Dike deformation near Eemshaven and Delfzijl measured with satellite radar interferometry

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***Abstract*—It is observed from satellite radar measurements that the dike between Eemshaven and Delfzijl in the north of the Netherlands shows instability. It can be possible that a development of these instability results in dike failure. The two possible failure mechanisms that may occur are settlement and slope-instability. In this research the displacements for different cross sections of the dike were calculated. By analysing the size and the direction of the displacements it is concluded that the dike shows over a length of approximately 110 meters some first indications for the failure mechanism slope-instability. When slope-instability may indeed occur in the future, a slice of soil will slide aside and the dike will fail. This can cause humanitarian and economic consequences. It is therefore necessary to inform the Waterschap Noorderzijlvest who are responsible for the maintenance to the dike.**

I. Introduction

In the north of the Netherlands between Eemshaven and Delfzijl, an 11.7 kilometers long dike is situated [1]. From satellite radar measurements, it is observed that the dike, over a distance of approximately 110 meters, shows instability. The satellite measurements of the displacement are visible in Figure 1, where the red points represent the largest displacements, up to $\sim$11 mm/y. The green and yellow points are relatively stable. The displacements are measured with radar signals that are taken from September 2013 till June 2017 with the TerraSAR-X satellite. The measurements consist of two independent time series, since the satellite measures displacements from two different flying directions. One time it flies over the dike form the south Pole to the north Pole (the *ascending orbit*) and the other time is flies from the north Pole to the south Pole (the *descending orbit*) [2].

A. Relevance of the research

The observed instability of the dike segment may be interpreted as an early warning for the the *Waterschap Noorderzijlvest*, responsible for dike safety [3]. Assuming that several types of catastrophic dike failure may be preceded by the gradual build-up of stress in the dike's structure, the early detection of small deformations is invaluable information for dike safety assessments. Obviously, a dike failure, where the dike will lose its function of retaining water, will result in a flooded hinterland what can cause huge humanitarian and economic consequences. Behind the dike, households and a big power station are situated. To prevent a potential dike failure, a study into the dike deformation and its potential driving mechanisms is of high importance.

Knowledge about the measurement techniques should be obtained. Furthermore, it should be investigated if the measurements are meaningful and what can be concluded from these measurements. Also, dike failure mechanisms should be studied to say something about the potential dike failure. If necessary, the waterschap Noorderzijlvest should be informed so they can take actions to prevent further displacement and potential dike failure.

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B. Aim of the research

The aim of this research is to investigate whether the measured displacements give indications for a possible dike failure. And if the dike may fail, what is the potential dike failure mechanism. There are a few failure mechanisms for dikes. If it is the case that the deformation indications lead to dike failure, there are two failure mechanisms that are likely to occur for this specific dike. These failure mechanisms are *settlement* and *slope-instability*, as further explained in section II. The aim of the research is to find out which of the two failure mechanisms may possibly happen at the dike.

The main research question is: *Which failure mechanism, settlement or slope-instability, may occur at the dike near Eemshaven and Delfzijl?*

C. Research questions

To give an answer to the main research question the research is divided in sub questions. These questions are:

1) What are the possible failure mechanisms for dikes and which failure mechanisms could possibly take place in this situation?
2) How are the measurements of the displacement obtained?
3) How reliable are these measurements?
4) Is it possible to make a visualization of the dike deformation of the dike near Eemshaven and Delfzijl?
5) How may the displacement possibly develop in the future and should the *Waterschap Noorderzijlvest* be informed?

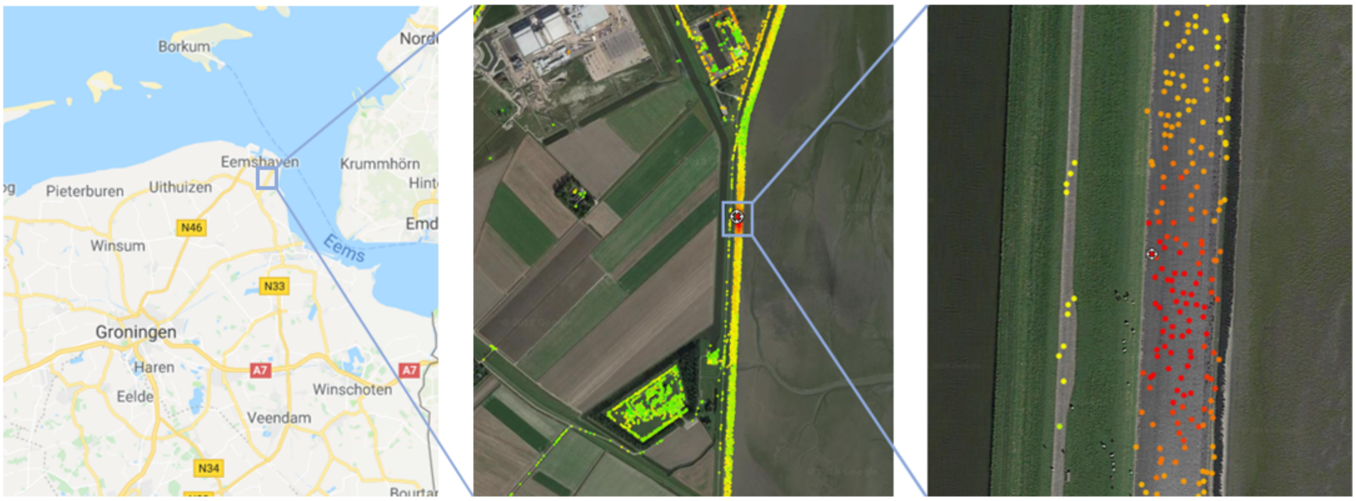

Fig. 1. Observed instability (deformation) of the dike between Eemshaven and Delfzijl, the Netherlands, indicated by red-colored measurement points. Red corresponds with ∼11 mm/y, while green is ∼0 mm/y in the line-of-sight to the satellites.

D. Research approach

First, knowledge about dike deformation is necessary. It should be investigated which displacements will be measured for different dike failure mechanisms to perform a prediction of which failure mechanisms may possibly occur in the future. Also, it should be known how these failure mechanisms develop in the future.

Further, some research on the measurement technique should be done. It must be investigated how the measurements are done and how the technique works. This is necessary to understand and interpret the data the correct way. As a result, better conclusions can be drawn. Also, it should be investigated if the results are meaningful.

When the possible failure mechanisms for the dikes and their characteristics are known and it is clear how the data of the deformation is obtained, the data can be analyzed. Afterwards, a statement may be made whether settlement or slope-instability may occur in the future. Dependent on the failure mechanism, it is perhaps necessary to inform the Waterschap Noorderzijlvest. If necessary, the Waterschap Noorderzijlvest should take action to prevent further dike failure.

II. Dike deformation

The displacement measurements of the radar satellites show that the outer slope of the dike is deforming over a length of approximately 110 meters, see Fig. 1. When these displacements continue they may result in dike failure and the dike will loses its function of retaining water. It is therefore necessary to investigate what may possibly happen with the dike. In this section, several failure mechanisms are considered and further investigated.

A. Failure mechanisms

There are several failure mechanisms for dikes in which a dike looses its water retaining function. The definition of failure for flood defenses is: *"Failure for flood defences is the loss or the water retaining function. This usually implies the initiation or development of a breach or simply excessive amounts of water passing the defence line (e.g. by overtopping)."*[4]

There are a lot of failure mechanisms for dikes. In this research only dike failure mechanisms where displacements will be measured are considered. These dike failure mechanisms are given in Figure 2 [5].

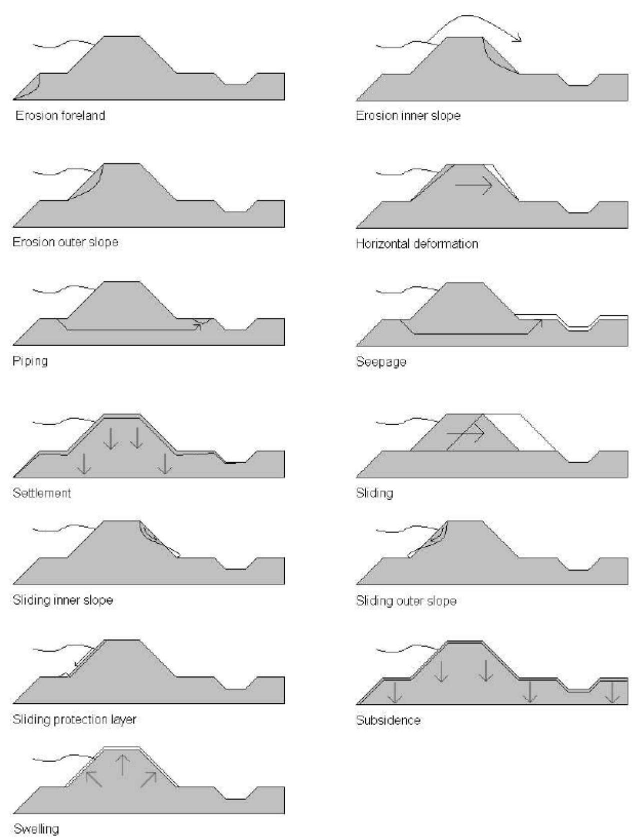

Fig. 2. Deformation mechanisms for dikes [5].

As visible from the satellite measurements, the displacement of the dike takes place over a larger length and width at the outer slope. From Figure 2 it can be seen that the only failure mechanisms where displacements are measured at the outer slope are [5]:

1) Erosion of the outer slope
2) Horizontal deformation
3) Settlement
4) Sliding of the outer slope (also called slope-instability, or macro-instability)
5) Sliding of the protection layer
6) Subsidence

Erosion of the outer slope: Erosion of the outer slope is a process where the soil particles of the dike are beat away by currents and waves. Erosion can lead to sliding of the outer slope if enough particles are moved aside. It will only occur below the water level. Since the displacements for the dike near Eemshaven are measured above the water level, it is not likely that erosion of the outer slope may occur.

Horizontal deformation: Horizontal deformation can be caused by a few things: ship collision, nipping ice and high water. The displacement will be only measured in horizontal direction. Since also vertical displacements are measured for the dike, horizontal deformation is not the likely failure mechanism that may occur.

Sliding of the protection layer: Sliding of the protection layer is almost the same as sliding of the outer slope, with the difference that for the first one only the protection layer slides away. Sliding of the protective cover takes seconds and the announcement of the failure can take days. Since it is measured that the dike is deforming for four years, sliding of the protection layer is not happening at the dike.

Subsidence: If subsidence occurs, a larger area (which is bigger than only the dike itself) shows vertical displacements. Since the dike shows only over a length of 110 meters larger displacements, another failure mechanism may occur.

The only two failure mechanisms that are left are *settlement* of the dike and *slope-instability*. These two failure mechanisms will be further explained in the sections below.

B. Slope-instability

When slope-instability occurs there are large scale stability problems. Not only the body of the dike will fail but also the soil layers underneath the dike fail [6]. A slice of ground, which can be schematized as a circular slice of soil, will move aside. At the crest of the dike a large crack is noticeable and the crest will subside. At the toe of the dike a deformation of the soil will be observed. The sliding of the circular slice of soil can also be schematized as a rotation of the slice. In Figure 3, a schematization of slope-instability is given. The black dotted line shows the circular slice of ground that will slide aside and rotate [5].

Slope-instability can occur at the inner and outer slope of the dike. Instability at the outer slope can be caused after a period of high water followed by a rapid fall of the water level at the outer face of the dike, this is also called a *sudden drawdown*. When this happens the pore water pressure in the dike remains high and causes the outer slope to slide away [4].

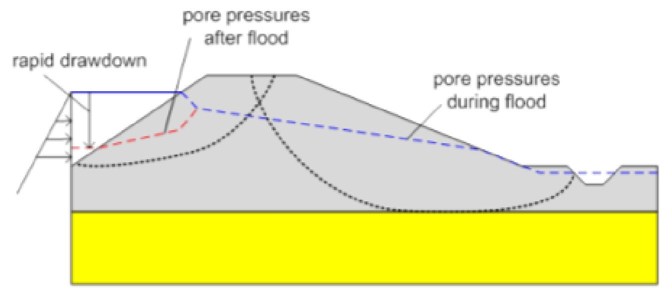

Fig. 3. Slope-instability at the outer slope (left side) and inner slope (right side) of the dike[4].

Slope-instability of the inner slope can be caused by high water levels at the outer face and infiltration through the dike over a longer period. This will result in a higher pore water pressure and lower effective stress. As a result the slope will slide aside [7].

If slope-instability occurs both horizontal and vertical displacements will be measured with the radar satellites. The vertical displacements over a cross section will not be the same at all points, since the top of the dike is expected to subside more than the toe. The actual catastrophic failure of the slope itself is expected to have a duration in the order of hours. However, indicative early-warning signs of the mechanism may be observed over a much longer period.

Parameters that can influence the slope-instability are [8]:

- the material of the dike and the soil,
- the presence of an impermeable top layer,
- the slope of the dike,
- the height of the dike, and
- pressure on the dike.

The pressure on the dike is mainly caused by the difference in water height of the two sides of the dike. This is caused by

- water level in the sea,
- ground water level at the inner side of the dike,
- permeability of the dike, or
- duration of the pressure

C. Settlement

Most dikes in delta area's settle in the order of decimeters after finishing construction of the dike. Settlement can be caused by two phenomena [9]:

1) **Consolidation:** Short after construction of the dike, the soil pressure in the ground increases due to the extra loading. Due to this increasing pressure, water flows out of the pores between the soil particles. The soil particles can be packed closer to each other.
2) **Creep:** Creep is a slower ongoing process in which the soil particles are packed closer to each other. Creep can be a constant process in which the dikes settles infinite [10].

Most dikes are designed for this settlement and have a design level after construction. If the settlement continues it can be possible that the dike is not high enough anymore to prevent hydraulic failure mechanisms such as overflow and over topping.

If settlement takes place, the satellite will only measure vertical displacements. The duration of the settlement takes as long as the cause of the settlement [5]. .

In Figure 4 a schematization of settlement for a dike is given.

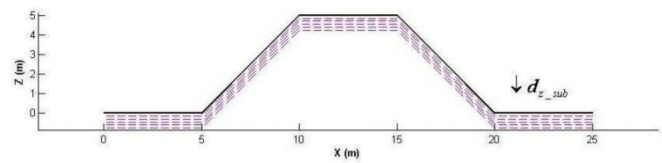

Fig. 4. Schematization of settlement of a dike [5].

III. Measurement technique

It is important to monitor the status of all the dikes in the Netherlands since failure can cause large damage. A big part of the inhabitants of the Netherlands is living below the sea level and seventy percent of the gross national product is earned there. Most inspections are done by expert observers who physically visit the dikes and do (visual) inspections. These observations are not very precise since even for the experts it is difficult to see minimal changes in the dike.

Some of the failure mechanisms for dikes can be recognized in advance since they will preceded by minimal structural changes. These changes can be measured as displacements of the dike. The displacements of the dike between Eemshaven and Delfzijl are measured with InSAR based methods [11].

InSAR is an acronum for Synthetis Aperature Radar. On which radar stands for radio detection and ranging [2].

A. Radar signal

A radar is as well an instrument as a technique. The radar was originally used as a military instrument and is developed to determine the position and the presence of objects. There are two types of radar systems, one is a pulse based radar and the other one is a phase based radar [12].

Pulse based ranging: A radar that is pulse based emits a radio signal (a pulse) which is transmitted in a particular direction. The signal is reflected by an object and the two-way travel time of the signal is measured since the signal has to travel back to the receiver. By knowing the speed of the signal the distance between the radar and the object can be calculated.

Phase based ranging: Satellites make use of phase based ranging. They are transmitting continuous waves which are reflected by objects at the earth surface. The reflected waves are coming back by the receiver with a phase difference. The receiver measures the distance to the object based on this phase difference Φ. By knowing the phase difference, the travel time can be calculated and afterwards the distance to the object can be calculated.

B. Imaging

Imaging radars are a specific class of radars. Synthetic aperture radar (SAR) is one of them. When making use of an antenna which can look sideways and is mounted underneath an aircraft or satellite, a whole area is illuminated. Waves are transmitted every $\Delta\tau$ seconds from the radar and are reflected by objects at the earths surface. This will cause phase differences and as a result, the distance to the object on the earth's surface can be calculated. Only the fractional phase difference is known. The difference in full wave lengths is not measured [12].

In Figure 5 it is visible how the antenna transmits pulses to the earth surface.

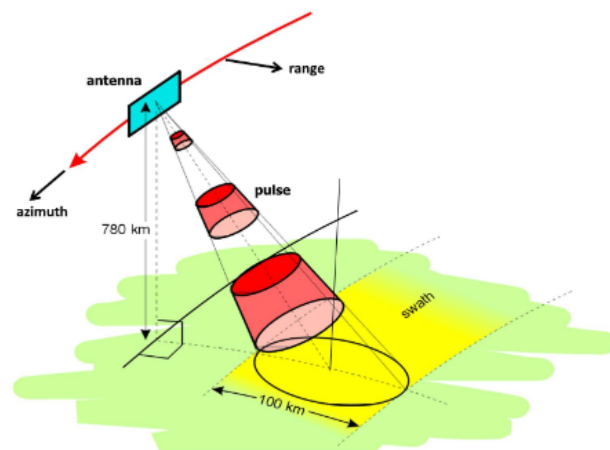

Fig. 5. A side-looking radar makes images [12].

When the satellite flies over the earth's surface an image is made. Objects at the earths surface with different distances to the receiver will result in different phase measurements. Every reflected signal is recorded by the receiver and is representing one pixel of the image. As a result, every pixel in the image represents a distance from the satellite to the earth's surface. When the satellite flies on, the next received pulses form the next row of the image. By stacking all the pixels together a two-dimensional image is created which consist of multiple pixels [12].

C. Radar interferometry

The problem with radars is that they cannot distinguish between a low building directly underneath the satellite and a taller building further away. If the distances to the satellite are the same, the measured phase differences will be the same and the two points end up in the same pixel of the image. To solve this problem another radar image is needed. This can be done by using two satellite which are having different orbital tracks [13].

An interferometric image is created by combining the phase measurements of the two different images. It is important that the scattering object should not change between the two images. In other words: the scattering should be coherent. A good example for coherent scattering are buildings, they do not change in time. Incoherent scattering is for instance grass that grows at the inner face of the dike, this will change over time and displacement of the ground surface cannot be measured.

D. Measuring deformations

For measuring deformations in the terrain, the difference between two interferograms is taken. This is called differential interferometry. If the two interferograms (taken on two different times) are exactly the same, no deformation in the terrain took place. If the interferograms are different, the phase difference between the two interferograms are caused by displacements in the line of sight of a satellite [5] . With differential interferometry small deformations can be measured with millimeter accuracy [2].

The imprecision of the measured deformation is caused by a few things:

1) Spatial decorrelation: The viewing angels between the two different images for the interferograms should not be to different from each other. This is because objects look different from different angles and it is necessary to maintain sufficient coherence.
2) Temporal decorrelation: SAR interferometry only works under coherent conditions. The objects should not change between the two interferograms (for instance grass that grows).
3) Atmospheric delays: The radar signals get delayed by the atmosphere. This result in an additional phase offset. The magnitude of this delay can be in the order of several centimeters.
4) Radar wavelength: The deformation is measured as a phase difference of the wavelength. The accuracy of the deformation depends therefore on the radar wavelength. The shorter the wavelength the more accurate the deformation. Nevertheless, shorter wavelengths are scattered by small objects where larger wavelengths

IV. Characteristics of the dike

The dike of this study is situated between Eemshaven and Delfzijl in the north of the Netherlands. The dike has a total length of 11.7 kilometers but within this study only the part in the red box of Figure 6 will be further considered. The coordinate system that is used for the study is the 'Rijksdriehoekcordinaten'. The upper RD y-coordinate that is taken into account is 604960, the lower RD y-coordinate is 604140. This will give a total length of the dike of 820 meters.

In Figure 7, a cross section of the dike is given. The dike has a crest height of 7.5 meters and a berm at both the sea side and the land side. The berm at the sea side is situated between points B and C in Figure 7. The crest and the berm at the sea side consist of grass where the lower part of the slope at the sea side consist of a revetment. The revetment is situated between points C and D and has a slope of 12°.

The dike is almost situated in north-south direction but has a small angle β of 4.2 degrees with respect to the north. See also Figure 8. At the dike, different directions can be determined. First of all, there is a dike-fixed coordinate system which consist of a longitudinal, transversal and normal direction. The longitudinal direction is the direction along the dike and is positive in the north direction. The transversal direction is the direction along the slope and is taken positive downslope. The normal direction indicates the direction orthogonal to the longitudinal and transversal direction and is positive upwards [13]. Also a horizontal and vertical direction can be determined. The vertical direction is positive upwards and the horizontal direction is positive to the east, which is in the direction of the sea side. See for a schematisation Figure 8.

TABLE I
INCIDENCE AND HEADING ANGLE OF BOTH TRACKS.

Track	**Incidence angle**	**Heading angle**
Descending	26.5°	192°
Ascending	31.1°	349°

V. Data

The data consists of displacement measurements with the TerraSAR-X satellite, which measures deformations by making use of satellite radar interferometry. The data consists of two different datasets which are obtained by the same satellite flying two different orbits. The first dataset is called the descending dataset and is obtained with the descending orbit. The other dataset is called the ascending dataset and is obtained by the ascending orbit.

The satellite measures displacements for a lot of points at the dike with an incidence angle, this is the viewing angle of the satellite, see also Figure 9. The incidence angles of both tracks are given in Table I. The displacements of points at the dike are measured in the direction of the Line of Sight (LOS) of the satellite. Both satellites do also have an heading angle. That is the angle of the flying direction of the satellite with the north.

A. Measurement Points

In both datasets, displacements of points at the dike are measured every 11 days, from June 2013 till June 2017. The descending dataset consist of displacements measured for 1076 points that are situated over the part of the dike that is studied. Where the ascending dataset consists of displacement measurements for 747 points. Every 11 days, displacements of these points, relative to the first measurement in June 2013, are measured. Based on all the displacement measurements, a linear displacement in meters per year is given in both datasets. During the rest of the research it will be assumed that the displacements have a linear behavior and the linear displacements given by the datasets are used.

In Figure 10, the coordinates of the points from which displacements are measured are given. The blue dots are the points that are measured by the ascending orbit where the red dots are the measurement points of the descending orbit.

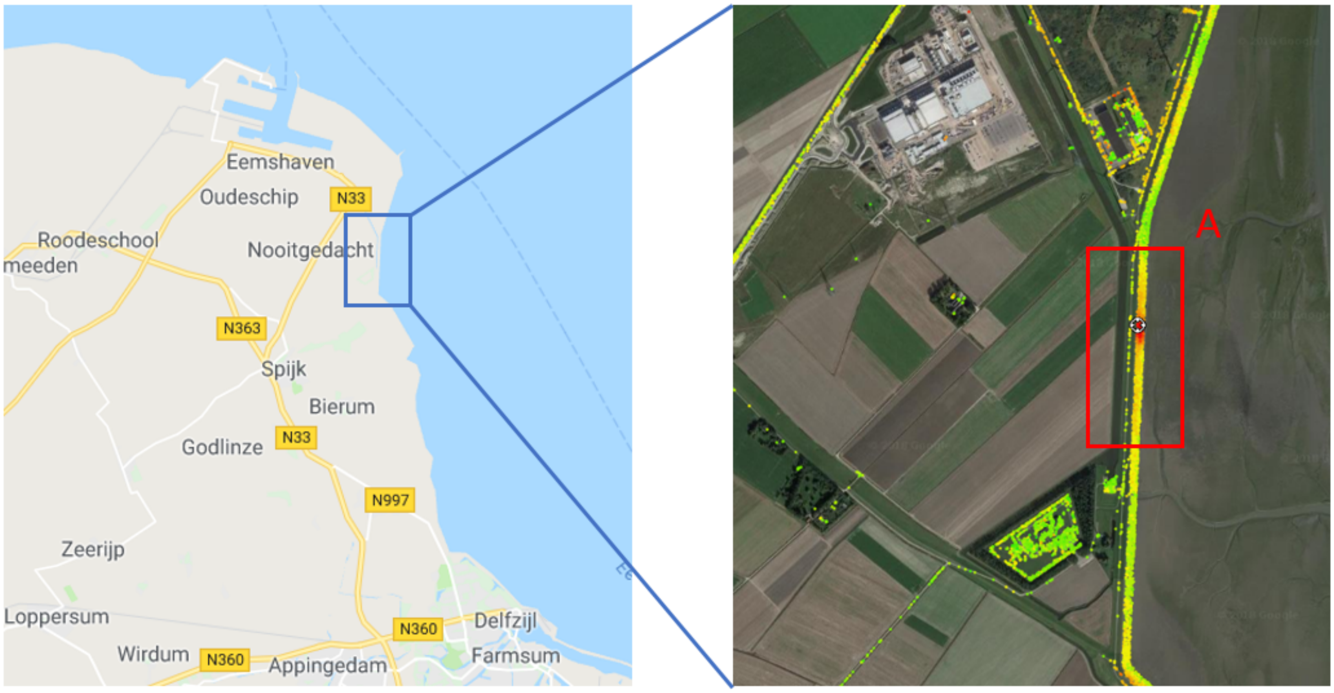

Fig. 6. Part of the dike that is studied.

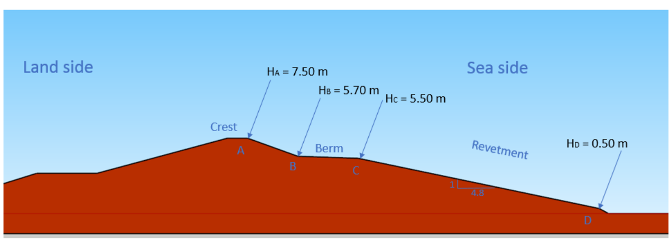

Fig. 7. Characteristics of the dike between Eemshaven and Delfzijl.

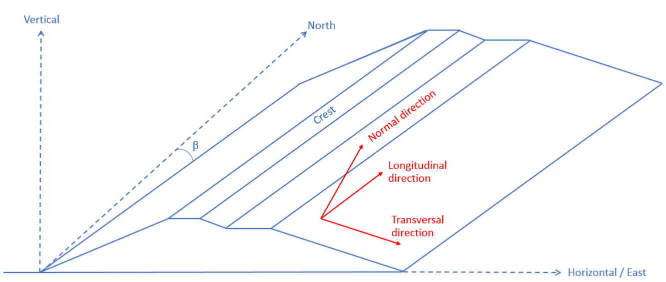

Fig. 8. Coordinate system at the dike between Eemshaven and Delfzijl.

As visible in Figure 10, there is a gap, where no points are measured. At this 'gap' the crest of the dike and the upper side of the slope at the sea side are situated, they both consist of grass. Since grass will not result in coherent scattering there are no measured points for this places. At the right side of the crest the outer slope of the dike is situated which consists of a revetment, this will result in coherent scattering. At the left side of the crest a road is situated which will also result in coherent scattering.

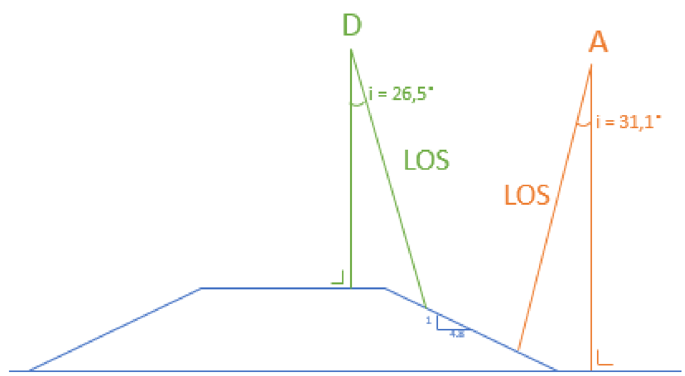

Fig. 9. Both satellelites are measuring deformations with an incidence angle. The displacements are measured in the Line of Sight (LOS) of the satellite.

VI. Methodology

The aim of the research is to find out which failure mechanism may occur at the dike: settlement or slope-instability. To say something about the possible failure mechanisms that may occur it is the aim to find out or there are some announcements of one of the two failure mechanisms. If settlement occurs at the dike, all points at the dike are expected to have only vertical displacements. If slope-instability occurs, also horizontal displacements should be visible since a slice of ground slides aside. It is also expected that the vertical displacement is not the same at all points. At the top of the dike the vertical displacements are expected to be larger than at the toe of the dike.

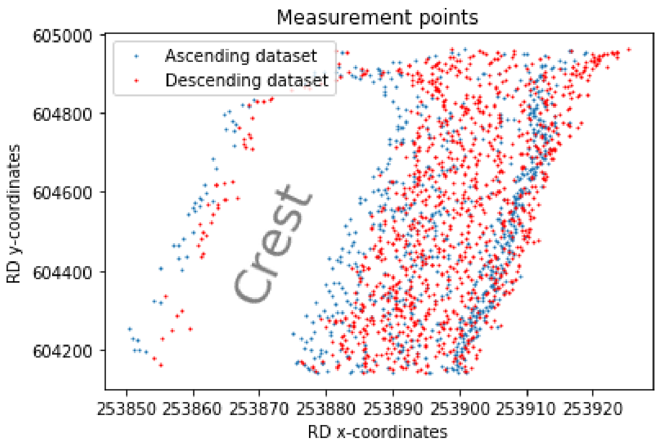

Fig. 10. Measurement points of the two different datasets.

A. Direction of the displacements over the whole dike

To make a distinguish between settlement or slope-instability, the horizontal and vertical displacements of the dike should be know. From the two different datasets only displacements in the line of sight (LOS) of the satellite are known. By making use of the method of Chang et al. [14] it is possible to determine the displacements in vertical and horizontal direction. This method requires that for a certain point, which is called point C for now, the displacements in the LOS measured with both the ascending and descending orbit should be known. As a result, the method will give displacements in longitudinal, transversal and normal directions. In the method it is assumed that the displacements in the longitudinal direction are zero.

From the displacements in the normal and transversal direction, the displacements in horizontal and vertical direction can be calculated. A schematization of the method of Chang et al. is given in Figure 11.

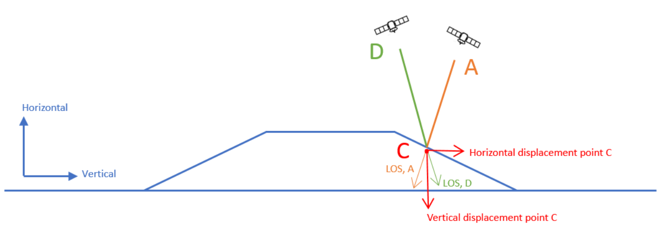

Fig. 11. With the displacement in the LOS measured with the ascending orbit (LOS, A) and the the displacement in the LOS measured with the descending orbit (LOS,D), it is possible to determine the horizontal and vertical displacement of point C.

Since the points measured with both datasets are not at the same locations, the method of Chang et al. can not be applied directly. Therefore the dike is divided in a number of cross sections which are having a certain width. Every cross section is again divided in a number of segments. See for a schematization of how this is done Figure 12. The cross sections are given with a letter (for instance A), where the different segments are given with a number. The cross sections are divided in 5 different segments, this is done to make a good distinguish between the displacements at the upper part of the dike and at the toe of the dike.

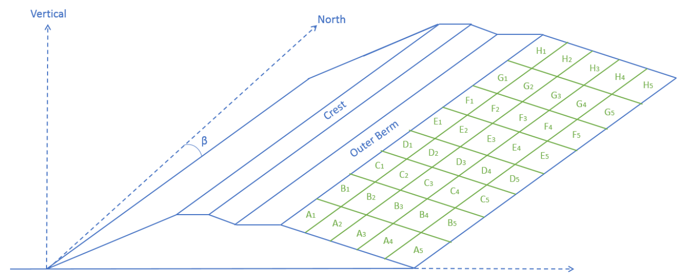

Fig. 12. The dike is divided in different cross sections which are given with by letter. The cross sections are again divided in five segments which are given by a number.

For each segment (for instance A1), the mean displacement in the LOS of the ascending orbit can be calculated, the same should be done for the descending track. Afterwards, the mean horizontal displacement and mean vertical displacement for that segment can be calculated by making use of the method of L.Chang. For each cross section, the displacement vectors can be plotted, this will be done in Python Software. As a result, something can be said about the size and the direction of the displacements. Also the size and direction of the displacements of the upper segments can be compared with the displacements of the segments at the toe of the dike. In this way, a first impression can be get about the possible failure mechanism. An example of a Figure that is obtained is visible in Figure 13.

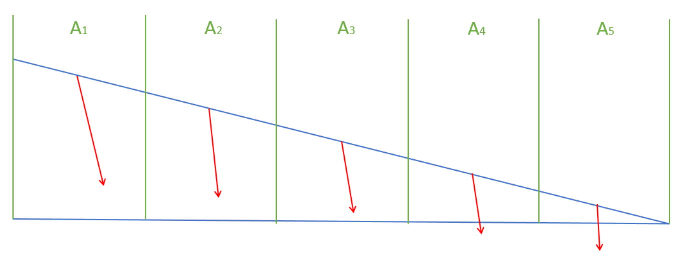

Fig. 13. When the displacements for all the segments in a cross section are known, the displacements can be plotted as vectors which consists of a horizontal and vertical component. For every segment a displacement vector is plotted.

B. Visualization of the displacements over the whole dike

When the direction of the displacement in all the cross sections is known, a visualization of the displacements is made. This is done to make the comparison between the cross sections more easy. For the visualization, the measurements of both the ascending and descending orbit need to be interpolated over the dike since the measurements of both datasets are not at the same locations. First, a grid of the dike will be produced and the displacements in the LOS of both tracks will be interpolated over these points. Now, for all the points in the grid, the displacements in the horizontal, vertical, transversal and normal direction can be calculated with the method of Chang et al. When this is done, the displacements in certain directions can be made visible by top views of the dike where the size of the displacements is given in different colors. With this visualization it is more easy to see where the displacements are the most extreme.

C. Rotational velocity

If it is likely that slope-instability may occur at the dike, the rotational velocity of different cross sections should be determined. If slope-instability may occur it is expected that circular slice of soil moves aside. This can also be schematized as a rotation where the circular slice will rotate around a point. It is also expected that the largest vertical displacement occurs in the upper segment of the dike, segment A1 in Figure 13. The smallest vertical displacement is expected at the toe of the dike.

The displacements can now be schematized as a vertical subsidence (dy) and an angle rotation (dω), see also Figure 14. The vertical subsidence dy can be obtained by taking the minimum vertical displacement. When subtracting this value of the rest of the displacement vectors, the rest of the displacement vectors will cause an angle rotation around point B in Figure 14.

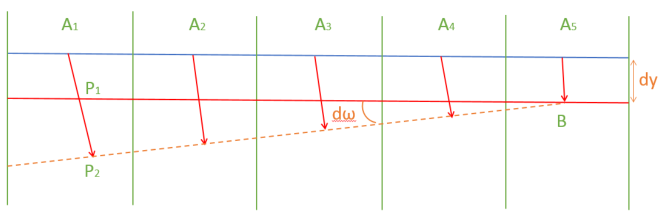

Fig. 14. If slope-instability may occur, the displacements can be schematized as a vertical displacement dy and an angle rotation dω.

The rotation angle can be calculated since the values of the remaining displacements vectors are known. Also the distances of the remaining vectors to the rotation point B are known. The rotation angle dω can now be determined by dividing the remaining vectors lengths by the distance to the rotation point. For instance, dividing the distance P1-P2 by the distance B-P1. For every cross section, 4 rotation angles can be determined. The final rotation angle is obtained by taking the mean value of the four rotation angles.

Finally, the mean vertical displacement dy as well as the angle rotation dω can be plotted in a top view of the dike by using different colors for different values. As both the vertical subsidence as well as the angle rotation increase at the same locations, it can be said that slope-instability may possible occur.

VII. Results

In this section the results of the research are discussed.

A. Displacements of all the points

In this research, measurements of the ascending and descending track are used to estimate the displacements of the dike. The displacements for all the points measured by the ascending track are given in Figure 15. The same is performed for the descending track and the results are visible in Figure 16. The time is plotted against the vertical displacement in meters. The measurements are taken relative to the first measurement in June 2013 (which is assumed as zero displacement). A negative displacement means the object is moving further away from the satellite (the dike subsides).

Fig. 15. Displacements in meters measured with the ascending track.

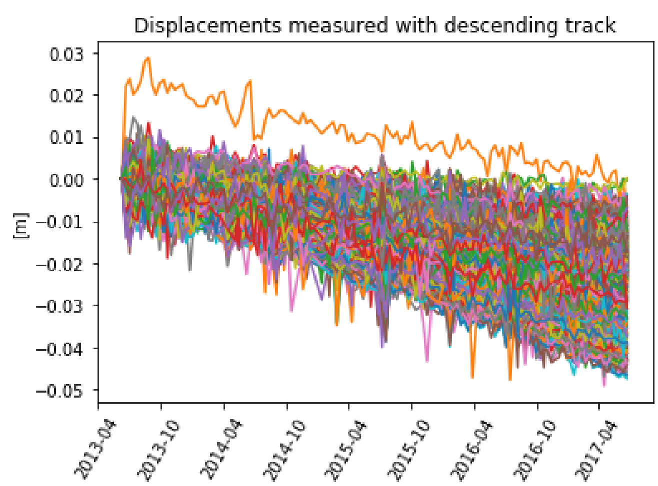

Fig. 16. Displacements in meters measured with the descending track.

As visible in Figure 15 and Figure 16, all the points at the dike are subsiding in the LOS of the satellite. The order of the subsiding is the same for both datasets and is between almost no final displacement and a final displacement of 4-5 mm. All the displacements lines are close together. However, for the descending track there is one point which is immediately above the rest of the points (the orange line in Figure 16). After the first measurement time, this point subsides again with the same order as the rest of the points. The same happens in the ascending dataset, there are four points which show this behaviour (the orange, blue and two green lines in Figure 15). It seems like something went wrong in the first measurement since all points show similar behaviour as the rest of the points after the first measurement.

The deformations are causing a phase difference between the current measurement and the first measurement in June 2013. Only fractional phase differences will be measured. So probably for the points that are lying above the rest of the measurement points, a phase difference is measured in the other direction than for the other measurements. When subtracting a half phase length of these measurements, the measurements are again in line with the rest of the measurements.

In Figure 17 and Figure 18 the final displacements of all the points measured for both datasets are given. At the y-axis the final displacements are given for different points at the dike. As visible, the most points having a final negative displacement around the 15-20 mm. Which means the dike is subsiding.

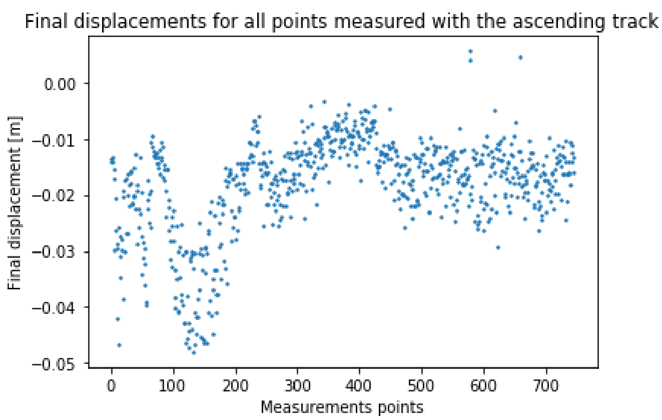

Fig. 17. Final displacements measured with the ascending track.

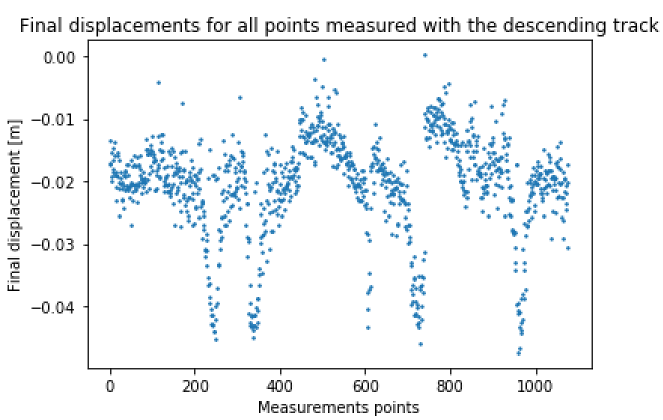

Fig. 18. Final displacements measured with the ascending track.

In both datasets there are a few points which are having a higher final displacement (around 35-50 mm). These points are probably situated at the critical part of the dike, where the displacements are the most extreme. In Figure 17, there are three points that have a positive final displacements which would mean the points moved upwards. As was visible in Figure 15, there were three points which were situated above the rest of the points which was probably caused by a wrong phase measurement. This are probably the points with the positive final displacement.

B. Location of most extreme displacements

To have an idea of where the displacements are the most extreme, the linear displacement measurements of both the ascending and descending track are interpolated over the dike. A grid with points over the dike is made. The distance between the points in y-direction is 1 meter where the distance between the points in x-direction is 0.5 meter. The grid is taken from the RD y-coordinate of 604400 to 604750. The RD x-coordinates are taken from 253870 to 253915. After the interpolation, for every point in the grid, the displacement in the LOS of the ascending track as well as the displacement in the LOS of the descending track is obtained. In Figure 19, two top views of the dike are given with displacements in LOS for the ascending and descending track. As visible, both datasets show a clear anomaly where the displacements are larger situated at the middle of the dike. The anomaly has a length of approximately 110 meters, from RD y-coordinate 604530 to 604640. At the north and the south of the dike, the displacements are minimal.

C. Direction of the displacement over the dike

To obtain the direction of the displacements, it is necessary to reduce the amount of measurement points. As was visible in Figure 10, there were also points measured at the right side of the crest. They will not be taken into account from now on. Also the most upper and lower parts of the dike are not taken into account anymore since the most critical part is present at the middle of the dike. The points that will be taken into account are visible in Figure 20. The new RD y-coordinates are taken from 604400 to 604775. The length of this part of the dike is 375 meters. The dike is divided in cross sections with a width of 15 meters, so in total 25 cross sections are considered. Figure 20 shows a top view of the dike, the cross sections are given with a letter.

The cross sections are again divided in five segments. For each segment the mean displacement in mm/year in the LOS of the descending track and the mean displacement in mm/year in the LOS of the ascending track can be determined. Afterwards the method of Chang et al. can be used to determine the displacement vectors in different directions for the segment. The parameters that are needed for the method of Chang et al. are given in Tabel II.

In some cases, for a segment there were no measurements from the ascending or descending track. In that case, it was not possible to determine the deformation vectors for that segment. For example in Figure 13 for segment A3 there were no measurements for the ascending track. In that case the mean displacements of segment A2 and A4 were taken to determine the displacements for segment A3.

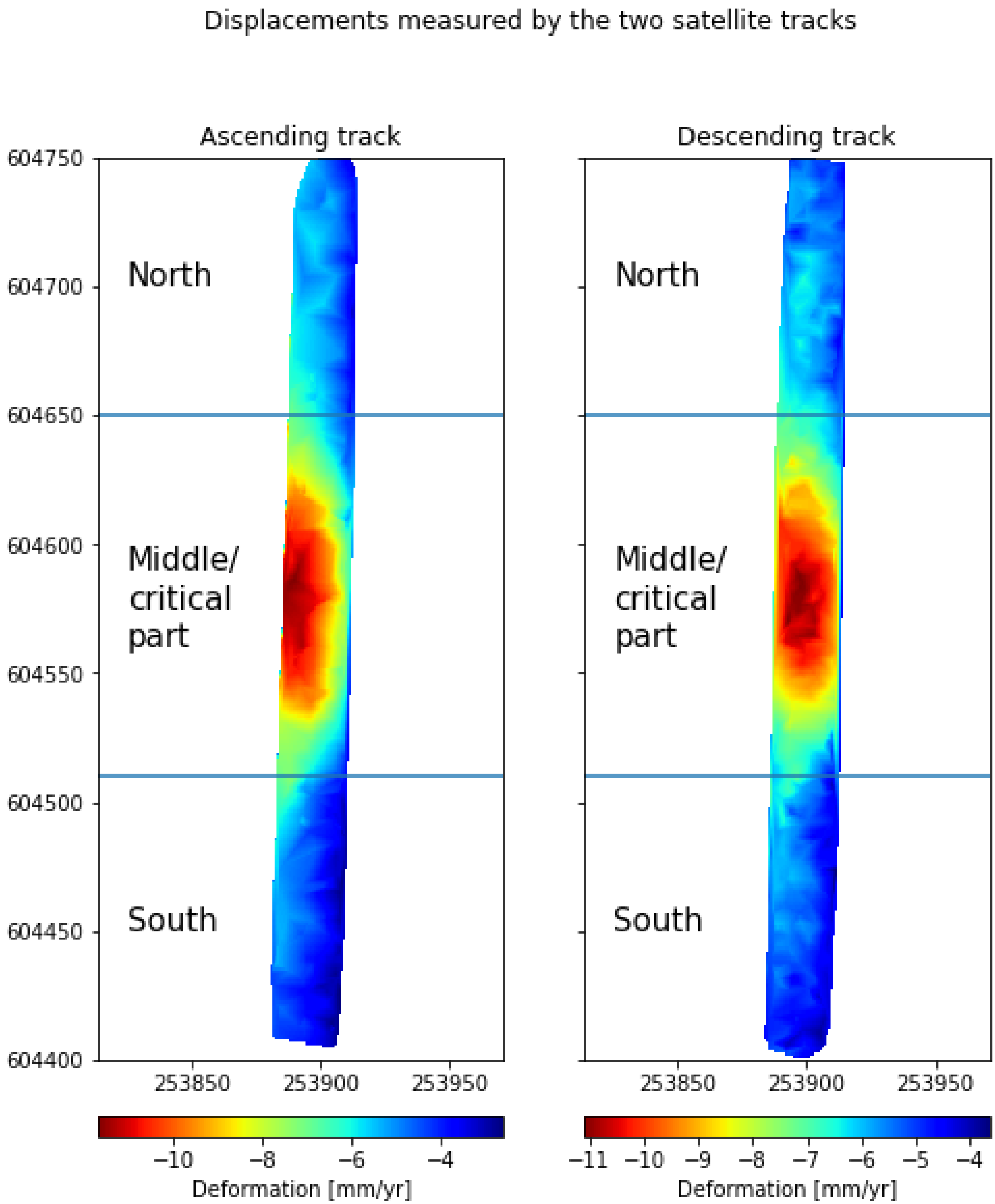

Fig. 19. Displacements in mm/year in the Line of Sight measured by ascending and descending track.

TABLE II
INPUT VALUES METHOD CHANG ET AL.

Data	Value
Slope of the dike	1:4.8 (or 12°, or 21%)
Azimuth angle β	4.2°
Incidence angle ascending track	31.1°
Incidence angle descending track	26.5°
Heading angle ascending track	349°
Heading angle descending track	192°

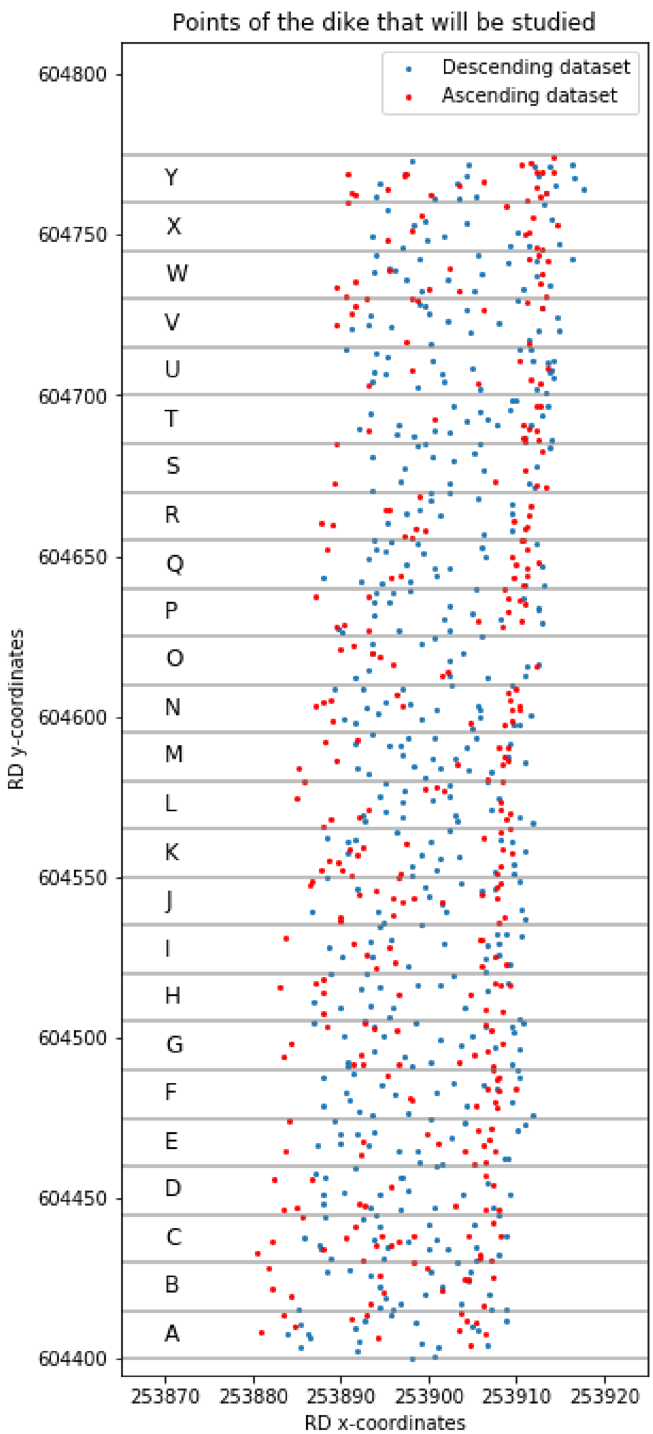

Fig. 20. The dike is divided in 25 cross sections with a width of 15 meter.

For each cross section, the measurement points of the ascending and descending track are plotted. Also the displacement vector in mm/year is plotted for each segment with the direction and size of the displacement. These vectors consist of a horizontal and vertical component. At the top of the vector the mean displacement in the horizontal respectively vertical direction are given. For each segment, also the transversal displacement vectors are plotted with the values on top of the vectors.

For each cross section, the x-axis shows the RD-x coordinates and at the y-axis the height. The first subplot shows the direction of the displacement. In the lower left corner, a reference arrow is given which shows the size of the displacement. In the second subplot the displacements in the transversal direction are given. These vectors are 3 times bigger than the vectors with the horizontal and vertical displacements.

The north and south of the dike

The north and the south of the dike are considered together since their behaviour is very comparable to each other. Both are not situated at the critical part of the dike. See for the locations of the north and the south of the dike Figure 20. In Figure 21, cross section B at the south of the dike is given. This plot is representative of the rest of the points at the north and south of the dike. The rest of the cross sections are given in the appendix. Some outstanding remarks of the displacements at the north and south of the dike are:

- As visible in the upper plot (with the direction of the displacement), all segments are moving downward and the direction of the displacement is to the left. Which means the dike subsides in the direction inside of the dike.
- There is no big difference in the displacements in horizontal and vertical direction between the different segments of the dike.
- There is a difference between the segments in the transversal direction. At the upper segments, the direction of the transversal displacement is downslope. Where at the lower two segments, the direction of the transversal displacement is upward, in the other direction.
- In the middle of the dike, the transversal direction is very small and almost zero.

Critical part of the dike In Figure 22 cross section K at the middle of the dike is shown. This cross section is representative for the other cross sections at anomaly. Some outstanding remarks of the anomaly are:

- The displacements given in Figure 22 are larger than at the north and the south of the dike. Which is reasonable since this cross section is situated at the critical part of the dike.
- The direction of the displacements is still downwards (which means the dike subsides) but instead of moving inside of the dike, the vectors at the upper three segments are now pointing in the other direction to the outside of the dike. Where the lower two vectors, at the toe of the dike, are still pointing inside of the dike. This can mean

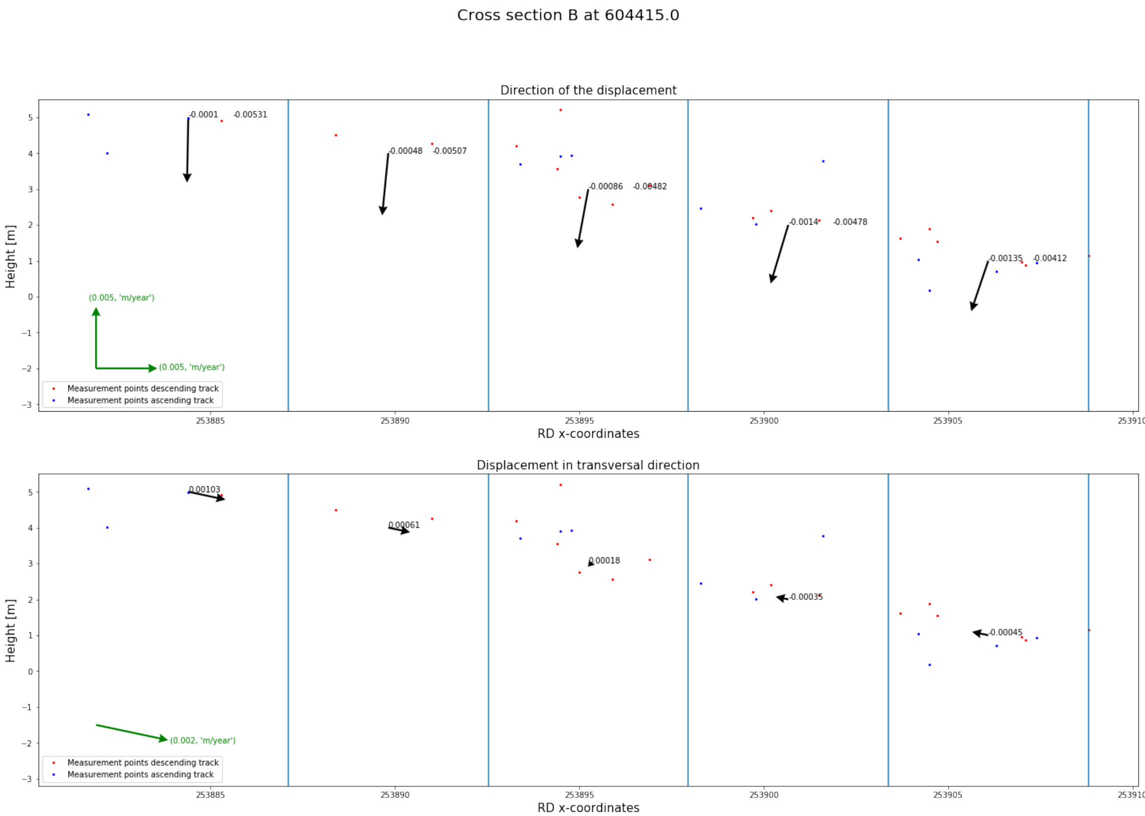

Fig. 21. Displacement vectors at the cross section B at the south of the dike.

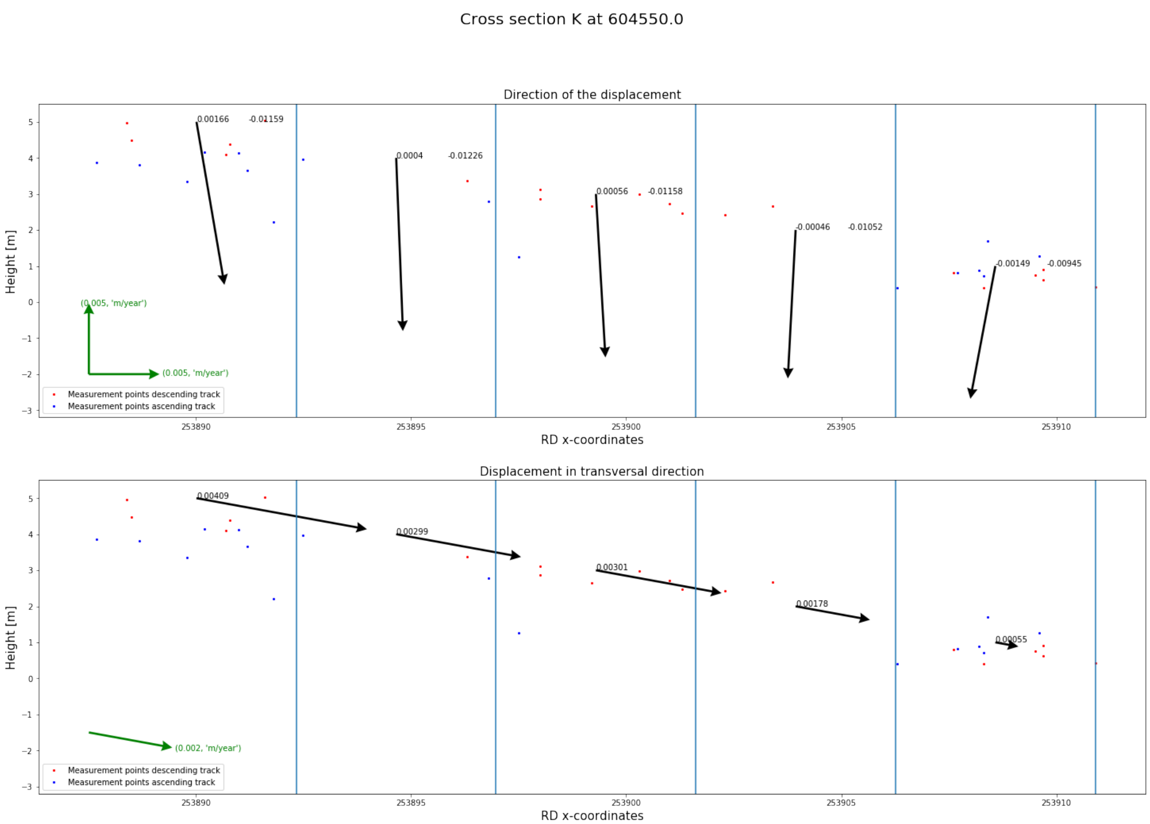

Fig. 22. Displacement vectors at cross section K at the critical part of the dike.

that the upper and lower part are moving a bit in the direction of each other.

- The upper segments have larger vertical displacements than the lower segments. Which means the upper segments are moving faster in vertical direction than the lower segments.
- The transversal vectors are bigger than at the north and the south of the dike.
- The transversal vectors are also having the same sign at the whole cross section. The vectors are all pointing downslope. However, the size of the transversal displacement is bigger at the upper segments. Which means the upper part is moving more downslope than the toe of the dike.

When going from south to north through all the cross sections (see the appendix), it is visible that at the cross sections where not much is happening, the displacements are comparable with the cross shown in Figure 21. When moving closer to the anomaly, it is visible that the vectors in the upper segments are first changing direction more the outside of the dike. When arriving at the anomaly, the most vectors did change its direction and are pointing to the outside of the dike just as in Figure 22.

D. Visualisation of the displacements in different directions over dike

With the interpolated values of the displacements in mm/year of the ascending and descending track it is possible to determine for every point in the grid the displacements in horizontal, vertical, transversal and normal direction. This is done with the method of Chang et al. The results are visible in Figure 23 and Figure 24. Some remarkable things of the two Figures:

- As visible in the two Figures, the anomaly, where the displacements of the dike are the most extreme, is situated over a length of approximately 100 meters (from RD y-coordinate 604530 to 604630).
- The vertical and normal displacements are the most extreme at the upper part of the dike. Which means the upper part of the dike is moving faster downwards in vertical and normal direction.
- For the anomaly, the displacements in horizontal and transversal directions are changing direction from the toe to the upper part of the dike. At the upper part of the dike, the horizontal and transversal displacements are in the direction of the sea side. Where at the toe of the dike, the horizontal and transversal displacements are in the direction to the land side.
- The transversal displacements become larger at anomaly. At the rest of the dike the displacements in transversal direction are quit small.

E. Rotation angle

For every segment also the rotation angle is determined and plotted as explained in the Methodology. Also the mean vertical displacement for each cross section is plotted. The results are visible in Figure 25.

In Figure 25 it is visible that at the anomaly, both the rotation angle and vertical displacements are bigger than at the south and north of the dike. At the anomaly, both values are twice as big than at the north and south of the dike. The rotations are small but the increase at the anomaly with respect to the north and the south of the dike is significant.

The results obtained by plotting the cross sections and the rotational velocity can also be combined. At the critical cross sections of the dike the displacement vectors are all pointing down. At the top of the dike they have a direction to the sea, where at the toe of the dike, the direction is to the land side. From Figure 25 it is visible that at the critical part of the dike, the cross sections have a rotational velocity.

When schematizing the dike as a horizontal line, as is done in Figure 26, the displacements given in Figure 25 can be given in two steps. First the segment is displaced by a mean displacement dy (from 1 to 2 in the Figure). Afterwards the dike is rotated with an angle d (from 2 to 3). The displacement vectors are also plotted in the Figure. As visible, the vector for the upper segment of the dike is pointing downwards and in the direction of the sea. The vector at the toe of the dike is pointing in the direction inside of the dike. The vectors having the same directions as the vectors in the Figure 22.

F. Summary of results

In the north and the south of the dike, the vertical displacements are the smallest and have a value of 5-6 mm/year. The direction of the displacements is mainly vertical but the vectors are also a pointing to the inside of the dike. At the anomaly, the dike shows larger vertical displacements of approximately 10-12 mm/year. The direction of the displacements is changed and the displacements are in the direction of the sea side. The transversal components of the displacements are also increasing when moving closer to the anomaly. In the north and the south of the dike they are almost zero but at the anomaly they are in the order of 4-5 mm/year. It can be said that at the critical part of the dike the displacements are downwards and in the direction of the sea. At the north and the south of the dike, the rotation angles are smaller than at the anomaly. At the critical part, the rotation angle doubled with respect to the north and the south. It can be said that there is a significant difference.

VIII. Discussion

Both datasets consists of independent measurements. They are obtained by different flying directions of the satellite. However, the displacements that are measured by the two flying orbits are of the same order. Also, both tracks measure the maximum displacements at the same locations.

The displacements are measured over a period of four years. During this period, the displacements show a linear behaviour. Since the dike shows a constant deformation in both datasets at

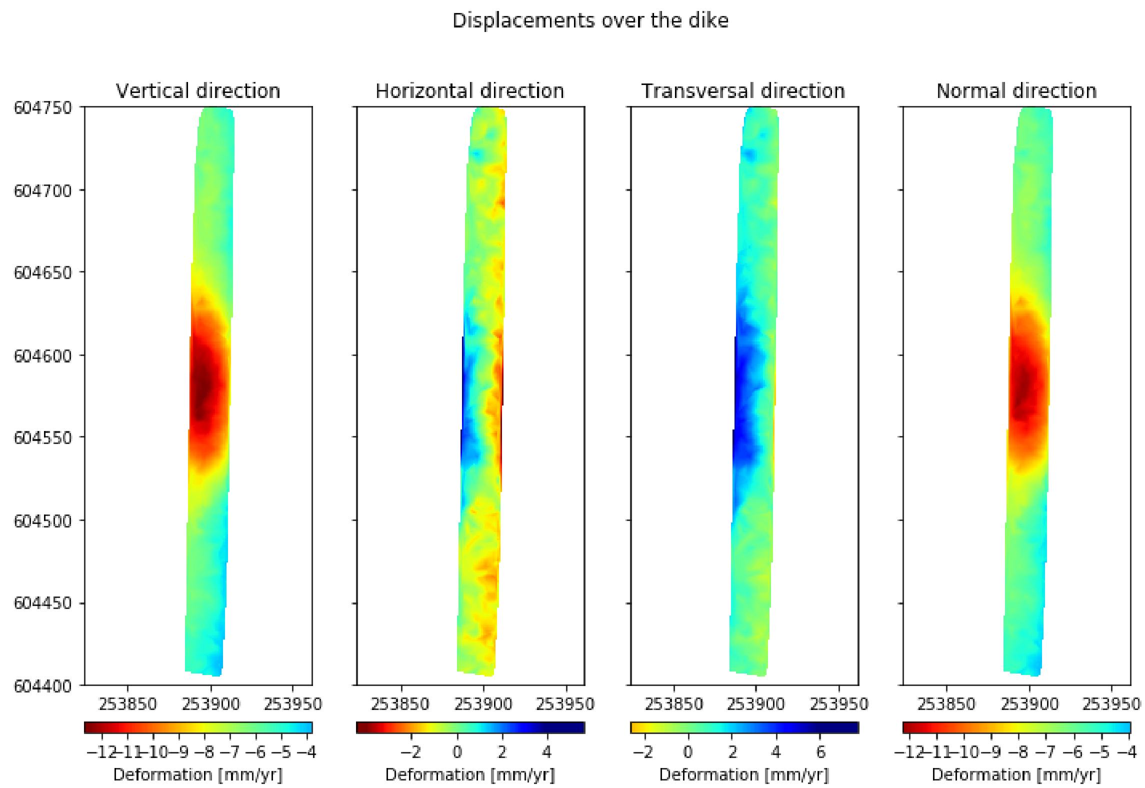

Fig. 23. Displacements over the dike in different directions.

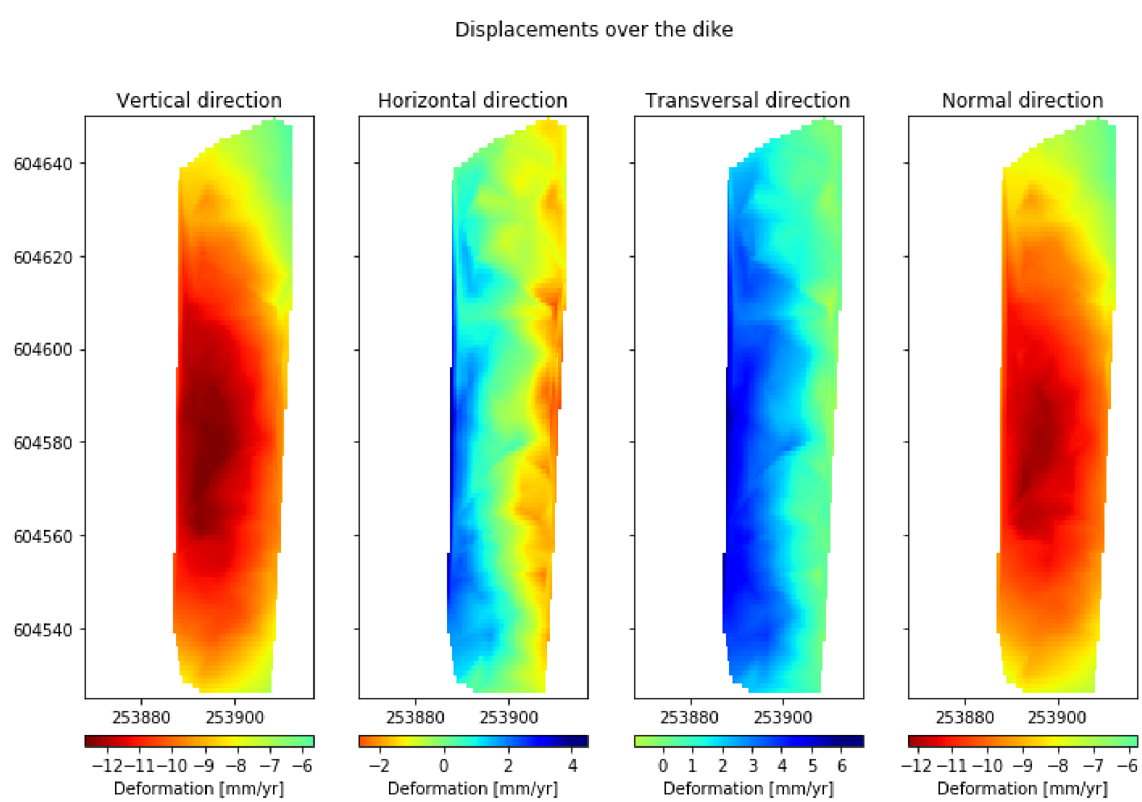

Fig. 24. Displacements over the dike in different directions with a zoom at the critical part of the dike.

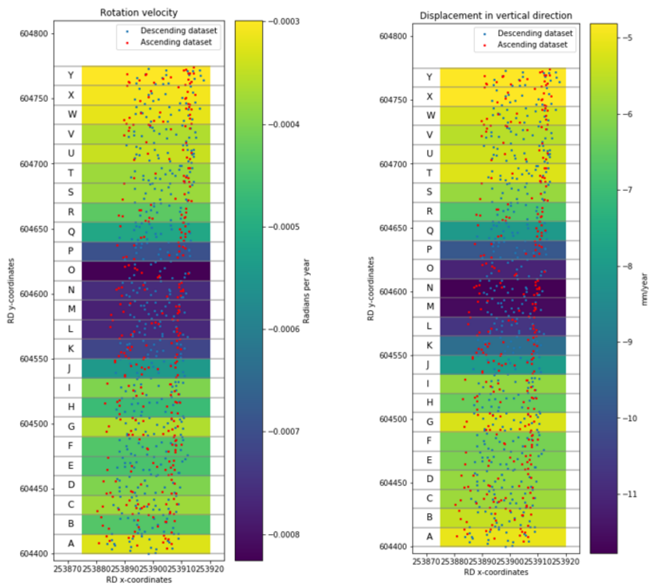

Fig. 25. The rotation angle and vertical displacement for different cross sections over the dike.

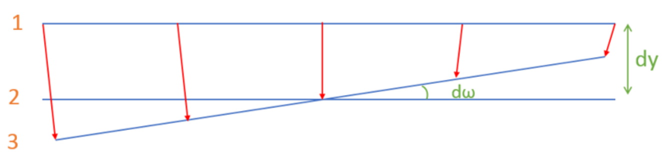

Fig. 26. The two methods of the cross sections and the rotation angle are combined.

the same location over a period of four years, it can be assumed that the deformation is not a result of measurement errors but that there is something happening at the dike. Since there are measurements for a total of 1823 points - which consists of 1076 points of the descending dataset and 747 points of the ascending dataset - a good analysis can be done. The points are approximately situated two meter apart from each other which means the measurements are quite precise.

The displacements are calculated for different segments in a cross section by making use of the method of Chang et al. The choice of the width of the cross sections and the amount of segments influences the amount of measurements within a segment. This influences again the size and the direction of the calculated displacement vectors. It can be possible that for choosing different dimensions of the segment, different displacement vectors were obtained.

In some cases, there were no measurements of the ascending orbit or the descending orbit for a segment (for instance for B2). In that case it was not possible to determine the displacement vector of the segment. Therefore, the mean value of the displacement vectors of B1 and B3 was taken. However, B2 has two more adjacent segments namely A2 and C2. These two were not taken into account but it can be possible that taking the average of A2 and C2 will result in more reliable results since the two segments are at the same level of the dike as B2. There were also cross sections where measurements were missing for two segments. For the cross sections where this is the case, the displacement vectors are quit uncertain.

At the beginning of the research, it is assumed that the displacements show a linear behaviour. Therefore, the linear displacement values, given in both datasets, are used during the research. The displacement results are therefore also given in mm/year. To make a reliable statement about the displacements, it should be investigated weather the displacements are indeed linear or not. The displacements are measured until June 2017, to obtain more accurate results, it is necessary to take the most recent measurements into account.

IX. Conclusion

In this chapter the answer is given to the main research question. The mean research question is:

Which failure mechanism, settlement or slope-instability, may occur at the dike near Eemshaven and Delfzijl?

If settlement may occur at the dike it is expected that mainly vertical displacements will be measured. If slope-instability may occur at the dike, it is also expected to see some horizontal displacements in the direction of the sea side and rotations caused by the slice of soil that slides aside. It is expected the horizontal displacements at the top of the dike are larger than the horizontal displacements at the toe of the dike.

At the north and the south of the dike the displacements are smaller than at the anomaly. The direction of the displacement is downwards and a bit in the direction inside of the dike. The angle rotation of the north and the south is also minimal. For this parts, it is the most likely that the dike is only going down in the direction inside of the dike. It is not likely that slope-instability may occur at this parts since the horizontal displacements would then be in the direction of the sea side. Also the angle rotations are expected to be larger. The dike is situated in the north of the Netherlands where gas is extracted from the ground. Because of the this gas extraction the soil settles and that is possibly what is measured at the north and south of the dike.

For the critical part of the dike, the vertical displacements become larger. The dike is moving faster in the vertical direction and it can be noticed that something is happening. The horizontal displacements are also changing direction to the sea side for this part. This could indicate the initial phase of slope-instability. However at the toe of the dike the horizontal displacements are still in the direction of the land side. As was visible in Figure 26, this can be caused by a an initial displacement dh and an angle rotation $d\omega$.

The fact that the angle rotations at the critical part of the dike are twice as big as at the south and the north of the dike can indicate that slope-instability may happen at the dike. If only settlement may occur, it is not expected that the rotations become larger at the critical parts of the dike. The fact that also the horizontal displacements are larger and in the direction of the sea side for the critical part confirm that slope-instability may occur.

At the critical part, the displacements show the possibility of the announcement of slope-instability. The announcement of slope-instability can take years, which means it is possible to measure displacements years before the real failure take place. However, measuring the announcement of slope-instability will not immediately say the dike will fail.

X. Recommendations

The conclusion is only based on satellite measurements. To say with more certainty which failure mechanism may possibly occur at the dike, some geo technical research should be done. Slope-instability is a large scale failure where also the inner body of the dike will fail. If slope-instability may occur, this should also be visible at the inside of the dike. Getting soil samples, can give more information about the possible failure mechanism of the dike.

If the displacements indeed result in slope-instability of the dike, the dike will fail and loses its function of retaining water. The hinterland will be flooded which can have humanitarian and economic consequences. Therefore, in this initial phase, the Waterschap Noorderzijlvest - who are responsible for the maintenance of the dike - should be informed about what is happening with the dike. The announcement of slope-instability can take years but the real failure itself (when the dike body slides aside) will take a few hours. When the failure slope-instability will indeed occur, waiting for action to prevent the failure should not be taken to long. When the failure itself is started, nothing can be done to prevent it.

During the research, the measurements that were taken into account were measured until June 2017 and assumed to be linear. To to better predictions of future behaviour of the dike, it should be investigated whether the displacements are indeed linear. Also the most recent measurements should be taken into account.

The dike is situated in the north of Groningen where gas is extracted. This can have soil subsidence and earthquakes as a result. It can be interesting to investigate what the effect is of soil subsidence and earthquakes on the stability of dikes. It can be possible that these two things affect the possible failure of the dike. It is also interesting to do research to the soil subsidence in the rest of the area around the dike. If displacements occur and they are in the same order as the displacements in the north and the south of the dike, it an be declared why the dike is subsiding in the north and the south.

Acknowledgment

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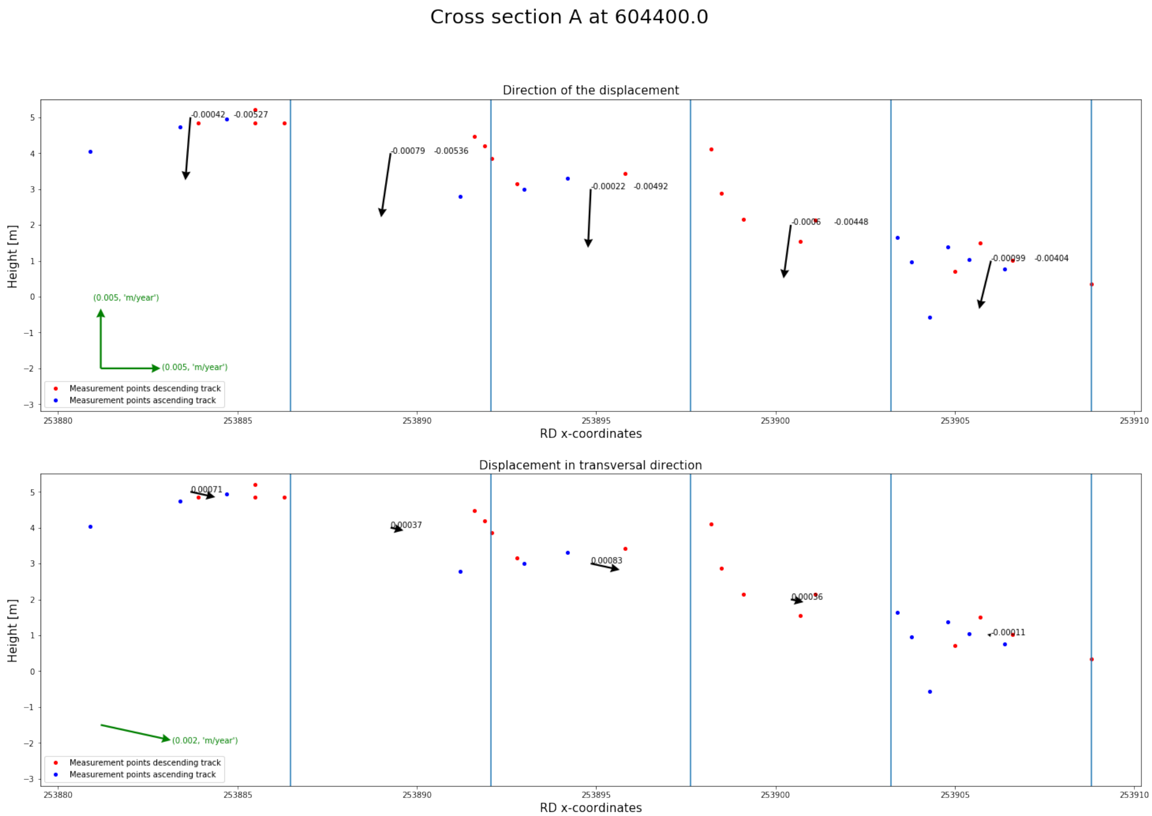
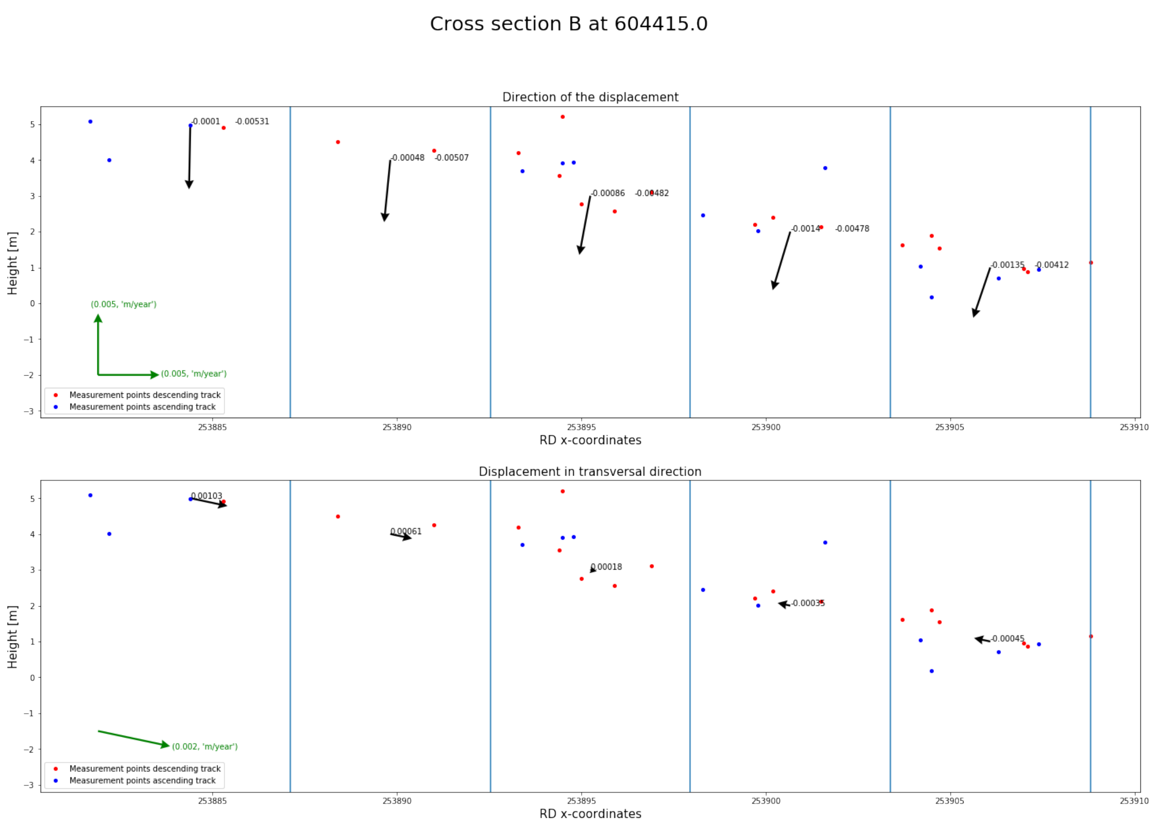
Wietske Brouwer

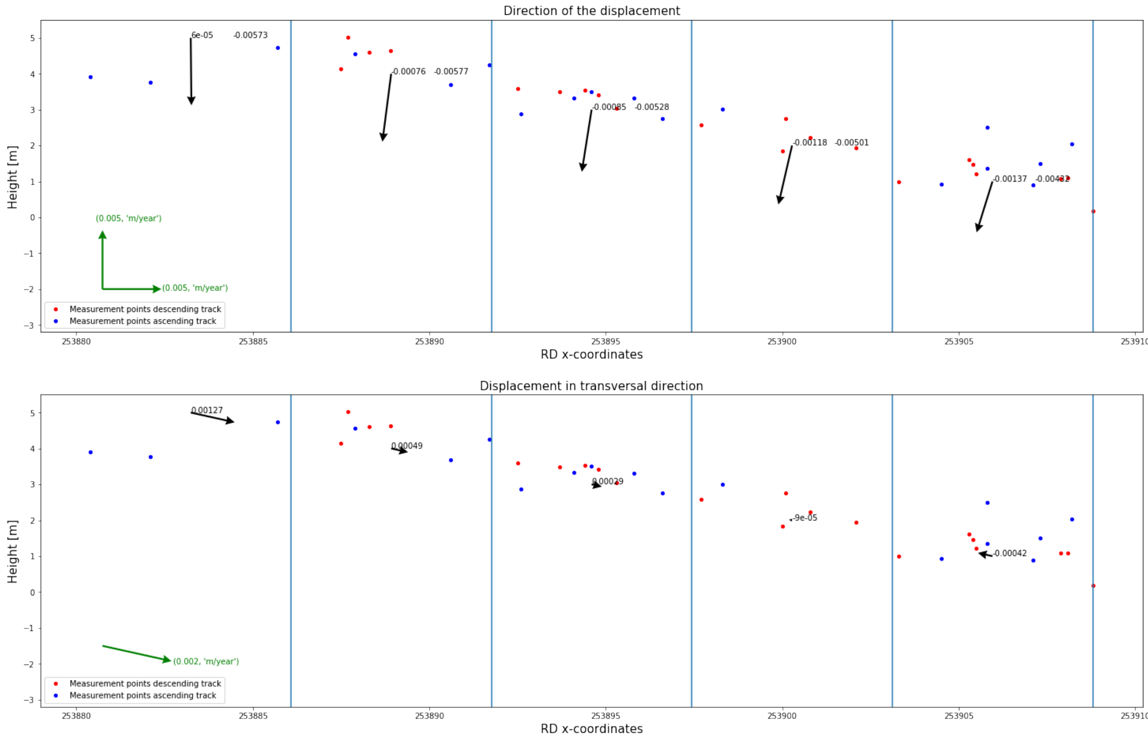
APPENDIX A
CROSS SECTIONS OF THE DIKE WITH THEIR DISPLACEMENTS

In the appendix, the Figures of all the cross sections of the dike with their displacement vectors are shown. The Figures are shown on the next pages.

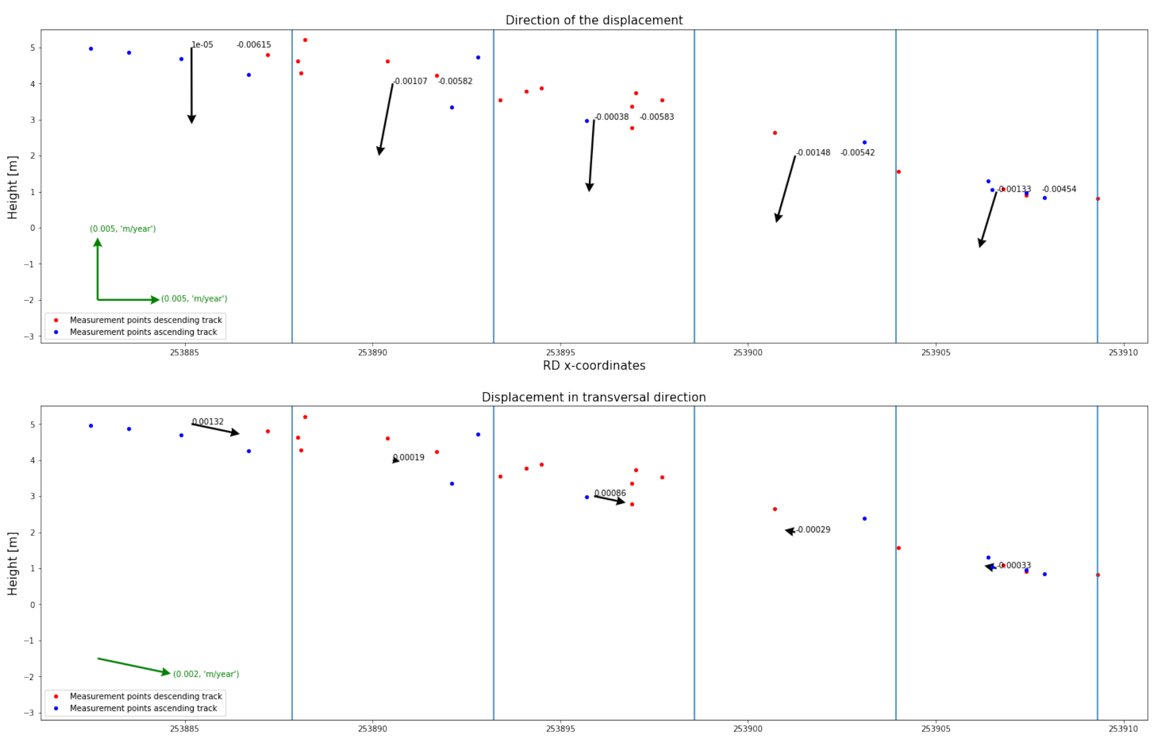

Cross section A at 604400.0
Direction of the displacement
Height [m]
RD x-coordinates
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Displacement in transversal direction
(0.002, 'm/year')


Cross section B at 604415.0
Direction of the displacement
Height [m]
RD x-coordinates
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Displacement in transversal direction
(0.002, 'm/year')

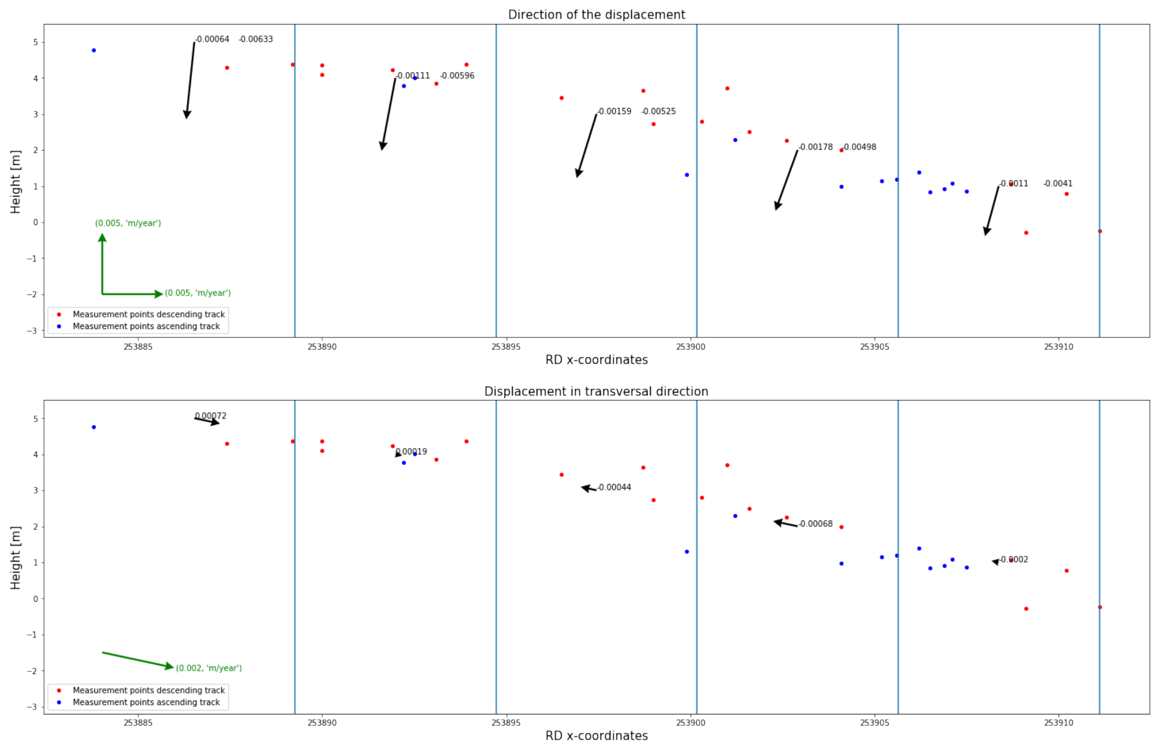
Cross section C at 604430.0



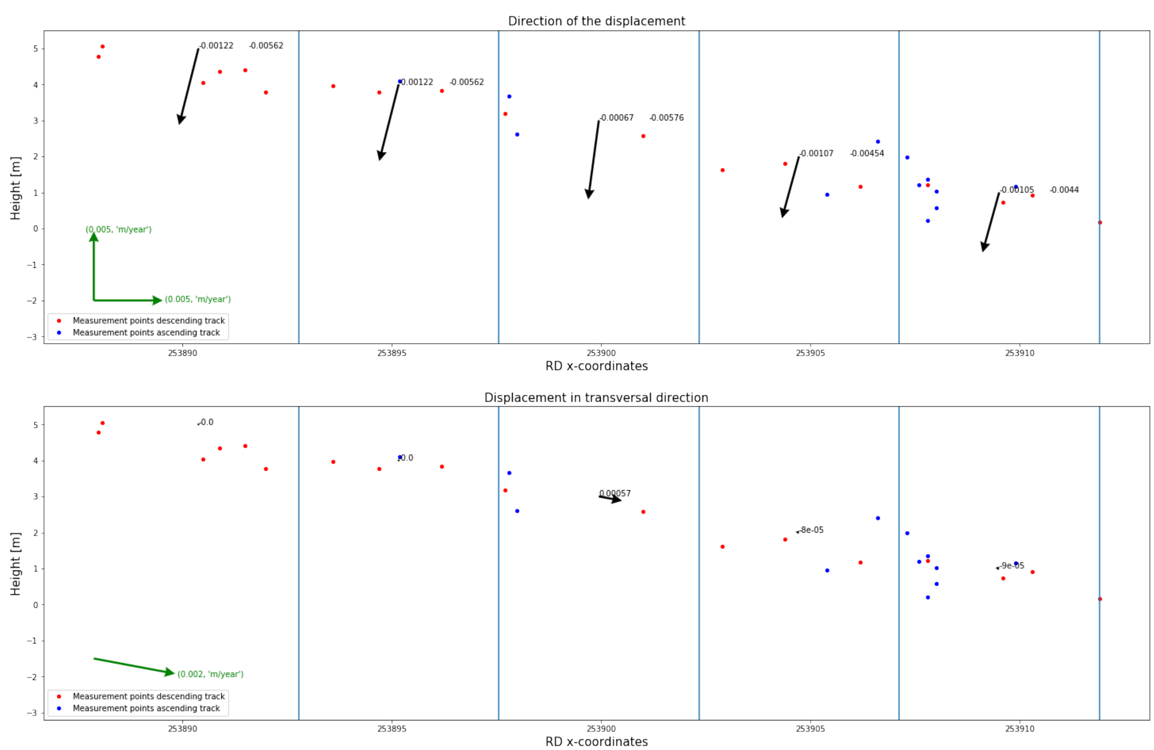
Cross section D at 604445.0

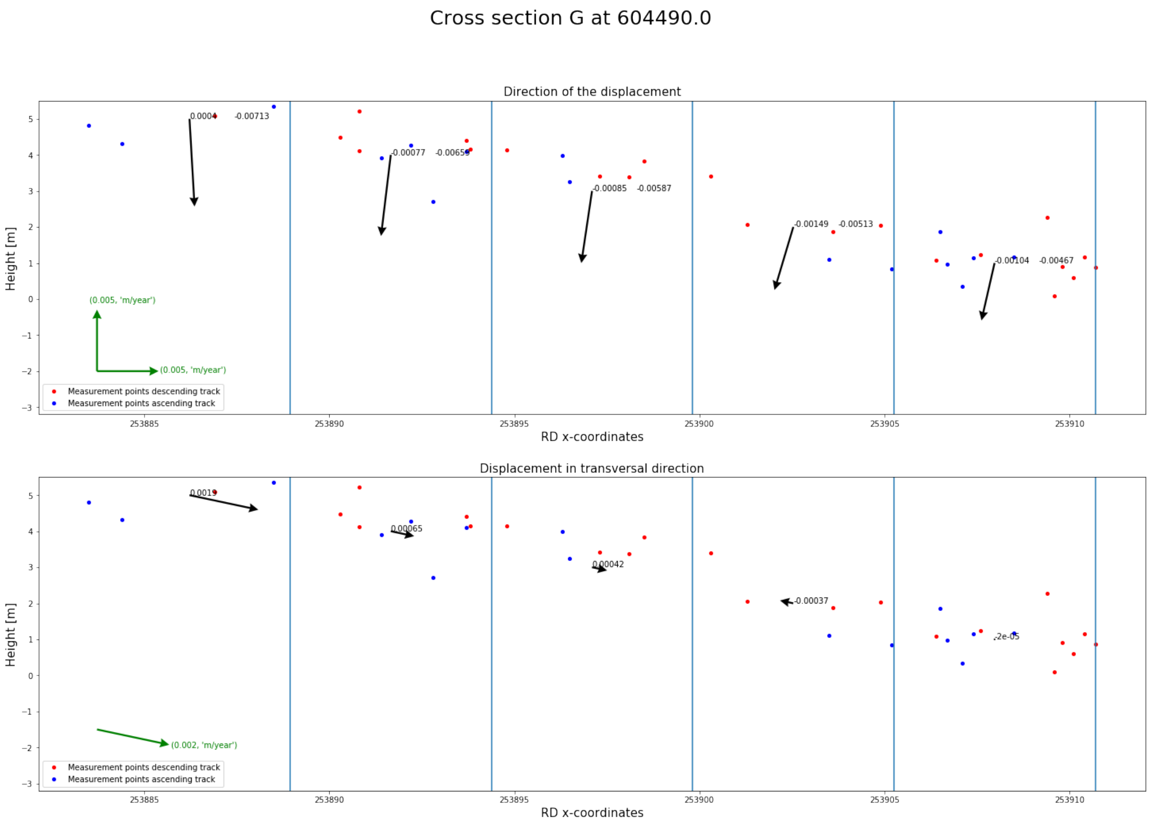


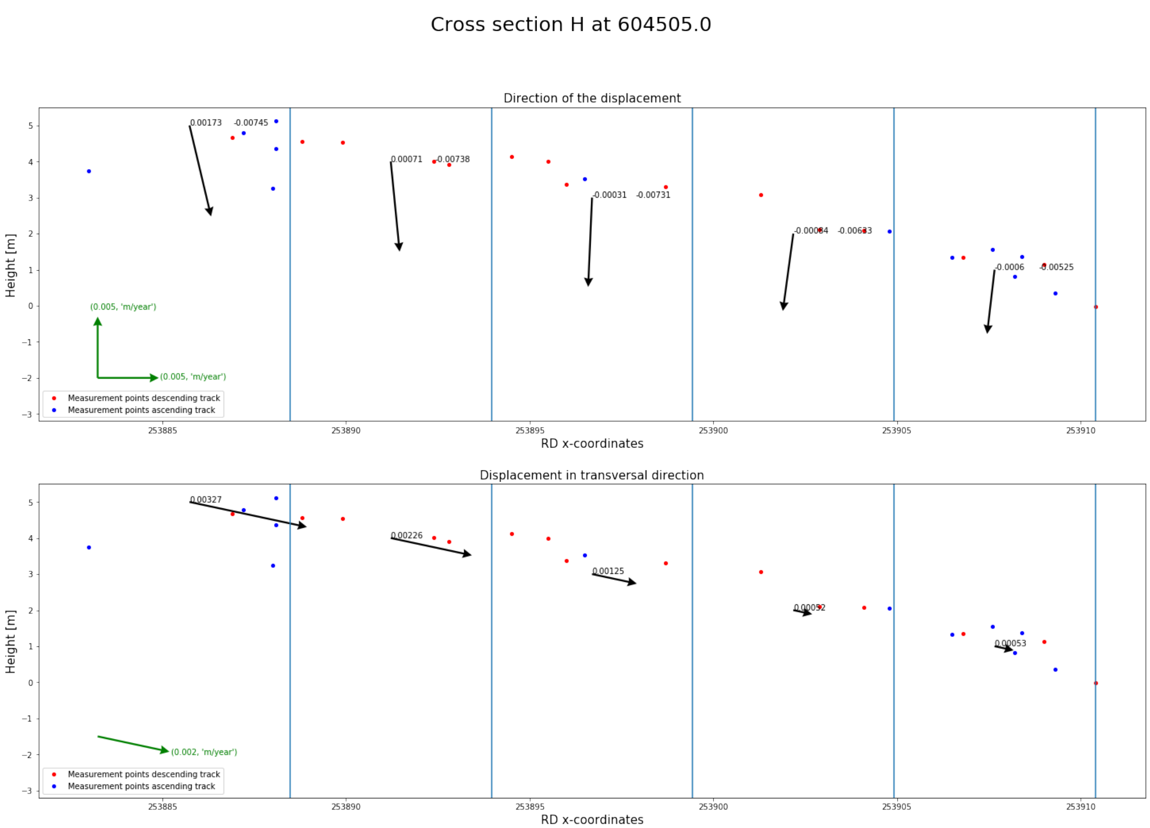
Cross section E at 604460.0



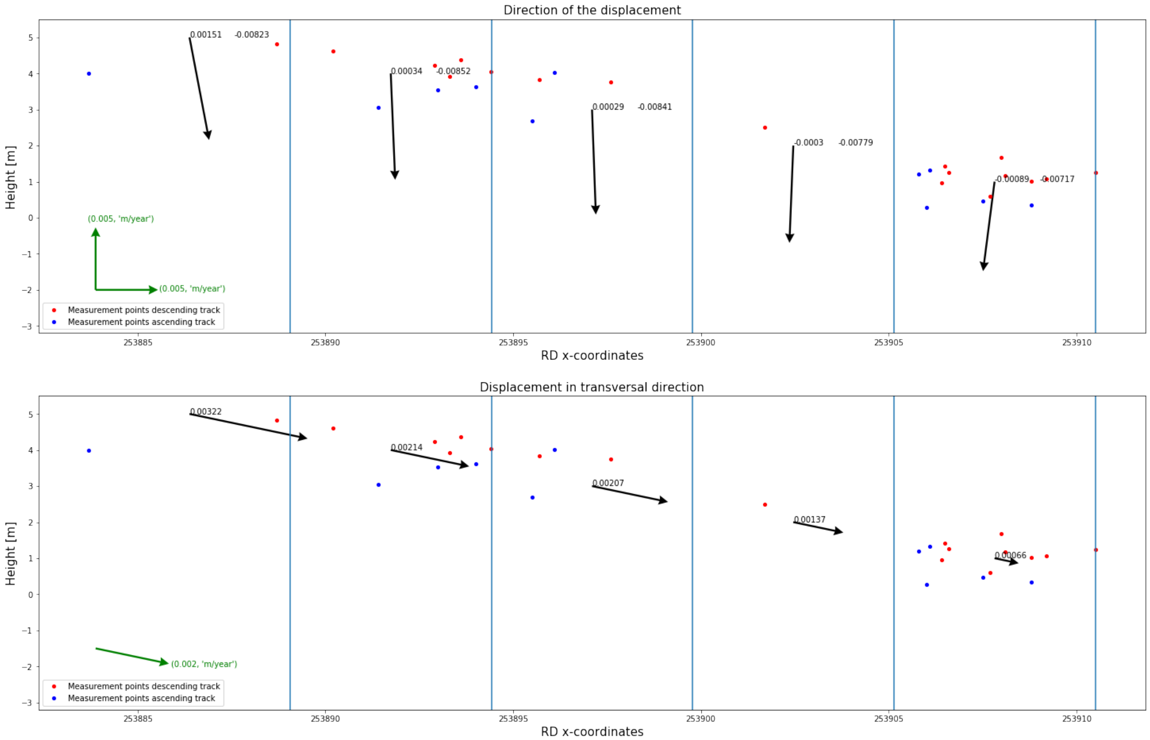
Cross section F at 604475.0



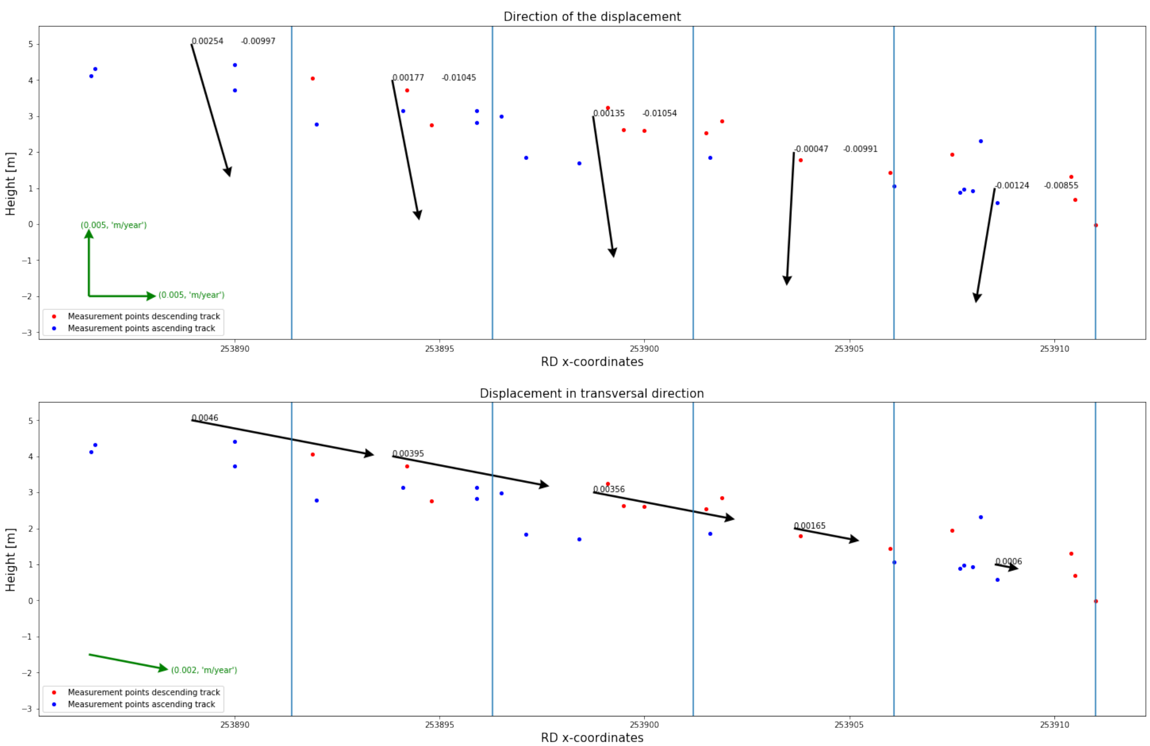

Cross section G at 604490.0
Direction of the displacement
Height [m]
RD x-coordinates
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Displacement in transversal direction
Height [m]
RD x-coordinates
(0.002, 'm/year')
Measurement points descending track
Measurement points ascending track

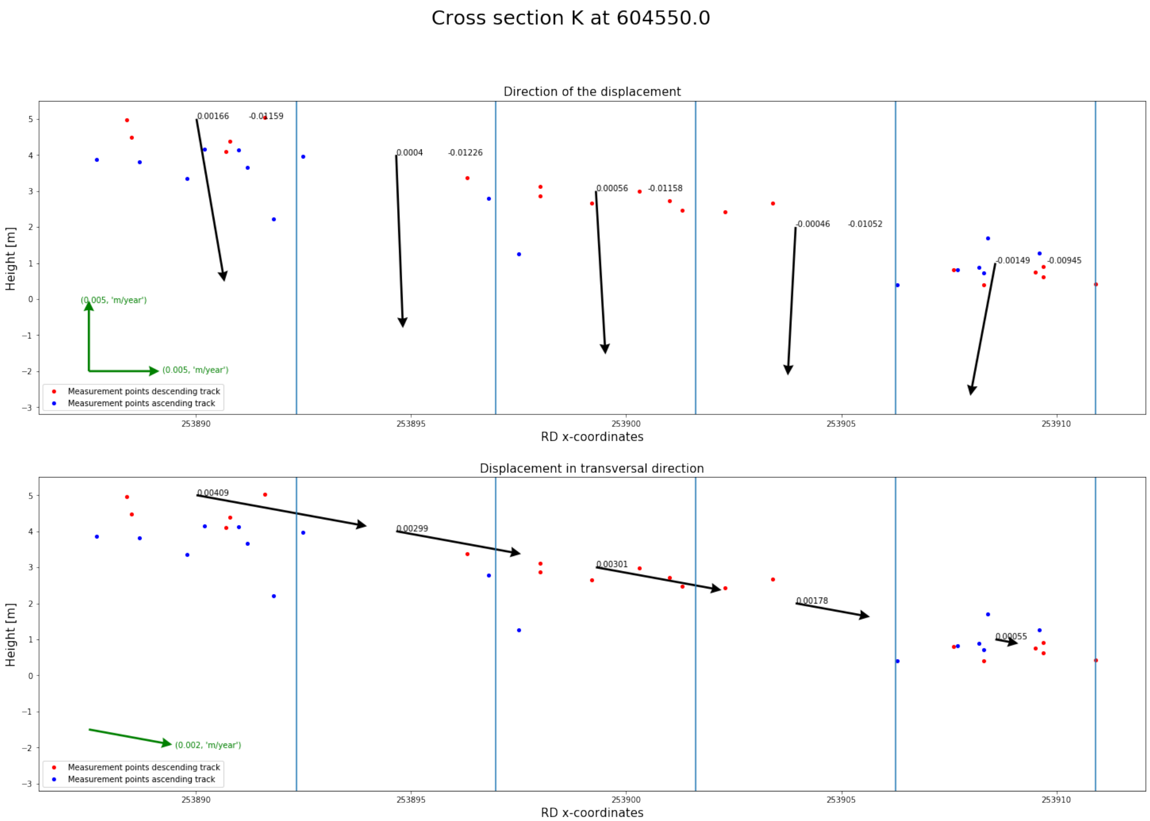

Cross section H at 604505.0
Direction of the displacement
Height [m]
RD x-coordinates
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Displacement in transversal direction
Height [m]
RD x-coordinates
(0.002, 'm/year')
Measurement points descending track
Measurement points ascending track

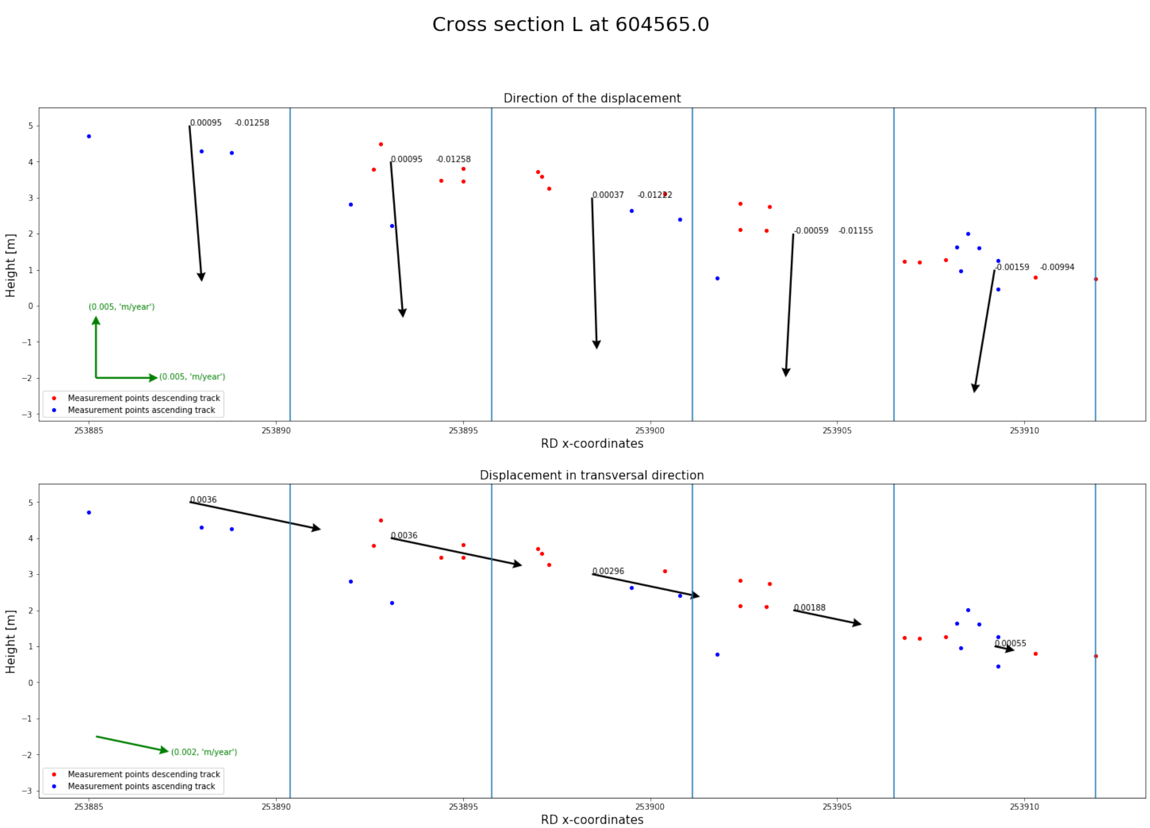
Cross section I at 604520.0



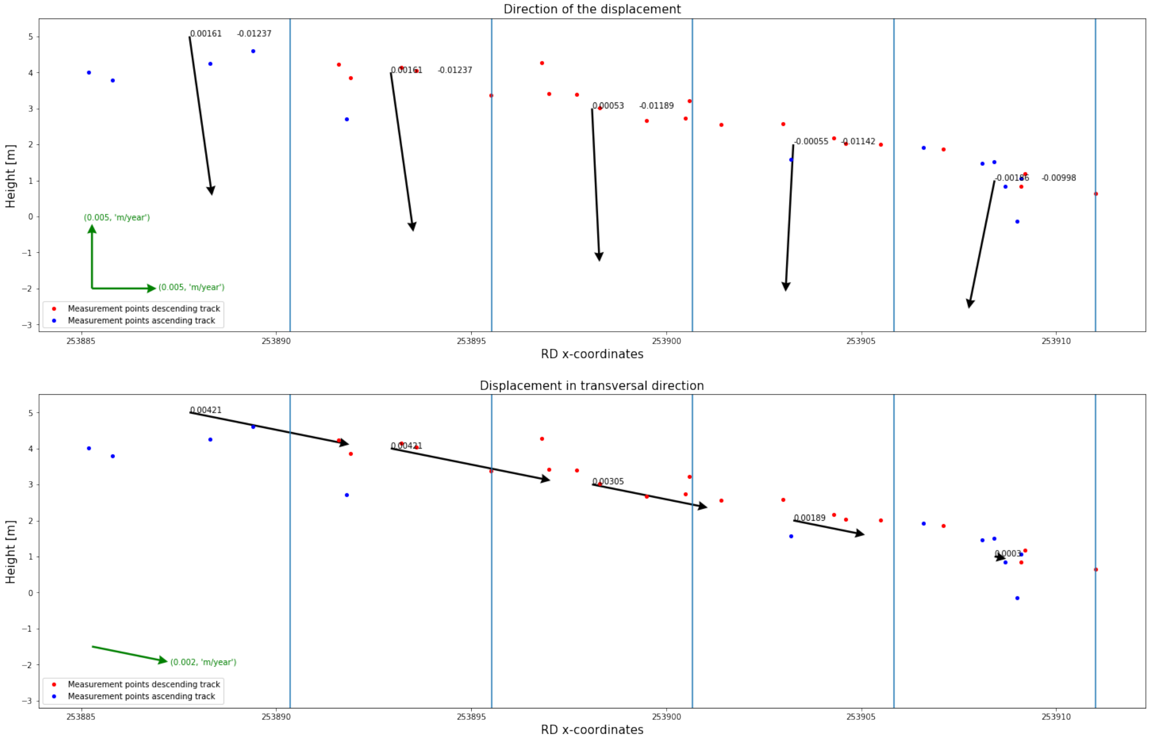
Cross section J at 604535.0



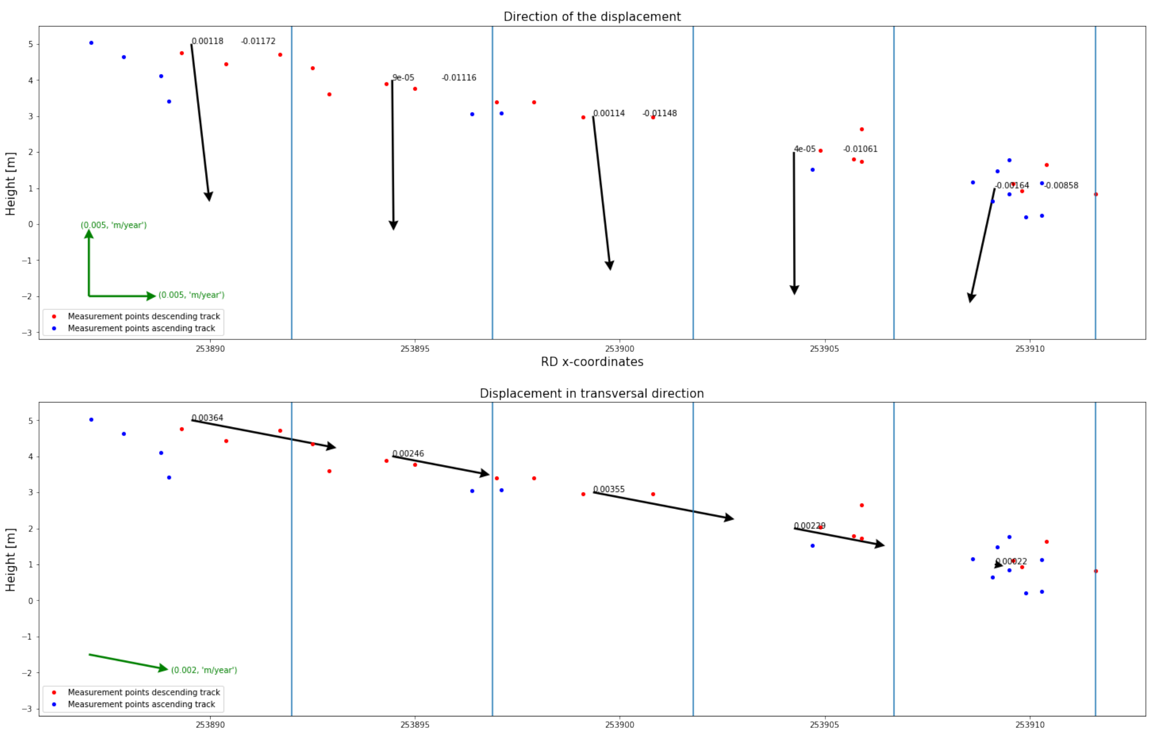

Cross section K at 604550.0
Direction of the displacement
0.00166
-0.01159
0.0004
-0.01226
0.00056
-0.01158
-0.00046
-0.01052
-0.00149
-0.00945
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Height [m]
RD x-coordinates
Displacement in transversal direction
0.00409
0.00299
0.00301
0.00178
0.00055
(0.002, 'm/year')
Measurement points descending track
Measurement points ascending track
Height [m]
RD x-coordinates

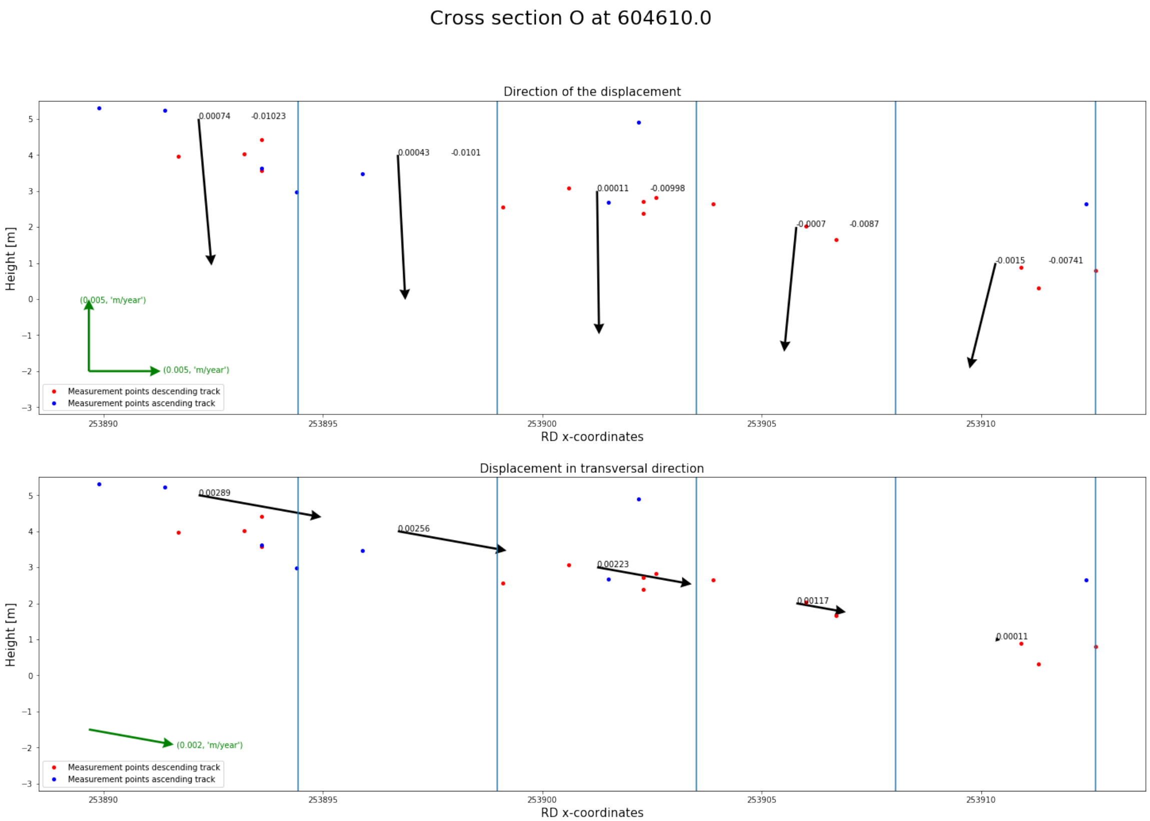

Cross section L at 604565.0
Direction of the displacement
0.00095
-0.01258
0.00095
-0.01258
0.00037
-0.01232
-0.00059
-0.01155
-0.00159
-0.00994
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Height [m]
RD x-coordinates
Displacement in transversal direction
0.0036
0.0036
0.00296
0.00188
0.00055
(0.002, 'm/year')
Measurement points descending track
Measurement points ascending track
Height [m]
RD x-coordinates

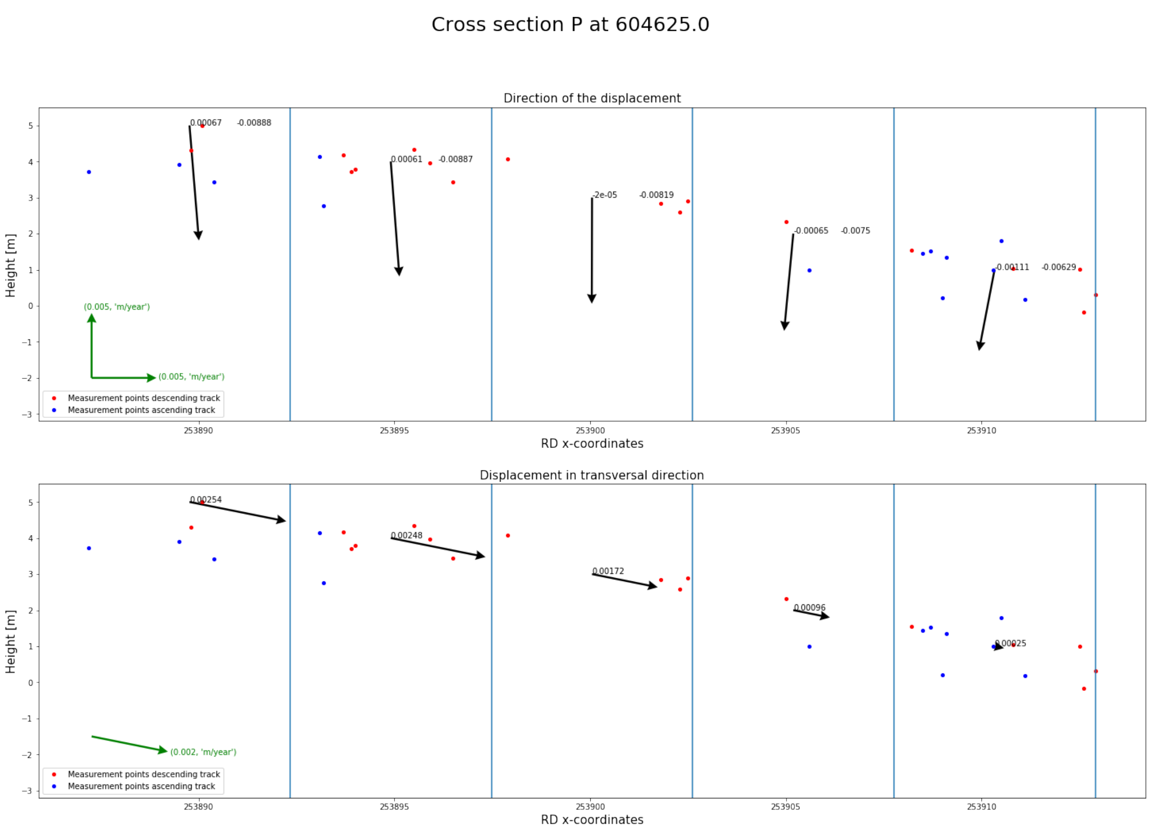
Cross section M at 604580.0



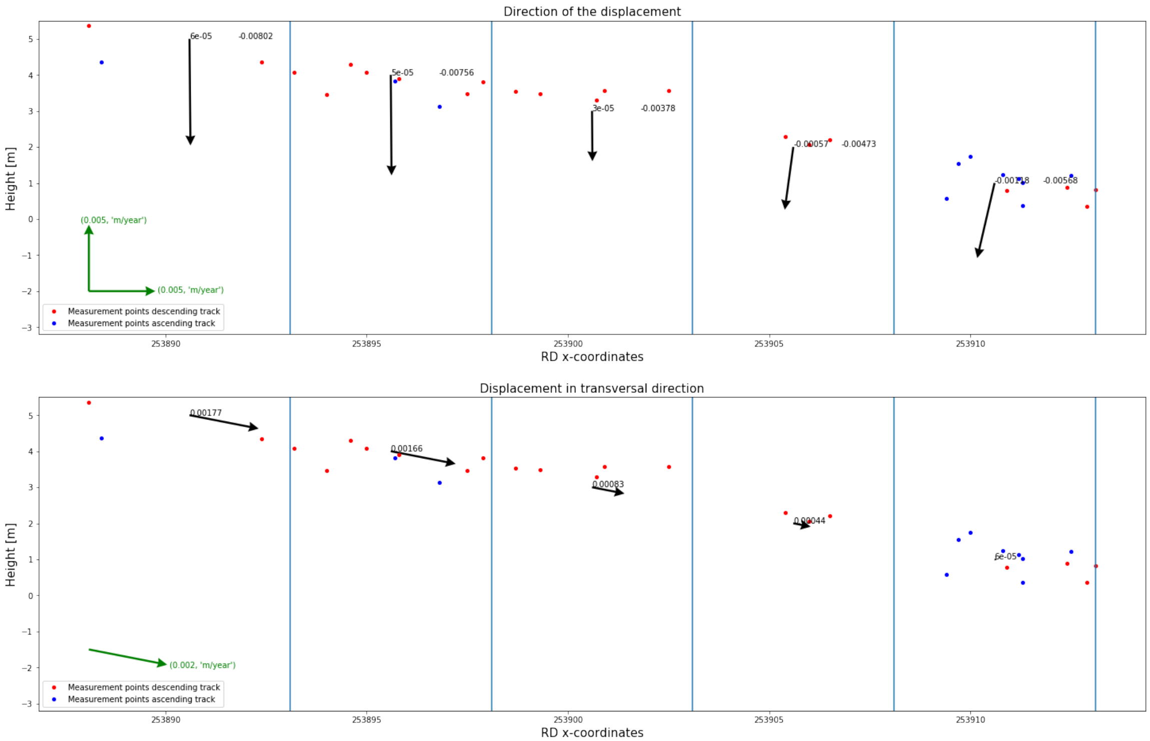
Cross section N at 604595.0



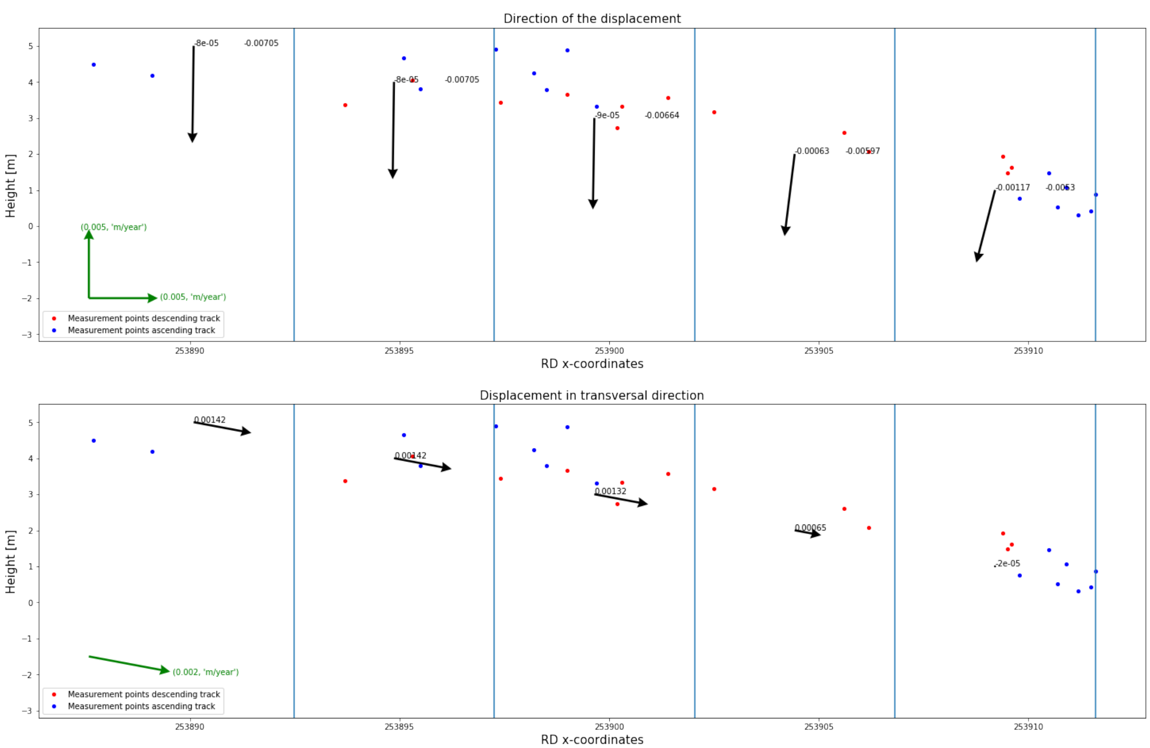

Cross section O at 604610.0
Direction of the displacement
0.00074
-0.01023
0.00043
-0.0101
0.00011
-0.00998
-0.0007
-0.0087
-0.0015
-0.00741
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Height [m]
RD x-coordinates
Displacement in transversal direction
0.00289
0.00256
0.00223
0.00117
0.00011
(0.002, 'm/year')
Measurement points descending track
Measurement points ascending track
Height [m]
RD x-coordinates


Cross section P at 604625.0
Direction of the displacement
0.00067
-0.00888
0.00061
-0.00887
-2e-05
-0.00819
-0.00065
-0.0075
-0.00111
-0.00629
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Height [m]
RD x-coordinates
Displacement in transversal direction
0.00254
0.00248
0.00172
0.00096
0.00025
(0.002, 'm/year')
Measurement points descending track
Measurement points ascending track
Height [m]
RD x-coordinates

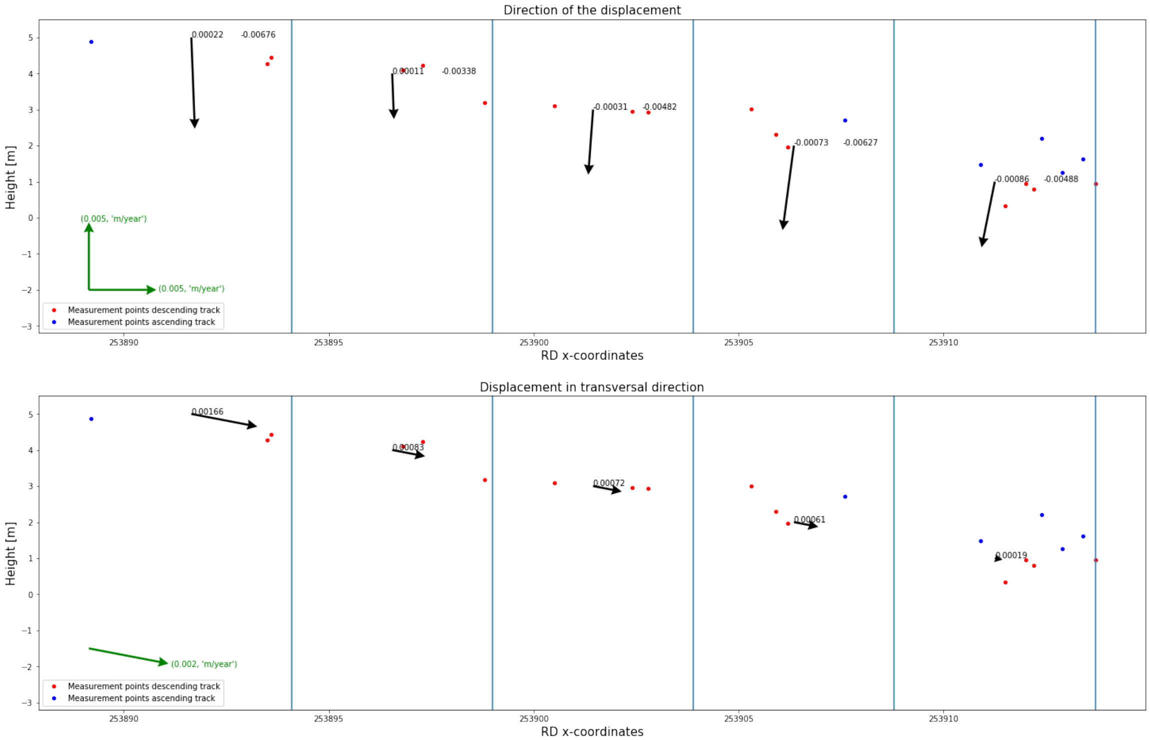
Cross section Q at 604640.0



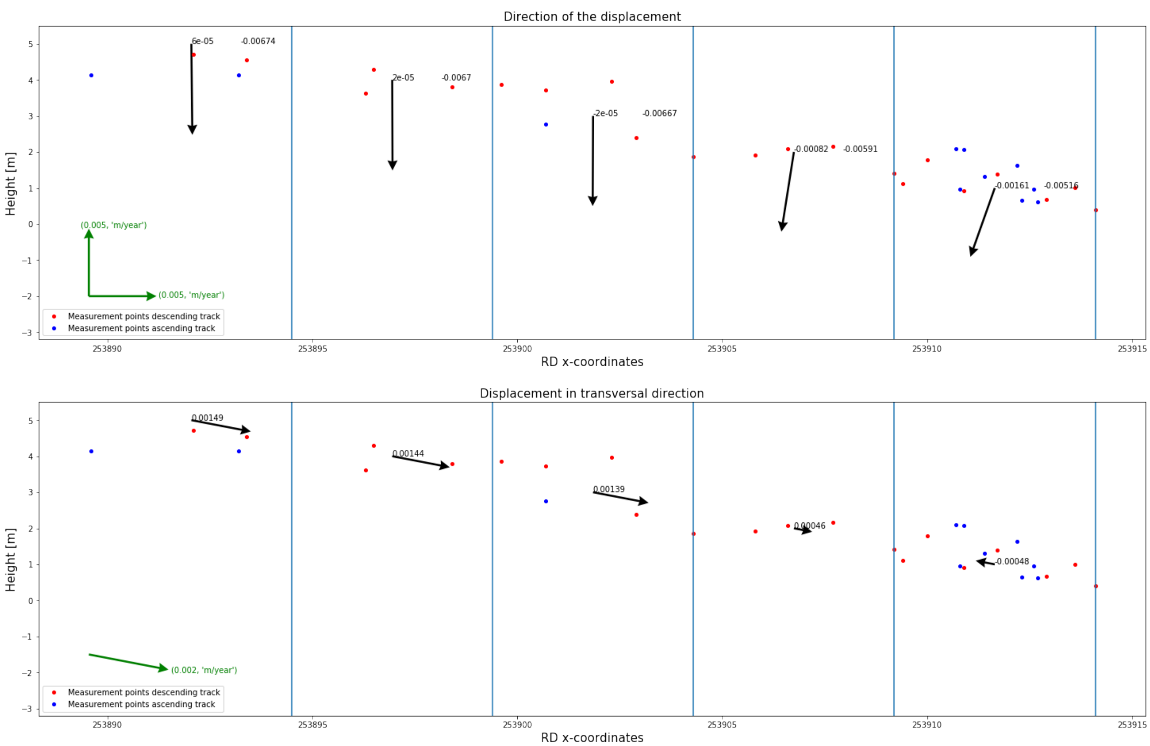
Cross section R at 604655.0



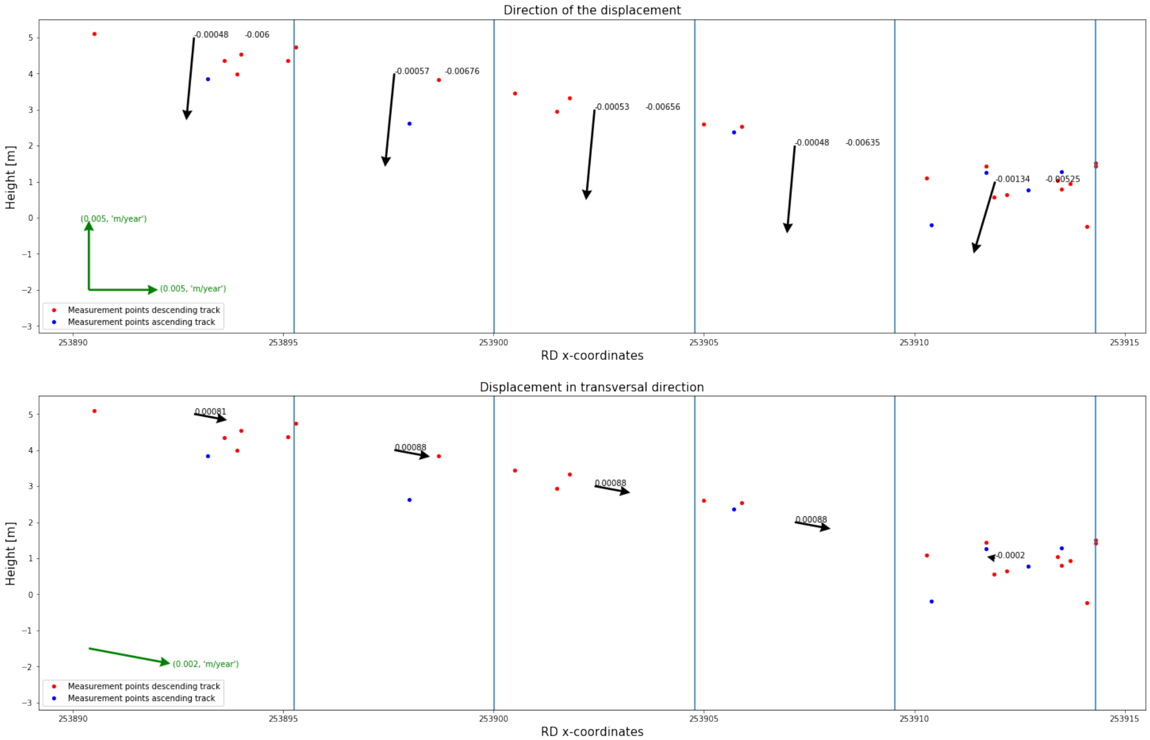
Cross section S at 604670.0



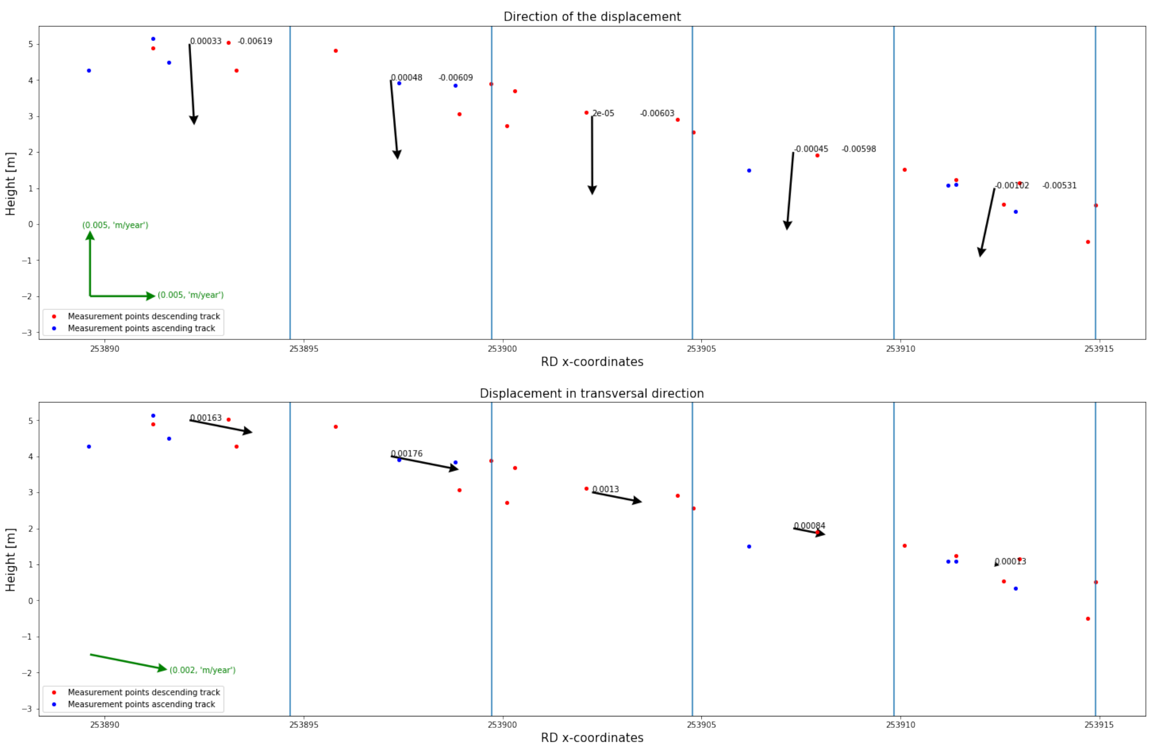
Cross section T at 604685.0

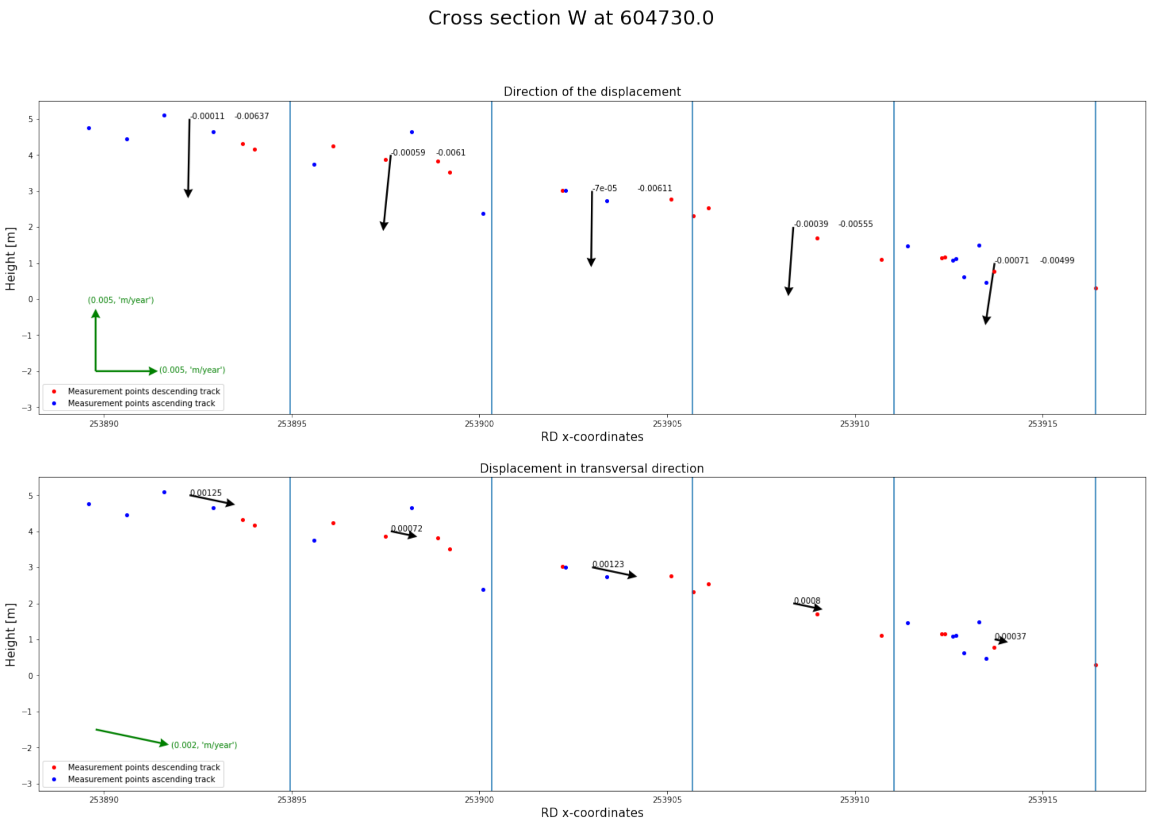


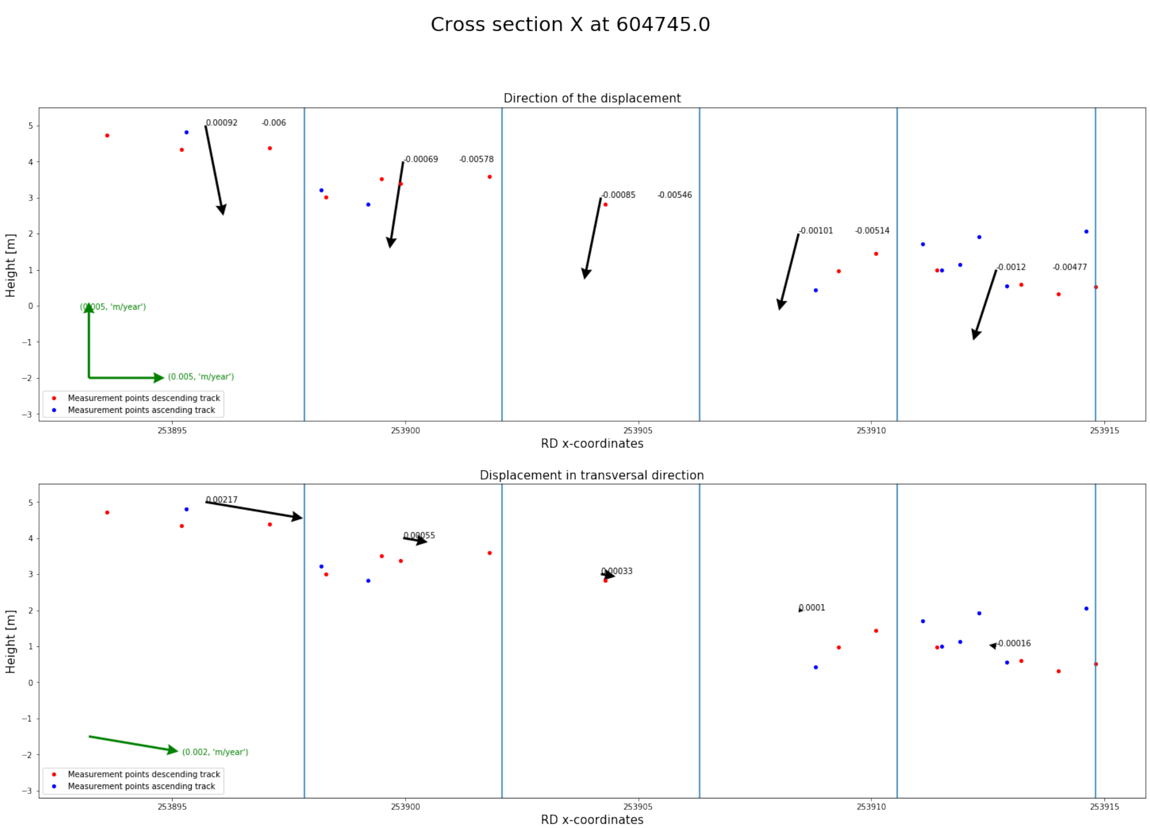
Cross section U at 604700.0

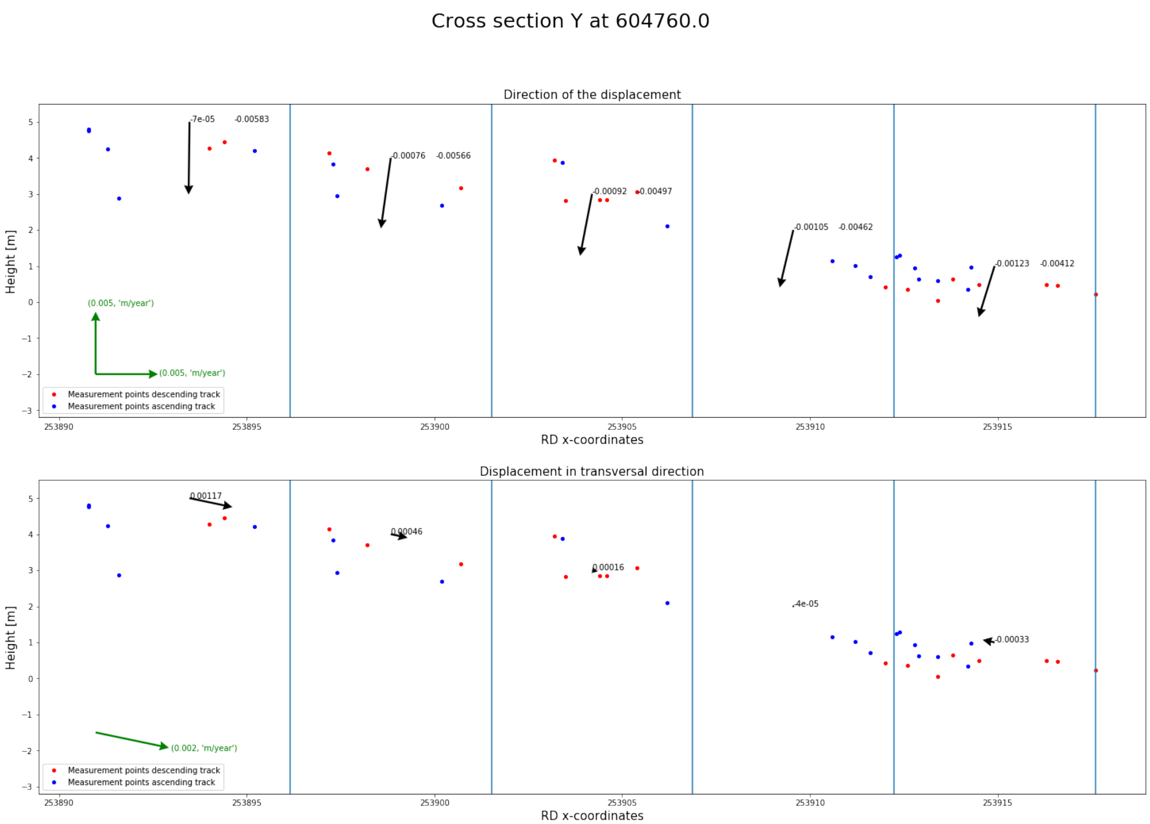


Cross section V at 604715.0




Cross section W at 604730.0
Direction of the displacement
Height [m]
RD x-coordinates
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
-0.00011
-0.00637
-0.00059
-0.0061
-7e-05
-0.00611
-0.00039
-0.00555
-0.00071
-0.00499
Displacement in transversal direction
0.00125
0.00072
0.00123
0.0008
0.00037
(0.002, 'm/year')


Cross section X at 604745.0
Direction of the displacement
Height [m]
RD x-coordinates
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
-0.00092
-0.006
-0.00069
-0.00578
-0.00085
-0.00546
-0.00101
-0.00514
-0.0012
-0.00477
Displacement in transversal direction
0.00217
0.00055
0.00033
0.0001
-0.00016
(0.002, 'm/year')


Cross section Y at 604760.0
Direction of the displacement
Height [m]
RD x-coordinates
-7e-05
-0.00583
-0.00076
-0.00566
-0.00092
-0.00497
-0.00105
-0.00462
-0.00123
-0.00412
(0.005, 'm/year')
(0.005, 'm/year')
Measurement points descending track
Measurement points ascending track
Displacement in transversal direction
0.00117
0.00046
0.00016
-4e-05
-0.00033
(0.002, 'm/year')