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Abstract

The objective of this project is the analysis of the behavior of the GPS station AMU2, located close to the South Pole. We processed the observations of the station over a period of 4 years (2015-2019) and evaluate shifts in vertical and horizontal position. The processing is realized with the RTKLIB software and the results are compared with the Jet Propulsion Lab online processing service. Our analysis showed that the station is moving at a speed of around 6m per year in the meridional component, 7.5m per year in the zonal component, and is sinking at a rate of 0.2 m per year. The comparison with the online processing service highlighted very similar values for the horizontal component and large differences in the vertical displacement. To interpret the displacement taking place in the area on the station we separated the horizontal and vertical component. The horizontal shift is due to the movement of ice sheets, related with the transport of ice from the interior to the ocean. The sinking has a less straightforward interpretation. After taking into consideration phenomena like ice melting due to climate change and ice accumulation, we concluded that the most likely cause for subsidence is the ice creep phenomenon: ice compression due to the weight of the station.

1. Introduction

The surface of the Earth is not static – many events and phenomena shape the very ground we walk on daily. Some of these events, like large scale earthquakes [Chuang et al., 2017] [Zedek et al., 2021], landslides [Huang et al., 2016] and volcanic eruptions [Lisowski et al., 2008] can quickly change the horizontal and vertical position of the land they occur on, whereas other events, such as sea level rise [Richter et al., 2012] or subsidence due to ground water extraction [Esquivel et al., 2006] are slower to change the landscape but have a significant impact over time. All these and many other occurrences can be monitored with GPS [Segall and Davis, 1997] and in some cases the processing of information in problematic areas can even lead to early warnings of events [Hoechner et al., 2013; Hsieh, 2017; Macciotta et al., 2016], which are crucial in a time where Earth's climate is becoming more severe and once rare events becoming more frequent.

In this project we focus on the processing of observations from the GPS station AMU2, located close to the South Pole, and we evaluate the behavior of its vertical and horizontal position shifts over a period of four years. This kind of monitoring is essential to understand the behavior of the region in terms of deformities over time and to guarantee the precision and reliability of GPS services and research that are currently using that base station.

2. Materials and Methods

2.1 – Area of Study

AMU2 is a GPS station located in Antarctica and is part of the POLENET ANET (Antarctica Network), a network of stations which are used for researching and monitoring several phenomena in the Antarctic region, such as seismology [Wilson et al., 2014], crust models [Baranov et al., 2021; Chaput et al., 2014] and tidal analysis [Tabibi et al., 2020]. The AMU2 station itself has mostly been used as a resource for the estimation of zenith troposphere delay [Li et al., 2022] and evaluation of ionospheric models [Okoh et al., 2018].

The AMU2 station is located at coordinates 89°59'56.4"S 116°32'16.8"W, with an altitude of 2820.115 m above the sea level.

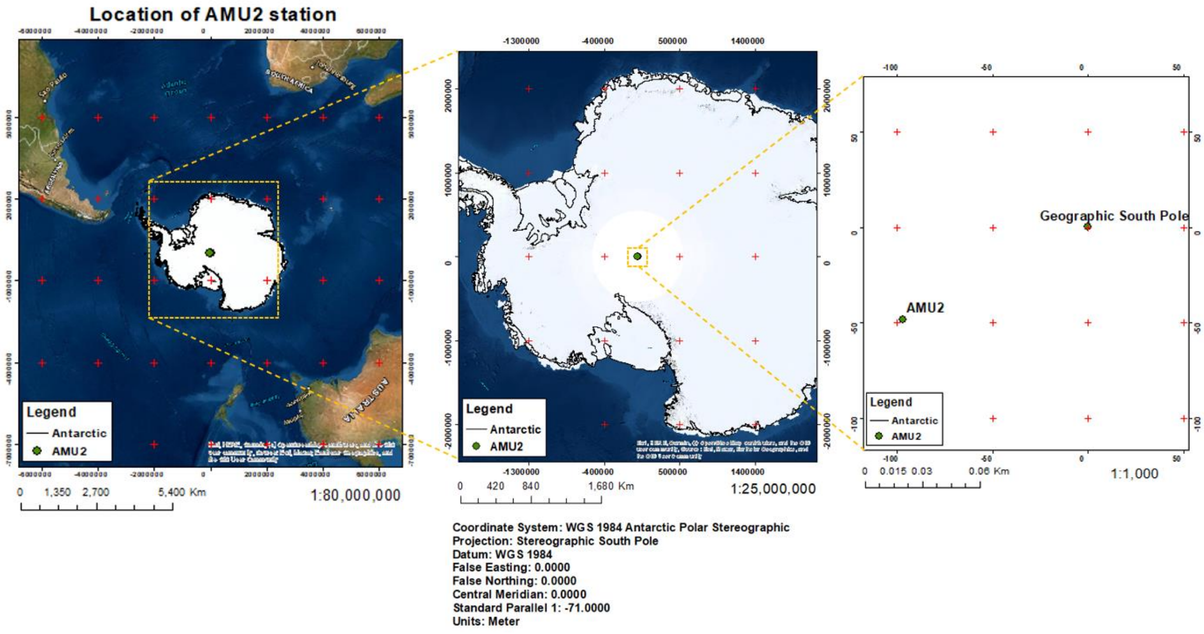

Figure 1 - Location of AMU2 station (shapefile courtesy of Gerrish [2022])

The station is a part of the Amundsen–Scott South Pole Station, the United States of America's scientific research station at the south pole. The area of the research base also includes one more GPS station, named AMUN, approximately 250m from AMU2.

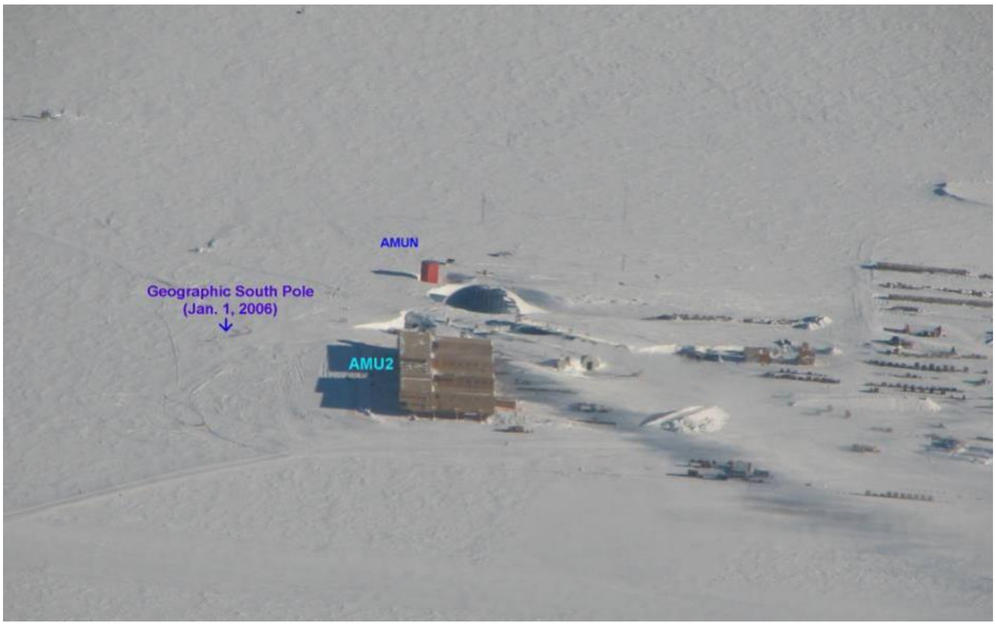

Figure 2 - Location of GPS stations on the Amundsen–Scott South Pole Station [Hothem, 2007].

AMU2 is operated remotely by UNAVCO, a non-profit university-governed consortium based in the USA. This GPS Base Station is comprised of a Trimble NetR8 GPS receiver, an Ashtech choke ring antenna, an Efratom rubidium frequency standard with power supply, a Wenzel frequency doubler, a 1x8 GPS antenna splitter, and associated power, Ethernet, and RF cabling. [Hothem and Mullins, 2012]. The station has gone through several elevation cutoff changes that affect the measurements, but all predate the years of interest for this study [Nevada Geodetic Laboratory, 2022.].

2.2 – Theoretical basis of the processing

The precise point positioning was developed toward the end of the decade of 1990, mainly for static applications, but it was quickly expanded to also include kinematic applications. PPP is a type of absolute positioning, that combines phase and pseudo-range measurements, which means it has the advantage of being able to work with just one receptor. This method requires the extensive modelling of all the errors present in the non-differentiated phase equation, in particular clock and orbital errors, as well as other errors not common to all positioning methods such as tides, ocean load, phase wind-up and differential group delay. [Mendes, 2022]
The processing in this project will be done with the RTKLIB software, which is an open-source program package, used for multiple types of positioning with GNSS. The steps taken and files used during processing will be further detailed in chapters 3.3 and 3.4. For this processing we will be considering Static PPP and Kinematic PPP. The main difference between these types of processing is that in static positioning, a GNSS receiver was required to be stationary whereas in Kinematic positioning a receiver can collect GNSS data while moving [Lotfy et al., 2020]. Although the GPS base should not be moving, it is necessary to consider this possibility as the goal of our study is to evaluate this movement.
In addition, we will also be comparing the results we obtained with the processing results from the Jet Propulsion Lab online processing service [JPL, 2022]. Online processing services are available 24h per day and are provided to users free of charge. There is only a need to upload GNSS observation files in standard or compress RINEX format to the servers and they download and provide their own precise ephemerides and clock correction files [Guo, 2015].

3.3 – Data

The first step to acquiring the data needed for this project was to select a date and convert it from Gregorian calendar date to GPS week (GPSW) and day of the year (DOY) as these formats are required for identifying the correct files that need to be used in the processing stage. The conversion was done using the FORTRAN language code developed in the lab classes during the semester.
For this project we will consider data from 2015, 2017 and 2019. Since none of these are leap years, we have chosen to use the 19th of July, which corresponds to DOY 200 in all three years. For 2015 this day

was a Sunday and GPSW 1854, for 2017 it was a Wednesday and GPSW 1958 and finally for 2019 this day was a Friday and GPSW 2062.

The relevant files for observations, navigation, satellite orbits, earth rotation parameters and clocks were obtained through ftp servers, namely CDDIS – NASA and LOX. The phase center variation file for the antenna and the differential code biases were obtained from the lab class exercise.

3.4 – Workflow

A diagram of the general workflow followed in this project as well as an example of the inputs used in the processing with RTKLIB can be viewed in figure 3.

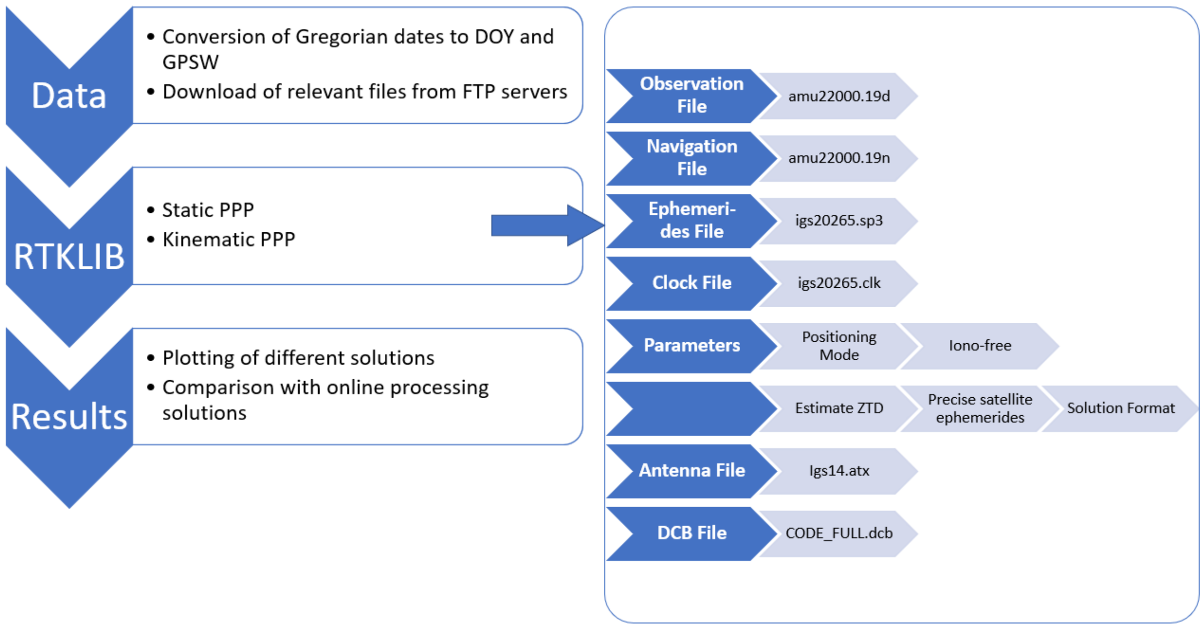

Figure 3 - Workflow diagram

3. Results

From the processing of the data with RTKLIB we first made sure that the date we selected for the project contained no information gaps or low satellite coverage, as this can be an issue when using information from Antarctica due to lack of solar energy produced during the six months of no sunlight and due to the inclined orbit of the satellites [Erol et al., 2021], respectively. Fortunately, there were no information gaps and the minimum number of satellites throughout the days observed was six, which was sufficient.

Figure 4 - Initial results from observations on DOY 200 2015, comparison of Static PPP (blue) and Kinematic PPP (green)

Observing the graphic on figure 4, we can see that the station's Kinematic PPP position shows some variation during the day in its horizontal components, trending around the Static PPP observation. In the vertical component there isn't a curve of variation, however there seems to be a lot more noise and rapid changes in position. The observations of years 2017 and 2019 show slightly less daily variation but are consistent with the 2015 results.

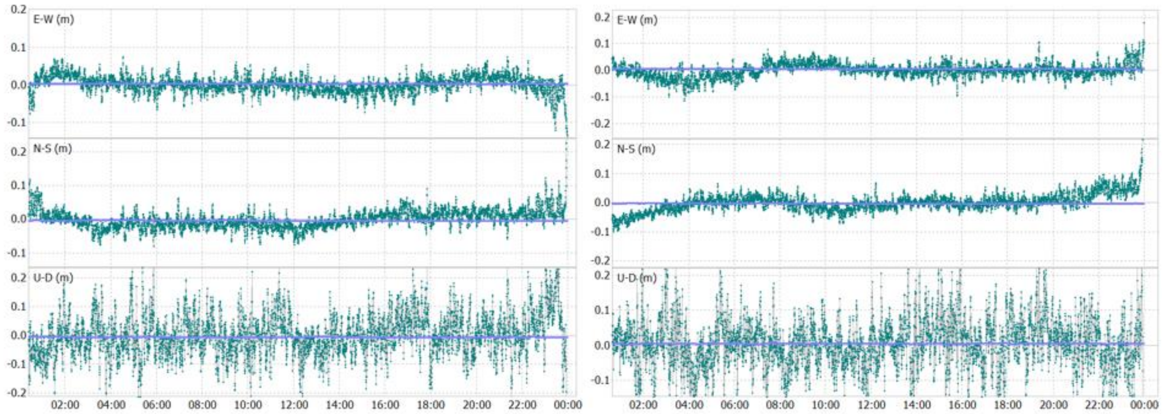

Figure 5 - Processing results for DOY 200 in 2017 (left) and 2019 (right)

Next, we want to look for the existence of horizontal and vertical deformation trends. For this effect we will work with projected coordinates (X,Y,Z) for the horizontal component and geographic coordinates (latitude, longitude and height) for the vertical component.

First, we looked into the changes in horizontal position with RTKLIB and plotted the positions obtained for each year in the same graphic (figures 6 and 7). The scale is not consistent between the two images as the 2019 is much further away than the 2017 result.

Figure 6 – Comparing the station horizontal position between 2015 (in green) and 2017 (in purple), with PPP static.

Figure 7 – Comparing the station horizontal position between 2015 (in green) and 2019 (in purple), with PPP static.

Unfortunately, it is not possible to see the three dates with both X and Y components combined using this software, so we used the coordinates obtained through the PPP static positioning and used Python to plot the results in 2D for the three years.

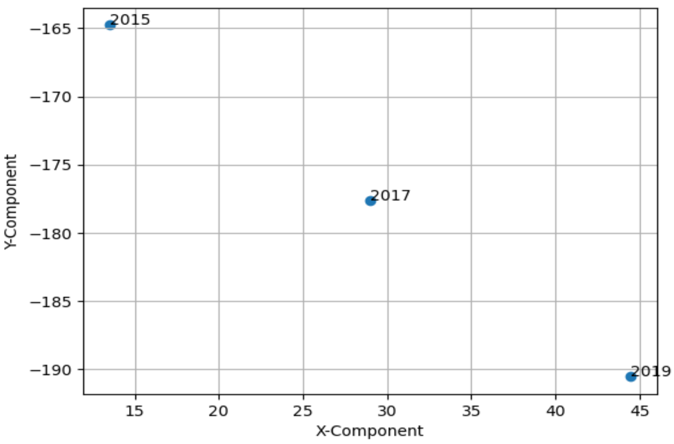

Figure 8 - 2D Shift in horizontal position

Comparing the results of the station position between the processed years, 2015, 2017 and 2019, we can say that the station suffered a displacement of approximately 15m in both the E-W and the N-S components between the 2015 and 2017 observations, moving a further 15m in both directions once more between 2017 and 2019.

Following the horizontal analysis, we processed the data once more using the geographic coordinates output to evaluate the vertical component, as demonstrated by the results below.

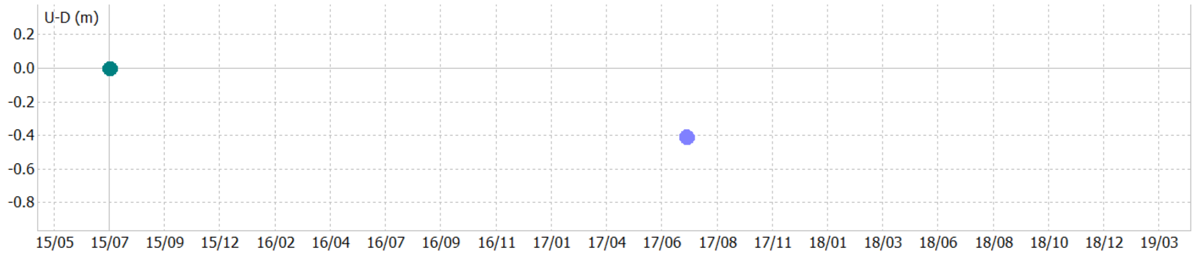

Figure 9 - Comparing the station vertical position between 2015 (in green) and 2017 (in purple), with PPP static.

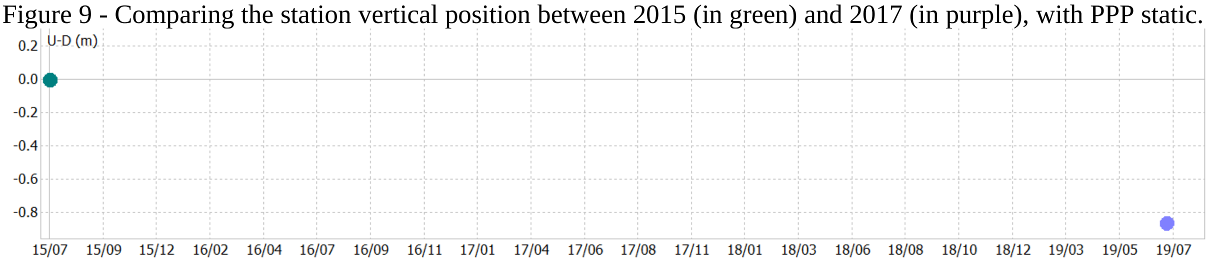

Figure 10 - Comparing the station vertical position between 2015 (in green) and 2019 (in purple), with PPP static.

From the analysis of these two outputs, we can see that there is a variation in the station height, which decreases around 40 cm between 2015 and 2017 and then a further decrease of around 45 cm between 2017 and 2019.

To analyze the station movements in more detail we decided to look at the output file with the processed coordinates. As previously discussed, to analyze the horizontal/planimetric component separately from the vertical/altimetric component we chose two different output formats for the coordinates, Cartesian and Geodetic.

Using Excel, we were able to determine the average coordinates of the station for each year, as shown in tables 1 and 2.

Table 1 - Average cartesian coordinates per year

	X(m)	Y(m)	Z(m)
2015	13.4889	-164.7678	-6359570.3216
2017	29.0000	-177.6473	-6359569.9116
2019	44.5000	-190.5314	-6359569.4606

Table 2 – Average geodetic coordinates per tear (WGS84/GRS80)

	Lat(°)	Lon(°)	Height(m)
2015	-89.998521	-85.319865	2818.0092
2017	-89.998389	-80.728547	2817.5999
2019	-89.998249	-76.853823	2817.1490

With the coordinates from tables 1 and 2 it is then possible to quantify the displacement that has occurred at the station. Tables 3 and 4 represent the differences in planimetry and altimetry from 2015 to 2017, from 2017 to 2019 and to have a value in absolute terms for the years being studied, an overall difference from 2015 to 2019.

Table 3 – Planimetric displacement

	ΔX(m)	ΔY(m)
2015->2017	15.5111	-12.8795
2017->2019	15.5000	-12.8841
2015->2019	31.0111	-25.7636

Table 4 – Altimetric displacement

	ΔHeight(m)
2015->2017	-0.4093
2017->2019	-0.4508
2015->2019	-0.8601

We can see that between 2015 and 2019 the station sank by about 0.8601 meters and that in planimetry it has shifted by around 30m in the E-W component and 25m in the N-S component.

At this stage of the report, our goal was to compare our obtained solutions with the solutions processed online. To do this we took the observation files we used and sent them to The Automatic Precise Positioning Service (APPS) which is a service provided by NASA Jet Propulsion Laboratory that receives GPS measurement files and applies the most advanced GPS positioning technology to estimate the position of any GPS receivers, whether they are static, in motion, on the ground, or in the air. The result of this process are the coordinates presented in Table 5.

Table 5 - Online processing coordinates per Year

	X(m)	Y(m)	Z(m)
2015	13.4900	-164.7685	-6359570.2784
2017	29.0013	-177.6444	-6359569.8576
2019	44.5031	-190.5306	-6359569.4222

To find the gap between our solutions and the ones processed online we calculated a difference between the coordinates of table 1 and table 5, hence obtaining the graph of figure 11.

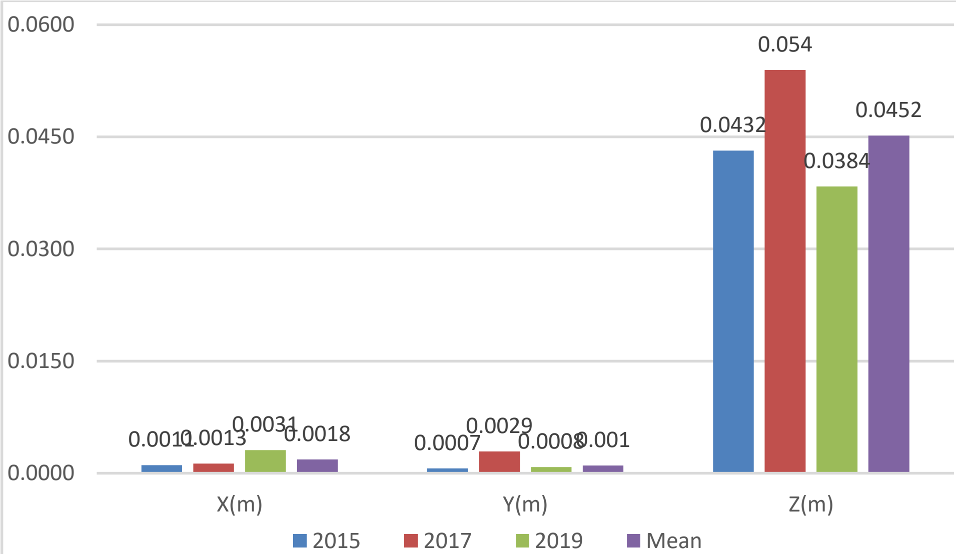

Fig. 11 - Comparison with online processing solutions per Year and mean

As in the output file of the online processing the coordinates came in cartesian coordinates and also geodetic coordinates, we were able to make the difference for the ellipsoidal height, as represented in figure 12.

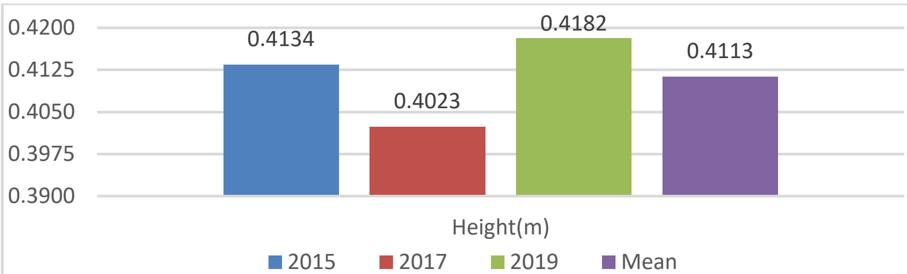

Fig. 12 - Comparison with online processing solutions per Year and mean (height)

4. Discussion

After processing and evaluating our results, it was clear that there was a deformation taking place at this station, so we investigated why this was happening. We once again separated the information in the horizontal and vertical components as it is likely they have different sources of deformation.

Regarding the horizontal shift, the most likely reason is due to the movement of the ice sheets. Ice sheets, also known as continental glaciers, are a large mass of ice that covers terrain in large area extensions, such as those existing in Greenland and Antarctica. Ice velocity is a fundamental characteristic of glaciers that measures the rate at which ice is transported from the interior regions towards the ocean.

Ice velocity ranges from a few cm/year to a few km/year on fast-moving glaciers and floating ice shelves [Rignot et al., 2011].

The vertical deformation was harder to explain. There is the possibility that all its movement is explained by the ice sheet movement, however we considered other options as well. We initially considered the possibility of the station sinking due to global warming and ice melting in the region. However, after further research, we concluded that this was most likely not the case, as this station is located right at the south pole, whereas the largest losses in ice mass tend to happen around the outer edges of the continent. We also considered the completely opposite approach – ice accumulation. However, although this is an issue that affects many other research equipment in the region, GPS sites in the Antarctic are generally installed on bedrock that typically remains snow-free [Konfal, 2021], so it seemed unlikely that this was the cause. Our last approach, and what seems to be the most likely cause for the subsidence found during this study, is the ice creep phenomenon. The ice creep is one of the largest challenges when building stations on ice sheets [*South Pole Station - Buildings at the South Pole*, n.d.], as the weight of a building can cause the ice to move locally, which makes the ice compress and shift away from sources of pressure. This can result in variable rates of sinking and can make keeping the building level a challenge. The newest research station at the south pole was built with some architectural elements to help maintain it level for a longer period of time, however, previous research stations had to be removed because they had started to sink at faster rates than expected [*US NSF - Arctic and Antarctic Research Area*, n.d.]. The steady subsidence of the station observed in the processing seems to be the most consistent with the ice creep sinking.

5. Conclusion

We have processed information from three days in three different years covering a 4-year time span and discovered a horizontal and vertical movement in the AMU2 GPS station. Further analysis revealed that the station is moving at a rate of around 6m a year on the N-S component, 7.5m a year in the E-W component and 0.2 m a year on the vertical component. The results obtained with RTK processing are quite like those obtained with the online processing center except on the Z component where there is a larger difference in values. We concluded that the movements in the station coordinates are the result of ice sheet velocity and ice creep due to the weight of the building the station is located on.

6. References

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