Soil Moisture

2023 GNSS-IR Short Course

Kristine M. Larson

PBO H_2O

Using GPS reflection data from NSF's Plate Boundary Observatory (PBO) to study the water cycle

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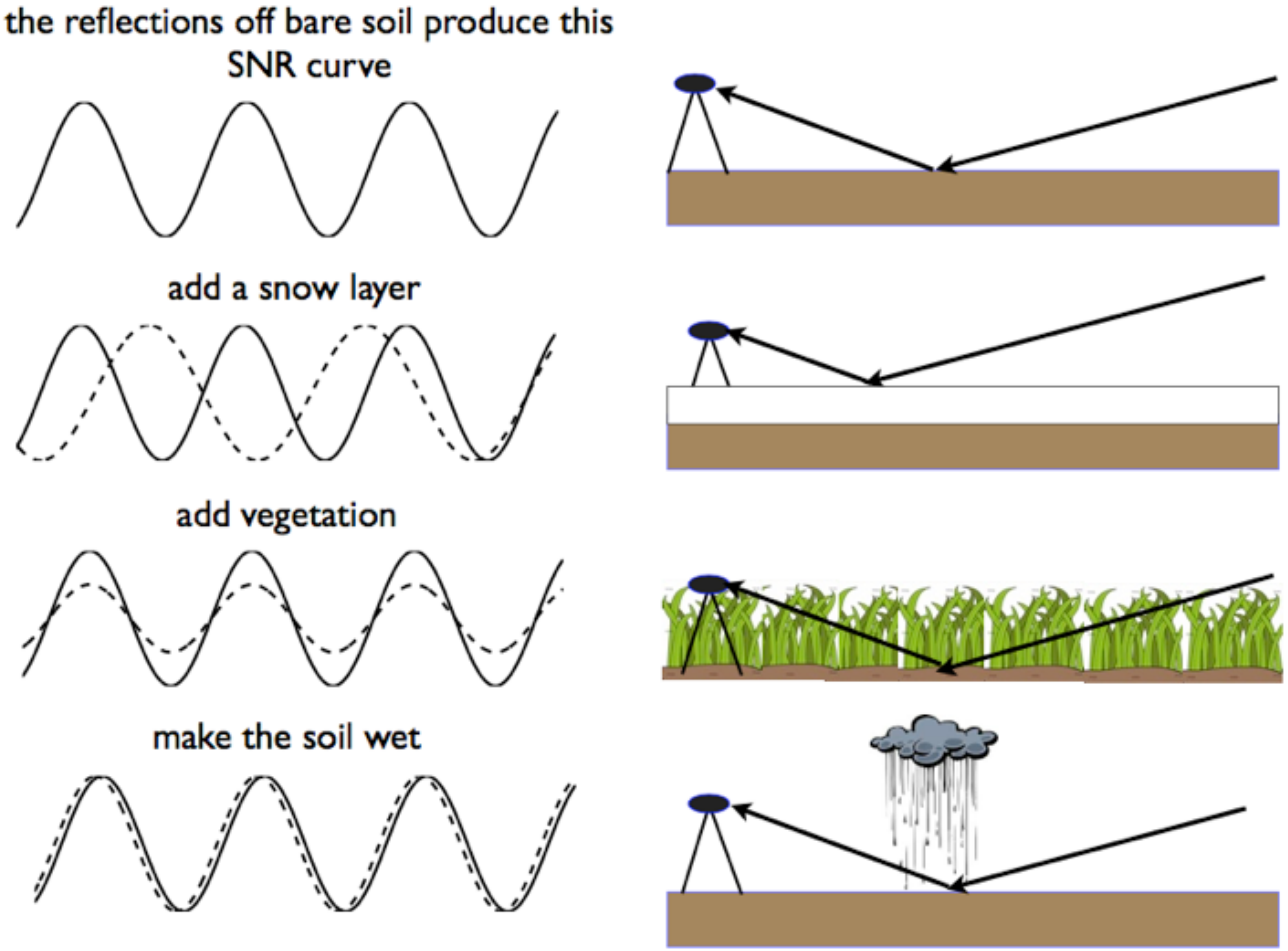
The cartoon version of GNSS-IR



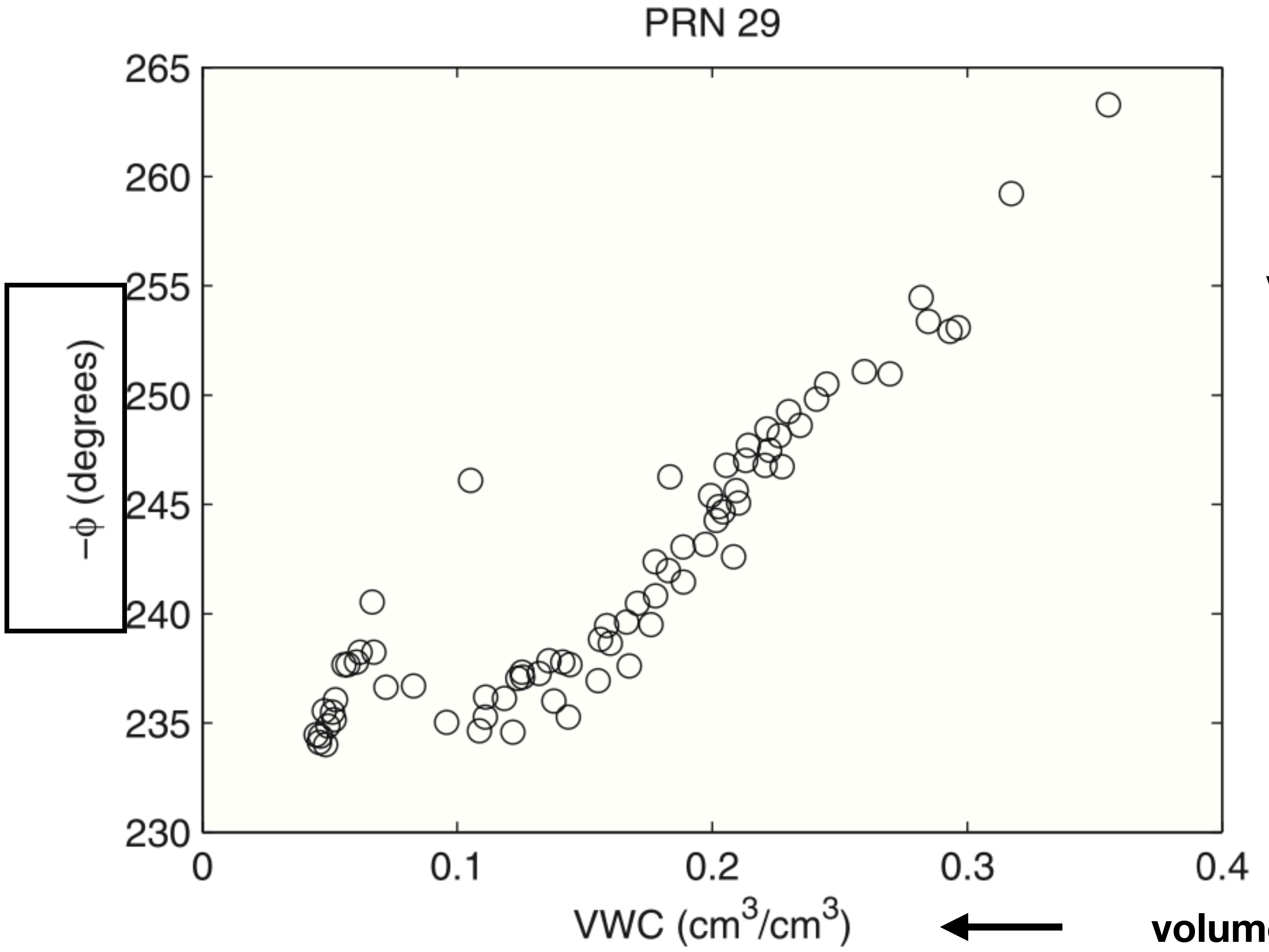
by far the hardest thing to measure

If there were no vegetation

it would be a lot easier to measure soil moisture

$$SNR = A \cos\left(\frac{4\pi h}{\lambda} \sin E + \phi\right)$$

Our first study fixed h and estimated A and ϕ

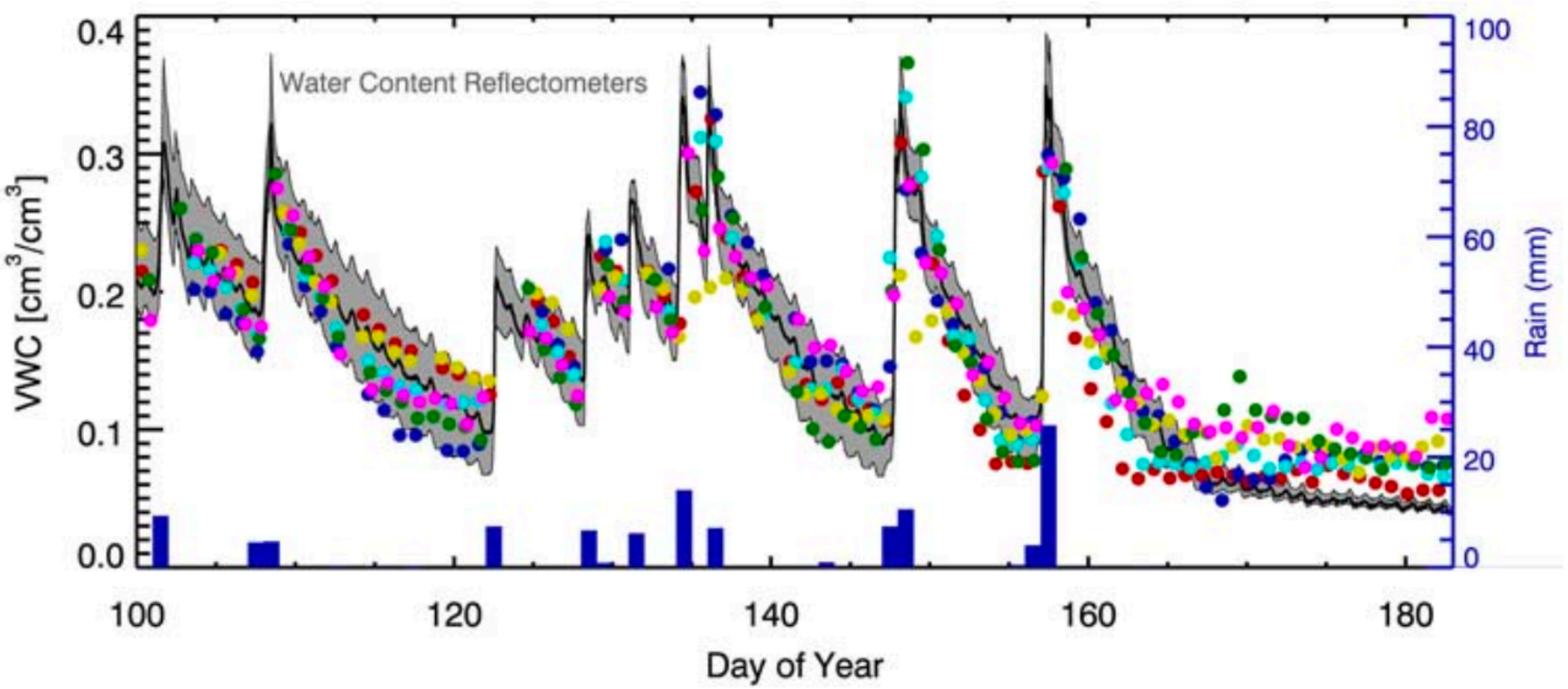


Notice the values of the phase!!!

volumetric water content

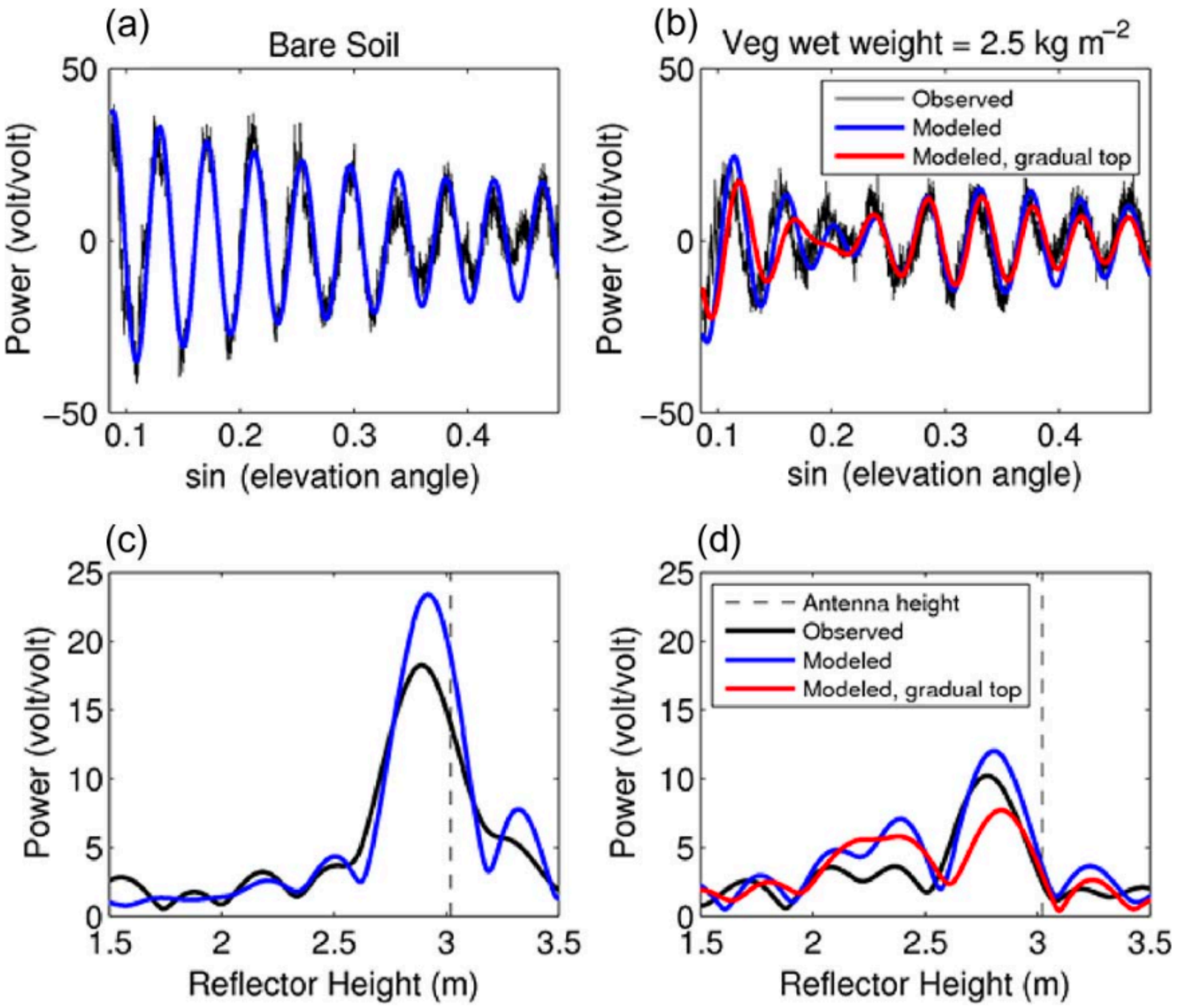
Figure 2. Estimated ϕ (for satellite 29) compared with VWC, as defined by the average of five water content reflectometers at depth 2.5 cm.

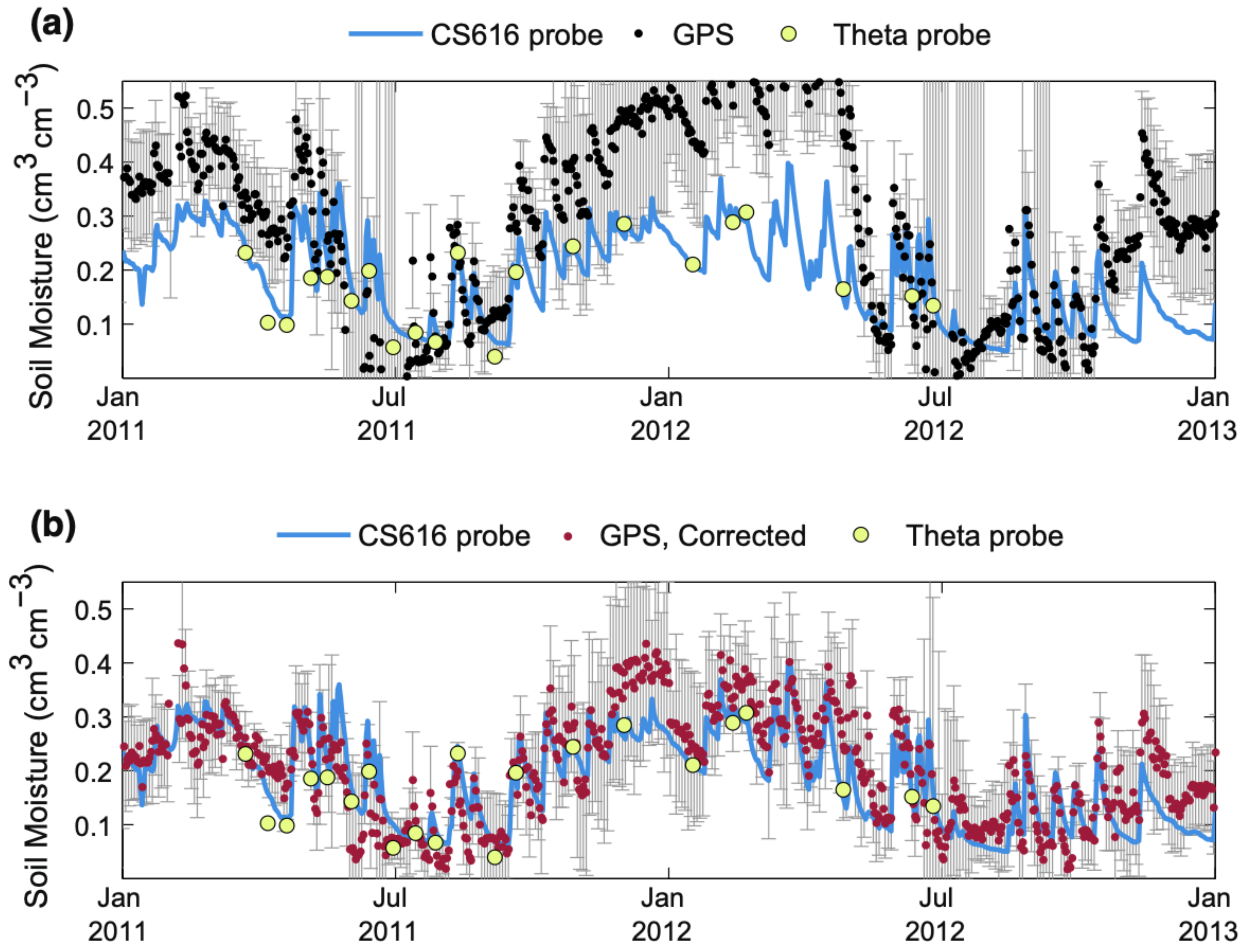
First paper: we simply scaled the ϕ measurements



GPS are the colored circles. Rain is dark blue bars.

1. Valery Zavorotny developed a bare soil model.
2. Clara Chew developed models to correct vegetation effects for her PhD thesis.





She uses the traditional estimation method (using phi as a proxy for soil moisture), but uses amplitude (A) to remove the vegetation effects.

How does that relate to the gnssrefl code?

- We need the same SNR data (so we can still use **rinex2snr**)
- We exclusively use L2C GPS data. This means default GPS orbits are fine.
- GPS has a repeating ground track. This is very useful for soil moisture. Can you measure soil moisture with other GNSS signals? Yes, but not with gnssrefl.

How does this relate to the gnssrefl code?

- Remember the height "h" (also known as the RH) is fixed in our model for phase phases.

- We use **gnssir** to find that value.

- We need to pick a good azimuth mask - we can use **quickLook**.

- In addition to gnssir, we need new code to

    - estimate ϕ (this code is called **phase**)

    - convert ϕ to Volumetric Water Content (VWC) and mitigate vegetation effects. This code is called **vwc**.

Keep in mind

- Reflector Heights are pretty easy to understand. Sure, there are biases associated with the kind of reflector it is (water, soil, snow), but RH is an <u>absolute measurement</u>.

- Phase is a <u>relative measurement</u>. You cannot take phase from GNSS-IR and say “this means the soil has a VWC of 0.13. Remember our first paper had phase values of 240.

- Our code takes advantage of the fact that there is pretty nice linear relationship between phase and volumetric water content. So it gives you a good time series for <u>VWC changes</u>.

- To define it as VWC, you can “level” your VWC changes using an *in situ* measurement, or you can do what we do, which is level it once per year to its lowest value (we suggest 6 months).

- I am teaching you the simple PBO H2O model. Clara Chew et al. developed a more advanced retrieval model in Matlab that I am happy to let someone else port to python.

Example: Portales, New Mexico: p038

Most notable feature? This is what you want your soil moisture sites to look like.

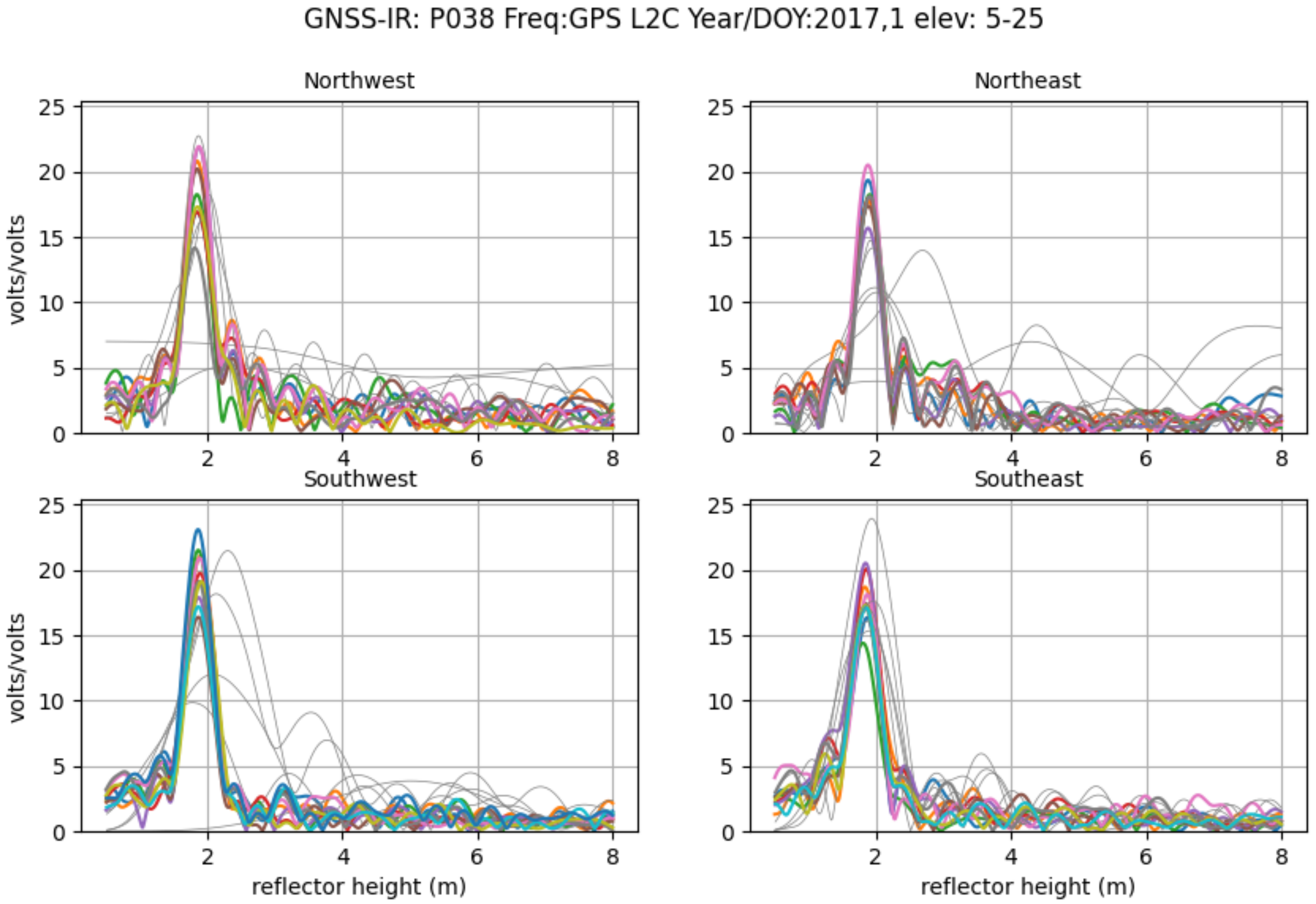
Start as you would with any new GNSS-IR site

- Translate one RINEX file using **rinex2snr**. Be sure it has L2C data in it.
- Use **quickLook** to pick azimuth and elevation angle mask
- Save analysis instructions with **make_json_input**
- Make more SNR files.
- Run **gnssir** for at least six months (we will do one year).

Test file on January 1, 2017

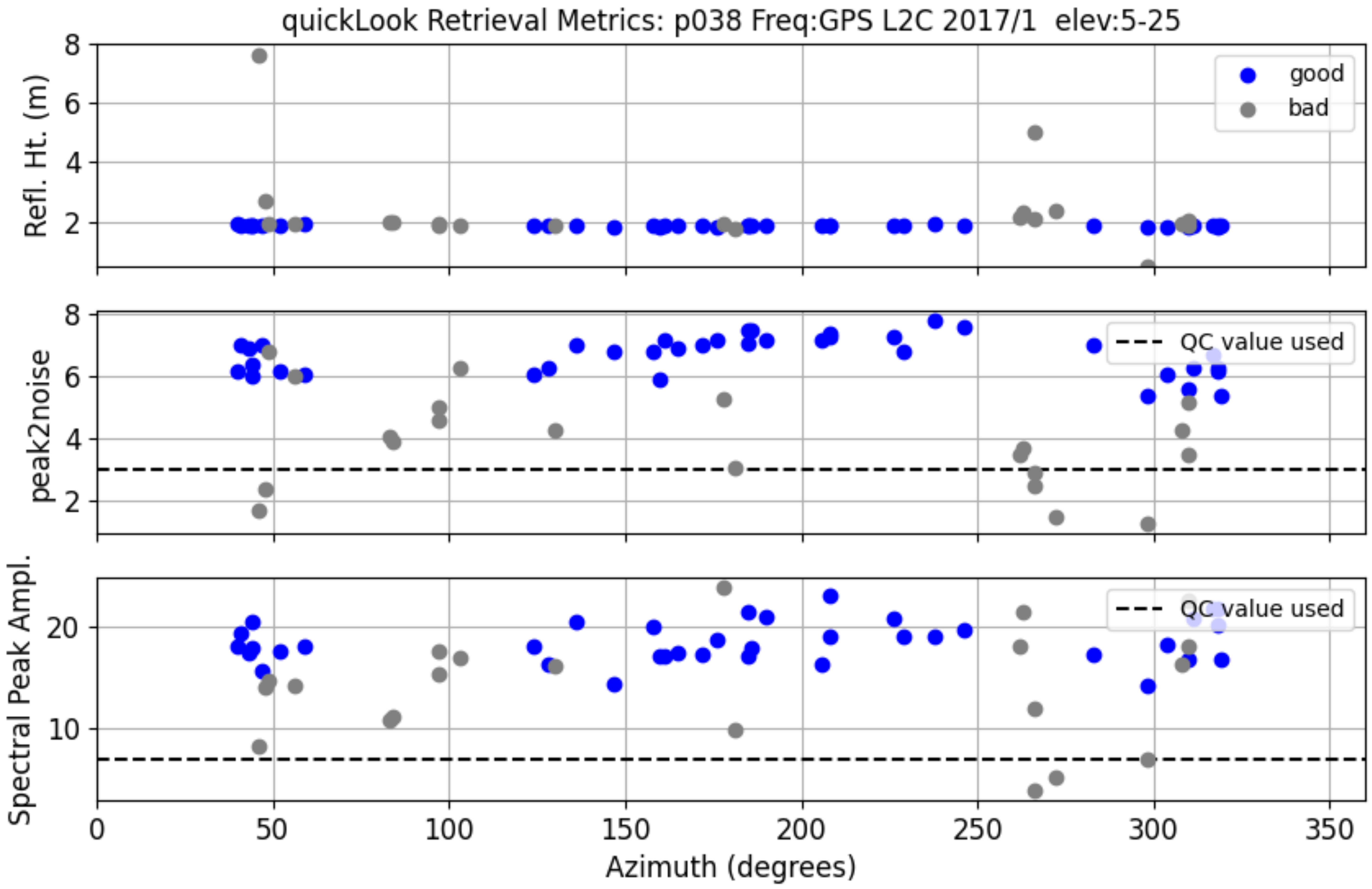
- L2C data are in the 1-Hz stream at UNAVCO or in the special archive at 15 second sampling (this is not available for all years).
- rinex2snr p038 2017 1 -archive special
- quickLook p038 2017 1 -fr 20

There is no reason to be shy about asking UNAVCO/Earthscope to provide you with RINEX files with L2C data. They will either have the data or they will not. *It is their job to let you have access to the data if it exists.*



High quality SNR data

January 1, 2017



You need *a priori* RH values

- make_json_input p038 0 0 0 -l2c T (keep the default azimuth regions)
- gnssir p038 2017 1 -doy_end 365 (estimate RH for an entire year)
- vwc_input p038 2017 # makes a list of satellite tracks

Why do you specify a year? Tells the code where to look. If you have multiple years, use the last one.

```
% apriori RH values used for phase estimation
% year/station 2019 p038
% tmin 0.05 (default)
% tmax 0.50 (default)
% Track  RefH SatNu MeanAz  Nval   Azimuths
%         m
   1  1.905    1   40.38    348    0   90
   2  1.889    5   52.94    349    0   90
   3  1.892    6   58.98    346    0   90
   4  1.876    8   43.24    349    0   90
   5  1.879   15   47.99    350    0   90
   6  1.879   26   45.50    348    0   90
   7  1.910   27   39.98    351    0   90
   8  1.888   31   60.49    347    0   90
   9  1.882    1  128.32    346   90  180
  10  1.862    5  176.32    186   90  180
  11  1.822    7  148.11    353   90  180
  12  1.845    8  157.38    350   90  180
  13  1.841   15  166.76    347   90  180
  14  1.884   24  127.31    263   90  180
  15  1.845   26  161.50    315   90  180
  16  1.867   27  136.36    348   90  180
  17  1.850   29  171.34    349   90  180
  18  1.845   30  161.33    350   90  180
  19  1.890    1  229.47    347  180  270
  20  1.881    3  192.04    350  180  270
  21  1.862    6  184.42    353  180  270
  22  1.909   10  243.80    346  180  270
  23  1.876   12  184.83    351  180  270
  24  1.866   17  204.12    352  180  270
  25  1.889   24  226.74    345  180  270
  26  1.875   25  206.17    348  180  270
  27  1.915   27  239.23    319  180  270
  28  1.875   31  186.22    351  180  270
  29  1.884   32  210.37    351  180  270
  30  1.849    1  319.78    348  270  360
  31  1.852    3  312.62    350  270  360
  32  1.834    9  303.54    349  270  360
  33  1.854   12  309.40    347  270  360
  34  1.843   24  317.14    348  270  360
  35  1.850   25  317.57    349  270  360
```

Note - this is the one I have on my computer - it was computed for 2019, not 2017.

It is stored in $REFL_CODE/input

Now estimate phase & then vwc

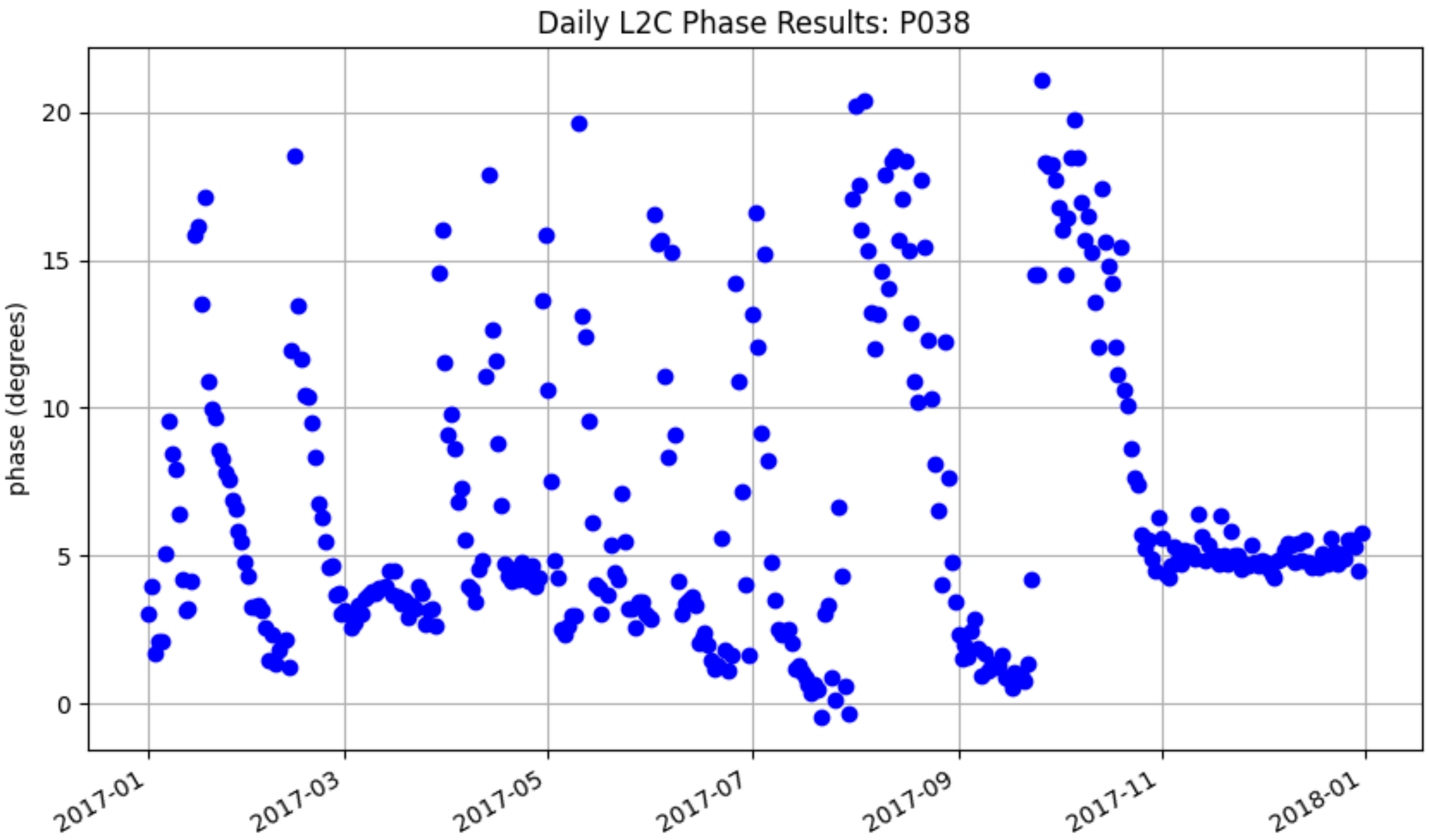
$$SNR = A\cos\left(\frac{4\pi h}{\lambda}\sin E + \phi\right)$$

- The phase estimation code is very fast.
- **phase p038 2017 1 -doy_end 365**
- **vwc p038 2017**

output of vwc: why colors? bad tracks?

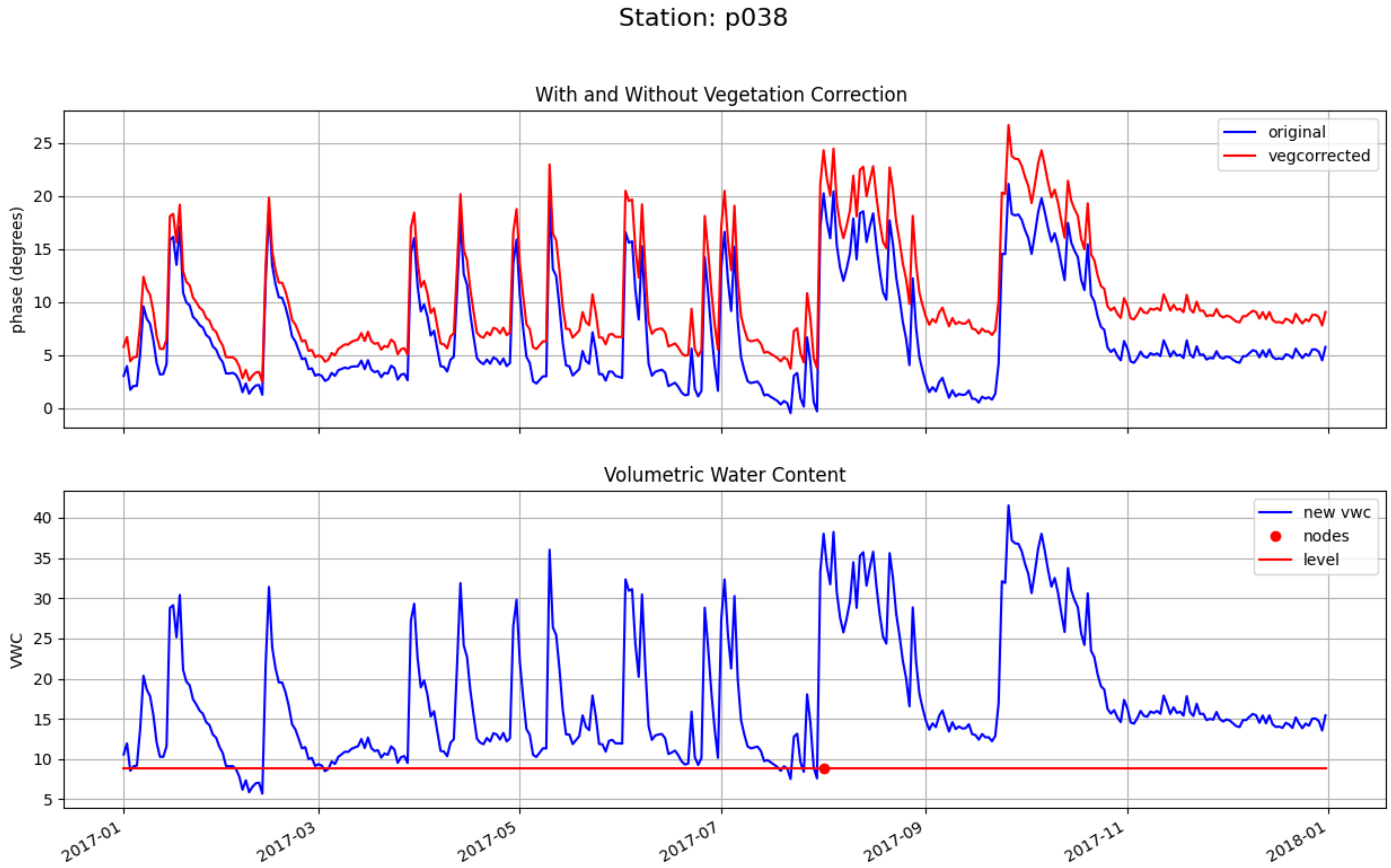
we have “zeroed” the phase results for each track

```
p038_tmp.txt /Users/kristine/Documents/Research/input/p038_phaseRH.txt
Npts  347 SatNu  1 Residual   3.20 Azims 270 360 Amp 1.08
Npts  347 SatNu  3 Residual   5.56 Azims 270 360 Amp 1.07 >>>>>  Consider Removing This Track <<<<<
Npts  345 SatNu  9 Residual   4.55 Azims 270 360 Amp 1.09
Npts  349 SatNu 12 Residual   3.18 Azims 270 360 Amp 1.07
Npts  348 SatNu 24 Residual   3.02 Azims 270 360 Amp 1.10
Npts  347 SatNu 25 Residual   3.39 Azims 270 360 Amp 1.07
Npts  346 SatNu 27 Residual   3.04 Azims 270 360 Amp 1.03
Npts  344 SatNu 29 Residual   7.84 Azims 270 360 Amp 1.05 >>>>>  Consider Removing This Track <<<<<
Npts  341 SatNu 30 Residual   2.93 Azims 270 360 Amp 1.05
Npts  346 SatNu  1 Residual   3.35 Azims   0  90 Amp 1.11
Npts  340 SatNu  5 Residual   2.98 Azims   0  90 Amp 1.11
Npts  346 SatNu  6 Residual   3.24 Azims   0  90 Amp 1.07
Npts  351 SatNu  8 Residual   3.42 Azims   0  90 Amp 1.10
Npts  348 SatNu 15 Residual   3.46 Azims   0  90 Amp 1.07
Npts  345 SatNu 26 Residual   3.67 Azims   0  90 Amp 1.08
Npts  348 SatNu 27 Residual   3.09 Azims   0  90 Amp 1.09
Npts  345 SatNu 31 Residual   4.18 Azims   0  90 Amp 1.06
Npts  344 SatNu  1 Residual   3.00 Azims 180 270 Amp 1.05
Npts  348 SatNu  3 Residual   2.48 Azims 180 270 Amp 1.08
Npts  352 SatNu  6 Residual   2.90 Azims 180 270 Amp 1.11
Npts  345 SatNu 10 Residual   3.80 Azims 180 270 Amp 1.07
Npts  350 SatNu 12 Residual   3.02 Azims 180 270 Amp 1.08
Npts  351 SatNu 17 Residual   3.24 Azims 180 270 Amp 1.12
Npts  345 SatNu 24 Residual   3.52 Azims 180 270 Amp 1.06
Npts  349 SatNu 25 Residual   3.61 Azims 180 270 Amp 1.08
Npts  342 SatNu 27 Residual   3.42 Azims 180 270 Amp 1.14
Npts  351 SatNu 31 Residual   3.10 Azims 180 270 Amp 1.09
Npts  351 SatNu 32 Residual   3.54 Azims 180 270 Amp 1.13
Npts  343 SatNu  1 Residual   3.96 Azims  90 180 Amp 1.07
Npts  187 SatNu  5 Residual   2.57 Azims  90 180 Amp 1.06
Npts  348 SatNu  7 Residual   5.97 Azims  90 180 Amp 1.07 >>>>>  Consider Removing This Track <<<<<
Npts  341 SatNu  8 Residual   2.90 Azims  90 180 Amp 1.08
Npts  348 SatNu 15 Residual   3.70 Azims  90 180 Amp 1.06
Npts  344 SatNu 24 Residual   3.39 Azims  90 180 Amp 1.10
Npts  340 SatNu 26 Residual   3.27 Azims  90 180 Amp 1.07
Npts  334 SatNu 27 Residual   3.48 Azims  90 180 Amp 1.09
Npts  350 SatNu 29 Residual   4.17 Azims  90 180 Amp 1.07
Npts  351 SatNu 30 Residual   2.93 Azims  90 180 Amp 1.09
```

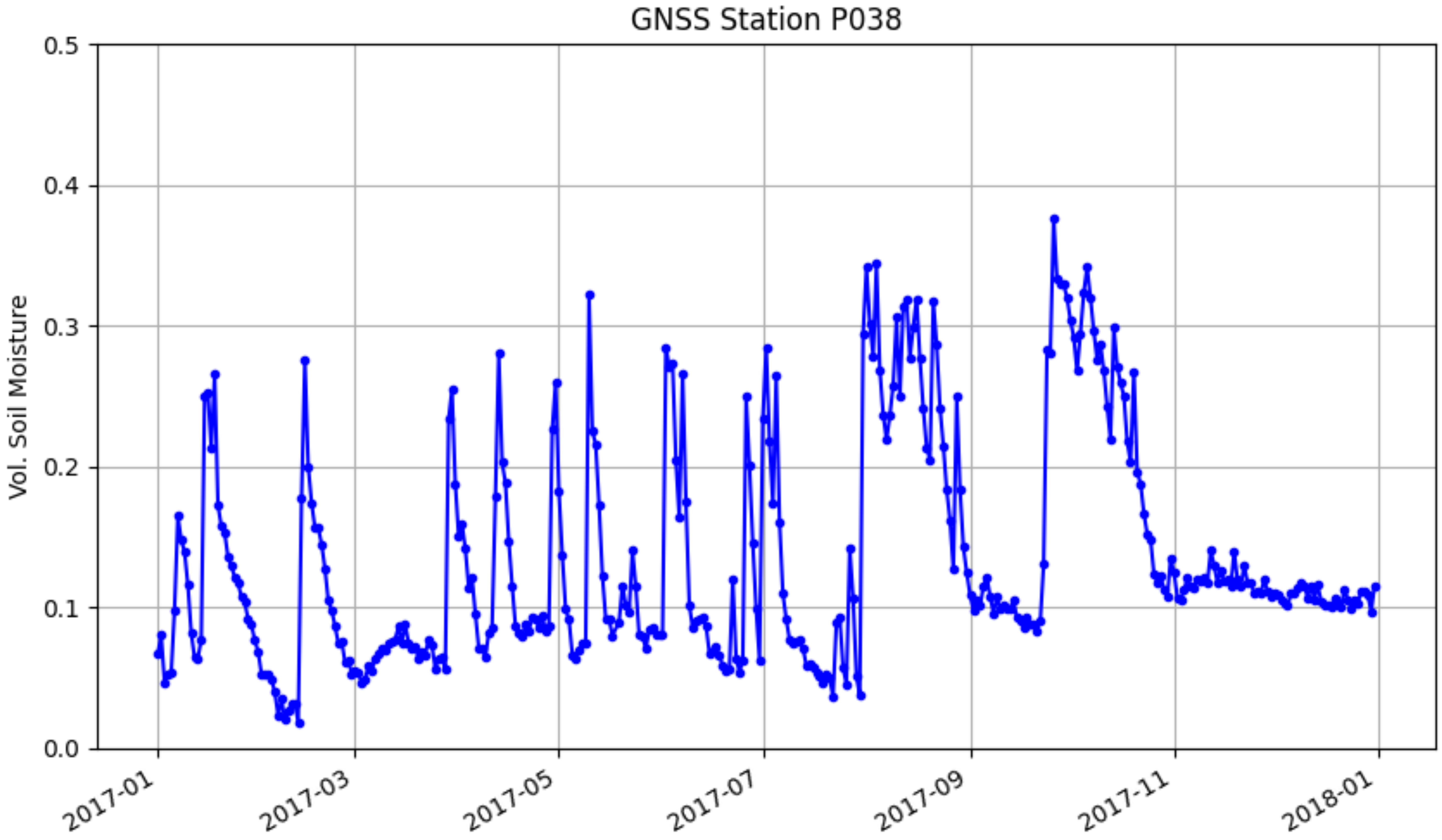


Daily L2C Phase Results: P038
phase (degrees)
20
15
10
5
0
2017-01
2017-03
2017-05
2017-07
2017-09
2017-11
2018-01

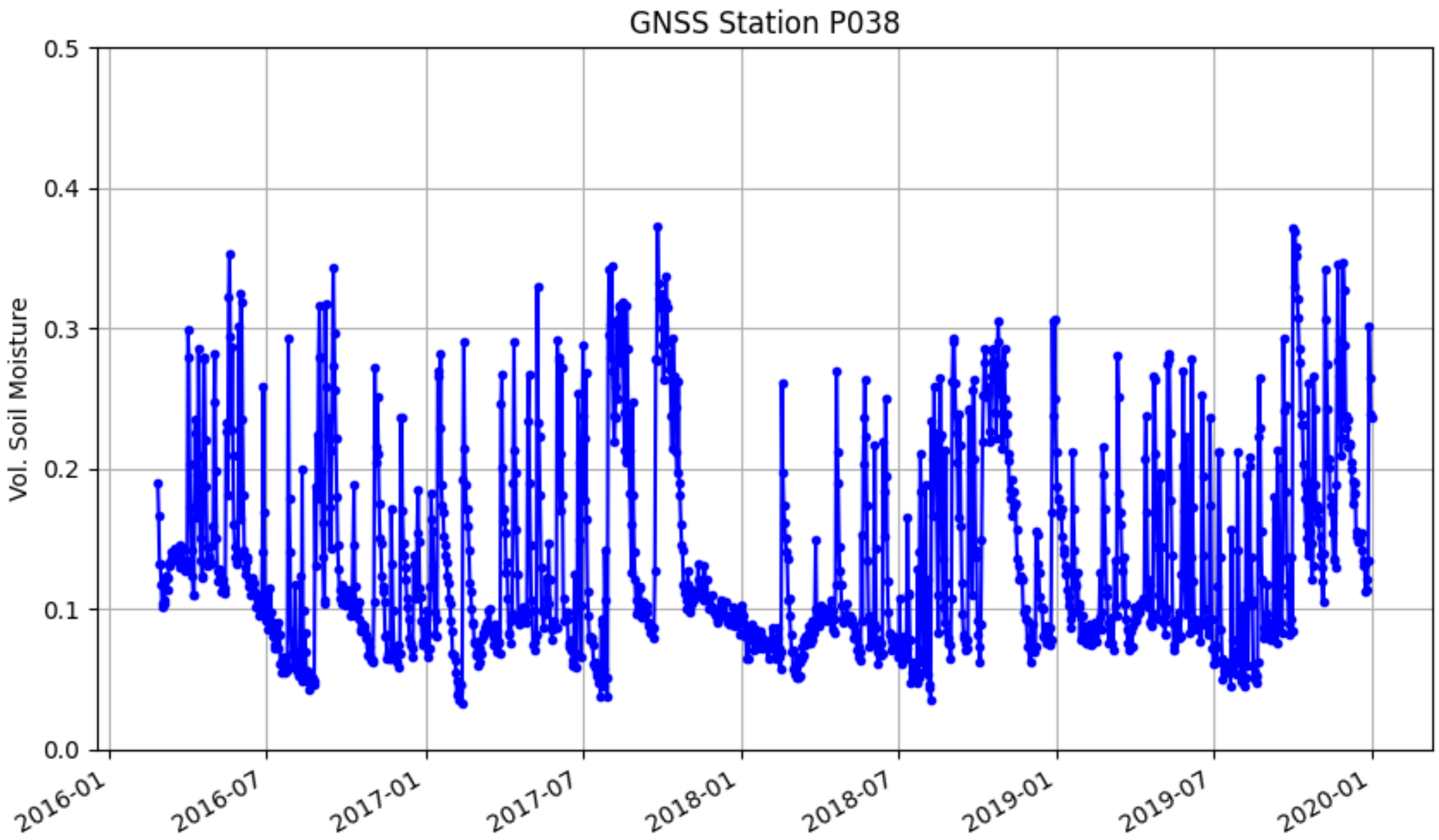
apply vegetation model of Chew et al.



Leveling the VWC series



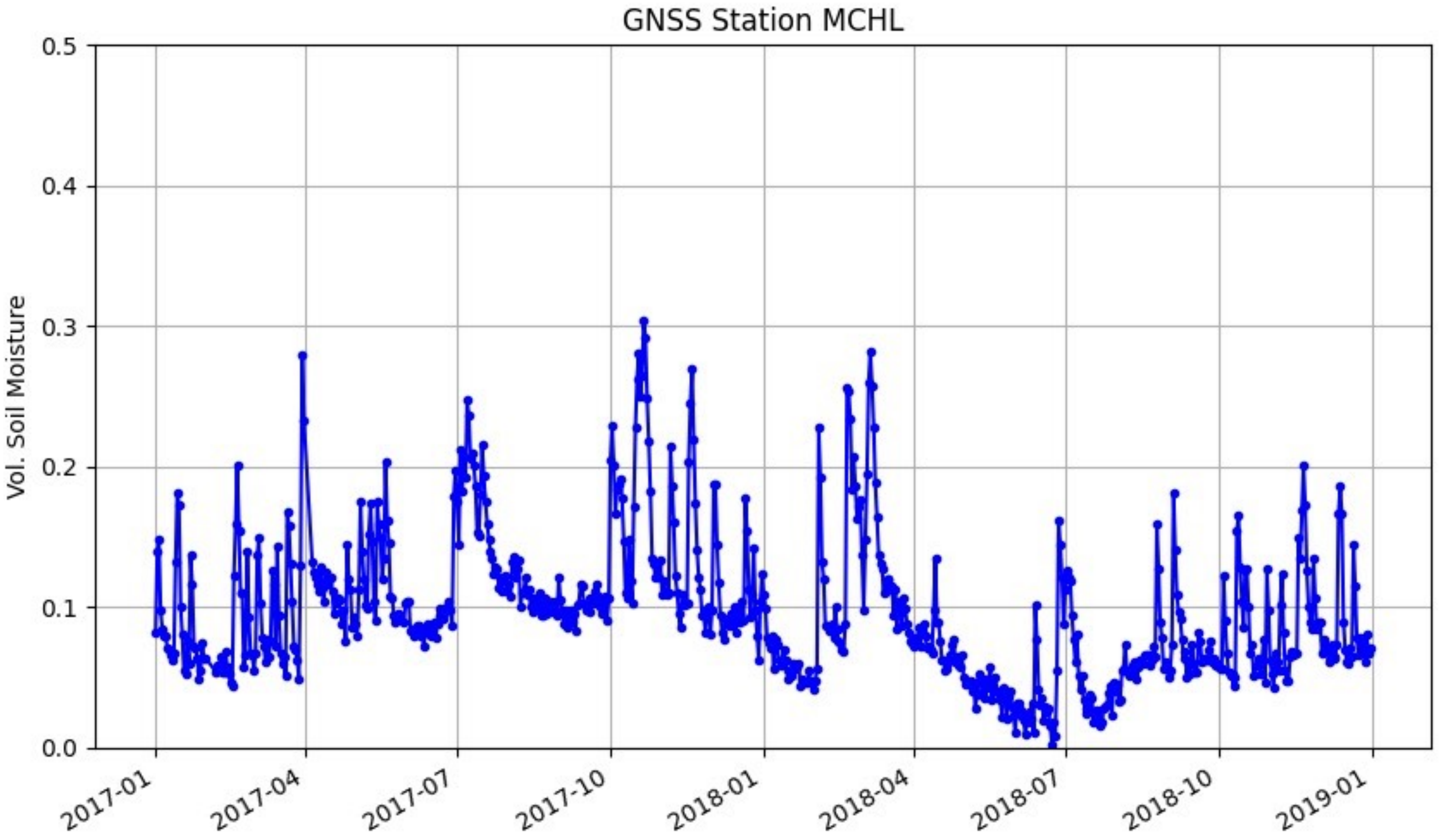
Four years of p038 results



vwc p038 2016 -year_end 2019

somewhere in Queensland

use case online covers 2017-2018



mchl00aus

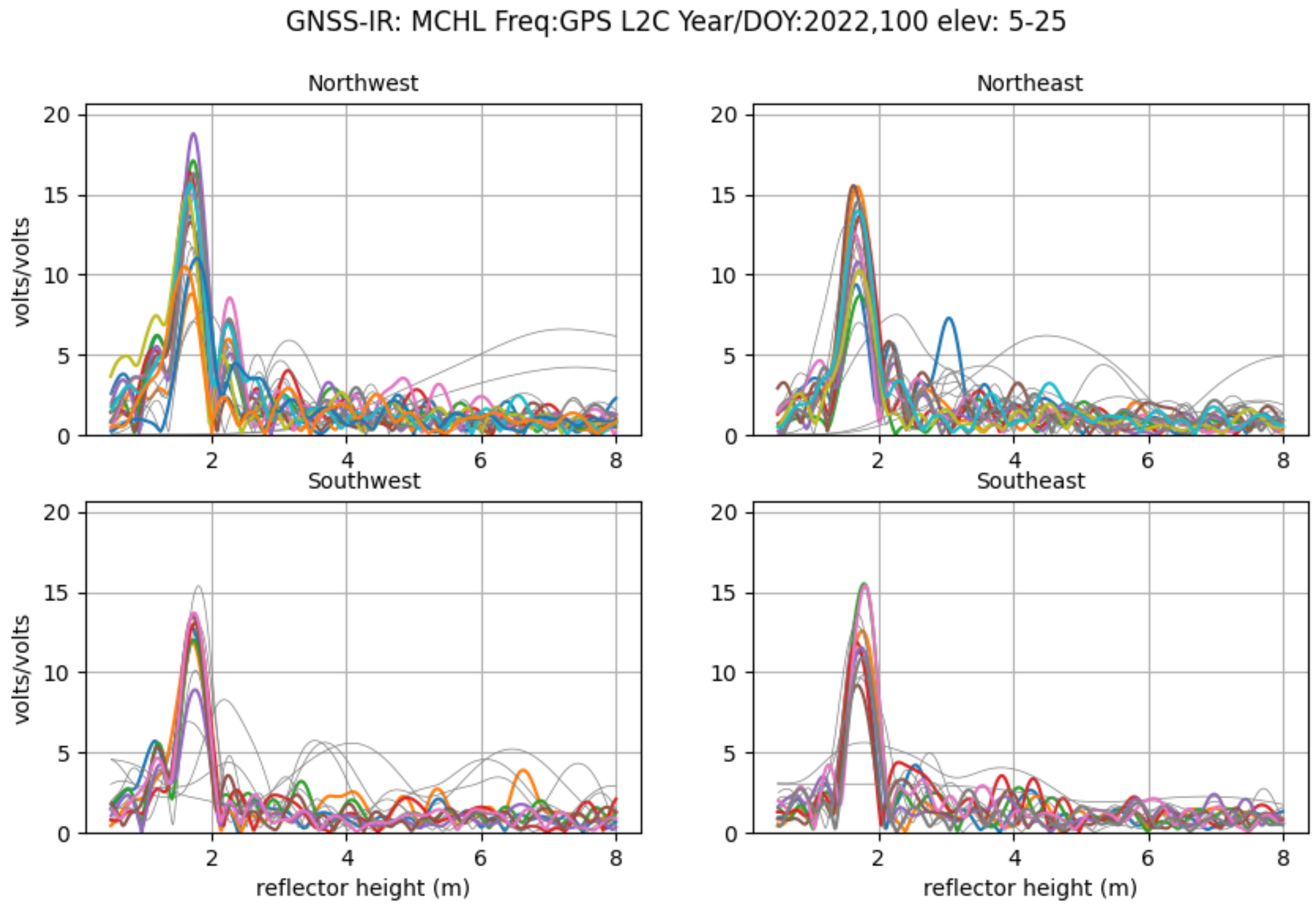
here we look at more recent data

```
rinex2snr mchl00aus 2021 1 -doy_end 366 -year_end 2022 -archive cddis
```

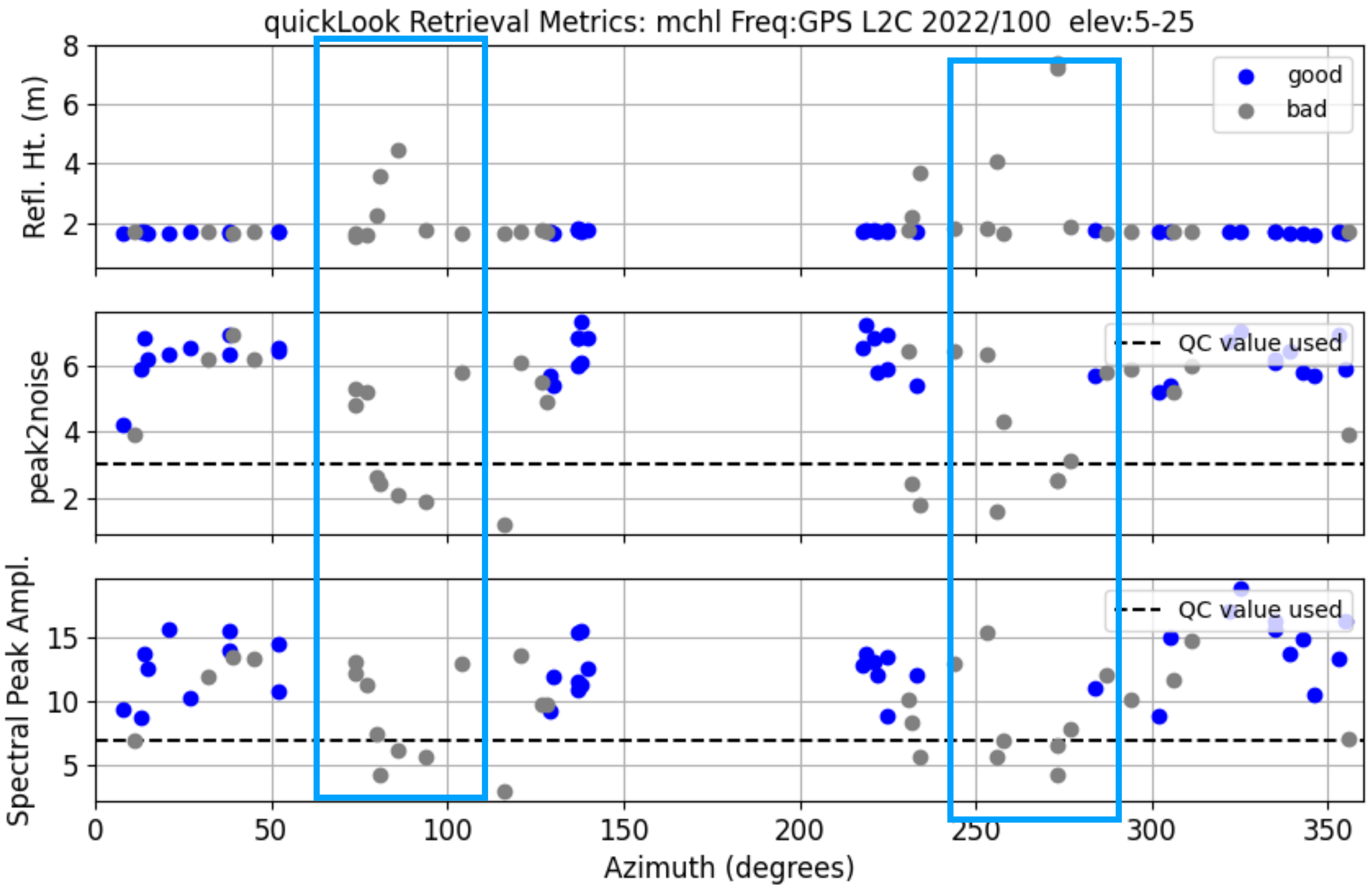
These data are also stored at GA. You should use that archive if you are in an Australian time zone. For me it is faster to use CDDIS

Why aren’t I using the rapid multi-GNSS orbits?

run quick look - make sure the data still look good.



notice the dead zones - these are mostly related to how the code treats satellite arcs that cross quadrant boundaries. it doesn't mean the soil is "bad" in these regions



```
make_json_input mchl 0 0 0 -l2c T
```

it is ok to use all GPS signals, i.e. this works

```
make_json_input mchl 0 0 0
```

Then compute RH. These are needed before you compute VWC

```
gnssir mchl 2021 1 -doy_end 366 -year_end 2022
```

vwc_input mchl 2022 - this figures out which tracks are available

```
% apriori RH values used for phase estimation
% year/station 2022 mchl
% tmin 0.05 (default)
% tmax 0.50 (default)
% Track  RefH SatNu MeanAz  Nval   Azimuths
%          m
   1  1.691    3    9.33    347    0   90
   2  1.688    4   39.19    347    0   90
   3  1.720    5   12.67    339    0   90
   4  1.725    6   12.97    320    0   90
   5  1.691    7   52.78    348    0   90
   6  1.658    9   21.77    351    0   90
   7  1.649   12   15.45    350    0   90
   8  1.692   18   51.51    348    0   90
   9  1.714   29   27.25    350    0   90
  10  1.702   30   36.82    351    0   90
  11  1.662   31    9.76    274    0   90
  12  1.717    5  138.54    349   90  180
  13  1.756    6  140.17    348   90  180
  14  1.784    8  138.68    348   90  180
  15  1.688   11  131.83    345   90  180
  16  1.757   15  137.80    348   90  180
  17  1.687   17  131.00    347   90  180
  18  1.779   26  137.76    348   90  180
  19  1.745   31  137.38    348   90  180
  20  1.646   32  123.51    174   90  180
  21  1.707    1  218.46    348  180  270
  22  1.721    3  233.74    222  180  270
  23  1.726    8  222.41    347  180  270
  24  1.728   24  222.02    349  180  270
  25  1.746   25  225.80    346  180  270
  26  1.730   26  226.36    263  180  270
  27  1.728   27  219.19    349  180  270
  28  1.654    1  339.60    348  270  360
  29  1.655    4  288.72    140  270  360
  30  1.703    7  303.52    347  270  360
  31  1.725   10  322.21    350  270  360
  32  1.683   11  356.26    139  270  360
  33  1.722   14  326.13    349  270  360
  34  1.691   17  354.56    350  270  360
  35  1.713   18  305.09    336  270  360
  36  1.717   23  335.49    344  270  360
  37  1.629   24  343.60    334  270  360
  38  1.695   27  335.85    347  270  360
  39  1.755   30  284.39    121  270  360
  40  1.648   32  347.53    351  270  360
```

40 tracks is way more than you need (code default is 10 I believe)

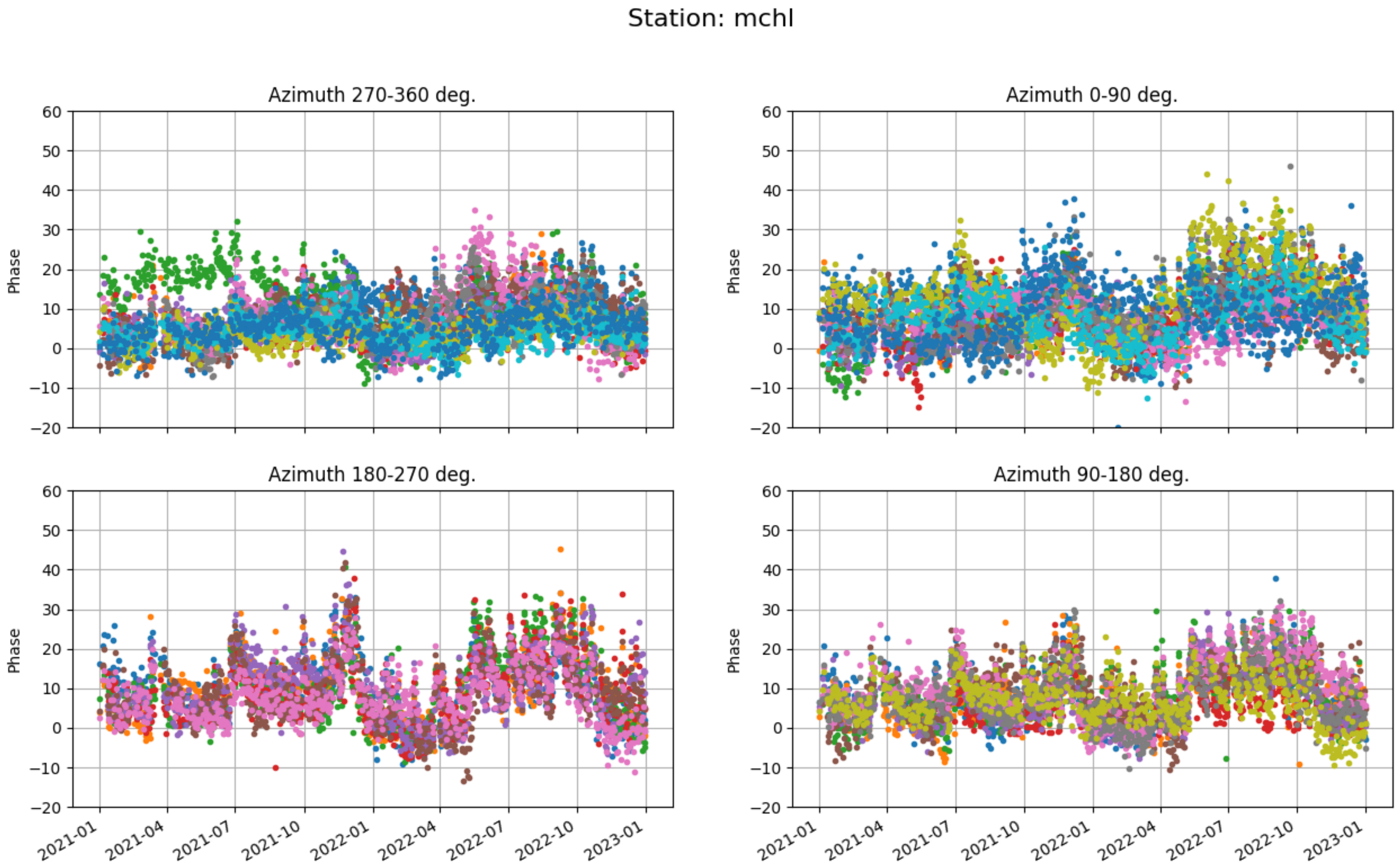
Compute phase

```
phase mchl 2021 1 -doy_end 366 -year_end 2022
```

and then compute VWC

```
vwc mchl 2021 -year_end 2022
```

assess quality of the tracks first



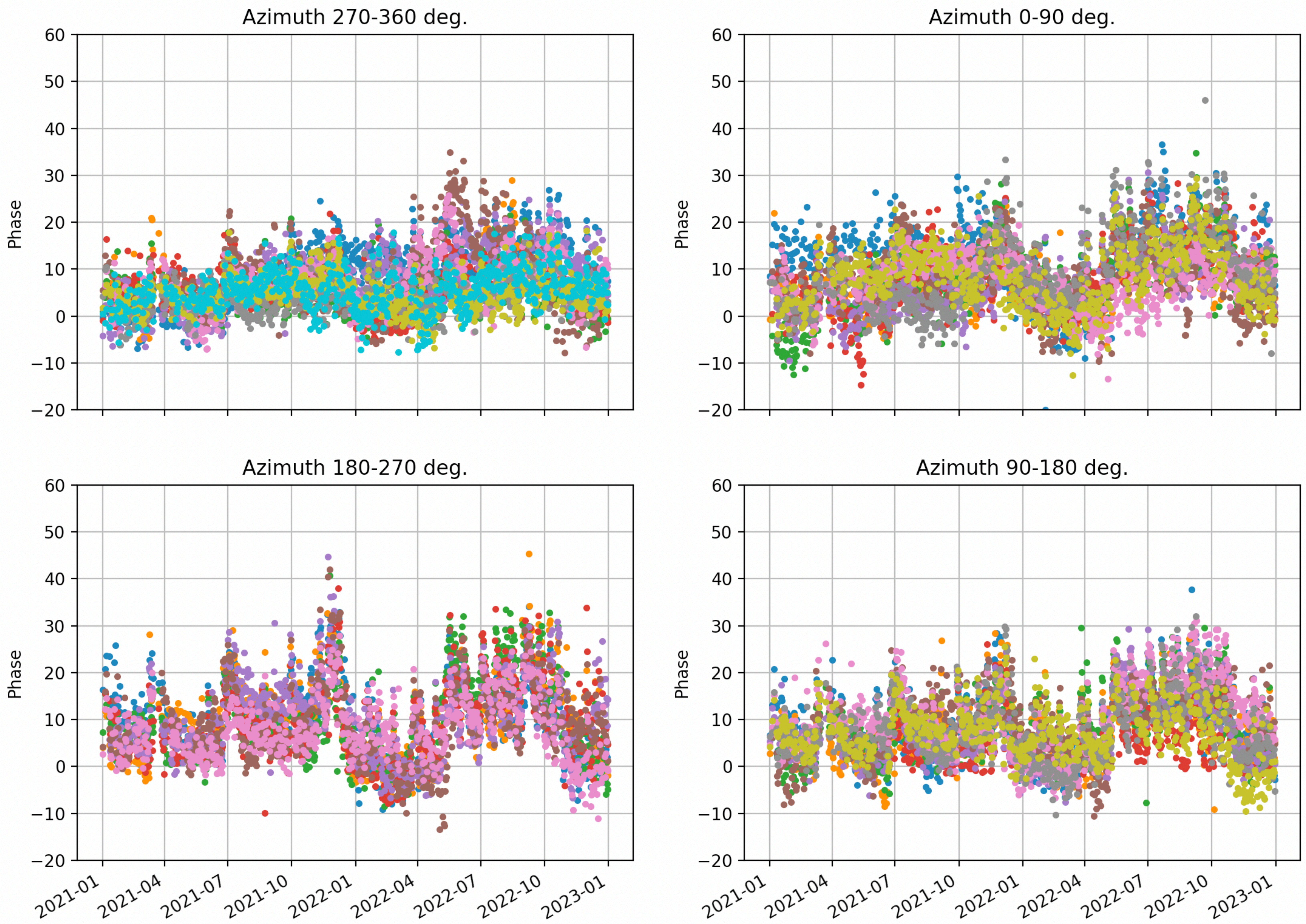
triggers on 5.5 - which is arbitrary. I would delete everything above 7. rerun vwc .

```
Npts  656 SatNu  1 Residual   5.40 Azims 270 360 Amp 1.08
Npts  105 SatNu  4 Residual   4.93 Azims 270 360 Amp 1.10
Npts  652 SatNu  7 Residual   7.15 Azims 270 360 Amp 1.10 >>>>>  Consider Removing This Track <<<<<
Npts  654 SatNu 10 Residual   3.53 Azims 270 360 Amp 1.10
Npts  659 SatNu 14 Residual   3.11 Azims 270 360 Amp 1.10
Npts  660 SatNu 17 Residual   5.11 Azims 270 360 Amp 1.08
Npts  639 SatNu 18 Residual   6.02 Azims 270 360 Amp 1.13 >>>>>  Consider Removing This Track <<<<<
Npts  653 SatNu 23 Residual   4.93 Azims 270 360 Amp 1.07
Npts  633 SatNu 24 Residual   4.20 Azims 270 360 Amp 1.11
Npts  653 SatNu 27 Residual   3.84 Azims 270 360 Amp 1.07
Npts  664 SatNu 32 Residual   4.42 Azims 270 360 Amp 1.07
Npts  659 SatNu  3 Residual   6.21 Azims   0  90 Amp 1.15 >>>>>  Consider Removing This Track <<<<<
Npts  656 SatNu  4 Residual   3.51 Azims   0  90 Amp 1.07
Npts  641 SatNu  5 Residual   5.13 Azims   0  90 Amp 1.19
Npts  652 SatNu  6 Residual   4.98 Azims   0  90 Amp 1.12
Npts  649 SatNu  7 Residual   4.36 Azims   0  90 Amp 1.06
Npts  659 SatNu  9 Residual   4.89 Azims   0  90 Amp 1.09
Npts  656 SatNu 12 Residual   5.80 Azims   0  90 Amp 1.09 >>>>>  Consider Removing This Track <<<<<
Npts  657 SatNu 18 Residual   5.74 Azims   0  90 Amp 1.12 >>>>>  Consider Removing This Track <<<<<
Npts  660 SatNu 29 Residual   7.81 Azims   0  90 Amp 1.14 >>>>>  Consider Removing This Track <<<<<
Npts  652 SatNu 30 Residual   4.23 Azims   0  90 Amp 1.09
Npts  619 SatNu 31 Residual   7.95 Azims   0  90 Amp 1.17 >>>>>  Consider Removing This Track <<<<<
Npts  657 SatNu  1 Residual   4.97 Azims 180 270 Amp 1.08
Npts  647 SatNu  3 Residual   4.88 Azims 180 270 Amp 1.12
Npts  654 SatNu  8 Residual   5.05 Azims 180 270 Amp 1.09
Npts  654 SatNu 24 Residual   4.67 Azims 180 270 Amp 1.08
Npts  641 SatNu 25 Residual   5.44 Azims 180 270 Amp 1.12
Npts  626 SatNu 26 Residual   5.41 Azims 180 270 Amp 1.10
Npts  659 SatNu 27 Residual   4.41 Azims 180 270 Amp 1.12
Npts  653 SatNu  5 Residual   4.18 Azims  90 180 Amp 1.08
Npts  647 SatNu  6 Residual   4.00 Azims  90 180 Amp 1.14
Npts  650 SatNu  8 Residual   3.77 Azims  90 180 Amp 1.09
Npts  355 SatNu 11 Residual   3.36 Azims  90 180 Amp 1.05
Npts  657 SatNu 15 Residual   3.52 Azims  90 180 Amp 1.07
Npts  597 SatNu 17 Residual   4.58 Azims  90 180 Amp 1.09
Npts  654 SatNu 26 Residual   4.75 Azims  90 180 Amp 1.08
Npts  656 SatNu 31 Residual   3.84 Azims  90 180 Amp 1.12
Npts  647 SatNu 32 Residual   4.29 Azims  90 180 Amp 1.10
```

```
vwc mchl 2021 -year_end 2022 -warning_value 7 -auto_removal T
```

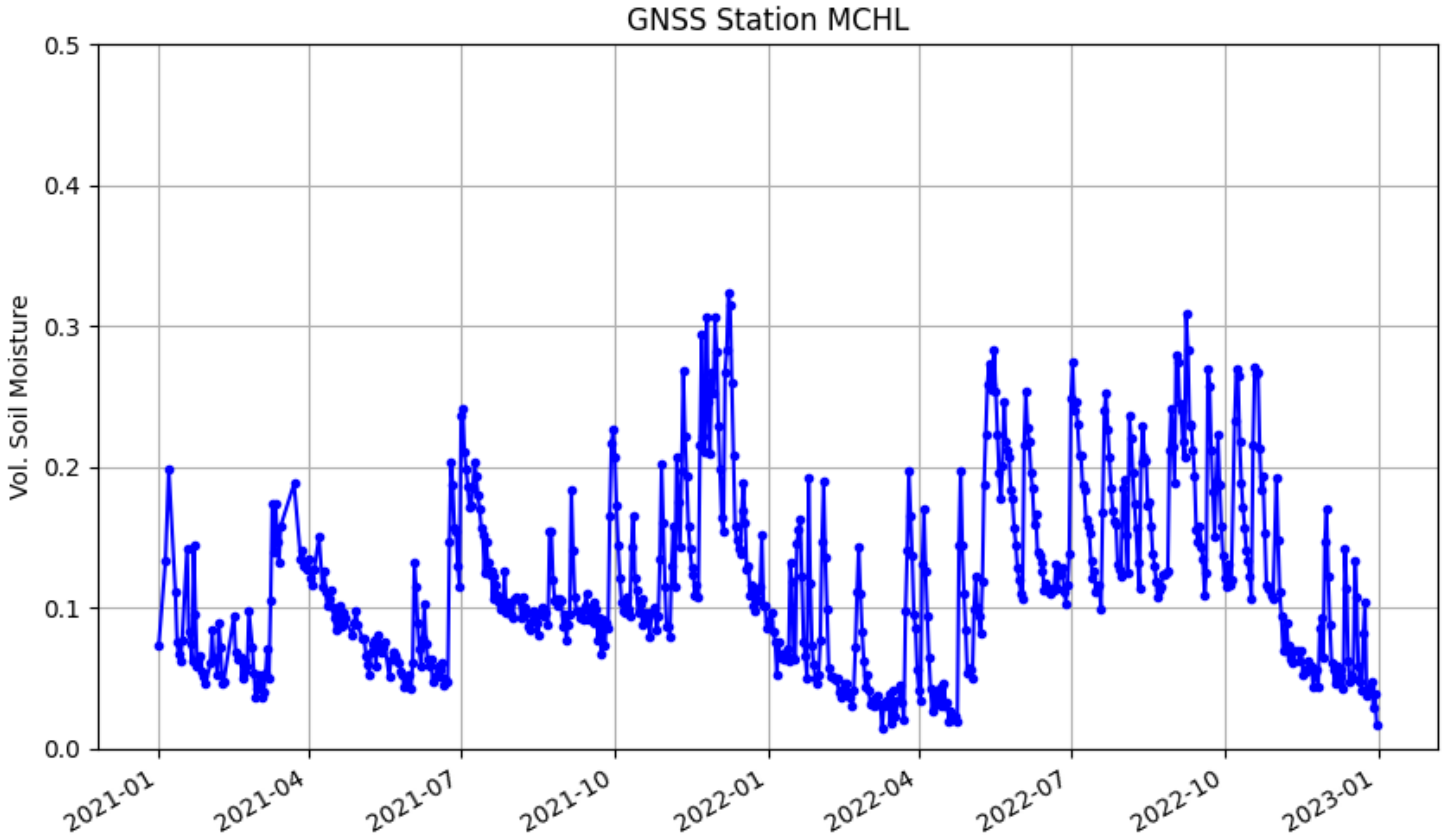
THEN run again

```
vwc mchl 2021 -year_end 2022
```



Question you might have: do you have to look at plots all the time? The answer is no. Set up an automated warning system. If we had needed to look at plots, PBO H2O could never have analyzed 150 soil moisture stations per day.

Final VWC series for 2021-2022

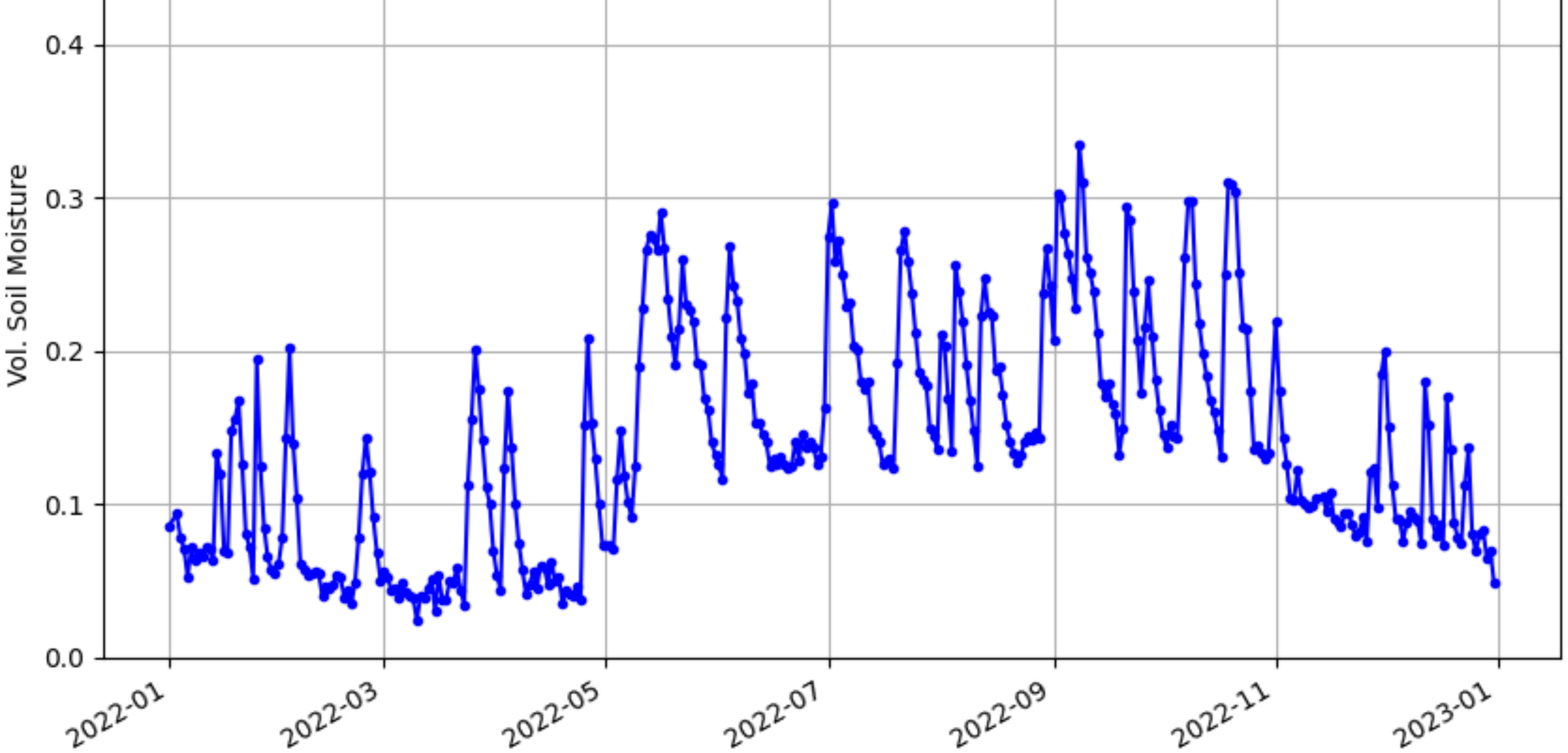


Number: 43020
Opened: 1884
Now: Open
Lat: 26.49° S
Lon: 147.98° E

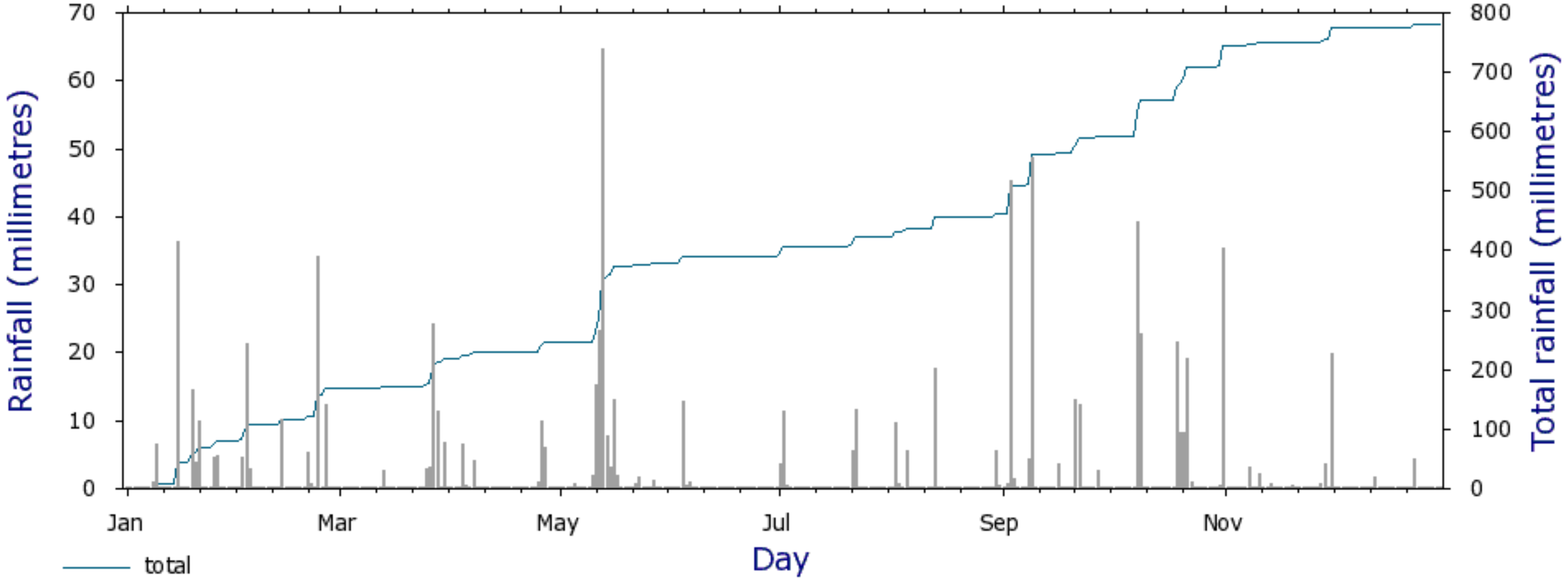
Station:mchl
Latitude: -26.35890466
Longitude: 148.14496051

http://www.bom.gov.au/climate/dwo/202205/html/IDCJDW4085.202205.shtml

http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=2022&p_c=-370162946&p_stn_num=043020



Mitchell Post Office (043020) 2022 rainfall



I leave the interpretation for hydrologists!

Things that can be improved

- The more advanced Chew/Zavorotny vegetation model is available, but *my group will not port it*. If someone is willing to port it from Matlab to python, please email me.

- min and max soil texture values can now be entered at the command line. but it would be better to save them in some kind of central file. *My group will take care of this in the not too distant future.*

- We need a database that alerts users that a receiver has changed. You might want to segregate the data from different receivers. Even if you don't, you will still want to know it happened. *My group will do this by end of the summer.*