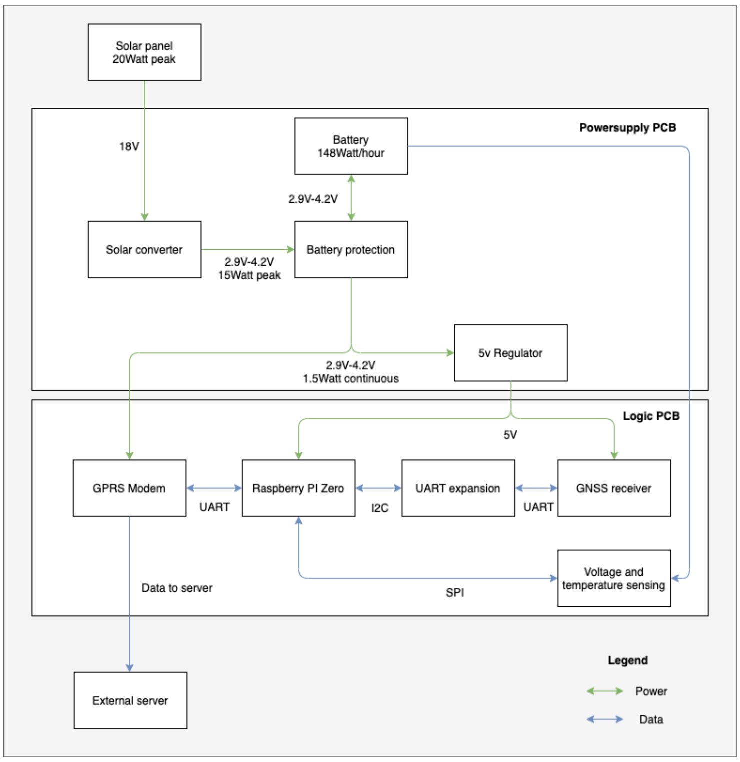
The newly designed GNSS reference-station consists of an antenna, solarpanel and electronics in a standard water tight electronics case. (figure 2.1) In this case, all power electronics are mounted on one PCB. Logic modules can be plugged in to headers on this PCB. The complete system costs less than 600 euro when build in small quantities.

The GNSS reference station may be mounted to the side of a building, a roof or in a separate setup in the field. There is no strictly prescribed method of mounting the system.

2.1. GNSS referencestation

2.2. PCB structure and technical information

The PCB consists out of a power section and a logic section (figure 2.2). The full schematic can be found in the PCB folder on Github. Each functional section in shortly described in this paragraph.



2.2. System structure of the GNSS reference station.

Battery
The battery capacity has been calculated using the off-grid PVgis tool (JRC Photovoltaic Geographical Information System (PVGIS) - European Commission, 2016).
When using a 20Watt solar panel the 148Wh battery should never run out of power in Kumasi, Ghana. However, one should realize that the same system will not be able to run continuously in the winter months in the Netherlands.
Eight 21700 lithium cells are used. It is advised to use the Samsung 50E cell because of their optimization for a high capacity at a low discharge rate.

Solar converter
The solar converter was designed based on the bq24650 chip from Texas Instruments. The MPPT voltage can be fixed to 18.2V or 12V using the jumper on the board. The charge current is limited to 5A and the temperature range in which the charger will be active is -3°C up to 55°C.

Battery Protection
The battery protection is based on the BQ29700 chip from Texas instruments. This chip operates two transistors. One which can cut-off charging (at 4.275V) and one which can cut-off discharging (at 2.8v). The chip will also cut-off the power at a current flow of more than 7A.

Beside the protection chip, also fuses are installed which protect each separate cell for over current. These fuses will also blow when a cell is connected in reverse.

It has to be noted that the BQ29700 chip will only enable the battery after the charger (solar panel in this case) has been connected and has charged the battery for a second.

Raspberry PI Zero
The Raspberry PI Zero receives data from the GNSS receiver and sends it to the webserver using the GPRS modem. There is an image available for the Raspberry PI SD-card in which the hardware is pre-configured. For configuring the mountpoint on the server etc. I refer to the software manual of Andreas Krietemeyer.

UART expansion
The UART expansion is a SC16IS752IPW chip from NXP. The chip communicates to the raspberry over the I2C protocol.

It has to be noted that the I2C baudrate of the raspberry has to be set to 400Kbits/S instead of the standard 100Kbits/S to properly receive the GNSS receivers signal at 115200baud.

In the Github software manuals folder, the configuration manual for the UART expansion can be found

Voltage and temperature sensing
Voltages can be read with the analog to digital converter MCP3008 chip.
1. Two leads are connected to the current shunt resistor of the solar converter. This can be used to read the charging current.
2. One lead is connected to the positive pole of the battery (only reliable when charger is off)
3. One lead is connected to the LM35 temperature sensor.

In the Github software manuals folder, the configuration manual for the voltage and temperature sensing can be found

GNSS receiver
The GNSS receiver is an simpleRTK2B Ardusimple receiver. The right configuration has to be done with Ublox Ucenter software. The configuration file for the receiver can be found in the software manuals folder.

GPRS Modem
The modem is directly powered from the battery. This is the most efficient while the modem needs high current up to 2A in bursts. The downside of this choice is that the modem will shut down when the battery voltage drops below about 3,4v (dependent on the modem) However, the used batteries have not a lot of capacity left below 3,4V.

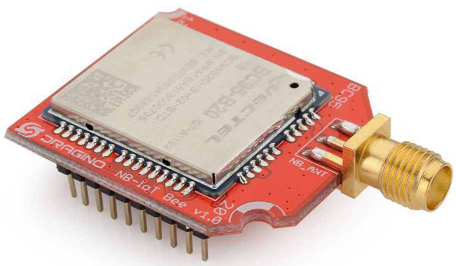
In the Github software manuals folder, the configuration manual for the GPRS modem can be found.

The PCB is designed so that a GPRS module can be installed. At this point of time the GPRS modules are by far the cheapest radio chips (€2,-), and the GPRS network is wide spread world wide. However in the Netherlands radio frequencies are valuable, therefore GPRS will be phased out in the future. Network provider KPN will maintain the network atleast until 2025.

To be able to use this device in the future, also an XBEE socket is available. Each XBEE module which can cope with voltages between 3,3V-4,2V is suitable. LTE-M XBEE modules are already available. For example: Digi XBee 3 Cellular LTE-M/NB-IoT - figure 2.3 (€86) or Dragino NB-IoT Bee - figure 2.4 (€33)

Although the XBee socket is properly prepared (Powersupply available, UART connection and reset pin is connected to raspberry PI). It has to be noted that the XBEE socket and the modules have not been tested. One should do some testing to be sure that everything works correctly.

2.3. *Digi XBee 3 Cellular LTE-M/NB-IoT*



2.4. *Dragino NB-IoT Bee*

3. List of tools needed

Before one can start assembling the GNSS reference-station we need to collect the right tools.

Wrenches/Spanners

Spanner 5.5
Spanner 7
Spanner 13
Spanner 18

Wrench cap 4.5
Wrench cap 5.5
Wrench cap 7

Allen key 2.5
Allen key 3
Allen key 6

Small wrench

Screwdrivers

Torx screw driver T8

Philips head screw driver

Other

File

hammer

center punch

Drills

drill machine

50mm hole saw
24mm hole saw

20mm drill bit
15mm drill bit
8mm drill bit
5mm metal drill bit
3mm drill bit

Electrical wiring tools

Crimping tool

Stripping pliers

Solder iron

Heatgun

Multimeter

4. Main unit assembly

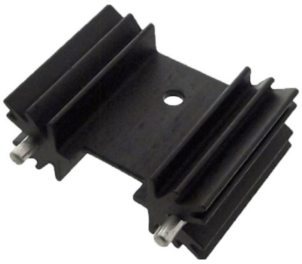
This chapter describes all steps to assemble the main unit of the reference station. A component list with shop links can be found in the documentation folder on Github.

4.1. (Optional) Solder heatsinks

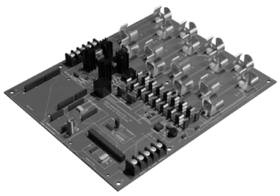
Tools to use

Solder iron

Materials needed

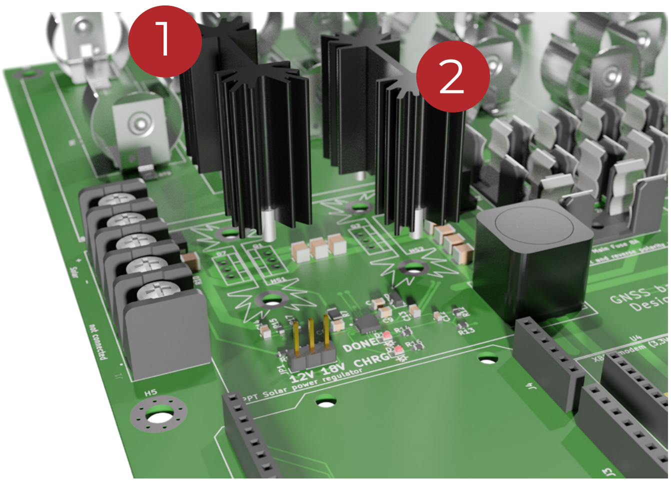


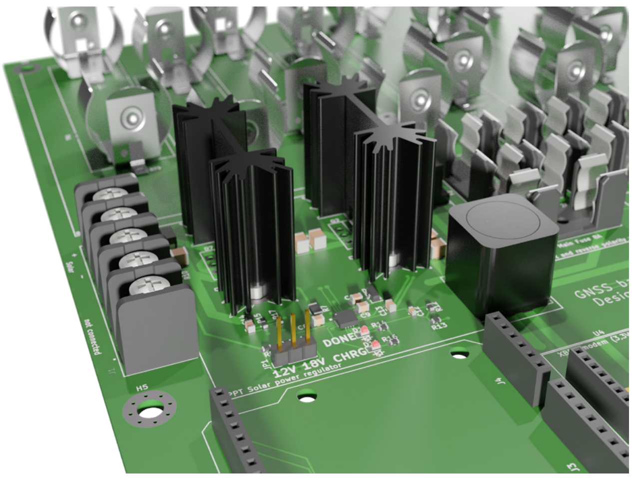
2x 513002B02500G



PCB

Task





This step is marked as optional - Heatsinks could be ordered pre-mounted. However, the chance is big that the transistors and diode will not be properly aligned with the heatsink during this process. Therefore it is advised to install them yourself.

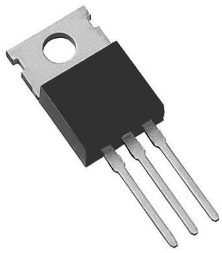
Solder the heatsinks flat tot the board at their designated positions HS1 and HS2. The solder should be applied from the bottom side of the board.

4.2. (Optional) Solder solar regulator components

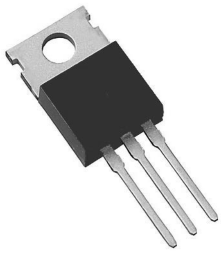
Tools to use

Solder iron

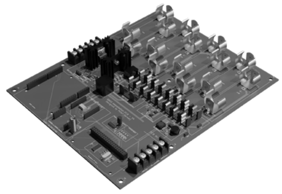
Materials needed



2x CSD18537NKCS
(Transistor)

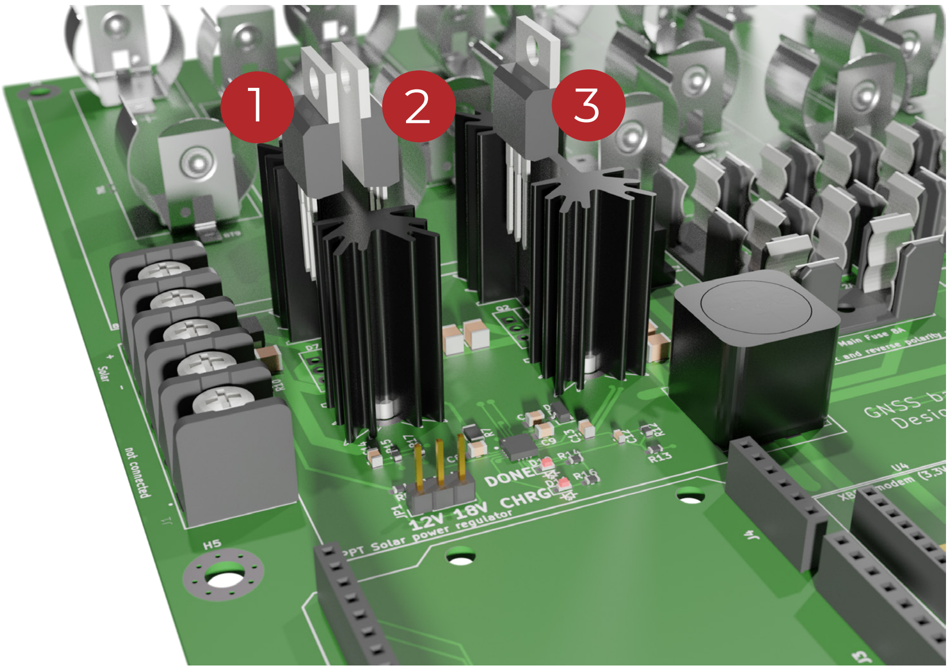


1x SBR10U40CT
(Diode)



PCB

Task



This step is marked as optional - Heatsinks could be ordered pre mounted. However, the chance is big that the transistors and diode will not be properly aligned with the heatsink during this process. Therefore it is advised to install them yourself.

Align the diode (1) and transistors (2&3) to their heatsinks. Then solder the legs from the bottom side of the board to the designated positions. The SBR10U40CT diode to footprint D12 and the CSD18537NKCS transistors to footprint Q1 and Q2.

Tip: The bolts of next step “4.3. Heatsink bolts” can potentially be used to align the diode and transistors

4.3. Heatsink bolts

Tools to use

Wrench cap 5.5

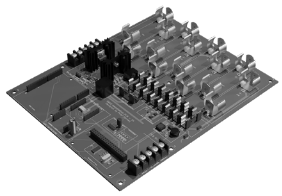
Small wrench

Allen key 2.5

Materials needed

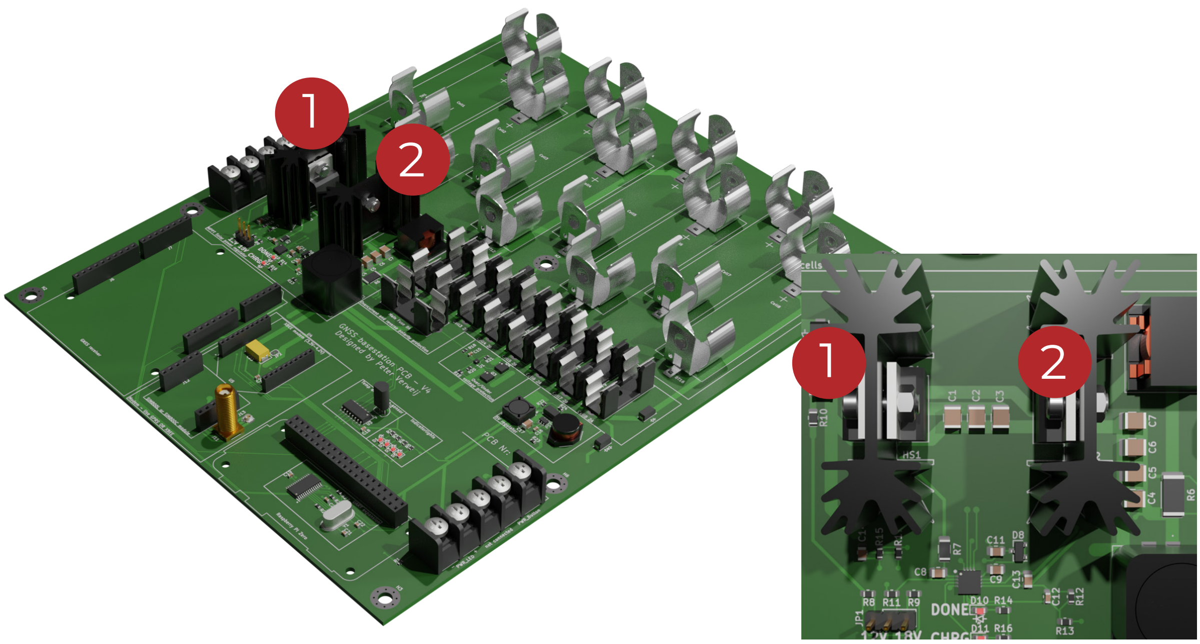
2x - m3x12

2x m3 nut



PCB

Task



The TO220 transistors should be attached to the heatsinks with an m3 bolt.
On heatsink1 both the TO220 transistor and TO220 diode are attached to both sides of the heatsink. On heatsink 2 only the transistor is attached by the bolt.

4.4. PCB spacers

Tools to use

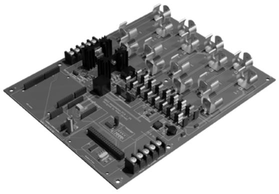
Wrench cap 4.5

Wrench

Materials needed

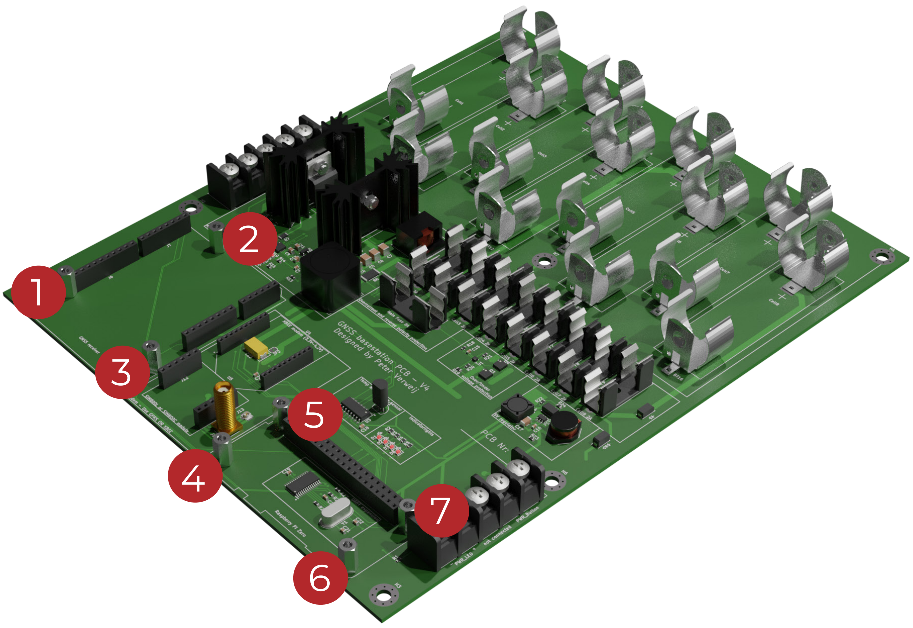
7x m2.5 standoff

7x m2.5 nut



PCB

Task



The seven m2.5 standoffs should be mounted to the PCB, the nuts on the backside should be tightened fairly so that the spacers will not turn when a screw is inserted later on.

4.5. Drill holes in backplate

Tools to use

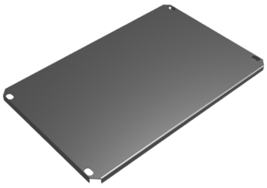

5mm metal drill bit

drill machine

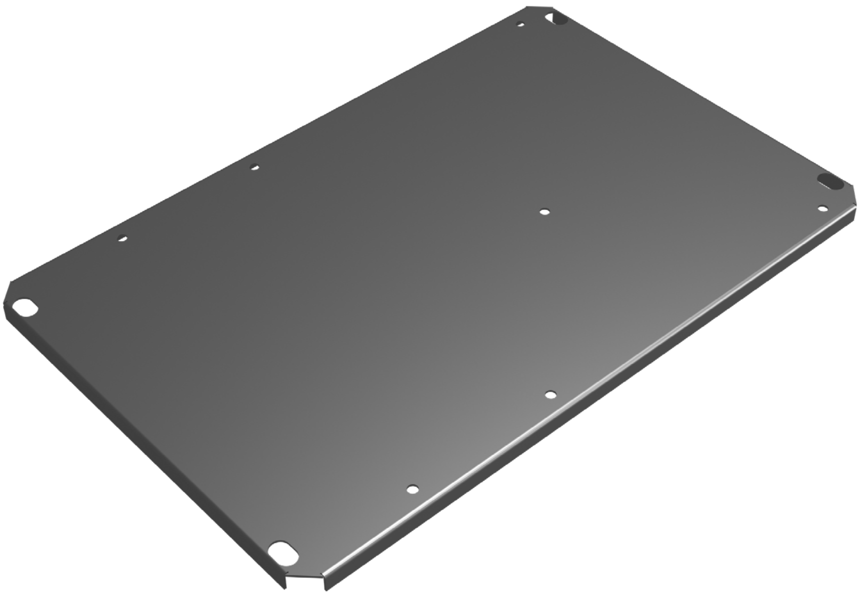

center punch


hammer

Materials needed


Backplate (included with case)

Task



7 holes of 5mm diameter should be drilled in the backplate. The exact pattern can be found in Appendix... The holes are 1mm wider than the m4 spacers which will be placed in the holes. The larger holes are useful while the construction is over-constrained.

Tip: When the PCB is in the good position on the backplate, a marker can be used to mark the correct spots on the backplate.
Using a center point to slam a dent will make drilling in the right position easier.

4.6. Attach spacers to backplate

Tools to use

Wrench cap 7

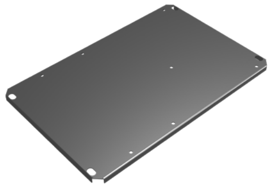
Wrench

Spanner 7

Materials needed

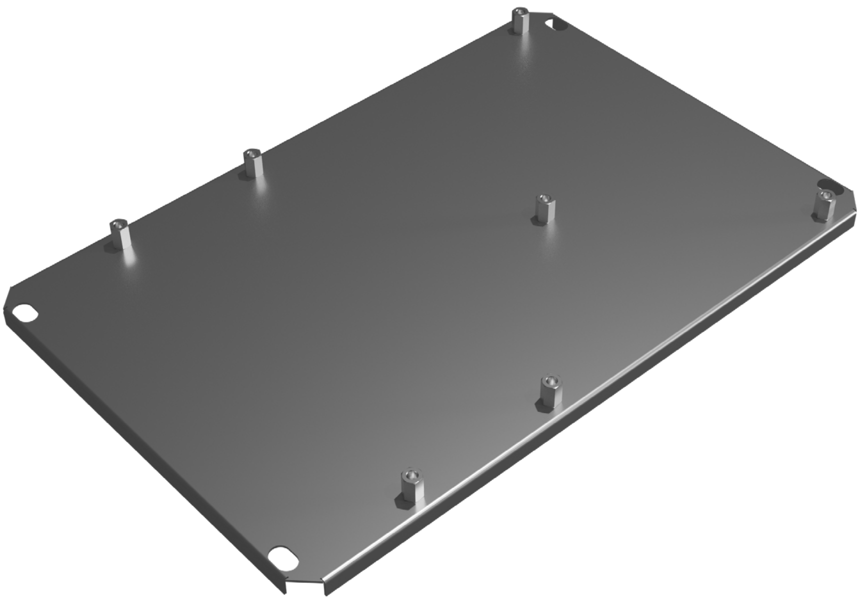
7x m4 standoff

7x m4 nut



Backplate

Task



Attach the 7 m4 standoffs to the backplate

Tip: Use the PCB for the positioning of the spacers before tightening the nuts.

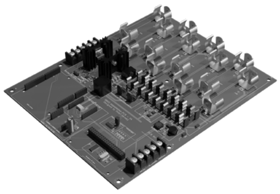
4.7. Mount board onto backplate

Tools to use

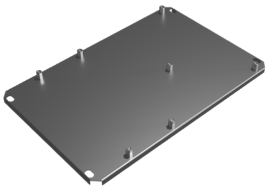
Philips head screw driver

Materials needed

7x m4 Pan head

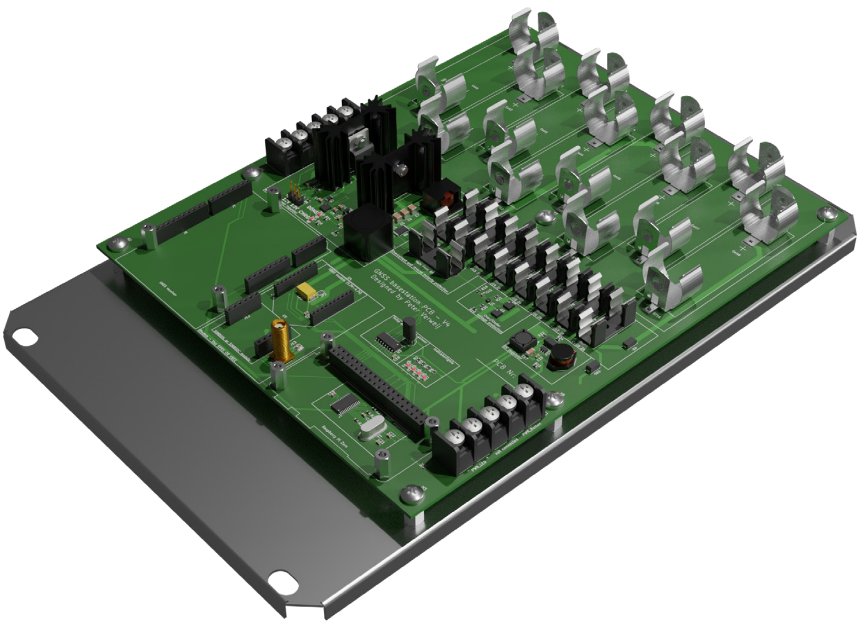


PCB



Backplate

Task



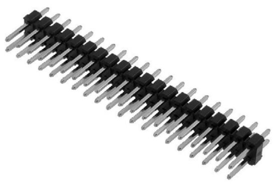
Screw in the 7 pan head screws to attach the PCB to the backplate.

4.8. Solder header to Raspberry PI

Tools to use

Solder iron

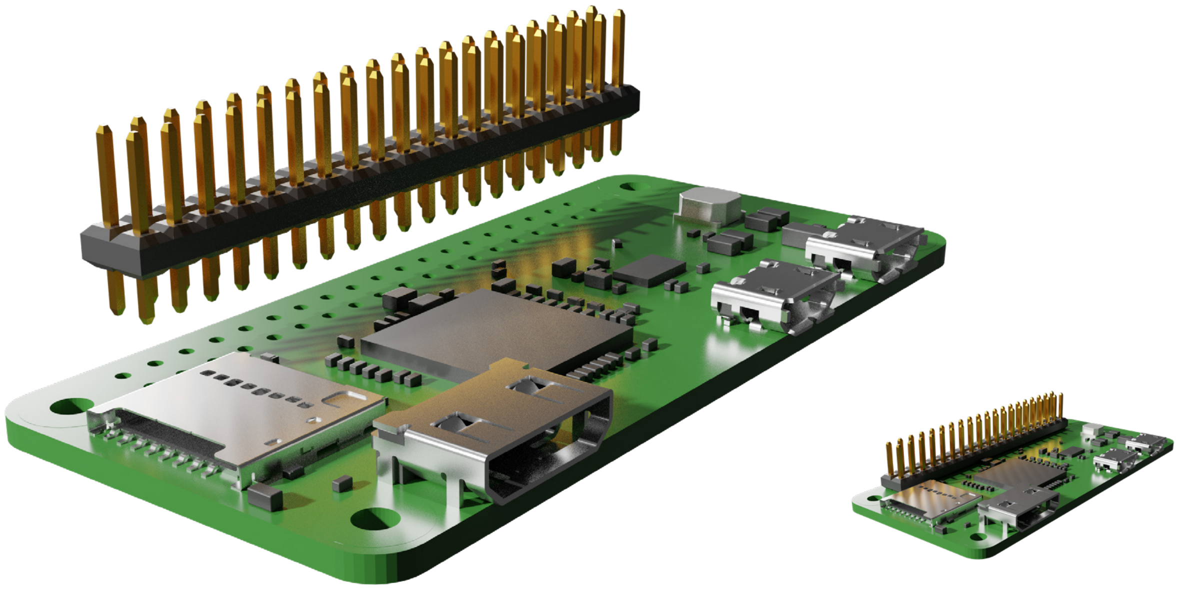
Materials needed



2x20 pinheader

Raspberry PI Zero

Task



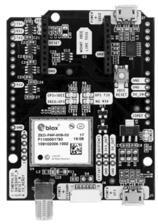
Solder a strip of 2x20 header pins to the upper side of the Raspberry PI Zero.

4.9. Solder headers to GNSS receiver

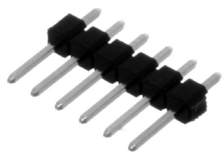
Tools to use

Solder iron

Materials needed

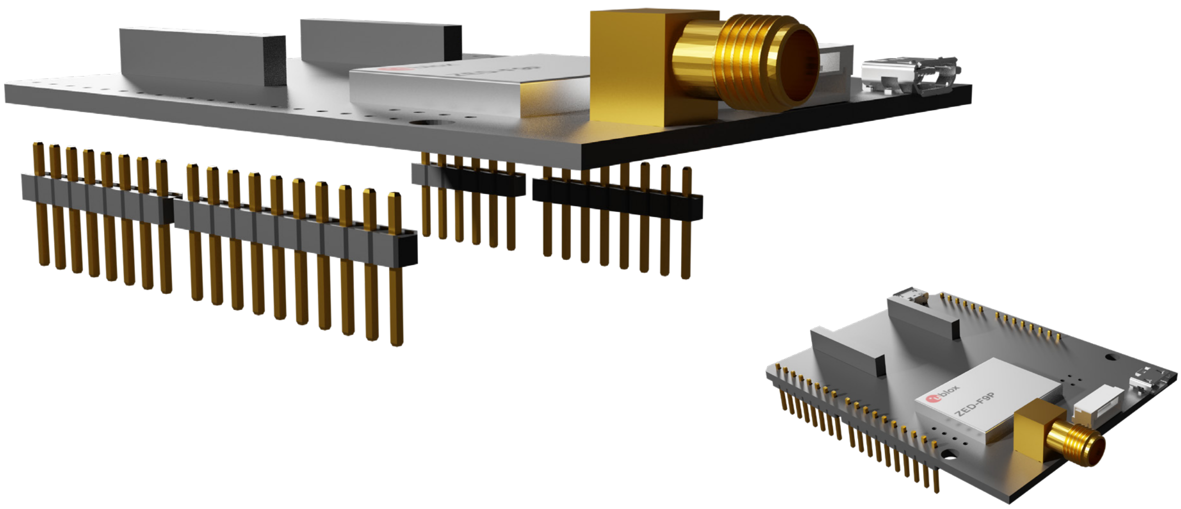


GNSS receiver



headerpins

Task



Cut two strips of 8 header pins, one of 6 pins and one of 10 pins. Solder these headerpins to the lowerside of the GNSS receiver.

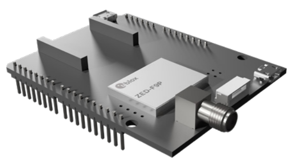
4.10. Attach GNSS receiver and Raspberry PI

Tools to use

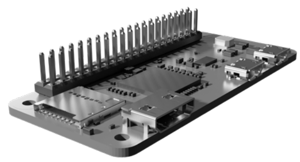
Philips head screw driver

Materials needed

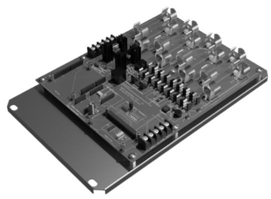
7x m2.5 Pan head



GNSS receiver

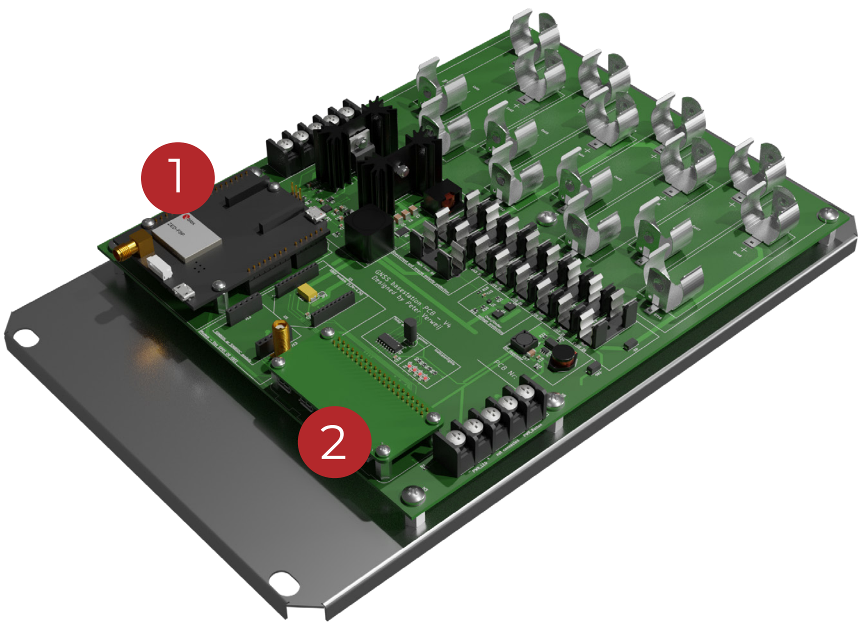


Raspberry PI zero



Assembled backplate

Task



Attach the GNSS receiver rigth side up (1) and raspberry PI upside down (2) to their headers. Thereafter they can be fixed with the 7 m2.7 pan head screws.

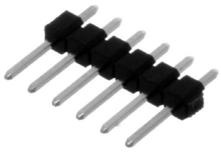
4.11. Solder headers to GNSS receiver

Tools to use

Solder iron

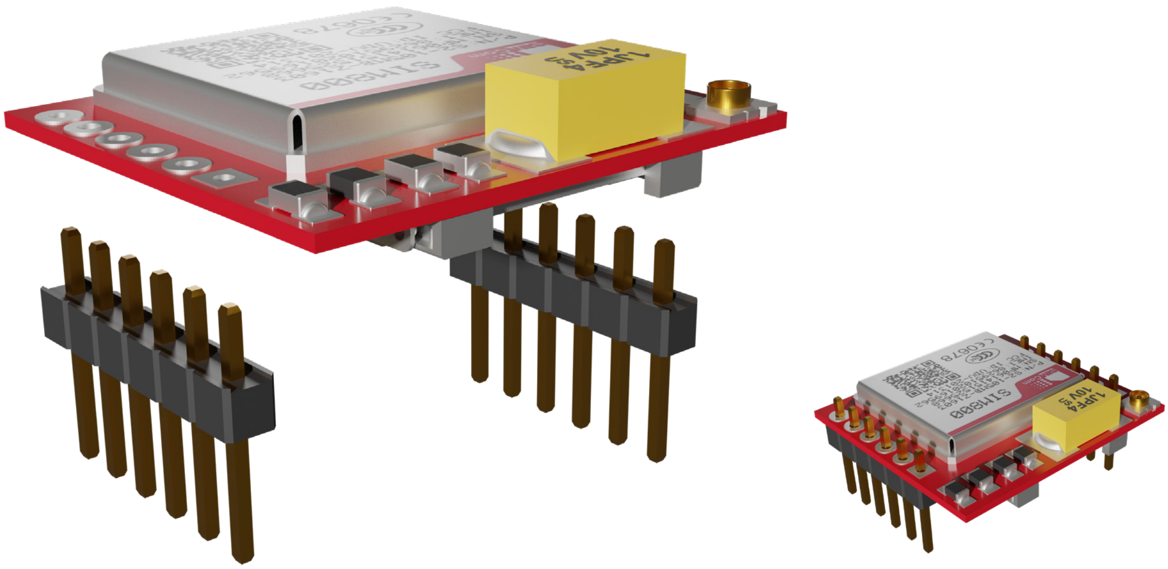
Materials needed

SIM800L module



headerpins

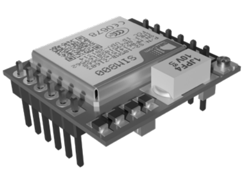
Task



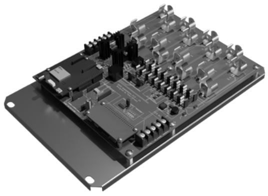
With the GPRS modem two strips of pinheaders are included (6pins). Solder these headerpins to the lowerside of the GPRS modem.

4.12. Attach the GPRS OR Xbee module

Materials needed



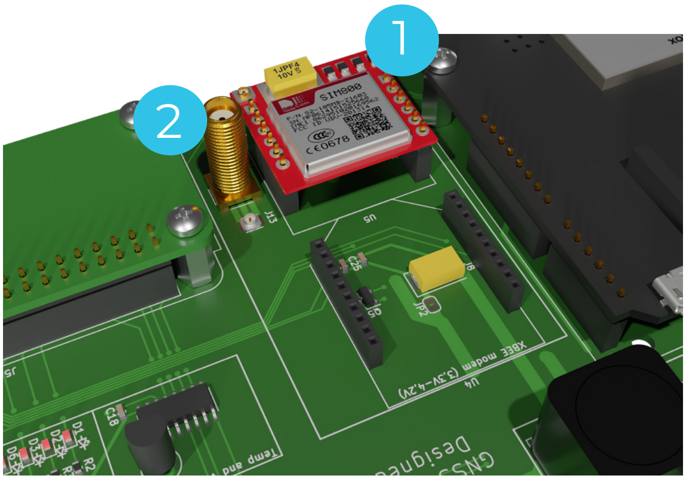
SIM800L module



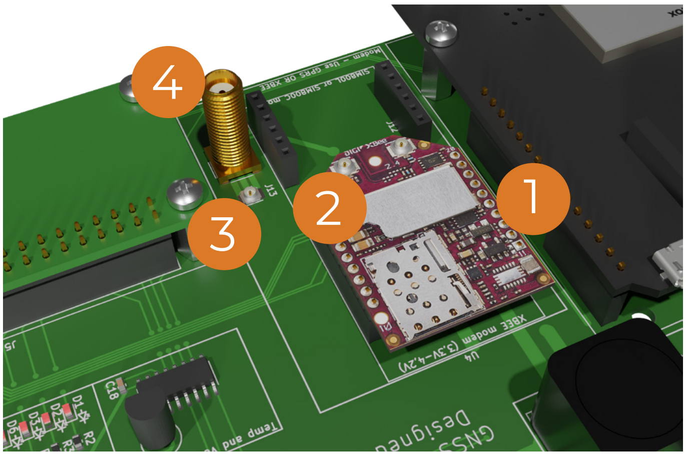
Assembled backplate

Task

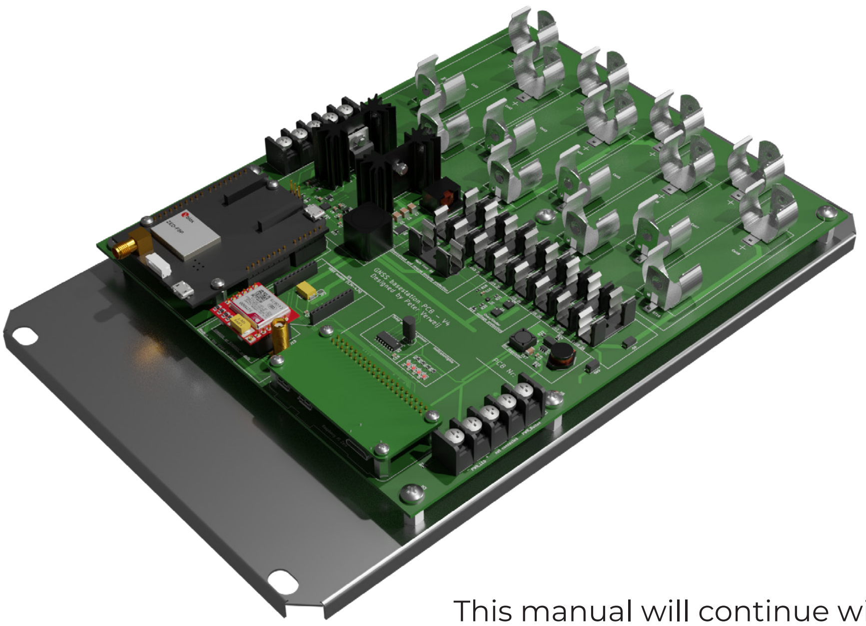
Attach a GPRS modem module OR a Xbee module for data communication.



GPRS modem
Attach the GPRS modem to its headers (1). The antenna is already wired to the SMA bulkhead internally. A SMA GPRS antenna can be connected to the bulkhead (2).



Xbee module (3,3v-4,2v)
Attach the Xbee module to its headers (1). If the Xbee module has a UFL connector (2) the antenna can be linked to the UFL connector on the main PCB (3) with a small UFL to UFL cable. Finally an SMA antenna can be connected to the bulkhead on the PCB (4).



This manual will continue with the GPRS module option.

4.13. Drill holes in bottom of box

Tools to use

Drill machine

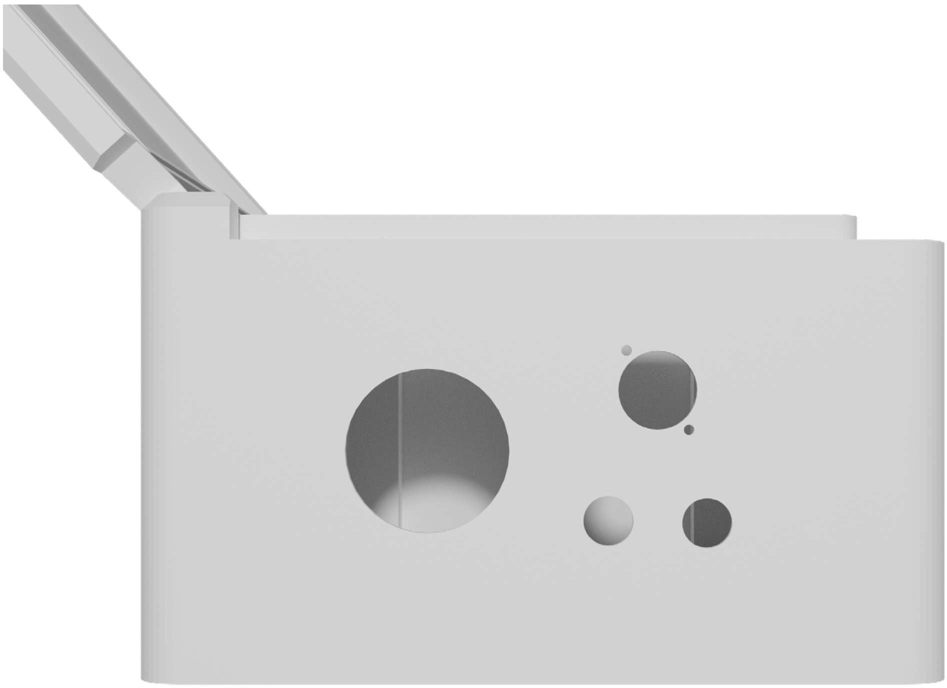
50mm hole saw
24mm hole saw

15mm drill bit
3mm drill bit

Materials needed

Case

Task



Drill the 6 holes in the bottom side of the box. The larger hole can be made with a hole saw. The exact hole pattern can be found in Appendix...

Tip: When using a hole saw try it first in a test piece. The hole saw tends to make a hole with a too big diameter.
Tip: having the holes in a sligthly different position does not harm the functioning of the device.

4.14. Drill holes in side of box

Tools to use

Drill machine

20mm drill bit
8mm drill bit

File

Materials needed

Case

Task

Drill the 8mm hole for the power led and the ...mm hole for the power button. The power button needs an extra slot on the side, which can be made with a file. If the click fingers of the power button do not slide in to the hole two slots can be filed for this purpose as well.
The exact hole pattern can be found in Appendix...

Tip: having the holes in a sligthly different position does not harm the functioning of the device.

4.15. Assemble solar power cable

Tools to use

Crimping tool

Stripping pliers

Solder iron

Heatgun

Materials needed

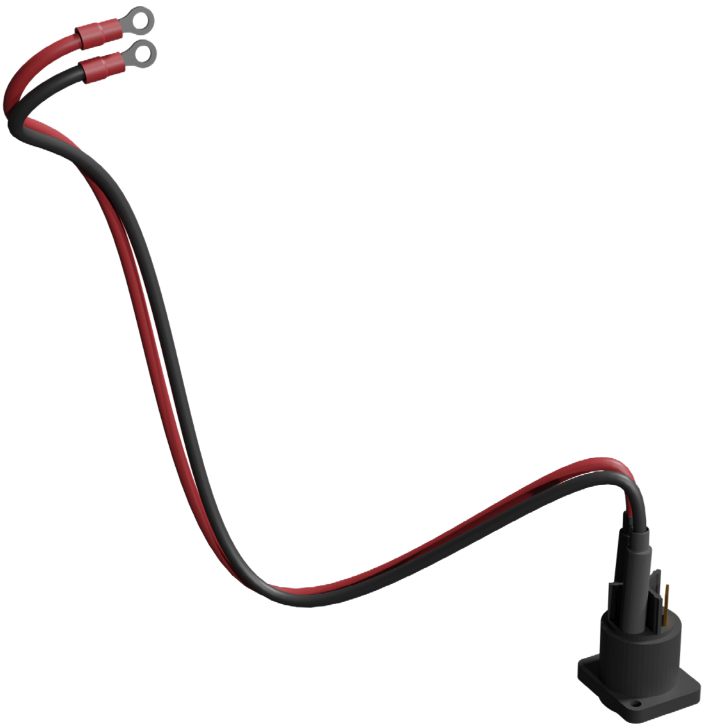
m4 cable lug

Wire 18AWG

Shrink tube

1x NAC3MPX-TOP

Task



Solder the red wire to L terminal and the black wire to the N terminal of the Neutric socket. Cover the terminals with shrink tube. The shrinking can be accomplished with a heatgun. Finally the two m4 cable lugs should be crimped to the other side of the wire with the crimping tool.

4.16. Assemble neutric socket

Tools to use


Philips head screw driver


Spanner 5.5

Materials needed


Assembled solar cable

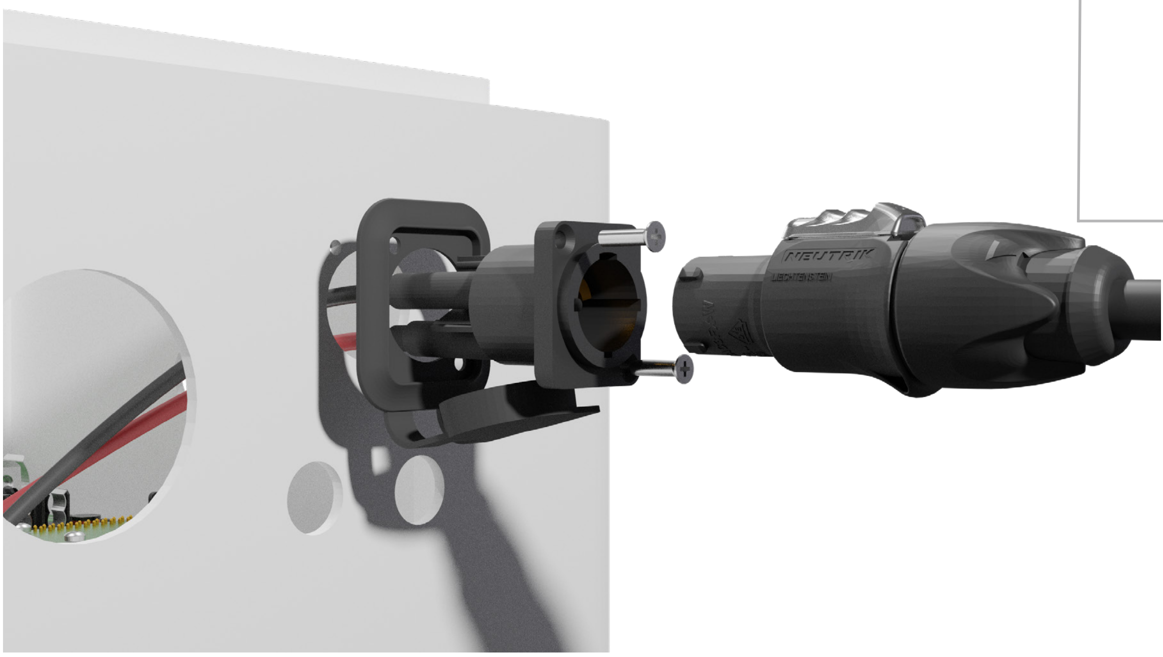

1X SCNAC-MPX


2x m3 countersunk philips head screw


2x m3 nut


Case

Task



Attach the neutric connector to the housing using 2 m3 countersunk philips head screws and nuts.
The male connector does not have to plugged in yet and is only in the image for illustrative purposes.

4.17. Insert cable glands and water drain

Tools to use

Spanner 18

Materials needed

2x PG9 cable gland

DD 084 Stego drain

Case with solar cable

Task

Screw the two cable glands in the lower side of the case. Tighten them with spanner 18. The large Stego drain can be tightened by hand easily.

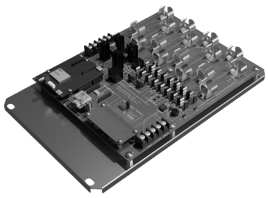
4.18. Insert assembled backplate in case

Tools to use

Philips head screw driver

Materials needed

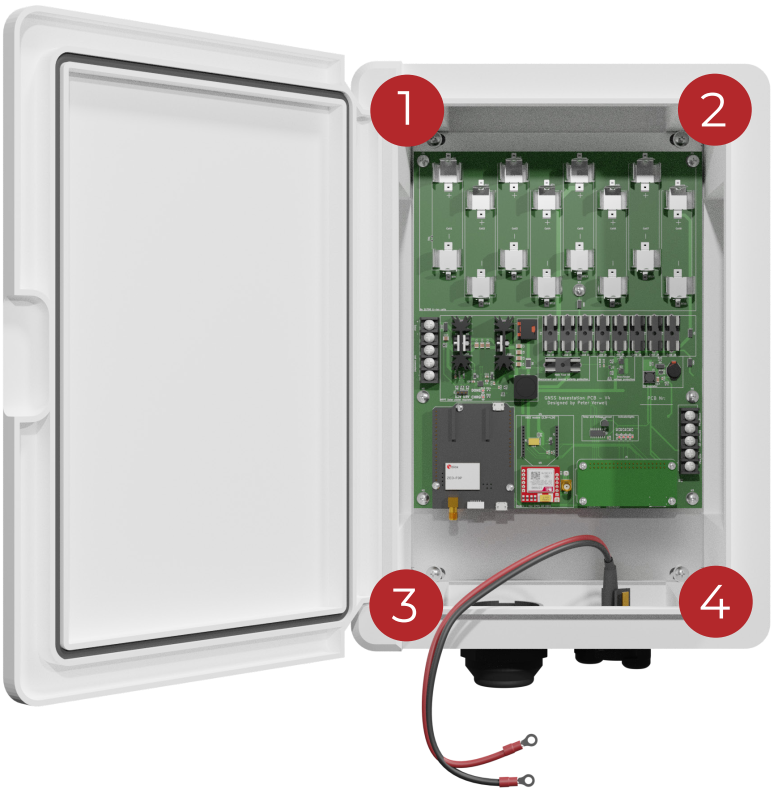
4x Self tapping screw (included with case)



Assembled backplate

Case with lower side assembled

Task



Screw the backplate with assembled PCB to the backside of the case using the 4 self tapping screws which were included with the case.

4.19. Attach solar power cable

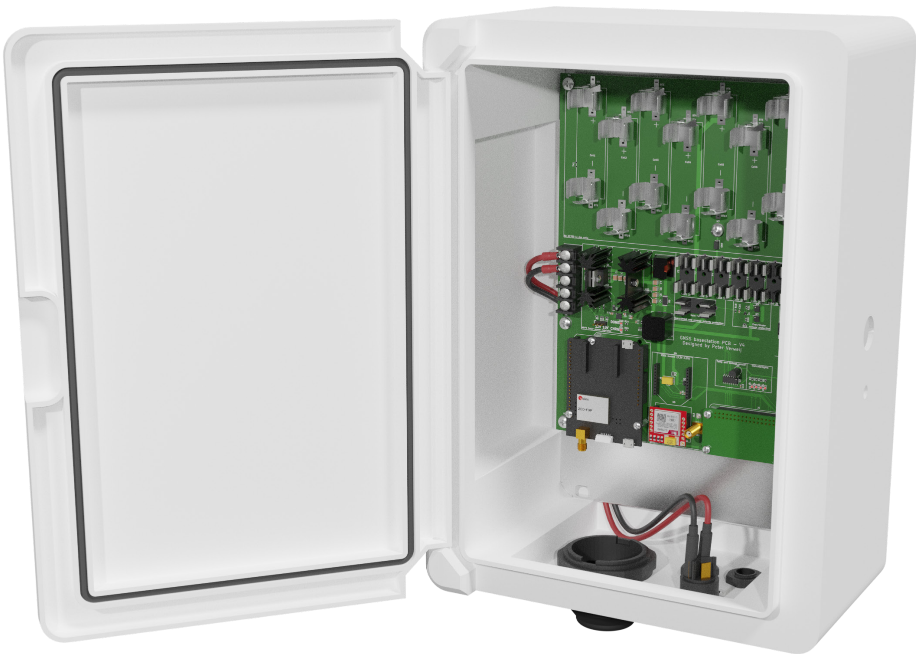
Tools to use

Philips head screw driver

Materials needed

Case with PCB

Task



Attach the solar power cable to the solar power terminals on the PCB. The red wire should be connected to the + terminal and the black wire should be connected to the - terminal

The solar power cable can be routed behind the PCB, as is done in the image above, when extra holes are drilled in step 4.3.

4.20. Assemble powerbutton

Tools to use

Crimping tool

Stripping pliers

Solder iron

Heatgun

Materials needed

m4 cable lug

Wire 18AWG

Shrink tube

Task

Solder two black wires to the terminals of the on/off button. Cover the terminals with shrink tube. The shrinking can be accomplished with a heatgun. Finally the two m4 cable lugs should be crimped to the other side of the wire with the crimping tool.

4.21. Assemble power LED

Tools to use


Crimping tool


Stripping pliers


Solder iron

Heatgun

Materials needed


m4 cable lug


Wire 18AWG


Shrink tube

Task

Solder a red wire to the gold terminal of the LED and a black wire to the silver terminal of the LED. Cover both terminals with shrink tube. The shrinking can be accomplished with a heatgun. Finally the two m4 cable lugs should be crimped to the other side of the wire with the crimping tool.

Warning: The cable lugs migth not fit through the LED nut or through the hole in the case. Therefore it migth be needed to crimp the lugs on after placing the LED in the case.

4.22. Insert powerbutton and power LED in case

Tools to use

Spanner 13

Philips head screw driver

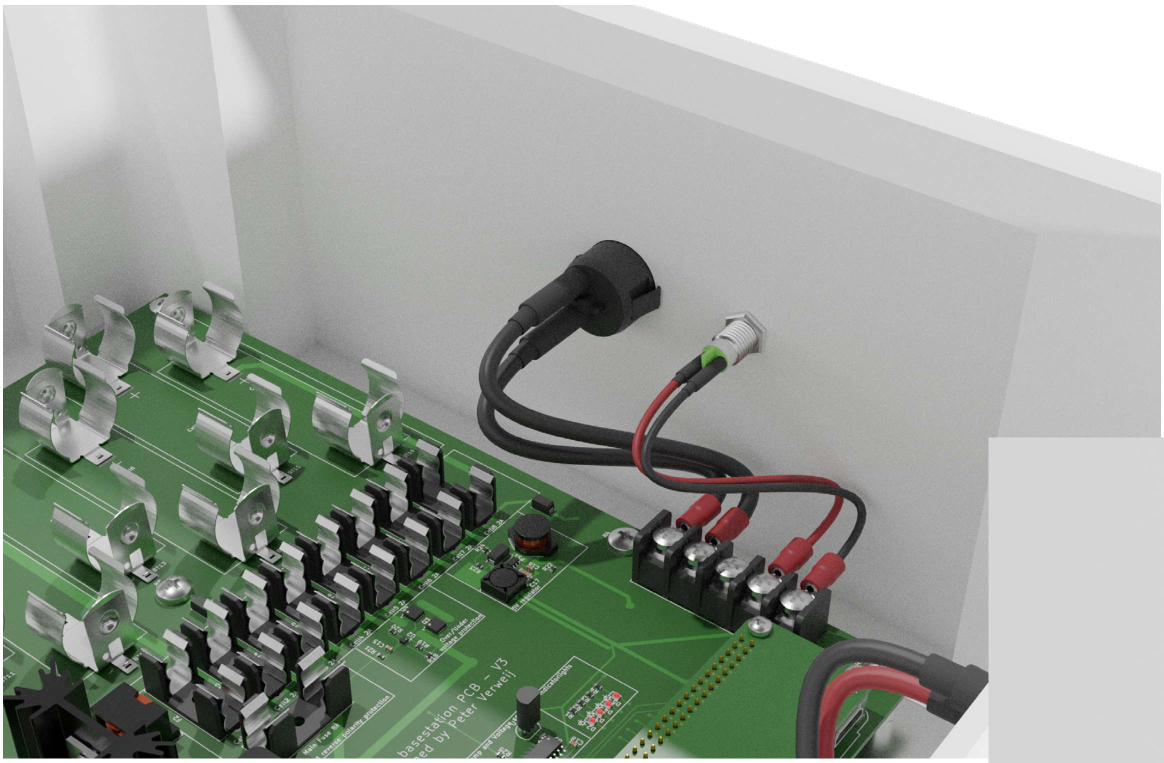
Materials needed

Assembled LED

Assembled PWR button

Case with PCB

Task

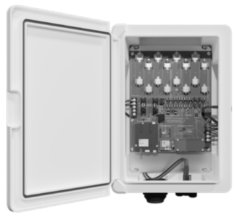


Mount the power LED and power button in the case. When the powerbutton does not click in place properly revisit step 4.10.

Attach the powerbutton cable to the powerbutton terminals (there is no wrong order). When attaching the cables of the power LED, make sure to connect the red wire to the + terminal and the black wire to the - terminal.

4.23. Insert jumper

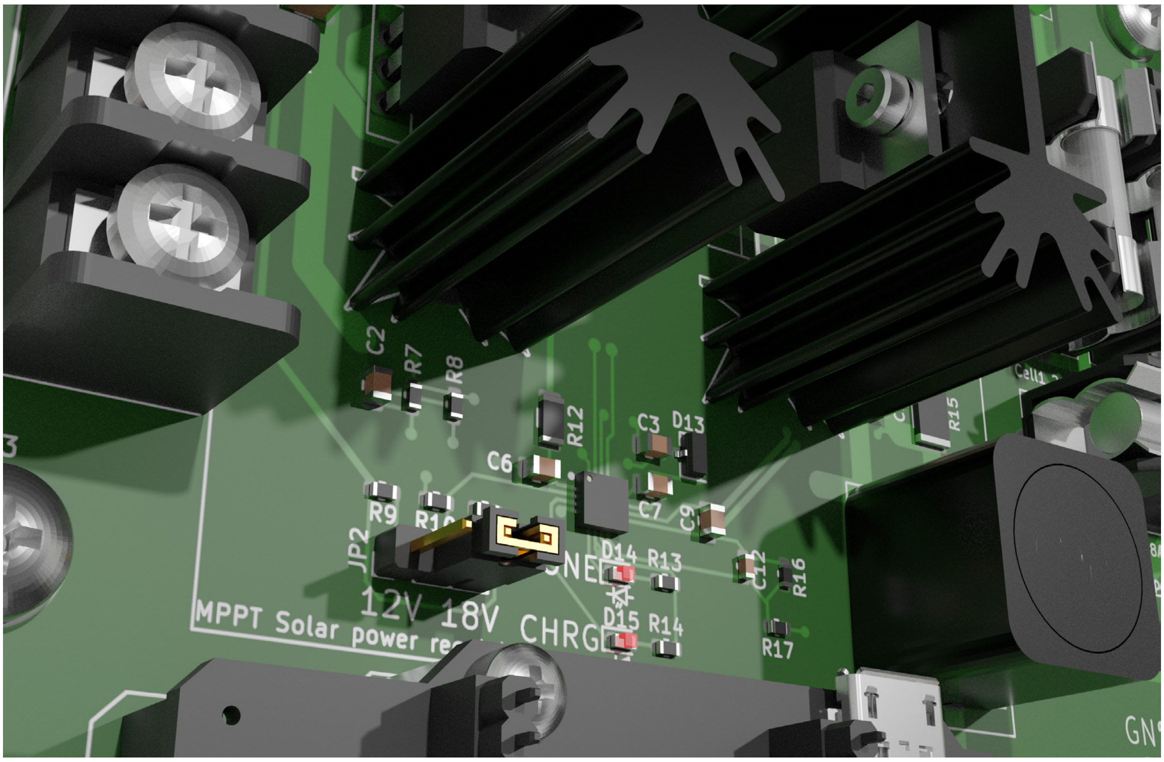
Materials needed



Case

2.54mm Jumper

Task



Put a 2.54mm jumper to the header pins at the side of which MPPT (Maximum Power Point Tracking) voltage will be used. In the image above 18v has been chosen.

18V Is suitable for the Victron solar panel used in this manual.

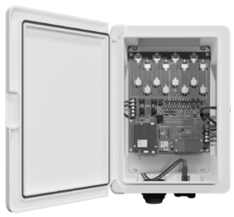
12V can be used for a fixed DC 12V powersupply. In this case inserted batteries will act as an Uninterruptible Power Supply (UPS). It has to be noted that this feature has not been tested.

4.24.Insert fuses

Tools to use

Multimeter

Materials needed

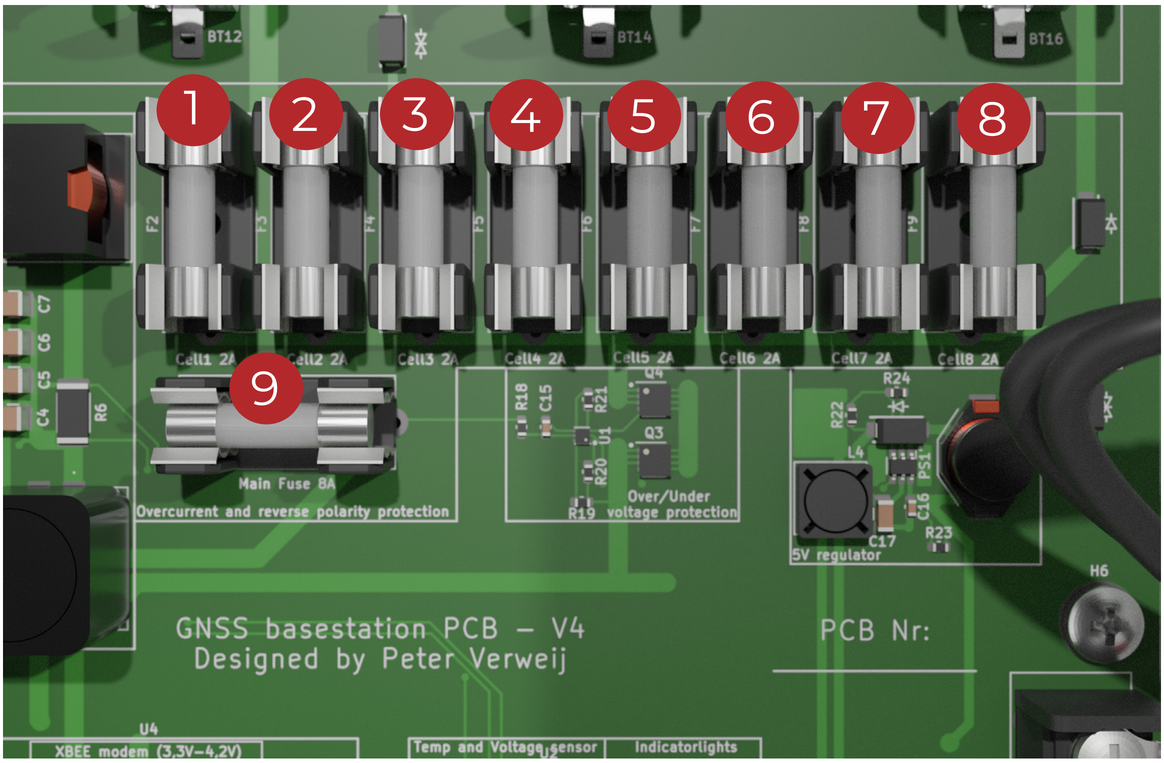


Case

1x Fuse 8A

8x Fuse 2A

Task



Check the integrity of your fuses by using a multimeter to measure if they conduct any electricity. Place a 2A fuse for each cell which will be in the device (1-8). Finally place a 8A main fuse (9).

5. Solar panel assembly

5.1. Attach cable to solar panel

Tools to use

Crimping tool

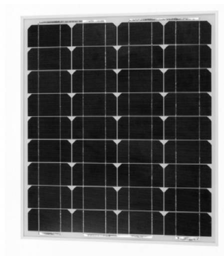
Stripping pliers

Philips head screw driver

Materials needed

2x m4 cable lug

Cable 2 wires 17AWG



20watt solarpanel

Put the cable in the junction box at the back of the solar panel. Crimp two cable lugs to this cable and attach the red wire to the positive terminal (1) and black cable to the negative terminal (2). This can be done with a philips head screwdriver. Finally, clamp the cable down with the bracket (3).

5.2. Attach male Neutrik connector to solarcable

Tools to use

Stripping pliers

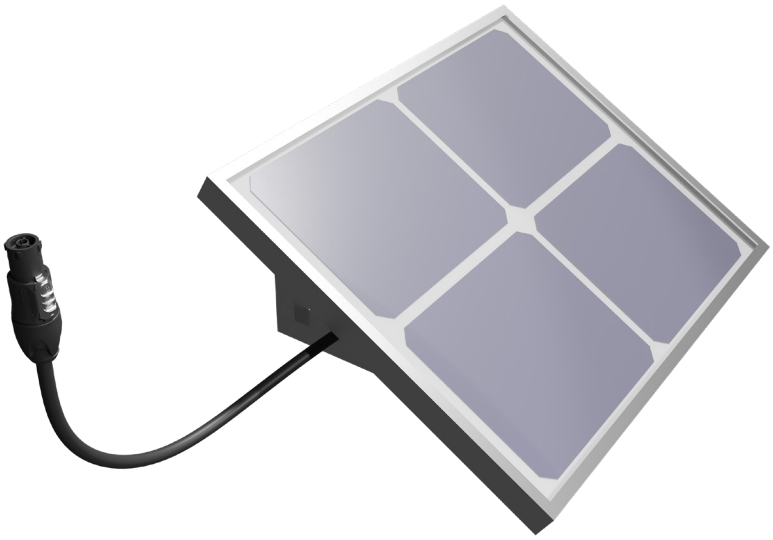
Torx screw driver T8

Materials needed

Solar panel with cable

1x NAC3FX-W-TOP

Task



Strip cable and mount the Neutrik connector to it. Take care to attach the black wire to the N terminal and the red wire to the L terminal. The terminals can be tightened with a torx screwdriver.

For more in detail assembly instructions of the neutrik connector, take a look at the assembly manual from Neutrik, which can be found at the following webpage;
https://www.neutrik.com/en/product/nac3fx-w-top

Tip: When screwed together, the connector locks itself. To openup the connector again, a locking mechanism should be pushed in with a flat head screwdriver. This instruction can also be found in Neutrik's assembly manual.

6. Antenna-top assembly

6.1. Assemble antennatop

Tools to use

Allen key 3

Allen key 6

2x - m4x25

2x m4 nut

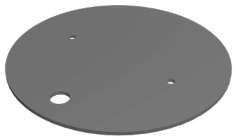
Materials needed

GNSS antenna

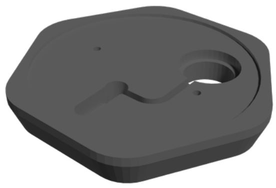
Cellular Antenna

1x - m8x40

1x m8 nut



Groundplane



Plastic bracket

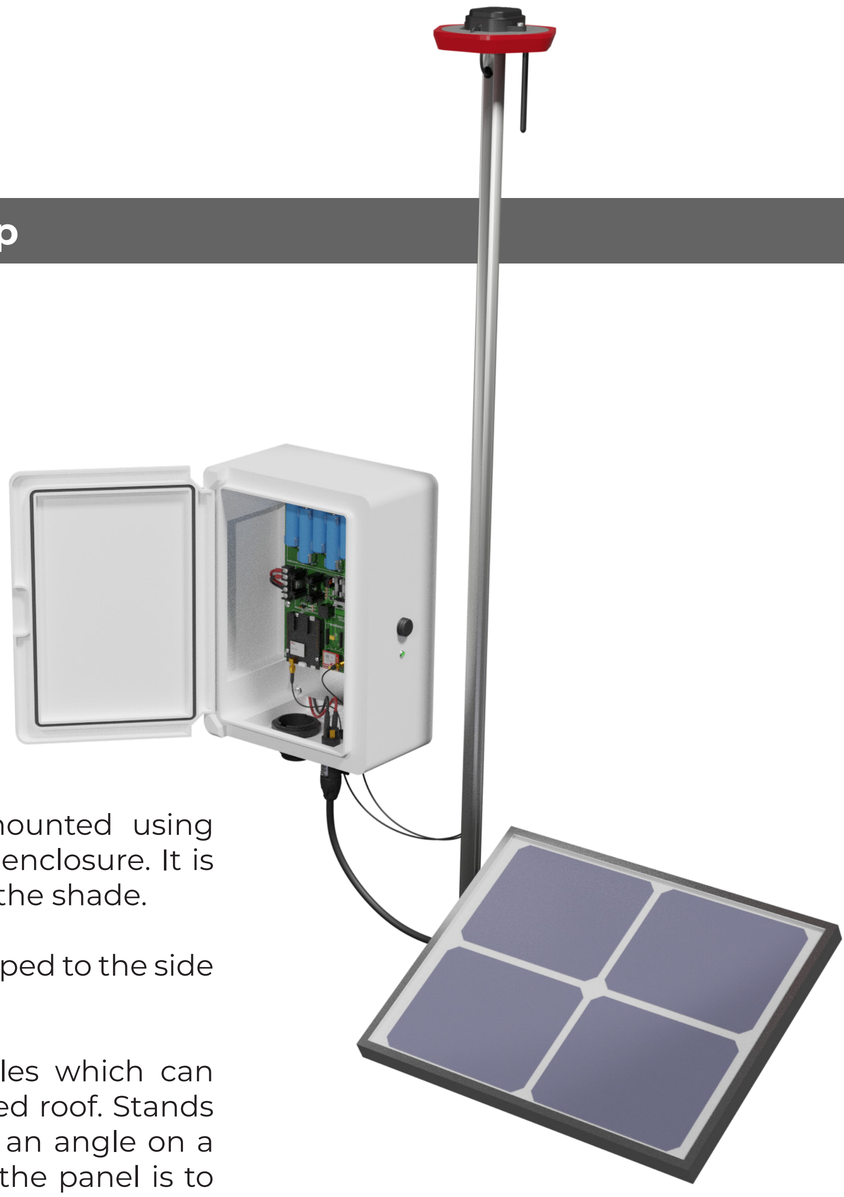
Task

Assemble the antenna top as can be seen in the exploded view on the left side of this page. Use the allen keys to tighten the bolts. Make sure to put the antenna wires through the gutter in the plastic bracket.

7. Start using reference station

Now it is time to start using the reference station. The setup could look like the one which can be seen below.

7.1. Mounting the setup



The enclosure can be wall mounted using the brackets supplied with the enclosure. It is advised to put the enclosure in the shade.

The antenna pole could be clamped to the side of a wall using an U-clamp.

Finally the solar panel has holes which can be used to mount it to an angled roof. Stands could be made to put it under an angle on a flat roof. The best direction for the panel is to face the equator (geographic south for Ghana) The best tilt angle is on average 17 degrees plus the latitude of the location according to (Uba & Sarsah, 2013)

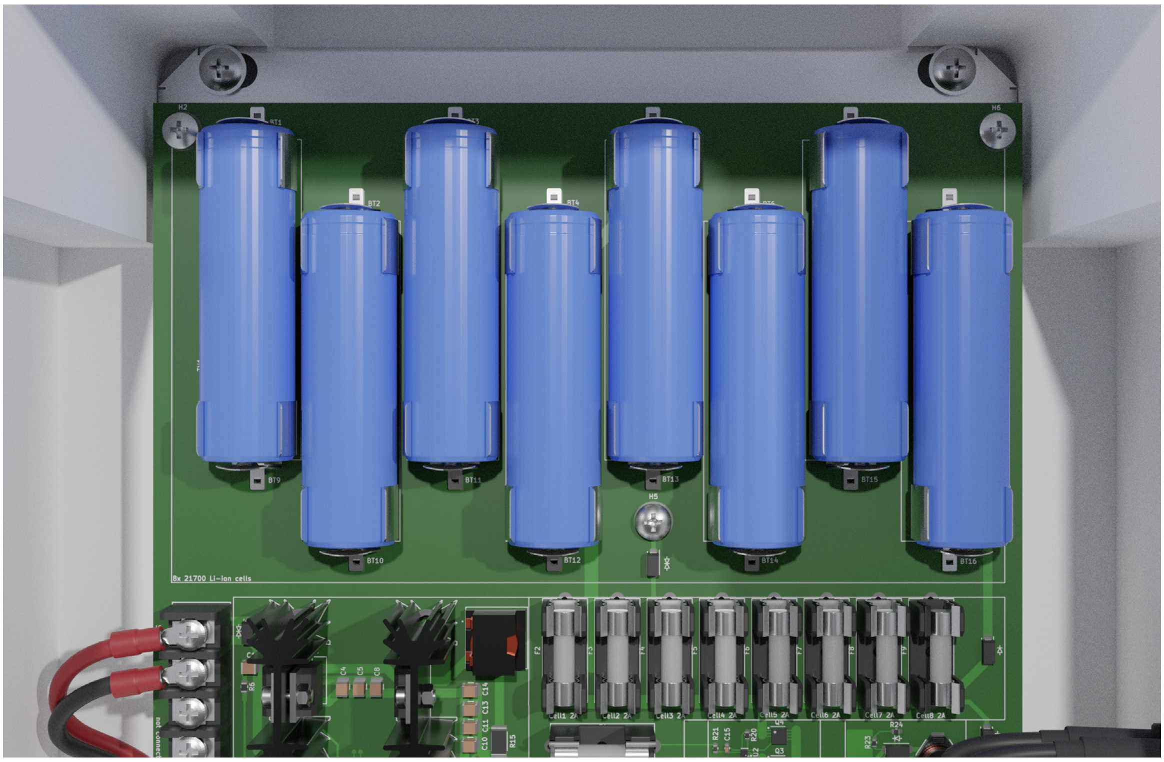
Probably different mounting methods suit different situations.

Warning: The current antenna cables are about 2,5-3meters. No test has been committed with extension cables.

7.2. Insert Lithium cells

Tools to use

Task



Handle the lithium batteries with care as there is a fire hazard in over/under charing them and large currents can flow on a short circuit.

Check the voltage of the 21700 cells, the voltage between cells which have to be placed may not deviate more than 0,1v. Insert the 21700 cells one by one with the + side up (as noted on the board)

Protection:
A reversed cell will blow the fuse which belongs to the cell.
A bigger deviation than 0,1v from the other cells will cause a large current to flow. This will probably also cause a fuse to blow.

7.3. Insert Lithium cells

Task

Attach the solarpower cable (insert and twist).

Tip: The battery protection circuit will only enable the battery after the charger has been applied for the first time. This means that the on/off function will not work before the charger has been attached and charged for a second.

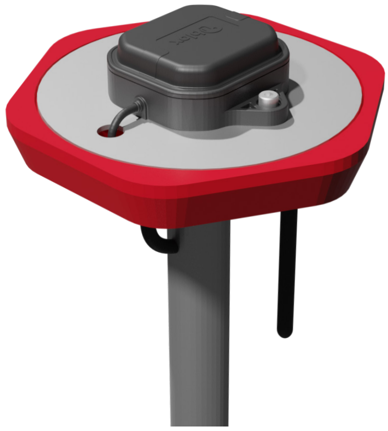
7.4. Antenna cables throughput

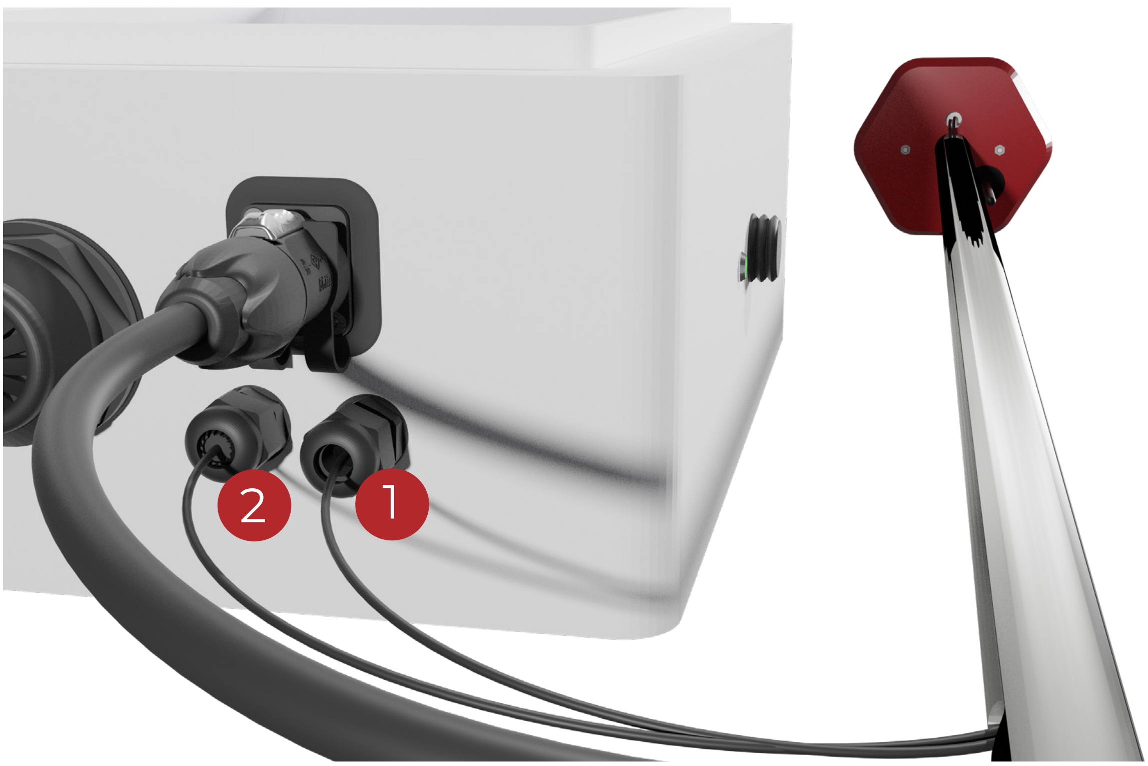
Tools to use

Allen key 6

Task

The antenna top can be clamped to the aluminium pole with its m8 socket head bolt. It is possible to wire the antenna cables through the pole.

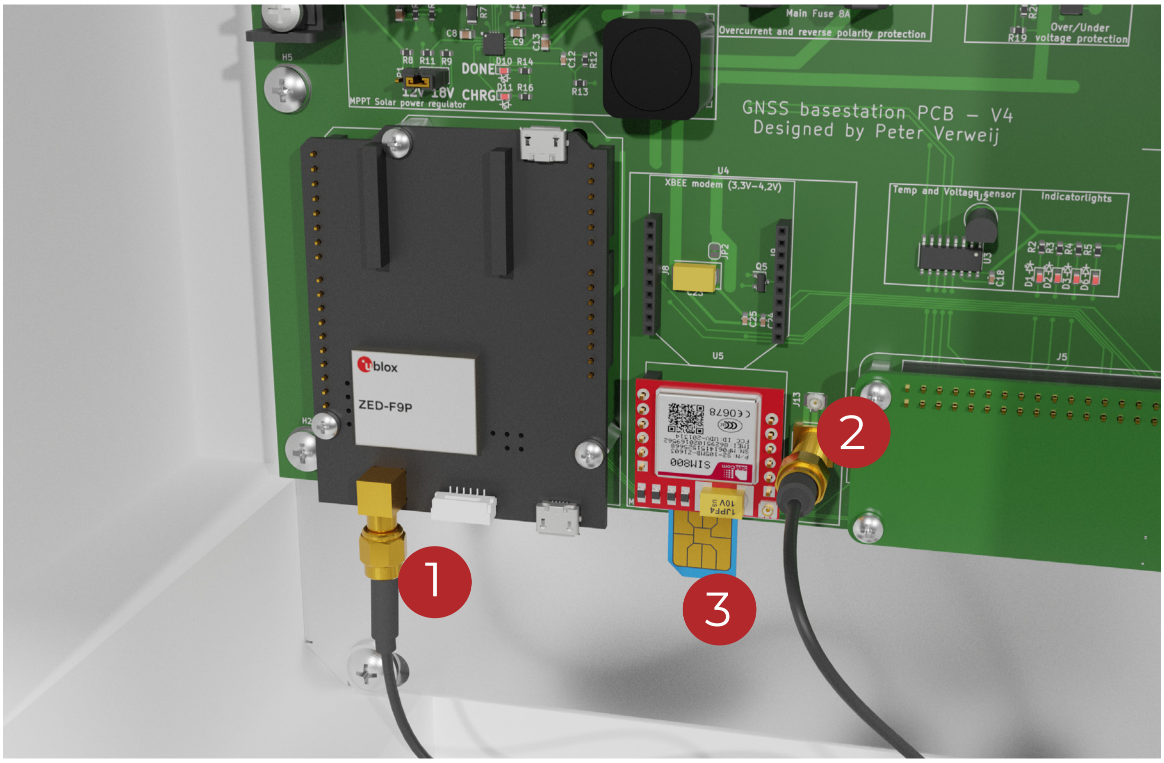




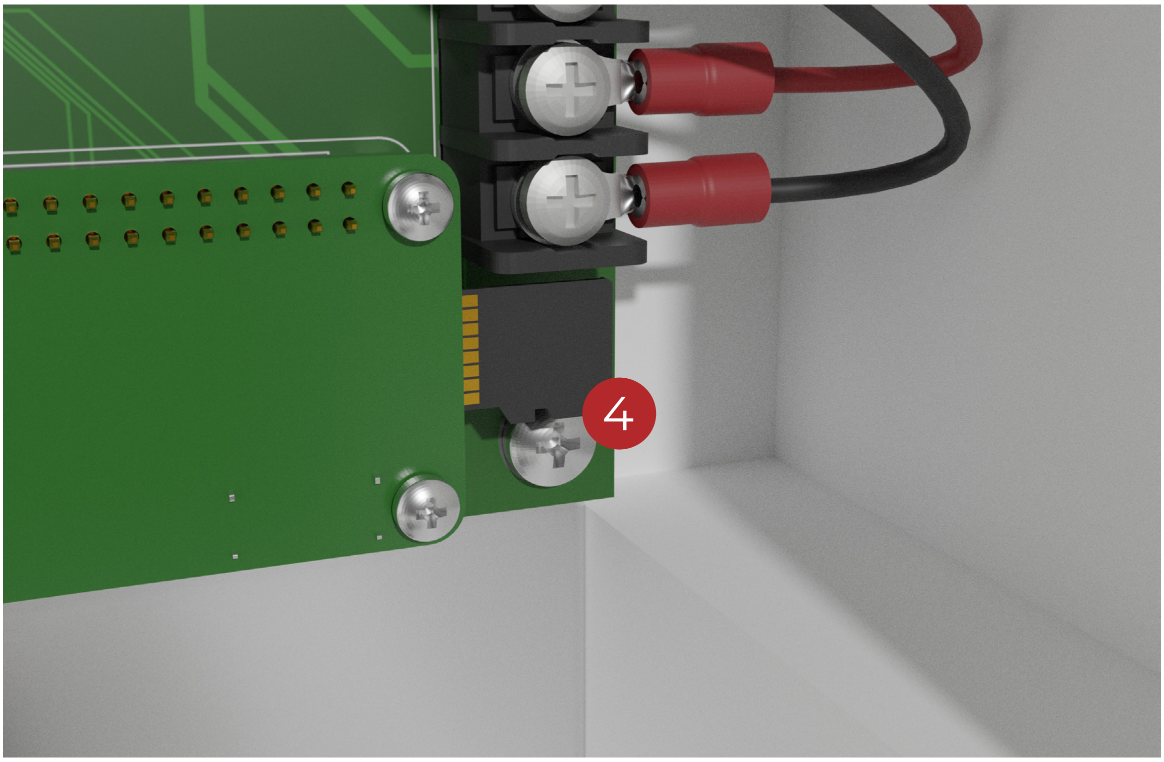
Put the antenna cables through the cable glands (1). Then tighten the nut of the cable gland to make them watertight (2).

7.5. Attach antenna cables, SIM and SD card

Task



The GNSS antenna should be connected to the GNSS receiver (1). The GPRS antenna should be connected to the modem (2). Also, the SIM-card should be installed (3).



Finally the SD-card with the reference station image should be inserted in the raspberry PI (4). For preparing the SD-card I refer to the software manual of Andreas Krietemeyer.

Now the device can be powered on.

8. Troubleshooting

On the reference station there are some LED's which give information about the system state;

Case LED
The LED on the enclosure will be on as soon as the powerbutton is turned on.

Charger
The Charge LED will be on when there is enough light and the charger has started charging.
The Done LED will be on if the battery voltage has been raised to 4,1V.
When both LED's are on, the charger is in error state. The charger is programmed to shut off under -5 degrees celcius or over 55 degrees celcius. (This is the ambient case temperature, the heatsinks will get hotter).

Raspberry PI
The raspberry PI internal green LED will blink it's LED on reading the SD card. There are 4 indicator LED's which can be programmed to turn on or off (see test program ...) These LED's can be put to use to troubleshoot software in the Raspberry PI.

GPRS modem
The GPRS modem has a red LED which blinks slowly on startup. On connection this led will blink fast.
It is possible that the modem is turned off (it turns off under 3,4v) while the raspberry PI is still running.

GNSS receiver
When the GPS-fix light on the receiver is flashing this means that there are enough satellites in sight to define a position.

9. Hardware test

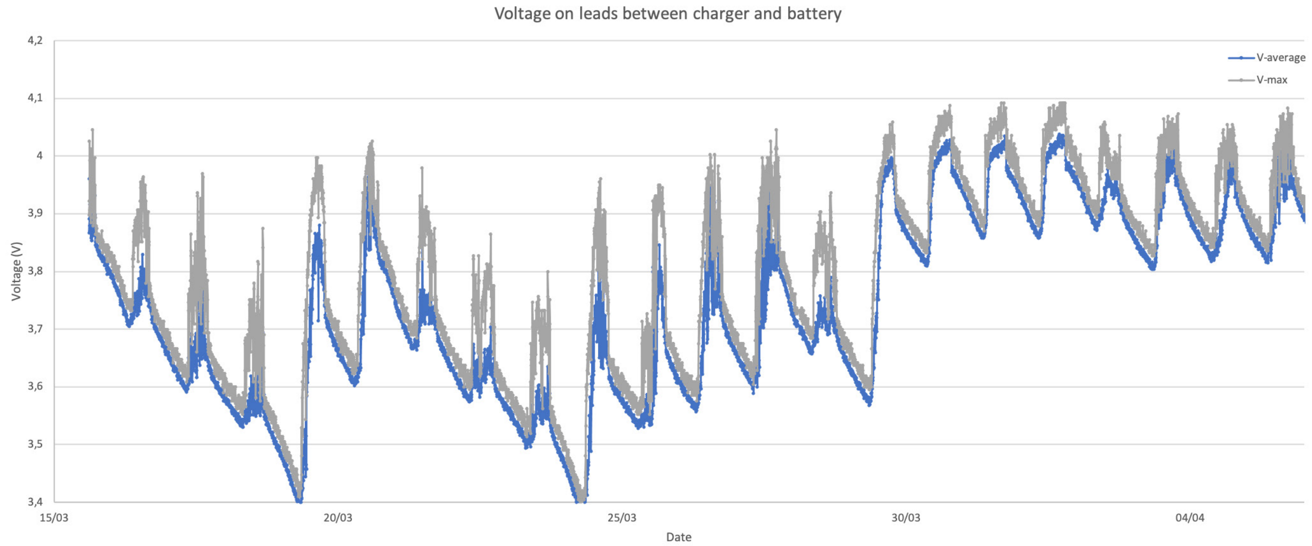
The hardware has been tested from 15 March 2021 until 6 April 2021 (22 days) in the Netherlands to check the behaviour of the power-supply and the cellular connectivity.

9.1. Setup

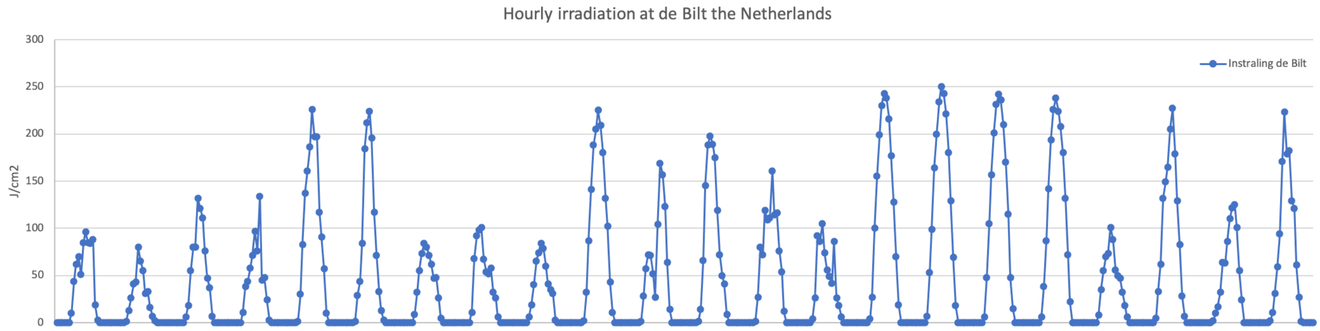
Position As can be seen above the system was placed on a roof next to an existing PV system. The solar panel is tilted 35 degrees and facing a few degrees west from the south axis.

Data In 15 days there was no connection loss. In total 1,6Gb of GNSS data has been send over GPRS. Which is about 106mb each day. This might be a little much for future purposes but a heavy load is positive for this power supply test.

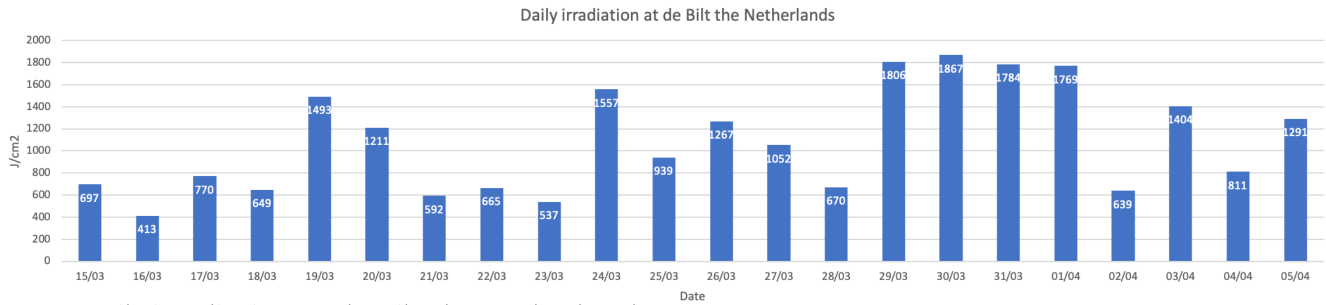
9.2. Results



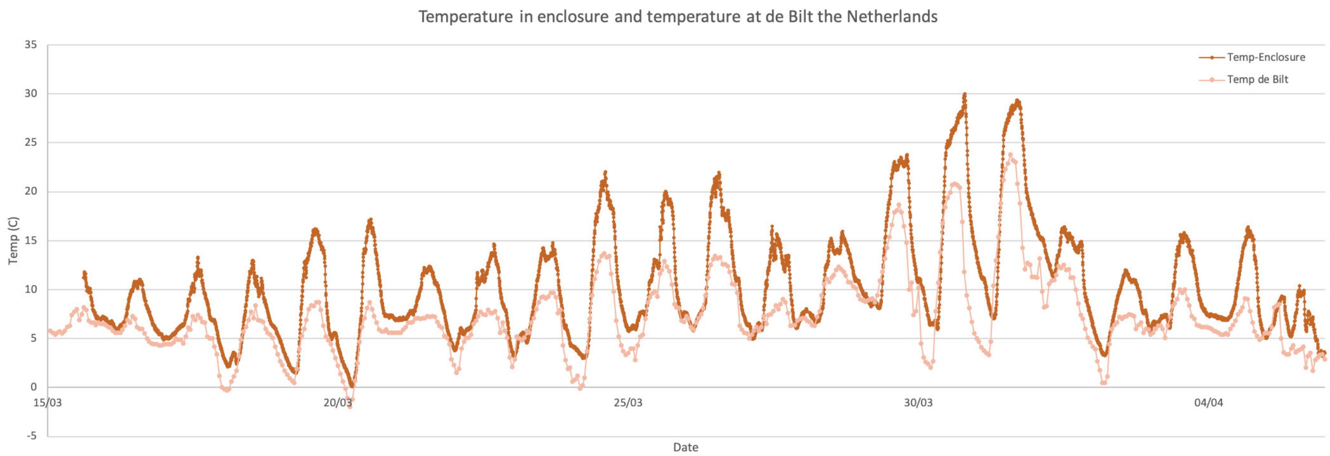
9.1. *Voltage on leads between charger and battery*



9.2. *Hourly irradiation at de Bilt, the Netherlands*



9.3. *Daily irradiation at de Bilt, the Netherlands*



9.4. *Temperature in enclosure and temperature at de Bilt, the Netherlands*

9.3. Conclusion of test

Battery voltage:
During daytime the charger raises the voltage on the circuit. Only at night time the true battery voltage can be seen. Also, the voltage measurement lead on the prototype PCB is close to the GPRS modem power input. Therefore the measured voltage is quite unstable and had to be sampeled for 20 times over 20 seconds to give stable readings.

Over the 22 days of the test the device did not stop functioning, however the average voltage dropped as low as 3,37V While the modem has a lower limit of 3,4V. Probably its cutoff limit is lower in reality.

It can be concluded that the device can run for 4 to 5 cloudy days with very low irradiation.

It can be concluded that the solar regulator can produce just enough power to exactly compensate for the night time use, when the daily irradiation is $939J/cm^2$. This was the case on 26 March. A lower irradiation will cause the battery to drain, a higher irradiation means that there will be more energy stored than used that day.

In Ghana the month with the least sun radiation is august. The average day in that month still has $3,8Kwh/m^2$ of irradiation. (Energy Commission, Ghana, 2001) This equals $1368J/cm^2$. Thus on average there is enough irradiation to keep the device running. The chance that there will be 5 consecutive days with less than $939J/cm^2$ irradiation is extremely small.

Temperature:
The used LM35 temperature sensor can only read positive temperatures.

During night time, the enclosure is only within a degree hotter than the outside temperature. This can be caused by the difference in height and location of the temperature sensors. Or it can be caused by the slight dissipation of heat in the enclosure in combination with almost no wind.

During daytime the temperatures can be raised as much as 10 degrees above the outside temperature. This is probably due to the dissipation of heat by the solar regulator and due to direct sunlight on the enclosure.

Other:
Despite a lot of wind and rain all electronics in the box were unharmed.

10. References

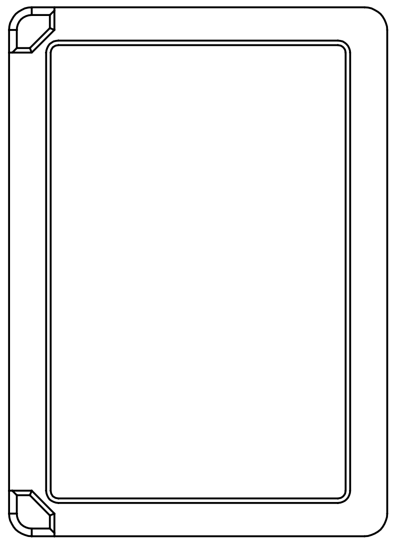
Energy Commission, Ghana. (2001). Energycom.gov.gh. *http://energycom.gov.gh/files/Solar%20 Data%20-%20final(1).pdf*

JRC Photovoltaic Geographical Information System (PVGIS) - European Commission. (2016, January 11). Europa.eu. *https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html*

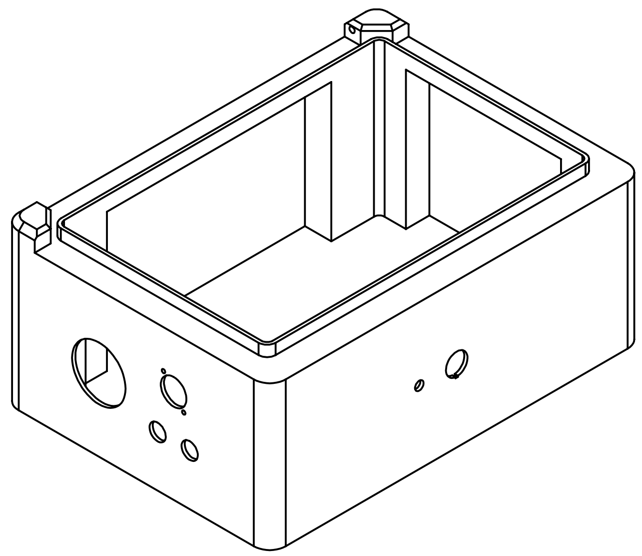
Uba, F., & Sarsah, E. (2013). Optimization of tilt angle for solar collectors in WA, Ghana. *https://www.imedpub.com/articles/optimization-of-tilt-angle-for-solar-collectors-in-wa-ghana.pdf*

11. Appendix

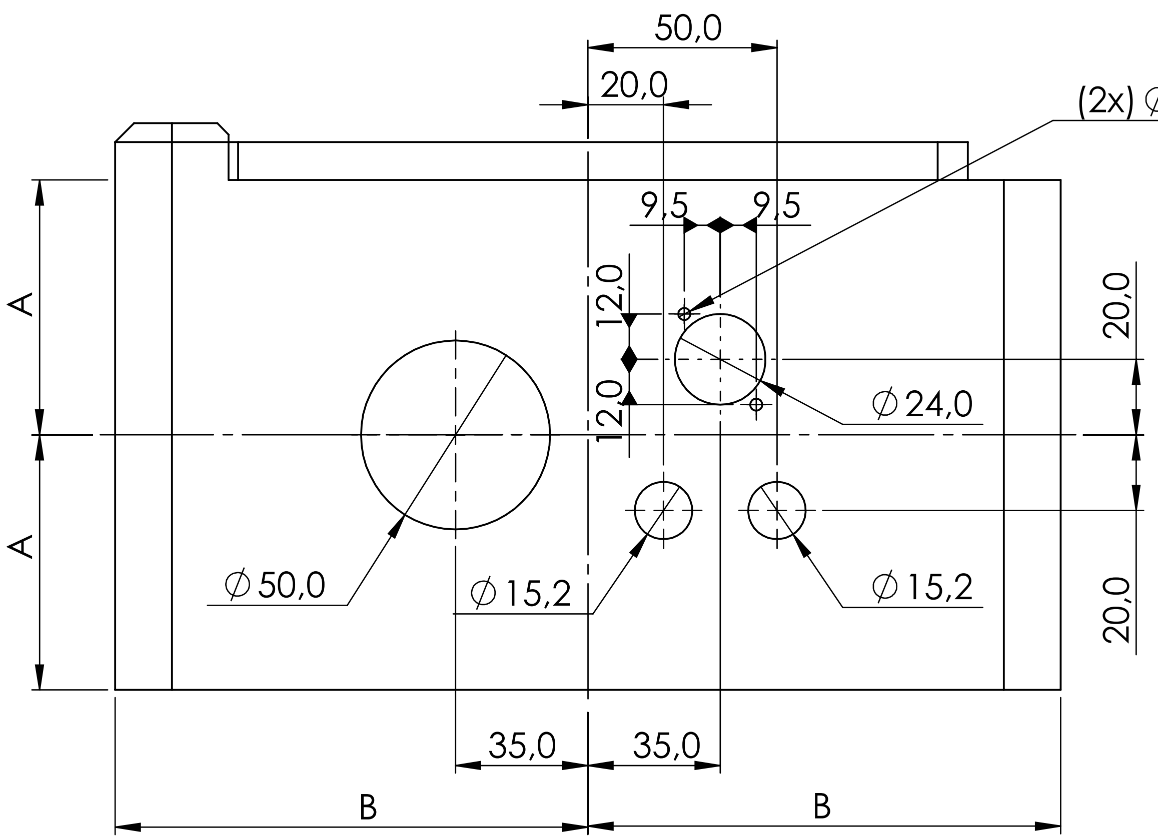
Appendix A. Enclosure holes measurements

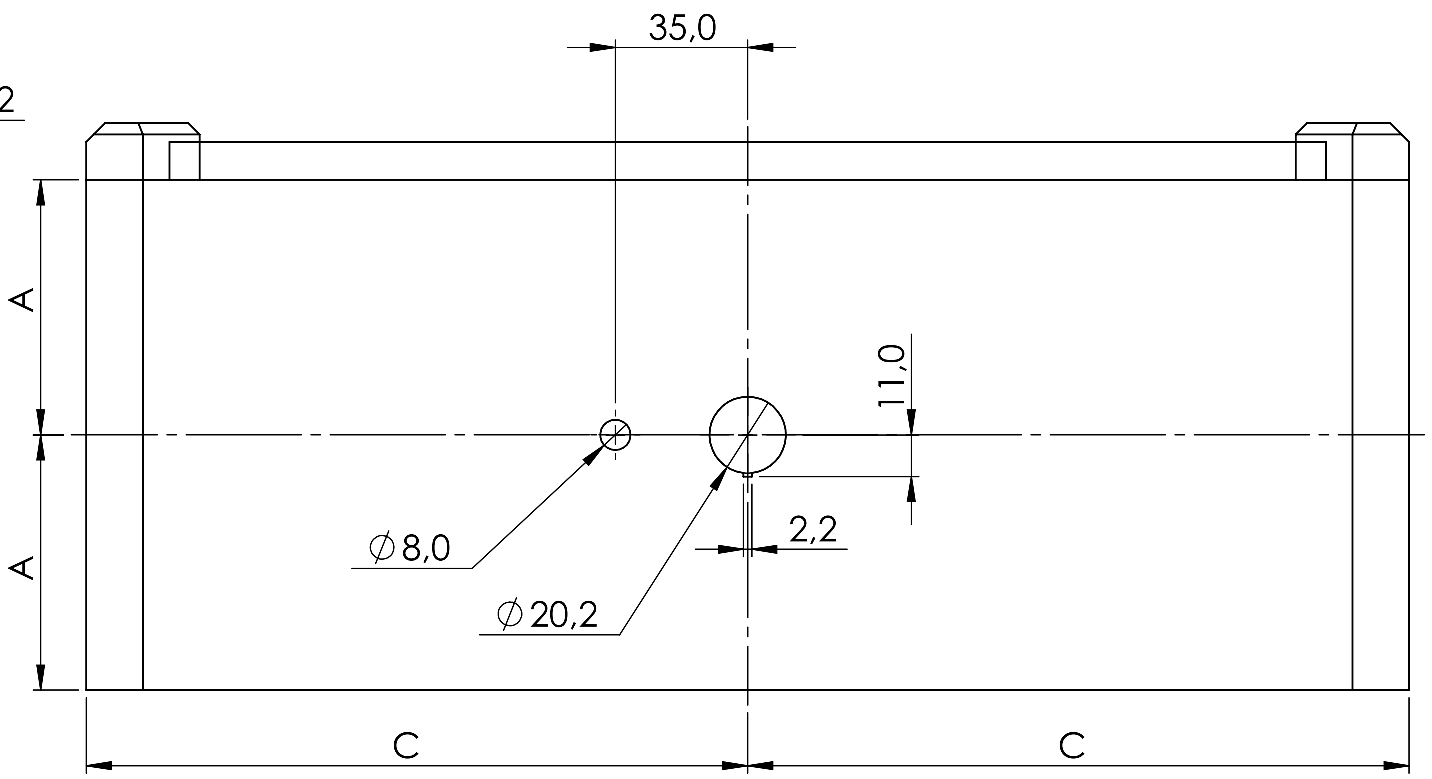


Scale 1:5



Scale 1:5

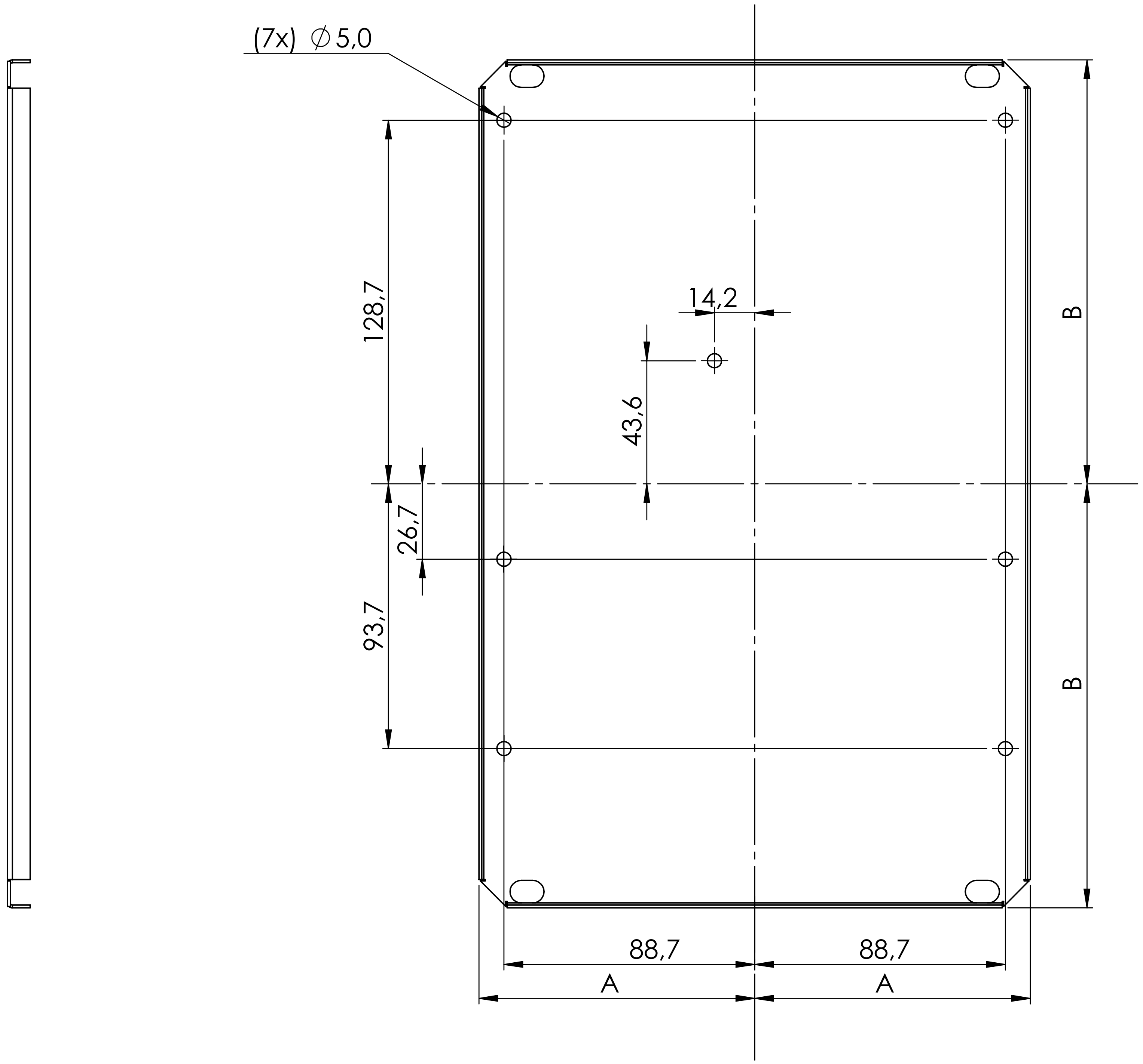




While outer dimensions of box have not been measured precisely, midpoints are only noted down as equal lengths.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE: Enclosure_Main with drilled holes	
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO. Enclosure_Main	A3
			WEIGHT:	SCALE:1:2	SHEET 1 OF 1

Appendix B. Backplate holes measurements



While outer dimensions of backplate have not been measured precisely, midpoints are only noted down as equal lengths.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:
Enclosure_backplate with drilled holes

DWG NO.
Enclosure_Backplate

A3

SCALE:1:2

SHEET 1 OF 1