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Analyzing the multipath of GPS time series to study snow properties

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Analyzing the multipath of GPS time series to study snow properties

By Ashlesha Khatiwada

Advisor: Hilary Martens

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Abstract:

Thousands of Global Navigation Satellite Systems (GNSS) receivers worldwide record signals sent by satellites to infer how each receiver (and the ground they are attached to) moves over time. The motion of GNSS receivers is used for many purposes, including studying tectonic deformation and changes in Earth's shape caused by surface loading. In this project, reflected wave arrivals contained within the multipath signal of GNSS time series are extracted and analyzed to advance understanding of snow properties in mountainous regions of Montana/Idaho, USA. Analyzing reflected signals in GNSS series has the potential to reveal properties of local snowpack, such as height, water content, snow surface temperature, dielectric properties, and density. Improving our ability to monitor the physical characteristics of snowpack and how they evolve over space and time is essential as properties of snow are key to understanding the slippage of one layer on another, which impacts avalanche hazard. Moreover, snowpack monitoring provides information about the availability of water resources and snow hydrology. This project focuses on analyzing the ray paths and attenuation of reflected GNSS signals, also using reflections to infer properties of snow. Traditionally, to study snow properties, one must manually dig a snow pit to study the snowpack and/or use expensive remote-sensing technologies (e.g. InSAR). However, digging snow pits can be dangerous due to avalanche risk as well as costly and time inefficient. Relatively low-cost GNSS stations that are now widely deployed worldwide present new opportunities to study snow properties, including in developing nations with fewer financial resources. We will use GNSS interferometric reflectometry (GNSS-IR) software developed by Kristine Larson (CCAR) to infer snow depth data from GNSS multipath. Results will be validated with snow-height data from nearby Snow Telemetry (SNOTEL) stations.

Introduction:

Seasonal snow plays a crucial role in Earth's environment and ecosystem, from regulating the temperature of the Earth's surface to replenishing rivers and reservoirs in many regions of the world to provide fresh water. Snow is an essential resource for the planet, but also brings hazards like an avalanche, that may impact human society gravely. Many people die or have their houses and facilities destroyed by avalanches each year.

There are two types of avalanches: slab avalanche, and loose snow avalanche. Slab avalanches occur when a dense, strong layer of snow forms over a weaker layer and the stronger layer, breaks over the slope causing all the snow to slide down at the same time. A loose snow avalanche occurs when the snow starts to flow from a point and fan outward as it moves downhill.

Many parts play a role in triggering avalanches. First, changes in temperature during the snowfall change the bonding structure of the snow; where the fresh snow bonds with the old snow weakly and creates weaker snow layers. Wind plays a significant part as well in locations where, if there are drifts deposited, these become an easy trigger point for avalanches. The snow slabs are made up of cohesive layers of snow which are typically formed as a result of high winds. The locations where snow has accumulated, such as in gullies and on ridgelines, are prone to avalanches as well.

Studying the height of the snow layer and its properties can help identify the avalanche-prone areas and possibly forecast the generation of such avalanches. Manually digging snow pits, taking measurements of snow height with snow pillows, remote-sensing technologies are some of the methods used to study the snow properties. However, these methods have their own temporal and/or spatial limitation, can be expensive, and can be labor-intensive and/or dangerous to perform. Moreover, developing countries and rural areas, where a lot of natural disasters occur, do not have the resources to afford many of these observational datasets. Therefore, we are proposing to use low-cost GNSS stations to extract the multipath data from GNSS signals to extract out the snow height of the snowpack. Extracting snow height is one of the first steps to studying snow properties.

A GNSS station is a system that includes the satellite, antenna, and receiver. The way it works is that several satellites will send a signal to the GNSS receiver and the time it takes for the signal to be received will be used to calculate its position. If the GNSS ground station moves over time due to seismic activity or other processes, it will record the change in displacement. In this research, we will not be looking at the direct signal from the satellite to calculate position, but rather the reflected multipath to extract information about the surrounding environment.

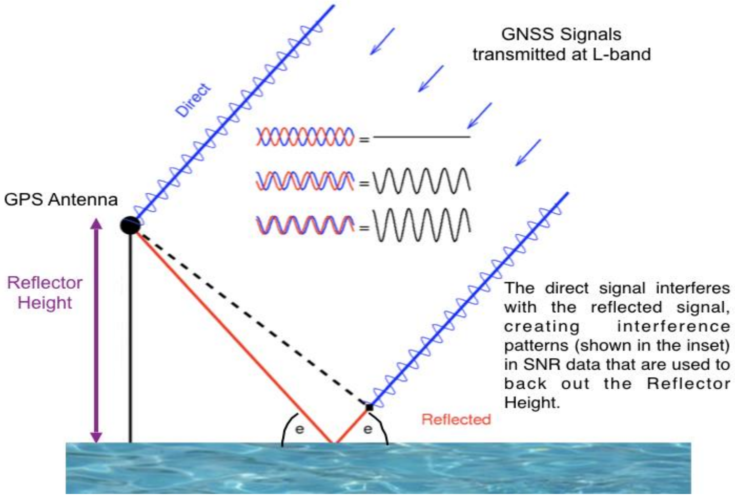


Figure 1: The multipath is the interference signal that is reflected off the environment not the direct signal that GNSS antenna receives from the satellite. (credit: Kristine Larson)

The multipath data is generated when signals from the satellite take different paths to the receiver and interference is measured (Larson et al. 2016, 2020). It affects the phase measurement and the frequency of the waves. Different objects may also affect the waves differently. Nearby vegetation and infrastructure, for example, will affect the reflectivity of the satellite signal to the GNSS antenna. Moreover, water and dry snow have different structures and bonding. The crystallography of water is different from snow. Moreover, as the snow metamorphoses, the crystal structure will change as well. Dry snow has more vacuum space than snow with some liquid water. These aspects change the frequency and the phase of the signal that the antenna receives and affects signal attenuation. In this research, we will be focusing on snowpack height, and we defer the analysis of distinguishing between different layers of snow to future work.

Kristine Larson's software, GNSS-IR will be used in this research to extract out multipath signals recorded by GNSS stations and then estimate the snow height. Furthermore, the research will compare and verify the estimates of snow height with an independent estimates of snow height from nearby SNOTEL stations.

Motivation:

In April 2015, Nepal was hit by a 7.8Mw earthquake. The earthquake affected a lot of lives, from causing many casualties to destroying infrastructure in the country. The earthquake also brought other natural hazards with it. Nepal went through severe landslides and avalanches right after it got hit by the earthquake, affecting even more civilians who had already lost a lot. During this time, I was in Nepal and personally experienced this event with my family.

Coming from Nepal, I know that developing countries have very little resources and budget to research natural hazards and to mitigate them. Moreover, there is not much technology available in the country to study these natural processes. Therefore, I became motivated to explore ways in which we can minimize the cost and use resources that are already available or cheaper to afford to study natural processes, mainly focusing on natural hazards and to help mitigate those hazards in the future.

I became interested in using GNSS data in this research after my fieldwork during summer 2020 in Selway, Idaho. During my fieldwork, I was assisting post-graduates on GNSS and weather station installation and gathering data from it. It was truly an amazing learning experience, and I became fascinated by how GNSS works. Through my research and my advisor's guidance, I became inspired to learn and research more on how GNSSS multipath error can be used to study the nearby environmental changes focusing temporal variations in snow height.

Method:

GNSS interferometric reflectometry (GNSS-IR) is a technique that uses reflected satellite signals recorded by GNSS stations, for sensing the near field environment. The software uses Signal-to-Noise ratio (SNR) data to estimate changes in the height of the reflecting surface. The software can be used to study various aspects of the environment such as seasonal snow accumulation, tides and storm surges, lakes and rivers, soil moisture, and ice sheets. Here, the software will be used to study seasonal snow accumulation.

An appropriate GNSS station needs to be picked for the GNSS-IR to work effectively. The geographic location, the surrounding environment of the GNSS station, and the amount of data the GNSS station gathers throughout the year will affect the quality of the reflected height estimate.

I wanted to focus my research near Montana and Idaho, as that is the place I had gone for my fieldwork. Therefore, I picked a few GNSS stations in this area. Moreover, the GNSS stations here were all Plate-Boundary-Observatory (PBO) stations which collects the type of data needed for the GNSS-IR.

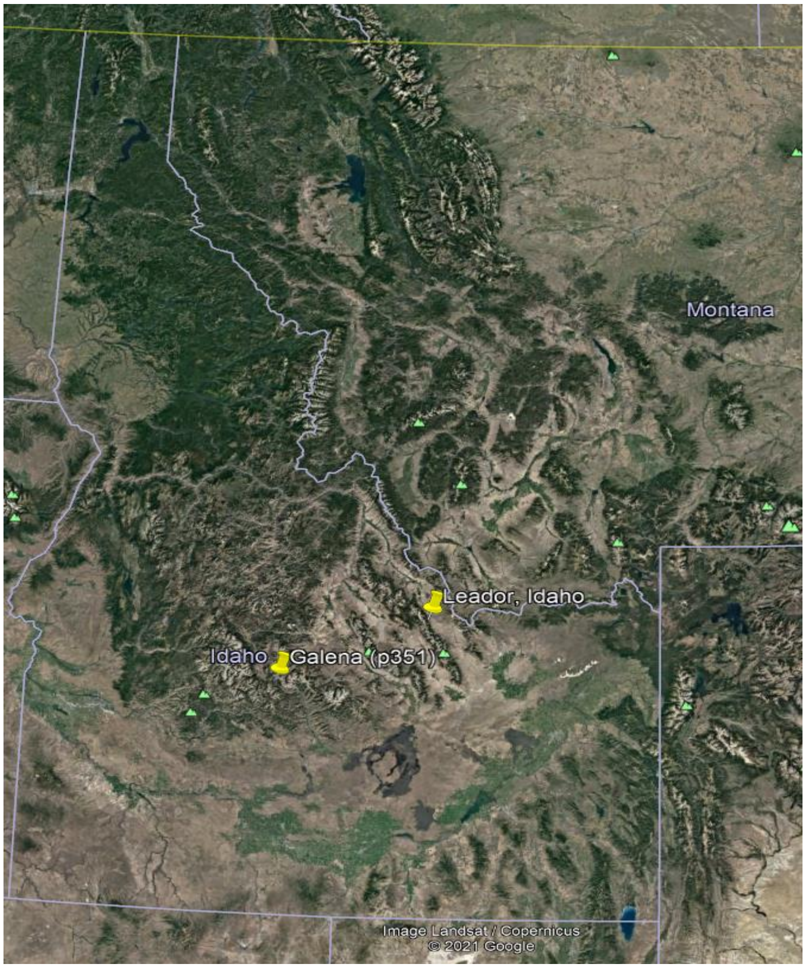


Figure 2: Locations of two GNSS station that will be used to extract snow height in this paper

To pick a good GNSS station, the first thing to do is to look at photographs of the site installation. The GNSS station should be in a flat area and have no obstructions nearby, including thick vegetation and infrastructure. If the GNSS is in plain sight, on level ground, and the GNSS antenna remains unburied during the winter months, then it is a good site to pick.

Figure 3: GNSS station P360at Galena, Idaho, during summer (left) and winter (right).The station is deployed on a flat surface. In winter the antenna is not completely buried by snowpack, so there is no loss of data.

Secondly, the software itself can be used to identify an appropriate station. One can use the “QuickLook” command from the software to generate a periodogram for a particular day to see if there are consistent peaks that correspond to the reflector height. If the periodogram has peaks that are not consistent and are all over the graph it means that certain satellite data from certain azimuths need to be discarded or that there are too many obstructions around the site that make the data less coherent. The figures below show an example of a periodogram from a good site with strong signal coherence and another periodogram from poor site.

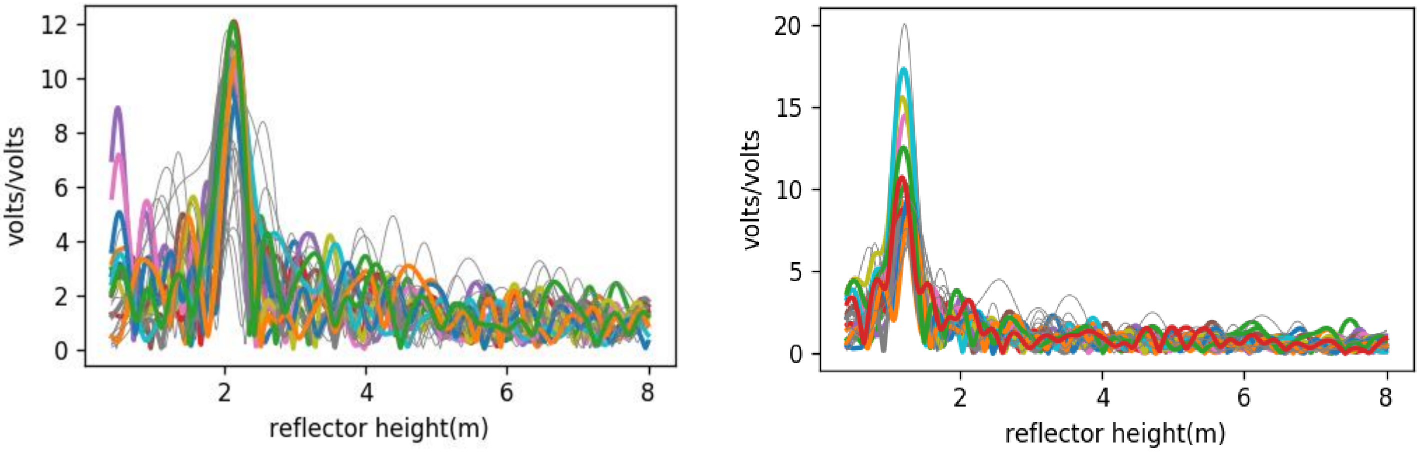


Figure 4: (left) A periodogram of GNSS multipath reflections during the summer months at a GNSS station near Galena, Idaho. A consistent peak and one large peak can be seen this is periodogram. This signifies that there is good data available for this station. (right) A periodogram from the same station during the winter months, when the reflector height is lower, indicating a shorter distance between the GNSS antenna and the reflector, and the likely presence of snow.

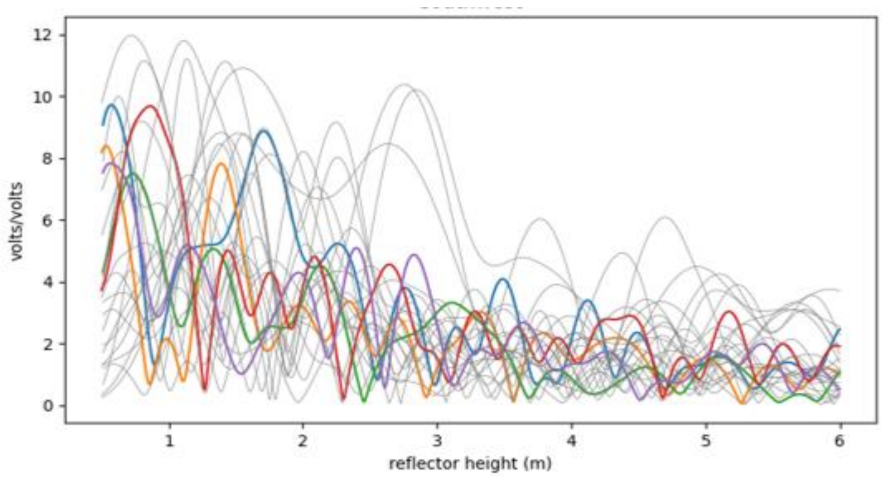


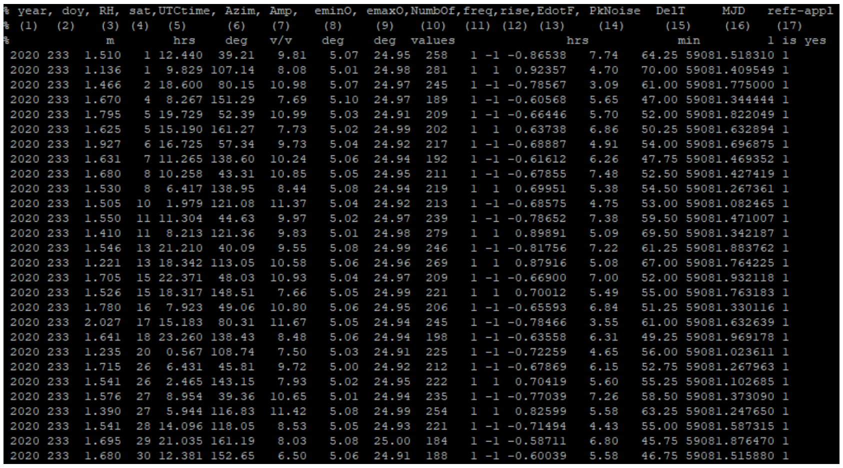
Figure 5: An example of a noisy data from the SELD GNSS station in Alaska, where there is no consistent peak to pick out the reflector height

After picking appropriate GNSS sites for the multipath analysis, the GNSS-IR software can be used to analyze data on the reflector's height.

In the end we will be comparing the GNSS extracted snow height with SNOTEL, which is an instrument that independently extracts snow height. The way SNOTEL measures snowpack height is by sending a laser beam at the ground and the time it takes for the laser beam to reflect back can be used to extract the snowpack height over time.

Data:

The GNSS-IR software extracts reflector height from the multipath data. The reflector height is the distance between the reflecting surface to the GNSS antenna. In summer, the reflector height is maximized since the reflection surface is bare soil and there is more distance from the GNSS antenna to the bare soil. During winter, the reflection height is relatively low, since there is snow accumulation and the signal from the satellite reflects off the top of the snow to the GNSS antenna. The software will extract out the reflector height for each day from various satellites and azimuthal angles. Hence, a mean filter must be used to extract out the average reflector height for each day. If there is no missing data, GNSS-IR command "daily_avg" can be used on a particular station to generate the mean for each day. However, often the stations have missing data throughout the year. Thus, in this research, I occasionally computed the daily mean reflector height manually. After computing the daily average reflector height, the data is ready to be plotted as a time series to analyze snow accumulation and melting throughout the year.



```
% year, doy, RH, sat,UTCtime, Azim, Amp,  eminO, emaxO,NumbOf,freq,rise,EdotF, PkNoise  DelT     MJD   refr-appl
% (1)  (2)   (3) (4)  (5)     (6)   (7)    (8)    (9)   (10)  (11) (12) (13)     (14)     (15)    (16)   (17)
%             m        hrs    deg   v/v    deg    deg  values              hrs            min         1 is yes
 2020 233  1.510   1 12.440  39.21   9.81   5.07  24.95  258   1 -1 -0.86538   7.74   64.25 59081.518310 1
 2020 233  1.136   1  9.829 107.14   8.08   5.01  24.98  281   1  1  0.92357   4.70   70.00 59081.409549 1
 2020 233  1.466   2 18.600  80.15  10.98   5.07  24.97  245   1 -1 -0.78567   3.09   61.00 59081.775000 1
 2020 233  1.670   4  8.267 151.29   7.69   5.10  24.97  189   1 -1 -0.60568   5.65   47.00 59081.344444 1
 2020 233  1.795   5 19.729  52.39  10.99   5.03  24.91  209   1 -1 -0.66446   5.70   52.00 59081.822049 1
 2020 233  1.625   5 15.190 161.27   7.73   5.02  24.99  202   1  1  0.63738   6.86   50.25 59081.632894 1
 2020 233  1.927   6 16.725  57.34   9.73   5.04  24.92  217   1 -1 -0.68887   4.91   54.00 59081.696875 1
 2020 233  1.631   7 11.265 138.60  10.24   5.06  24.94  192   1 -1 -0.61612   6.26   47.75 59081.469352 1
 2020 233  1.680   8 10.258  43.31  10.85   5.05  24.95  211   1 -1 -0.67855   7.48   52.50 59081.427419 1
 2020 233  1.530   8  6.417 138.95   8.44   5.08  24.94  219   1  1  0.69951   5.38   54.50 59081.267361 1
 2020 233  1.505  10  1.979 121.08  11.37   5.04  24.92  213   1 -1 -0.68575   4.75   53.00 59081.082465 1
 2020 233  1.550  11 11.304  44.63   9.97   5.02  24.97  239   1 -1 -0.78652   7.38   59.50 59081.471007 1
 2020 233  1.410  11  8.213 121.36   9.83   5.01  24.98  279   1  1  0.89891   5.09   69.50 59081.342187 1
 2020 233  1.546  13 21.210  40.09   9.55   5.08  24.99  246   1 -1 -0.81756   7.22   61.25 59081.883762 1
 2020 233  1.221  13 18.342 113.05  10.58   5.06  24.96  269   1  1  0.87916   5.08   67.00 59081.764225 1
 2020 233  1.705  15 22.371  48.03  10.93   5.04  24.97  209   1 -1 -0.66900   7.00   52.00 59081.932118 1
 2020 233  1.526  15 18.317 148.51   7.66   5.05  24.99  221   1  1  0.70012   5.49   55.00 59081.763183 1
 2020 233  1.780  16  7.923  49.06  10.80   5.06  24.95  206   1 -1 -0.65593   6.84   51.25 59081.330116 1
 2020 233  2.027  17 15.183  80.31  11.67   5.05  24.94  245   1 -1 -0.78466   3.55   61.00 59081.632639 1
 2020 233  1.641  18 23.260 138.43   8.48   5.06  24.94  198   1 -1 -0.63558   6.31   49.25 59081.969178 1
 2020 233  1.235  20  0.567 108.74   7.50   5.03  24.91  225   1 -1 -0.72259   4.65   56.00 59081.023611 1
 2020 233  1.715  26  6.431  45.81   9.72   5.00  24.92  212   1 -1 -0.67869   6.15   52.75 59081.267963 1
 2020 233  1.541  26  2.465 143.15   7.93   5.02  24.95  222   1  1  0.70419   5.60   55.25 59081.102685 1
 2020 233  1.576  27  8.954  39.36  10.65   5.01  24.94  235   1 -1 -0.77039   7.26   58.50 59081.373090 1
 2020 233  1.390  27  5.944 116.83  11.42   5.08  24.99  254   1  1  0.82599   5.58   63.25 59081.247650 1
 2020 233  1.541  28 14.096 118.05   8.53   5.05  24.93  221   1 -1 -0.71494   4.43   55.00 59081.587315 1
 2020 233  1.695  29 21.035 161.19   8.03   5.08  25.00  184   1 -1 -0.58711   6.80   45.75 59081.876470 1
 2020 233  1.680  30 12.381 152.65   6.50   5.06  24.91  188   1 -1 -0.60039   5.58   46.75 59081.515880 1
```

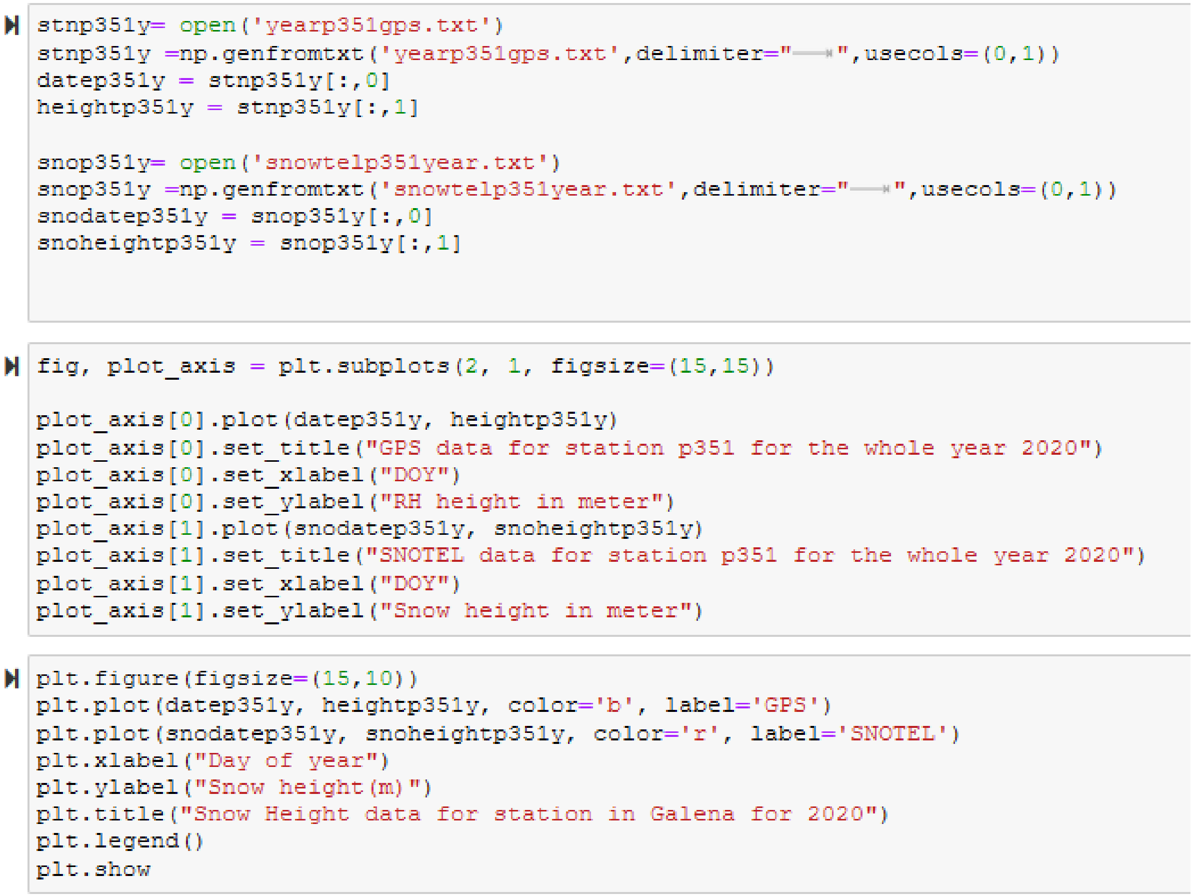
Figure 6: Results from the GNSS-IR software, which shows the reflector height for different satellites at different azimuths. This data will be used to find the daily mean reflector height.

Results:

After collecting the daily mean reflector heights from GNSS-IR, I subtract the reflected height on each day from the bare soil height during the summer months to estimate snow height each day (using Microsoft Excel). The time series of snow heights are then transferred to Python for plotting. Figure 7 shows the Python code I wrote to plot the time series of the snow height derived from GNSS multipath and from SNOTEL in the same figure.

Figure 8 shows snow height extracted from GNSS multipath for the Galena station and from a nearby SNOTEL station for a period of four months in 2020. The blue line represents the GNSS estimates of snow height and the red line represents the SNOTEL estimates of snow height. The trends of the lines appear similar, suggesting a strong correlation. The maximum snow height from SNOTEL is 1.6 meters; for GNSS, the extracted maximum snow height is 1.4 meters. Figure 9 is identical to Fig. 8, but shows the full year of 2020.

In figure 10, I show a comparison of GNSS-derived snow height (top panel) and SNOTEL-derived snow height (bottom panel) for another GNSS station in Leador, Idaho. The figure depicts snow heights over the full year of 2020.



```
stnp351y= open('yearp351gps.txt')
stnp351y =np.genfromtxt('yearp351gps.txt',delimiter="→",usecols=(0,1))
datep351y = stnp351y[:,0]
heightp351y = stnp351y[:,1]

snop351y= open('snowtelp351year.txt')
snop351y =np.genfromtxt('snowtelp351year.txt',delimiter="→",usecols=(0,1))
snodatep351y = snop351y[:,0]
snoheightp351y = snop351y[:,1]
```

```
fig, plot_axis = plt.subplots(2, 1, figsize=(15,15))

plot_axis[0].plot(datep351y, heightp351y)
plot_axis[0].set_title("GPS data for station p351 for the whole year 2020")
plot_axis[0].set_xlabel("DOY")
plot_axis[0].set_ylabel("RH height in meter")
plot_axis[1].plot(snodatep351y, snoheightp351y)
plot_axis[1].set_title("SNOTEL data for station p351 for the whole year 2020")
plot_axis[1].set_xlabel("DOY")
plot_axis[1].set_ylabel("Snow height in meter")
```

```
plt.figure(figsize=(15,10))
plt.plot(datep351y, heightp351y, color='b', label='GPS')
plt.plot(snodatep351y, snoheightp351y, color='r', label='SNOTEL')
plt.xlabel("Day of year")
plt.ylabel("Snow height(m)")
plt.title("Snow Height data for station in Galena for 2020")
plt.legend()
plt.show
```

Figure 7: Code used to plot snow height from both SNOTEL and GNSS data.

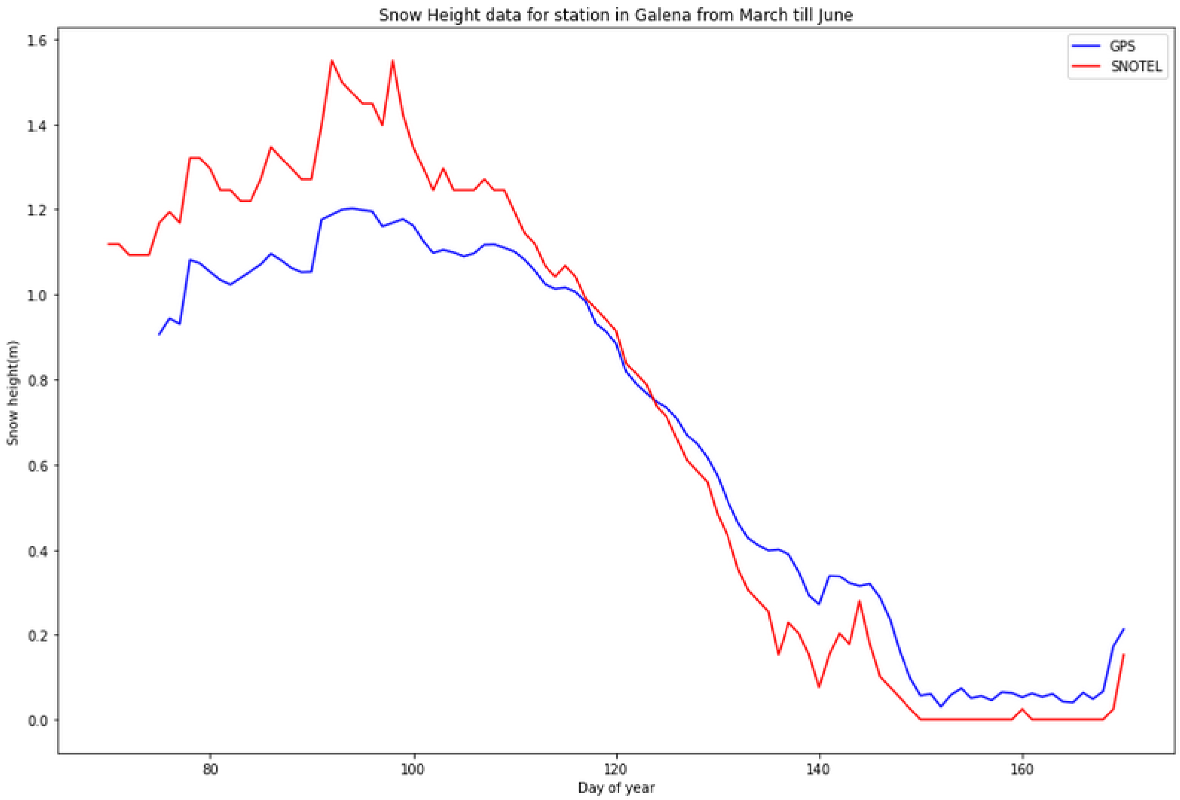


Figure 8: This graph shows that the GNSS extracted snow height follows a similar trend of snow height extracted off of SNOTEL. The figure shows March-June of 2020.

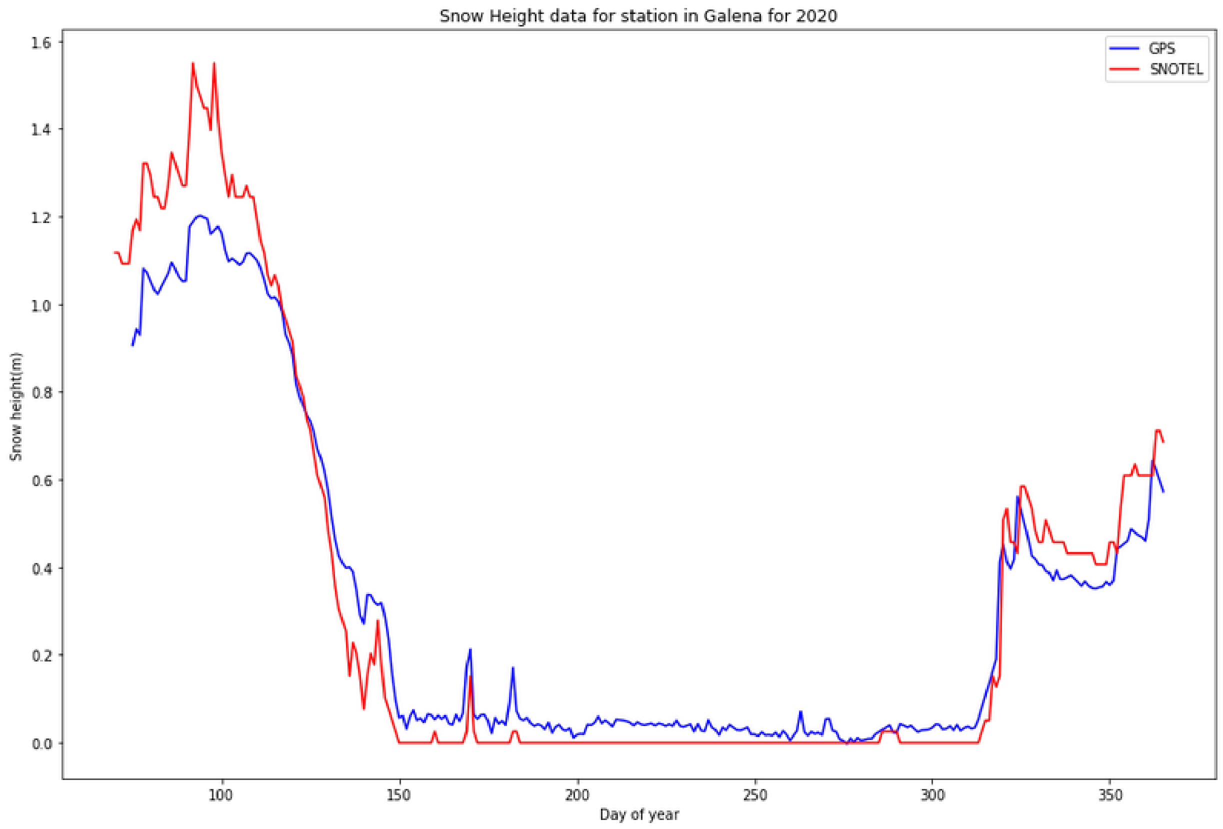


Figure 9: This graph shows snow height data form GNSS and SNOTEL for the entire year of 2020. There is a similar trend between GNSS and SNOTEL, indicating a strong correlation.

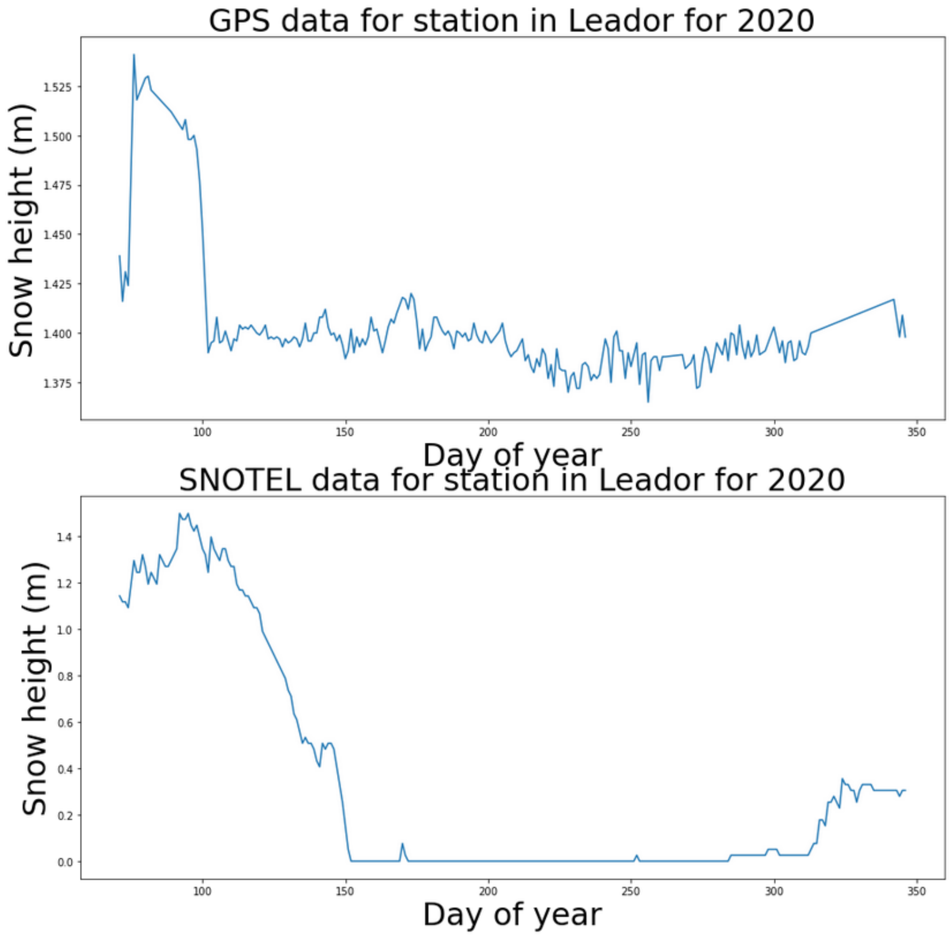


Figure 10: GNSS and SNOTEL extracted snow height from stations near Leador, Idaho. The GNSS site was located on a slight slope, with the antenna being partly buried during the winter, which resulted in missing data (including fewer data recordings each day).

Analysis:

From the result, we can see that the snow height estimated from GNSS multipath and the snow height extracted from SNOTEL match the trends of the seasonal snowpack height.

The station in Galena, Idaho, (see Fig. 1) was one of the stations that yielded higher-quality results than other stations due to its optimal site location and surroundings. The station lies on a flat surface and there were no obstructions at the site. Moreover, this station was the closest in proximity to a SNOTEL station, which we are using for an independent comparison. The proximity of the SNOTEL to the GNSS station affects the results since snowpack can vary significantly between different mountain ranges. The comparisons are provided for four months of snow accretion through to snow ablation in the year 2020 (Figure 8) for Galena and a year-long time series of snow height for the year 2020 (Figure 9). The bare soil reflector height is constructed during summertime and it came out to be 1.9 meters. To find the snow height daily, I subtracted the daily estimated reflector heights from the 1.9 meters reference height.

On the snow height data for the station in Galena, Idaho, from March through June, we can see that the GNSS station records 1.4 meters as the maximum snow height and the SNOTEL records a maximum of 1.6 meters of snow height. The difference of 0.2 meters reflects a combination of error in the GNSS and SNOTEL measurements of snow height, as well as spatial variations in snow height between the two stations.

To analyze this result further, we will use the Pearson correlation coefficient to test the relationship between the result we obtained from SNOTEL and GNSS extracted snow height. Figures 11 and 12 shows the graphs of SNOTEL vs GNSS estimates of snow height for the year 2020 and for subset of 4 months, respectively, at the station in Galena. The graph and the Pearson correlation coefficient both show that there is a strong linear relationship between GNSS ad the SNOTEL estimates of snow height. This means that the result we obtained for snow height from GNSS multipath signals corresponds well with the estimates of snow height from nearby SNOTEL station. In other words, the GNSS multipath provides independent measurement of snow height at this site.

```
Pearson Correlation Coeffecient is: 0.9643142353584174
```

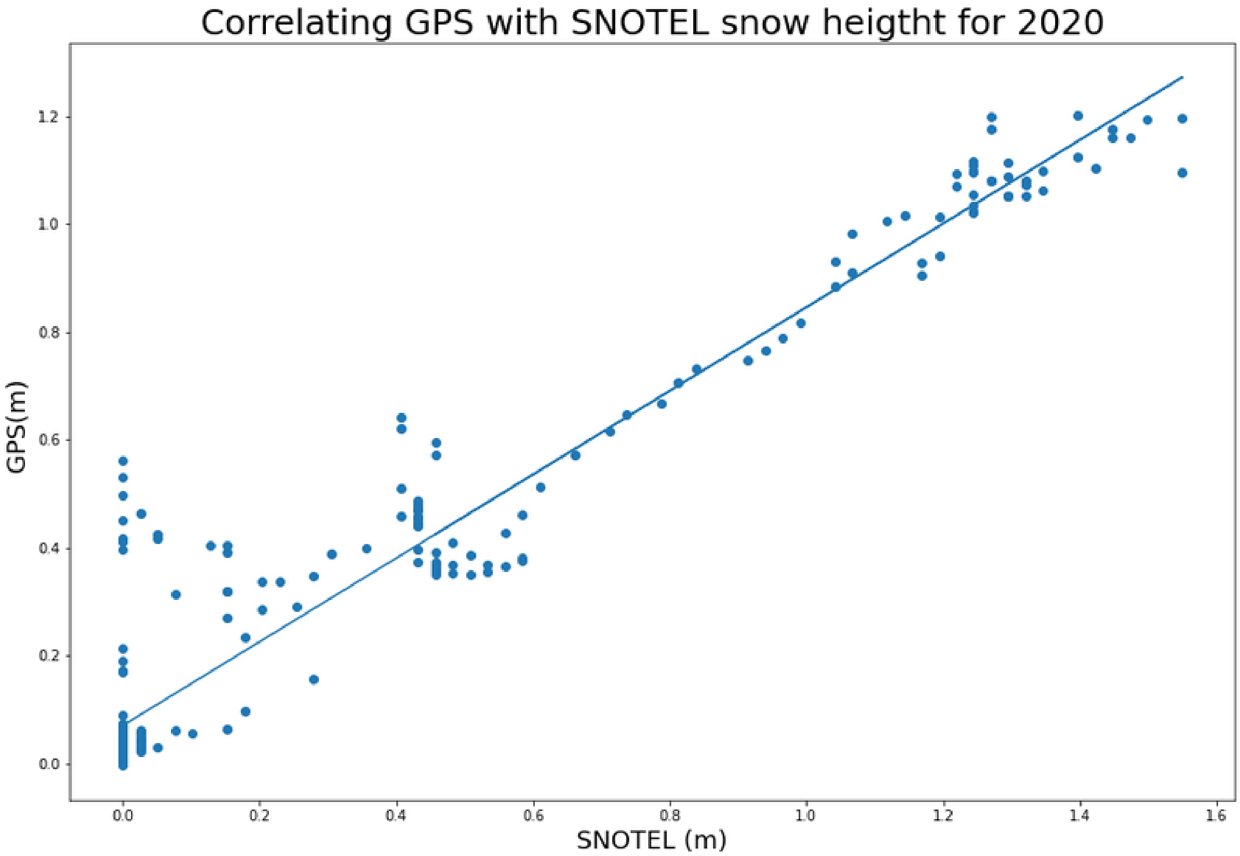
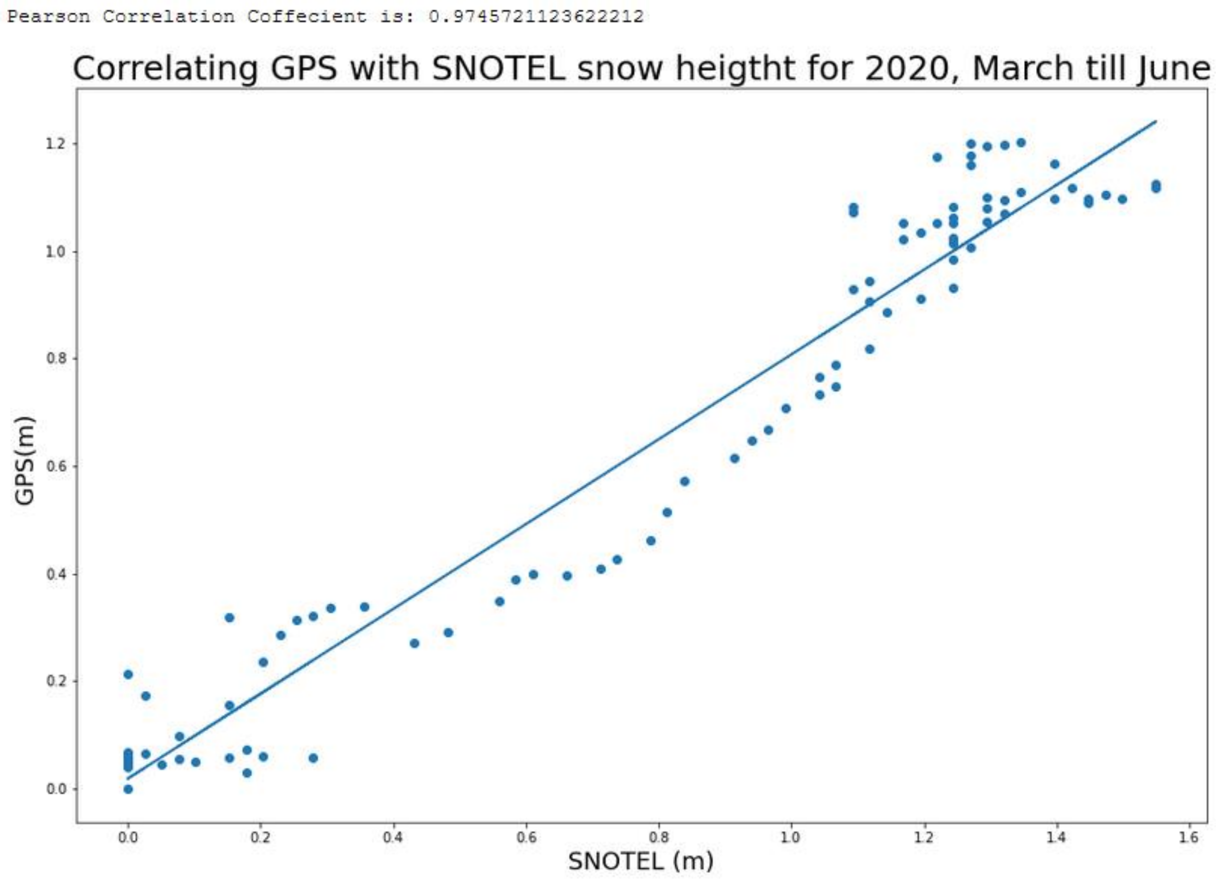


Figure 11: GNSS and SNOTEL estimates of snow height near Galena, Idaho, in 2020 yield a correlation coefficient of 0.96, indicating a strong, positive linear relationship.



```
Pearson Correlation Coffecient is: 0.9745721123622212
```

Figure 12: Same as Figure 11, but for a 4-month period from March-June 2020. The GNSS and SNOTEL estimates of snow height yield a correlation coefficient of 0.97, including periods of both snow accumulation and snow ablation. This suggests that the GNSS and SNOTEL estimates of snow height have a strong, positive linear relationship.

To explore whether the promising result obtained from the GNSS station in Galena can be applied at other GNSS stations, we show the results for a GNSS station at Leador, Idaho in Figure 10. This site exhibits a poorer correlation between GNSS and SNOTEL, which may likely be due - at least in part - to missing data, especially in March and April. This missing data in the springtime may be due to the station receiving too much snow, such that the GNSS receiver becomes buried under the snowpack. In figure 10 it may look like the data is continuous, however when extracting the SNR each day from different satellite azimuth, the station only had one or two data received from the satellite. Usually, the stations have 20 or more data sets to find the average. Hence, because there were only a couple for this site, there is missing data for each day which affected the daily height extracted for this site. The Leador station elevation is high and in a mountainous area, hence the antenna might have been buried by the snow pack for it to result in missing datasets.

Even though we strategically selected stations that are primarily located in flat areas, the station at Leador is situated in a slightly hilly slope that I hypothesized would not make a big difference in the beginning. However, when I compared the results with stations that are on very flat land with this station, it can be noticed that the data has lower quality to extract snow height and correlates relatively poorly with the SNOTEL estimate of snow height.

Future Works:

I would like to investigate more in this method and apply it in different stations. Larson, K.M. and E.E. Small (2016) mention that the GNSS multipath method works well for PBO stations that have choke rings and that are located in very flat areas. I selected stations in this study that are well suited for this methodology. However, I would like to expand more and see how this method can be manipulated and tweaked to work on different stations that may not be in a perfect setting of flat land or stations where there may be obstructions, like mountains. I am interested to explore the data further.

Moreover, my goal is to apply this methodology to another set of GNSS stations in Selway, Idaho. I assisted with installing and gathering data for the Selway GNSS network in summer 2020. I aim to compare the GNSS estimates of snow height with actual snow heights measured by digging snow pits in the field during the winter months.

Another route we could go in this research is that we can apply different models mathematically to estimate snow bulk density from the snow height timeline of each day to estimate the snow water equivalent (SWE), to quantify the water supply in a particular area.

Conclusion:

The result from the Galena GNSS station shows that there is a strong correlation between GNSS extracted snow height and an independent estimate of snow height from a nearby SNOTEL station. Therefore, this method of using GNSS multipath to extract snow height is valuable. Even though the GNSS stations need to be deployed on relatively flat surface with minimal obstructions around them, I think it can be overcome by further research and learning to discard certain satellite azimuths out of the data set to get better data in less-than-ideal settings. Overall, for GNSS stations that are deployed on a flat surface with no obstructions, GNSS reflectometry provides a great opportunity to study snowpack. Moreover, this method can be applied to different parts of the world, especially in developing countries where there are already existing GNSS stations to study snowpack in a relatively cost-effective way.

Appendix:

I wanted to provide some additional information on how the GNSS-IR software determines snow height.

The software uses L1 GNSS signal-to-noise ratio (SNR) data to estimate snow depth. (The L2 frequency can also be used, but this would require a manual change from the software defaults.)

The software uses Lomb Scargle periodograms to evaluate and retrieve the dominant frequency (reflector height). Peak frequencies are extracted from each periodogram of SNR data from rise and setting satellites in communication with the ground-based receiver. The snow depth is the daily average of the SNR peaks for all satellite signals in a given day.

The equation to extract out the Signal-to-Noise ratio (SNR) is as follows:

$$\mathrm{SNR}(e) = A(e)\sin\left(\frac{4\pi H_R}{\lambda}\sin e + \phi\right),$$

where λ is GNSS wavelength, ϕ is phase constant, H_R is vertical distance between GNSS antenna phase center and the horizontal reflecting surface (i.e., the reflector height), A(e) amplitude of SNR data, and *e* is the elevation angle of the satellite above the horizon. As a satellite rises and sets, the multipath reflections off of a planar surface change, so there is the use of sin(e) in the equation. SNR data is time dependent. To estimate the reflector height, it is important to have an accurate multipath frequency.

The information that a user must provide to the software for simple extraction of reflector height for a day includes: the receiver sampling interval (sec), the station's geographic location, GNSS frequency, and elevation angle limits. Then, the code will simulate the rising and setting of individual satellites and compute the median average frequency in meters, which can be directly related to the reflector height.

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