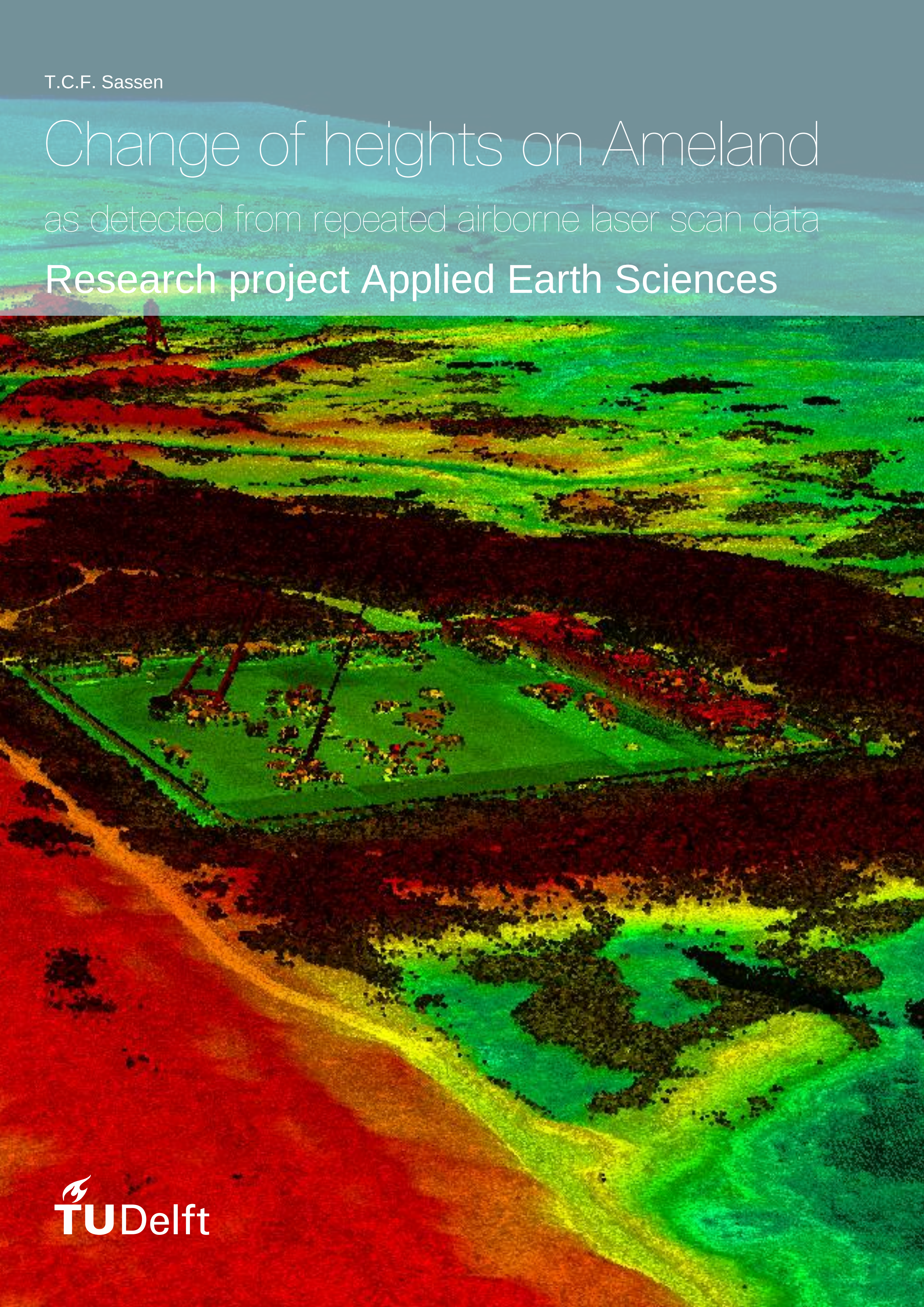
T.C.F. Sassen

Change of heights on Ameland

as detected from repeated airborne laser scan data

Research project Applied Earth Sciences



TU Delft

Change of heights on Ameland

Research Project Applied Earth Sciences

By

T.C.F. Sassen

Supervisor TU Delft: Dr. R.C. Lindenbergh
2nd Supervisor TU Delft: Dr. J.E.A. Storms
Coordinator: Dr. K.H.A.A. Wolf

Preface

This report was written as main part of the minor Research Project Applied Earth Sciences, by Tom Sassen at the Delft University of Technology. This research looks at height differences on Ameland through different datasets and tries to find the cause for the changes. It also tries to detect if gas extraction in the eastern part of the island has a noticeable influence on the total height change. The goal of this report is to better understand height changes on Ameland. This is important, because the ecosystem on the island is fragile and small changes relative to the sea level can cause large differences. I would like to thank dr. R.C. Lindenbergh for supervising the research and guiding me through the process. I would also like to thank dr. J.E.A. Storms and dr. A.J. Gelderblom for proofreading the report.

T.C.F. Sassen

Delft, January 2016

Abstract

This research was done as main part for the minor Research Project Applied Earth Sciences. In this research we look at processes that cause height changes on Ameland. We focus on 3 types of processes:

- Gas extraction
- Sedimentation and erosion
- Local changes like construction of houses

We try to see if the subsidence due to gas extraction is larger than the other processes and if it is visible in the net height changes. To answer this question, we investigate 2 datasets:

- AHN data
- Deltares data

AHN is a database containing the heights of the entire Netherlands at 3 different points in time. The Deltares data contains an area between Ameland, Schiermonnikoog and Friesland. This dataset is shot 7 times over a period of 4.5 years.

For AHN we look at a grid and a point cloud and for the Deltares data we look at just a grid. For the grid comparison we use 2 methods:

- Difference between two datasets at shot different points in time
- Fitting a trend

For the point clouds we compare the difference in z direction between a point cloud and a triangulated mesh.

All different datasets and methods show net subsidence in the order of centimeters to decimeters. This is small compared to the potential errors in the datasets. This means we can say subsidence takes place and that it is stronger than the other processes, but we cannot accurately say how much subsidence takes place.

Contents

1 Introduction

Topography changes constantly. On Ameland this has 3 main causes: subsidence due to gas extraction in the eastern part of the island, sedimentation and erosion due to wind and water and local changes like constructing houses. The subsidence can be compensated to some degree by sedimentation.

This research is done as main part of my minor Research Project Applied Earth Sciences for the Applied Earth Science bachelor. The question this research tries to answer is:

What changes of heights take place on Ameland and is the relative subsidence due to gas extraction notable?

To answer this question, we look at height data from the island. The biggest source of height data is AHN. AHN stands for Actueel Hoogtebestand Nederland, or current height file Netherlands. This data is gathered by Rijkswaterstaat (Department of Waterways and Public Works) and Waterschappen (waterboard). Since 1997 there have been 2 versions of AHN and the third version is being gathered at the moment. This means that for Ameland we have 3 datasets for a period of 18 years.

Because subsidence is an important problem, there has been a lot of research to check if the subsidence on Ameland would not become a threat to local ecosystems. One of these researches is done by Deltares, who did a project in the Waddenzee between Ameland and Schiermonnikoog. This data covers a smaller area then our AHN dataset, but is a little more precise and has been shot more frequently, which gives a clearer image of what really happened.

Another research is done by Johan Krol from NAM. The NAM is the Nederlandse Aardolie Maatschappij (Dutch Petroleum Society) and is the company that is actively extracting gas in Ameland. He measured the sedimentation on different locations on Ameland and the Wad, by checking how much deeper or shallower a measuring point has been buried under the sand. By doing this for multiple points since the year 2000, he gets an idea of the sedimentation around Ameland and by comparing these findings to the known subsidence a real height change of the ground can be calculated.

2 Processes triggering height change

Height change on land can have multiple causes. On Ameland there are 3 main causes for these changes:

- Gas extraction
- Erosion and sedimentation
- Local changes

It is also possible that multiple causes affect the same location, so they can amplify each other, or, on the contrary reduce or even cancel each other out. In this research we aim at detecting of the total movement. It has already been proven that subsidence takes place on Ameland, but when the sedimentation can keep up with it, it will not influence the local ecosystems on the island.

2.1 Gas extraction

Around 300 million years ago during the Carboniferous age there was a lot of peat in the north of what we now call the Netherlands and the North Sea, as can be seen in Figure 1. Nowadays this peak is buried under a thick layer of sediments and has turned into gas. [1]

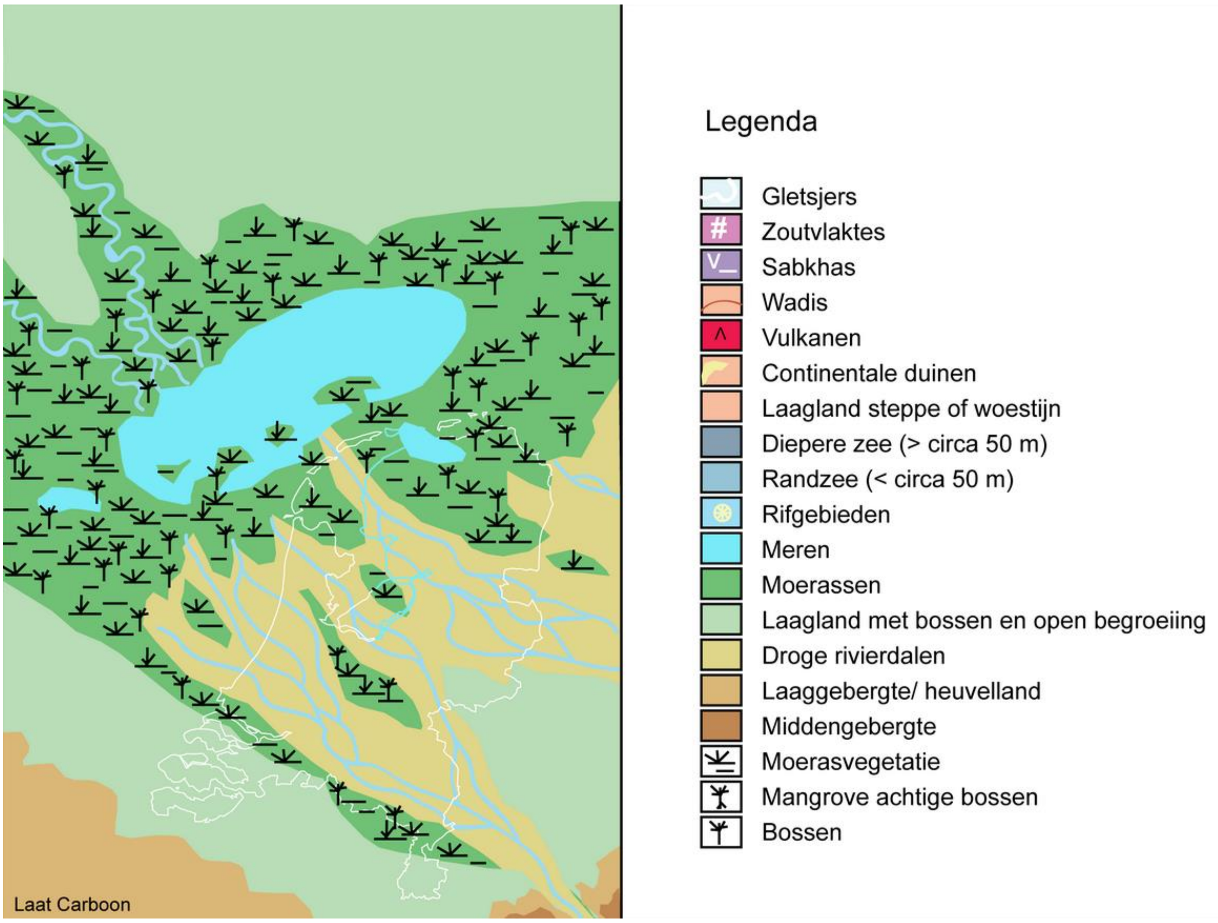


Figure 1 The Netherlands during the late Carboniferous age. [1]

At a depth of around 3500 meters a sandstone layer can be found. This layer can be seen as the dark red layer in Figure 2. At some points this layer contains gas from this old peat. One of those points is the gas reservoir underneath Ameland. [2]

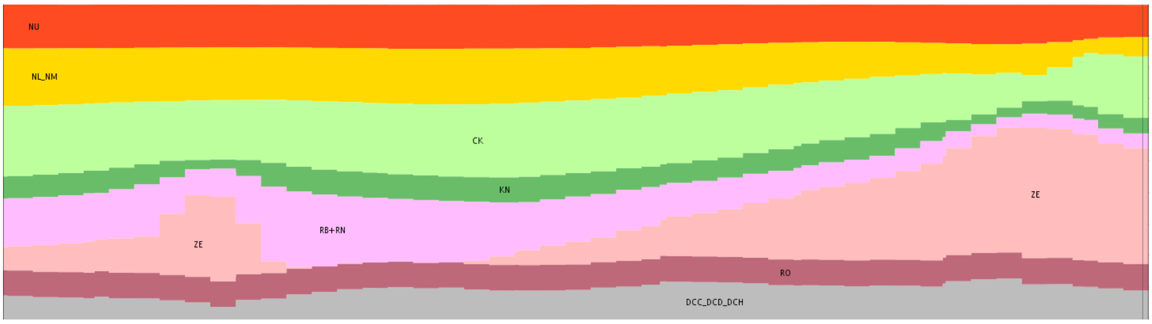


Figure 2 Profile of the eastern part of Ameland. The left side of this figure is in Buren, the right side is the east coast of Ameland. The depth of the picture is 4000 meters and the width is 11400 meters. [3]

In the nineteen sixties the first signs of the gas reservoir underneath Ameland were registered, but due to the complicated geology it took over 20 years before production could start. Multiple companies drilled holes before, but they found little or no gas, so there was no actual gas production. [2][4]

In 1983 the NAM started building the unmanned satellite platform Ameland-Oost-2. This platform is in contact with 3 of the producing gas pipes of the reservoir and was built for connection with the western part of the field. The location is the upper left location shown in Figure 3. [5]

In 1984 the building of the production platform Ameland-Westgast-1 was started. This platform is the upper right location shown in figure 3. This is the main platform and around 10 people work on it. All gas from the 3 locations goes to this platform for a first separation of gas, water, and gas condensate. [5]

The last platform is the lower location shown in figure 3 on the left and figure 3 on the right. This location is on land and the construction of this platform started in 1986. This platform is surrounded by manmade dunes to try and make it blend in with the nature. This platform is one of our test locations. [5]

Figure 3 Left: Locations of gas extraction around Ameland. [6] Right: Drilling location on Ameland. [5]

Our reservoir is a smaller reservoir in the Netherlands but still produces a lot of gas. That is why there are plans for new wells and expansion. Because of this, new researches have to be done every once in a while. Those researches are done by the NAM to measure how much subsidence is the result of their drilling. Those researches are also mandatory when they want to drill new wells. For every well there needs to be a permit and those will not be handed out if there is no research about the impact. [2]

In this case we look at 2 researches. The first one is done by Johan Krol. Johan is an ecologist who lives on Ameland. The goal of his research is to look at the impact of the subsidence on the biodiversity of the area. His research area is the Waddenzee, the offshore part to the south of Ameland. The gas extraction takes place mostly to the north of Ameland, so the research area should be in parts with little subsidence. [5][7]

His research started in 2000 and has expanded over the years. He gets his data by measuring the length of a string. This string is connected to a base located under the surface. When the sea deposits or erodes the sediment on top of the base, the length of the uncovered string will change, as we can see in figure 4. This way we know how much new sediment is deposited or eroded. By doing this for a lot of points on multiple areas, as seen in figure 5, he gets an image of the sedimentation of the Waddenzee to the south of Ameland. [7]

Figure 4 String used to measure sedimentation speed in the research of Johan Krol [7]

When the sedimentation is added to the absolute subsidence we get the relative subsidence. For this research the subsidence as measured by the NAM is taken.

In figure 5 we see the location of the measuring points. The result of this research is split into the 5 regions of interest, which are specified in table 1 and figure 5. For Oost-Ameland no average subsidence is given, so the 2 extreme values are used. [7]

Region	Subsidence in mm/year	Sedimentation in mm/year	Total in mm/year
Oost-Ameland	(min) -0.3 (max) -7.0	+7.3	(min) +7.0 (max) +0.3
West-Ameland	0	+5.9	+5.9
Engelsmanplaat	0	+1.2	+1.2
Paesens	-2.14	+10.8	+8.66
Schiermonnikoog	0	+7.1	+7.1

Table 1 Subsidence, sedimentation and total height change as found in the research done by Johan Krol [7]

This means that on average there is subsidence in Oost-Ameland and Paesens, but after subtraction of the sedimentation there is no net subsidence in all 5 regions. All these areas are in parts that are sometimes below the water level and are therefore subject to stronger sedimentation forces than our research area on dry land.

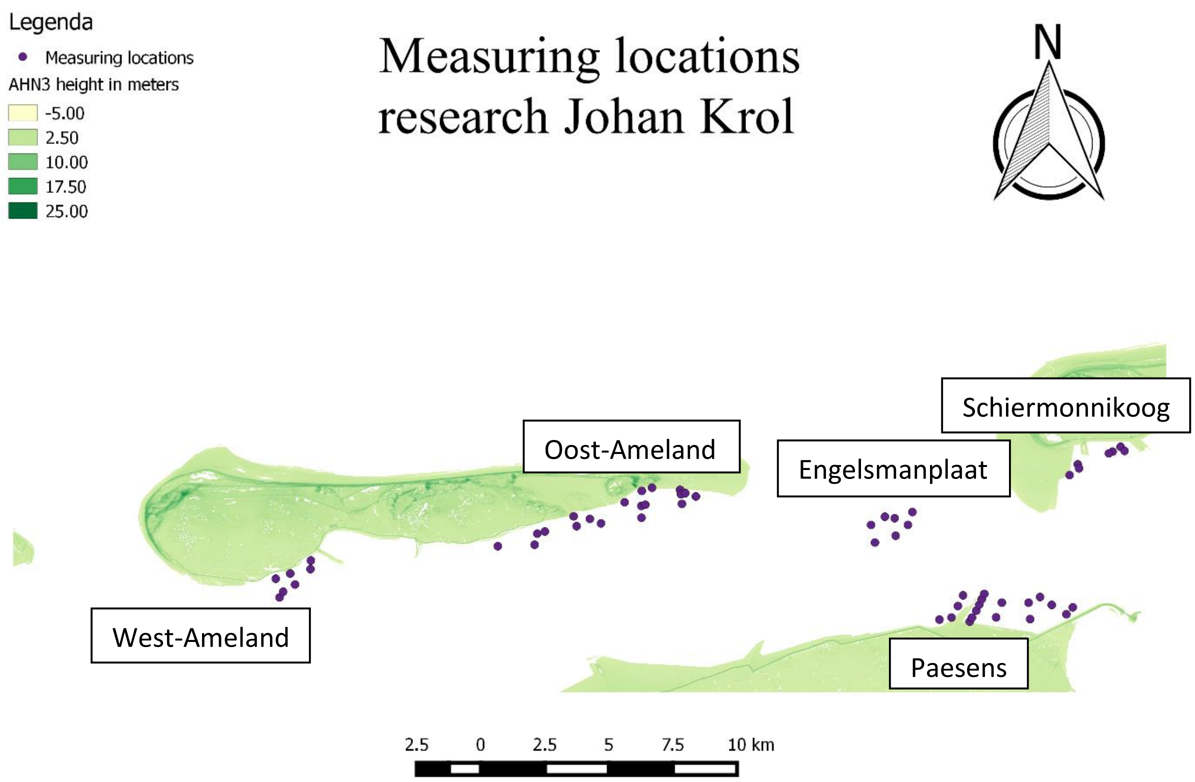


Figure 5 Points used in Johan Krol's research

Another research we take a look at is done by Deltares and commissioned by NAM. This research looks at the Waddenzee between Ameland, Schiermonnikoog and Friesland, as can be seen in Figure 6. [8]

Figure 6 Region of interest of Deltares research [9]

The research uses 7 datasets of the area, taken over the span of 4 and a half years. The datasets contain height data created with the LiDAR method and presented on a 1 meter x 1 meter grid. We received the following datasets.

- Spring 2010
- Spring 2011
- Autumn 2011
- Autumn 2012
- Autumn 2013
- Spring 2014
- Autumn 2014

We received these datasets in the form of a Matlab file, so it could be used in this research. The most important conclusion of their research was that nothing could be said about the influence of subsidence on that area. The main reason for this is that the timespan of 4 and a half years is too short to notice these kind of changes. [8]

2.2 Erosion and sedimentation

Another cause for height changes on Ameland is erosion and sedimentation. Ameland is an island in the Waddenzee and is therefore subject to a lot of wind and waves. This causes movement of the dunes. When a dune moves there will be erosion in its back and sedimentation in the front. We can see this in Figure 7 as red and blue lines for respectively the erosion and sedimentation around the dunes. In the figure we see a dune on the north coast of Ameland moving to the south.

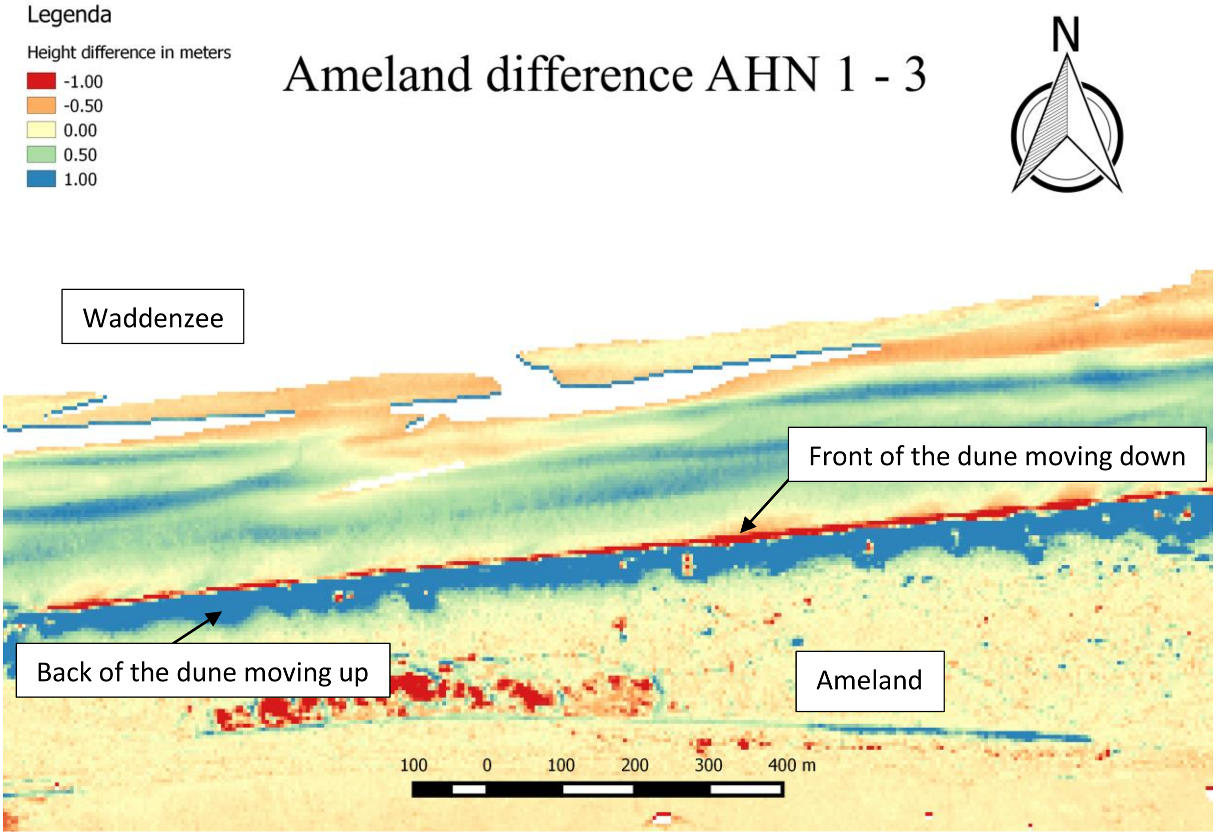


Figure 7 Dune migration between AHN 1 and AHN 3 on the north coast of Ameland.

The sedimentation and erosion are also influenced by humans, as Rijkswaterstaat drops about 3 million cubic meters of sand 400 meters out of the coast of Ameland. The Netherlands wants to keep its current coastline. Because of the natural movement of the dunes human intervention is needed to maintain this coastline. [10]
Another way humans step in to stop nature from going its course, is the stripping of dunes. Dunes are stripped of the grasses and other vegetation that was not there originally. This is done in order to restore the original vegetation and the local ecosystems. Because the grasses are removed, the wind can once again influence the dunes a lot. [11]

2.3 Local changes

When a house is constructed, or a tree grows, it causes a local height change. These changes can be a lot larger in height than the other 2 examples as described in 2.1 and 2.2, but they are also a lot smaller in area. In figure 8 a new building, a removed building and a removed tree can be seen.

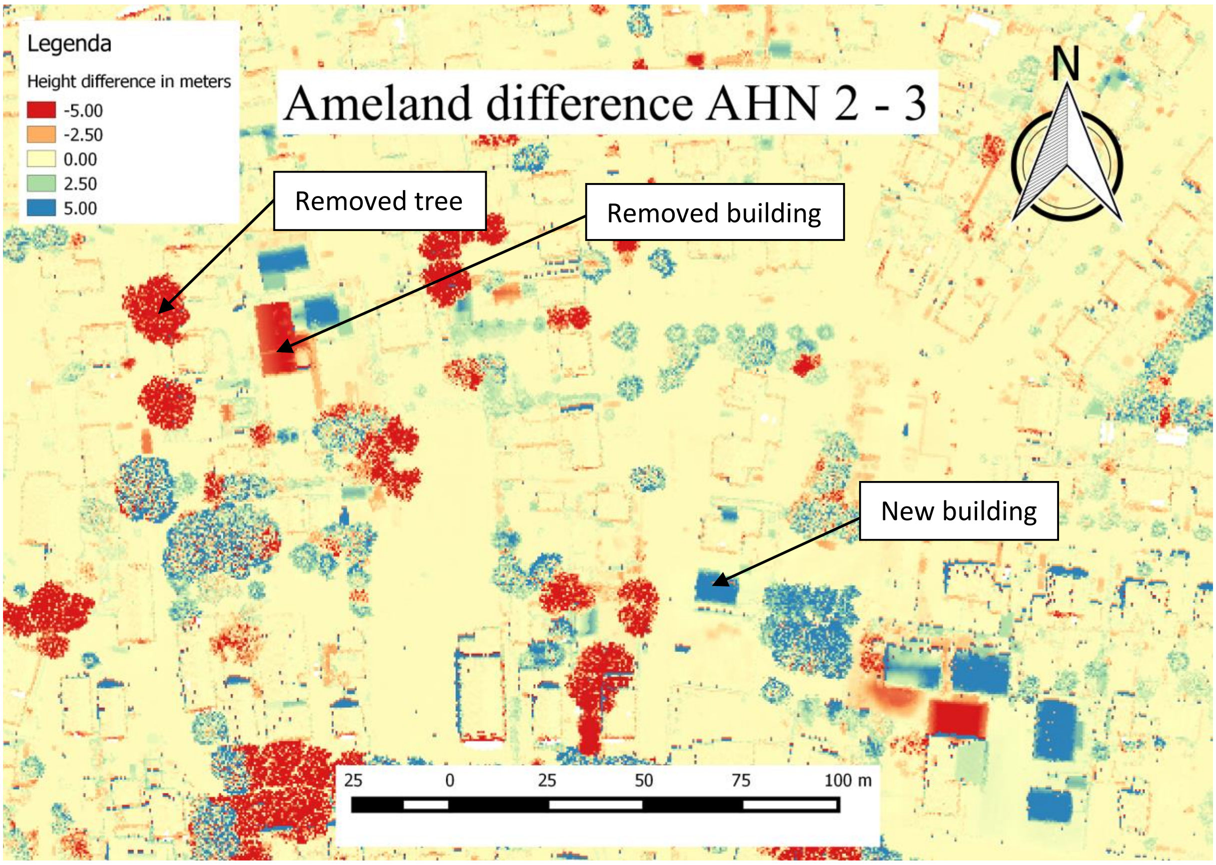


Figure 8 Height difference between AHN 2 and 3 with raw data and with 0.5 meter grid

These changes can have a lot of impact on the total change. For some research, the building of houses and growing of trees is not important. That is why the filtered version of the data is available. In this version buildings and trees are removed and will no longer influence the data. In figure 9 and 10 the same area as in Figure 8 can be seen, but in this case the filtered versions are compared. It is clear that the buildings and trees influence the total change a lot less in the filtered version.

We do however still see some orange lines. This might be explained by the fact that the two maps do not fit exactly on top of each other. When there is a small horizontal error in the data, this might result in the houses being a little more to the south in one dataset compared to the other. When we then compare the heights from both datasets we compare heights of a roof to the height of the street and the map will display some height change.

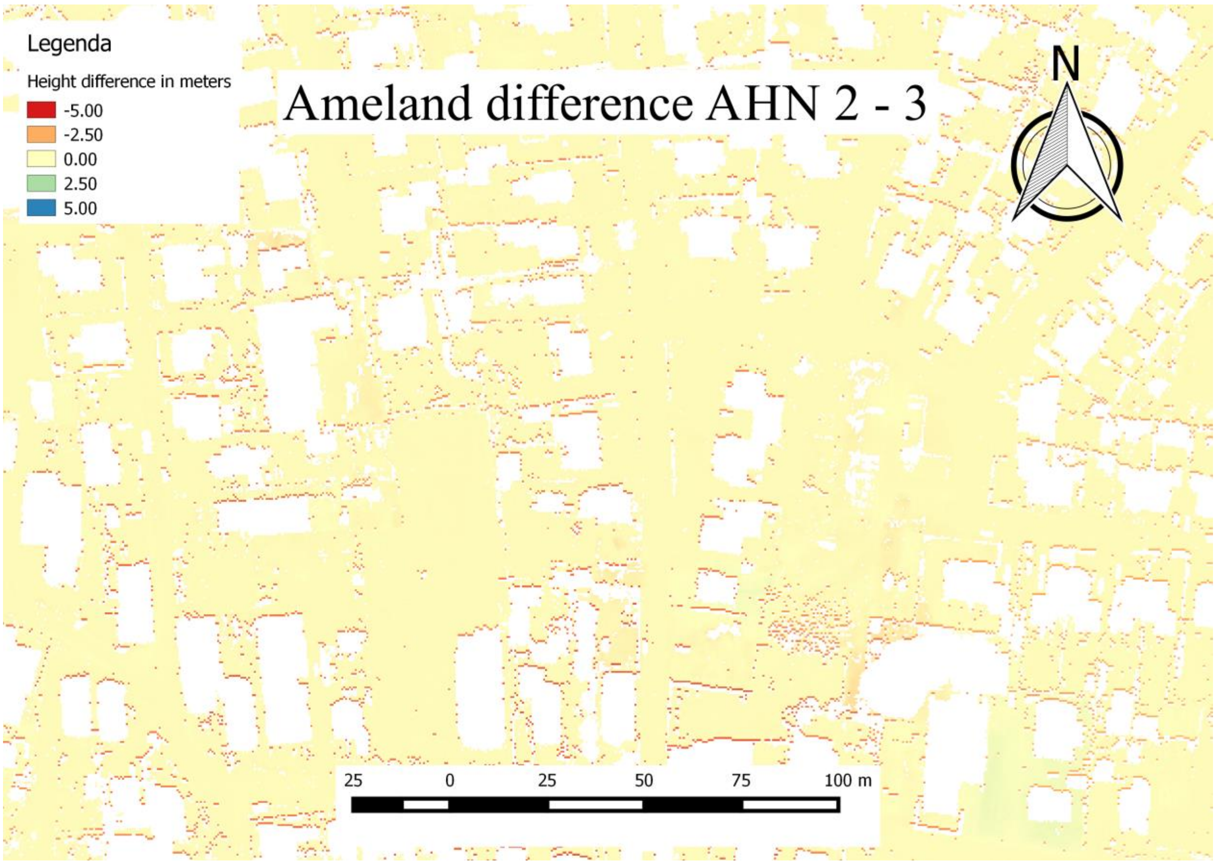


Figure 9 Height difference between AHN 2 and 3 filtered and with 0.5 meter gridsize

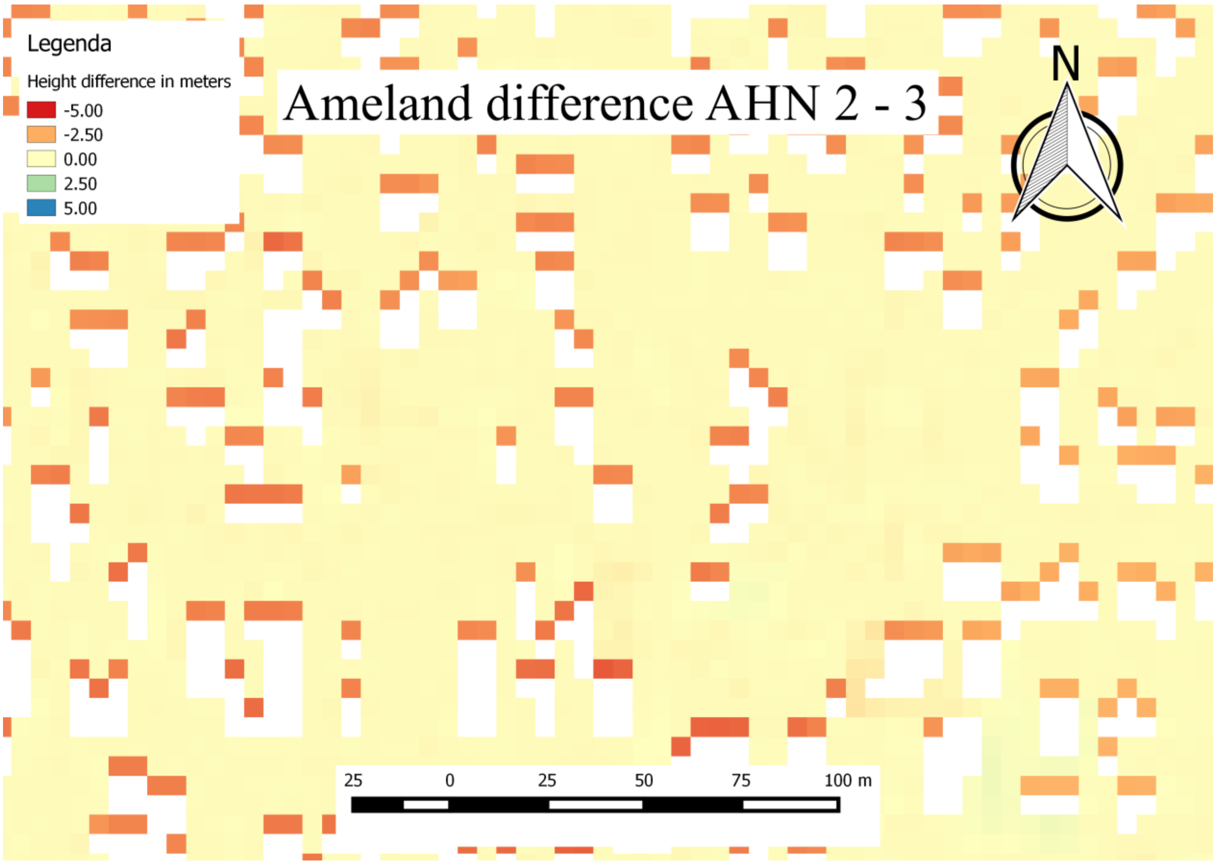


Figure 10 Height difference between AHN 2 and 3 filtered and with 5 meter gridsize

3 Data collection and processing

In order to solve our question, we look at 2 different datasets, AHN and the Matlab file of Deltares. The data for both of these sets is collected with a method called LiDAR. The resulting data points are then turned into point clouds (AHN) or grids (AHN and Deltares).

3.1 LiDAR

AHN data is obtained by LiDAR or laser altimetry. This is a method where a plane or helicopter flies over an area and scans the area it flies over. [12] To do this there is a laser on board of the plane that fires light pulses down. Since the speed of the pulse is known and the travel time can be measured, the distance of source to object can be calculated by:

$$\Delta X = \frac{v}{2 * \Delta T}$$

Here ∆X is the distance between the light source and the reflecting object in meters, v is the speed of the laser in meter per second and ∆T is the travel time of the laser in seconds.

Now that the distance between the plane and the measured point is known, we only need the exact location of the plane, which is measured by GNSS(GPS) and the orientation of the plane, which is measured by IMU. IMU stands for Inertial Measurement Unit and is a device that can measure an object's angular rate. This tells us if the plane flies perfectly horizontal or at a slight angle.

One way of scanning the area is when the plane will fly in certain paths and will cover strips of land while flying. At certain points during this flight the laser will scan the area inside a 30 degrees' cone underneath the plane. This way one gets circles of scanned area which can cover the entire map when they overlap each other. Figure 11 shows how this works for a plane flying over an area while scanning it. [13]

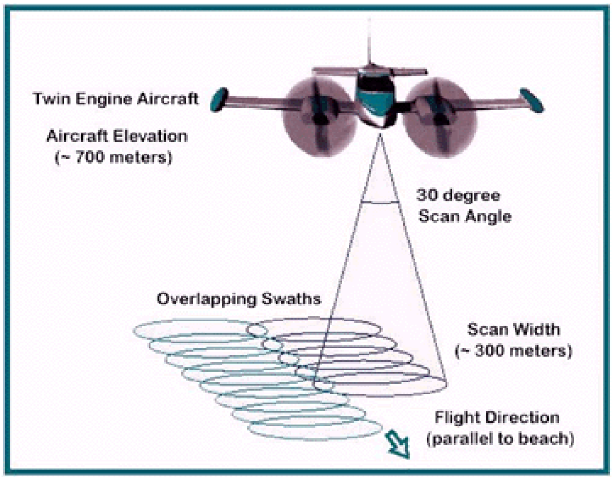


Figure 11 Data collection using LiDAR. [12]

When the plane flies over water it will also scan this part. The quality of the reflection on water is depending on a few factors: [14]

- The angle, a large angle to the normal will result in a weaker reflection
- The depth of the water, deeper water will result in a weaker reflection
- The wavelength and strength of the laser

This can clearly be seen in this data from Deltares, as they flew over a 'Wad' and therefore had a lot of water in their data. In figure 12 one clearly sees the direction of the flight paths of the plane. At some points on those paths we notice that parts of the scanned area have no data, this is because one of the above mentioned factors is causing a loss of quality of the reflection. When we see that in the center of the of the flight path there is data, but to the sides there is not, that must mean that the angle of the reflection is too big there and the loss in quality prevents us from getting a valid data point.

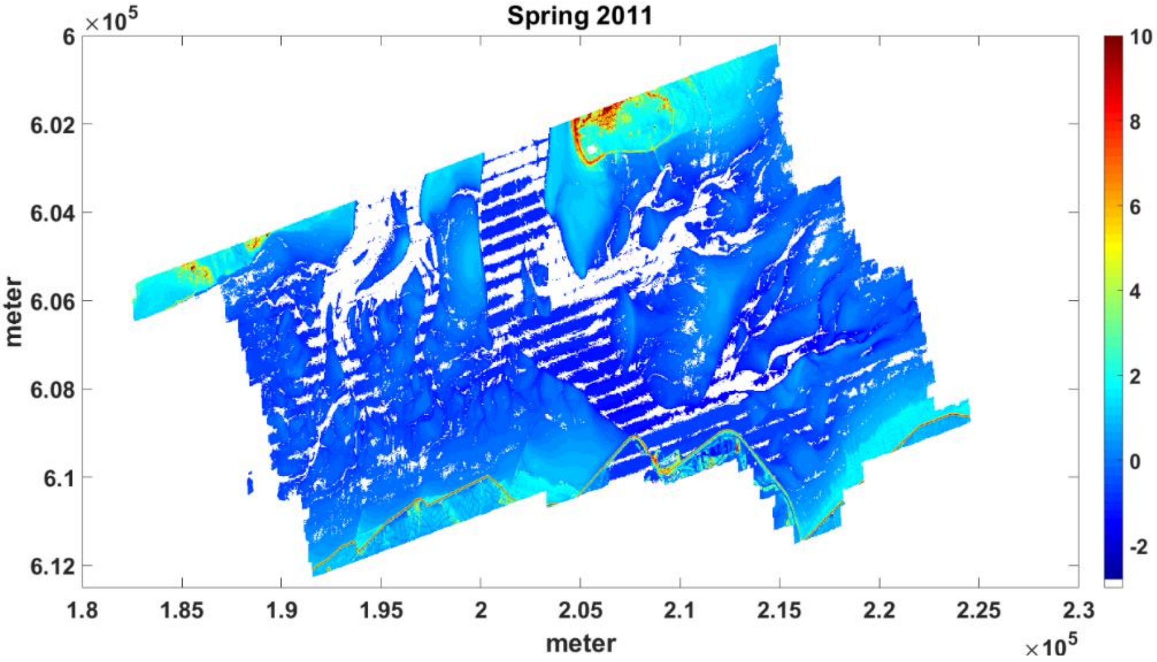


Figure 12 Deltares data of the Waddenzee between Ameland and Schiermonnikoog showing how water affects LiDAR data

3.2 AHN

The biggest source for our data is the AHN source. AHN stands for Actueel Hoogtebestand Nederland (Current Height File Netherlands) and is a publicly available dataset of the heights in the entire Netherlands.

Once the data is gathered through LiDAR, it is in the form of a point cloud. A point cloud is a file that stores all data values and their coordinates in a vector format. The point clouds can be downloaded in LAZ (short for LASZip) [15] file format which is a compressed LAS (short for LASer) [16] file, a public file format for 3-dimensional point cloud data.

The point clouds are also transformed into grids with different cell sizes. For AHN 1 the cell sizes are 100*100 meters, 25*25 meters and 5*5 meters. For AHN 2 and 3 the available cell sizes are 5*5 meters and 0,5*0,5 meters. [12] These grids are given in a GeoTIFF file format, which is a raster image (TIFF) that can store geographical data. [17] A comparison between the LAS and geoTIFF data can be seen in figure 16.

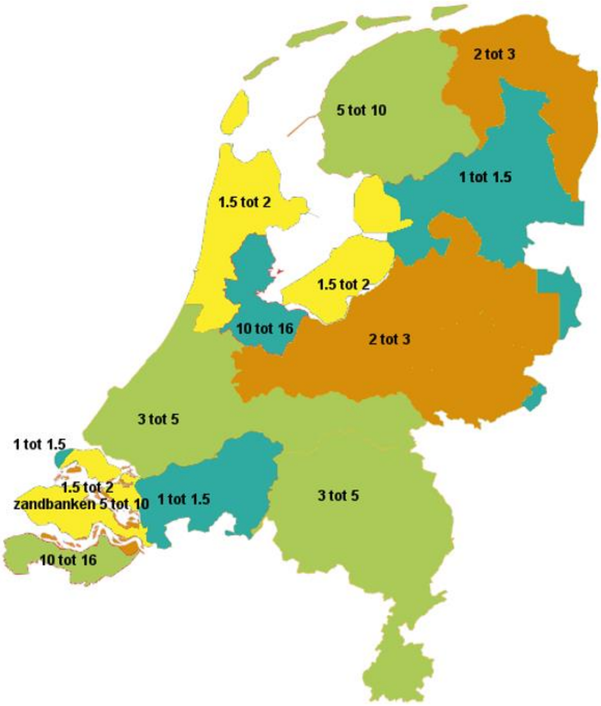


Figure 13 Point density in points per m² in AHN 1. Source: Kwaliteitsdocument AHN 2 by Niels van der Zon

The reason for this difference in size is that AHN 1 is a lot older. When they started with the data gathering of AHN 1 in 1996, the LiDAR method was a lot less mature than it is now. This meant that the point density and overall quality of AHN 1 is less than that of AHN 2 and 3. This difference is also visible in AHN 1 itself, as certain parts have a higher density than other parts, as can be seen in figure 13.[12]

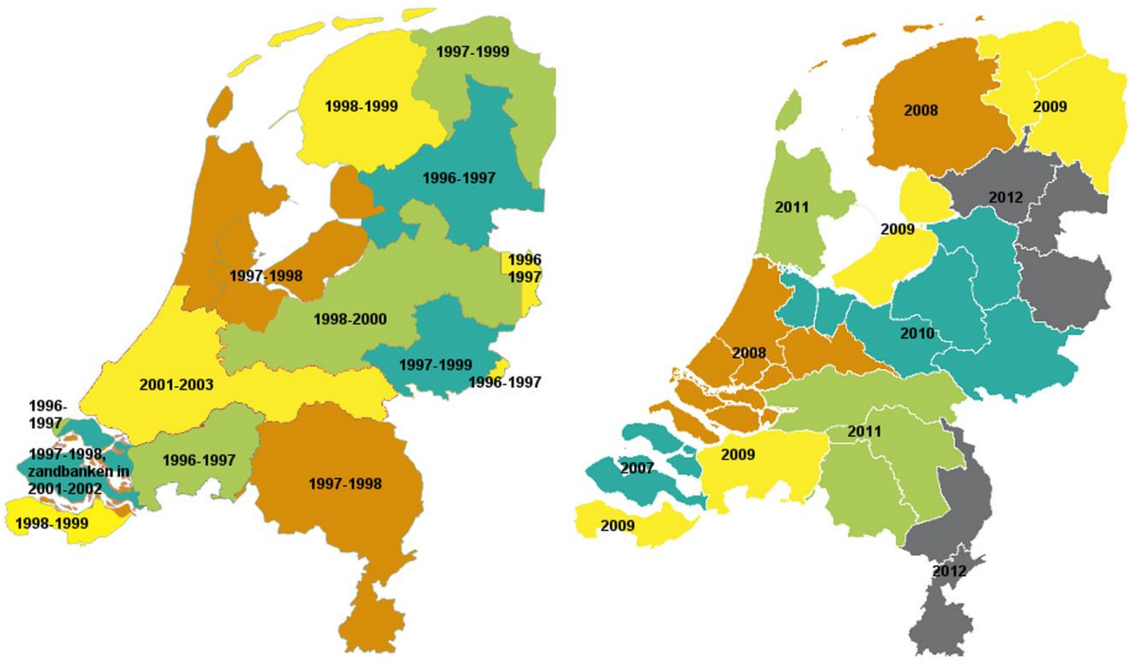


Figure 14 Data gathering periods for AHN 1(left) and 2(right) Source: Kwaliteitsdocument AHN2 by Niels van der Zon

Figure 15 AHN 3 schedule for data gathering
Source: Kwaliteitsdocument AHN2 by Niels van der Zon

When AHN 1 was completed in 2003, the first data points were already 7 years old and could use an update (figure 14 left). This is why they started a pilot of AHN 2 in 2006 and the creation of AHN 2 was started in 2007 (figure 14 right). This took until 2012 and in 2014 AHN 3 was started. The planning is that in 2019 AHN 3 will be finished (figure 15). AHN 2 and 3 work with newer technology and the specifications are declared in end terms. This means that there are some conditions that the final file must meet. It is also possible to compensate for a lower point density by obtaining a higher precision. [12]

The data is downloadable in 2 datatypes, point clouds and grids. Grid files are a lot smaller than the original point cloud and can very easily be used for simple calculations. The drawback of using these grids is that this data has been processed from a point cloud to a grid. This causes a loss of information, because the grid shows a small tile with a certain height for the entire tile and this is of course not the case in the real world.
The point cloud is very detailed, because it gives the height of only one point with its coordinates, but it gives no information about the surrounding space. A problem with point clouds is that the points in different clouds will not be on exactly the same spot. This means it is not possible to just compare both clouds. Therefore, one will first need to do a form of interpolation. The difference between a point cloud and a grid is visualized in figure 16.

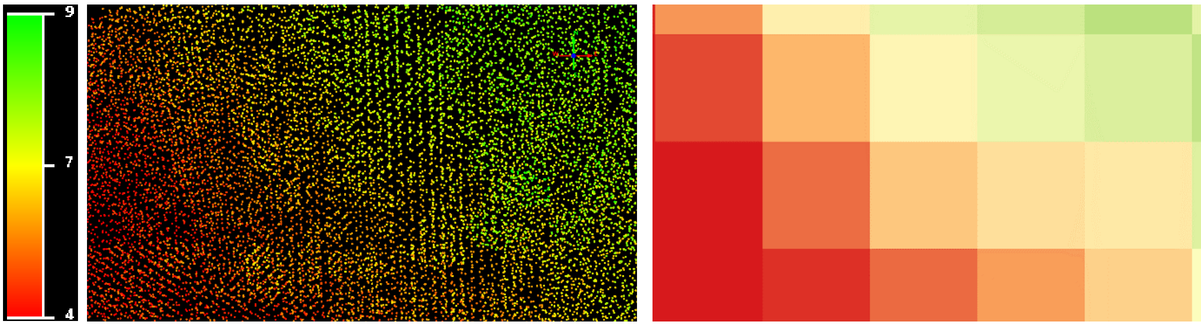
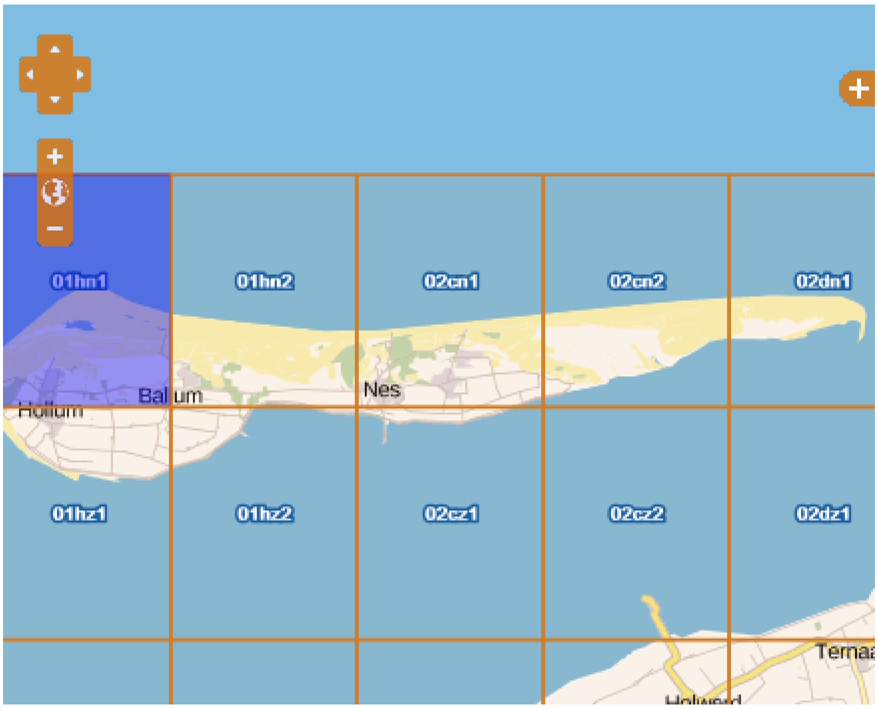


Figure 16 Example of a point cloud (left) and a grid (right). They show the same area (25x20 meters) and use the same colorscale of 4 to 9 meters.

AHN is a very large database (over a Terabyte) and because of that the data is divided into smaller tiles. These tiles are 5 km east to west and 6,25 km north to south. [12] On www.pdok.nl there is a viewer that shows what tiles you need when you want data from a certain area (figure 16).

Figure 17 PDOK viewer [18]

Zooming in on Ameland we get the following image.



KAARTBLAD: 01HN1		
INHOUD	FORMAAT	LINK
0,5 meter raster dsm	GeoTIFF (gezipt)	Download
0,5 meter raster dtm	GeoTIFF (gezipt)	Download
5 meter raster dsm	GeoTIFF (gezipt)	Download
5 meter raster dtm	GeoTIFF (gezipt)	Download
Puntenwolk	LAZ	Download

Figure 18 AHN tiles needed for Ameland [15]

From figure 18 it is clear the following tiles are needed for this research:

- 01hn1
- 01hn2
- 02cn1
- 02cn2
- 02dn1
- 01hz1
- 01hz2
- 02cz1
- 02cz2
- 02dz1

The raster data is available in 2 types: filtered and unfiltered. The unfiltered point clouds contain data points of the entire island. This means the data is not just data of the ground, but also contains for example trees and rooftops. For researches where just the ground is needed there is a ground level raster, this is the filtered dataset. Here all cells that contain the height of something that is not the ground are removed and the cell is left empty. For AHN 1 and 2 only this ground level data is available, but for AHN 3 you can download both. When we compare the filtered version with the unfiltered version, we get a map like in figure 19. Here the difference between the 2 maps is displayed with a color, blue for small or no changes and red for larger changes. White means that in at least 1 of the datasets there is no data. [12]

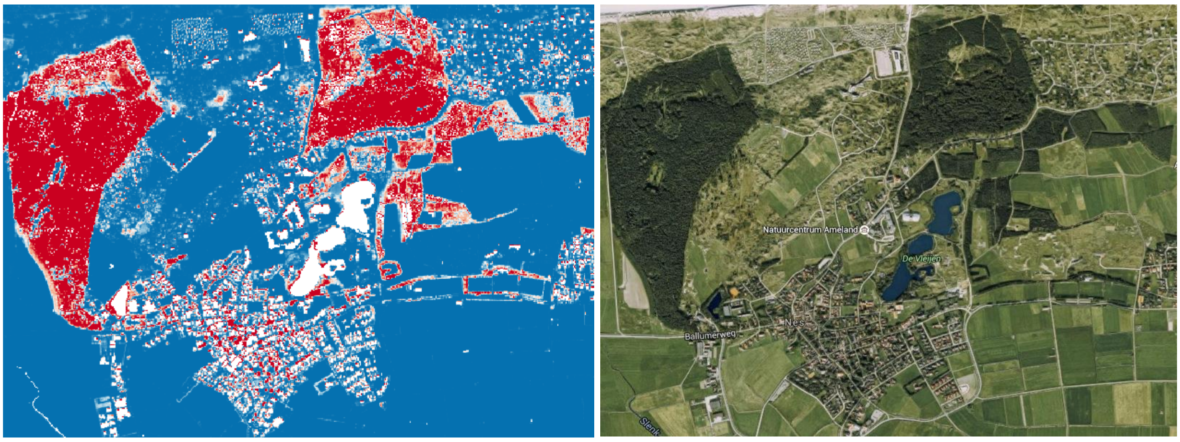


Figure 19 Left: difference between raw and filtered data in AHN. Right: image taken from Google Maps of the same area. The area is the village of Nes on Ameland.

When we compare this map to a Google Maps image of the same area, we see that the red spots line up with villages and forests. This is as we expect it to be, since we said earlier that trees and buildings should be filtered out of the data in the ground level dataset. Since for AHN 1 and 2 only the ground level is available, we will only compare the ground level of AHN 3 to the ground level of AHN 1 and 2.

The most noticeable differences between AHN 1, 2 and 3 are on the coast. Their coast lines are all different. This is probably because the datasets have a cut off, as we will see later in the method section in chapter 4.2. The data is cut off at -1 meter. Since the sea bottom can change a lot over some time it can be very different where the data will be cut off. We will not be finding any difficulties with this, as we will get a no data value once we try to do a calculation on a no-data value cell and a normal cell. This means we will only get a valid answer for the cells that have a value in both cells.

The AHN datasets contain a lot of data. For Ameland alone we are already dealing with almost 3 million points in the smallest dataset. The exact number of valid data points per dataset is shown in table 2.

AHN	Point cloud	5 meter grid
1	25.980.585	4.257.878
2	1.111.769.410	3.178.221
3	959.255.480	2.913.386

Table 2 Number of points in the point clouds and grids for AHN 1, 2 and 3.

For AHN 1 and 2 the requirements concerning the error are known. The maximum systematic error for both is set at 5 centimeters. The maximum standard deviation for AHN 1 is set at 15 centimeters and for AHN 2 at 5 centimeters. The real systematic error and standard deviation can differ per region, as different companies did the data collection, but the maximum errors are known. [12]

The standard deviation is an error that is present in every value in the data and can be caused by something like not correcting for the height of the plane correctly. This can result in an error of a few centimeters that is present in multiple values in the dataset. The systematic error is an error for a specific to a data value and is also called noise.

3.3 Deltares LiDAR data

Another dataset we used is created by Fugro and commissioned by the NAM. The dataset is used in a research done by Deltares. This dataset contains 7 different sets of the area in the Waddenzee between Ameland, Schiermonnikoog and Friesland. The datasets are created in: [8]

- Spring 2010
- Spring 2011
- Autumn 2011
- Autumn 2012
- Autumn 2013
- Spring 2014
- Autumn 2014

The datasets were delivered to Deltares in the form of a 1m x 1m grid. The processes needed to create this grid were not described. This grid was then processed into a 10m x 10m grid by Deltares. This was done by taking the average of all the smaller grid cells in a larger grid cell. When there was no data available in a grid cell there was no interpolation done and the grid cell would just be left empty. [8]

The data was collected with a water level below -0.7 meter NAP. However, at some points the water level could still be higher than -0.5 meter NAP. That’s why Deltares made a cut off at -0.5 meter NAP and used this new dataset for their research. [8]

The mean and maximum error of a grid cell are $4*\sqrt{2}$ and 8 cm as can be found in [Deltares].

Dataset	Number of valid grid cells
Spring 2010	2.570.916
Spring 2011	2.252.420
Autumn 2011	2.466.507
Autumn 2012	2.466.507
Autumn 2013	2.663.837
Spring 2014	2.866.958
Autumn 2014	2.706.430

Table 3 Number of valid grid cells in the Deltares data

The last 2 datasets were created using a laser that should get better returns in wet environments. [8] In table 3 we see an increase in the number of data values for the last 2 datasets, so this laser probably does get better returns.

4 Programs and methods

The total method used to solve our research question can be split into 4 parts:

- Grid wise differences
- Correction for systematic errors
- Trend estimating
- Cloud to mesh differences

These methods will be discussed after discussion of the programs that were used to complete these methods.

4.1 Programs

QGIS

QGIS is a free and open source Geographic Information System. In this research we use it for comparing grids, visualizing datasets and creating maps.

It was very easy to create multiple maps of the same area with different datasets, because you can save all the settings of your map. This means that you can create 2 maps, that cover the exact same area and have legend and scale on the same place, but show different data. Another good thing about QGIS is that you can download a lot of plugins.

For larger grids the functions like "merge" and "raster berekeningen" could crash, but this did not mean the entire program would crash.

LAS Tools

LAS Tools is a paid tool that can be used to prepare and process LAS data. In this research we used the tools laszip for unzipping LAZ files into LAS files and lasclip to cut a dataset with a shapefile we created earlier. The program moreover has a lot more options like sampling, conversion into different file formats and turning a point cloud into a grid.

Some good points about LAS Tools are that the program works very easy and that because it does not have to show the point clouds, it is faster and will not crash as often as programs like CloudCompare.

CloudCompare

CloudCompare is a program that can load and compare point clouds. In this research we first use it to compute a mesh for the point cloud, then we compare this mesh to the other point clouds and finally we visualize the differences.

This program is easy to use, but can be a little slow and is not capable of comparing large point clouds.

Python and Matlab

Python and Matlab are scripting languages that were used for calculations that could not easily be done by the other programs. A beginners course for both languages was followed in order to use them.

4.2 Methods for change detection

Grid wise differences

The Ameland dataset consists of 10 tiles. To make it easier to work with first the tiles were merged into one big tile. This can be done in QGIS, a program that we use to calculate and visualize geospatial datasets. QGIS has a built in function “merge” to complete this task. Once this is done the datasets also need some calculations to make them comparable. AHN 1 needs to be converted from centimeters to meters and AHN 2 and 3 need to have the same no-data value as AHN 1.

Once the datasets are prepared they can be compared. We can look at the height difference in 2 ways. The first one is to just compare the heights of one AHN-set to another one and visualize the differences. This can be done in QGIS and in Python. Since we have 3 datasets we can get 3 calculations:

- AHN 1 – AHN 2
- AHN 2 – AHN 3
- AHN 1 – AHN 3

The resulting datasets can be displayed in QGIS. To make sure we display the results clearly, we try different colorbar boundaries for every dataset. The boundaries used are:

- [-5 5] meters
- [-1 1] meter
- [-0.5 0.5] meters
- [-0.1 0.1] meters

These boundaries mean that every value that is outside these boundaries will get the value of their nearest boundary.

The Deltares dataset can be treated in the same way as the AHN grid. The big difference is that we now have 7 datasets instead of 3. We start with displaying the original data with as color boundaries at -2 meter and 2 meter. After this we can compare the different datasets, to visualize the height differences:

- Spring 2011 – Spring 2010
- Autumn 2011 – Spring 2011
- Autumn 2012 – Autumn 2011
- Autumn 2013 – Autumn 2012
- Spring 2014 – Autumn 2013
- Autumn 2014 – Spring 2014

The color boundaries are set at -0.25 meter and 0.25 meter.

Next we take Autumn 2014 – Spring 2010 to look at the influence of the color boundary. We test this using:

- -5 and 5 meter
- -1 and 1 meter
- -0.5 and 0.5 meter
- -0.25 and 0.25 meter
- -0.1 and 0.1 meter

After this we look at simplification of the data. We do this by creating larger grid cells and look if a subsidence or uplift system becomes clear. We try 2 different methods for creating these larger grid cells. In the first method we take all the small grid cells in the bigger cell and calculate the average. After this we replace the original value in the smaller grid cell with the average value we just calculated. This way the dataset can be displayed easily. The second method takes the grid cell in the center of the larger grid cell and uses this value to again fill all smaller cells in the large cell. We try these methods for a few different sizes of the large cell:

- 25 x 25 cells
- 50 x 50 cells
- 100 x 100 cells
- 200 x 100 cells
- 400 x 400 cells

Correction for systematic errors

In the AHN 1 and AHN 2 comparison, there is clearly more subsidence visible in the north east of Ameland than there is in the rest of the island. In the other 2 comparisons it seems as if the island as a whole is subsiding. This is strange, so we need to find out why this is. In order to find it out we use Python to create histograms of the following datasets:

- AHN 1
- AHN 2
- AHN 3
- AHN 1 – AHN 2
- AHN 2 – AHN 3
- AHN 1 – AHN 3

If we add or subtract a little to the entire dataset and set the mean at 0 we get a more accurate picture of the subsidence. We can use Python to find the current value for the mean. Here the median is found by taking all values in the dataset, order them by height and then take the middle value. The mean is found by taking the histogram and finding the bar with the most values in it. We use the means to correct the datasets with the following calculations:

- AHN 1 – mean
- AHN 2 – mean
- AHN 3 – mean

These new datasets can again be visualized in QGIS.

Next we take a larger area to see if other changes show up. The data however does not fit perfectly together, as can be seen in figure 20. We see on the main land that the is a large vertical line through the data we see on the main land that the is a large vertical line through the data that divides it in two. This is because the total AHN dataset is made of multiple datasets that are put together. These datasets might be corrected in a different way and will have a different systematic error.

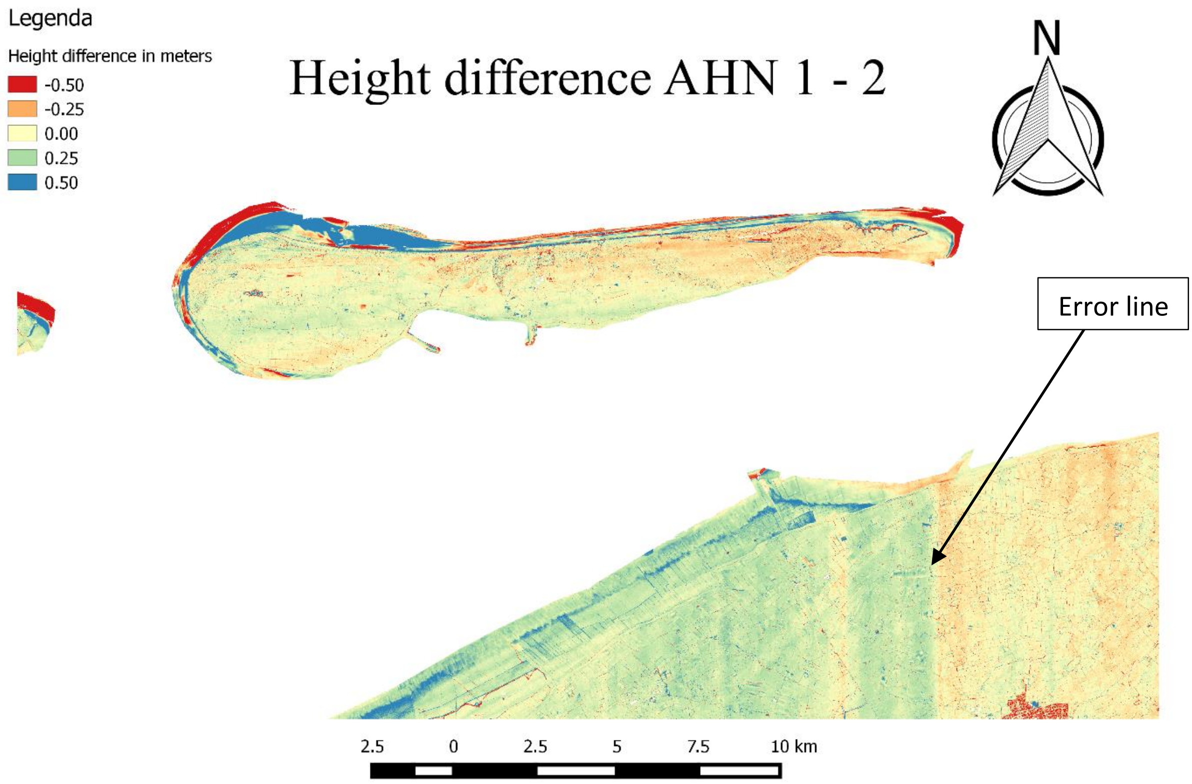


Figure 20 Uncorrected height differences AHN 1 and 2

The data is split into 4 different datasets in QGIS with the clipper tool. The regions are as follows:

- Ameland
- Terschelling
- Green part of Friesland
- Orange part of Friesland

All 4 regions are then again corrected for systematic errors as done before for just the island. The result of this can be seen in figure 21. This is done for the sets AHN 1 – AHN 2, AHN 2 – AHN 3 and AHN 1 – AHN 3.

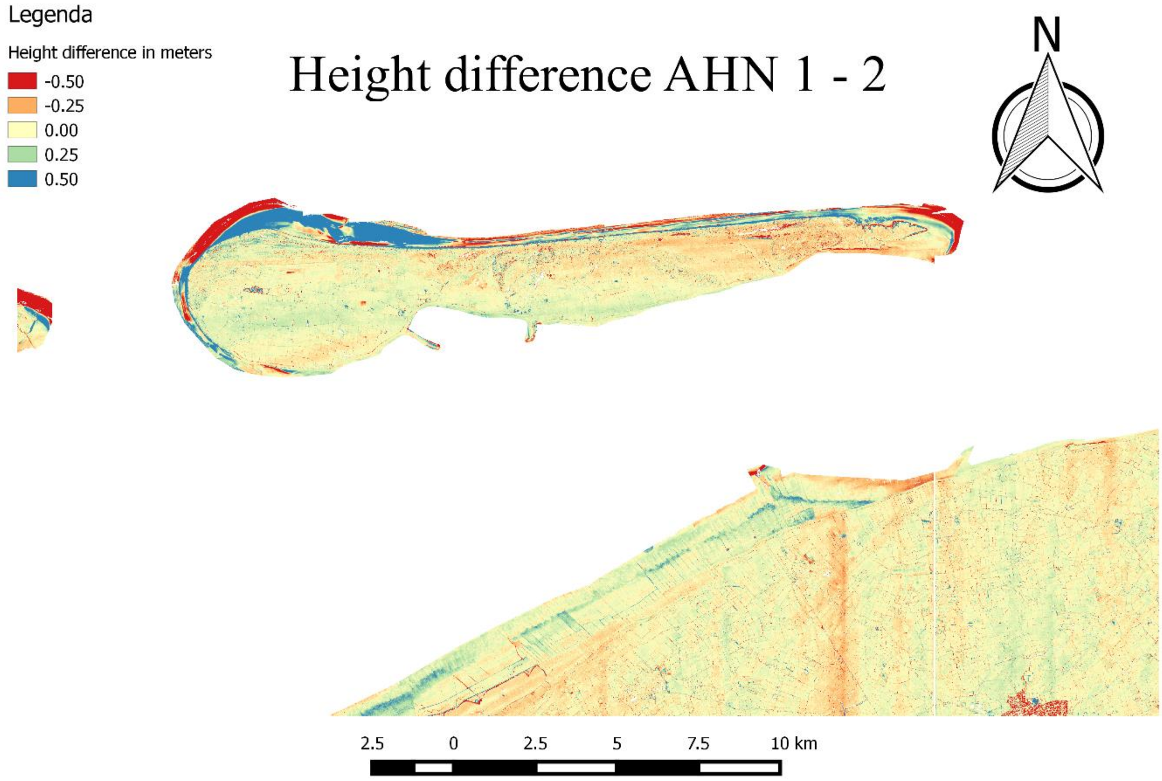


Figure 21 Corrected height differences AHN 1 and 2

Trend estimating

Another way is to find a linear formula for the heights in every raster cell. This can be done by writhing a Python script. This method assumes that the height change in every cell can be described by the following formula:

$$h = h_0 + bt$$

Here h is the height in meters at time t, h_0 is the height in meters at t = 0, b is height change in meters per year and t is the time in years.

Next the least squares formula can be used to find the variables h_0 and b for every raster cell. The least squares formula is a mathematical formula to calculate a best fitting line with a certain formula through multiple points. These points can be gathered in an experiment and when they don't exactly fit in a line this formula can be used to still be able to find the needed variables. This principle is demonstrated in figure 22. H_0 should be the same as AHN1 in our case, as this is the height at t = 0 and b is the slope. The slope is the height change per period, which is what we want to know. With this least squares formula it is also possible to calculate the error. As can be seen in figure 22 the least squares solution gives an error for every value. This error is the distance between the actually measured point and the value at the same time given by the fitted line. The absolute value for all 3 AHN values can be added together and divided by 3 to get a signed average of the errors.

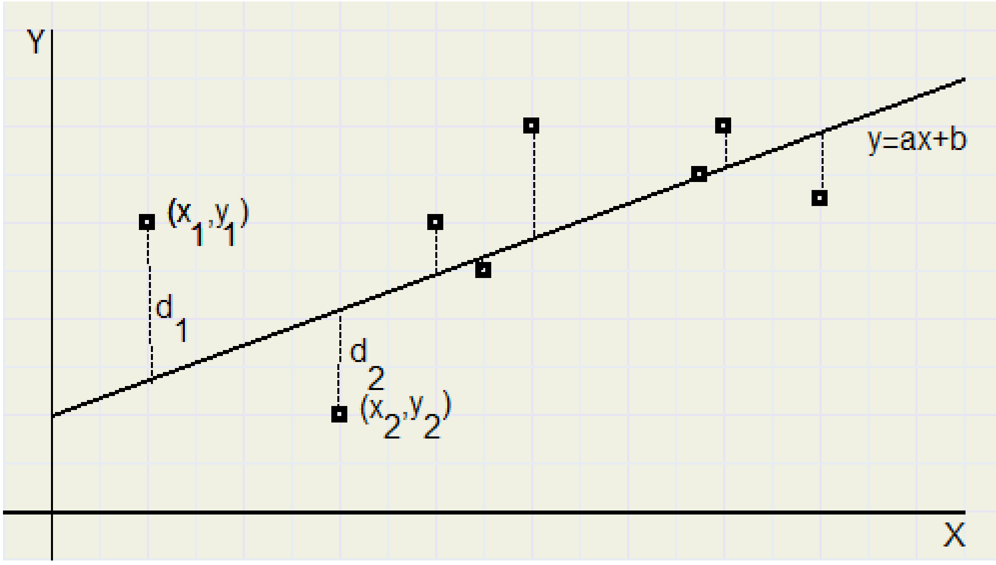


Figure 22 Least squares principle, showing the original data and the least squares solution. [19]

The least squares solution can be found through a Python script which will give a h_0 and a slope for every grid cell. The inputs for this script are the 3 datasets and a matrix that contains the dates of acquisitioning of the data. In this case we used years for these dates, so we used 0, 9 and 16 for AHN 1, 2 and 3 respectively. This means that our resulting slope will be in meters per year. We visualize the h_0 and AHN 1 so we can see if they show the same.

Next we display the slope and the difference between AHN 3 and 1 with the following color boundaries:

- 0.025m/yr
- 0.01m/yr

The least squares formula does give an option to look at the accuracy of the image, as the accuracy of the data values with respect to the original data can be found through the following formula:

$$\hat{e} = h - \hat{h}$$

Here ê is the error in meters, h is the real height in meters and $\hat{h}$ is the height at the same time given by the least squares method.

The average of the 3 local errors can be calculated with:

$$\hat{e} = \frac{1}{m}\sum_{i=1}^{m}|\hat{e}_i|$$

Here ê is the average error and $\hat{e}_i$ is the local error

We can now show these average errors in a map.

We can also visualize how many values were used in the least squares method. As not all maps have valid data at the same cells it is possible that some cells use 3 data point, while others only use 2. We again visualize this in Python.

Lastly we can closer investigate at the part that is subject to subsidence. We use QGIS to create a shapefile over this subsidence area. Next we clip the corrected datasets for AHN 1 and 2 for AHN 2 and 3 and for AHN 1 and 3. In Python we can write a script to calculate the average of the height changes in this clipped datasets, the area of the clipped datasets and the volume change.

For the Deltares data we can again do the same, but first we need to filter the bit of water that is still left in the data, because this water can vary in the different datasets and could show subsidence or uplift when there is none. We choose -0.5 meter as cutoff because this is the value Deltares used as cutoff and because this cleans up all the data points in the trenches where still water is present. We apply this cutoff by deleting every value below -0.5 meter.

When this is done we can apply the least squares method we used for the grids. The method is the same but now we use 7 datasets instead of 3. The times we used here are again in years, so we again get a slope in meters per year. We used the following times for the script: 0, 1, 1.5, 2.5, 3.5, 4 and 4.5.

First we visualize the h_0 and Spring 2010 with color boundaries -2 and 2 meter.

Next we plot the slope and difference between Autumn 2014 and Spring 2010 with color boundaries:

- -0.1 and 0.1 meter
- -0.05 and 0.05 meter
- -0.01 and 0.01 meter

Now we can get an idea of the error by again calculating the average error and plotting it with boundaries:

- 0 and 0.25 meter
- 0 and 0.1 meter

Then we plot the number of values per grid cell.

Lastly we calculate the average height change for all grid cells combined for both the slope calculated with the least squares method and the difference between Spring 2010 and Autumn 2014 divided by 4.5 years.

Cloud to mesh differences

Besides using grids it is also possible to look at the AHN data by using the point clouds. We use the program CloudCompare to compare the different point clouds. As we saw in chapter 3.2, the point cloud data contains a lot more data points than the grid data. The datasets are in fact so big, that the program can't handle them and crashes. That is why we take small regions of the original data and look at those instead. We have 4 different locations:

- Location 1: gas extraction
- Location 2: village with buildings
- Location 3: small airport with a large flat area
- Location 4: dunes

We start with creating the shapes of the locations in QGIS. These shapes can then be saved in a shapefile. Now we can use the LAS clip tool from LAS tools to cut the original data with the boundaries of the shapefile. When this is done we have 12 small datasets, 4 locations for AHN1, 2 and 3.

These smaller datasets can not yet be compared, because CloudCompare does not allow for 2 point clouds to be compared with signed distances. This means that it can compute the distances between the 2 datasets, but it will use the absolute distance and will not show if subsidence or uplift took place. When we compare a mesh with a point cloud we do get signed differences.

A mesh is a triangulation of the original point cloud. When a triangulation is created a triangle is made between 3 points of the dataset. On this triangle a plane is created, so we now have a plane in stead of 3 points. When this is done for all points we have a surface, which means we have a Z value for the entire area. Now we can compare these Z values with another point cloud.

To make a mesh out of a point cloud we use the CloudCompare tool Delaunay 2.5D (XYplane). We first used Meshlab for this, but that program applied a lot of smoothening which made the results unreliable. For this triangulation we maintain the “Max edge length” at 0 (figure 23), which is the default value. When it is set at 0 this means there is no maximum edge length and the triangulation will be created untill all points are used.

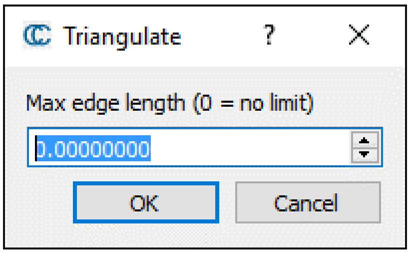


Figure 23 CloudCompare Delaunay 2.5D (XY plane) settings

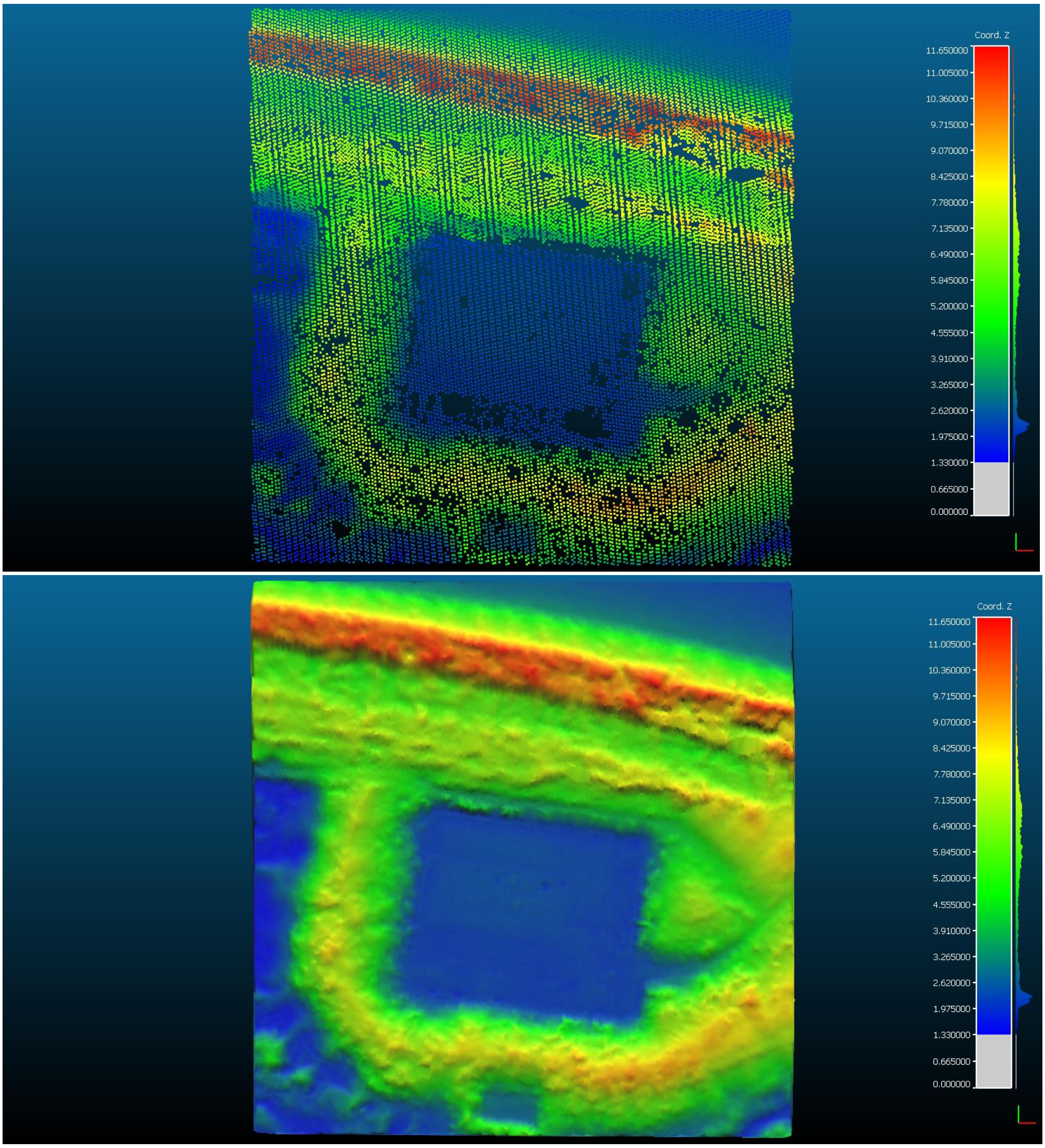


Figure 24 Top: point cloud of region 1 in AHN 1 visualized in CloudCompare.
Bottom: Mesh of region 1 in AHN 1 created in CloudCompare

The tool then creates a mesh as seen in figure 24, which we can use to compare. Now we select the point cloud and mesh we want to compare and start the tool Distance computation. We leave all the settings on default and click compute, as can be seen in figure 25. Once this is done we click ok.

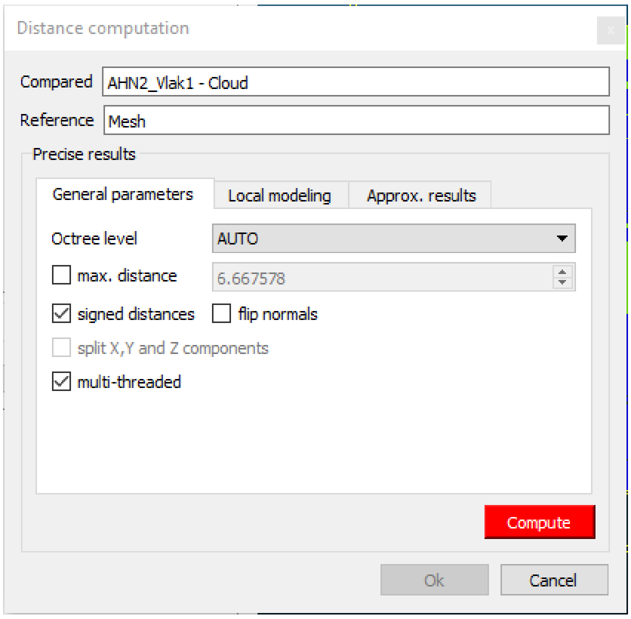


Figure 25 Distance computation tool

This function creates a Scalar field for the data. The Scalar field associates a scalar value from the Z height to every point in the dataset. We need these Scalar fields, because CloudCompare has some functions that need a Scalar field to work. We can also turn the original point clouds into Scalar fields by using Edit->Scalar fields->Export coordinate(s) to SF(s). We can create a histogram for this Scalar field when we select the original point cloud and click on edit->Scalar fields->Show histogram (figure 26).

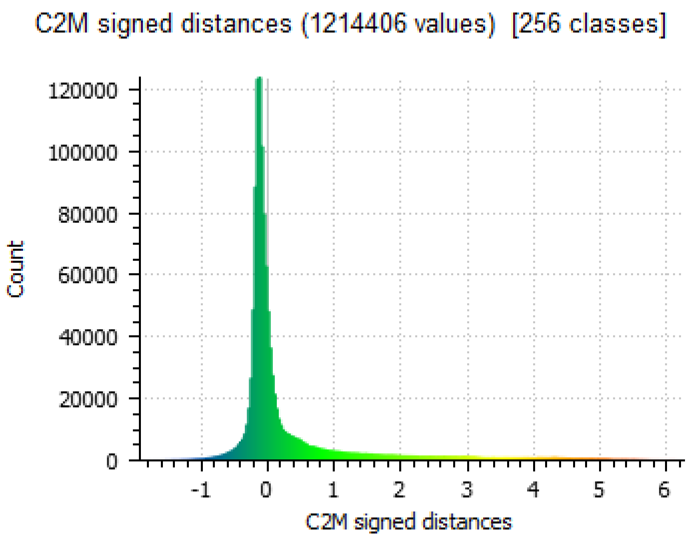


Figure 26 Histogram of the mesh of AHN 1 and point cloud of AHN 2 at Location 1.

We get the following 2 histograms per location:

- Mesh AHN 1 compared to point cloud AHN 2
- Mesh AHN 1 compared to point cloud AHN 3

These histograms can then be exported to excel. In excel we can easily find the average and the most occurring value. These values can again be compared to see if subsidence or uplift takes place at the location.

5 Results

5.1 Region of interest

For this research we have a few different regions of interest. For the AHN grid we use the 10 tiles that cover Ameland, as can be seen in figure 27.

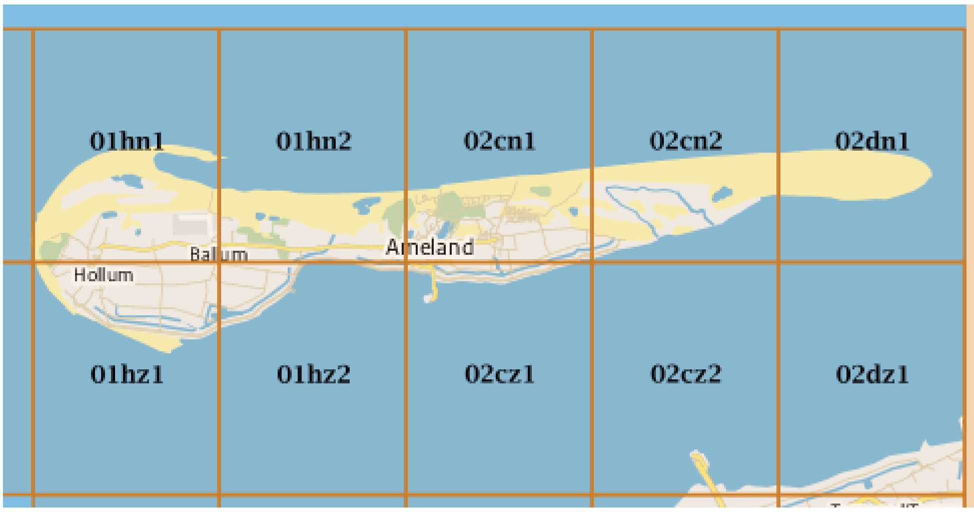


Figure 27 AHN tiles for region of interest. [18]

This region is large enough to compare regions with and without:

- Subsidence due to the gas extraction
- Moving dunes
- Villages that have buildings

It is also small enough as we only look at an island and a very small part of the main land.

For the point cloud part of AHN we have 4 different regions as can be seen in figure 28. These regions all represent a different terrain class:

- Location 1: gas extraction
- Location 2: buildings
- Location 3: large flat area with no subsidence
- Location 4: dunes

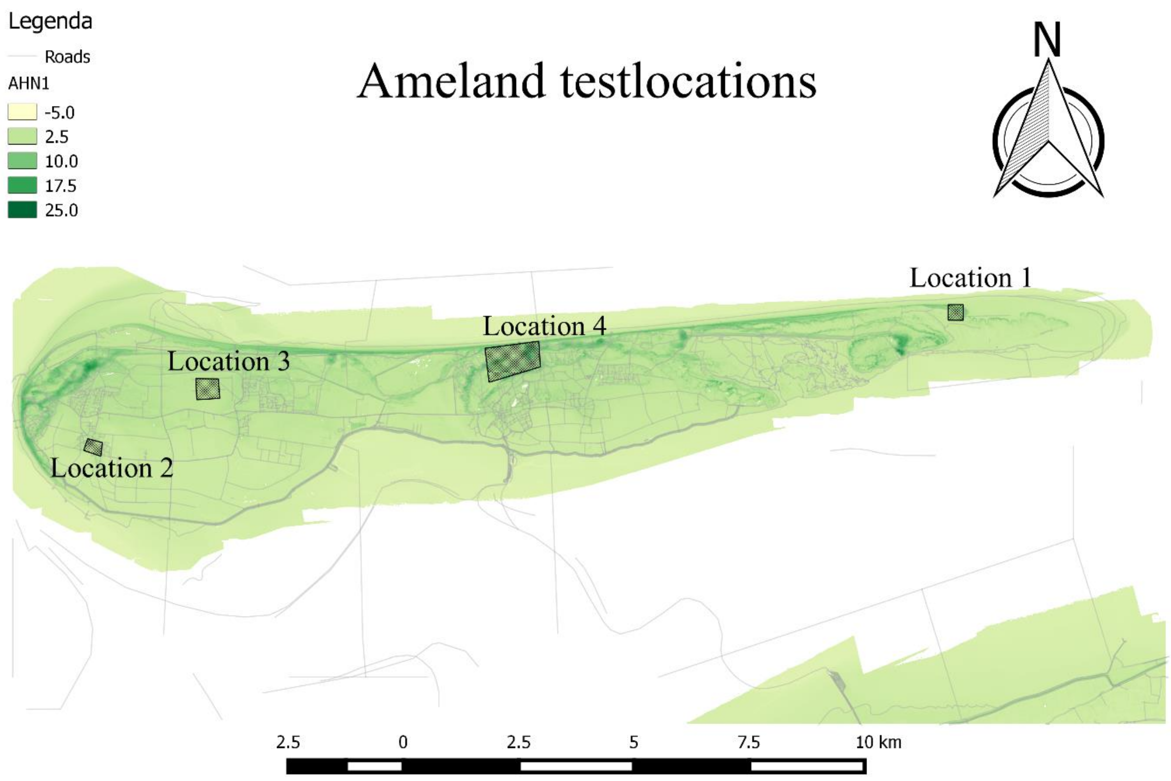


Figure 28 Test locations used for point cloud comparing

This way we should be able to compare different processes that influence height changes. Next we will look at the test locations individually with images taken from Google Maps.

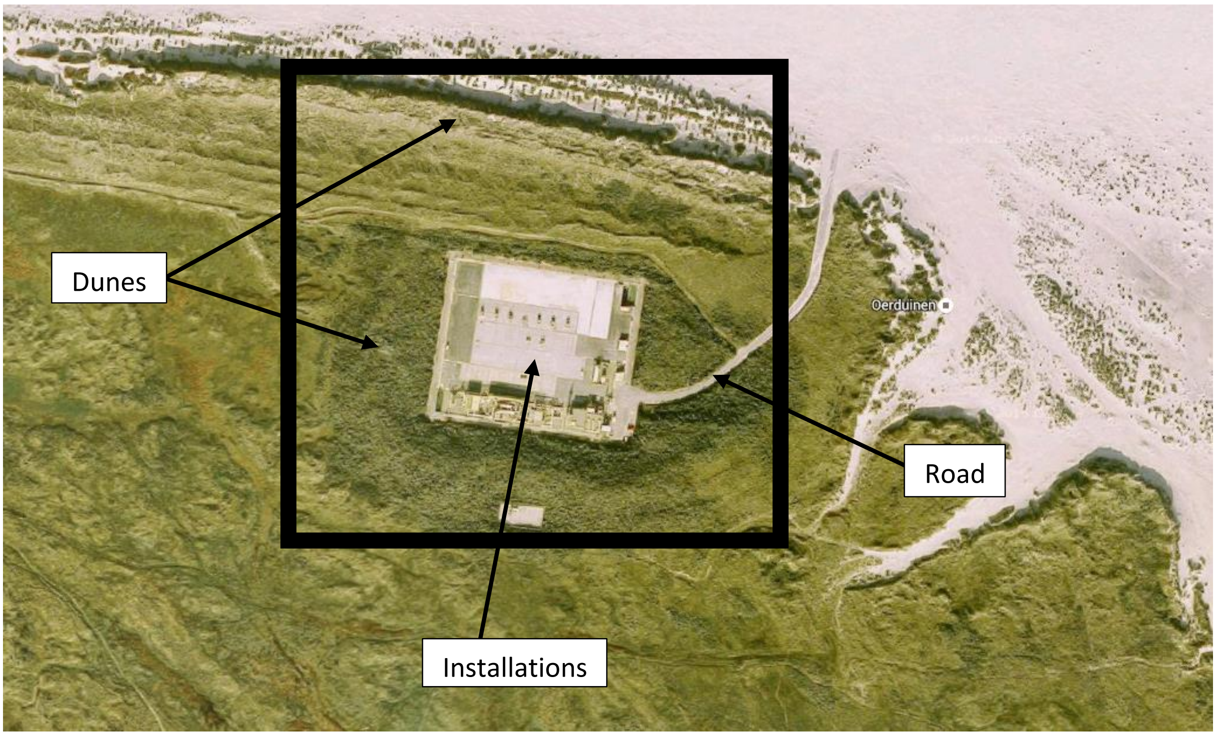


Figure 29 Test location 1 as seen in Google Maps

In figure 29 we see test location 1. We see the installations in the middle of the area and around that and in the north we see some dunes. We also see a small road on the right.

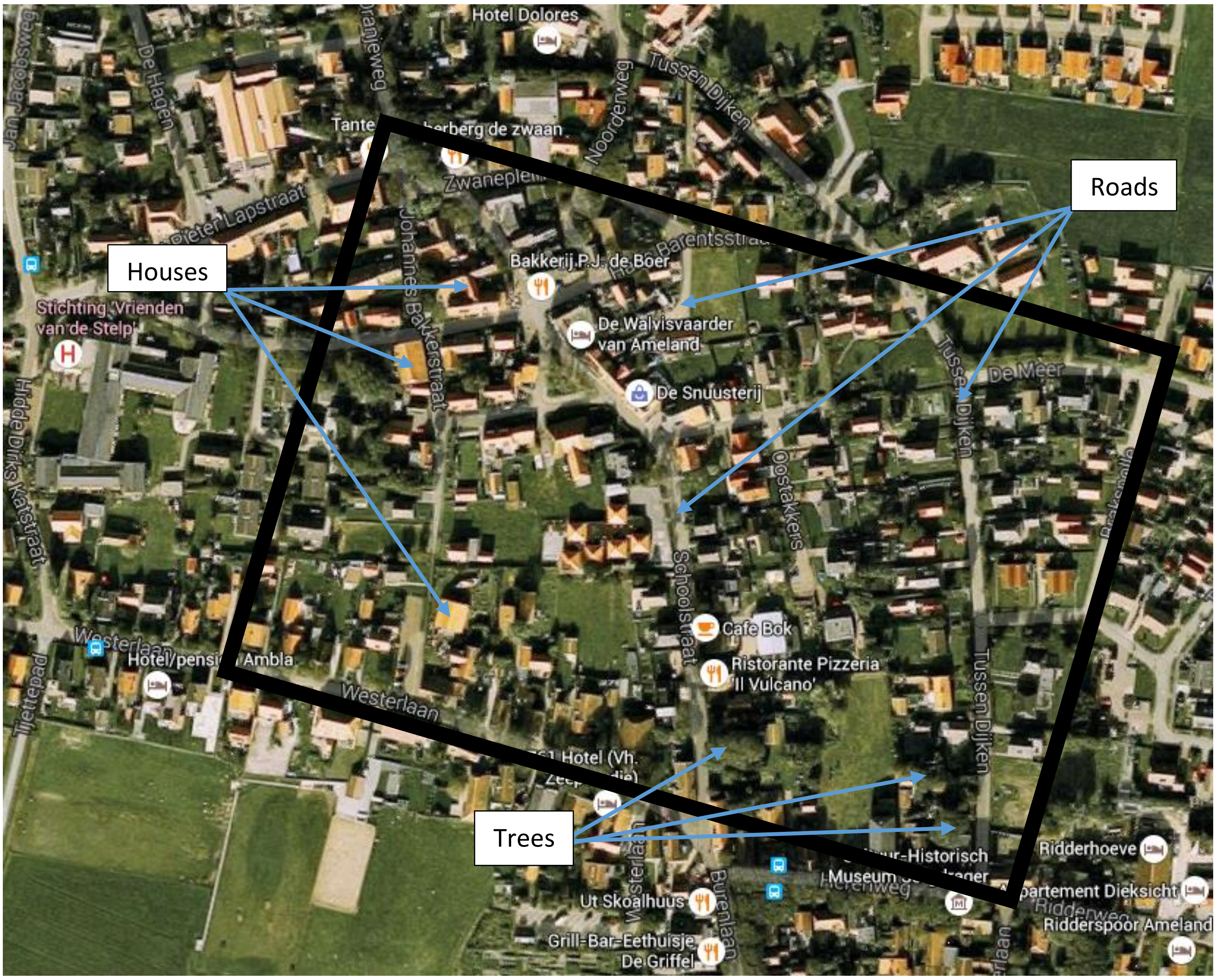


Figure 30 Test location 2 as seen in Google Maps

In Figure 30 we see test location 2. In this location we see multiple houses, roads and trees.

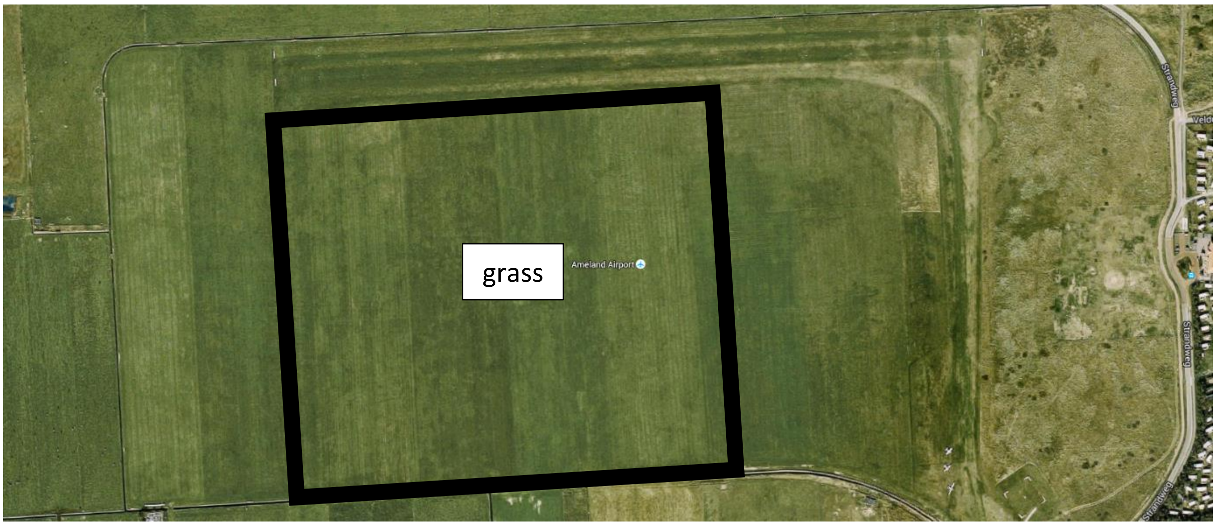


Figure 31 Test location 3 as seen in Google Maps

In figure 31 we see test location 3. This is just a small airport and we only see a lot of grass.

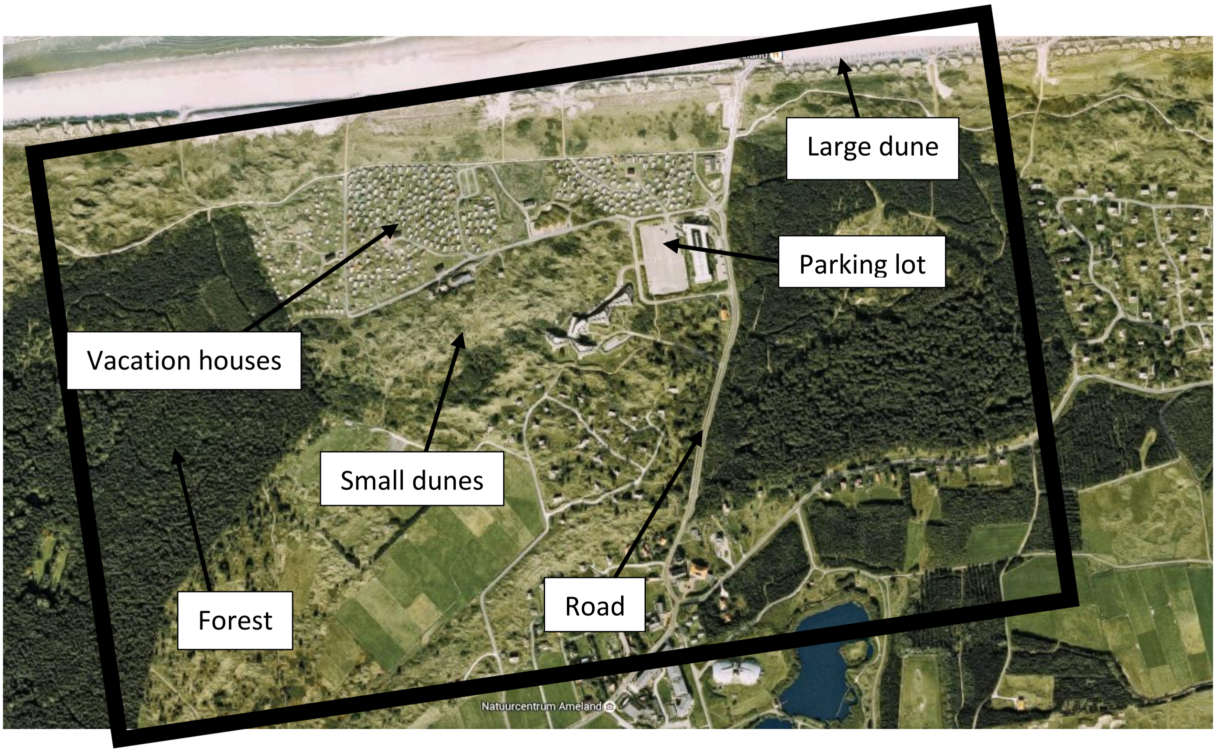


Figure 32 Test location 4 as seen in Google Maps

In figure 32 we see test location 4. In this test location we see multiple things. We see a forest, vacation houses, a parking lot, roads, a large dune and smaller dunes.

Lastly we have the data we received from Deltares as seen in figure 33. Here we choose to use the same region as they did. They chose this area, because they were interested in the changes that took place in that part of the Waddenzee.

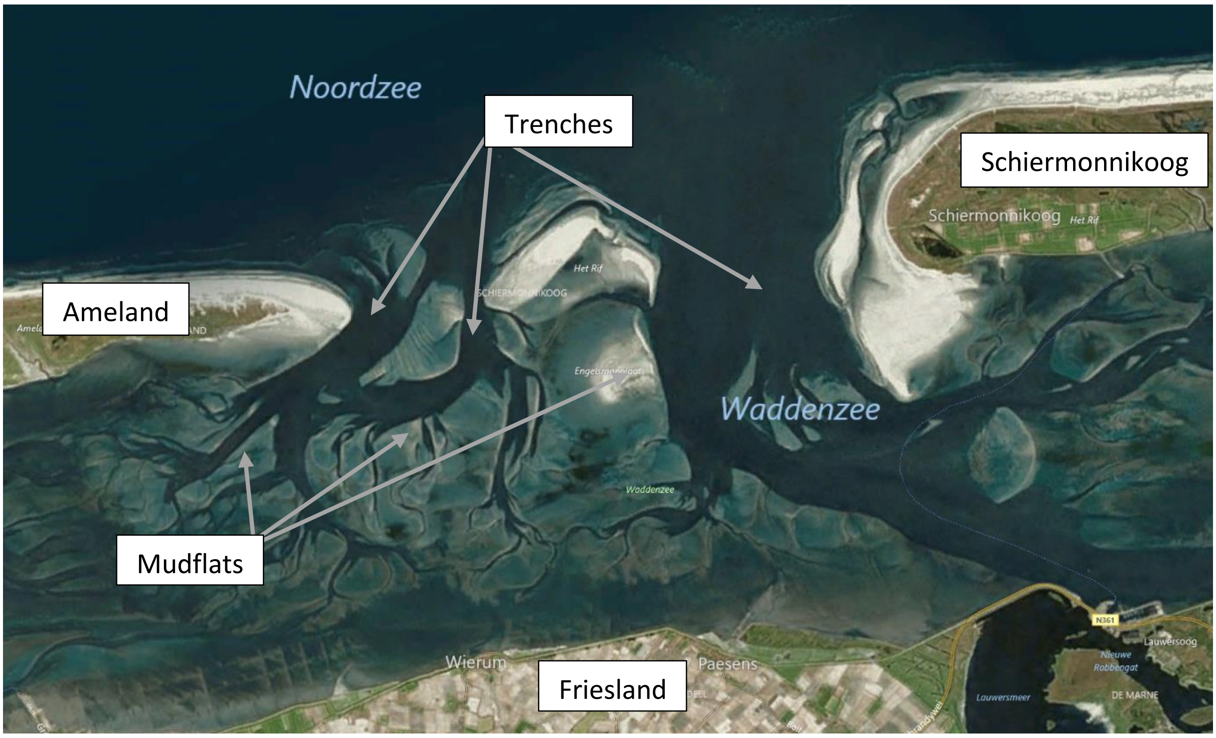


Figure 33 Region of interest of the research done by Deltares

5.2 AHN grid comparison

We start with the grid version of AHN. The first results we then get are the maps for AHN 1, 2 and 3. AHN 1 is shown in figure 34, all maps can be found in appendix A. These maps are created in QGIS and show the heights on the island. When we look at figure 34, we notice that some dunes show up quite clearly, but that the rest of the island seems quite smooth.

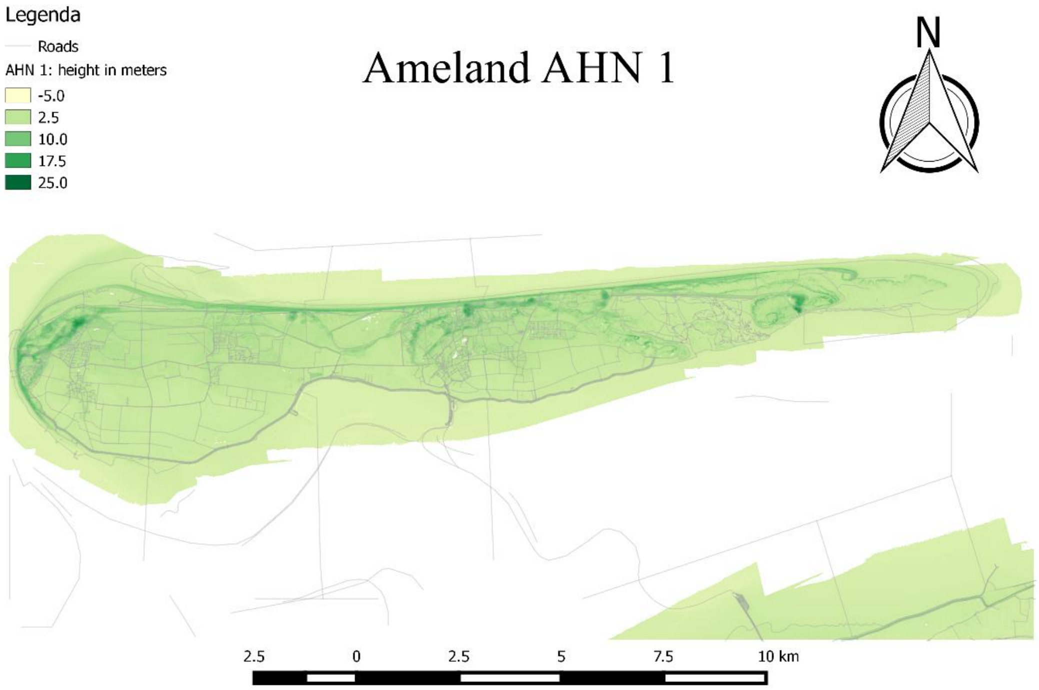


Figure 34 Ground-level AHN 1 data in Ameland in meters

When we compare AHN 1 to AHN 2 we get the maps that can be seen in figures 35, 36, 37 and 38.

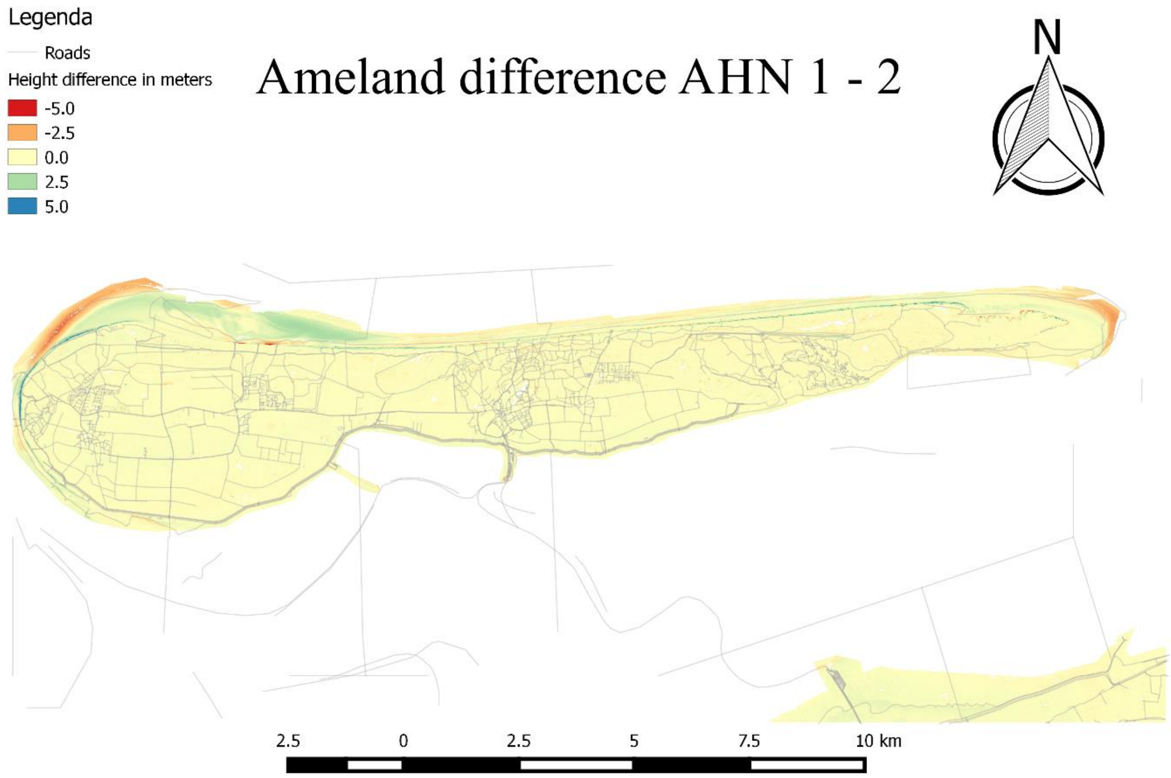


Figure 35 Comparing AHN 1 and 2 with boundaries on -5 and 5 meters

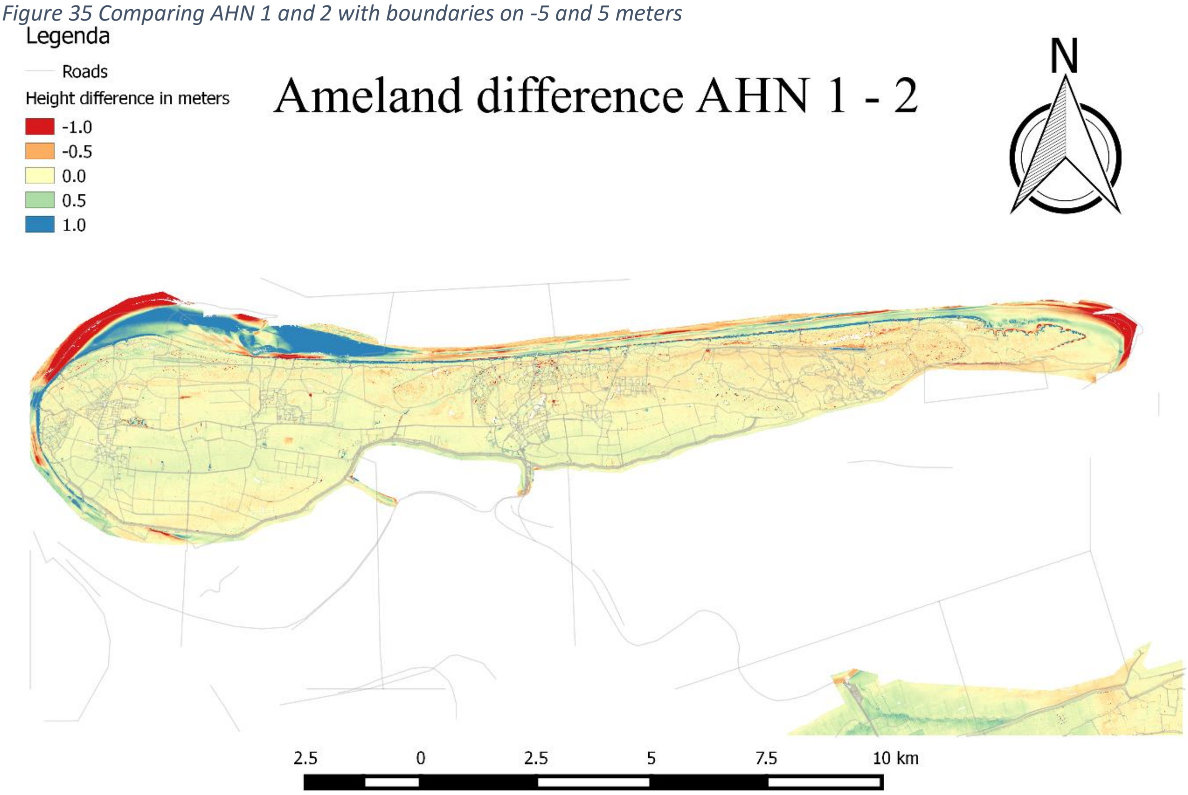


Figure 36 Comparing AHN1 and 2 with boundaries on -1 and 1 meters

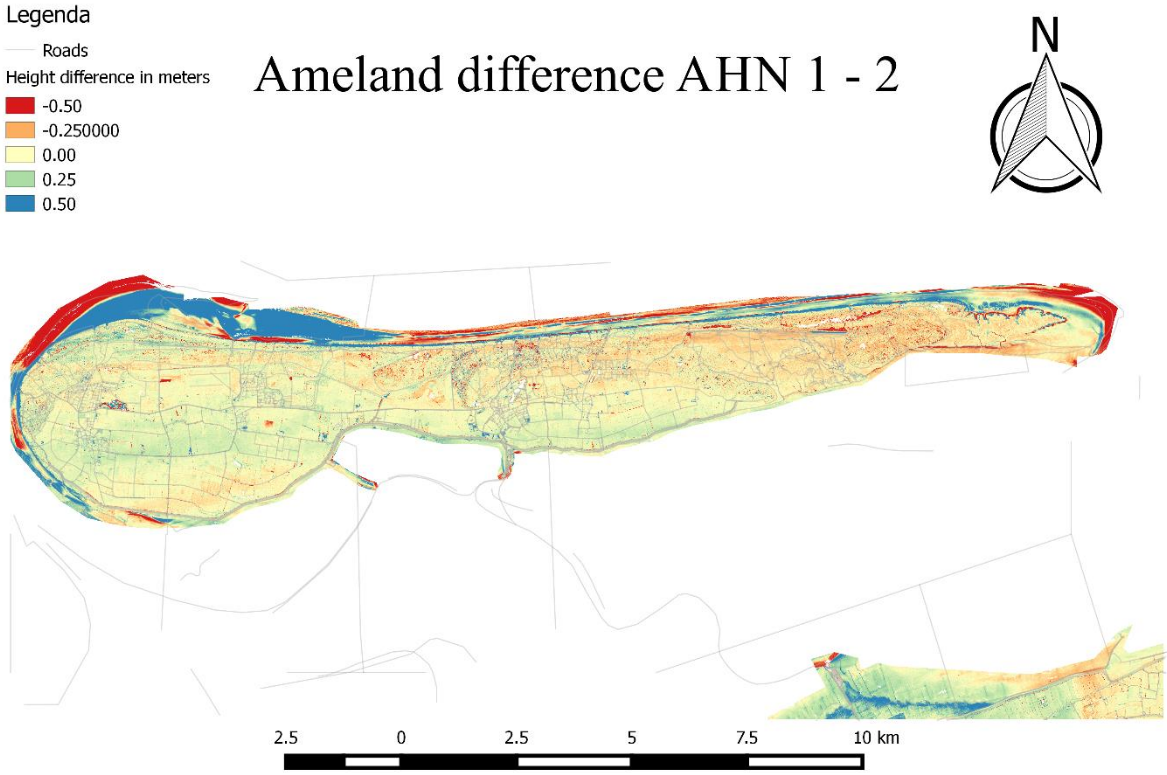


Figure 37 Comparing AHN 1 and 2 with boundaries on -0.5 and 0.5 meters

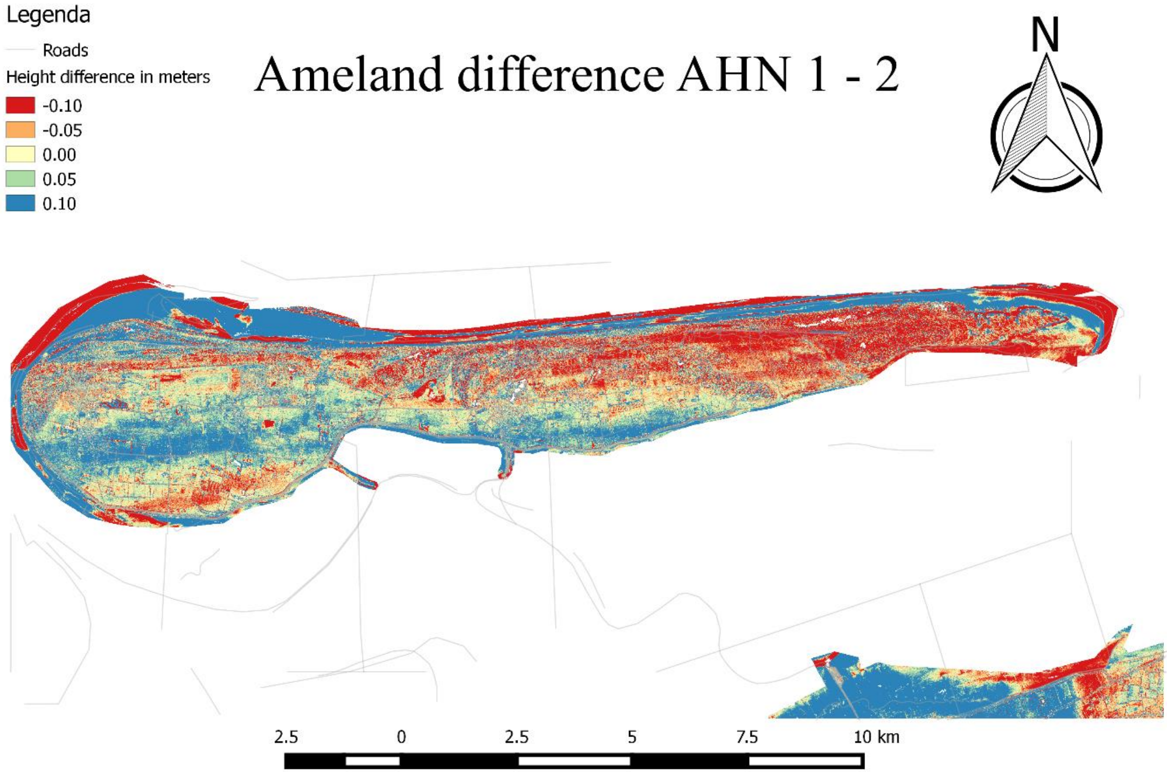


Figure 38 Comparing AHN 1 and 2 with boundaries on -0.1 and 0.1 meters

When we look at these maps, the first thing that we see is that the subsidence in the east becomes a lot more visible when we apply small boundaries. This is what we expect, as gas extraction takes place on the eastern part of the island. Another thing we notice is that there are some very large local changes in the north west of the map. These changes can be explained by the fact that they are happening in parts that are sometimes under water and are therefore subject to the erosion and sedimentation forces of the sea, which are stronger than the sedimentation and erosion forces of wind. We also see that the results obtained with the boundaries -5 and 5 meter and -1 and 1 meter are less clear than -0.5 and 0.5 meter and -0.1 and 0.1 meter. For the comparison between AHN 2 and 3 and AHN 1 and 3 we will only show the -0.1 and 0.1 meter boundaries. The full comparison can be found in appendix B.

Next we visualize the same maps for AHN 2 and 3 in figure 39.

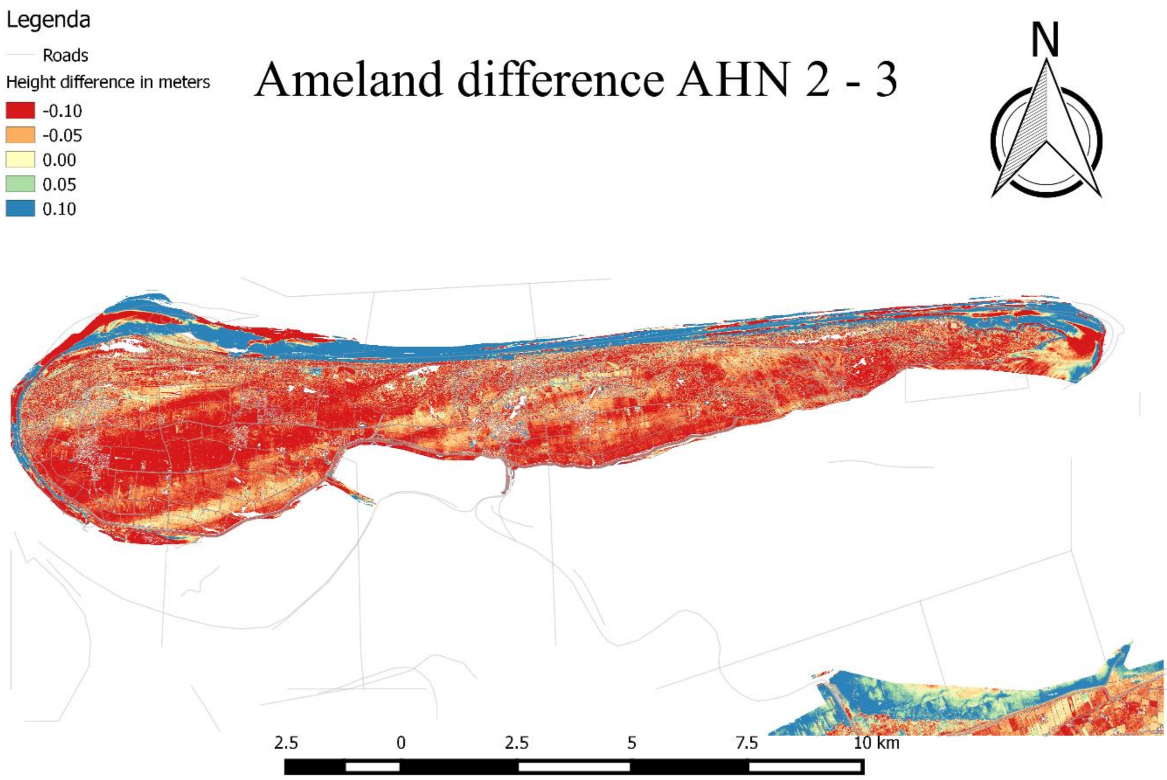


Figure 39 Comparing AHN 2 and 3 with boundaries on -0.1 and 0.1 meter

When we look at this map we notice 2 things. The first thing is that we see lines on the map. The lines go from the bottom left to the top right and are probably not natural. We assume this has something to do with the flight path during the collecting of the data. We are not able to solve this right now, but it would be something to look at in future researches. The second thing we notice is that almost the entire island turns red. This should mean that the entire island is subjected to subsidence. This cannot be true, so we need to correct this.

Lastly we visualize the difference between AHN 1 and 3 in figure 40.

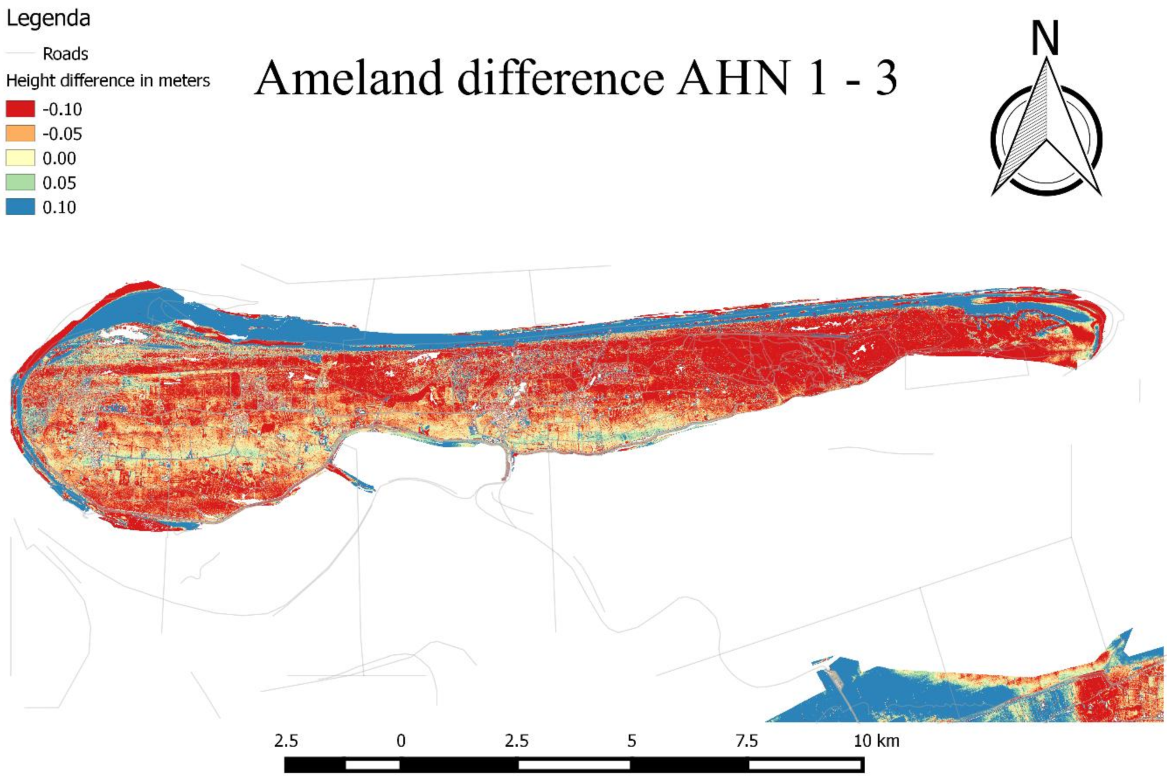


Figure 40 Comparing AHN 1 and 3 with boundaries on -0.1 and 0.1 meter

We again notice the same 2 things as we did when comparing the maps of AHN 2 and 3. The lines are a bit more horizontal this time, but still it is probably something that is just wrong with our data.

Since we saw the subsidence in the entire island we assume there is some correction that needs to be done on the dataset. For this we created the histograms seen in figures 41, 42, 43, 44, 45 and 46.

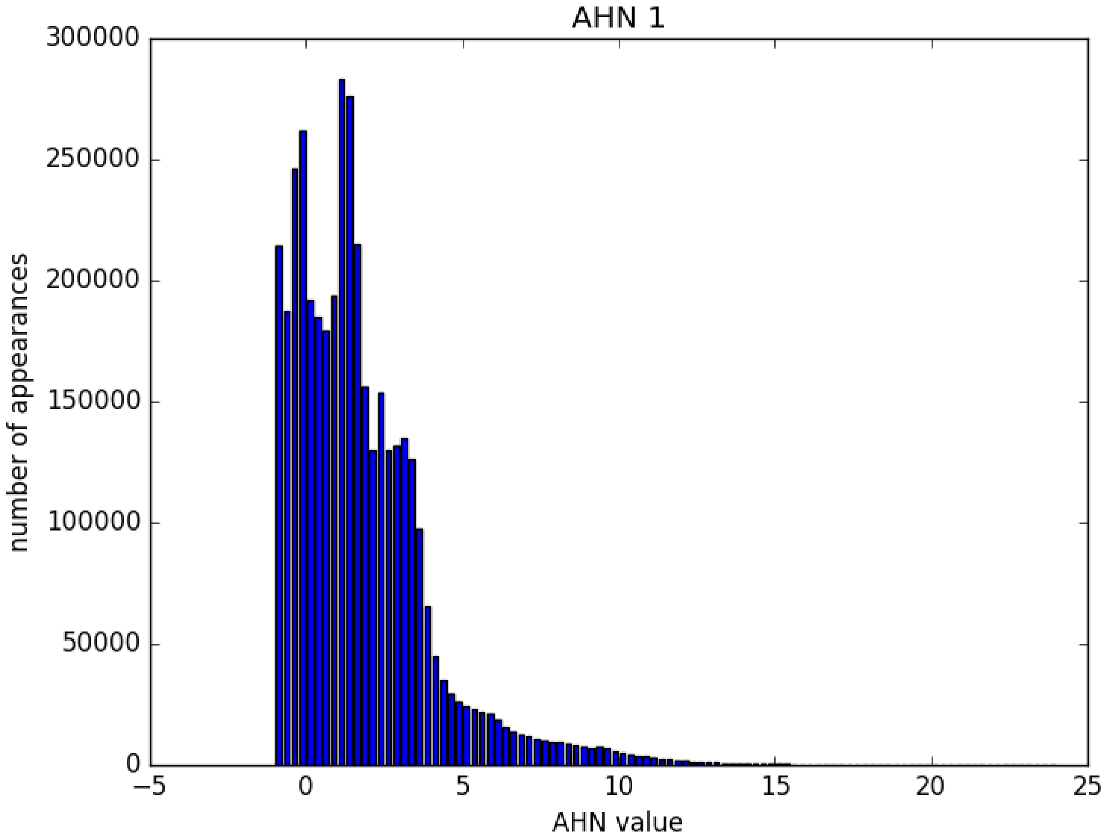


Figure 41 Histogram of the heights in AHN 1

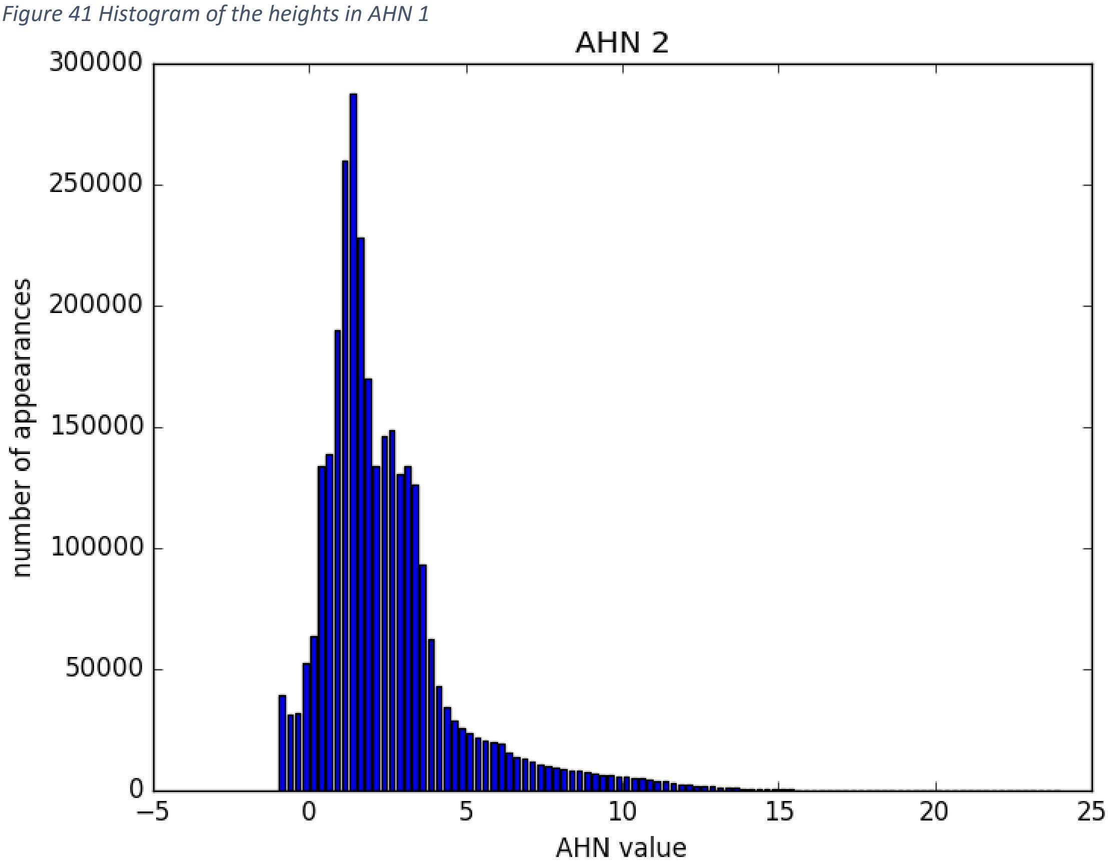


Figure 42 Histogram of the heights in AHN 2

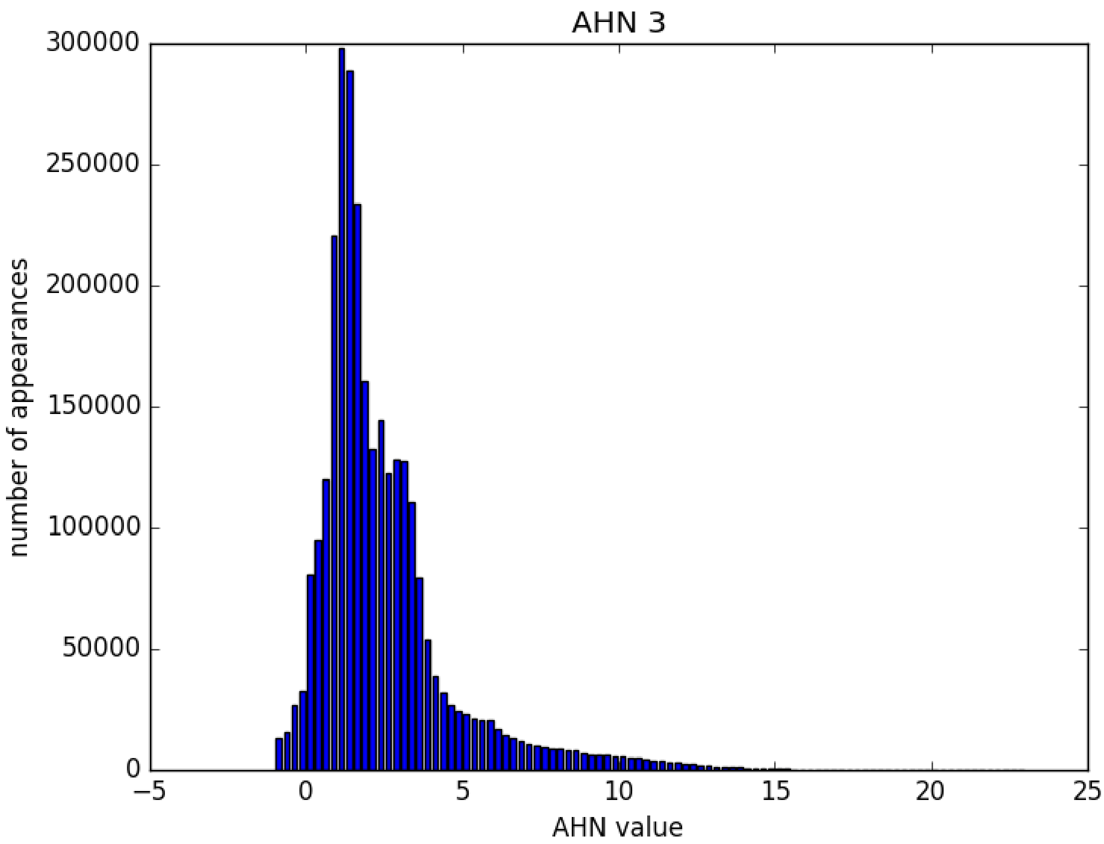


Figure 43 Histogram of the heights in AHN 3

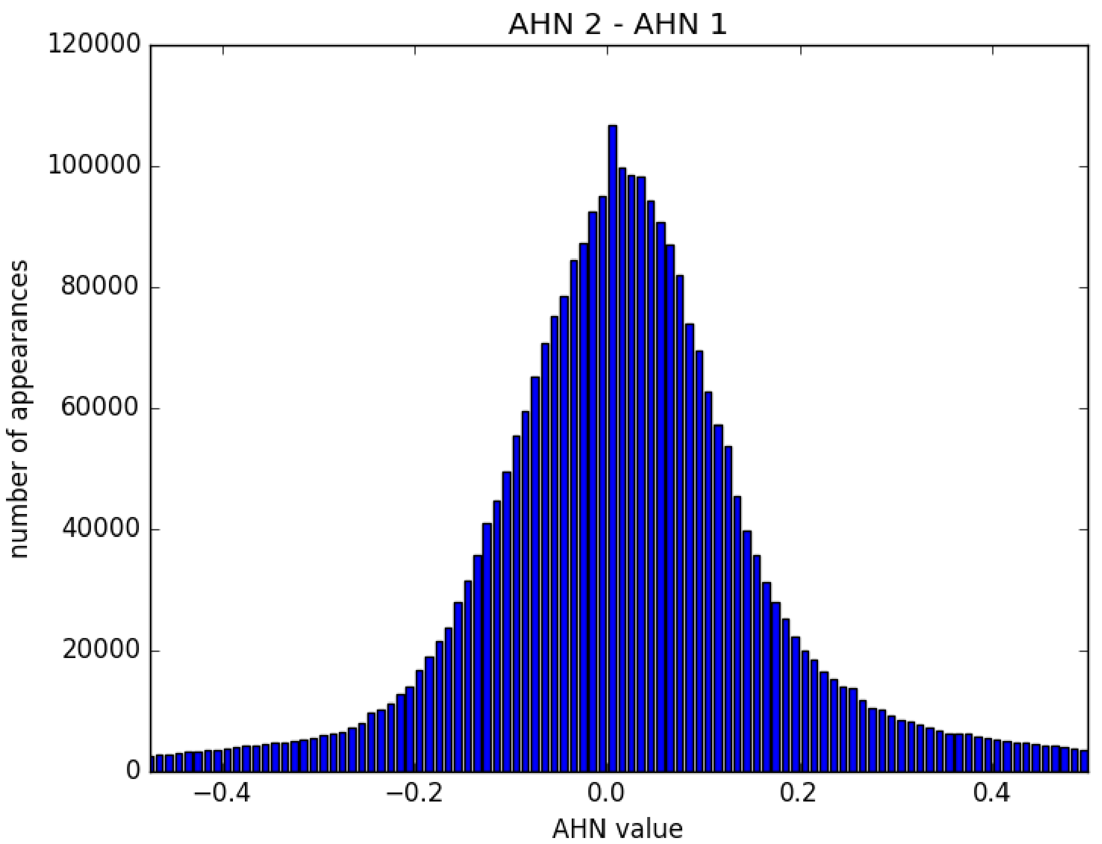


Figure 44 Histogram of the height differences in AHN 1 and 2

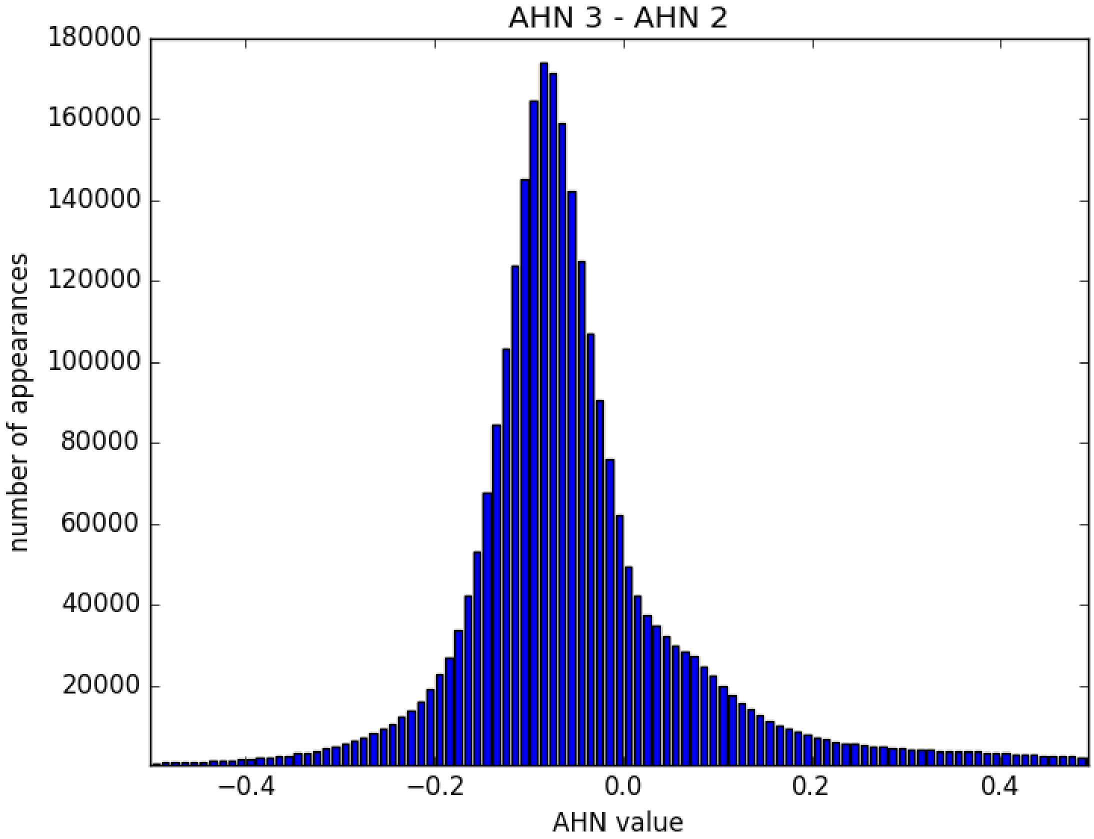


Figure 45 Histogram of the height differences in AHN 2 and 3

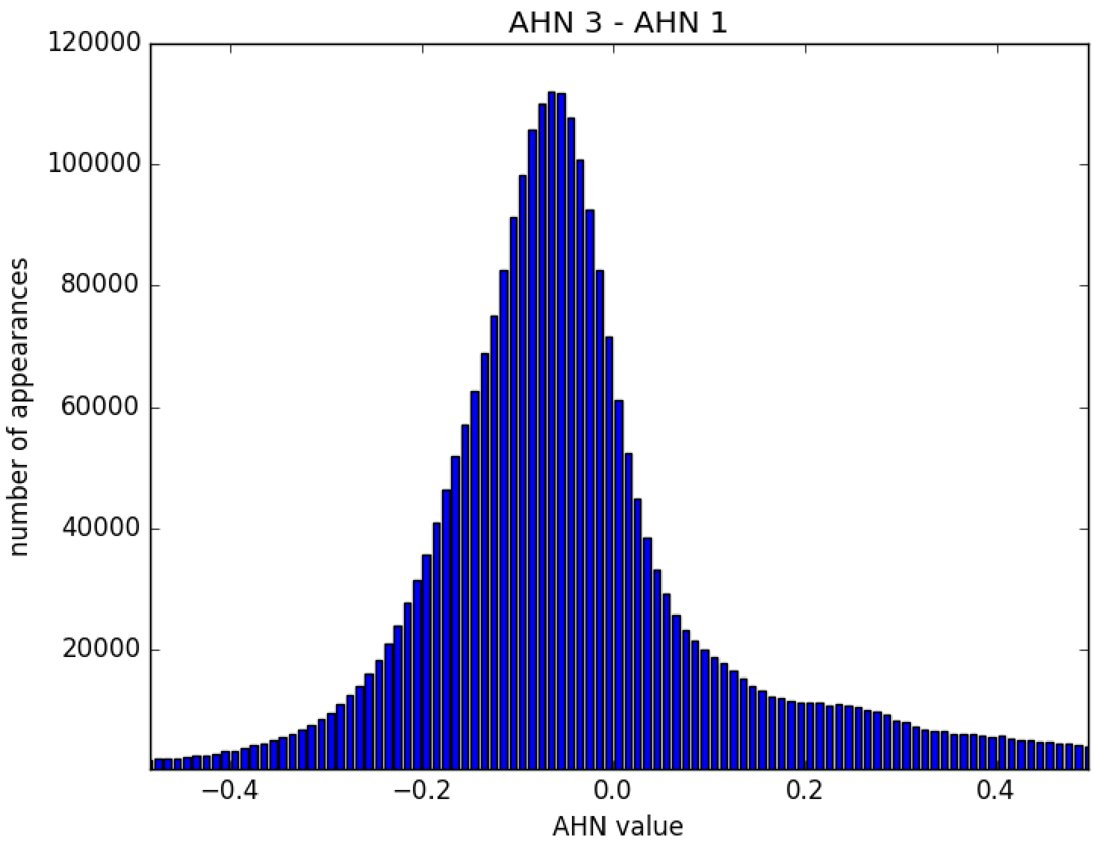


Figure 46 Histogram of the height differences in AHN 1 and 3

Looking at figures 41, 42 and 43 we notice 2 things. This first thing is that all 3 datasets have no data below -1 meter. This is probably just an arbitrary cutoff, which is used because of the sea level. Another thing we notice is a very large peak at 0 on AHN 3. This is due to the filtering. When the houses and trees were filtered out, they got the value 0 in some places instead of the no-data value that should have been there. This only happened in the AHN 3 dataset and that is why we see this peak.

Looking at figures 44, 45 and 46 we see nice bell shapes in the data as we would expect. However, it is notable that the tops are not at 0. We find the means and medians as in table 4, by detecting the bar with the most values and calculating the middle value.

Comparison	Median in meters	Mean in meters
AHN 1-2	0.019	0.02/0.03
AHN 2-3	-0.069	-0.09/-0.08
AHN 1-3	-0.055	-0.07/-0.06

Table 4 Medians and means for the comparissons between two AHN datasets

When we correct the datasets with these values we get the maps seen in figures 47, 48 and 49.

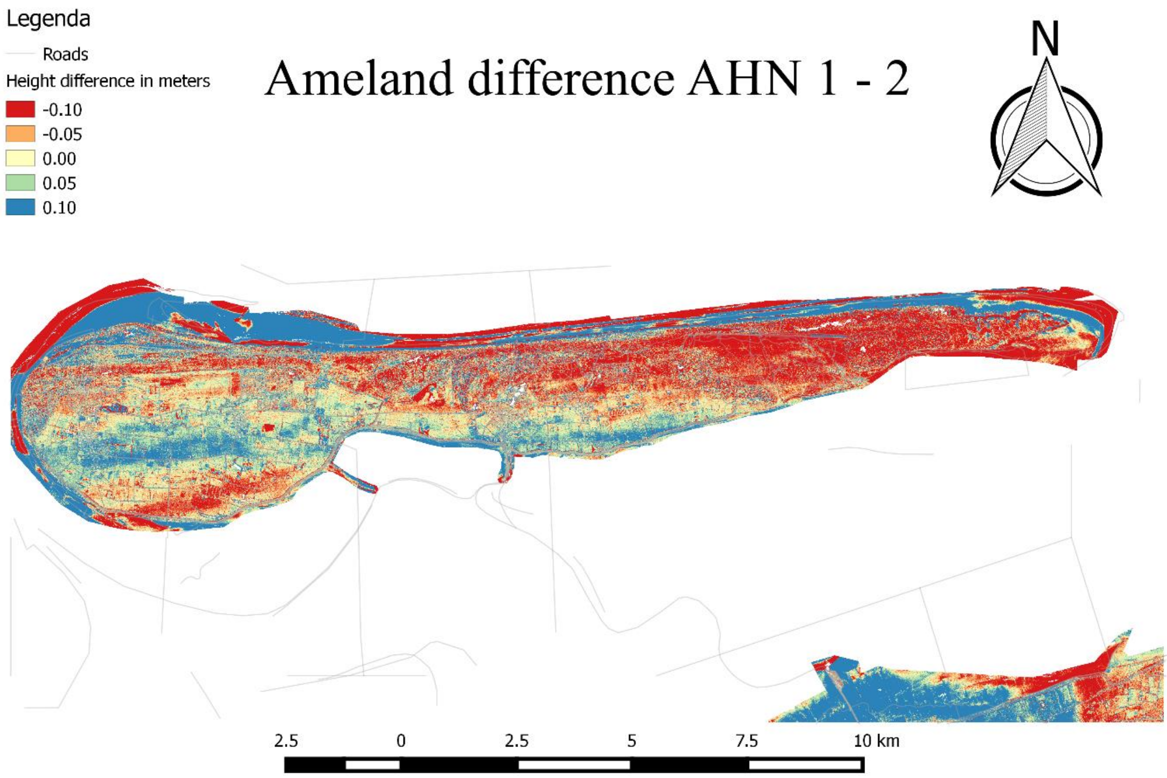


Figure 47 Corrected height difference AHN 1 and 2 with boundaries on -0.1 and 0.1 meter

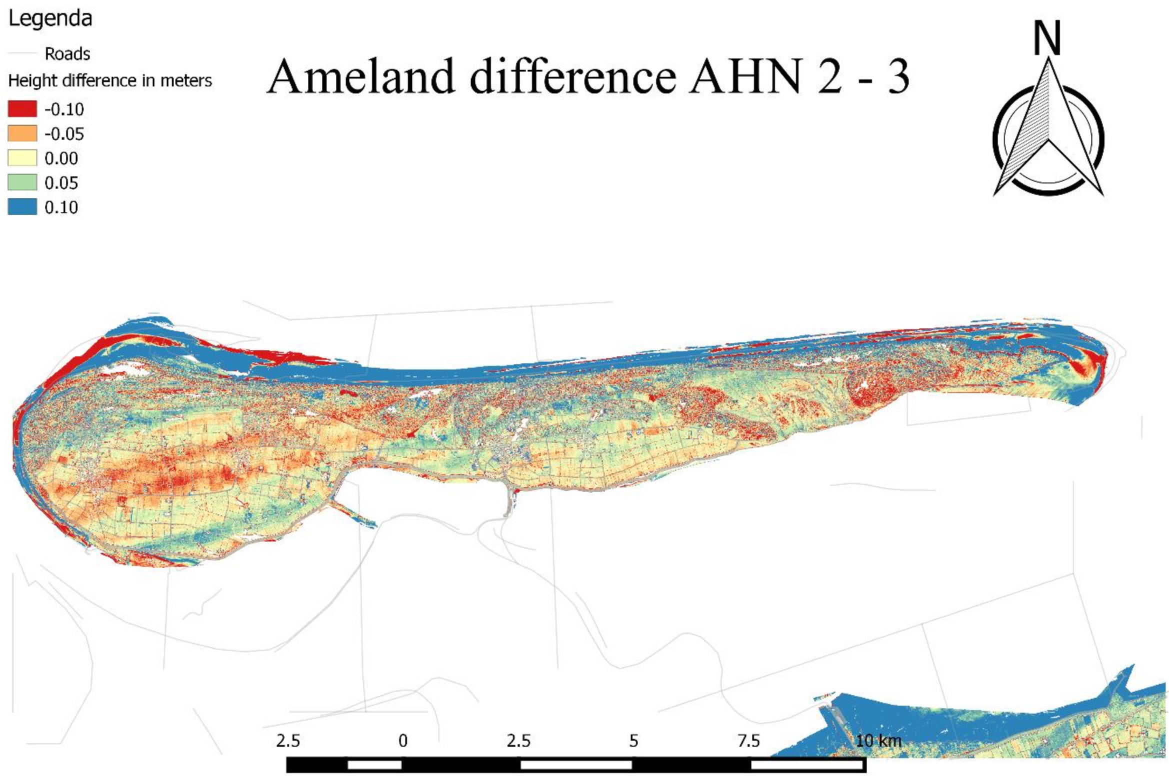


Figure 48 Corrected height difference AHN 2 and 3 with boundaries on -0.1 and 0.1 meter

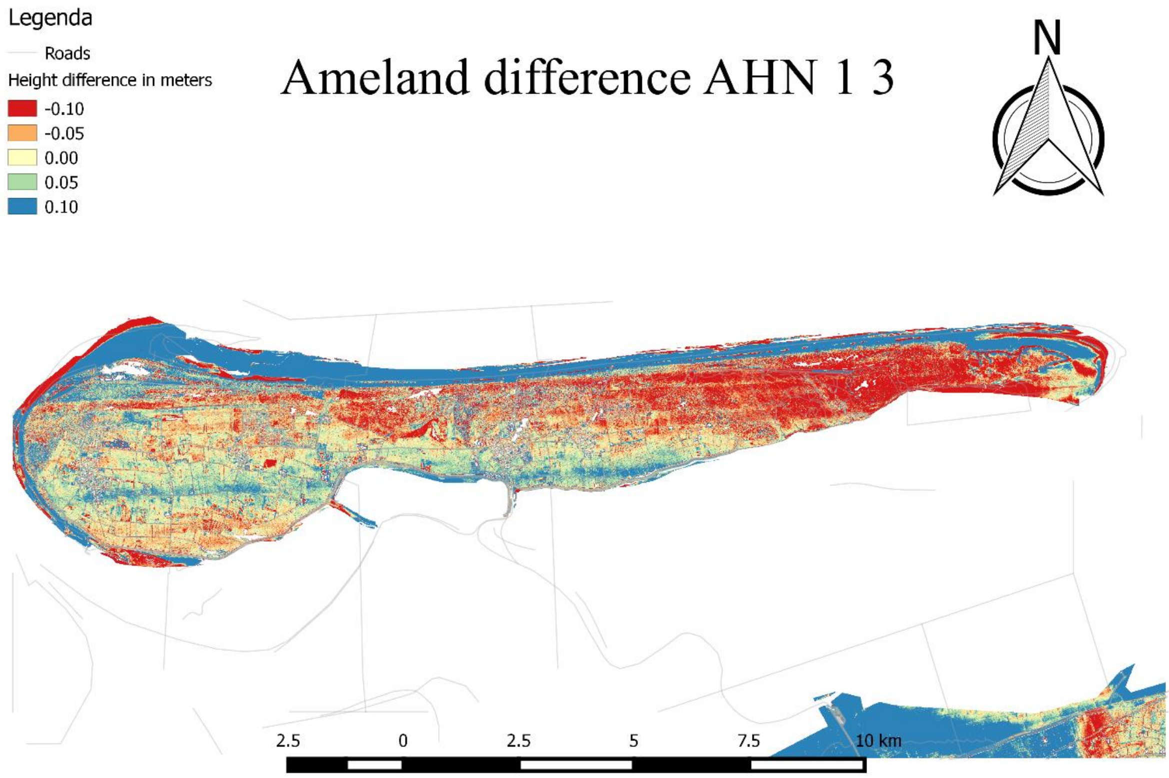


Figure 49 Corrected height difference AHN 1 and 3 with boundaries on -0.1 and 0.1 meter

When we look at figure 47 we still notice the subsidence in the east. In figure 48 we notice only some subsidence in the east. In the west we still notice some lines that make up almost all the height changes there. This means that there is still more subsidence in the east than there is in the west. Lastly in figure 49 we still notice some horizontal lines, but what changed after the correction is that we now can see a lot more subsidence in the east than we see in the west.

Next we visualize the larger maps in figures 50, 51 and 52 to see if this subsidence is really related to the gas extraction, or if it is something bigger. We use Friesland to check if nothing strange is happening to the data.

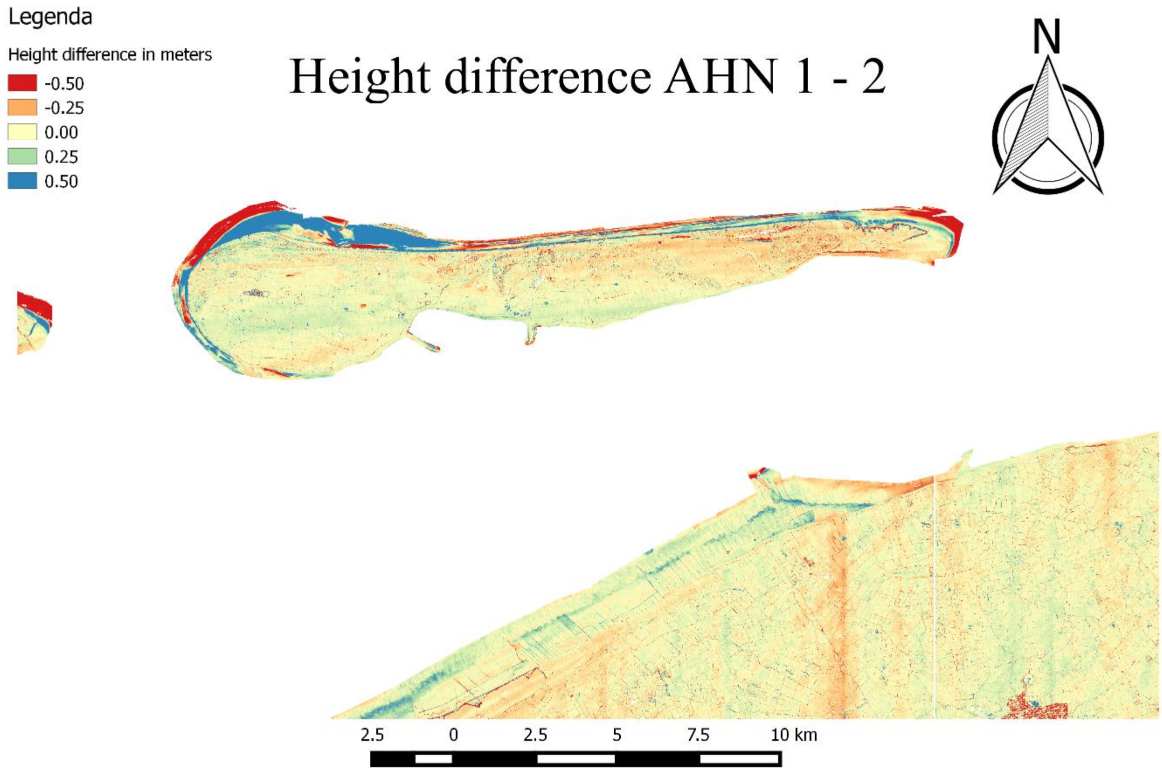


Figure 50 Height difference AHN 1 and AHN 2

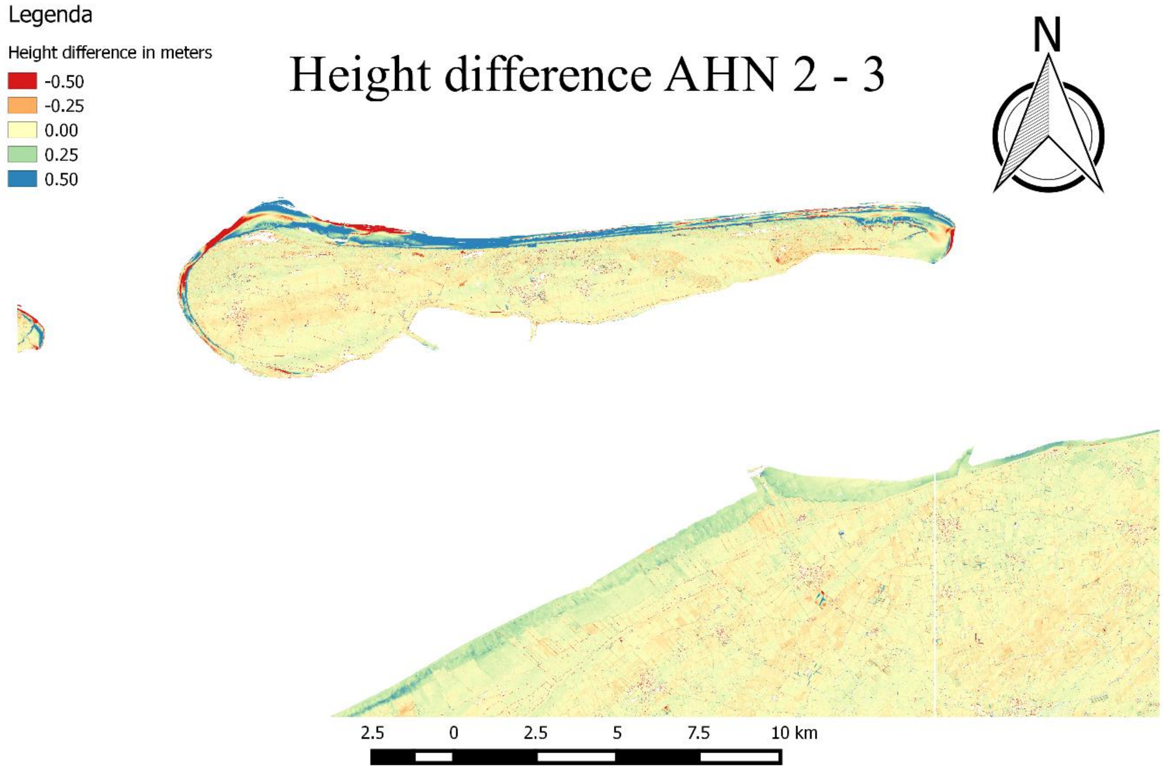


Figure 51 Height difference AHN 2 and AHN 3

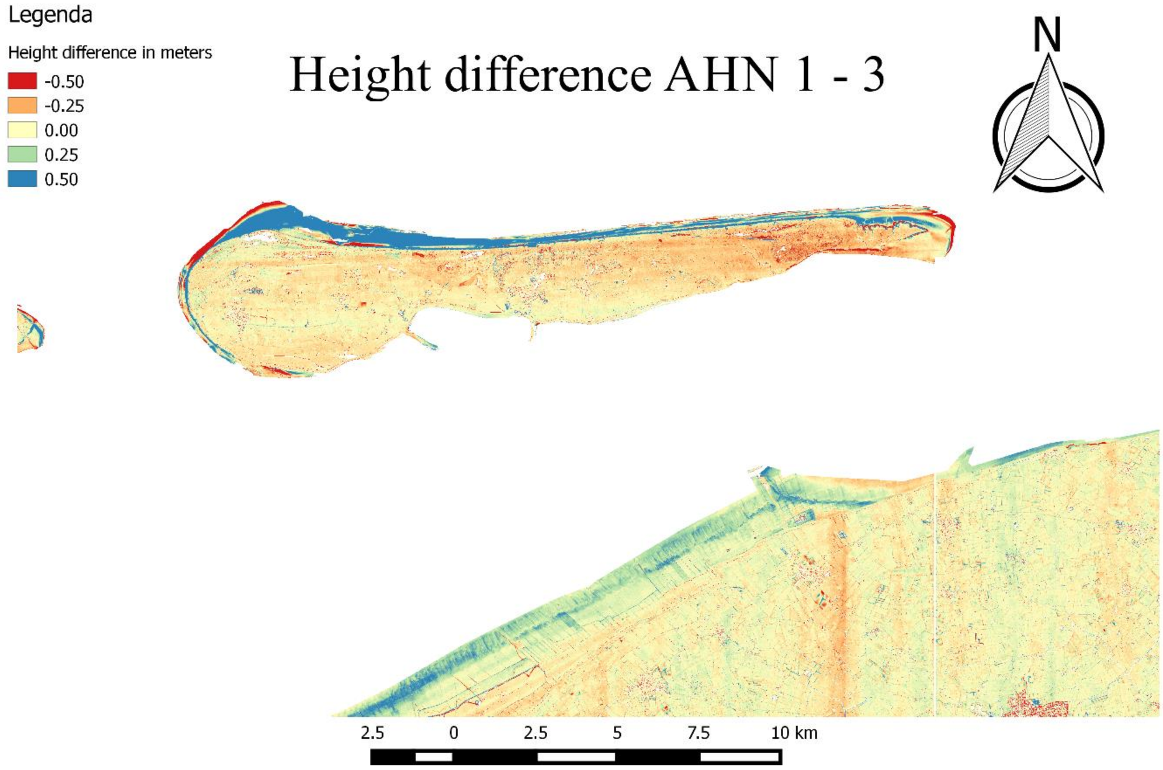


Figure 52 Height difference AHN 1 and AHN 3

When we look at figures 50, 51 and 52, we see a few things. First we see again some lines appearing in the data, insinuating that these errors are also present on the main land and not just bound to Ameland. Next we notice that there is no clear subsidence or uplift going on that cannot be explained by errors in the data or erosion or sedimentation at the coast. This means that the subsidence on the east of Ameland is probably happening because of the gas extraction on Ameland.

Next we apply the least squares method on the AHN grid data. This method gives us a h_0 and a slope. First we compare h_0 to AHN 1 in figures 53 and 54 in order to see if there is no mistake made in the formula.

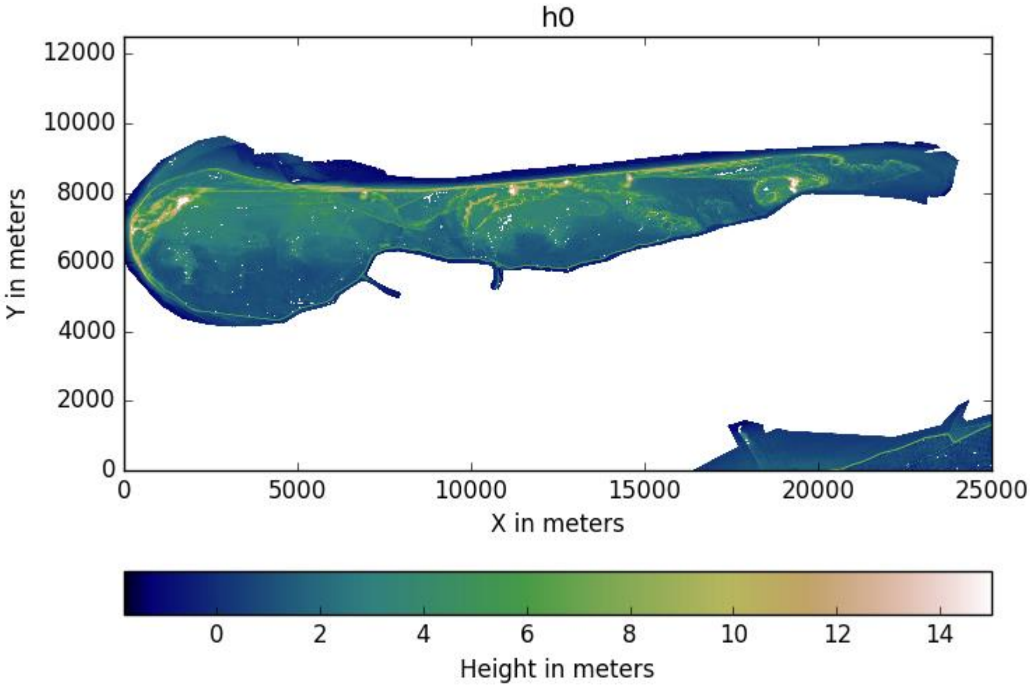


Figure 53 h_0 calculated with the least squares method in Python

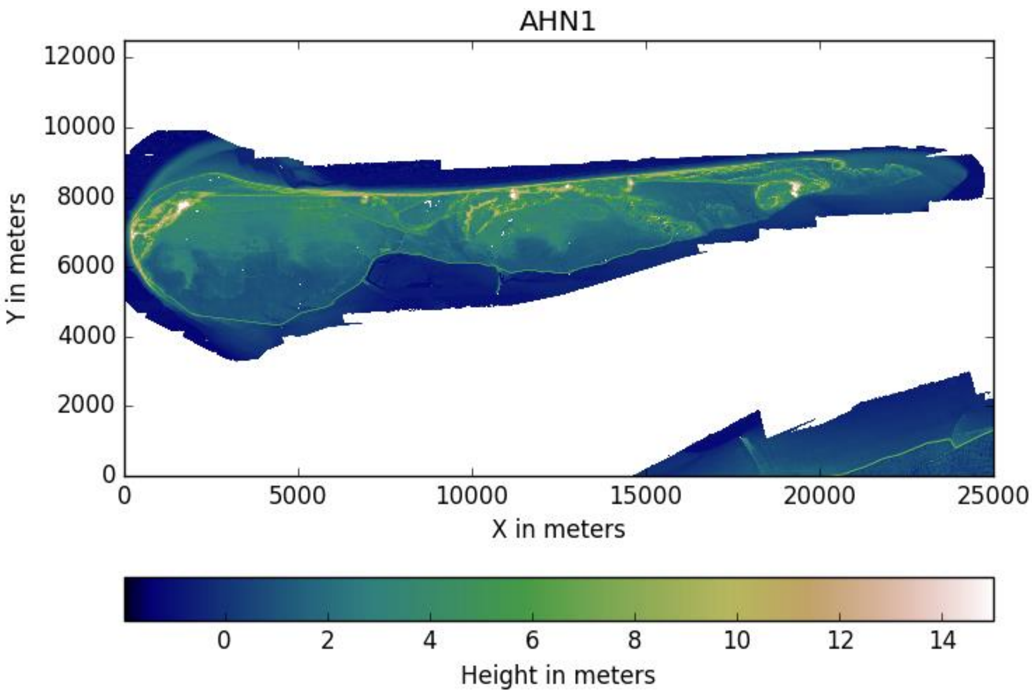


Figure 54 AHN 1 visualized in Python

When we compare these 2 maps we notice there are less no-data value cells in the AHN 1 map. This is because we need at least 2 data points and since AHN 2 and 3 are filtered differently from AHN 1 there are more cells where the least squares method was not possible then there were cells in AHN 1 without a value. When we visualize the absolute difference between the 2 maps we get figure 55.

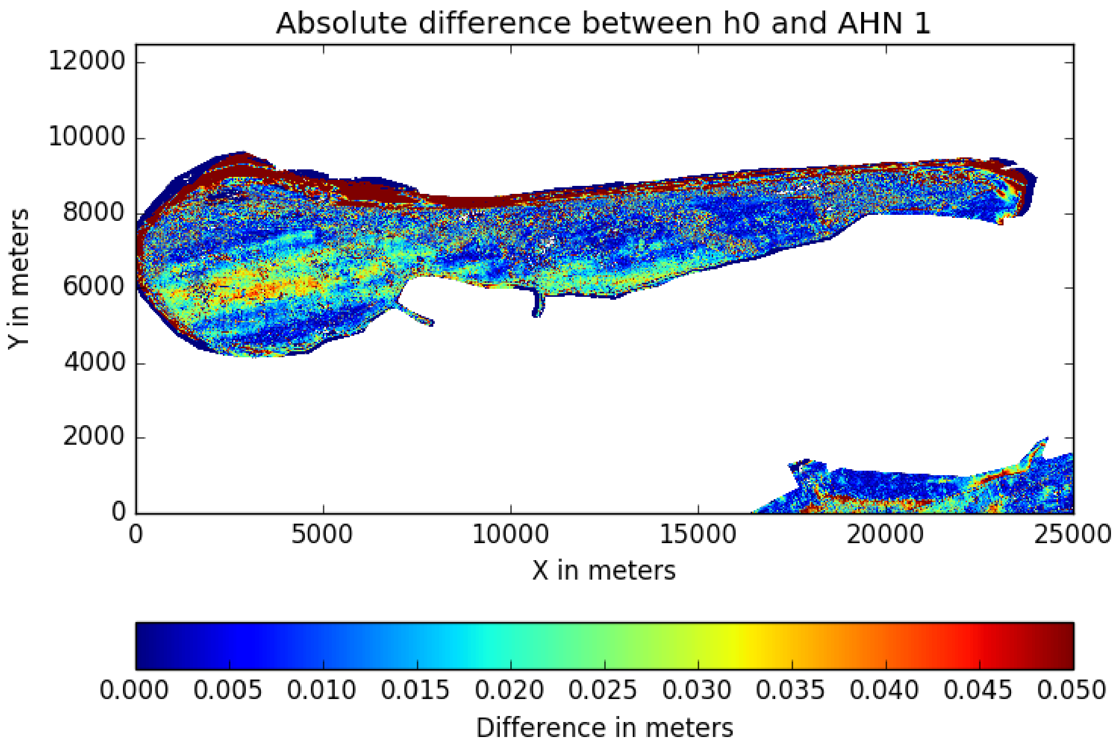


Figure 55 Difference between h0 found with the least squares formula and AHN 1

Here we once again see the lines going from the south-west to the north-east. On these lines the error is larger than on the rest of the island. We also see a larger error just out of the coast in the north, western and eastern part of the island. Next we compare the slope calculated with the least squares method with AHN 3 – AHN 1 in figures 56, 57, 58 and 59. We use boundaries -0.025 and 0.025 m/year and -0.01 and 0.01 m/year.

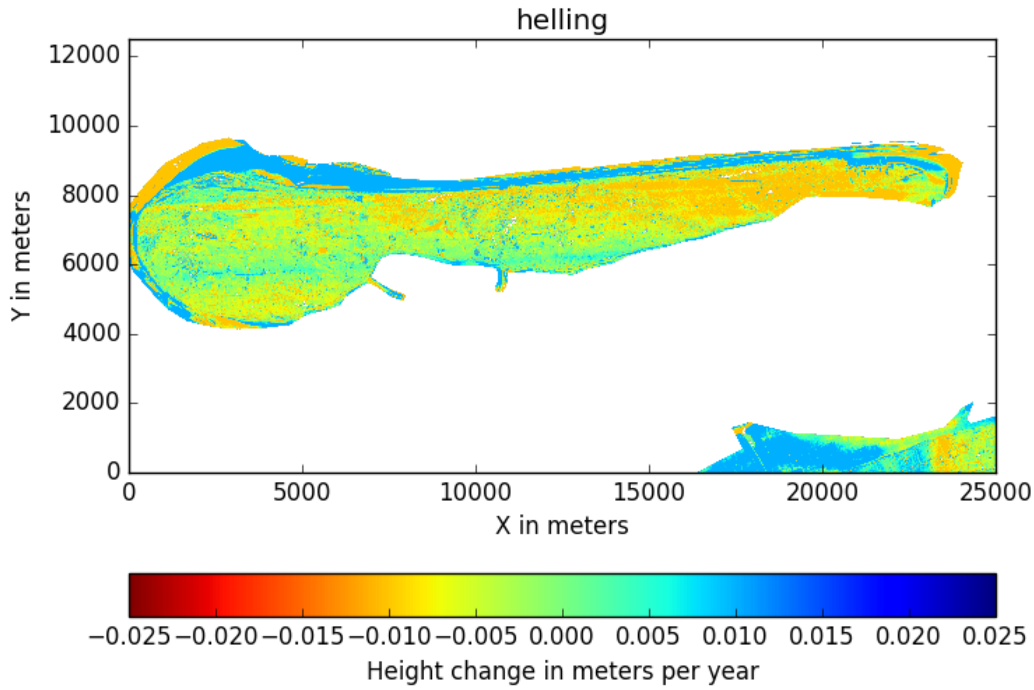


Figure 56 Slope calculated with the least squares method with boundaries on -0.025 and 0.025 m/year

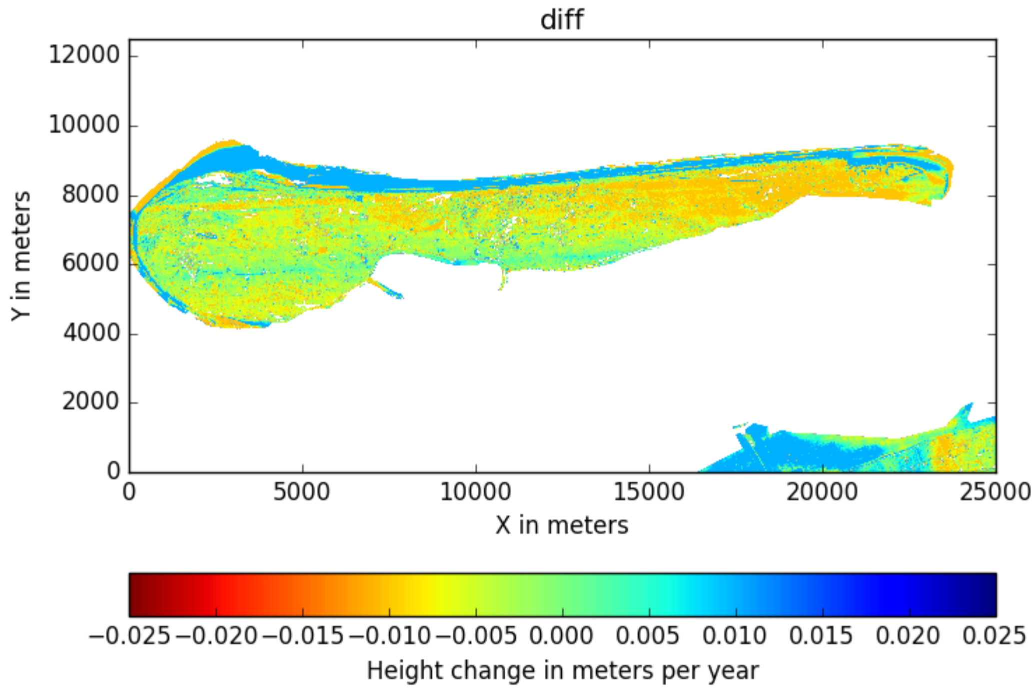


Figure 57 Map comparing AHN 1 and 3 with boundaries -0.025 and 0.025 m/year

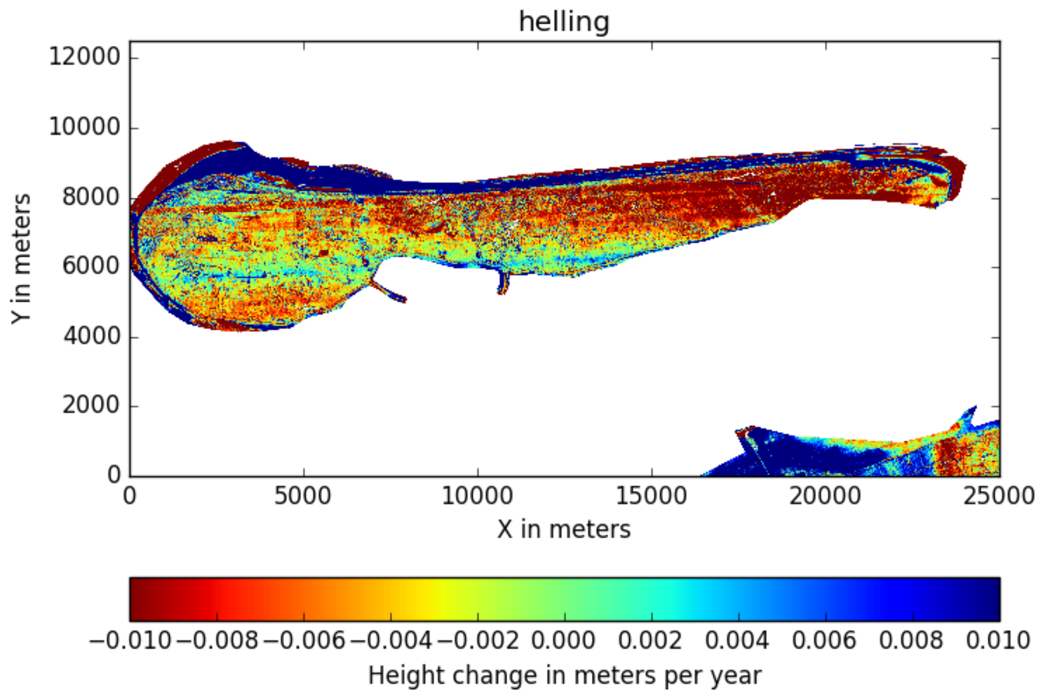


Figure 58 Slope calculated with the least squares method with boundaries on -0.01 and 0.01 m/year

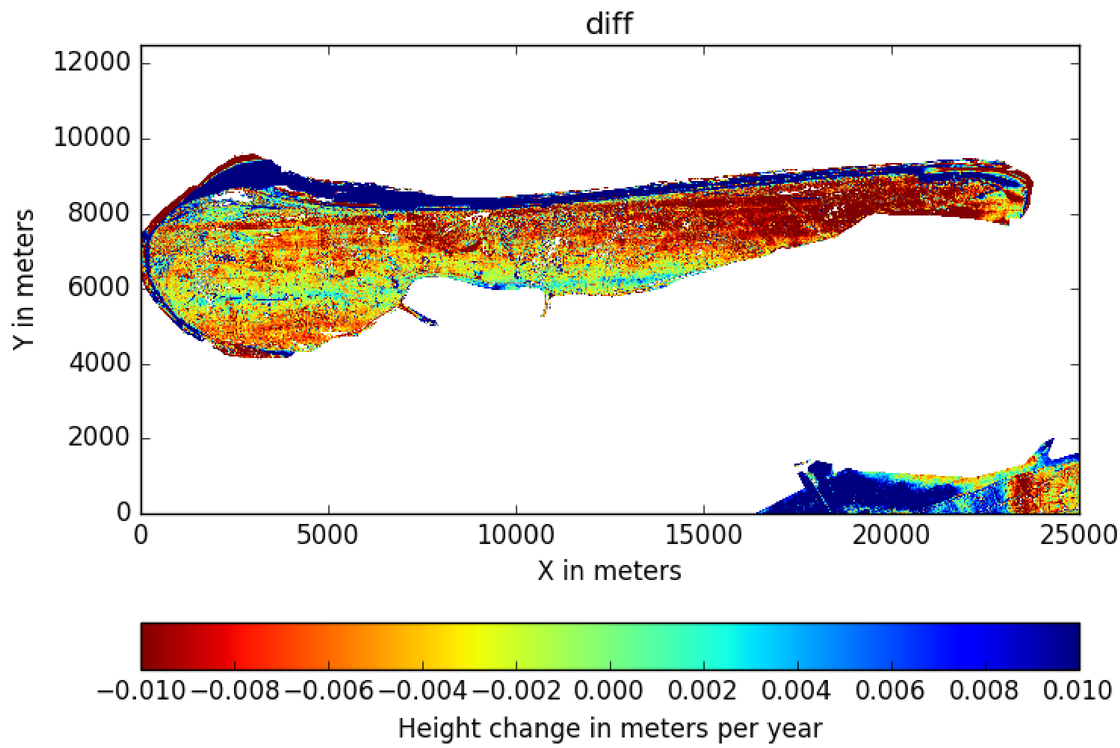


Figure 59 Map comparing AHN 1 and 3 with boundaries on -0.01 and 0.01 m/year

When we look at those figures we notice a little more subsidence in the western part of Ameland in the comparison between AHN 1 and 3 than for the least squares solution. We do notice that both methods give a subsidence of more than 1 cm per year in the center of the subsidence area for figure 58 and 59. Since AHN 1 was created back in 1998/1999, the total subsidence should now be over 17 centimeters according to the least squares method.

To get a better look at the errors we visualize the difference between both methods in 60.

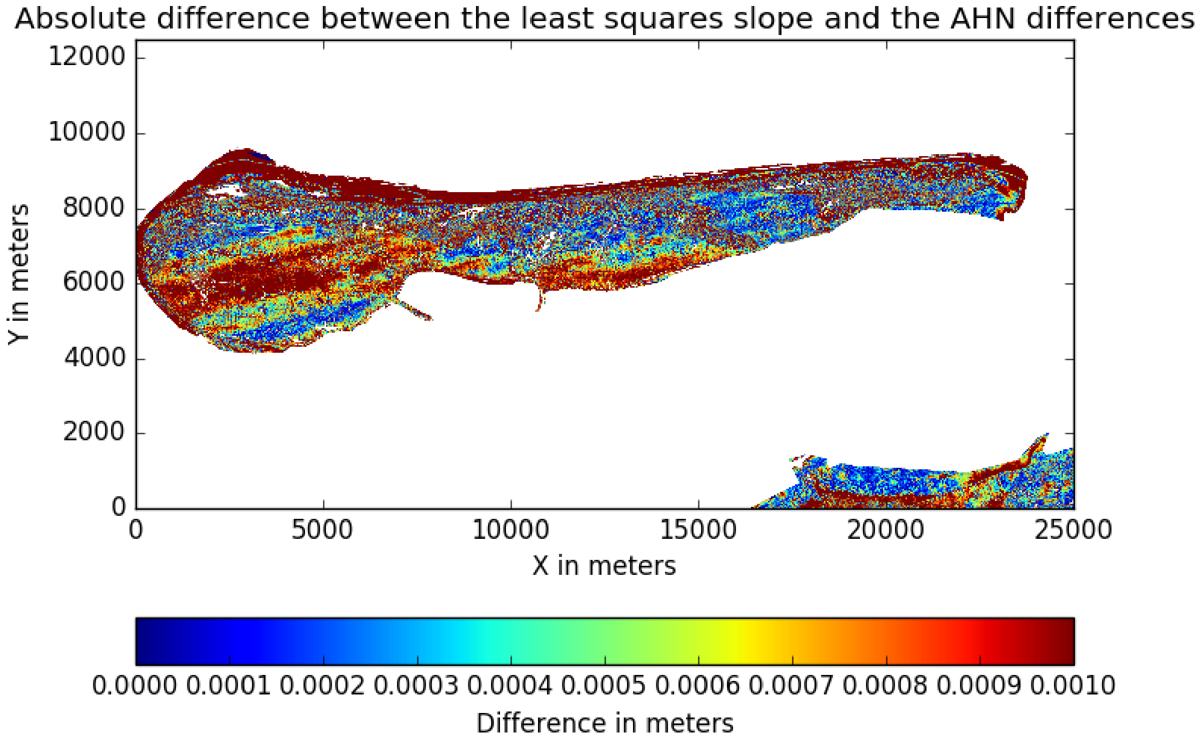


Figure 60 Difference between the slope calculated with the least squares formula and the difference between AHN 1 and 3

When we look at figure 60, we notice that the error is larger in the west, on the south coast and in the sea on the north. Around the subsidence area the data is a little more precise. The errors again show the lines going from the south west to the north east. This is an error in the data.

Next we use Python to calculate and visualize the error of the least squares method and the number of data values per grid cell as can be seen in figures 61, 62 and 63. For the errors we use boundaries on 0 and 1 meter and on 0 and 0.02 meter.

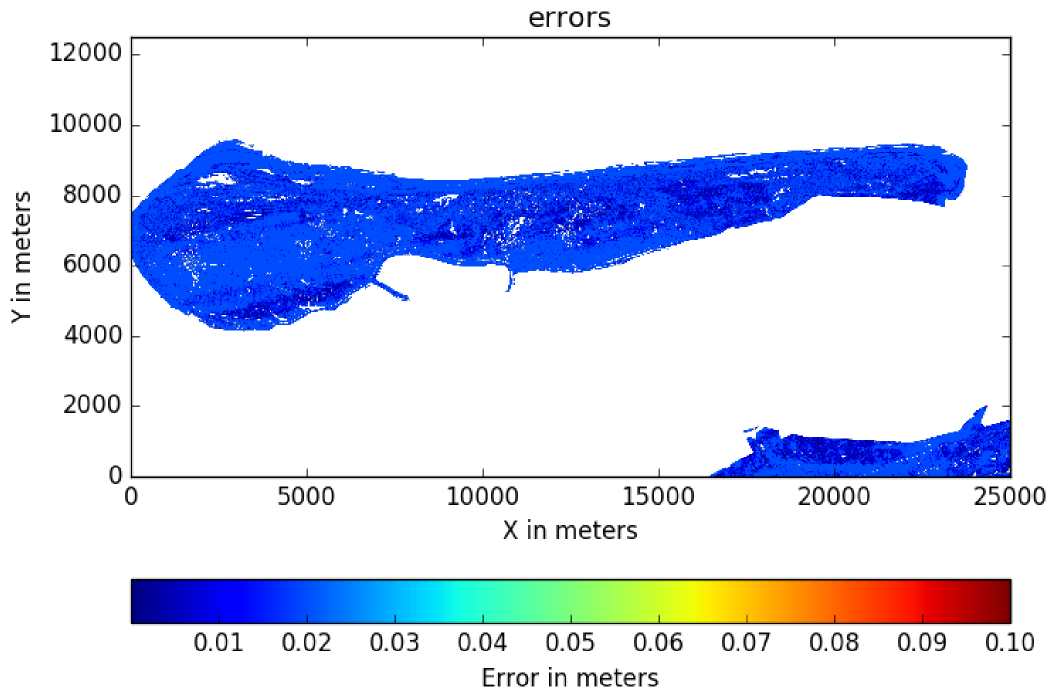


Figure 61 Least squares errors with boundaries on 0 and 0.1 meter

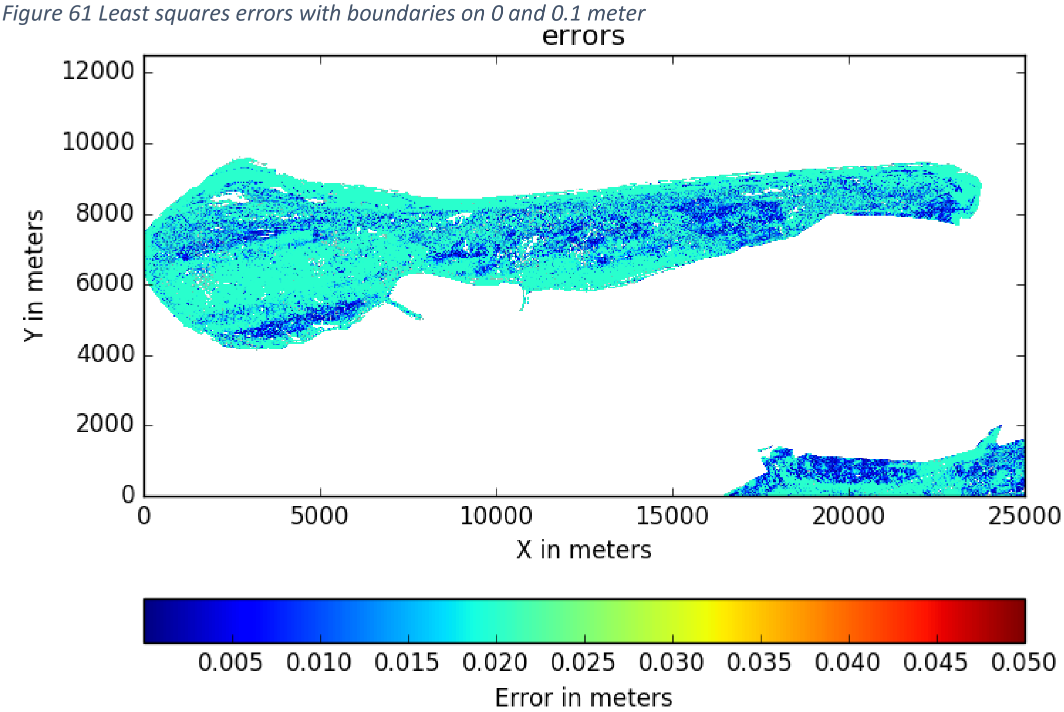


Figure 62 Least squares errors with boundaries on 0 and 0.02 meter

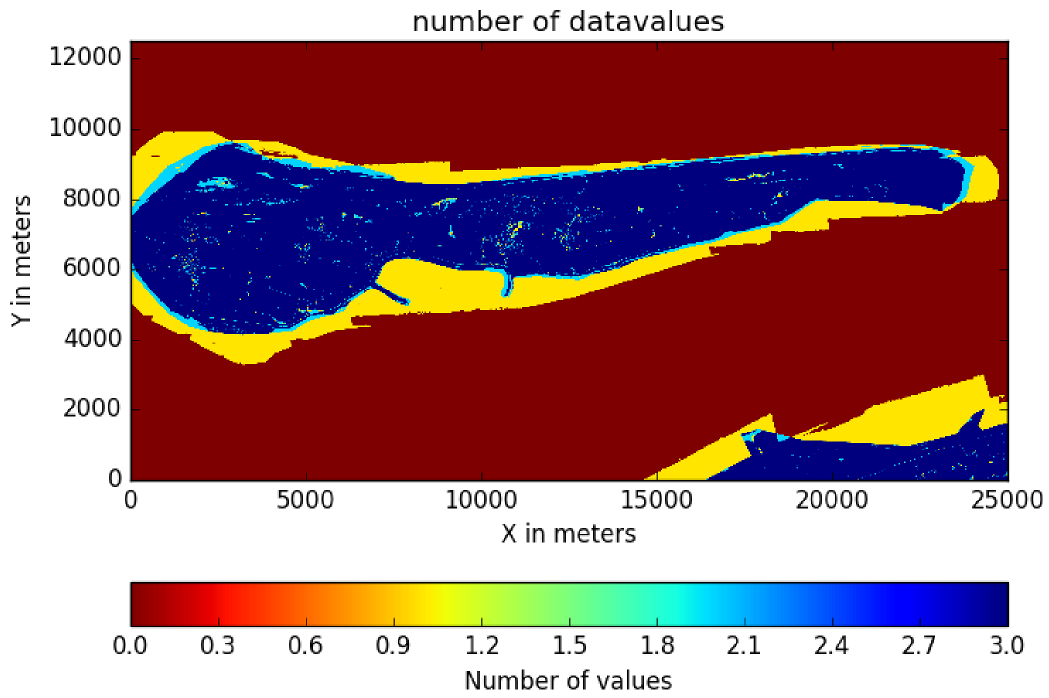


Figure 63 Number of data points used per grid cell for the least squares method

In figure 61 we can see that all errors are quite small. In figure 62 we see that the error is about the same for the entire island, except for a few small regions that follow exactly the stripes we saw in the map that compare AHN 2 and 3. The average error for the least squares method is mostly around 1 centimeter. When we look at figure 63, we see that most of the region has 3 data values, the beach is where we see a clear difference. This is because AHN 1 has data points further offshore then AHN2 and 3.

Before we look at the grid version of AHN we calculate the average height change of the subsidence area. First we clip all 3 datasets with the shape seen in figure 64. We use this shape, because we follow the subsidence area, but we only look at the parts on the island, so we filter out the parts that are sometimes below water level.

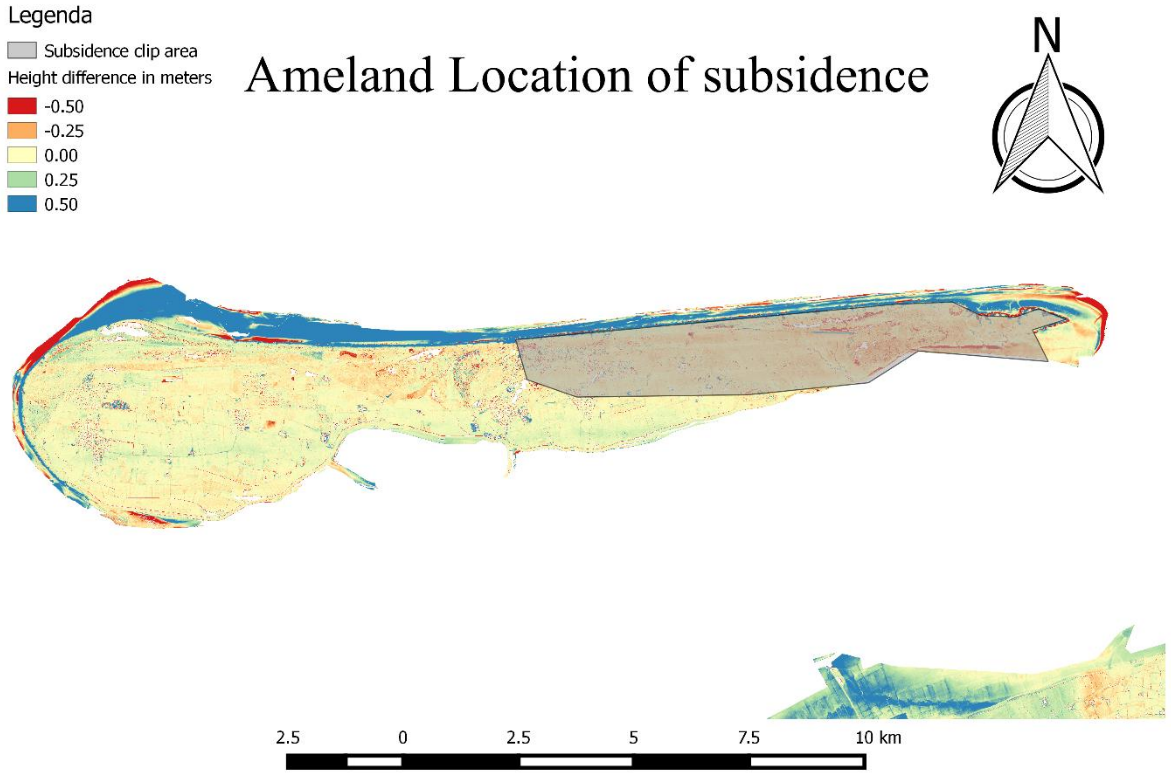


Figure 64 Location of the shapefile used to clip the datasets

When we use these clipped datasets and run the script we get the following results:

Comparing	Average height change in m	Area in m^2	Volumatic change in m^3	Timespan in years
AHN 1 and AHN 2	-0.095	15,260,500	-1,443,235	9
AHN 2 and AHN 3	-0.020	14,933,550	-300,492	6
AHN 1 and AHN 3	-0.110	14,978,500	-1,641,144	15

Table 5 Average height change between two AHN datasets in the subsidence area

We see that in all cases there is a little average subsidence for the total area. This change however, is small compared to the error of AHN data. When we compare the results we get from these methods to the research done by Johan Krol we that he saw no net subsidence in all 5 test areas. In two of those areas there was subsidence caused by gas extraction, but this was compensated by strong sedimentation speeds. In the AHN data we can look at two of his test areas namely: West-Ameland and Oost-Ameland, as can be seen in figure 65.

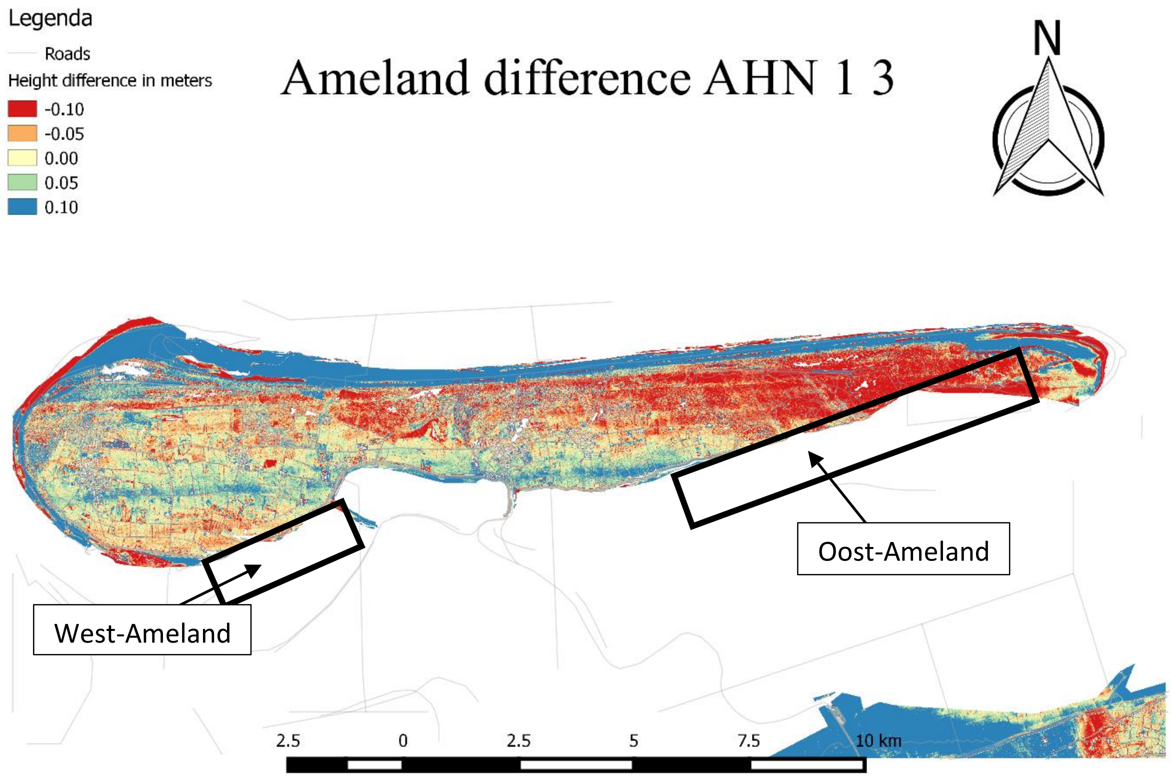


Figure 65 AHN 1 compared to AHN 3 showing the corresponding areas of Johan Krol's research

In West-Ameland there was no subsidence, according to the original report, however we do see some net subsidence in our own data in the South-Western part of Ameland. This can be caused by a few things. First it is possible that this is erosion, since the area of Johan Krols research is subject to both the erosion and sedimentation forces of wind and water while our data is only affected by wind. This could cause erosion on our area while there is sedimentation on the area investigated by Johan Krol. It is also possible that there is an error in this data, but since we saw a net subsidence of over 10 centimeters for a period of 16 years and his data showed a net uplift of 5.9 mm per year for a period of 8 years the difference is very large. We do notice that most of the subsidence in this area takes place between AHN 1 and 2 which is between 1998 and 2008, while Johan Krol only started measuring on this location in September of 2006. This could be another reason for the large difference.

In Oost-Ameland Johan Krol detected no net subsidence. This was due to strong sedimentation, because there was in fact subsidence caused by the gas extraction. This subsidence varied between 0.3 and 0.7 mm per year. In our own research we looked at the average subsidence in the subsidence area. This area saw a decline of 11 centimeters in a period of 15 years. This comes down to 7.3 mm per year. This is very close to the maximum subsidence of 7 mm per year found by Johan Krol and therefore seems plausible.

5.3 AHN cloud to mesh comparing

Now that we have looked at the grid version of AHN, it is time to zoom in a little and look at the 4 point cloud regions.

First we look at the normal point clouds visualized in CloudCompare (figures 66, 67 and 68). We will look at region 2 here, as it is best for showing the differences. The other regions can be found in appendix C.

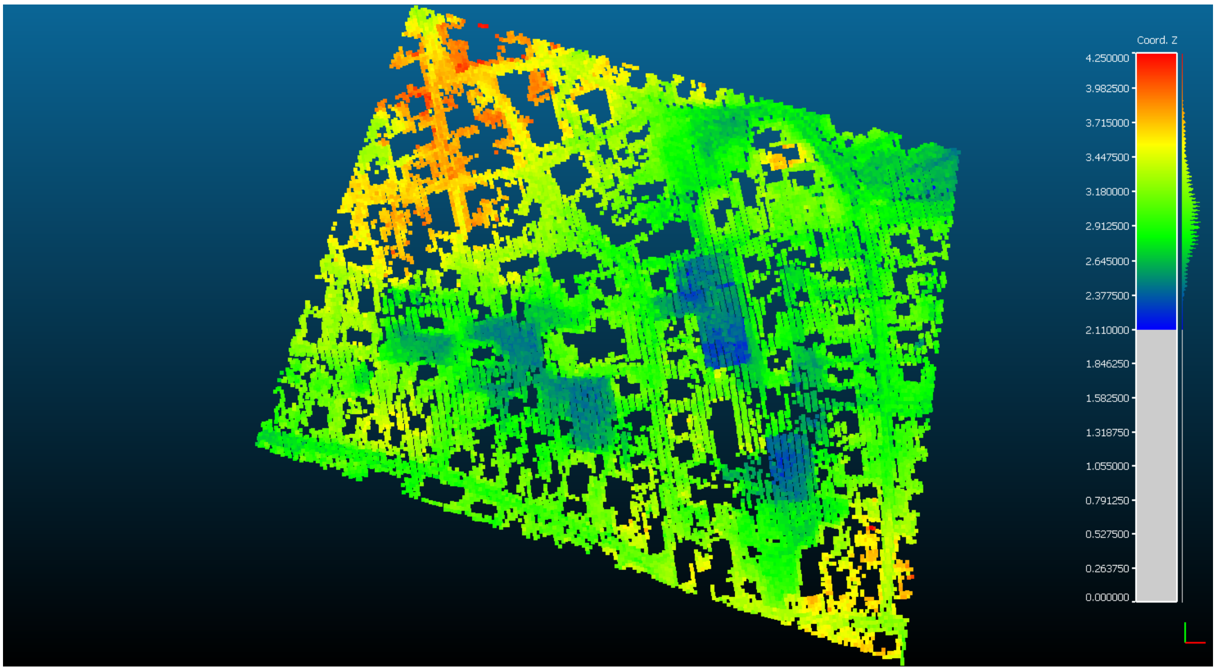


Figure 66 Point cloud of AHN 1 on region 2

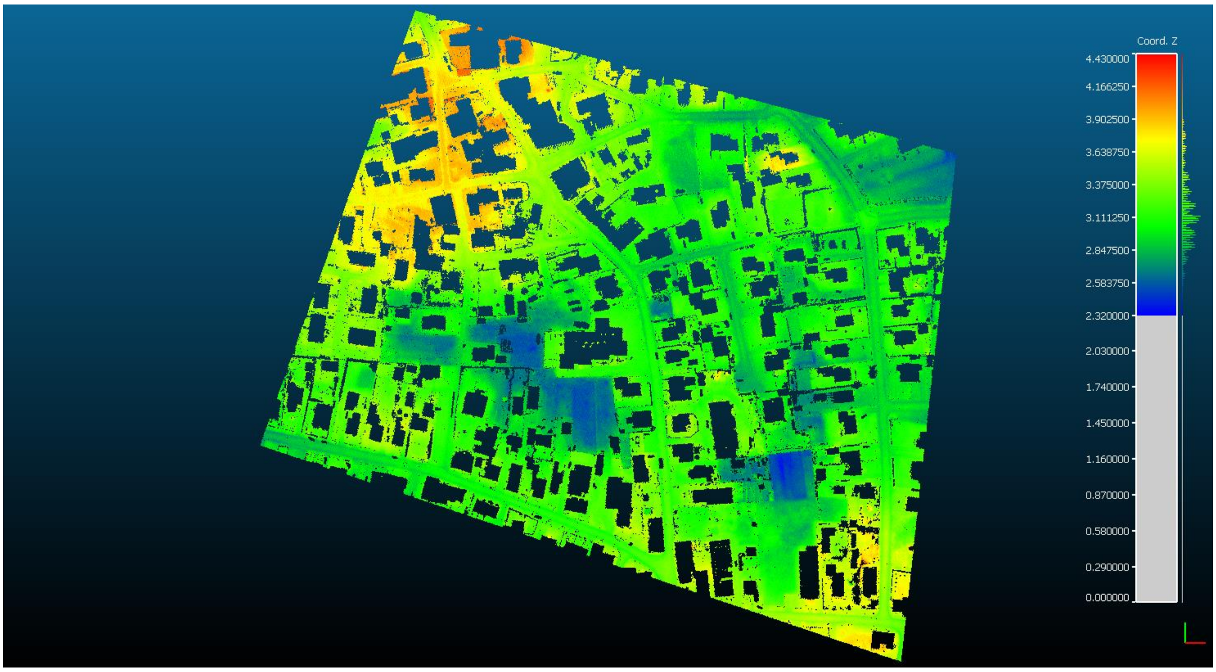


Figure 67 Point cloud of AHN 2 on region 2

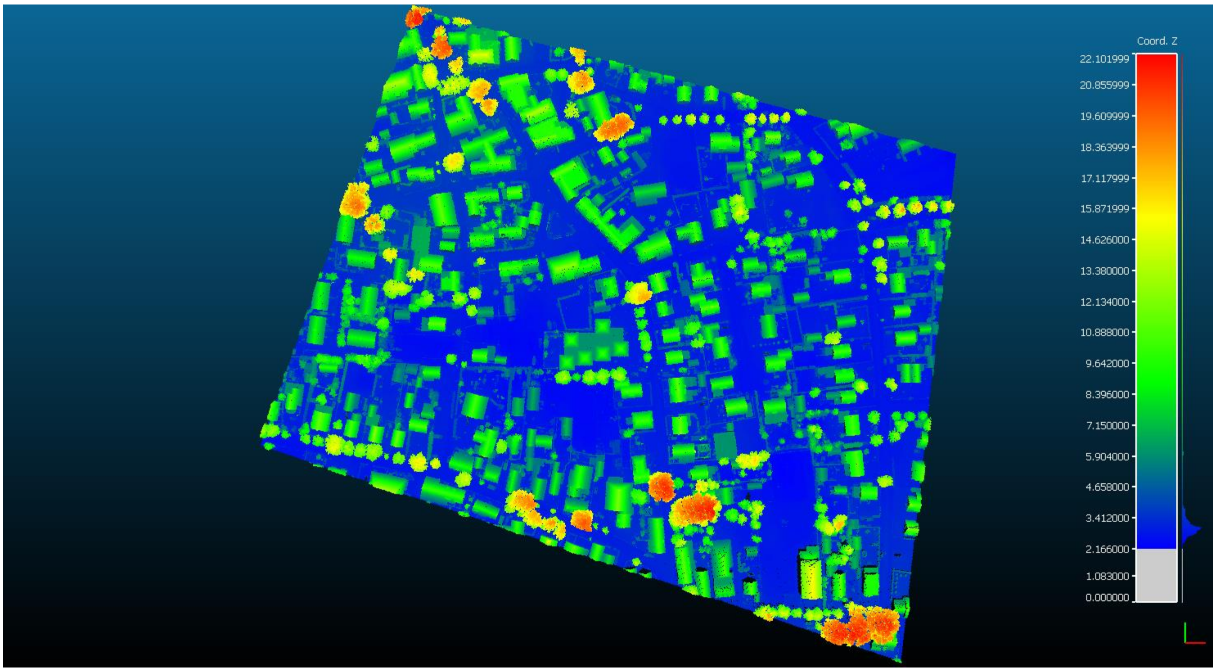


Figure 68 Point cloud of AHN 3 on region 2

When we compare AHN 1 with AHN 2, we notice that the colors on AHN 2 are a lot brighter. This is because AHN 2 has a lot higher point density than AHN 1. The filtering of the buildings is more or less the same between these 2 datasets. When we compare AHN 3 with AHN 1 and 2, we notice that AHN 3 has a lot higher point density than AHN 1, but it seems about the same as AHN 2. Something that is very different on AHN 3 is the filtering. The point clouds of AHN 3 have no filtering, which means that trees and rooftops will be visible. This can be a problem when trying to interpret the results that we get, but since the filtered version of AHN 3 and the unfiltered versions of AHN 1 and 2 are not available we do not have a choice.

Next we compare the mesh to the point clouds. We first look at region 1 in figures 69 and 70.

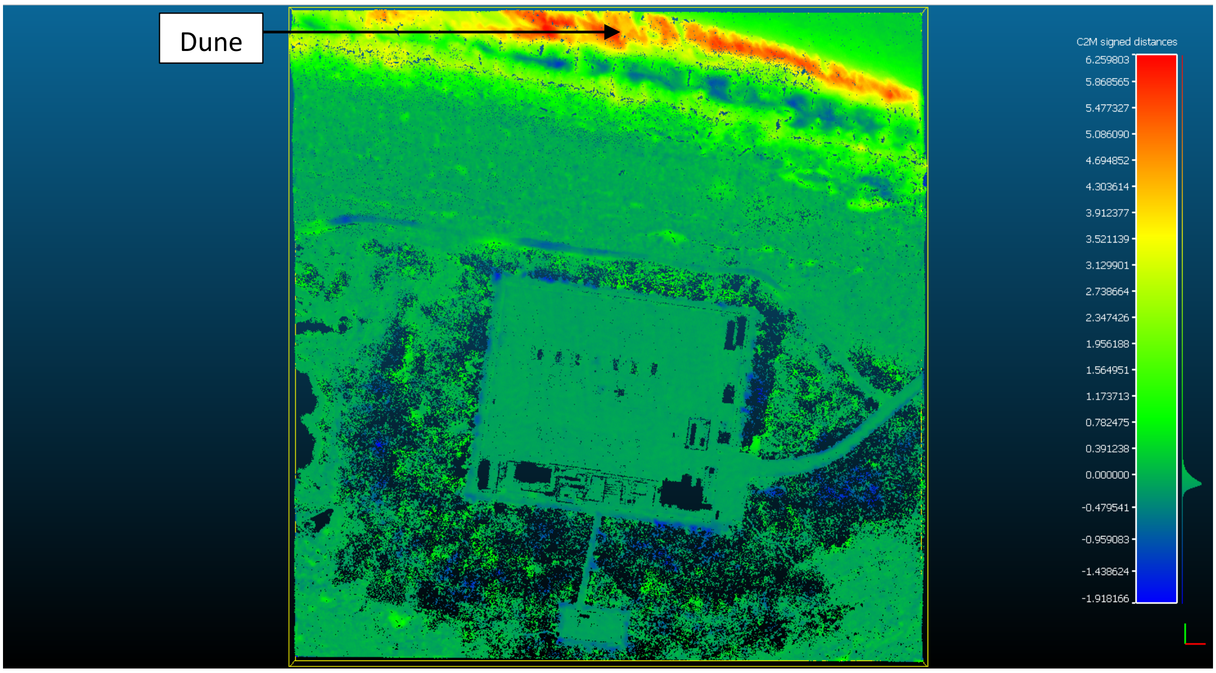


Figure 69 Comparison between mesh AHN 1 and point cloud AHN 2 on region 1

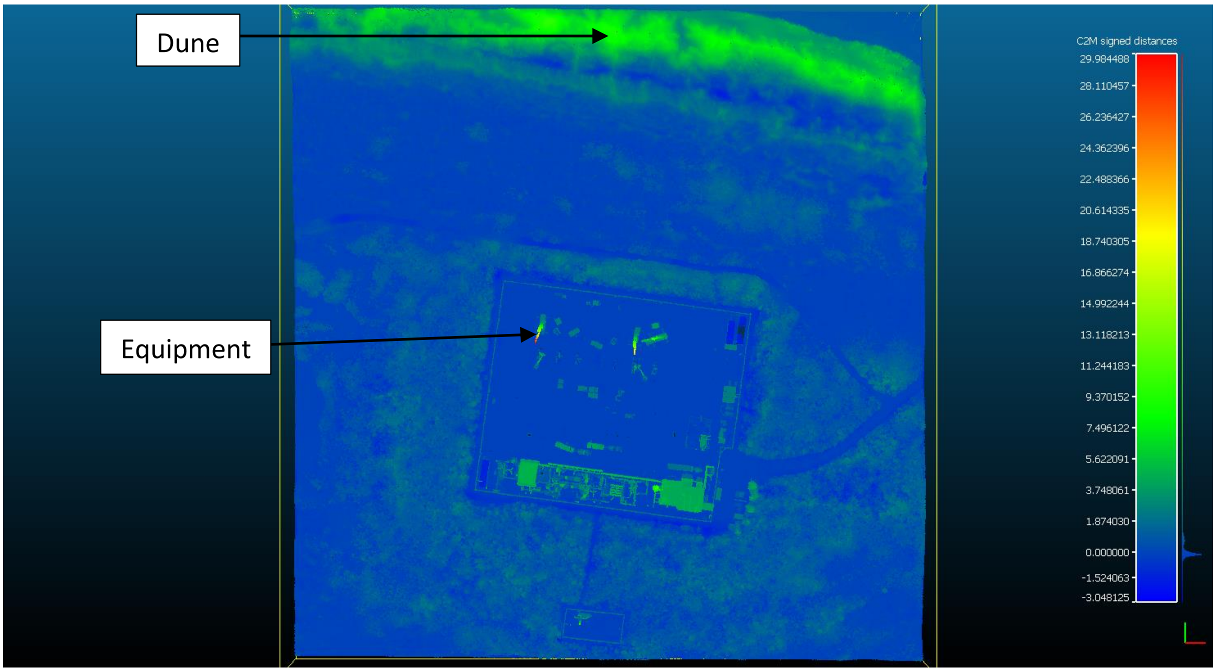


Figure 70 Comparison between mesh AHN 1 and point cloud AHN 3 on region 1

The first thing we notice is that in figure 70 there is a much larger maximum difference. This is because in AHN 3 some of the gas extraction equipment is not filtered out. This equipment is a lot higher than the surrounding area. In AHN 1 and 2 the installations are filtered out and that's why it produces a very large difference. We can filter the data at a certain height and when we use a maximum of 10 meters here, we lose the installations. This can be seen in figure 71.

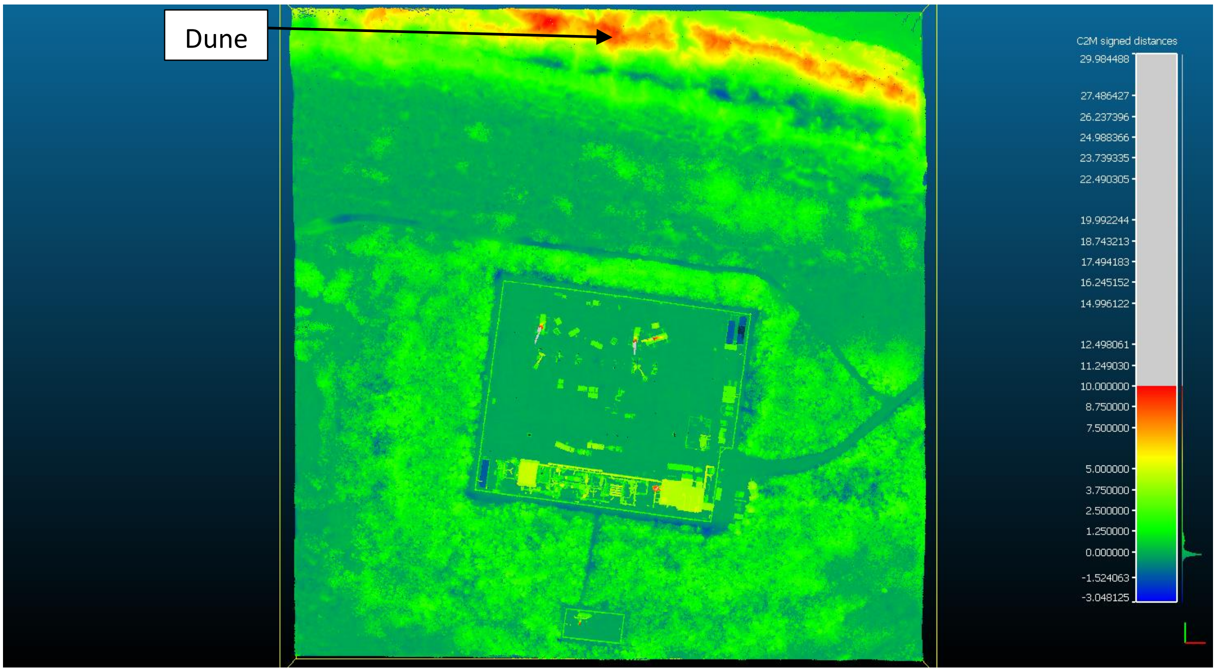


Figure 71 Comparison between mesh AHN 1 and point cloud AHN 3 on region 1 with pipes filtered out.

When we now compare figures 69 and 71, we see that the largest changes, both positive and negative, take place on the dunes. The top of the dune in the top of the figures is getting higher. The changes on the rest of the area are a lot smaller and we cannot really tell the average movement of the area by just these figures.

Now we take a look at region 2 in figures 72, 73 and 74.

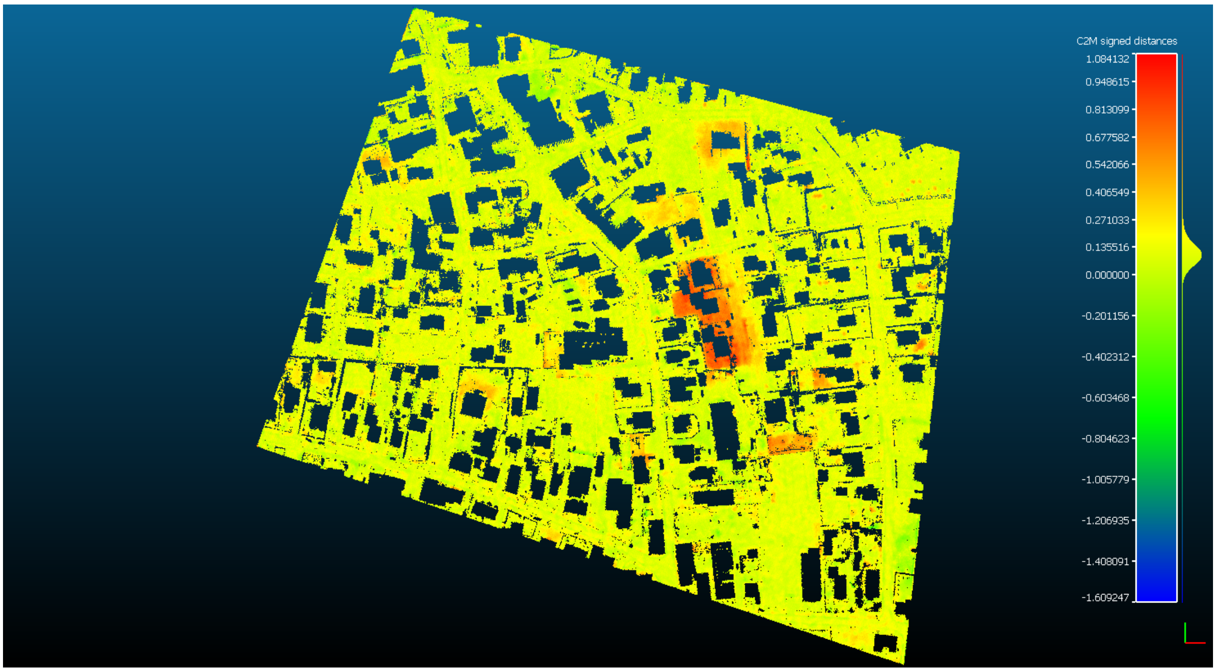


Figure 72 Comparison between mesh AHN 1 and point cloud AHN 2 on region 2

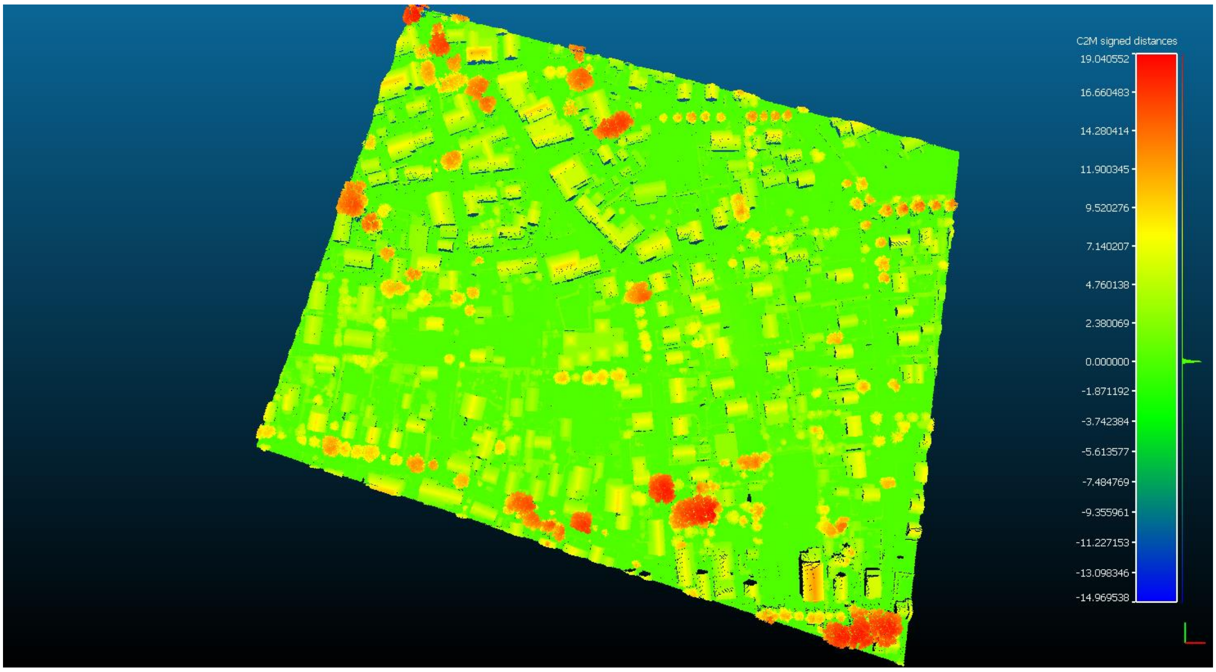


Figure 73 Comparison between mesh AHN 1 and point cloud AHN 3 on region 2

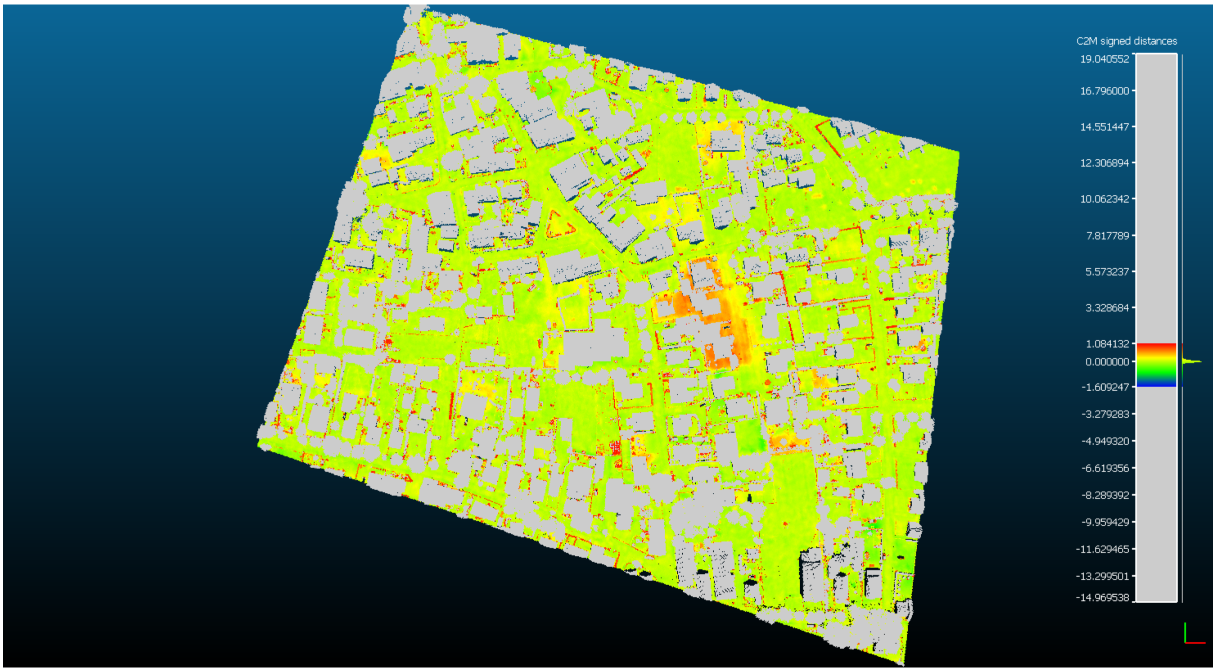


Figure 74 Comparison between mesh AHN 1 and point cloud AHN 3 on region 3 with houses filtered out.

For region 2 we again need to filter the comparison between AHN 1 and AHN 3, because the houses and trees make the changes on the ground too small to see as can be seen in figure 73. When we compare figures 72 and 74 we notice a large red area a little to the right of the center of both figures. This probably due to the building of some houses, because there are no houses filtered out in AHN 1 at that location, while there are houses filtered out there for AHN 2 and 3.

Next we look at region 3 in figures 75 and 76.

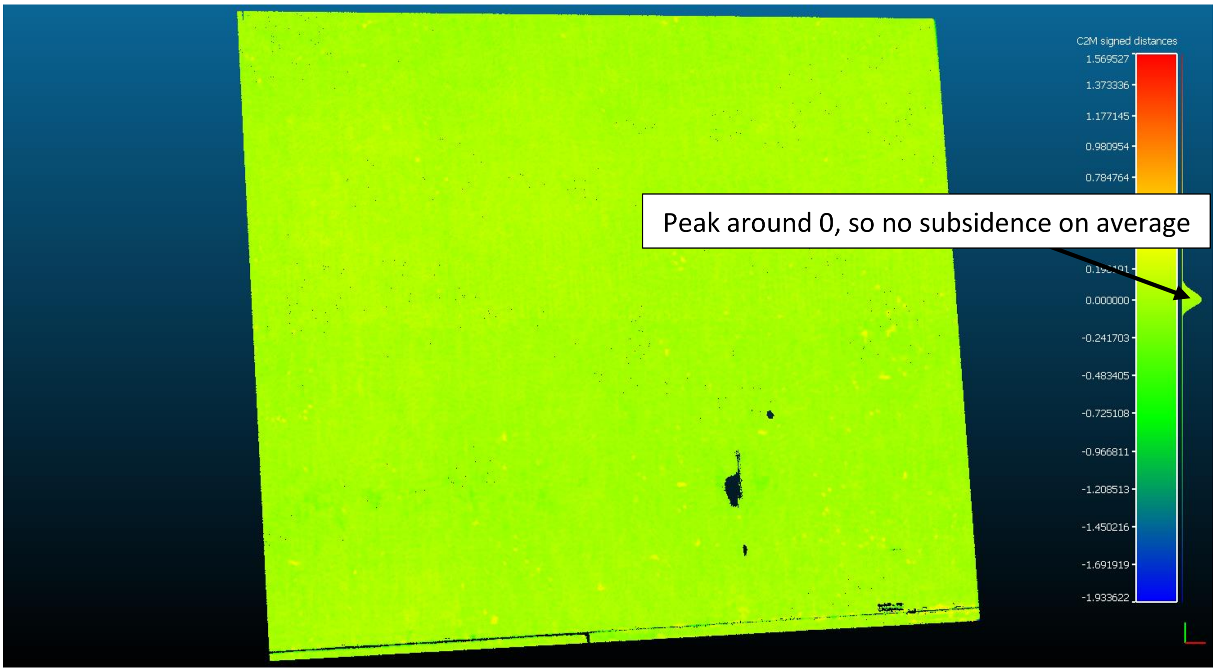


Figure 75 Comparison between mesh AHN 1 and point cloud AHN 2 on region 3

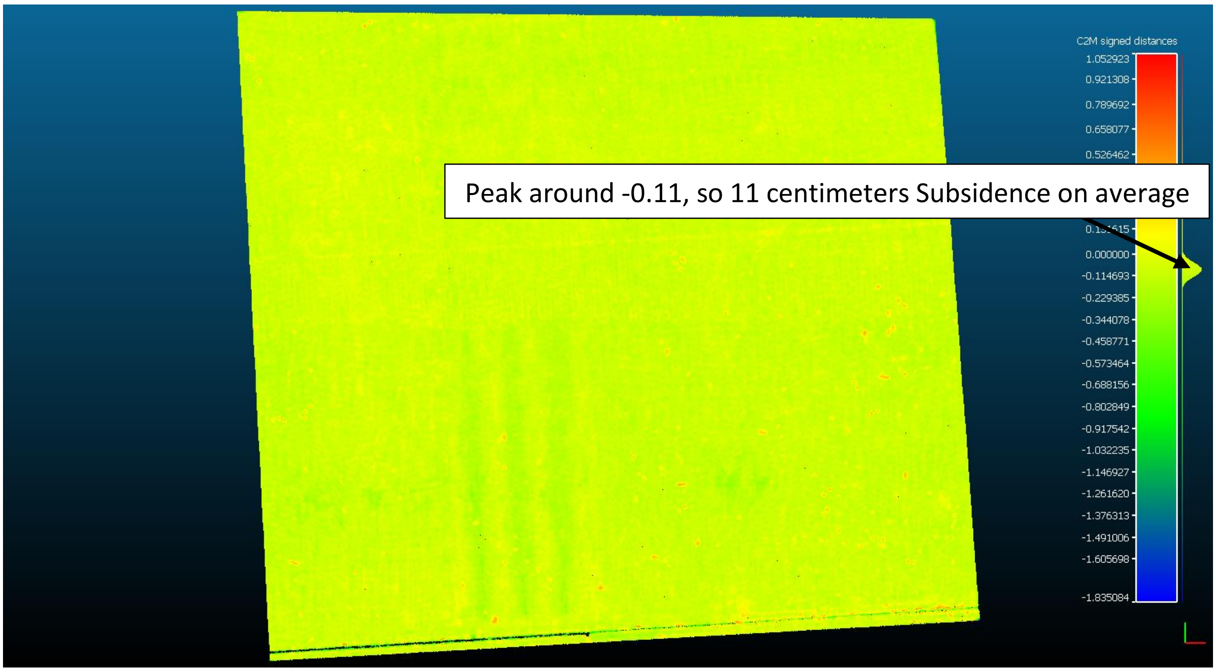


Figure 76 Comparison between mesh AHN 1 and point cloud AHN 3 on region 3

When we look at figures 75 and 76, we notice that the locations change very evenly when they change. This is visible because the entire plane is the same color, there is no hole or hill visible in the changes. That is good because this area was chosen as a neutral area where no changes should take place. The location is on a runway of a small airport and is far from the gas extraction. The area is also completely covered in grass, so there will not be a lot of sedimentation. A problem occurs in figures 76 as there is quite some subsidence, which is not as expected. This could be an error in the equipment, as the entire area subdues around 11 centimeters while nothing happened to the area in the period between AHN 1 and AHN 2.

Lastly we look at region 4 in figures 77, 78 and 79.

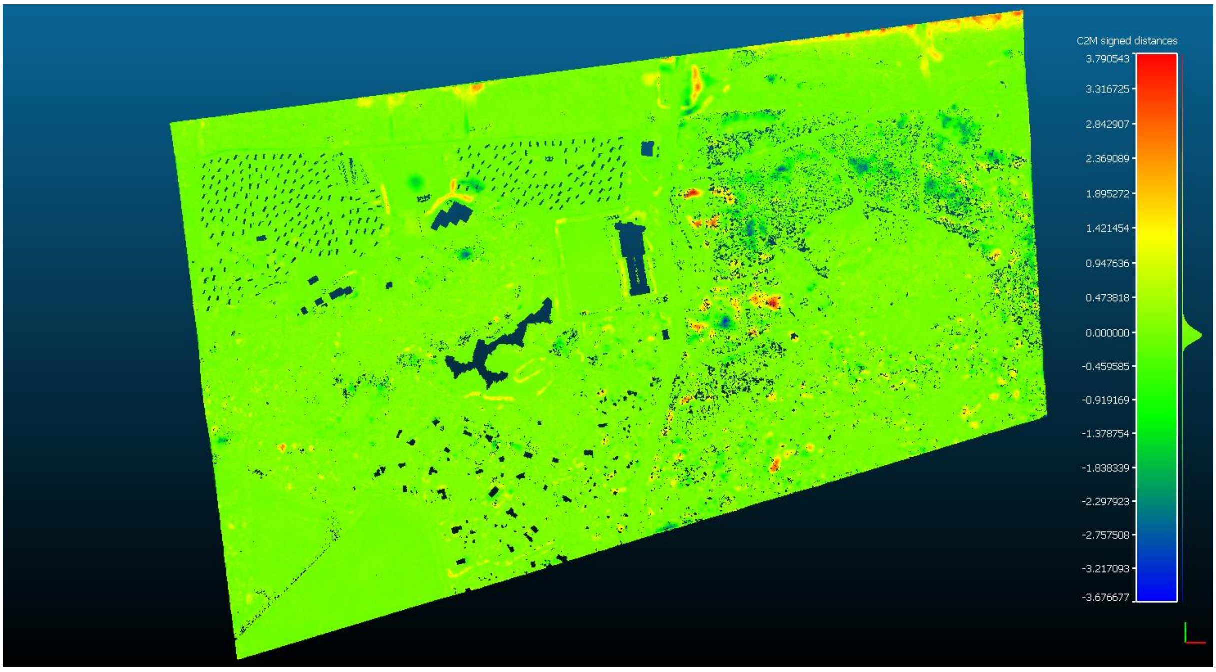


Figure 77 Comparison between mesh AHN 1 and point cloud AHN 2 on region 4

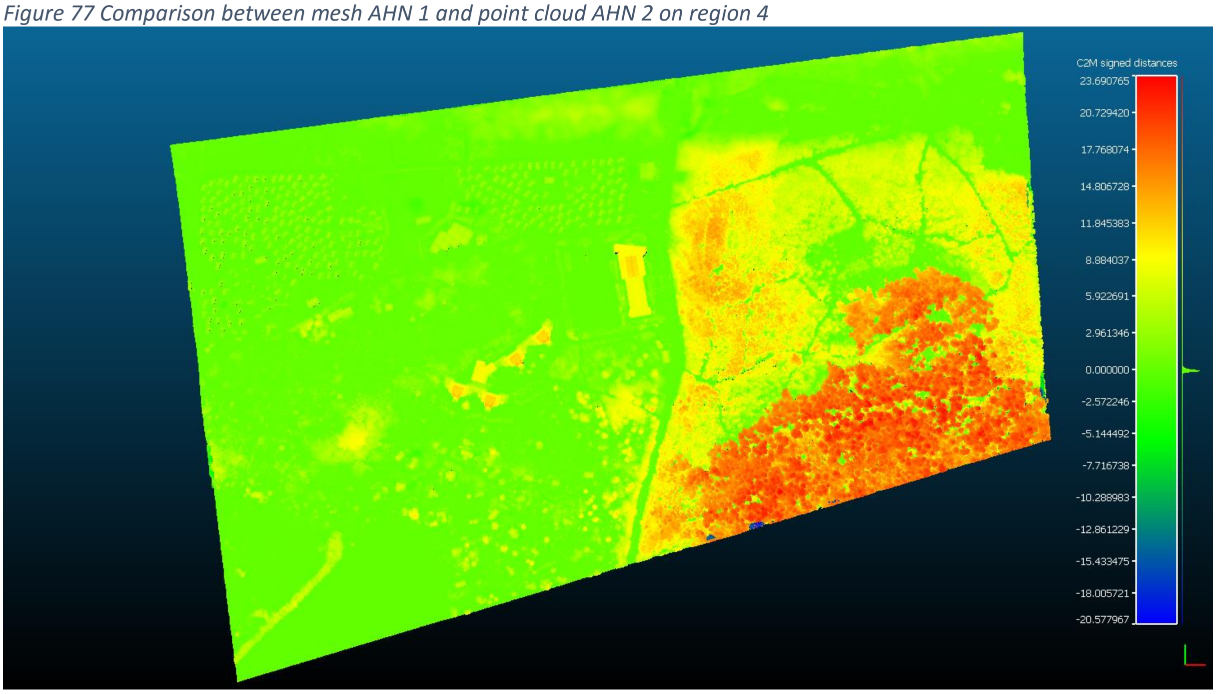


Figure 78 Comparison between mesh AHN 1 and point cloud AHN 3 on region 4

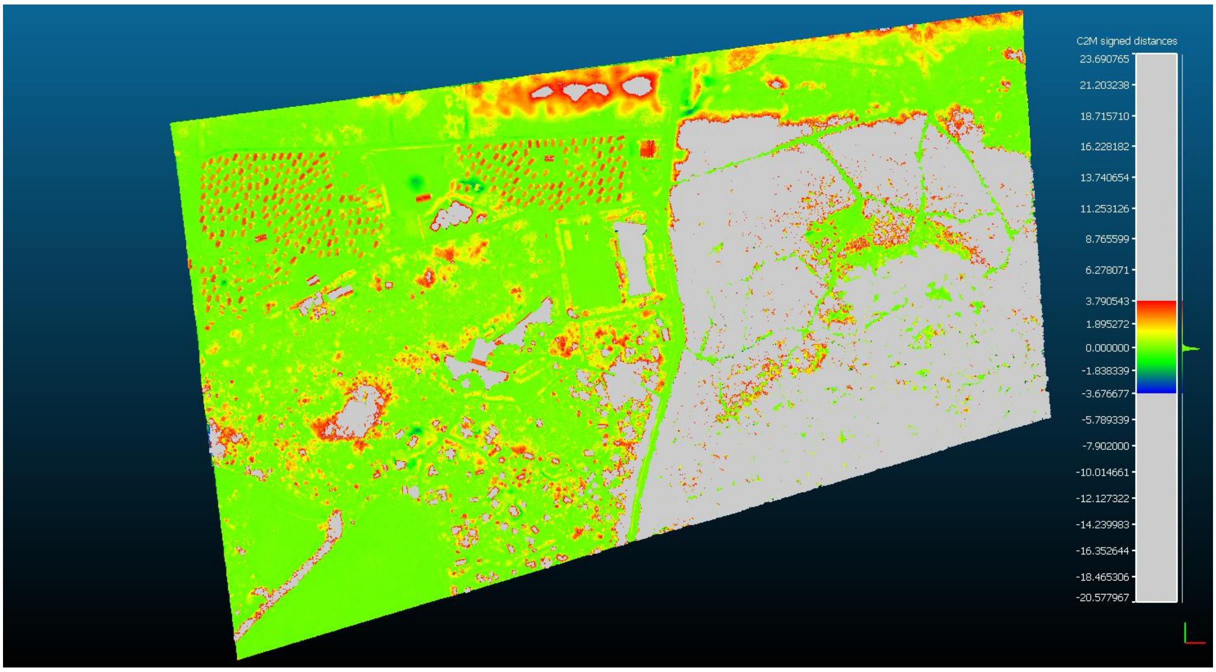


Figure 79 Comparison between mesh AHN 1 and point cloud AHN 3 on region 4 with trees filtered out

The height changes of the ground in figure 78 are very small compared to the height of the trees, so we filter these out and get figure 79. When we compare figures 77 and 79 we notice that on figure 79 a lot more changes are visible. These changes may have been caused by unfiltered trees and houses, but the larger changes in the top of the figure are located in dunes without trees and buildings, so this must be due to sedimentation.

When we take the average change for every region, we can compare them and see if we can recognize a pattern. We plot the changes in figure 80.

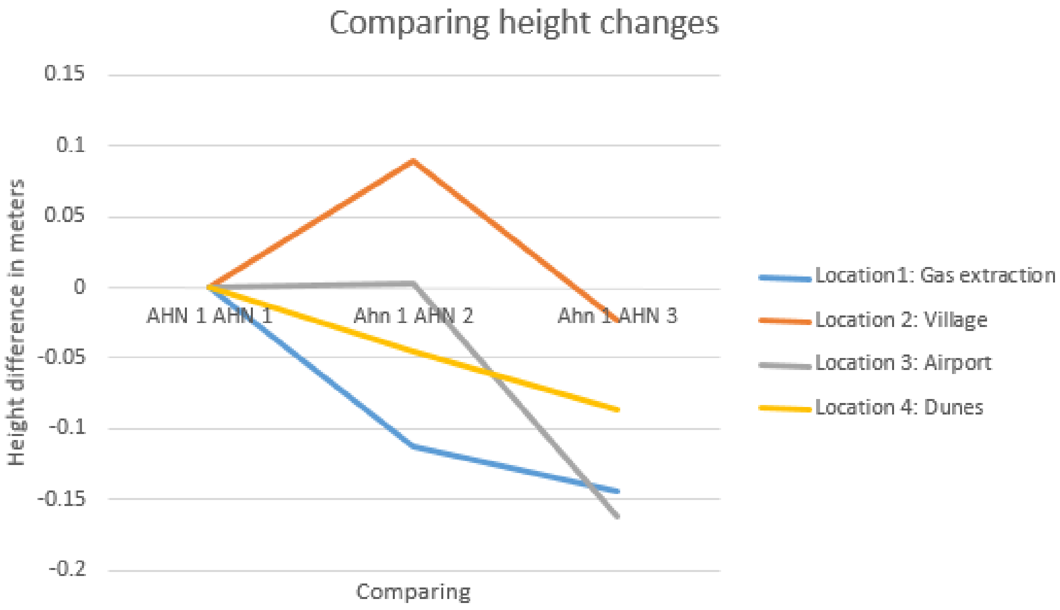


Figure 80 Average height change per area

When we look at figure 80, we notice that Location 3 stays very stable between AHN 1 and AHN 2, but changes a lot between AHN 2 and AHN 3. This could be due to instrumentational errors, as the area should not be subject to a lot of changes.

Next we see that Location 2 first rises between AHN 1 and 2 and then declines between AHN 2 and AHN 3. These large changes could be due to the fact that this location is in the middle of a village. This means that the changes can be very large and local. It also explains how it can go up between AHN 1 and AHN 2 and down between AHN 2 and AHN 3, as buildings can be constructed and demolished.

Location 1 and 4 both go down gradually. They are both situated in the subsidence circle, but Location 4 is farther from the center. That is why the subsidence of Location 1 is larger than the subsidence of Location 4.

This also proves that the subsidence by gas extraction is too large to be compensated by sedimentation on the island. In location 1 the subsidence is almost 15 centimeters for a period of 15 years, which means an average of 1 centimeter per year. This is not a very large change compared to the possible errors of this data.

To get an idea of the size of the locations we have the following box dimensions given by CloudCompare:

Location	Box dimensions in square meters
1	110,752.3
2	153,730.4
3	237,090.5
4	1,065,571.6

Table 6 Box dimensions of the different test locations

For location 1 this means an area of 110,752.253 m^2 with a subsidence of 15 centimeters, which would come down to 16,612.8m^3 volume change in 15 years.

Lastly we take a look at the possible error found in location 3. To do this we find new test locations that all meet the following requirements:

- Large flat area
- No buildings
- Few or no trees
- Not in the subsidence area

We find the 5 locations shown in figure 81, that meet those requirements. All locations are located on a large area that is either covered in grass or are part of a farm field.

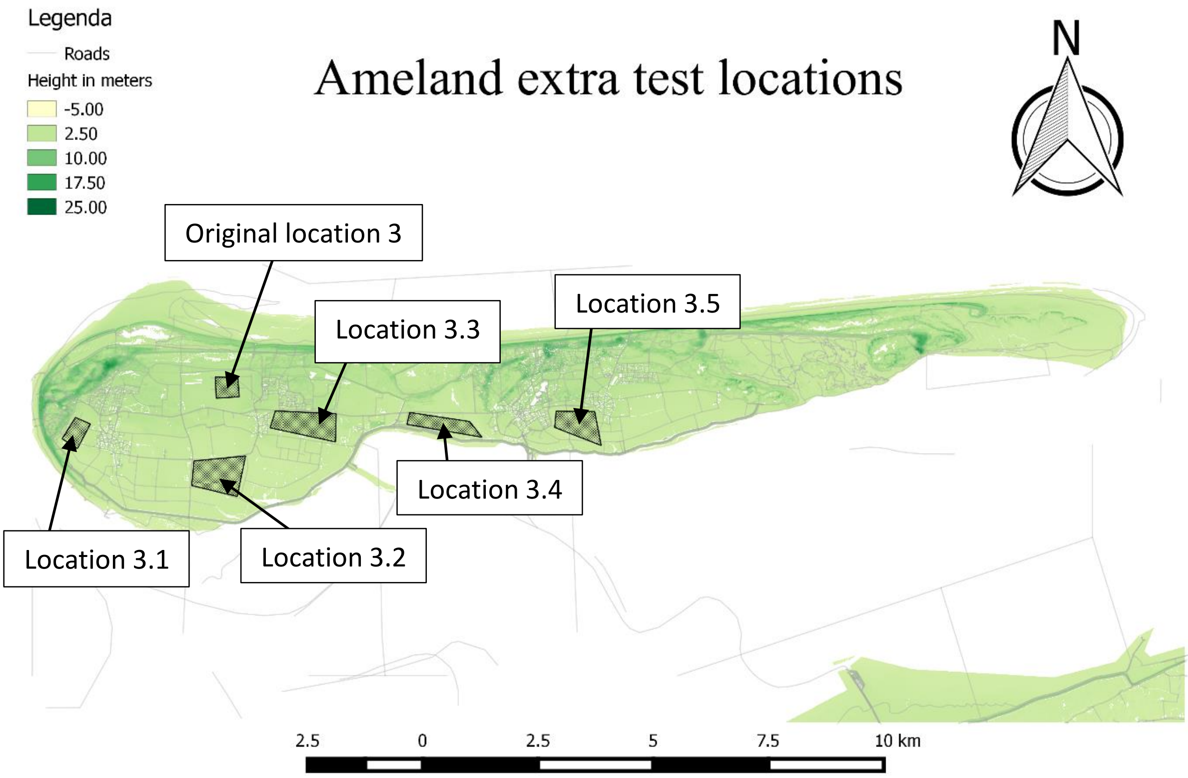


Figure 81 Extra test locations used to find the possible error in location 3

Next we use the same method as for the original 4 test locations to see what is happening. We again visualize the height changes in excel using the same methods and end up with figure 82.

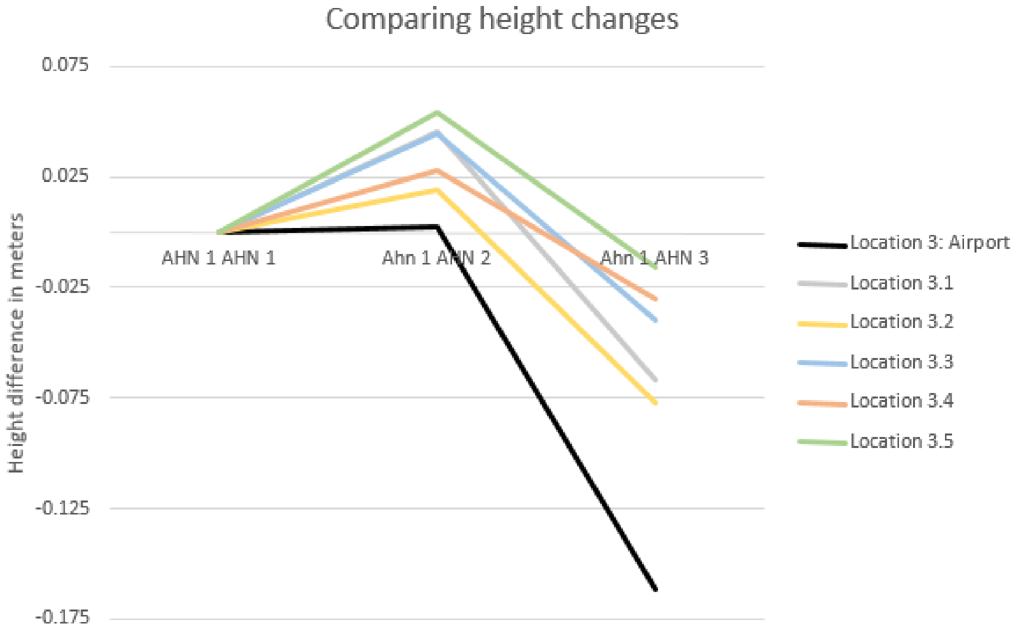


Figure 82 Height changes location 3 compared to the extra test locations

In figure 82 we notice a few things. First we see that all locations follow the same trend where they first increase between AHN 1 and AHN 2 and then decrease between AHN 2 and

AHN 3. Next we notice that even though the original location 3 does follow the same trend, its increase is a lot smaller and its decrease is a lot bigger. Since we do not expect height change in these 5 test locations, we assume that the source for the height change is an error in the data. We can use the average of these 5 test locations to correct the heights changes of all locations in figure 82. This results in figure 83.

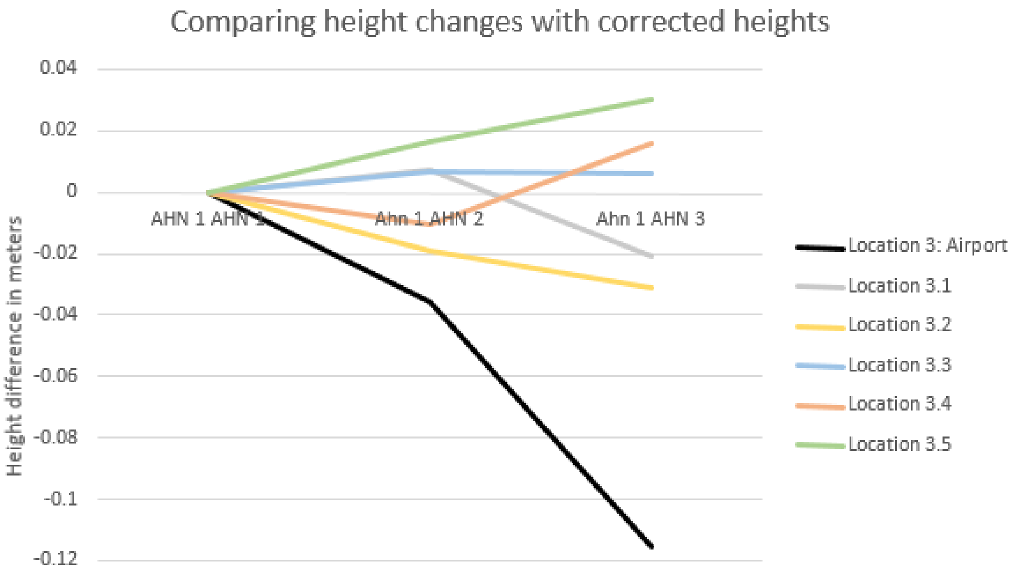


Figure 83 Height changes location 3 compared to the extra test locations, corrected with the average of these locations

Now we see very little change in the heights for all locations, except for the original location 3. We assume a systematic error in this location, because there is no reason to expect height change on this location and similar locations show no large changes. Because of this we use the average of the new test locations, to compare with the other original locations, as can be seen in figure 84.

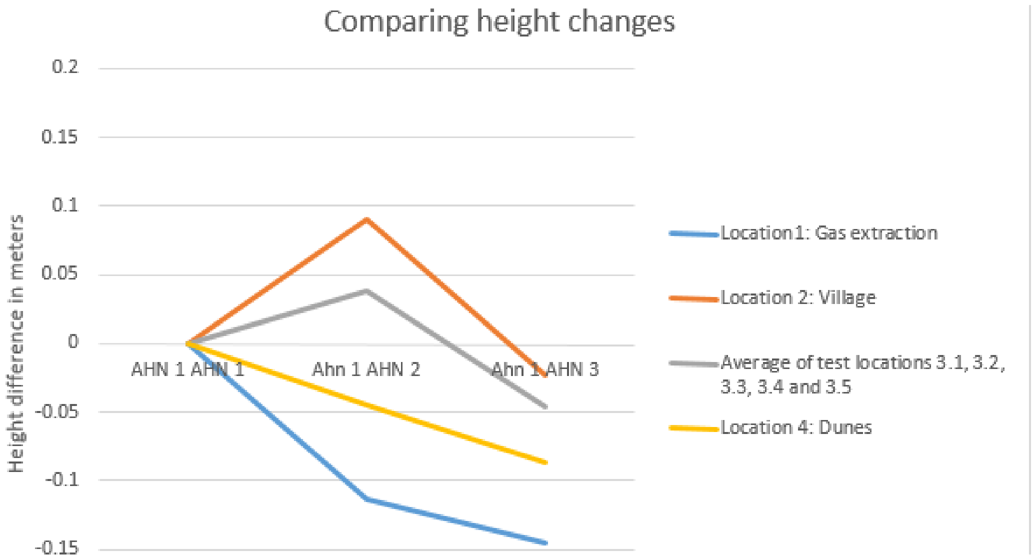


Figure 84 Comparing height changes in the original test locations to the average of the new locations

Now we see there is little height change in location 2 and the average of the new locations, there is a little subsidence taking place in location 4 and most subsidence takes place in location 1. These results are more like what we would expect to see.

5.4 Mudflat area monitored by Deltares

Deltares focuses on the part between Ameland, Schiermonnikoog and Friesland. We start with visualizing the original 7 datasets in Matlab in figures 85, 86, 87, 88, 89, 90 and 91. For these maps we use color boundaries on -2 and 2 meters.

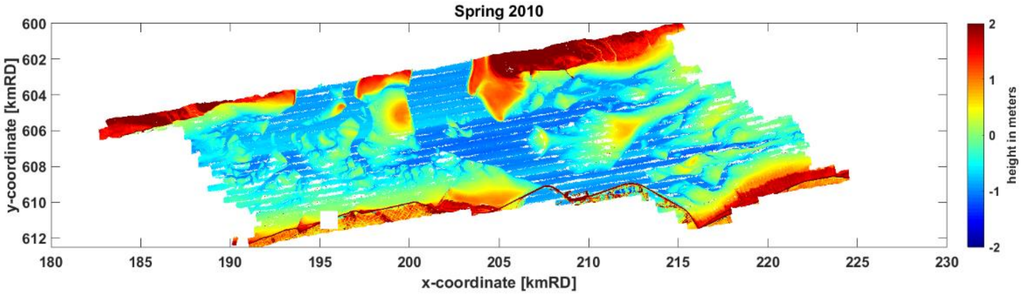


Figure 85 Deltares data Spring 2010

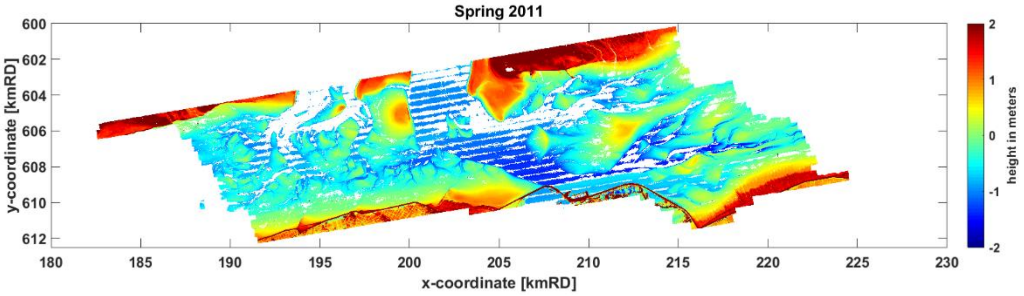


Figure 86 Deltares data Spring 2011

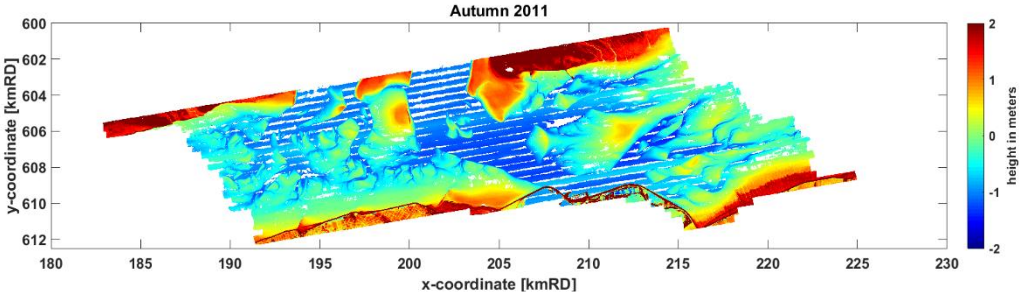


Figure 87 Deltares data Autumn 2011

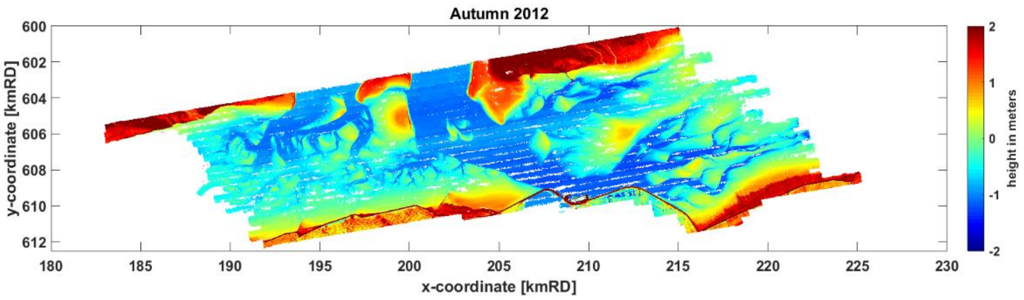


Figure 88 Deltares data Atumn 2012

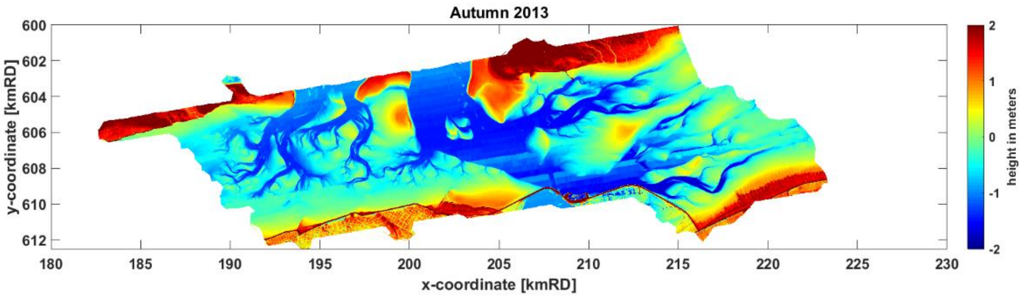


Figure 89 Deltares data Autumn 2013

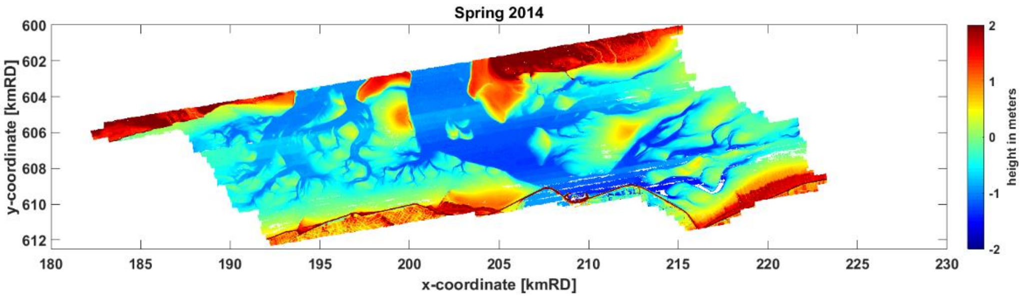


Figure 90 Deltares data Spring 2014

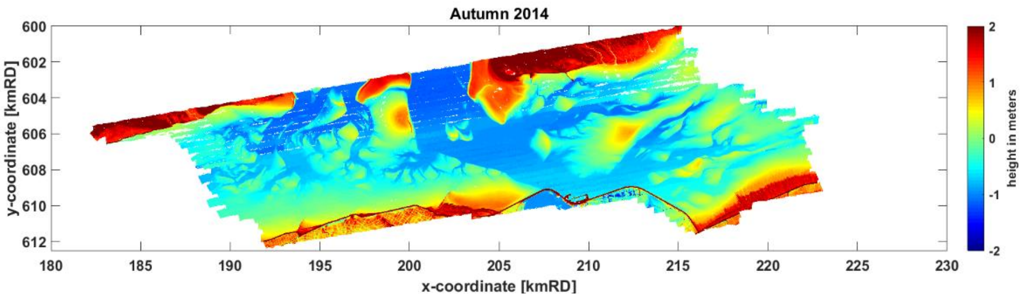


Figure 91 Deltares data Autumn 2014

We notice that in all maps white lines appear in the data, though they are not always as clearly visible. These white parts are cells without data. The reason for this is that the LiDAR method does not work properly in areas with water as explained in chapter 3.1. We also notice that Autumn 2013, Spring 2014 and Autumn 2014 have less no-data points and look a lot better than the other datasets. This is because the methods and instruments have improved over time and Spring 2014 and Autumn 2014 are actually created with a different laser that would be better for this type of surface. The blue parts are lower than the rest of the map, this is because these parts are trenches and this explains why most of the no-data values are in the blue areas.

Next we compare the datasets with each other. We compare every dataset with the one created after that. This way we get the 6 maps shown in figures 92, 93, 94, 95, 96 and 97. For this we use color boundaries on -0.25 and 0.25 meter.

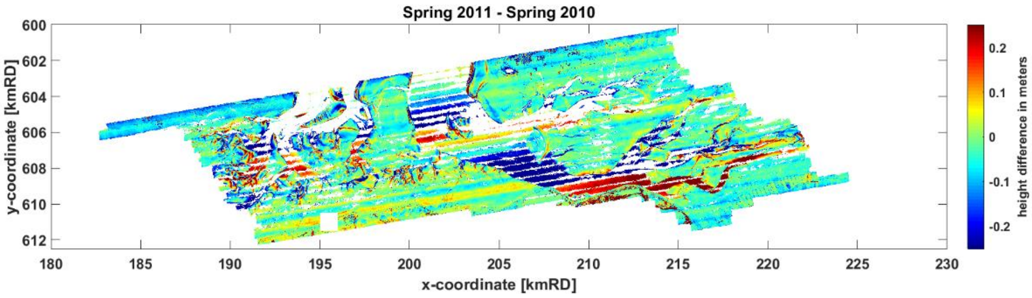


Figure 92 Height difference between Spring 2010 and Spring 2011

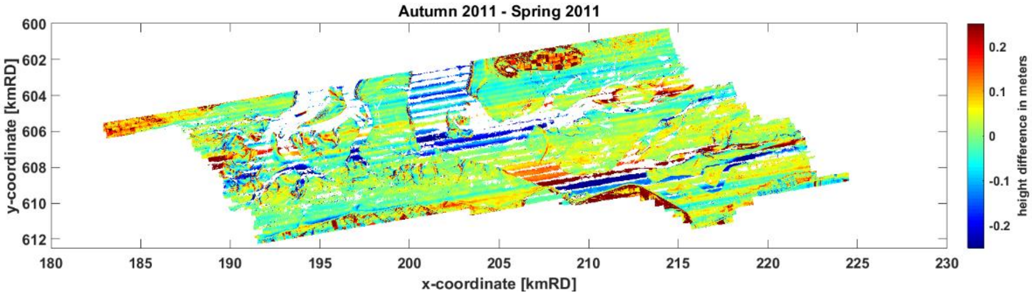


Figure 93 Height difference between Spring 2011 and Autumn 2011

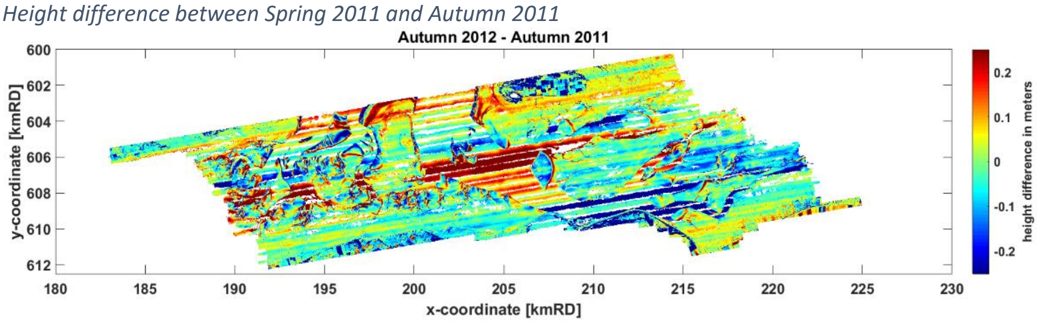


Figure 94 Height difference between Autumn 2011 and Autumn 2012

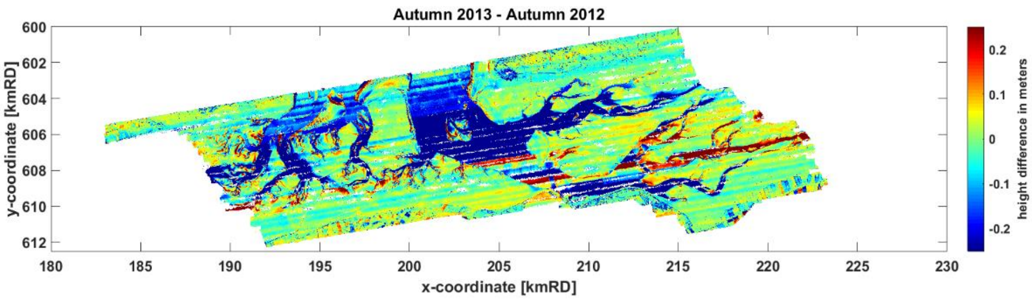


Figure 95 Height difference between Autumn 2012 and Autumn 2013

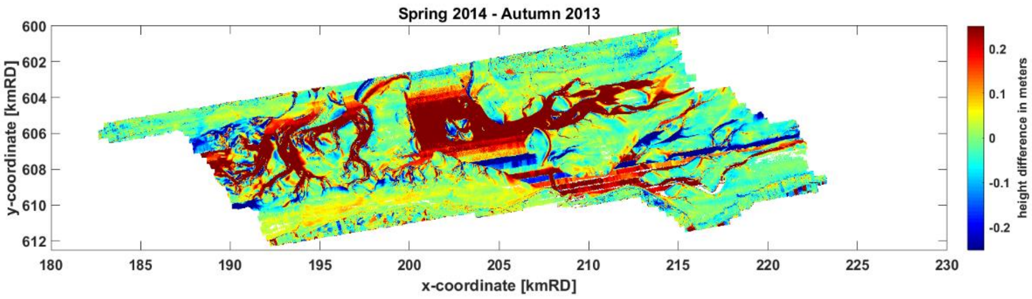


Figure 96 Height difference between Autumn 2013 and Spring 2014

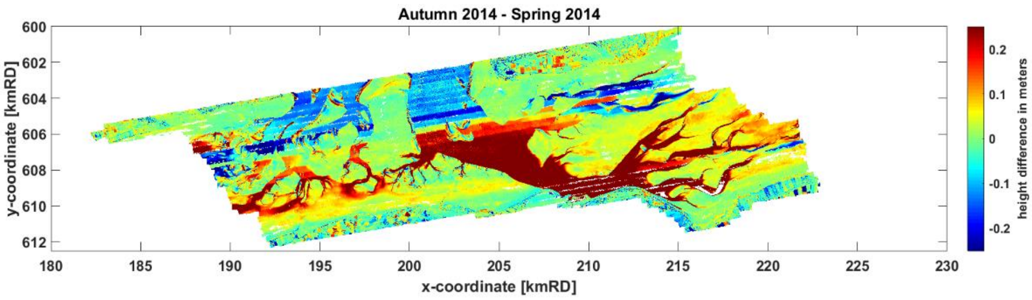


Figure 97 Height difference between Spring 2014 and Autumn 2014

When we look at these maps, we notice 2 things. The first thing we notice is that the different flight paths can have quite a high impact when you compare neighboring data points in a wet area. This is caused by possible changes in the water level while the ground remains stable. This will result in uncertainties in the wet areas. Another thing we notice is that the changes all apply to small areas, so one area can be going down, while an area really close to it is coming up. This is probably due to the fact that this area is sometimes below the water level and is therefore subject to a lot of erosion and sedimentation. This does make it hard for us to see what is really happening though.

To try and see the bigger picture here we visualize a total difference map by comparing Spring 2010 with Autumn 2014 as can be seen in figure 98. We use different color boundaries on:

- -5 and 5 meter
- -1 and 1 meter
- -0.5 and 0.5 meter
- -0.25 and 0.25 meter
- -0.1 and 0.1 meter

For figure 98 we only show -0.25 and 0.25 meter, the other comparisons can be found in appendix D.

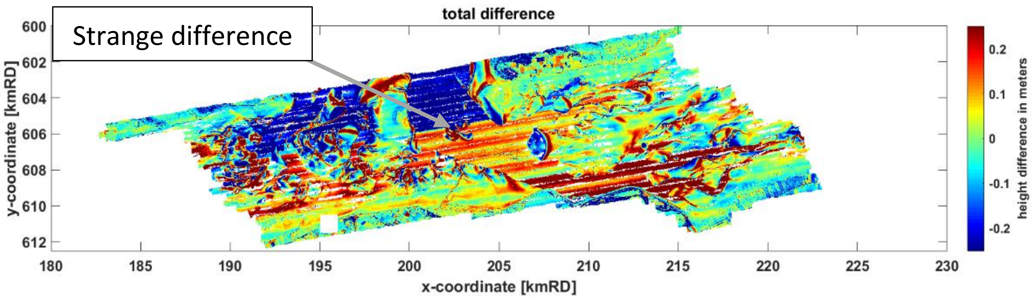


Figure 98 Height difference Spring 2010 and Autumn 2014 with boundaries on -0.25 and 0.25 meter

When we look at this map we clearly notice that the largest differences are found in the trenches. We also notice a sharp line with a very large difference half way through the trench. This is probably due to the fact that it takes more than one day to finish gathering the data. It could be that they did one part the first day and when they came back the next day they started at a different time with a different water level. This would explain why the change is so direct and almost only visible in the trenches. We do not really notice any trends that could show what is happening.

Next we try to visualize the larger trends by simplifying the dataset. We do this with 2 different methods. The first method takes all values of grid cells in a larger grid cell and takes the average of those cells. The second method takes the middle grid cell inside this larger grid cell and uses this value for the larger grid cell. We use 5 different grades of simplifying:

- 25 x 25 cells
- 50 x 25 cells
- 100 x 100 cells
- 200 x 200 cells
- 400 x 400 cells

We start with visualizing the first method in figure 99. We only show the 400 x 400 cells here. The complete comparison can be found in appendix E.

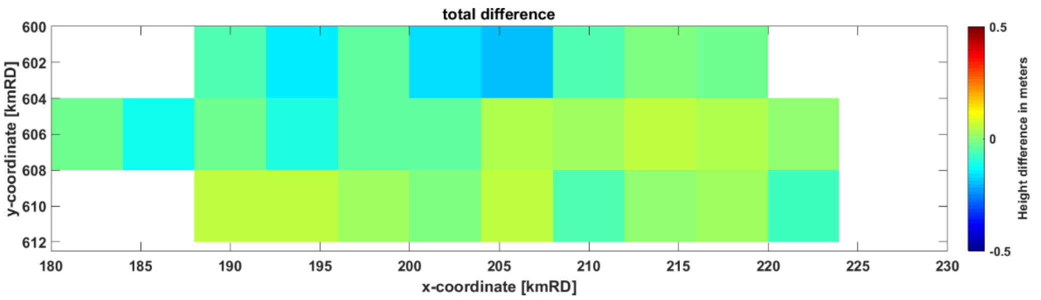


Figure 99 Simplified 400 x 400 data of comparison between Spring 2010 and Autumn 2014

In figure 99 we seem to see some subsidence in the north part of the map, but this is probably due to the water level in the trenches over there. Also the changes are very small. This is because the changes are very local and when an average is taken the total change is still very small. The only cells that show a larger change are the ones that represent the trenches.

A way to prevent this averaging is using the second method of taking the middle value, as is shown in figure 100. Once again we only show the 400 x 400 cells map, the full comparison can be found in appendix F.

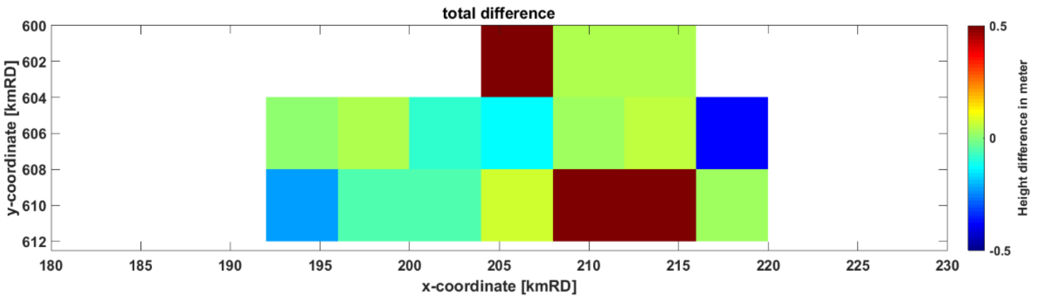


Figure 100 Simplified 400 x 400 data of the comparison between Spring 2010 and Autumn 2014

A problem with this method is that if there is no data in the middle of the cell, the entire cell will not have a valid value. This will result in a loss of data. When we look at figure 100, we notice much larger changes than we got from the first method. However, most of these changes are not representative for what is happening in that area. The 2 red cells in the bottom of the map show the changes in the trench. The bright blue cell to the right of the map is situated in an area where there is a lot of uplift and parts with small changes, but due to the fact that the middle of the cell was in a small part with large subsidence, it now looks as if the entire area is subject to subsidence. This method will not work for this data.

Since the trenches make it harder to spot the real trends we filter this data out of the dataset. For this we use a cut off at -0.5 meter NAP. This means that every value below -0.5 meter NAP will be deleted. The -0.5 meter cutoff is chosen, because it deletes the trenches, but not the rest of the data and because according to the report from Deltares there is still water present up to these heights. In figure 101 we can see how the dataset from Spring 2010 changes when the cutoff is applied. When we look at figure 101 we notice that it looks a lot cleaner than before the cutoff, which is what we want.

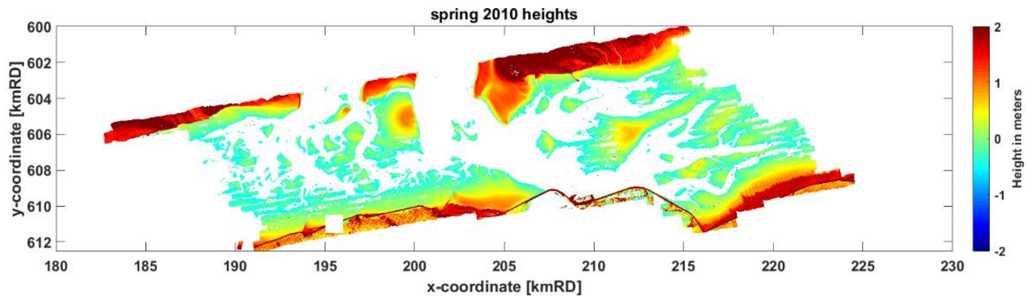


Figure 101 Spring 2010 dataset with cutoff applied at -0.5 meter NAP

Next we use these new datasets for the least squares method that we already applied to the AHN datasets. First we compare Spring 2010 to the h_0 calculated by the least squares method in figures 101 and 88.

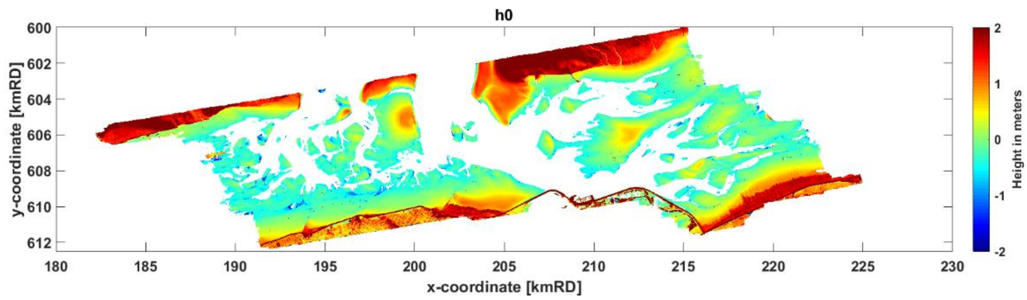


Figure 102 h_0 calculated by the least squares method

When we compare h_0 to Spring 2010 we notice that the last no-data lines have disappeared in this method and that the small square of missing data in Spring 2010 is now also covered by the least squares method.

We also notice some small areas with values below the cutoff. This probably occurs in areas where there is no data for Spring 2010 and Spring 2011. When uplift has been taking place over the last years the low parts are cut off in the first datasets, but after the uplift the area is above the cutoff. This means that with the least squares method this data below the cutoff can once again be available in the dataset. However, since the area was above the cutoff at some point we know that these low values do not represent the water level.

Now we can compare the slope to the difference between Spring 2010 and Autumn 2014. Both maps are showing height change in meters per year, so we can directly compare them. We compare both with boundaries at:

- -0.1 and 0.1 meter per year
- -0.05 and 0.05 meter per year
- -0.01 and 0.01 meter per year

Here we only compare at -0.05 and 0.05 meter per year in figures 103 and 104, but the full comparisson can be found in appendix G.

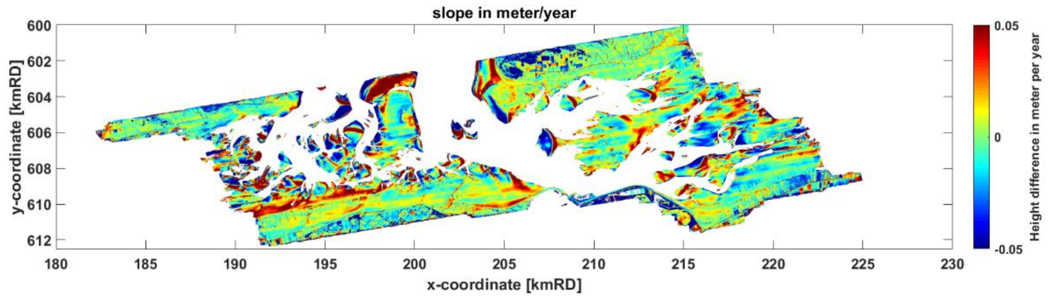


Figure 103 Slope in meter per year calculated by least squares method

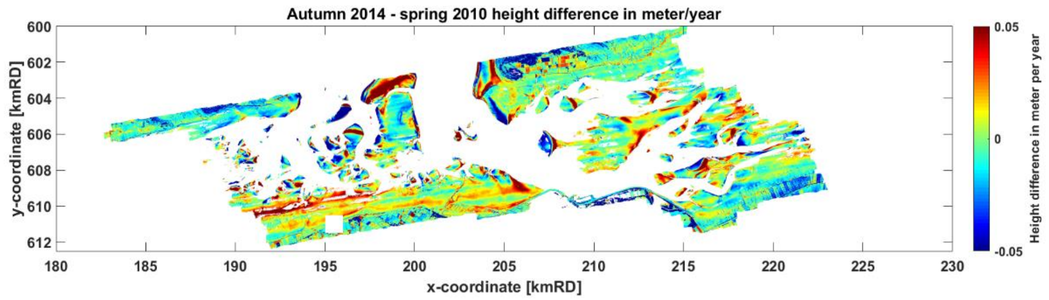


Figure 104 Height difference between Spring 2010 and Autumn 2014 in meter per year

When we compare figures 103 and 104 we notice that most changes are the same, but in the west the least squares solution has more valid data points. We do see that in the north west some subsidence takes place. This is the east coast of Ameland and the subsidence is similar to the subsidence we saw when comparing AHN values.

Next we look at the errors of the least squares in figures 105 and 106.

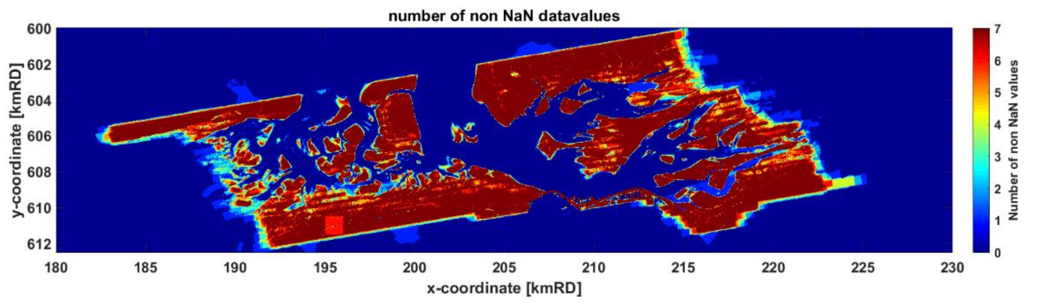


Figure 105 Number of data values used in least squares method

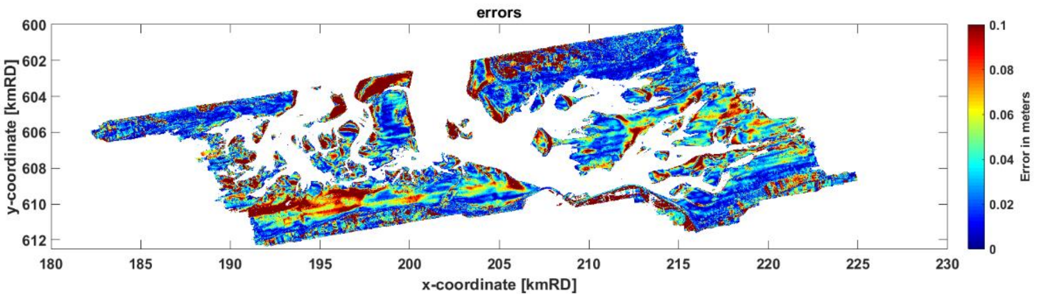


Figure 106 Average error of the least squares result in meters

In figure 105 we notice that most cells have 6 or 7 values and will probably give a trustworthy result, but in the far east and west and between the trenches in the west the cells have a little less valid data points and the results there might be less accurate.

When we look at figure 106 we notice that dry land has a lower error than parts that are sometimes below water level and the west coast of Schiermonnikoog. The Wad has no real trend for the average error so we cannot really say anything about how correct these results will be.

We can also simplify the filtered data with the same methods we used before. In figures 107 and 108 we see the simplification with method 1 and 2 respectively. Here again we only show 400 x 400 cells and the full comparison can be found in appendix H.

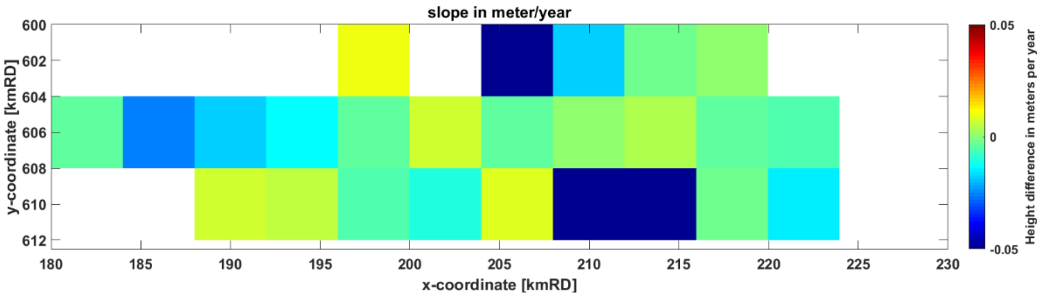


Figure 107 Simplification of least squares solution method 1

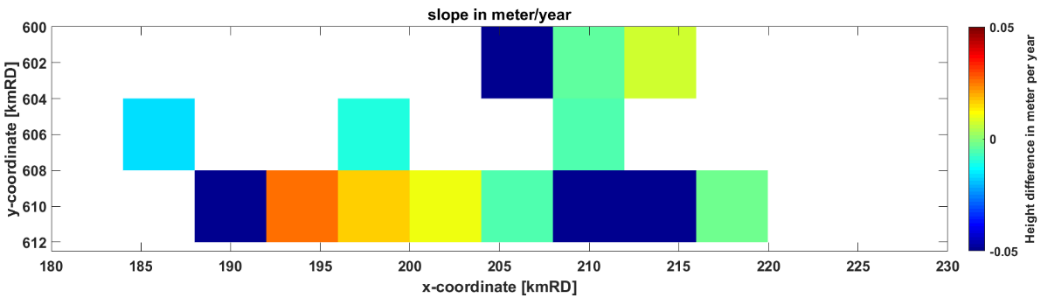


Figure 108 Simplification of the least squares solution method 2

When we look at figures 107 and 108 and compare it to the simplified images before the cutoff we see a lot more subsidence taking place. When we compare the 2 different methods we notice that the largest difference occurs in the south west. This is where the coast of Friesland is. The reason for this change may just be the different implementations of the methods used. For method 1 we also notice subsidence in the north west. This is nice because this is the location of Ameland, so this is just more proof that the subsidence is stronger than the sedimentation there.

We can also use Matlab to calculate the average slope from the least squares solution. This is -0.0114 meter per year. This is a small subsidence of a little over 1 centimeter a year. The total area of the map is 18,743,550m^2. This means that there is a volume change of -187,435.5 m^3 per year. When we do the same for Autumn 2014 - Spring 2010 we get an average height change of -0.0088 m^2 per year and -164,943.24 m^3 per year. Both show a small subsidence for the total area and the results are very close to each other, but the change is very small compared to the maximum change of 8 centimeters per grid cell.

Next we can again compare these results to The results found in the research done by Johan Krol. We can see in figure 109, that we have 4 areas that overlap in this dataset. However, we need to zoom in on this data to be able to see any results. We will discuss the four areas one at a time.

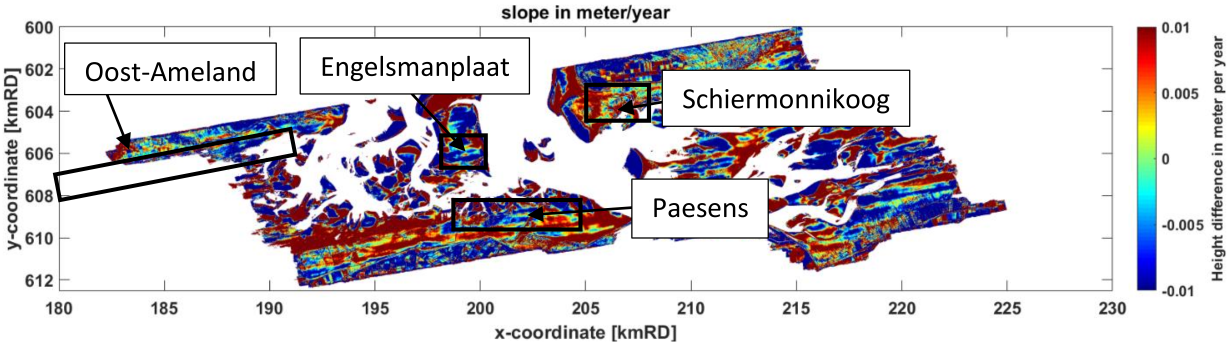


Figure 109 Deltares LiDAR data with the corresponding research areas of Johan Krol

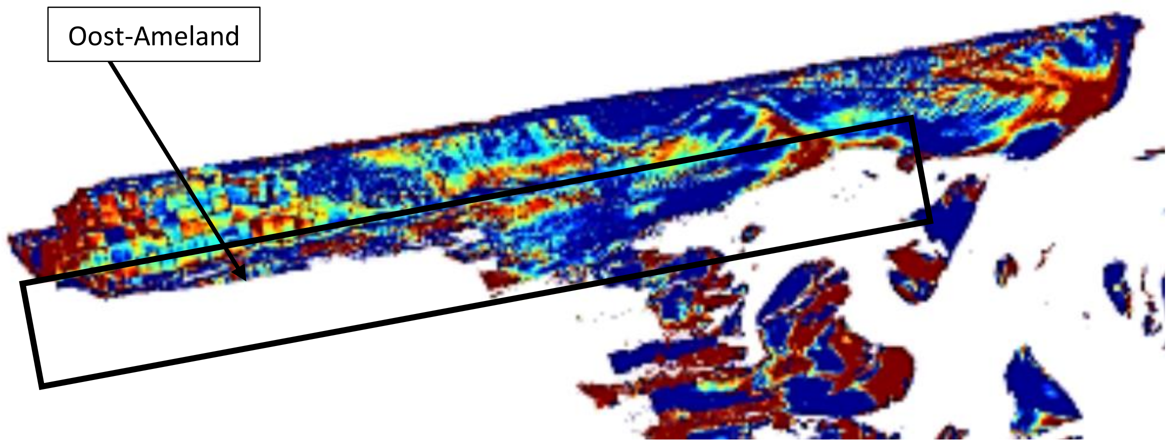


Figure 110 Deltares LiDAR data showing Oost-Ameland

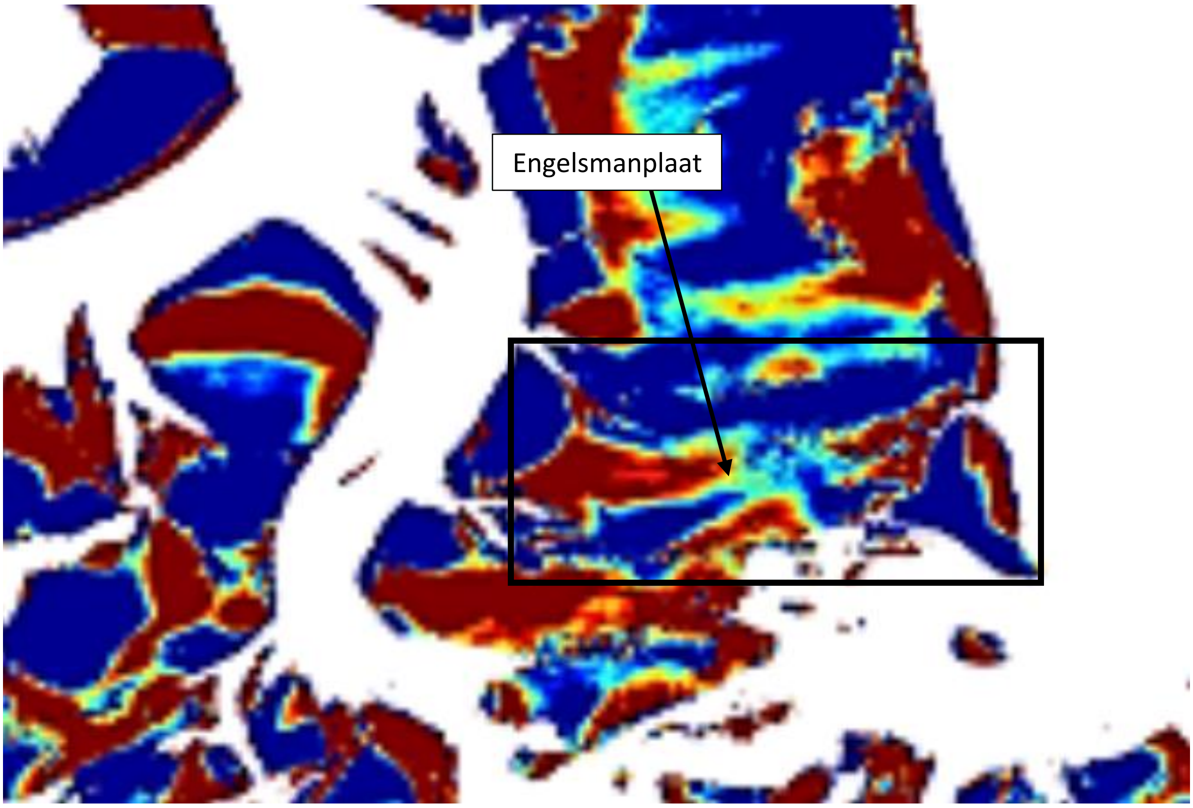


Figure 111 Deltares LiDAR data showing Engelsmanplaat

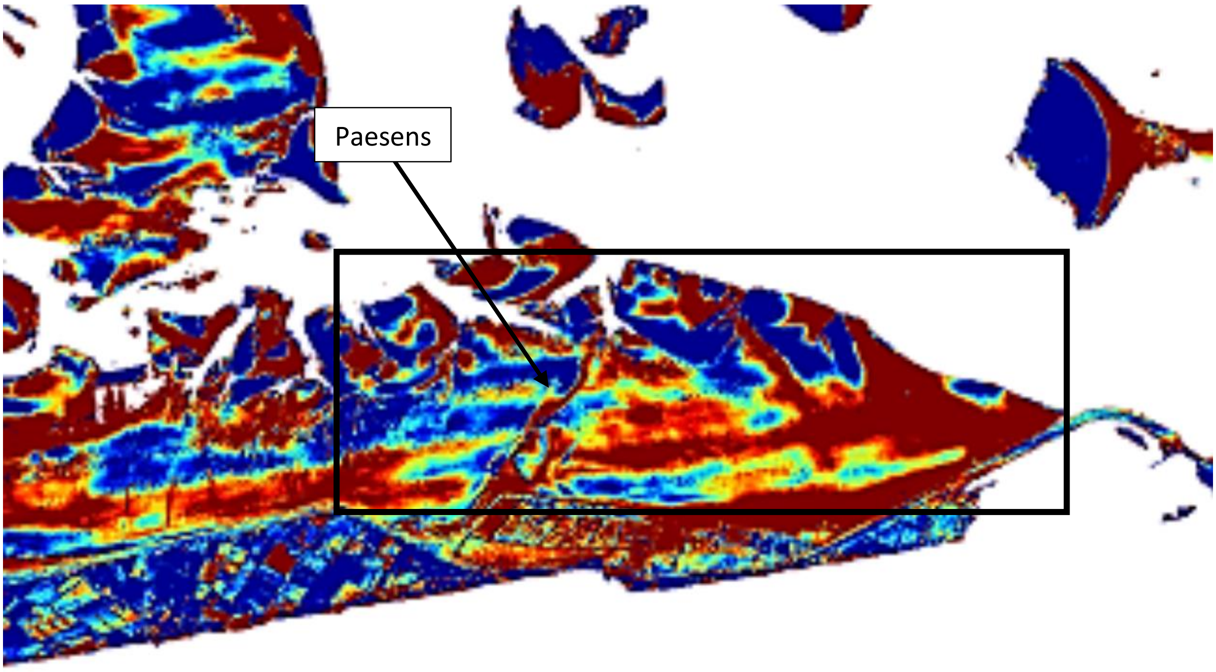


Figure 112 Deltares LiDAR data showing Paesens

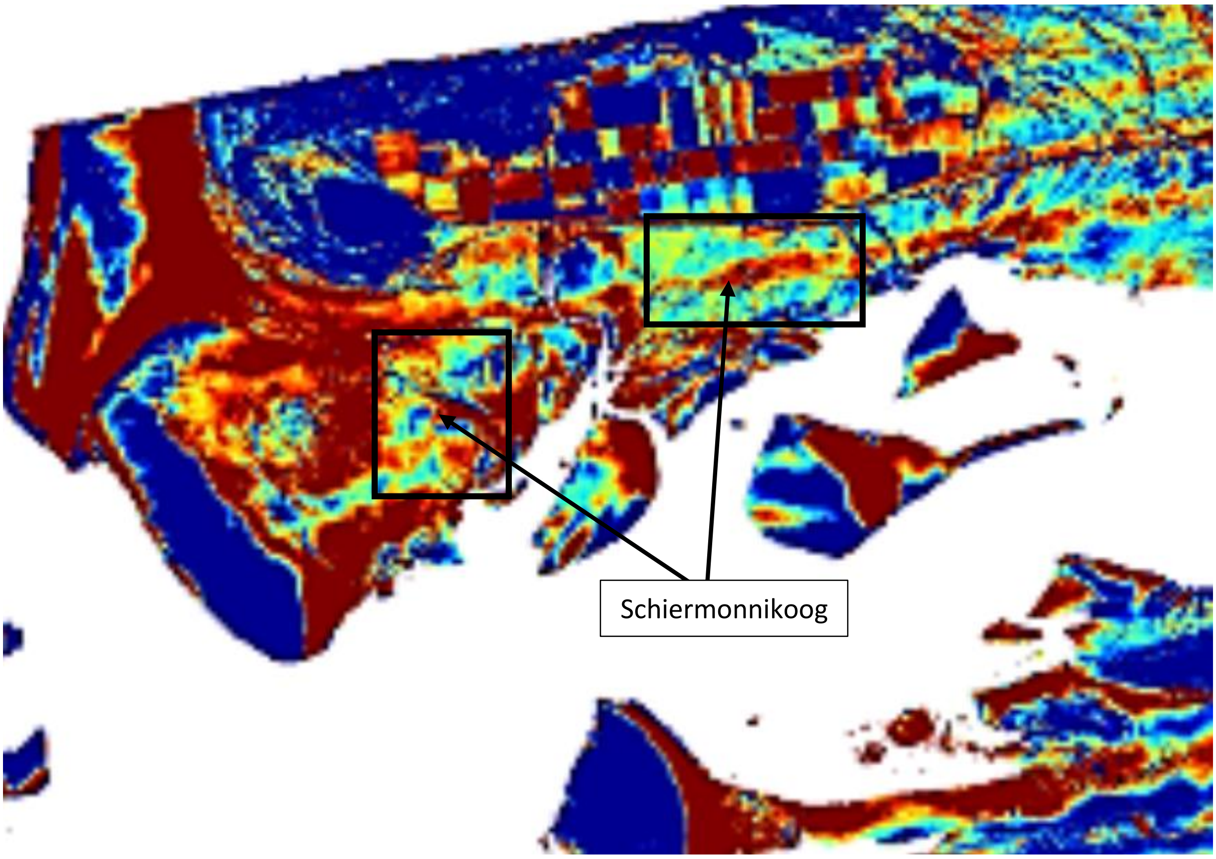


Figure 113 Deltares LiDAR data showing Schiermonnikoog

First we look at Oost-Ameland in figure 111. Here we again see that most of our data is close to the research area used by Johan Krol, but not in it. For the data that we can see we see mostly net subsidence of more than 1 cm per year. This is different from what we see in the results of Johan Krol, where we see a net uplift. A possible explanation for this is that Johan Krol looks at averages of the area and we see only a part of the data. Sedimentation in parts that are subject to sedimentation by the sea is much stronger than in parts that are only subject to sedimentation by wind. Since we filter all areas that are below water level, we only have areas that are subject to wind sedimentation. Johan Kroll placed his measuring locations in areas that are mostly subject to sedimentation by water, as they are on a 'wad'. This difference in sedimentation forces might explain the difference we detect between our data and the data of Johan Krol.

Next we look at Engelsmanplaat. Here we see both net uplift as subsidence. Johan Kroll saw an average net uplift, but is was small. Since we see about the same amount of uplift as subsidence, the average will be a very small change in height. As we can see on figure 112, this area is subject to a lot of height change, but since it moves both up and down there is not a clear direction for the area. This is confirmed by the results of Johan Krol, as the amount of sedimentation is the smallest of all test locations.

In Paesens, we see again both uplift and subsidence. This time however, there is a lot more uplift. This is confirmed by Johan Krol, as this area is subject to the most uplift of all his locations. In this area Subsidence by gas extraction does take place, but it is not of the same reservoir as we were looking at with our AHN dataset. We can see this subsidence when we look at the south of figure 113. Here we see the main land of Friesland and we clearly see that this part is subject to a lot more subsidence than neighboring parts that are just out of the coast.

Finally, we look at the two areas of Schiermonnikoog in figure 114. Here we mostly see uplift and only very little subsidence, but the uplift is not as strong as for Paesens. We see the same in the results of Johan Krol, as he detected a sedimentation of 7.1 mm per year. This is a large sedimentation, but not as large as in Paesens, where he detected a sedimentation of 8.66 mm per year.

6 Conclusion

In this research we look at height changes on and around Ameland and try to find out if the gas extraction has a notable influence. We use different methods and datasets to find the answer to this. Every method and every dataset shows that subsidence does take place around the east of Ameland and that it is stronger than the sedimentation in that region as can be seen in table 7. However, in all cases the total change was smaller than the potential errors in the used datasets. This means that we can say that subsidence takes place, but we cannot with any certainty say how much.

Dataset	Subsidence in meter per year
AHN grid (Subsidence area)	-0.007
AHN point cloud (location 1)	-0.009
Deltares LiDAR data	-0.011

Table 7 Subsidence in meter per year for different datasets

Something that can be improved in the future is the quality of the data. We know that AHN 2 and three have a lot better quality than AHN 1, so comparing those should give a better result. Another way to improve the data we have is by trying to correct some errors in the data. We did this by creating a histogram and making sure the data fits together, but we left the lines that we saw in figures 48 and 49. When those errors are filtered out a result would also be more reliable.

Another point that could use some closer investigation is the filtering of AHN data. All 3 the datasets treat filtering differently. For AHN 1 there is interpolation at places where the buildings are situated, for AHN 2 this is less and for AHN 3 it is even below that. This results in small changes that should not be there. A good example for this can be seen in figures 9 and 10. The center of the buildings is nicely filtered, but there is still some data left at the sides. This can cause errors in average changes and distorts maps.

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Appendix

Appendix A

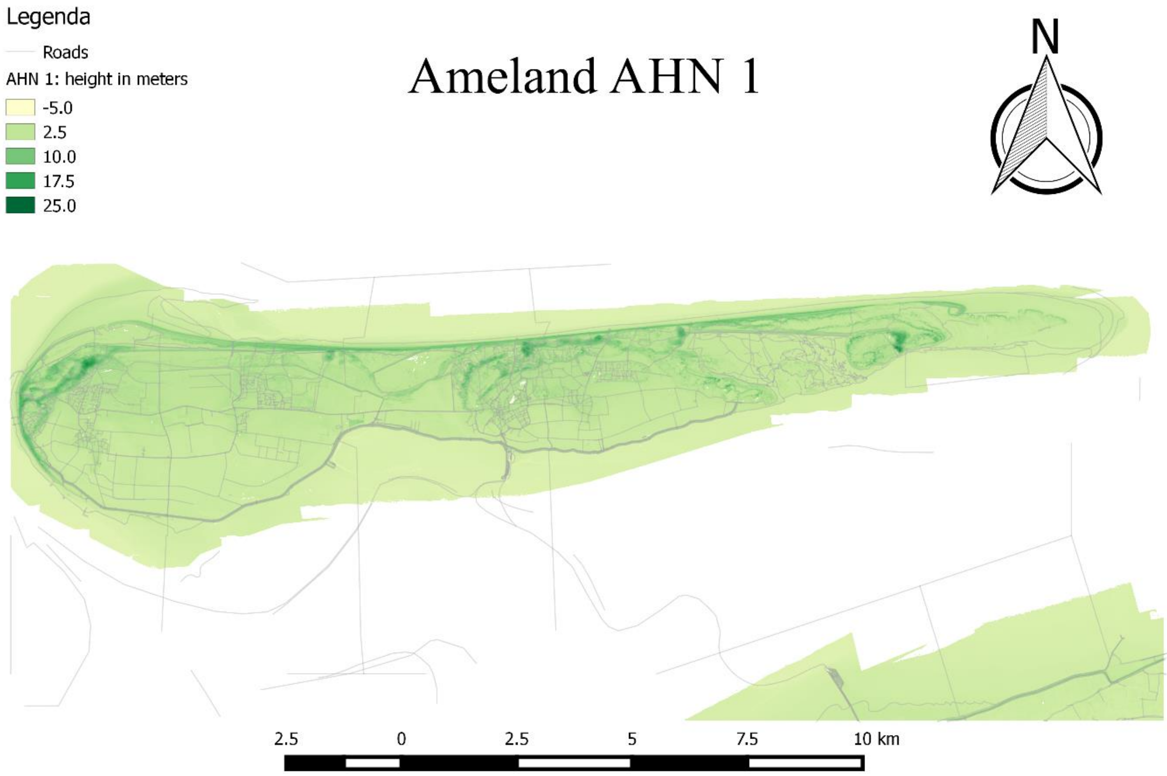

Figure 114 AHN 1 visualized in QGIS

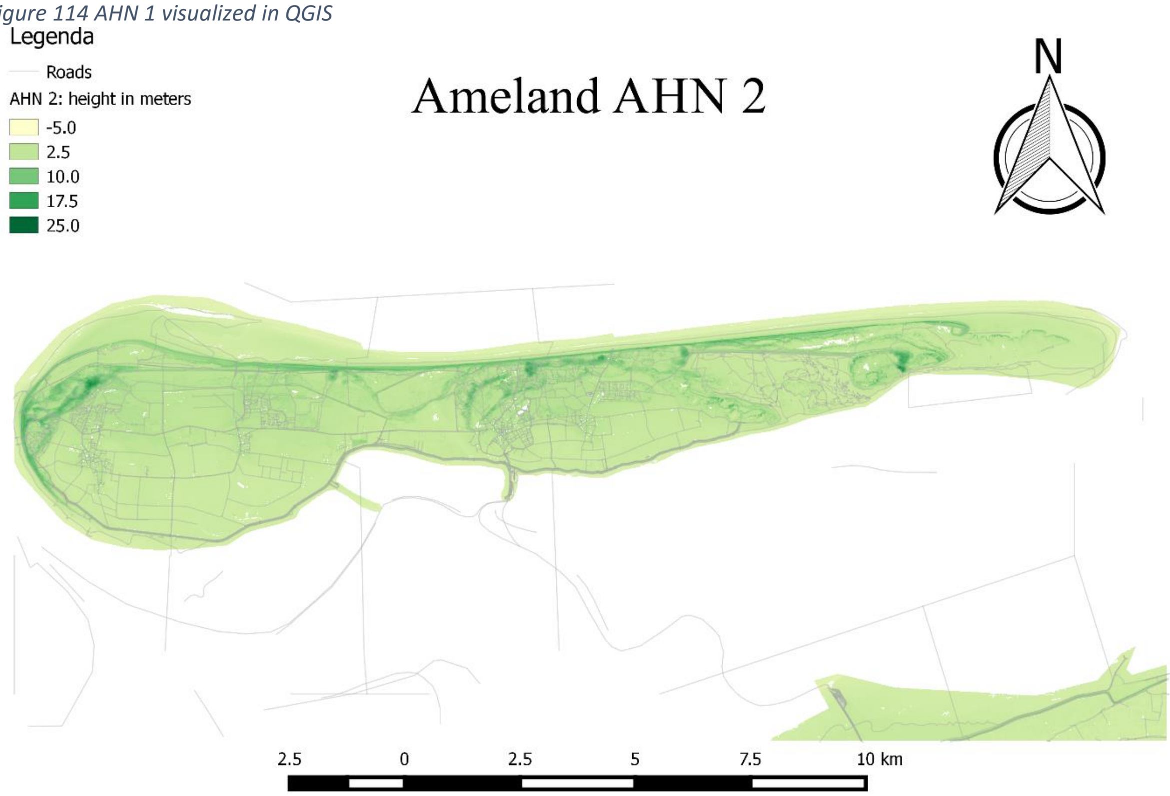

Figure 115 AHN 2 visualized in QGIS

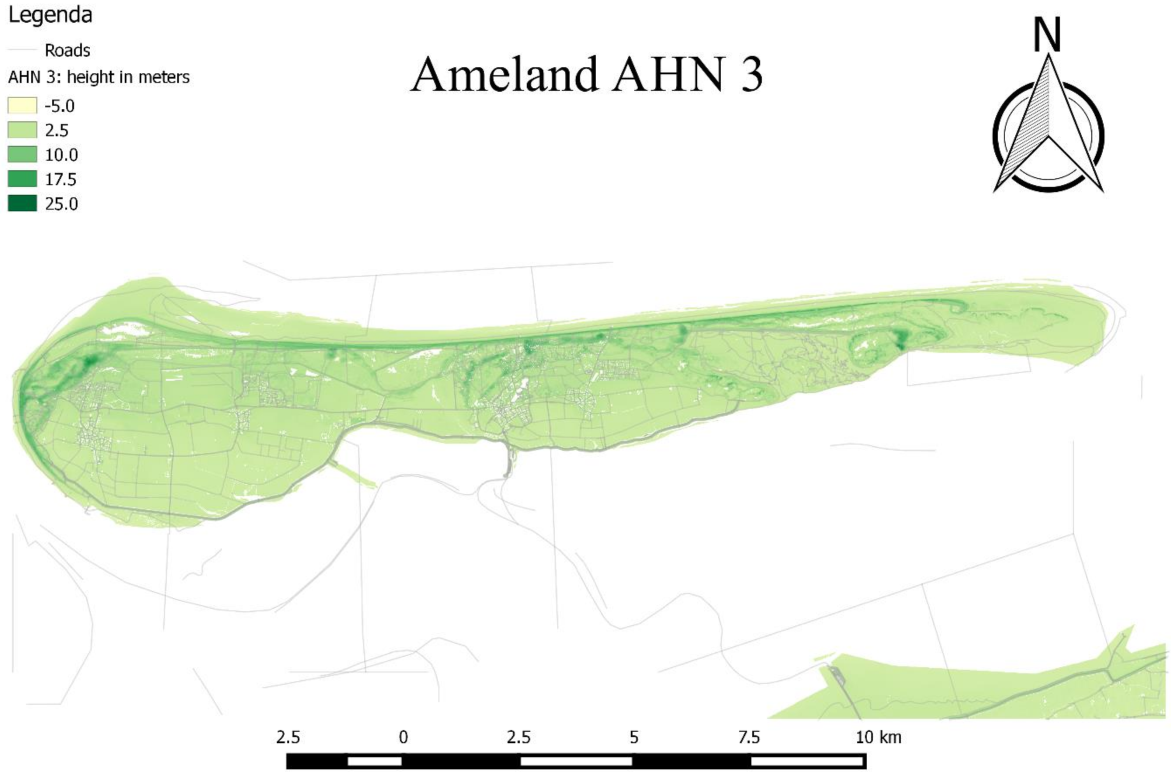

Figure 116 AHN 3 visualized in QGIS

Appendix B

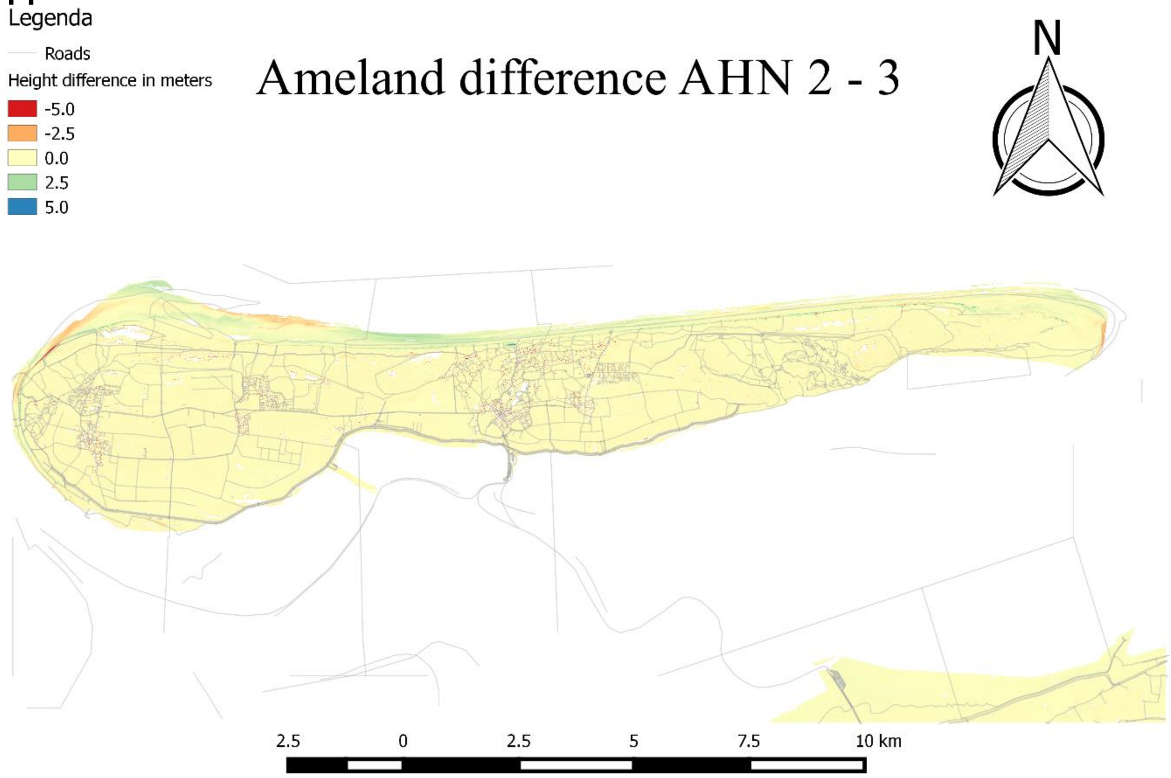

Figure 117 Comparing AHN 2 and 3 with boundaries on -5 and 5 meters

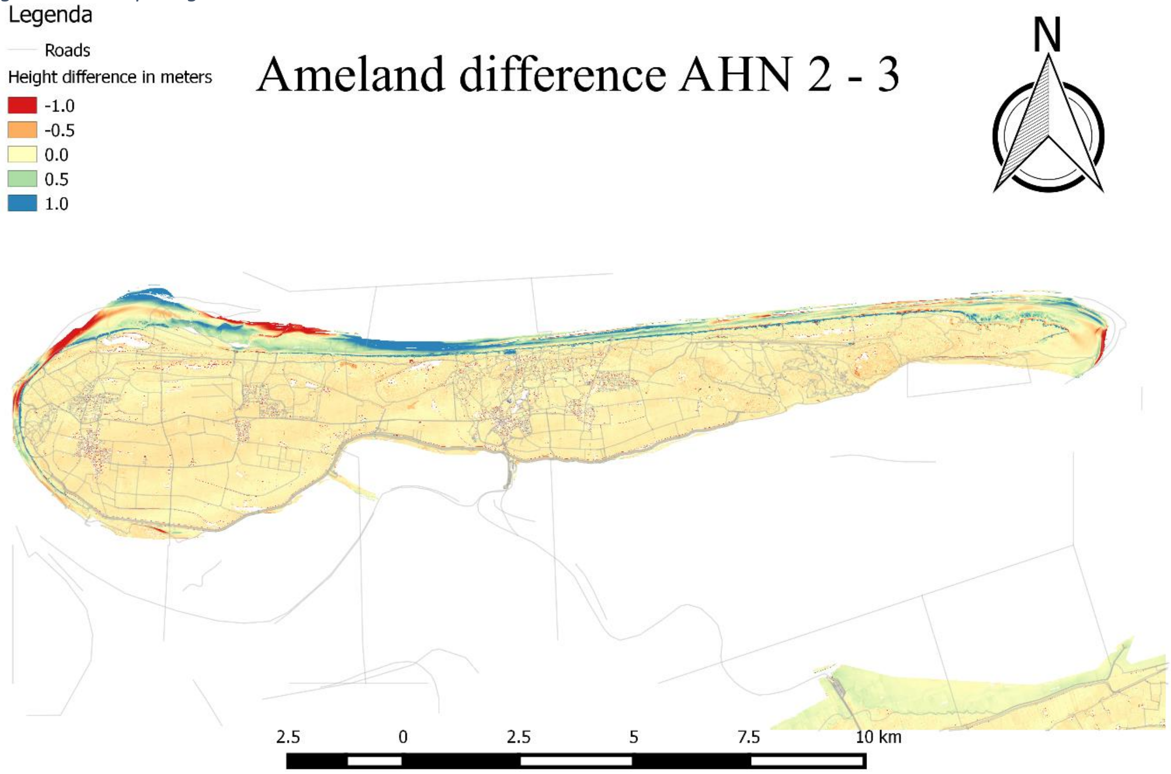

Figure 118 Comparing AHN 2 and 3 with boundaries on -1 and 1 meter

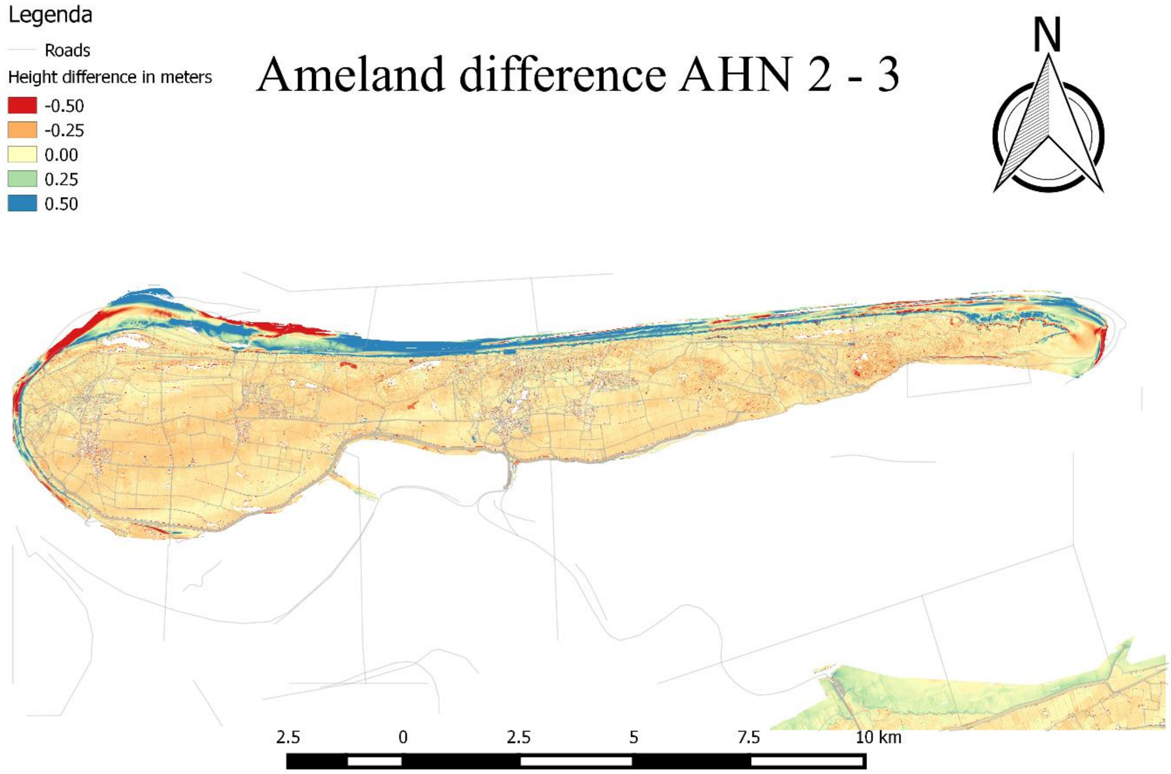

Figure 119 Comparing AHN 2 and 3 with boundaries on -0.5 and 0.5 meter

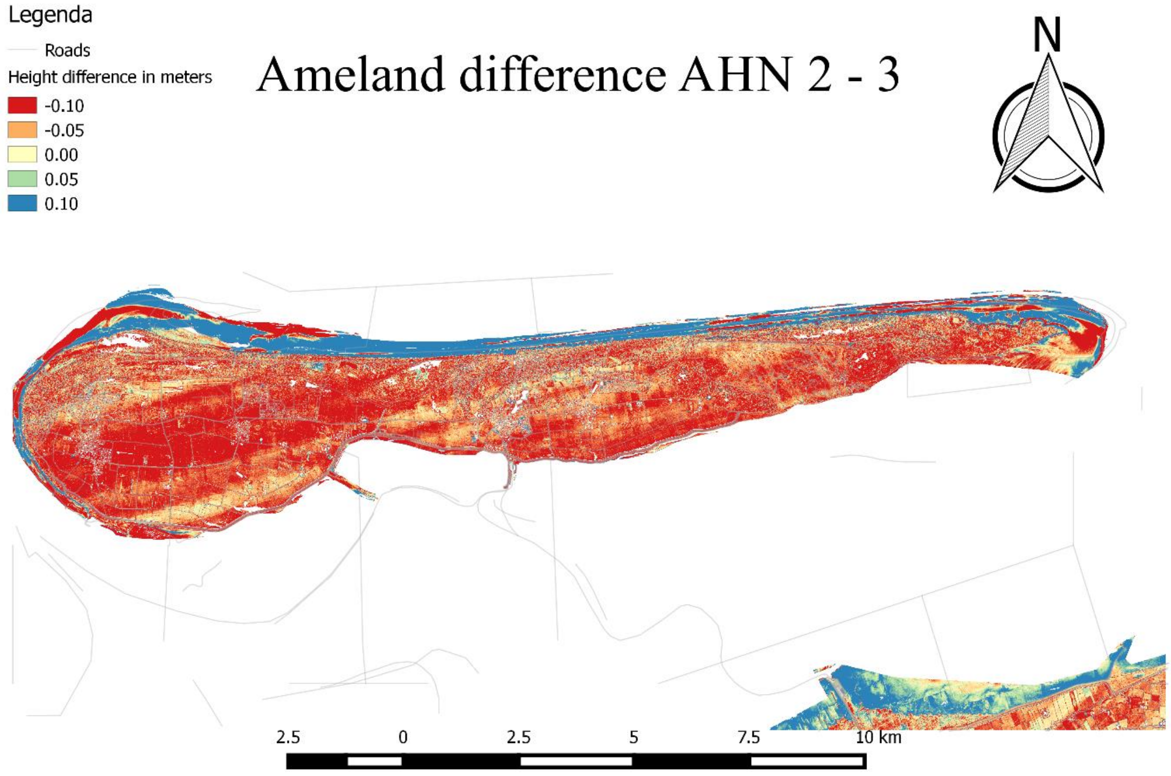

Figure 120 Comparing AHN 2 and 3 with boundaries on -0.1 and 0.1 meter

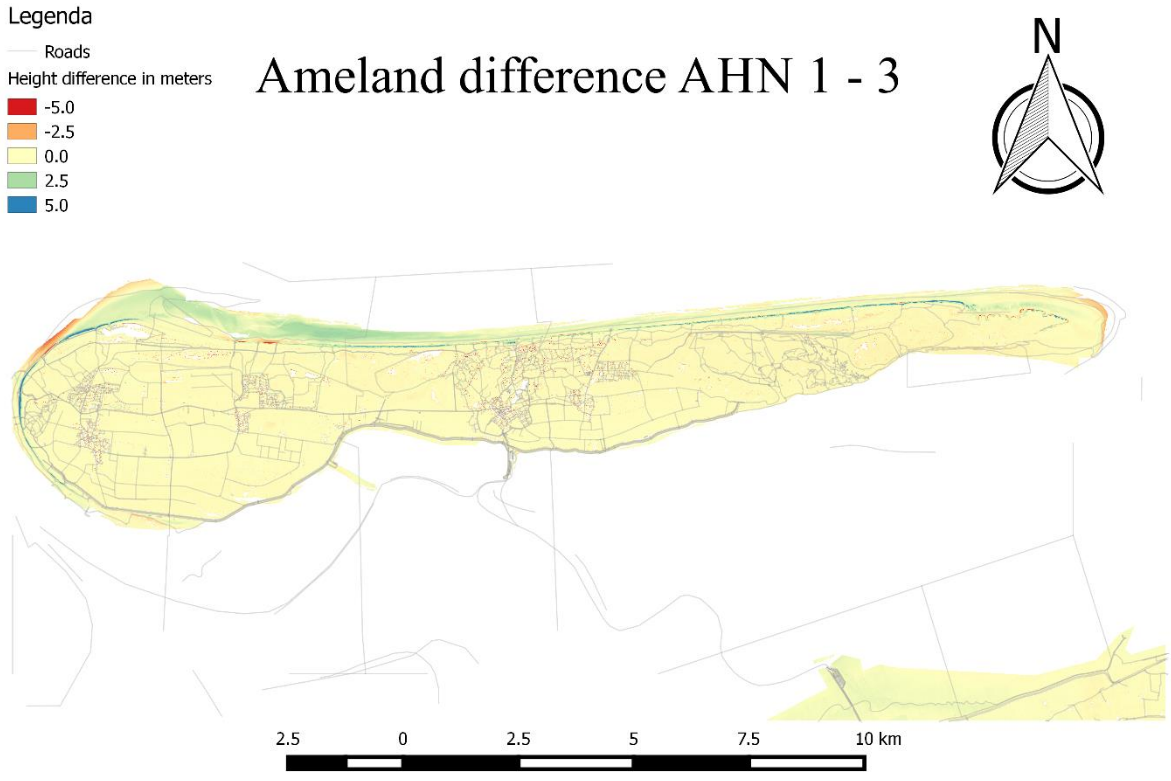

Figure 121 Comparing AHN 1 and 3 with boundaries on -5 and 5 meters

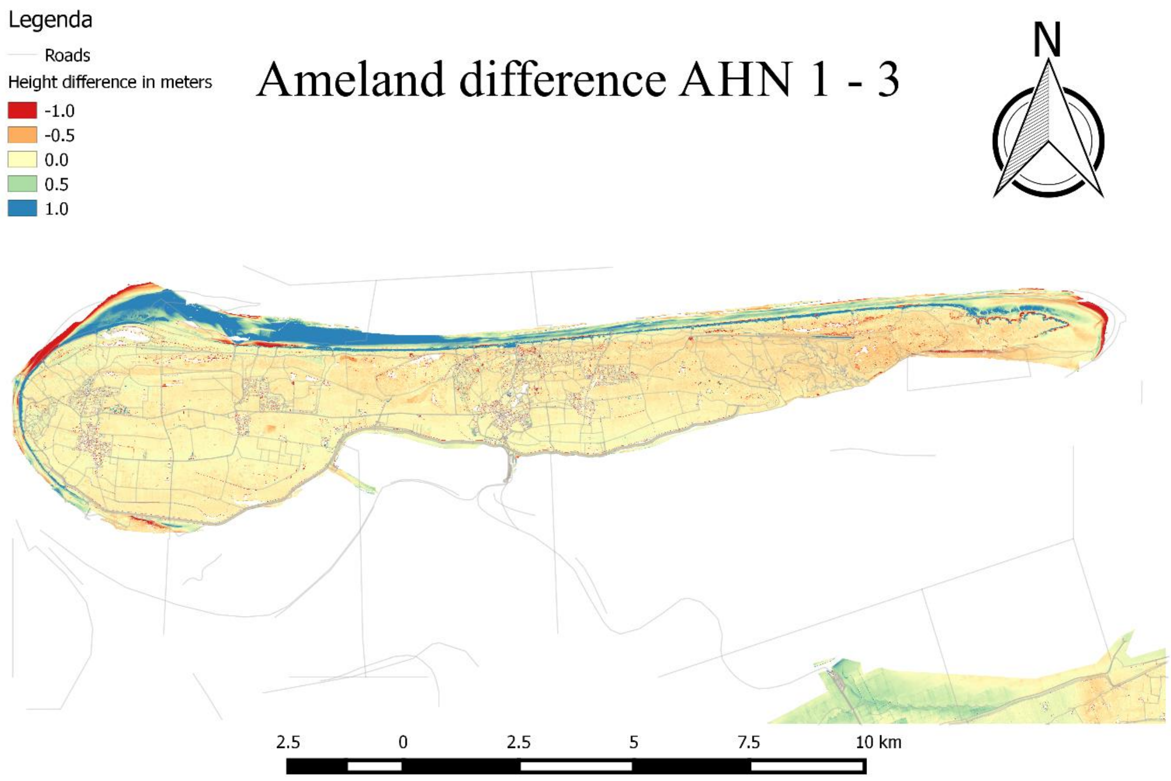

Figure 122 Comparing AHN 1 and 3 with boundaries on -1 and 1 meter

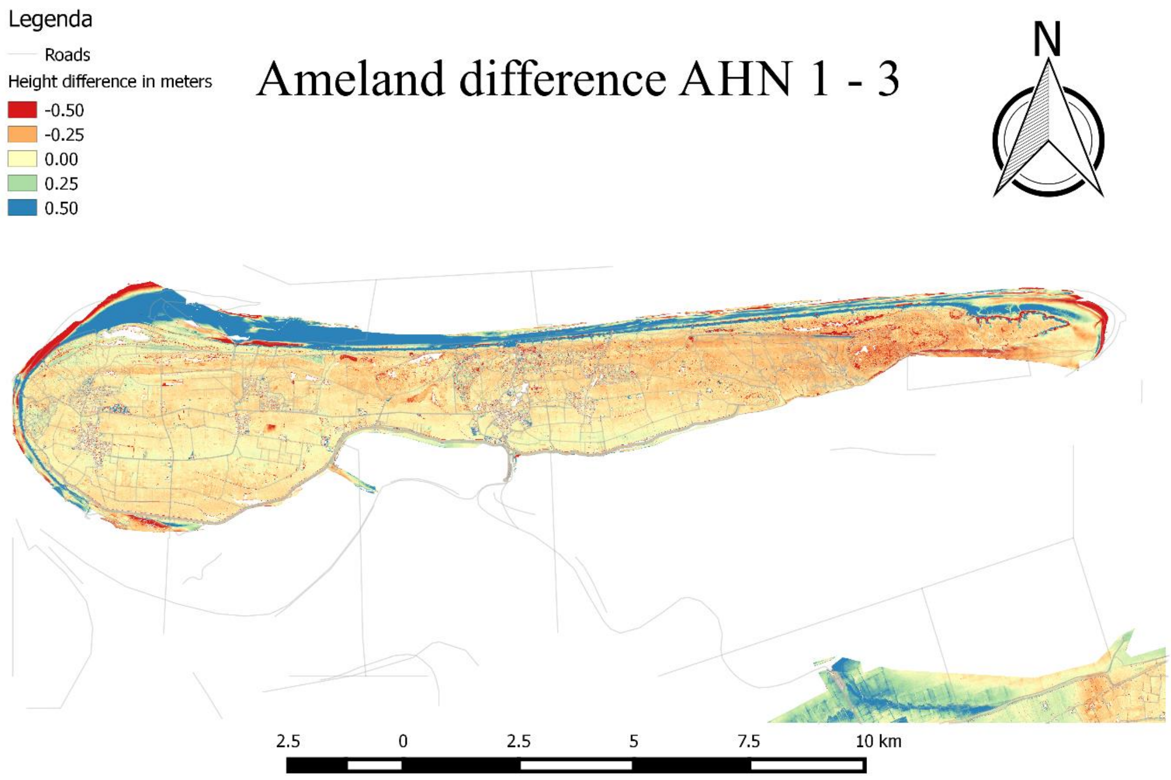

Figure 123 Comparing AHN 1 and 3 with boundaries on -0.5 and 0.5 meter

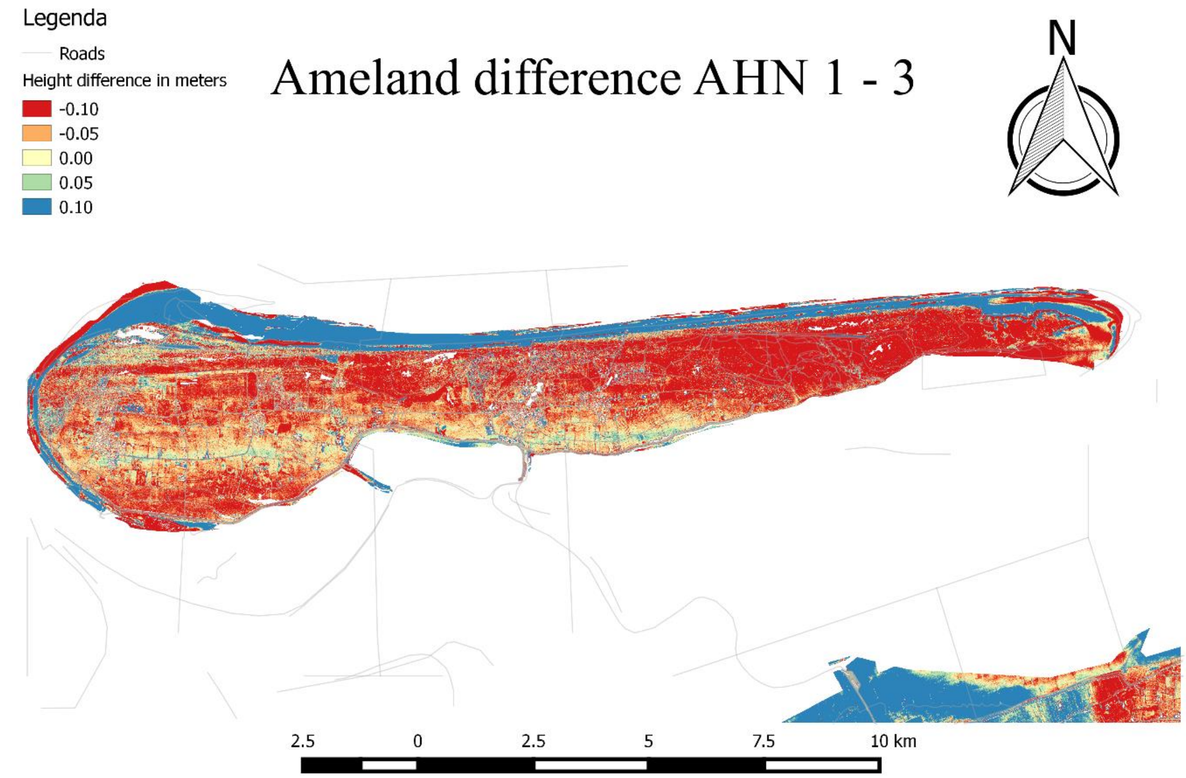

Figure 124 Comparing AHN 1 and 3 with boundaries on -0.1 and 0.1 meter

Appendix C

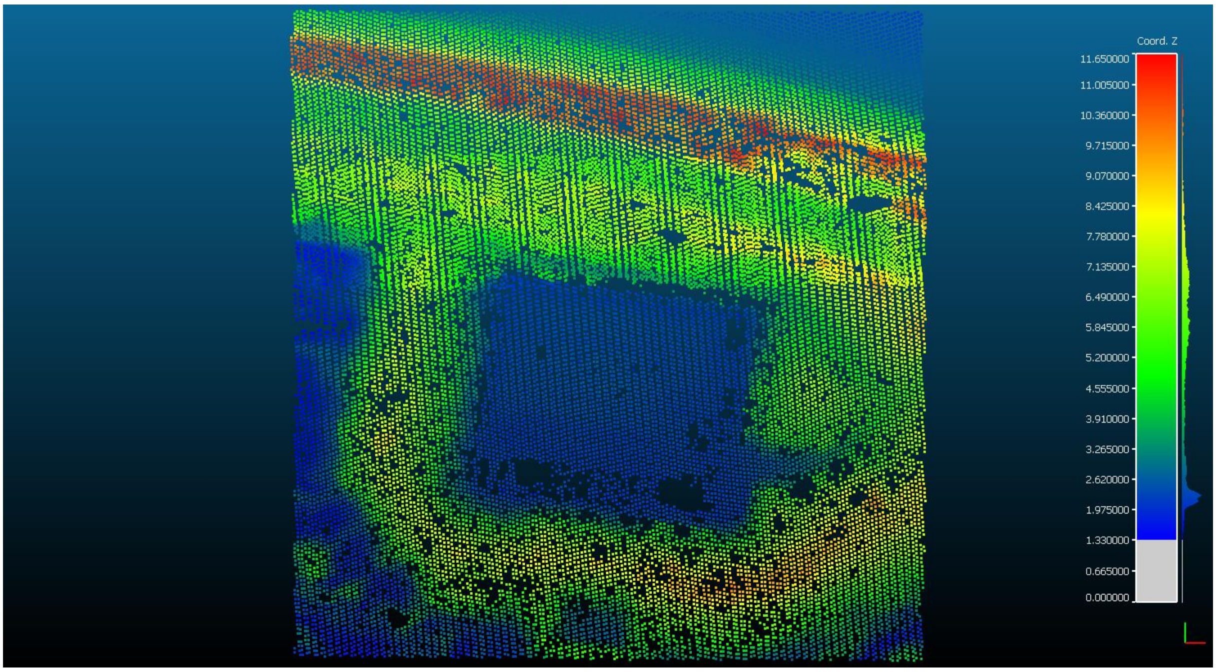

Figure 125 Point cloud of AHN 1 on region 1

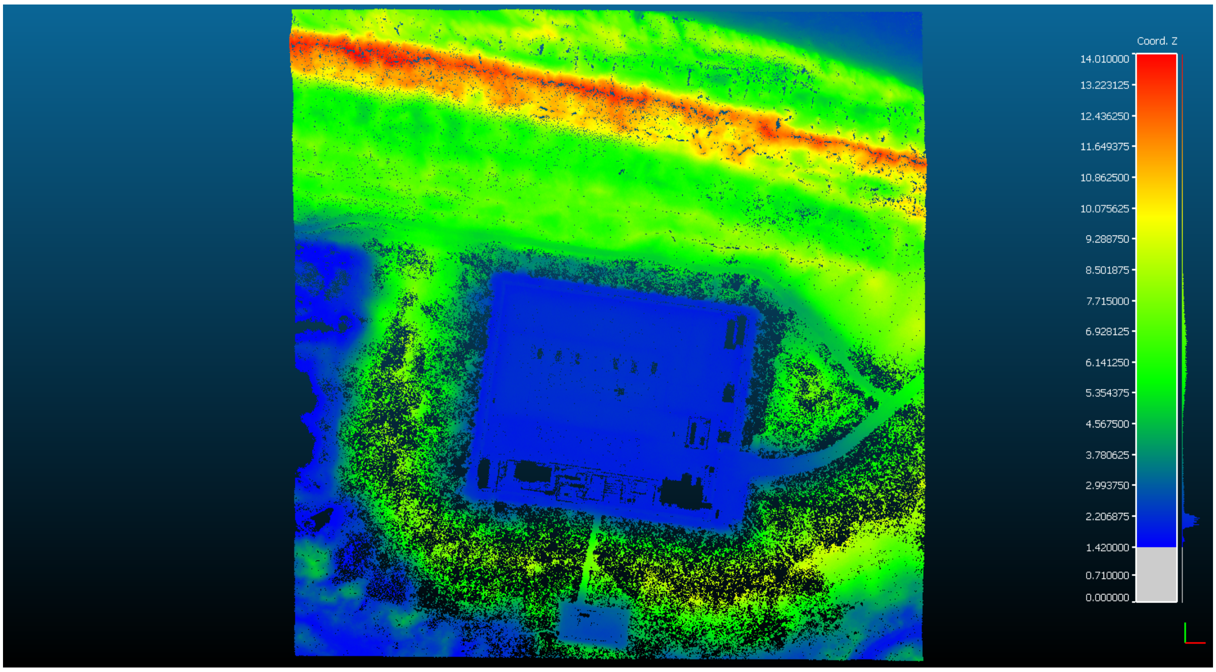

Figure 1262 Point cloud of AHN 2 on region 1

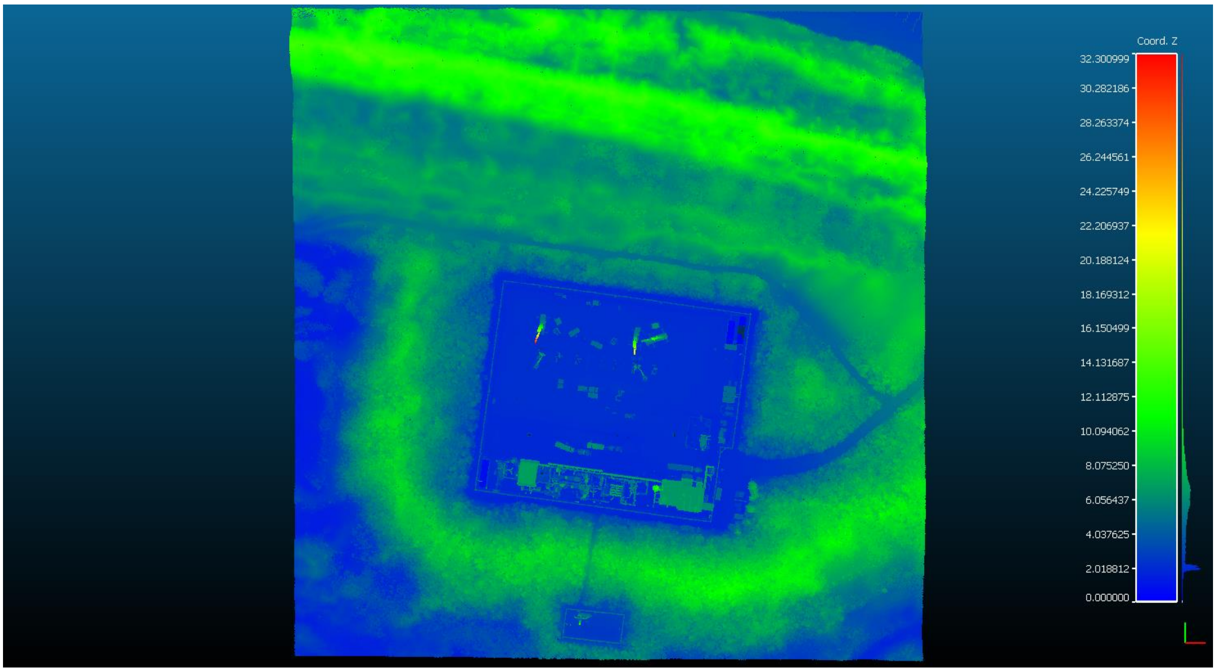

Figure 127 Point cloud of AHN 3 on region 1

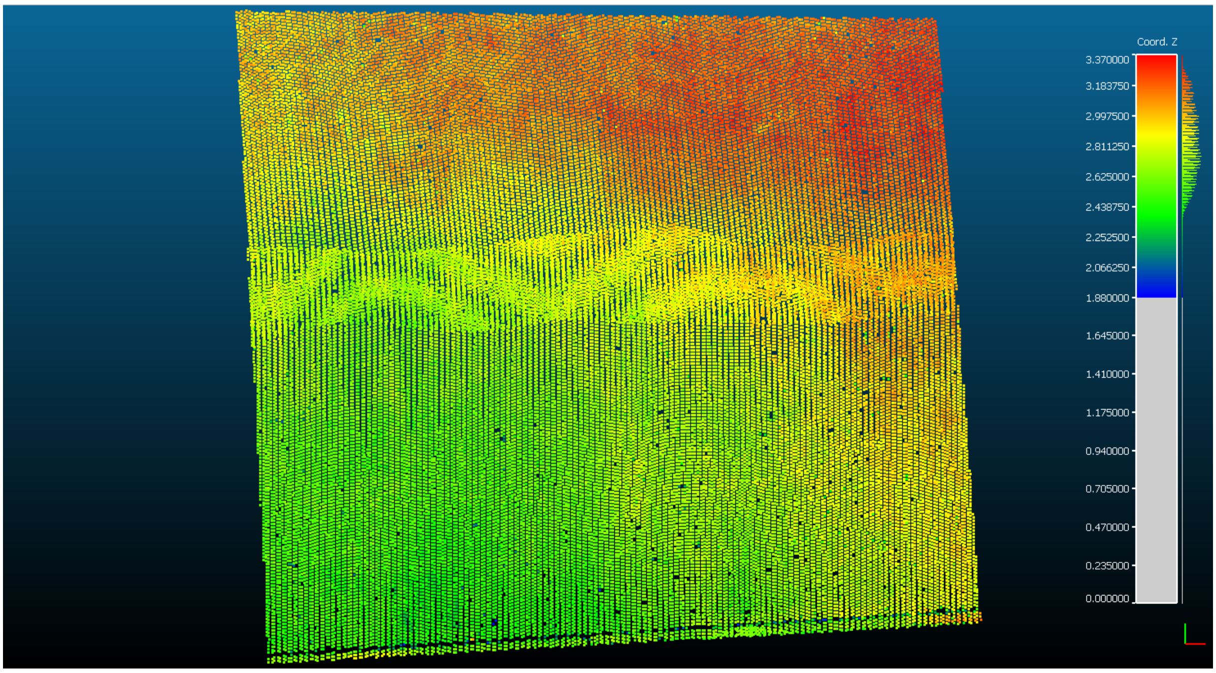

Figure 128 Point cloud of AHN 1 on region 3

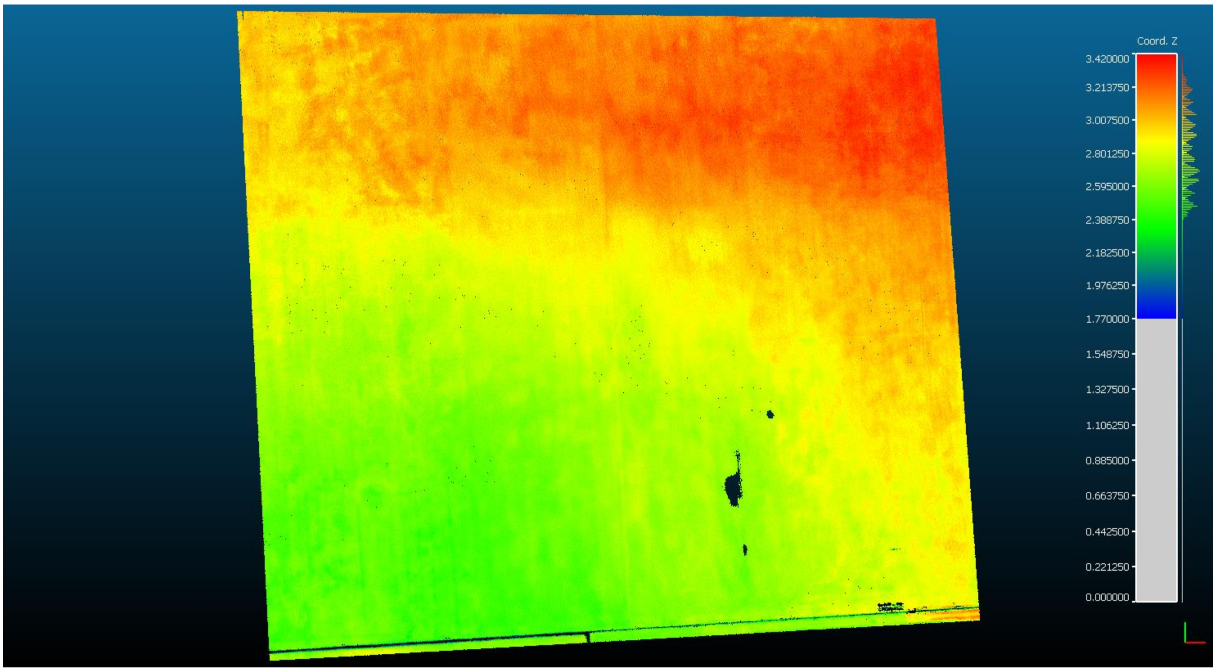

Figure 129 Point cloud of AHN 2 on region 3

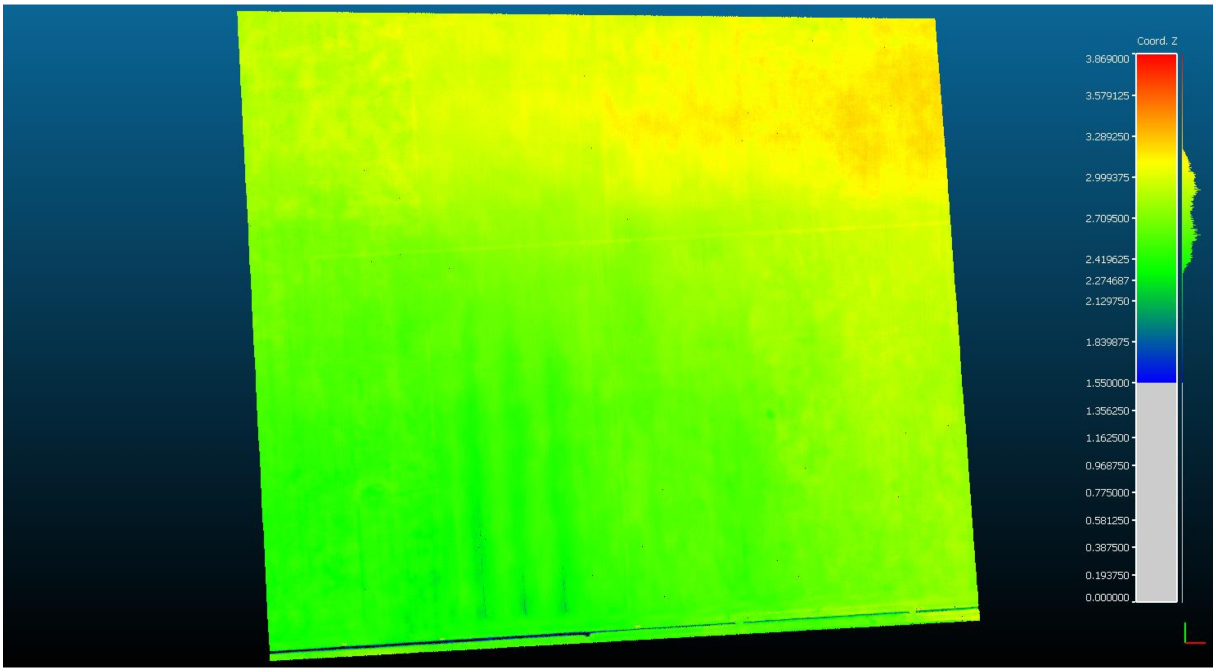

Figure 130 Point cloud of AHN 3 on region 3

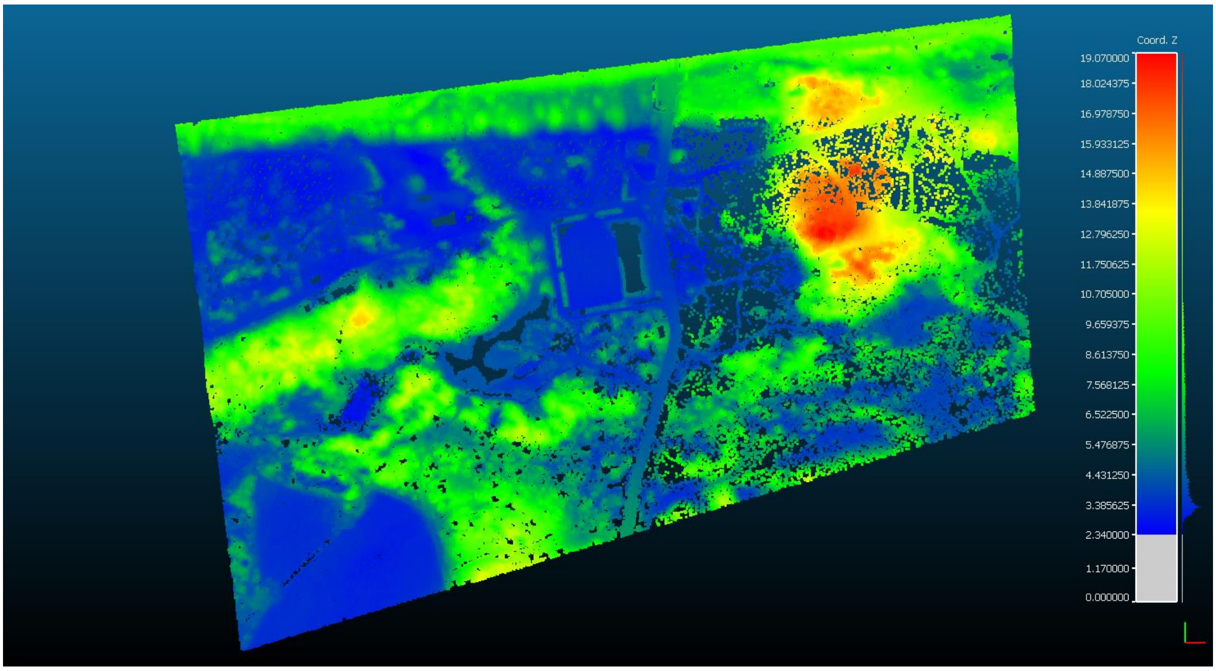

Figure 131 Point cloud of AHN 1 on region 4

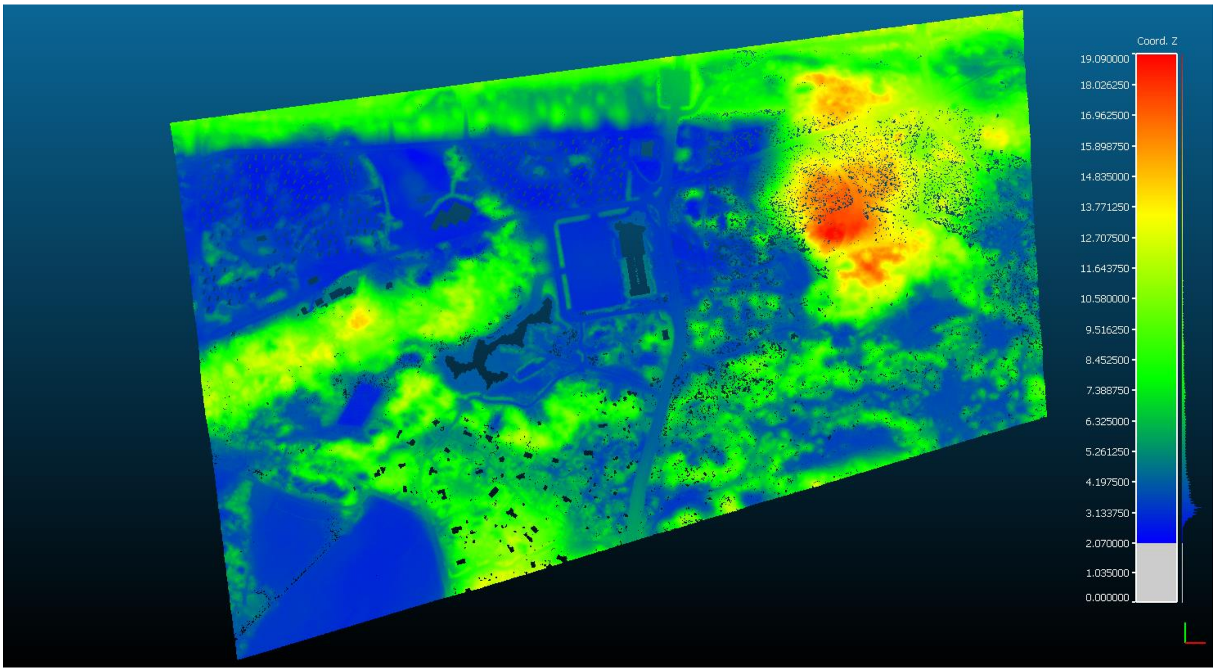

Figure 132 Point cloud of AHN 2 on region 4

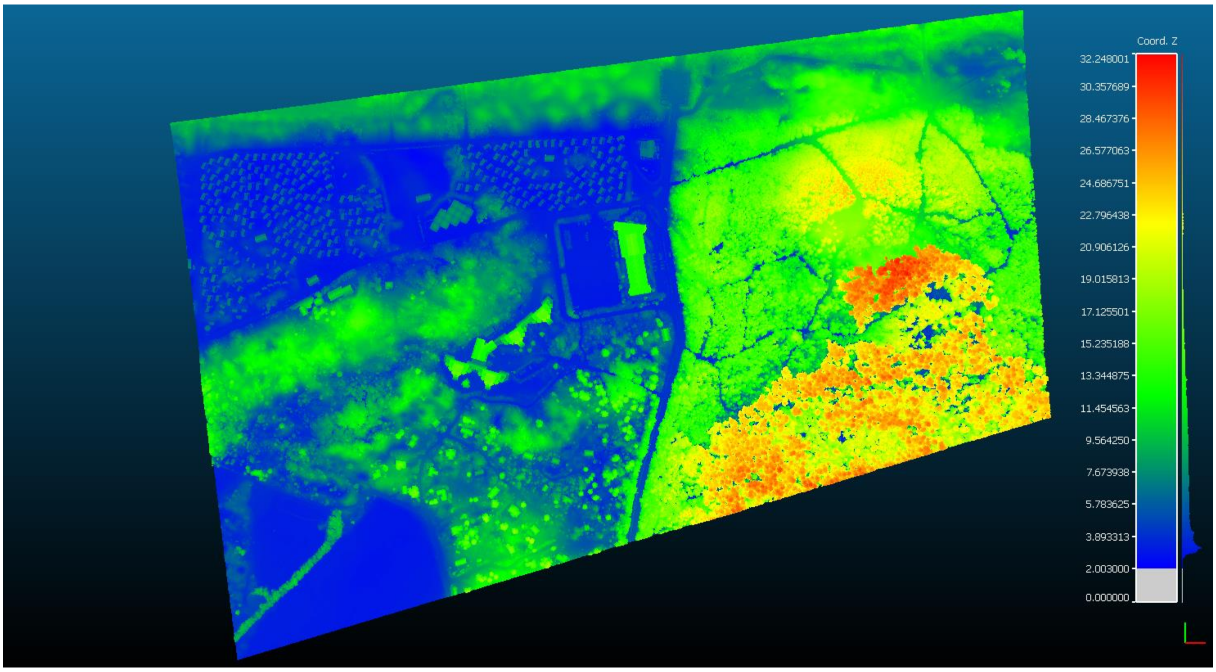

Figure 133 Point cloud of AHN 3 on region 4

Appendix D

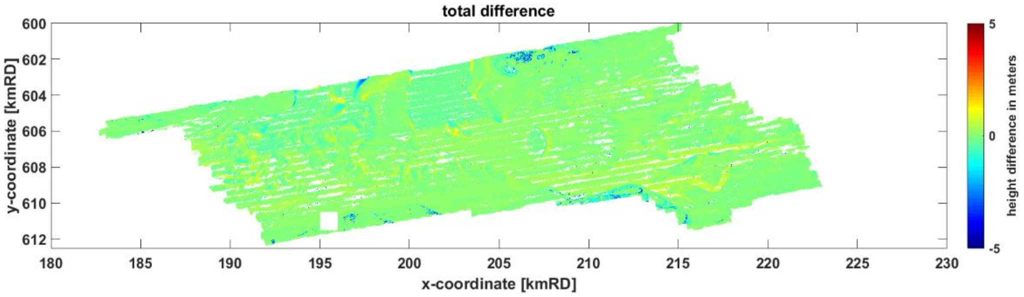

Figure 134 Height difference Spring 2010 and Autumn 2014 with boundaries on -5 and 5 meters

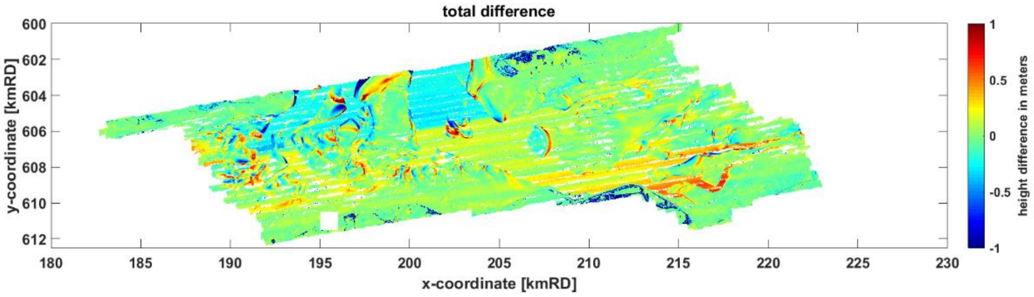

Figure 135 Height difference Spring 2010 and Autumn 2014 with boundaries on -1 and 1 meter

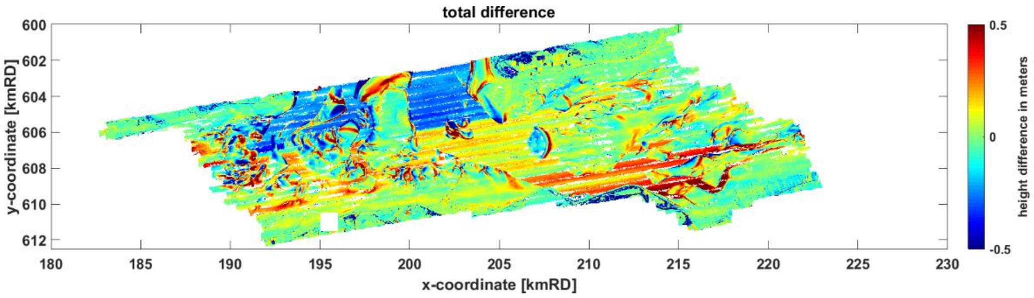

Figure 136 Height difference Spring 2010 and Autumn 2014 with boundaries on -0.5 and 0.5 meter

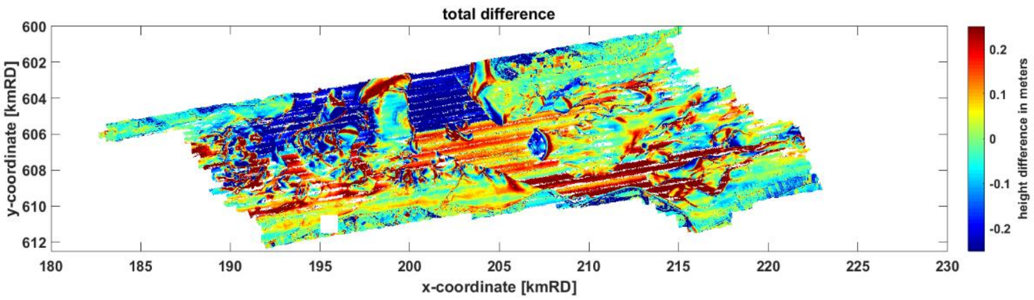

Figure 137 Height difference Spring 2010 and Autumn 2014 with boundaries on -0.25 and 0.25 meter

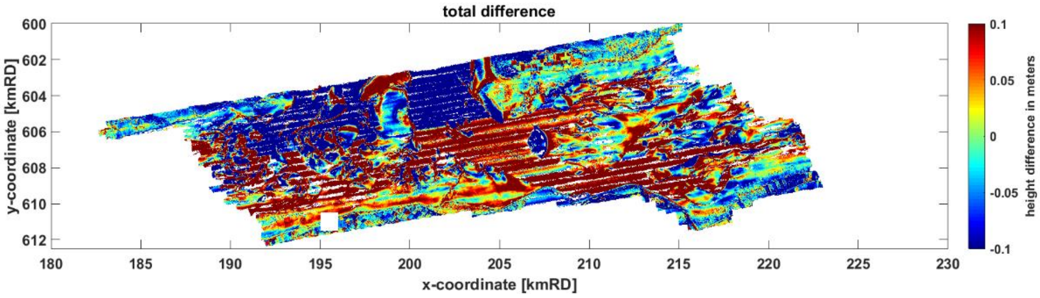

Figure 138 Height difference Spring 2010 and Autumn 2014 with boundaries on -0.1 and 0.1 meter

Appendix E

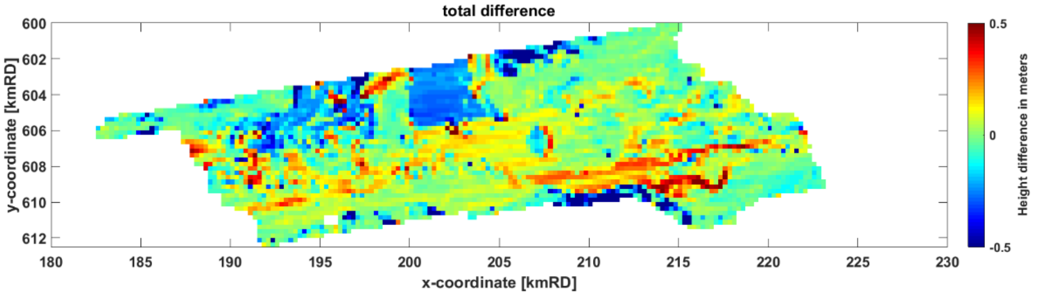

Figure 139 Simplified 25 x 25 data of comparison between Spring 2010 and Autumn 2014

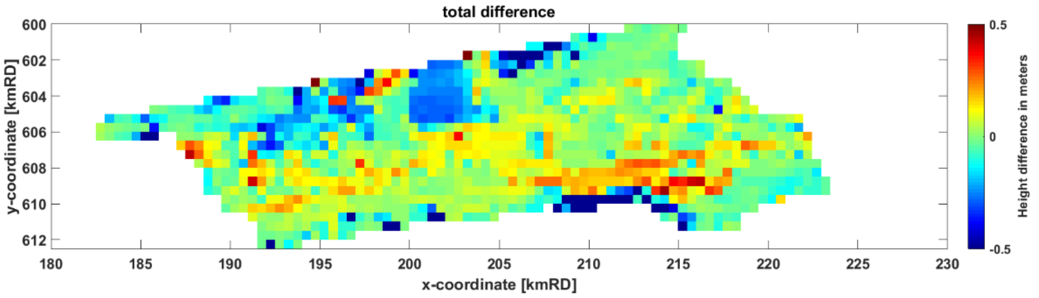

Figure 140 Simplified 50 x 50 data of comparison between Spring 2010 and Autumn 2014

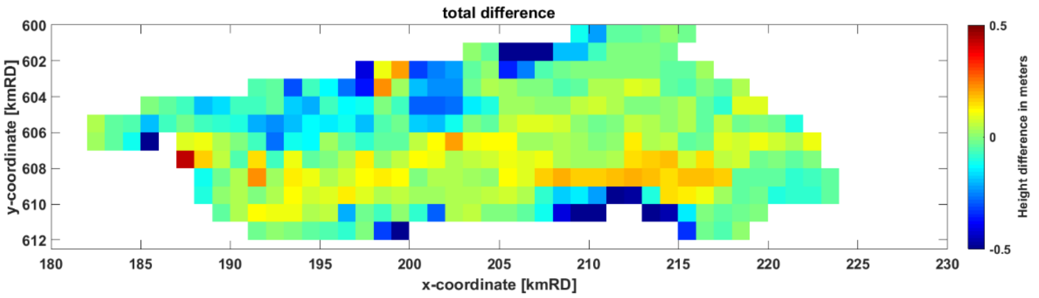

Figure 141 Simplified 100 x 100 data of comparison between Spring 2010 and Autumn 2014

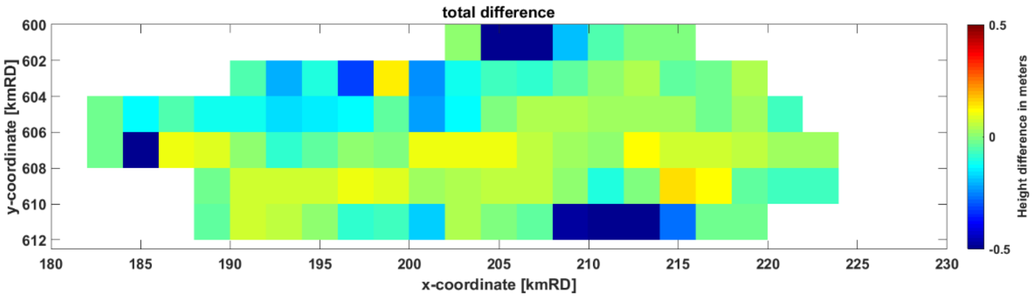

Figure 142 Simplified 200 x 200 data of comparison between Spring 2010 and Autumn 2014

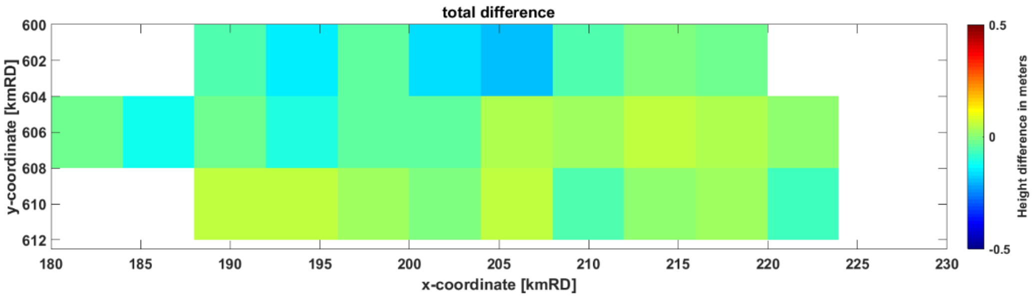

Figure 143 Simplified 400 x 400 data of comparison between Spring 2010 and Autumn 2014

Appendix F

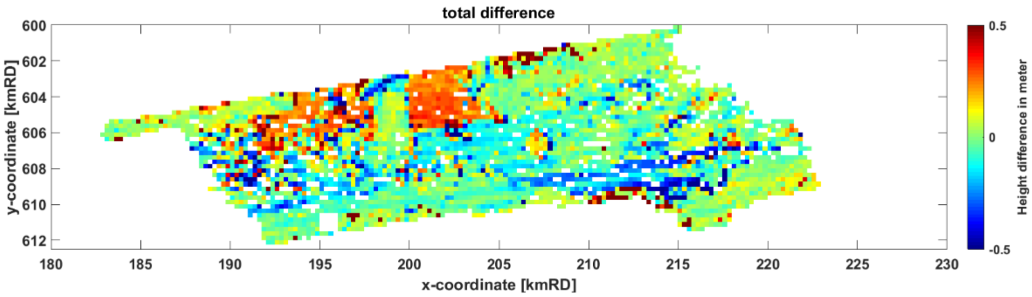

Figure 144 Simplified 25 x 25 data of comparison between Spring 2010 and Autumn 2014

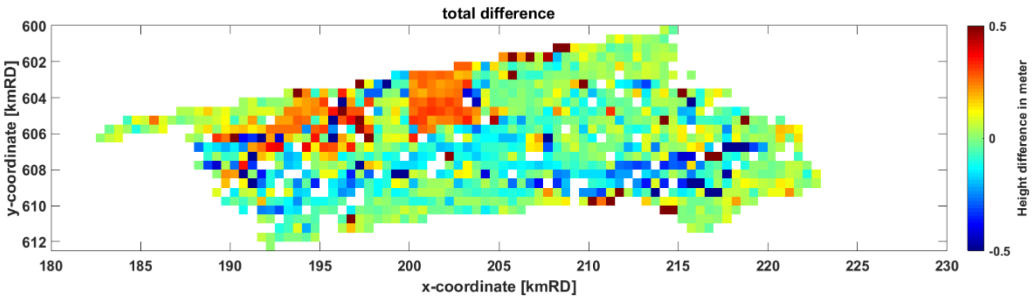

Figure 145 Simplified 50 x 50 data of comparison between Spring 2010 and Autumn 2014

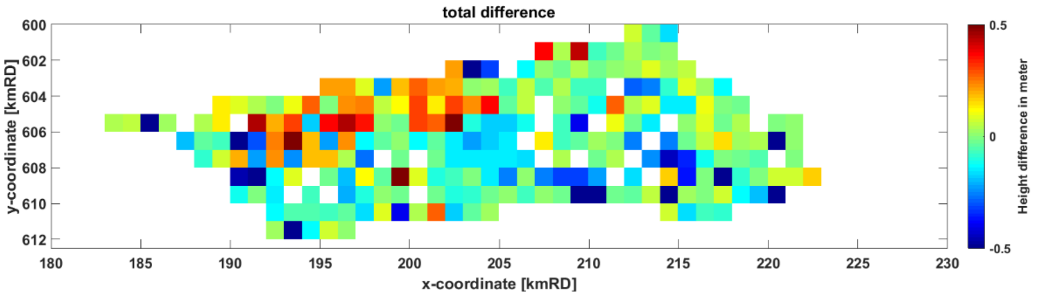

Figure 146 Simplified 100 x 100 data of comparison between Spring 2010 and Autumn 2014

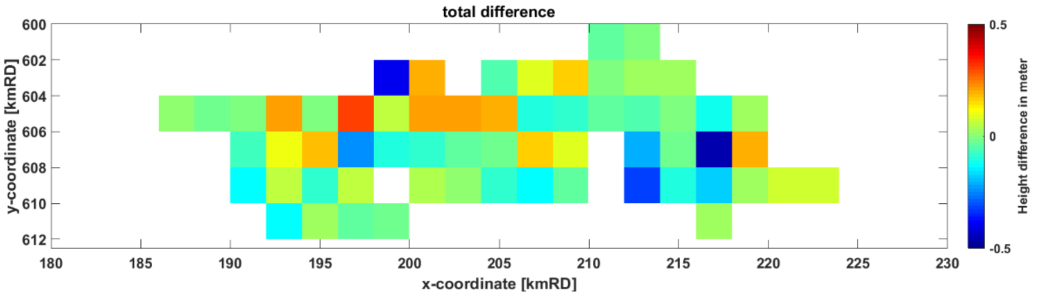

Figure 147 Simplified 200 x 200 data of comparison between Spring 2010 and Autumn 2014

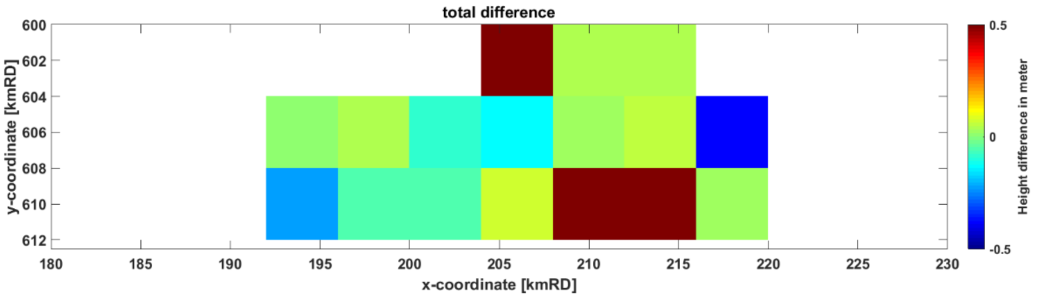

Figure 148 Simplified 400 x 400 data of comparison between Spring 2010 and Autumn 2014

Appendix G

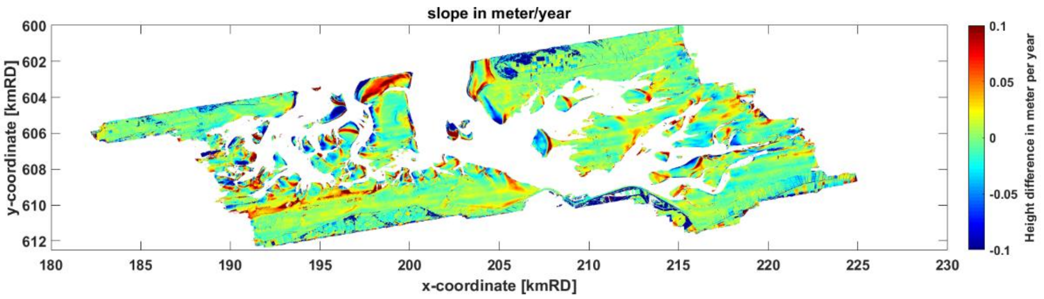

Figure 149 Slope in meter per year calculated by least squares method with boundaries on -0.1 and 0.1 meter per year

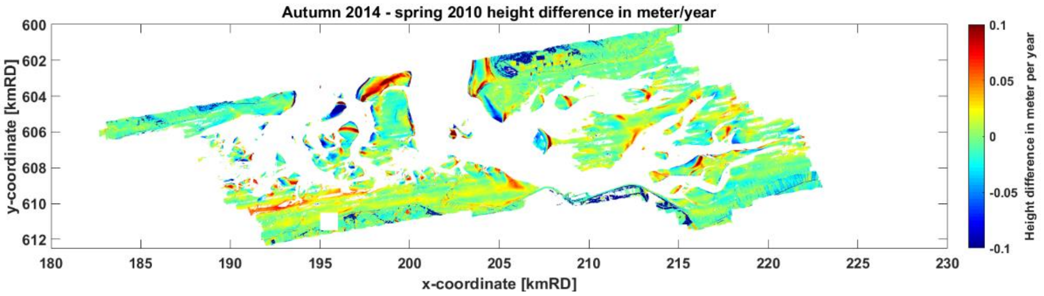

Figure 150 Height difference between Spring 2010 and Autumn 2014 in meter per year with boundaries on -0.1 and 0.1 meter per year

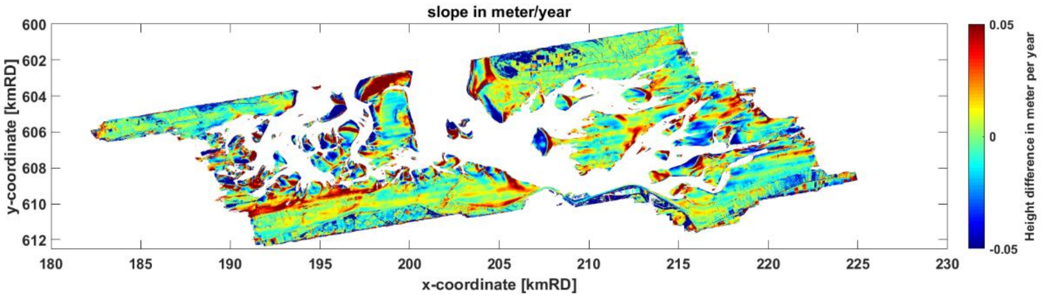

Figure 151 Slope in meter per year calculated by least squares method with boundaries on -0.05 and 0.05 meter per year

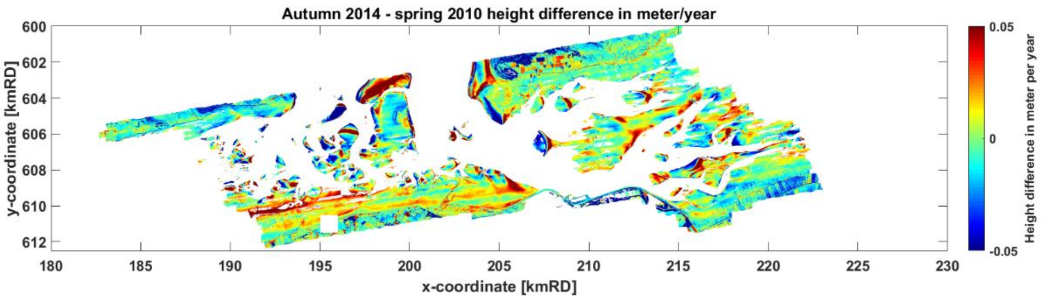

Figure 152 Height difference between Spring 2010 and Autumn 2014 in meter per year with boundaries on -0.05 and 0.05 meter per year

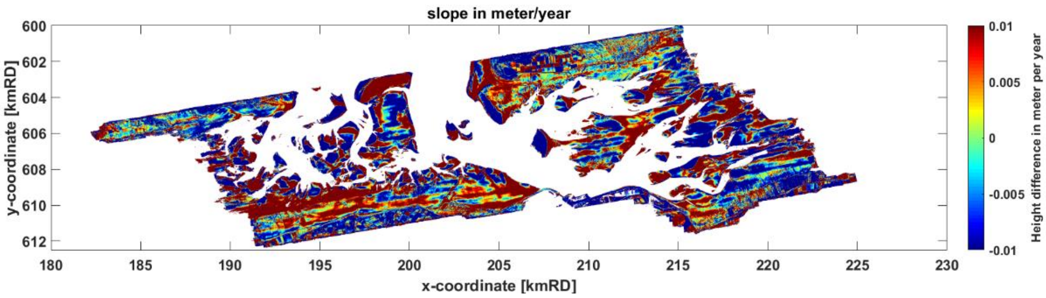

Figure 153 Slope in meter per year calculated by least squares method with boundaries on -0.01 and 0.01 meter per year

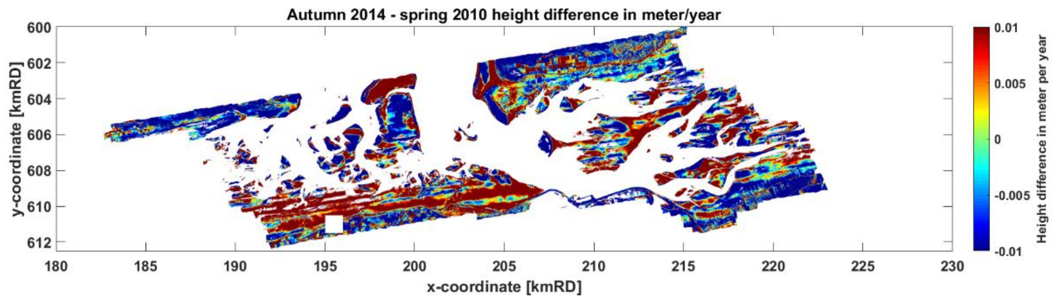

Figure 154 Height difference between Spring 2010 and Autumn 2014 in meter per year with boundaries on -0.01 and 0.01 meter per year

Appendix H

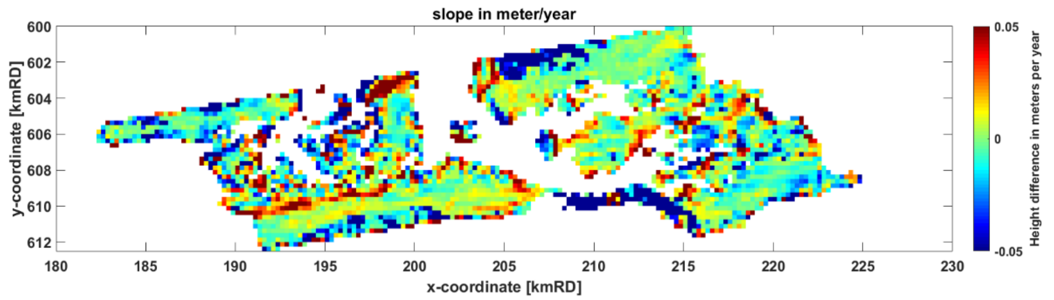

Figure 155 Simplified 25x25 version of least squares solution with method 1

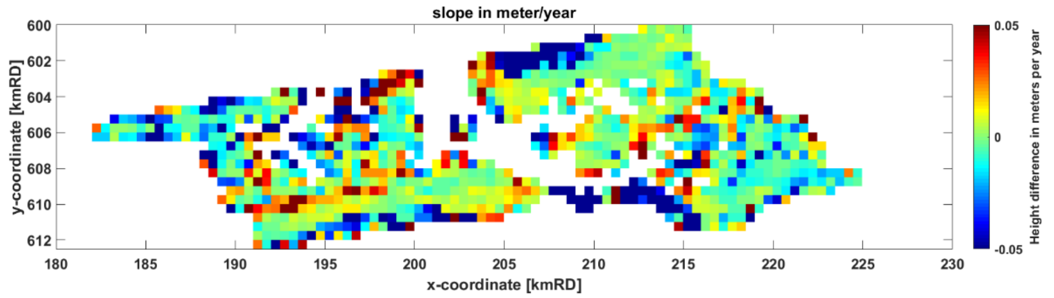

Figure 156 Simplified 50x50 version of least squares solution with method 1

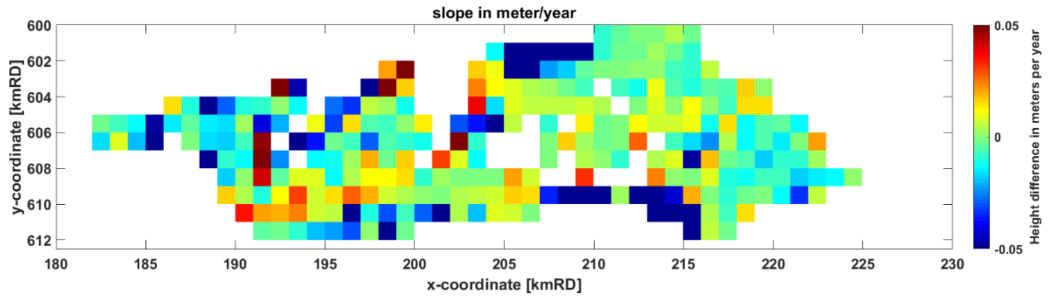

Figure 157 Simplified 100x100 version of least squares solution with method 1

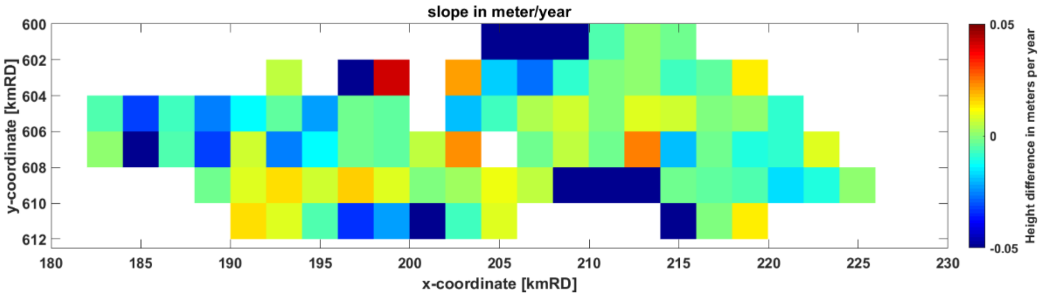

Figure 158 Simplified 200x200 version of least squares solution with method 1

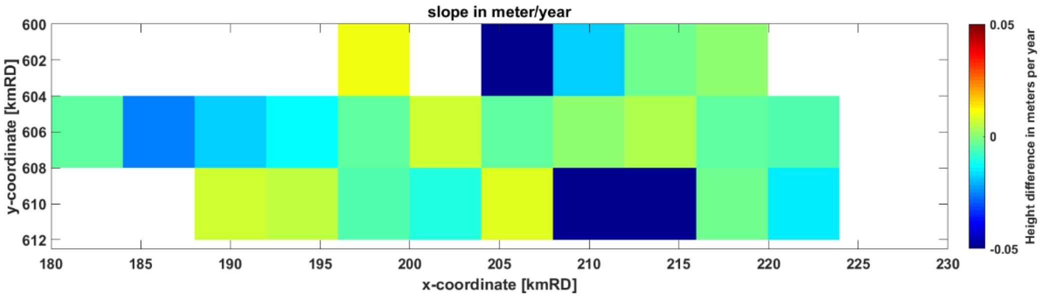

Figure 159 Simplified 400x400 version of least squares solution with method 1

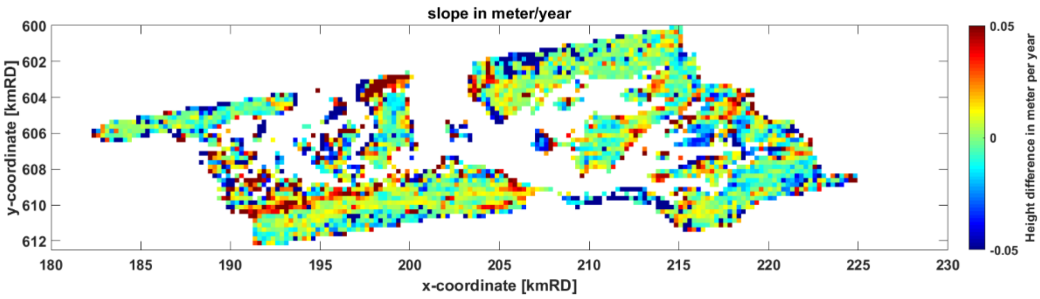

Figure 160 Simplified 25x25 version of least squares solution with method 2

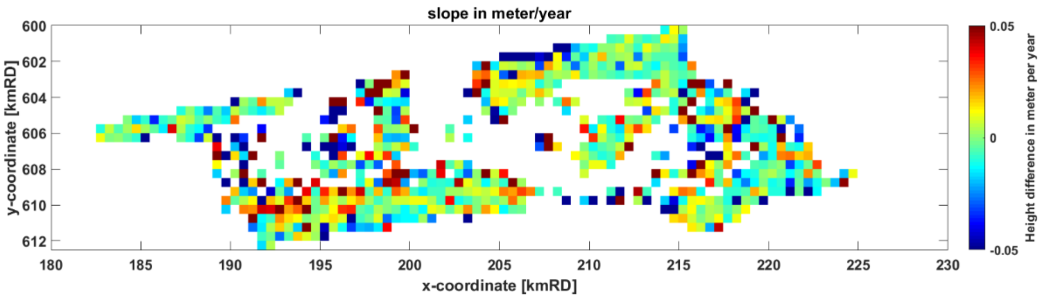

Figure 161 Simplified 50x50 version of least squares solution with method 2

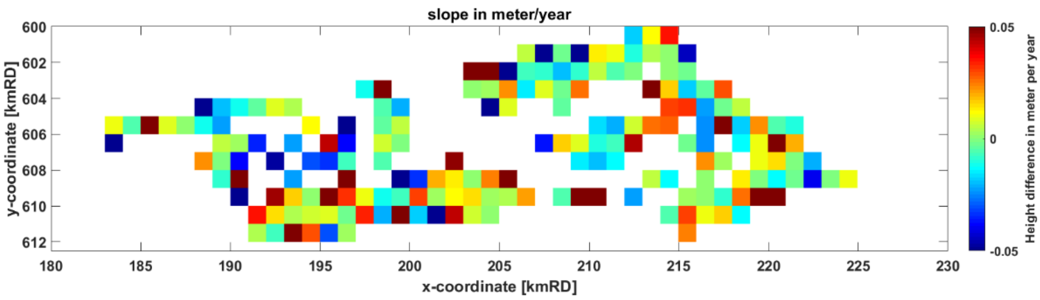

Figure 162 Simplified 100x100 version of least squares solution with method 2

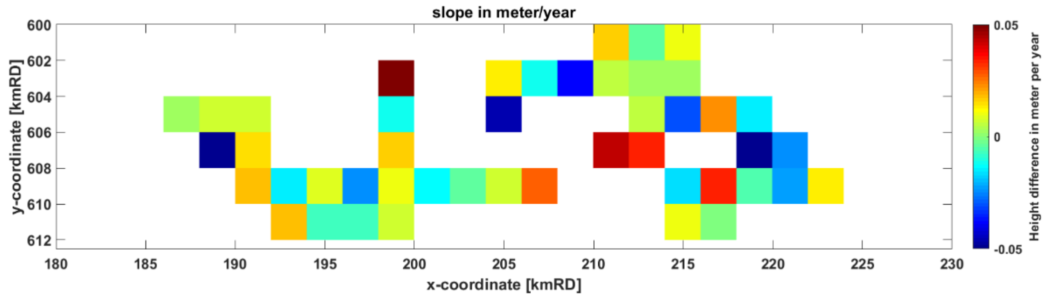

Figure 163 Simplified 200x200 version of least squares solution with method 2

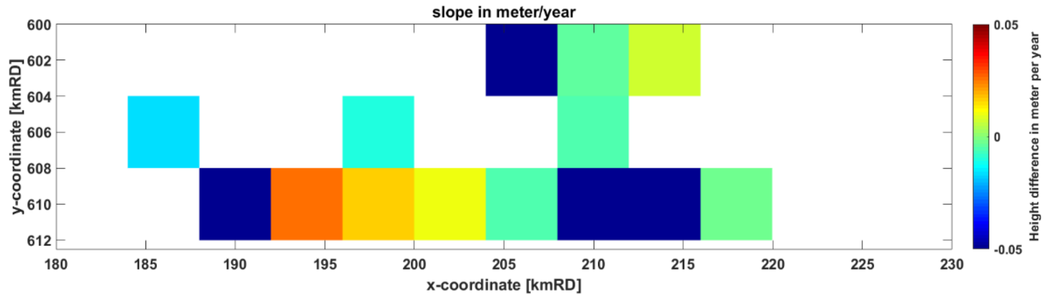

Figure 164 Simplified 400x400 version of least squares solution with method 2