QUALITY ASSESSMENT OF GNSS/IMU DERIVED NAP HEIGHTS

USING RILA AND RDNAPTRANS2018

Rijkswaterstaat
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Abstract

The purpose of this thesis is to do quality assessment of GNSS/IMU derived NAP heights for The Netherlands (NAP) using Fugro RILA technique and the RDNAPTRANS2018 published by Rijkswaterstaat. The use of Global Navigation Satellite System (GNSS) is growing rapidly in order to determine the position (both horizontal and vertical). However, the GNSS is only able to give the geometric height which is the position on the ellipsoid, which have a drawback that the surface of constant ellipsoidal height are not equipotential surface, and hence these heights need to be transformed into traditional height systems such as the Normaal Amsterdam Peil (NAP) used in The Netherlands. In order to derive these NAP heights from the GNSS heights, a (quasi-) geoid model along with corrector surface model is used to convert from one height to another. In this study the newly computed local quasi geoid model NLGEO2018 rather than the NLGEO2008 is adapted using RDNAPTRANS2018 along with Fugro Rail Infrastructure aLignment Acquisition (RILA) technique which makes use of GNSS/IMU to obtain ellipsoidal height. It was found upon using the older transformation procedure RDNAPTRANS2008, which makes use of NLGEO2008, a mismatch in the order of 17mm between the NAP and GNSS-derived NAP from RILA. This error is not only due to the geoid itself but also the systematic errors in the different height system. However, this new geoid NLGEO2018 along with the new transformation procedure of RDNAPTRANS2018 allows a more accurate conversion of ellipsoidal to normal heights and this study focuses on this quality assessment of the new GNSS/IMU derived NAP heights and investigate how well NAP heights be obtained using RILA technique based on the new geoid. It was found with the use of the new geoid and the new transformation model RDNAPTRANS2018, the mean height difference was reduced from 12mm to 3.6mm showing a better fit of GNSS heights to NAP heights. An error budget was also calculated, to understand the reliability of these RILA measurements with the NAP heights. This error budget includes all the uncertainties from all error sources, namely RILA derived height, geoid height and the levelled height, followed by hypothesis testing. The highest uncertainty was from GNSS/IMU measurements from RILA system followed by the levelling and then the gravimetric quasi-geoid. Finally from this analysis, areas where the terrestrial surveying can be avoided was found. It was found that near the stations, tunnels, high vegetation had the highest uncertainty due to poor GNSS reception. It was also found that level crossing also showed a constant systematic offset between the two heights potentially due to the materials of the level crossings.

Preface

I would like to first of all thank my assessment committee Sandra Verhagen, Cornelis Slobbe and Hans van der Marel who were available throughout the whole project and helped me with the thesis throughout by providing their valuable feedback. They helped me in understanding the process and the problem in a brief and constructive manner. I would also like to thank my company supervisors Luc Amoureus from Fugro and Bas Alberts from Rijkswaterstaat who has provided me with all the guidance and answering all my stupid questions when I was stuck. I would also like to thank ProRail for the meetings we had in the past year and through the research for further analysis of this study. Finally special thanks to Jasper Hellemons from Fugro, who gave this opportunity to me and believed in me.

Moreover, I would also like to thank my friends and family with their love and support which also made it possible for me to finish my thesis.

U. Rajvanshi
Delft, October, 2021

Contents

List of Acronyms

GNSS Global Navigation Satellite System

IMU Inertial Measurement Unit

RD Rijksdriehook

NAP Normaal Amsterdams Peil

RILA Rail Infrastructure aLignment Acquisition

LiDAR Light Detection And Ranging

GCP Ground Control Points

CORS Continuously Operating Reference Stations

VRS Virtual Reference Stations

MSL Mean Sea Level

IAG International Association of Geodesy

NN Nearest Neighbor

PMG Primaire Meetkundige Grondslag

1 Introduction

The Dutch railways have seen a huge increase in the amount of people travelling, and with this increase in percentage of the people travelling every year, rail monitoring becomes of huge importance to make sure the travel is efficient and safe. Rail monitoring is not a new concept and has been carried out since the 19^{th} century. Traditionally, surveyors would use leveling for determining vertical heights since it is a very accurate measuring method, and countries all over the world have defined their own vertical datum as their official reference system for heights. The official vertical datum used by The Netherlands is the *Normaal Amsterdams Peil* (NAP) or Amsterdam Ordnance Datum, which is the reference surface for heights. NAP is currently published every 10 years for relatively stable areas and 5 years for unstable areas through a second order network. Heights are positional attributes for geo-related data and become an essential in surveying, engineering, mapping and other geoscience activities (Steinberg and Even-Tzur, 2008) (Varga et al., 2016).

The use of Global Navigation Satellite Systems (GNSS) along with aid from other sensors such as IMU and LiDAR has seen a rapid growth in surveying over the past decades in order to determine the horizontal positioning and the geographic height. One such measurement system is the RILA (**R**ail **I**nfrastructure a**L**ignment **A**cquisition) system developed by Fugro that can collect large amounts of geographical and geometric data, like the absolute and the relative track geometry, required for rail monitoring, in a short period of time by connecting a carbon fiber unit to a train. The RILA system is able to connect to any passenger train and measure at line speed up to 200 kmph without the need to alter or affect the train's normal operating performance. It consist of GNSS receiver of 5Hz and IMU of 300Hz with a 360° LiDAR scanner. The system is able to provide the horizontal and the vertical positioning in both absolute and relative heights. (Fugro, n.d.)

Despite the fact that leveling results into very accurate results, it is also one of the most time consuming, expensive and labour intensive methods. As a result, countries are trying to exploit GNSS/leveling to obtain heights w.r.t. the (quasi-)geoid[1] , and have started adopting a normal height system. The geoid is defined as the equipotential surface of the Earth's gravity field that corresponds most closely with the mean sea level (Hofmann-Wellenhof and Moritz, 2006). In the Netherlands, a local quasi-geoid model has been recently computed by Slobbe et al., 2019 using remove-compute-restore procedure with the expectation that this model allows a more accurate conversion of GNSS derived (ellipsoidal) heights to NAP (normal) heights. The vertical distance between the quasi-geoid and the reference ellipsoid is called the quasi-geoidal height or height anomaly, denoted as ζ Vaníček et al., 2012. The relation between the ellipsoidal height obtained from the GPS h and the normal height H_N can be defined as:

$$h_{GPS} = H^N + \zeta \tag{1.1}$$

See Fig. 1.1. Given the quasi-geoid undulation ζ, one can determine normal height using the ellipsoidal height (Gillins, 2017). However, GNSS-derived normal heights depend on the achievable accuracy of the ellipsoidal heights and geoid undulation data (Steinberg and Even-Tzur, 2008) and countries worldwide try to get the best possible accuracy by improving their geoid models. (Featherstone, 1998)(Featherstone et al., 1998) (Zilkoski, 1990)(Saari et al., 2015).

[1]The term quasi-geoid and geoid are interchanged throughout this report, however they are not the same, but differences are very small

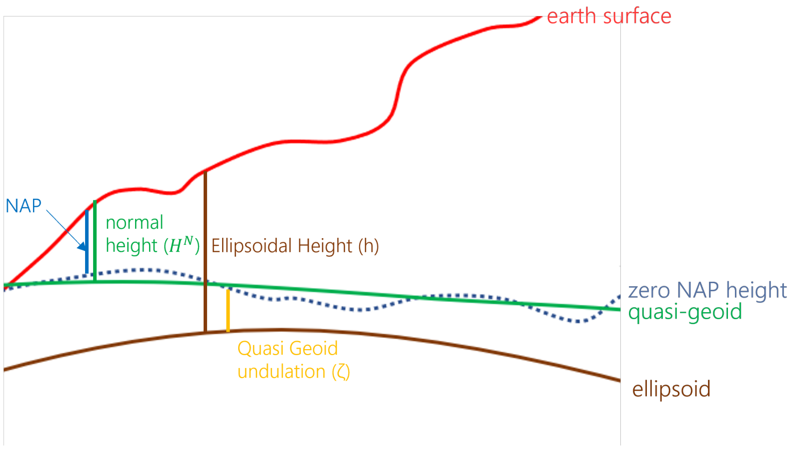

Figure 1.1: Height reference system showing orthometric, ellipsoidal and geoid height along with the geoid, NAP, ellipsoid and earth surface

The total transformation from elliposidal heights derived from GNSS measurements to RD and NAP (and vice versa) is officially known as RDNAPTRANS™[2] In 2008, the version RDNAPTRANS2008 was released using NLGEO2008, where the transformation paramaters were revised from previous RDNAPTRANS model due to the adjustment of the location of the Netherlands in Europe. In 2019, with the publication of RDNAPTRANS2018 and the release of NLGEO2018, the transformation and the correction grid have also been revised and with the idea that RDNAPTRANS2018 provides a better connection from ETRS-89 to RD-NAP.

In the past years Fugro performed a large number of rail track surveys using the train-mounted RILA system. These projects are commissioned by ProRail in the Netherlands to provide accurate information about the rail geometry which is then used for rail maintenance but also to combine with other data (such as the LiDAR from helicopter) in a consistent reference system and as the basis for construction work (stake out, *in Dutch: maatvoering*), which requires the need of absolute height within acceptable accuracy.

The track from Den Bosch to Nijmegen was surveyed four times in 2016 using the RILA system. However, biases between heights derived from GNSS/IMU and the levelled NAP heights when connecting them back using RDNAPTRANS2008 were found. As mentioned in above, GNSS/IMU derived normal heights depend on the quality of the GNSS data but also on the quality of quasi-geoid. This becomes important when comparing the data processed using RDNAPTRANS™2008 or the latest released RDNAPTRANS and the significant differences observed with the two tranformation models. In order to do such an assessment, Ground Control Points (GCP) can be used as validation measurement, despite them also having uncertainty associated with it. But since the uncertainty coming from GCP is much lower than a system using GNSS/IMU, they can be used as validation. Upon usage of GCP and GNSS/IMU post-processed data with RDNAPTRANS2008, a misfit of over 2.5cm was found in certain areas. Since acquiring these GCP data at the center of the railtrack is expensive and labor-demanding, it becomes of vital importance to check upon the quality of these GCPs as well. Since there has been no rigorous assessment of height differences between RILA derived NAP heights and NAP heights based on GCP, this research will aim to do this assessment. Since GCP height data may be affected by outliers, a procedure will be proposed to identify and remove those, in order to get hold of good validation data. This kind of analysis demands for preparation of total error budget, which this research also aims to achieve.

Another motivation for this analyis is that organisations like ProRail and Rijkswaterstaat want to avoid leveling too close to the tracks because of number of reasons such as operational costs, safety and technique being expensive to implement. Moreover, the result of this analysis is important for NSGI (*Nederlandse Samenwerking Geodetische Infrastructuur*)and Rijkswaterstaat to understand what geodetic infrastructure such as good transformation between ETRS89 and NAP is needed for users like ProRail and Fugro.

[2]RDNAPTRANS™ is a trademark under NSGI, and throughout this report is mentioned as RDNAPTRANS only, unless necessary

The goal of this research is to analyse the impact of the new RDNAPTRANS2018 on the GNSS-IMU rail measurement campaigns and investigate how well NAP heights can be derived from Fugro RILA measurements, making the additional terrestrial measurements superfluous. The basis of this research is the following research question:

> **What is the impact of using RDNAPTRANS2018 on the accuracy of the NAP heights obtained with the Fugro train mounted RILA system upon comparing them to validation data from Ground Control Points?**

In order to make the research more structured, sub-questions have been formulated:

1. What is the impact of RDNAPTRANS2018 on the quality of GNSS derived NAP heights compared to RDNAPTRANS2008? Do the differences between leveling- and GNSS/leveling-derived NAP heights improve? What is the variation in height from point to point, both relatively and absolutely.
2. Which validation points (ground control points) can be used and what kind of outlier removal strategy is to be applied in order to get hold of good set of points which are reliable?
3. What are the contributors in the total error budget used in this assessment including RILA derived GNSS heights, levelling and quasi-geoid heights using RDNAPTRANS2018?

The thesis is organised as follows: In Chapter 2 a theoretical background is provided to inform the reader about GNSS, geodetic datums and the Fugro RILA system. Chapter 3 showcases the data used throughout the research and the methodology is explained about the RILA data processing along with RDNAPTRANS2018 procedure. The results can be found in Chapter 4 along with discussion of the results. Finally a conclusion answering the research questions and recommendations are available in Chapter 5.

2

Height Determination using RILA

2.1. RILA system

The RILA (**R**ail **I**nfrastructure a**L**ignment **A**cquisition) system developed by Fugro is a measurement system that can collect large amounts of geospatial data, like the absolute and the relative track geometry of the rail track, reducing the measurement cost and increasing the measurement frequency. The RILA system can be mounted to any passenger train and other types of rail vehicles as can be seen in Figure 2.1. Using the RILA system, data can be collected without impeding regular railway operations and without any roadway workers on or near the track. Moreover such a measurement system can be used for specific tasks such as track maintenance and gauging. The RILA system is an attractive solution when compared to traditional terrestrial survey methodologies, allowing modelling of a railway network to a very high level of accuracy. Within this 3D information data set, many different users are able to extract their required information without the need for a site visit, or traditional surveying improving even further the safety profile. The RILA system integrates laser scan technology with GNSS/IMU and three video cameras.

2.1.1. RILA Sensors

The RILA system consists of a GNSS receiver of 5Hz and an IMU of 300Hz with a 360° LiDAR scanner and three cameras. Figure 2.1 shows an image of the RILA system mounted on a Dutch train showing all the system components. Relative GNSS positioning using Continuously Operating Reference Stations (CORS) network and surveying of the track is done at least four times resulting in a precision of $15mm$ for the vertical heights and $8mm$ for the horizontal location, given good GNSS reception and good availability of CORS.

The RILA system also comes equipped with two rail scanners which projects a laser beam on each rail using laser vision systems and captures the rail profile. In addition, the relative track geometry can be derivative from the absolute track position, which determines the track maintenance and safety issue.

Furthermore, the data is combined with 360° laser scanner and a panoramic imaging system to supply ultra-high density LiDAR point cloud data of the entire route. Each laser scanner rotates at 200 Hz, recording one million points per second. With the 3D point cloud, the rail corridor can be measured in high accuracy which can be used to check clearances and overhead catenary systems.

2.1.2. RILA Data Processing

The RILA data processing consists of mainly three steps from the start of trajectory processing, GNSS processing to point-cloud matching. Since the results obtained are independent from the train type the procedure of RILA data processing is similar in all cases. The calculated GNSS location of the GNSS antenna is determined by using a reference GNSS CORS network. The absolute position is calculated during post-processing during which the GNSS and the IMU data are combined using either loosely coupled approach or tightly coupled approach depending on the survey environment, and together with the data from a CORS network, the position, velocity and the orientation of the RILA system is calculated. After processing, the trajectory of both systems are presented in a global coordinate

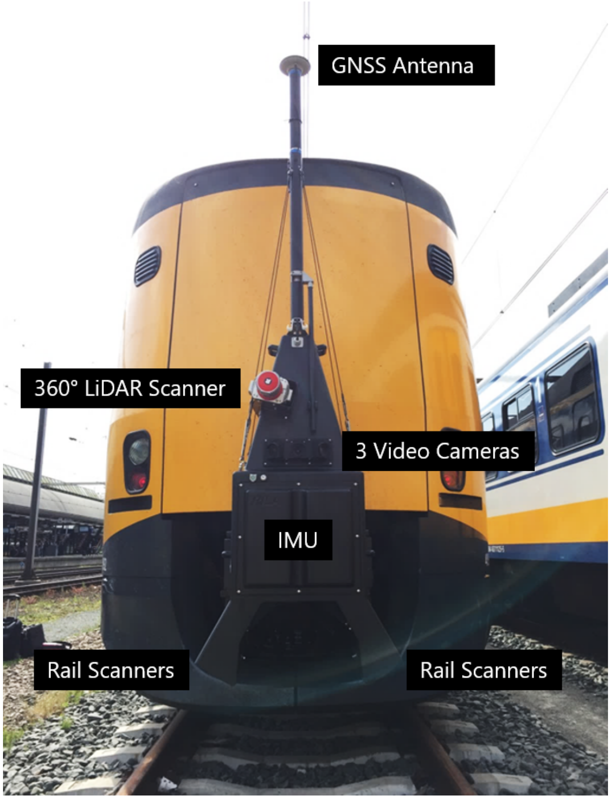

Figure 2.1: Fugro RILA 6.0 system and its components (Credits: Fugro)

system, ETRS-89 for The Netherlands. With the combination of GNSS and IMU the coordinates and angles (roll, pitch and heading) of the RILA frame are calculated. See Figure 2.2 for the flow chart of this processing method.

Along with the IMU data, the lever arm calibration and the laser scanning measurements a track center line for each survey run can be determined (See Figure 2.3 for track center line visualisation). This is called a RILA Track dataset. The quality of this RILA Track is primarily determined by the accuracy of the kinematic GNSS/IMU processing. Typically, the standard deviation of a kinematic GNSS trajectory is around $25mm$ in horizontal and $35mm$ in vertical. During the calculation of the RILA Track the algorithms make use of the very specific geometrical properties of rail tracks. Rail tracks will always have a smooth course without any sharp curves. When combining several RILA track center lines one can get an idea of the improvements in the precision that follows from these special geometrical properties of rail track.

Since the standard modus operandi is to measure 4 runs, which all result in an independent track position, it is possible to get an accurate track center line by a weighted average of these 4 runs. The standard deviation of the average will be smaller than that of the individual runs. Finally, a correction algorithm is applied where the track distances based on the LiDAR data is used as ground truth to correct the results of RILA track lines. This methodology can be found in Figure 2.4. The uncertainties for these individual processing steps at 95% confidence can be found in Table 2.1.

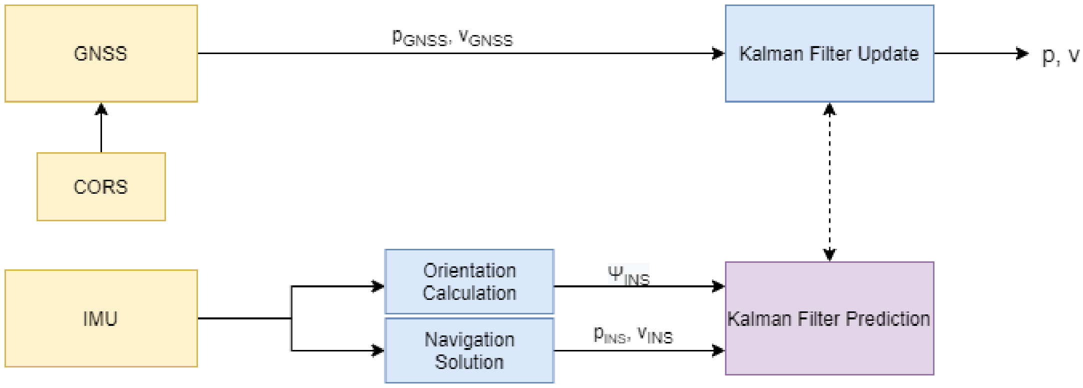

Figure 2.2: Real time RILA trajectory processing pipeline using GNSS, IMU and CORS. p and v are the position and velocity attributes respectively, and Ψ is the orientation

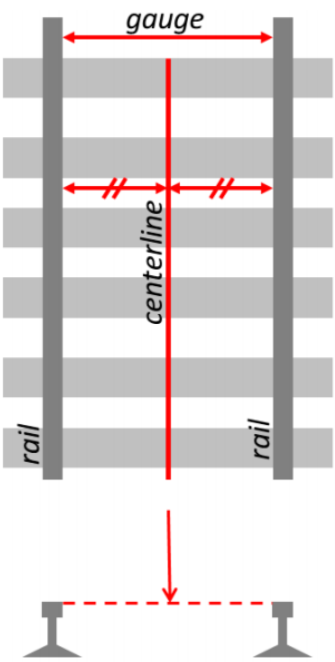

Figure 2.3: Schematic presentation of centerline, gauge and rails (Oude Elberink and Khoshelham, 2015).

Standard Deviation	Horizontal (2D) position [mm]	Vertical position (Z) [mm]
Absolute Track center line positioning (only RILA-Track)*	10	15
Absolute Track center line positioning (RILA-Track + RILA360 integrated)*	8	12
Absolute RILA360 Point Cloud positioning (RILA-Track + RILA360 integrated)	10	15

Table 2.1: Uncertainties involved with the RILA positioning. (* based on minimum 4 surveys with good GNSS reception) (Fugro, nd).

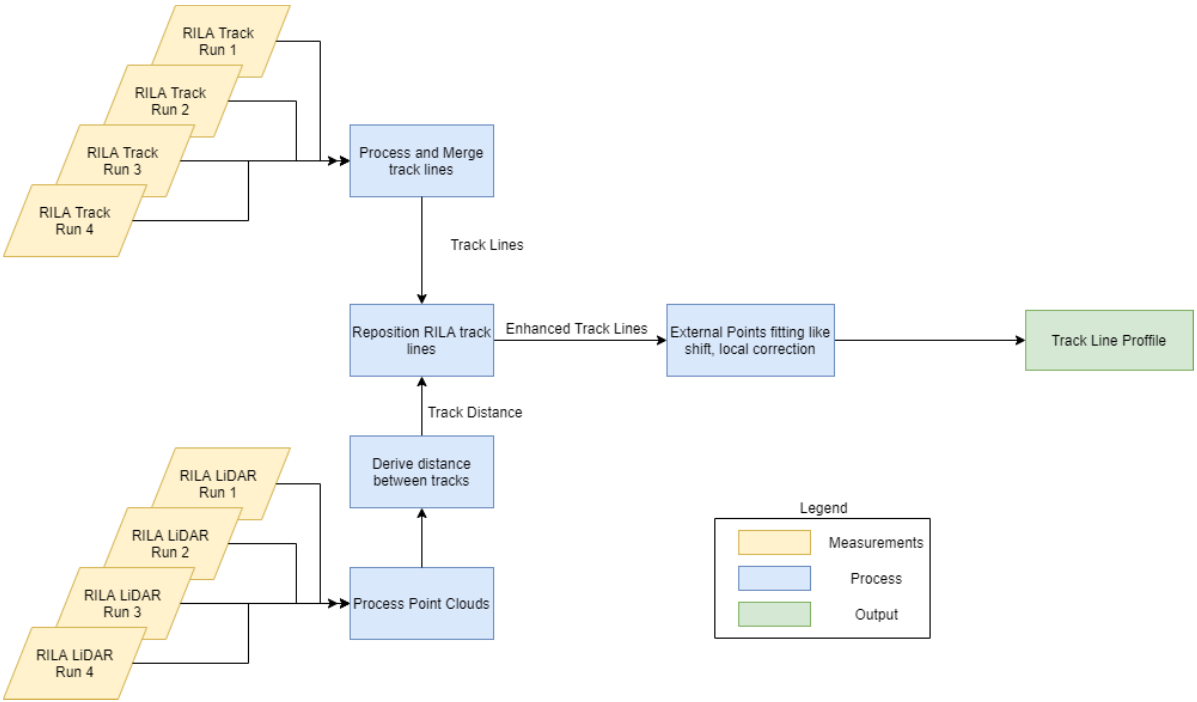

Figure 2.4: RILA Track and RILA 360 merge data processing using external points (GCP).

2.2. Height systems and transformations

In order to define the height systems, firstly Earth is modelled with an ellipsoid. The most commonly used ellipsoid to describe the shape of the Earth is the World Geodetic System 1984 or commonly known as WGS 84 defined by the US Defence Department and Geocentric Reference System 1980, GRS 80 defined by International Association of Geodesy (IAG). Upon using GNSS on certain position, the position obtained is the position with respect to the ellipsoid.

The main drawback of ellipsoidal heights is that surfaces of constant ellipsoidal height are not equipotential surfaces. Hence, in an ellipsoidal height system, it is possible that water flows from a point with low 'height' to a point with a higher 'height'. This defies one on the main purposes of height measurements: defining water levels and water flow (van der Marel, 2020). Another important part in the height system and transformation is the, (quasi-)geoid. The geoid is an equipotential surface which coincides with the mean sea level (MSL) over the ocean considering when there would not be any winds or currents perturbing the ocean surface and neglecting tidal forcing, solid Earth movements and hydrology. Since gravity is dependent on the Earth mass, the (quasi-)geoid is shown as irregular surface. The heights that are given in relation to the national height datum are heights above the (quasi-)geoid (or close to it because of the errors associated with calculation of the quasi geoid) by making use of traditional surveying technique called as levelling. These heights are also referred to as normal heights and are purely levelled heights. The height reference system can be seen in Figure 1.1. However, GNSS-derived normal heights depend on the achievable accuracy of the ellipsoidal heights and geoid undulation data (Steinberg and Even-Tzur, 2008). Countries worldwide try to achieve accurate geoid models, since the vertical component obtained with GNSS provides the least accuracy out of all three components. For more information regarding the height systems, the following literature is recommended: (Gillins, 2017)(Featherstone, 1998)(Featherstone et al., 1998) (Zilkoski, 1990)(Saari et al., 2015) (Fotopoulos, 2005)(Fotopoulos et al., 2003)(Fotopoulos, 2003)(Hein and Rockville, 1985)(Kim et al., 2018).

2.2.1. RDNAPTRANS2008 and RDNAPTRANS2018

The official coordinate transformation between European ETRS89 coordinates and Dutch coordinates in RD and NAP is called RDNAPTRANS ("RDNAPTRANS - NSGI", 2020) (Lesparre et al., 2020) . It is determined by the partnership of Kadaster, Rijkswaterstaat and Dienst der Hydrografie, working together under the name Nederlandse Samenwerking Geodetische Infrastructuur (NSGI). The RDNAPTRANS transformation procedure is well documented and example source code of the older versions in C and MATLAB is available free of charge. Since the introduction of RDNAPTRANS in 2000, several new versions have been released. The current version is RDNAPTRANS™2018. This version contains a new datum transformation based on the updated ETRS89 coordinates of realisation ETRF2000 with a new and more precise quasi-geoid grid model is used. This NLGEO2018 quasi-geoid model covers a larger area including a large part of the North Sea. A change with big impact is the use of a new data format of the grid files and a corresponding transformation procedure that changes the order of the steps of the transformation and uses a fixed height in the datum transformation (see Figure 2.5). As a result, the transformation is now possible conform a de facto standard by including the datum transformation in the correction grid (variant 2). This allows straightforward implementation in software like GIS packages and can resolve current problems due to incorrect implementations of the transformation (Lesparre et al., 2020). In this study variant 2 has been made use of to do conversion using RDNAPTRANS procedure.

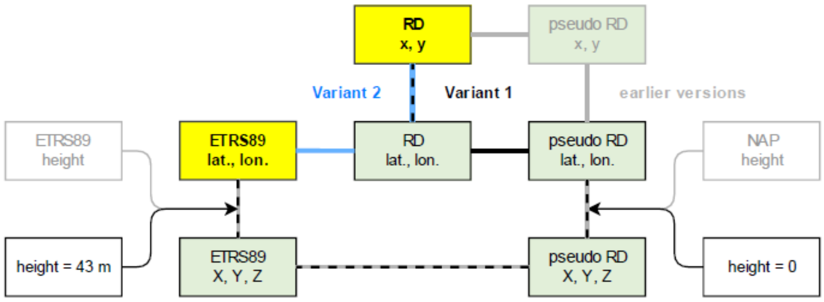

Figure 2.5: Transformation procedure of RDNAPTRANS™2018 implementation variant 1 (black lines) and implementation variant 2 (blue lines) compared to RDNAPTRANS™2008 and earlier versions (grey lines). (Lesparre et al., 2020)

2.2.2. NLGEO2008 and NLGEO2018

The NLGEO2004 geoid is used for the RDNAPTRANS2004 and RDNAPTRANS2008 procedure, which made use of some 13,000 relative gravitational measurements which were carried out in a grid of almost 8,000 points (1 point per 5 km^2 (Bruijne et al., 2005) along with additional gravitational measurements on Belgian and German territory and a set of 84 GPS/levelling points from the fifth precise levelling to define a correction surface to the gravimetric geoid (Bruijne et al., 2005)(van der Marel, 2020). The geoid can be seen in Figure 2.6 with geoid height in meters with respect to the GRS80 ellipsoid in ETRS89. Over the land area of the Netherlands, the precision of the NLGEO2004 geoid is $1.3cm$ and upon applying an innovation function (Slobbe et al., 2019), this reduces to $0.7cm$.

In 2018, a new quasi-geoid called NLGEO2018 was computed for the Netherlands and Exclusive Economic Zone by Slobbe et al., 2019 based on remove-computer-restore approach using a parametrisation of spherical radial basis functions. This approach accounts for systematic errors in the gravity datasets and enables a proper error propagation and the computation of the full variance-covariance matrix of the resulting quasi-geoid (van der Marel, 2020)(Slobbe et al., 2019). As can be seen in Figure 2.6 on the left, the model was computed over a much larger domain than NLGEO2004 using radar altimetry data, terrestrial gravity anomalies, airborne gravity disturbances, and shipboard gravity anomalies. In Figure 2.7, the differences between the two quasi-geoids is shown, with a mean value of $7.3mm$. NLGEO2018 makes use of the same GNSS/Levelling points as that of NLGEO2004, however differences are observed in the two geoids primarly due to reprocessing of the GNSS heights, a different innovation function and higher resolution of the grid.

2.2.3. Normaal Amsterdam Peils (NAP)

Normaal Amsterdams Peil or commonly known as NAP is the official height reference system in the Netherlands dating as early as 1818. The primary NAP grid is comprised of about 300 underground points and 70 posts (*nulpalen*). In order to be able to determine the height relative to the NAP everywhere in the Netherlands, approximately 35,000 benchmarks have been installed throughout the country. These NAP level marks have a height relative to the NAP and are anchored in residential houses, bridges and viaducts or structures with an appropriate stability. This way the water level or the height of a building can easily determined. Nearly anywhere in the Netherlands, a benchmark can be found within a distance of 1 km.

To support the exploitation of the NLGEO2018 gravimetric quasi-geoid for the conversion of GNSS derived heights to the NAP height system, several post-processing steps must be applied. First, as the NAP height system is a mean-tide height system and the quasi-geoid was transformed from the zero-tide to the mean-tide system. Thereafter, a corrector surface (also called 'innovation function') has been estimated from the differences between the geometric quasi-geoid at 82 GNSS/levelling points and the gravimetric quasi-geoid. Finally, the transformation from the tide-free permanent tide system adopted in the GNSS community and the mean-tide system adopted in NAP, has been applied (Slobbe et al., 2019).

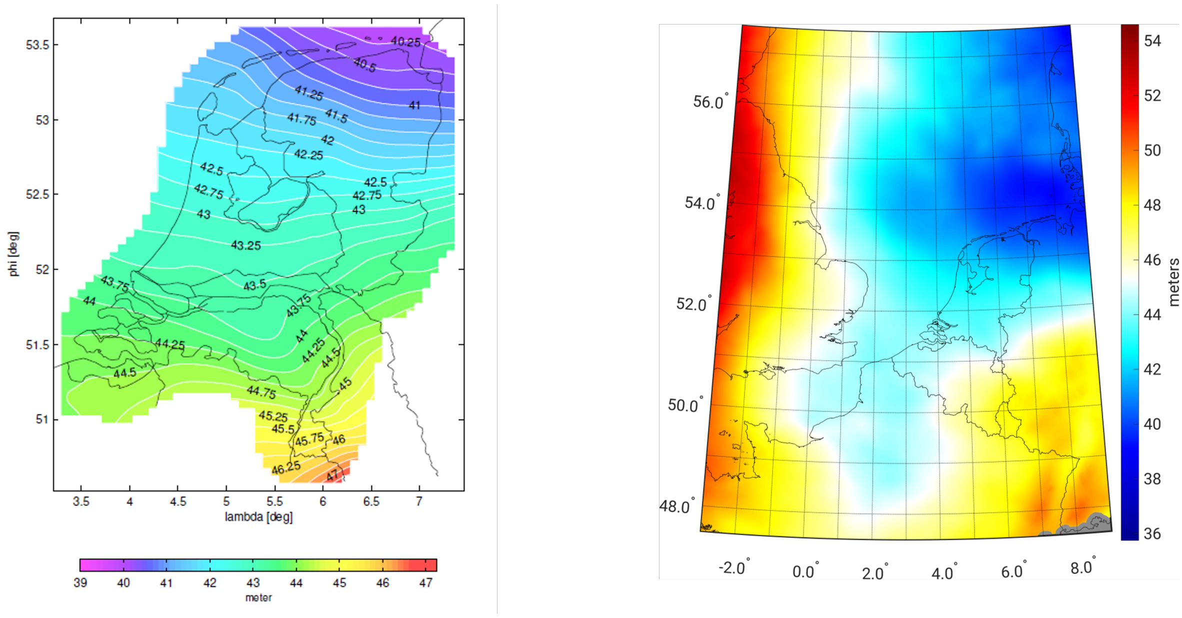

Figure 2.6: left: NLGEO2004 used in RDNAPTRANS2008 with geoid height in [m] with respect to the GRS80 ellipsoid in ETRS89 ((Bruijne et al., 2005), right: NLGEO2018 quasi–geoid for the Netherlands with geoid height in [m] with respect to the GRS80 ellipsoid in ETRS89. Clearly visible the much larger domain over which the NLGEO2018 quasi–geoid is computed (Slobbe et al., 2019)

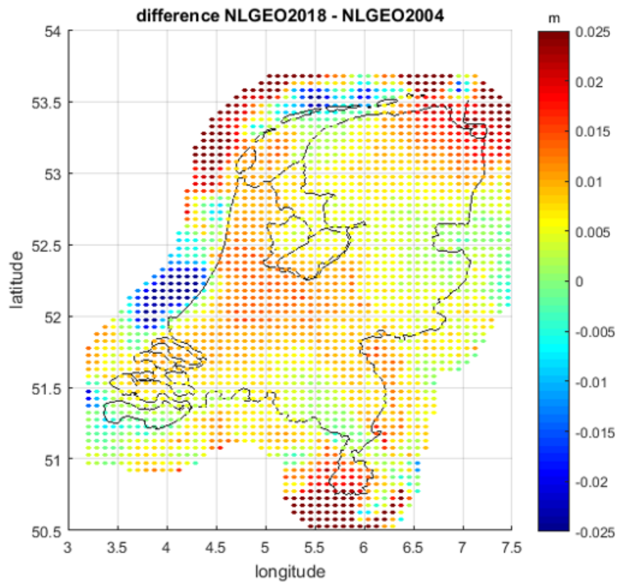

Figure 2.7: Differences between NLGEO2018 and NLGEO2004

3

Data and Methodology

In this chapter, the data used throughout this research to assess the quality of RILA-derived heights along with the methodology applied to answer the research questions introduced in Chapter 1 is explained.

3.1. Data

In this research, the rail track which is focused on to assess the new quasi-geoid is *Den Bosch* to *Nijmegen*, where the acquisition of the RILA data was performed in 2016. The prominent reason to choose this data set was mainly due to the fact that the control points were measured during the same period of the acquisition of data, which rules out the error due to subsidence or other natural phenomenons. The rail track is shown in Figure 3.1. It is to be noted that the methodology mentioned in this chapter is applicable for all the surveys where RILA data acquisition has been carried out.

In order to validate the RILA measured heights, terrestrial measurements using classic levelling technique or total station are required. Hence 19 level crossings located between Den Bosch and Nijmegen were measured with traditional terrestrial levelling techniques with reference to a national geodetic network of benchmarks. Due to limited access for the levelling survey team, also 7 bridges were measured by a mirrorless total station survey (See Fig. 3.2). Coordinates of level crossings and bridges were calculated and used as control points for the height. Also 3D coordinates of 13 switches on Den Bosch, Oss, Wijchen and Nijmegen stations were measured by total station and were used as fitting points.

Figure 3.1: Scope of the project from Den Bosch to Nijmegen

Figure 3.2: Geographic overview of control points (yellow = XYZ for switches, blue = Z for crossings and bridges)

3.2. Methodology

As mentioned in Chapter 1, an offset between RILA derived NAP heights using RDNAPTRANS2008 and levelled NAP heights was found. It was speculated that one of the reasons for this offset could be due to the GNSS-IMU processing. A previous research was conducted by Fugro to check if the offset in RILA elevation height was indeed due to processing. For this purpose, a setup was designed with RILA collecting GNSS data and a Leica GPS receiver collecting data and a total station measuring the distances accurately. Then these observations were processed and then cross-referenced with each other to check for the possibility of wrong computations in the process. However, it was concluded that in transforming the trajectory data from ETRS89 to the RDNAP and then georeferencing the results and railhead detection no abnormal shift was applied to the results. It was concluded that the other resources that could bring uncertainty to the results are either GNSS processing using Virtual Reference Stations or RDNAPTRANS procedure and the external control points which were used to validate the results. This research aims to check for the quality of heights with RDNAPTRANS™2018 and the ground control points used by Fugro. This will be done by applying the following procedures.

3.2.1. Implementation of RDNAPTRANS™2008 and RDNAPTRANS™2018

As introduced in earlier chapter about the RDNAPTRANS procedure, the offset was observed by making use of RDNAPTRANS2008. which makes use of NLGEO2008. The new quasi-geoid model NLGEO2018 aims to provides a better connection to the NAP heights, therefore it is important to update the RILA Track lines (merge from 4 surveys) based on NLGEO2018. This is applied using RDNAPTRANS2018 by making use of the python library `pyproj`[1] and making use of the NLGEO2018 grids. However, since the heights were already in NAP heights from RILA, it was decided to make use of RDNAPTRANS2008, in order to convert the heights in ETRS-89.

The final merged track center line (called RILA Track Line in Figure 3.4) was converted into ETRS89 coordinates making use of the old quasi-geoid grid and RDNAPTRANS correction grid. These were then processed with new quasi-geoid to give what in this report is being referred to as the updated heights.

3.2.2. Projection of RILA captured heights in ProRail mileage

All railway lines in the Netherlands can be identified with a unique *geocode*, which is defined as a number between 1 and 999 (shown in red in Figure. 3.3). In combination with the mileage on a railway line (shown as 2 digit number in black in Figure. 3.3), the location of each piece of railway line can be indicated. The combination for example, 095/7.860 (=geocode/kilometre), is the location of the Dorpsweg level crossing in Maartensdijk, taking the center of the road as the measuring point. ProRail uses this data for the management and maintenance of the railway lines and is their linear reference for railways. Since the result from GNSS/IMU processing and implementation of RDNAPTRANS™ results in *Rijksdriehook* coordinate system, the data needs to be aligned with ProRail mileage reference in

[1]GitHub link available via: https://github.com/pyproj4/pyproj

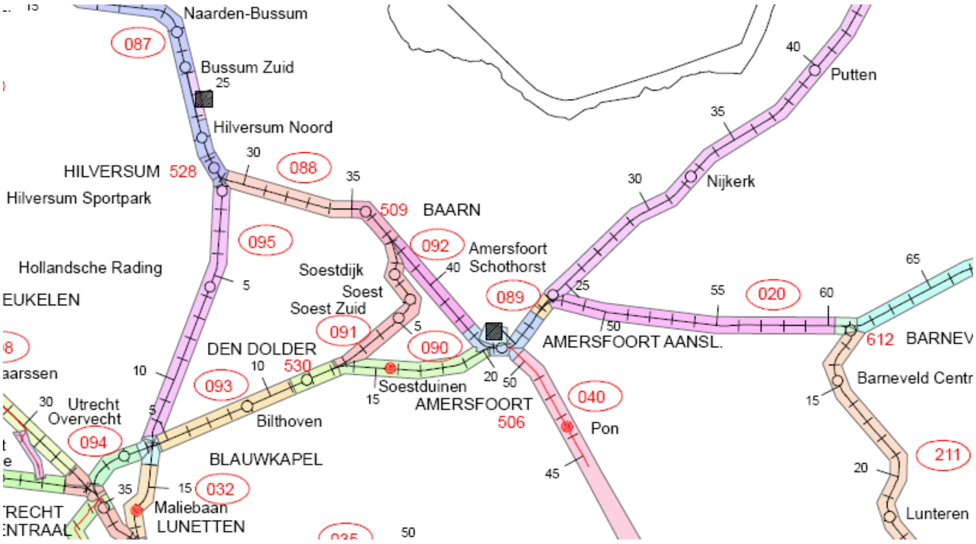

Figure 3.3: ProRail Geocode and Kilometer point shown in red and black respectively (ProRail)

order to assess and compare the data. This is done by linear interpolating the hectometer points using the geocode, and assigning mileage to each X, Y location nearest to the hectometer point.

3.2.3. Error Analysis

In order to do any impact assessment, error analysis is major part of that research. This means getting hold of good validation dataset by applying certain outlier removal strategy along with preparation of total error budget to understand the reliability of RILA measurements with levelled heights. Finally, variogram analysis is performed to understand the spatial variability between t data points as function of their distance and relative variation among these points.

An overview of the methodology used in this research can be found in Figure 3.4

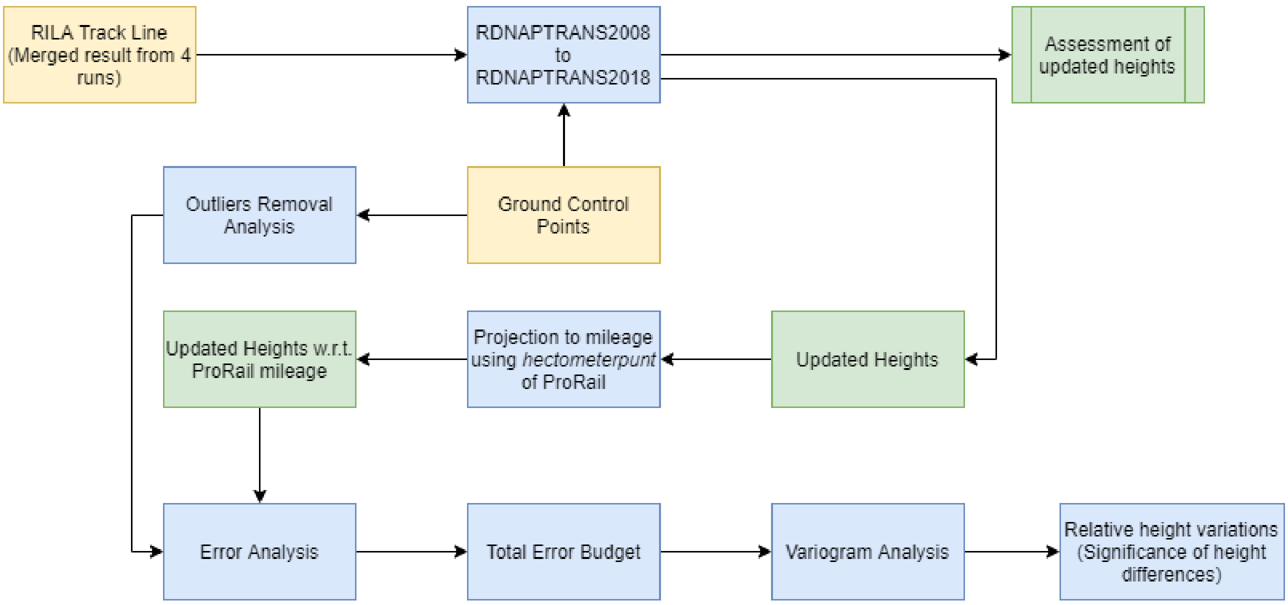

Figure 3.4: RILA Track height update based on NLGEO2018 quasi-geoid

4

Assessment of RILA-derived heights

As already mentioned in Chapter 3, the focus of this research is on the assessment of RILA derived heights for the Den Bosch to Nijmegen route. This chapter is devided into three main sections. The chapter starts by giving an overview of the impact of RDNAPTRANS2018 procedure over RDNAPTRANS2008 in Section 4.1 explaining the behavior of ground control points, followed by the outlier removal strategy in Section 4.2. Finally the error budget is computed and analysed in Section 4.3.

In Figure 4.1 the original survey heights with reference to the NAP can be found which used RDNAPTRANS2008 to provide RILA derived NAP heights. The data is plotted as the function of RILA track chainage which can be defined as the length of the track which gives individual value of chainage for each track. Every 1 meter of track holds information about the track centre line height and the from the merge of four individual runs. Upon plotting the heights on chainage in Figure 4.1, it can be seen that from 170km onwards the data is mirrored on the horizontal axis. It is not surprising since from 120km to 170km is the track run from Den Bosch to Nijmengen and from 170km onwards the train is returning back from Nijmegen to Den Bosch on adjacent track.

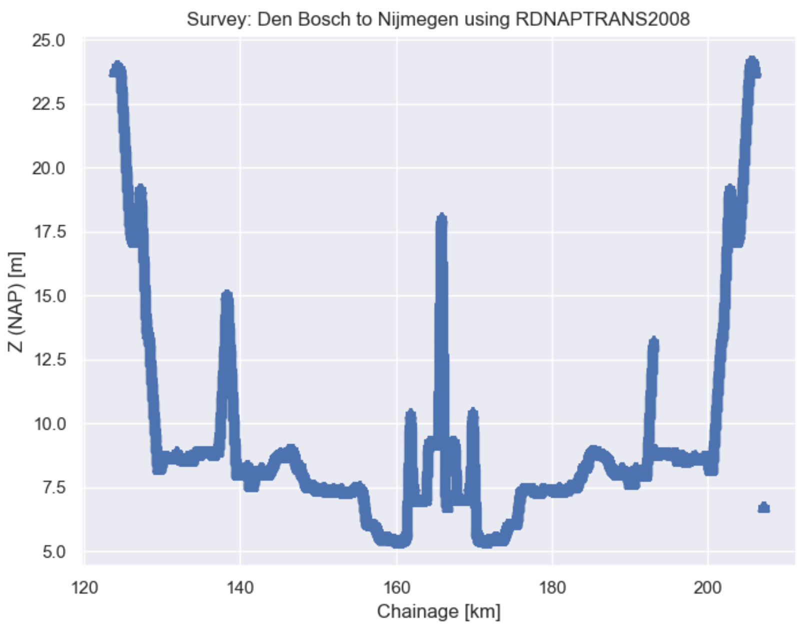

Figure 4.1: Processed RILA heights with reference to NAP based on RDNAPTRANS2008

4.1. Impact of RDNAPTRANS™2018 over RDNAPTRANS™2008

In this section, assessment of RDNAPTRANS2018 over RDNAPTRANS2008 is studied. Firstly the implementation of variant 2 of RDNAPTRANS2018 is scripted using *Python* and verification of the implementation from NSGI website (“RDNAPTRANS - NSGI”, 2020) is confirmed. This was made possible by using the newly computed quasi-geoid NLGEO2018, where the transformation was done directly to the corrected heights given by the model in RDNAPTRANS2008 to RDNAPTRANS2018 using the vertical datum grid and the quasi-geoid grid. This implementation was verified based on the test done using https://www.geopinie.nl/transform/rdnap_etrs89_transformation.

The result of the RDNAPTRANS2018 application can be seen in Figure 4.2 for the combined survey of four runs finalised in August 2016 along with the residual height in bottom figure, which is defined as the absolute difference between the height obtained from 2008 and 2018 transformation model. The horizontal axis shows chainage based on RILA kilometrage and the vertical axis shows NAP heights obtained with RDNAPTRANS2008 and RDNAPTRANS2018. Since the scale of image expands along $100km$, and the differences in the heights are in centimeter level, the blue and orange line seem to be on top of each other, and hence the residual heights can be seen in the bottom panel.

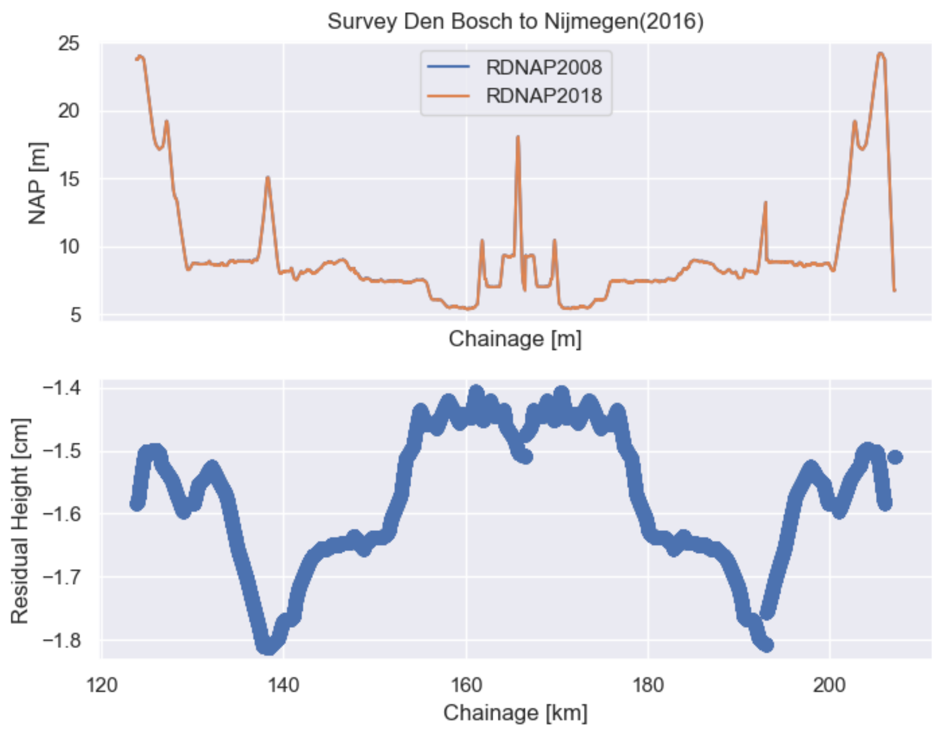

Figure 4.2: Top figure shows the survey with respect to RILA chainage along the track, bottom figure shows the residual height or the height difference between the two quasi-geoids

In Figure 4.3, a zoomed cross-section of the area shown in previous image can be seen where the heights from RDNAPTRANS2008 are an order of $16mm$ higher than heights obtained from RDNAPTRANS2018. The residual is more or less a constant value with some fluctuation due to the interpolation upon the implementation of RDNAPTRANS procedure.

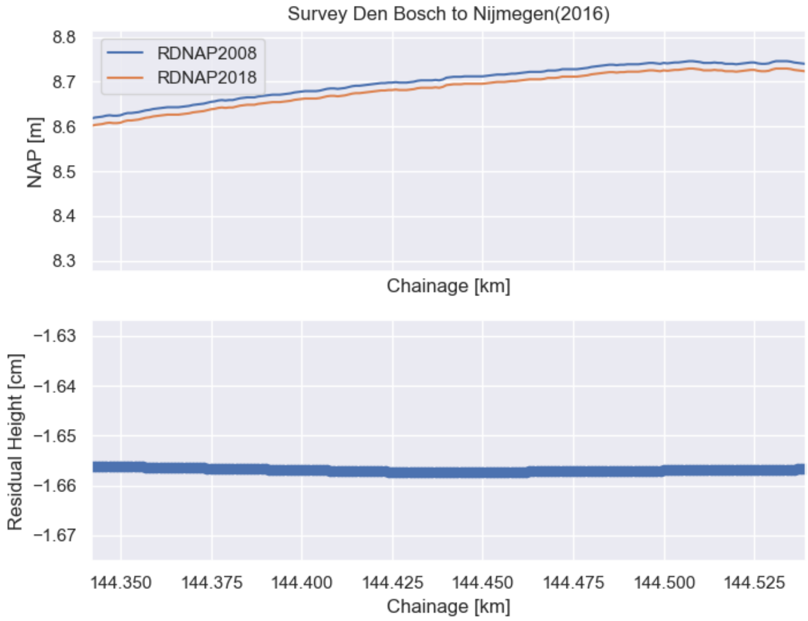

Figure 4.3: A zoomed cross section of the heights and the residuals

In order to understand the differences from the two models and the validation measurements, ground control points are introduced to this data set.

4.1.1. Ground Control Points: Location and Validation

Ground Control Points (GCP) are benchmarks levelled using Total Station or levelling technique at the railway switches and crossings along with railway bridges. In Figure 4.4, the horizontal coordinates of the track profile are plotted along with the locations of these ground control point measurements in order to validate the heights from RILA data. Hence 19 level crossings located between Den Bosch and Nijmegen were measured with the traditional spirit levelling techniques with reference to NAP, the national geodetic network of benchmarks. Due to limited access for the levelling survey team, also 7 bridges were measured by a mirrorless total station survey. The coordinates of level crossings and bridges were calculated and used as control points for the height. Also 3D coordinates of 13 switches on Den Bosch, Oss, Wijchen and Nijmegen stations were measured by a total station.

A zoomed section of the RILA track and the ground control points is shown in Figure 4.5. It can be seen already from this figure, that not all the ground control points lie on the track center line computed from the RILA processing. This indicates that the track surveyed using RILA and the track levelled by a total station were not the same tracks, in this case, the adjacent track was surveyed instead. There are some more control points like the one mentioned here, hence adding outliers to our validation dataset. The data from GCP 129 to GCP 133 are disregarded since these points, despite holding a chainage value of the railway track, are not valid for the railway track where RILA operated as seen in Figure 4.5. These outliers were eliminated for further analysis in this section and in addition an outlier removal strategy was applied as described in Section 4.2.

An important remark to be made about Figure. 4.5 is that there is no change in the X and Y direction upon making use of RDNAPTRANS2018. This was expected since the major change in the new transformation model is mainly the quasi-geoid and the new correction grid along with the transformation parameters, resulting in sub-mm change in the X and Y location.

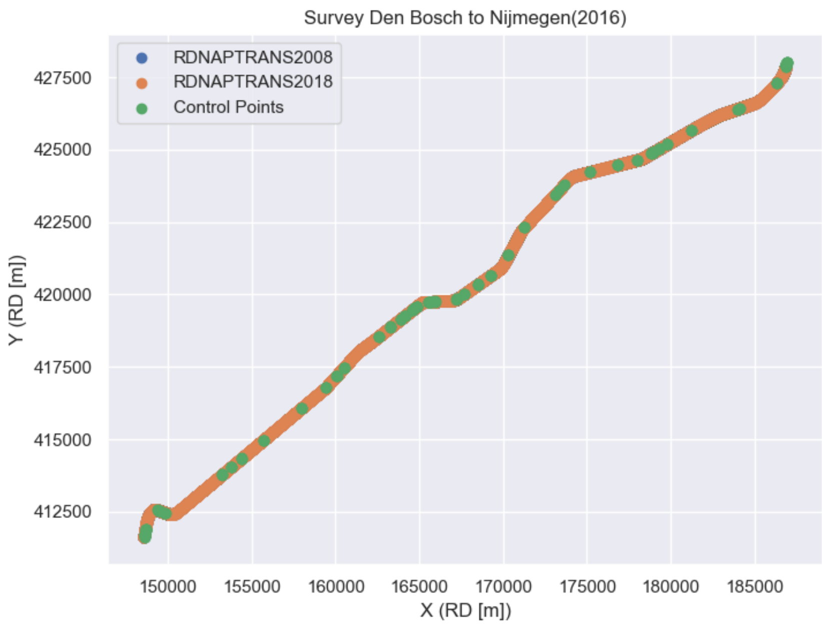

Figure 4.4: Location of the Ground Control Points on the survey

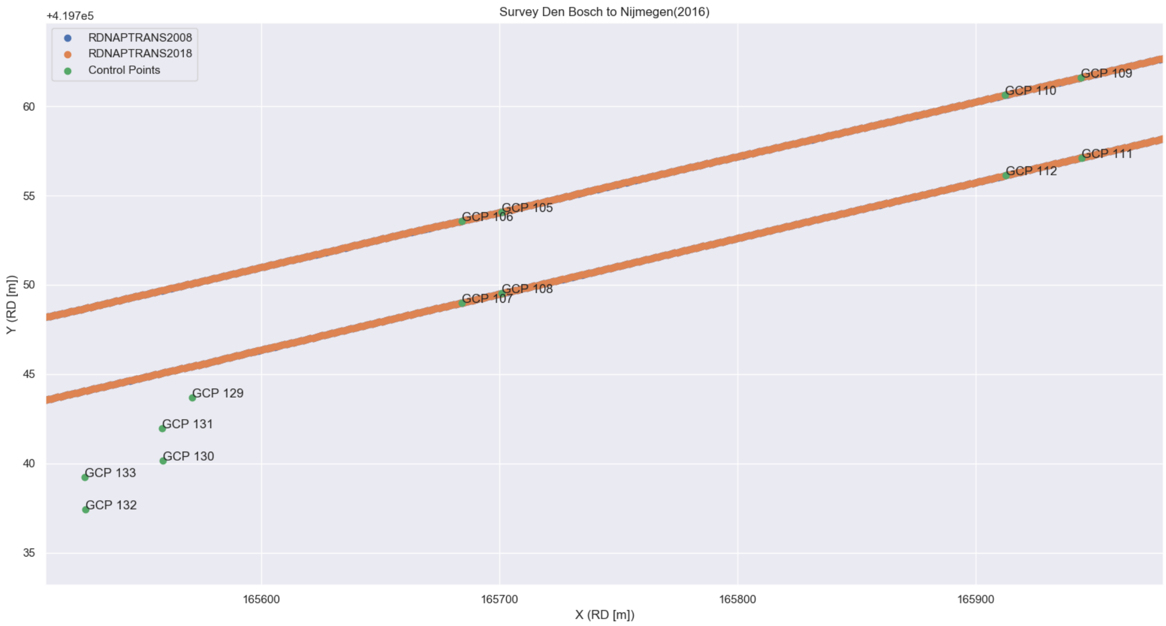

Figure 4.5: Ground control points locations on the track in a zoomed section

Since there is no change observed in X and Y with the new use of RDNAPTRANS2018, the NAP heights derived from GNSS-IMU processing for individual track can be seen in Figure 4.6 for the forward and the backward track using both transformation models for a $5km$ stretch of the data.

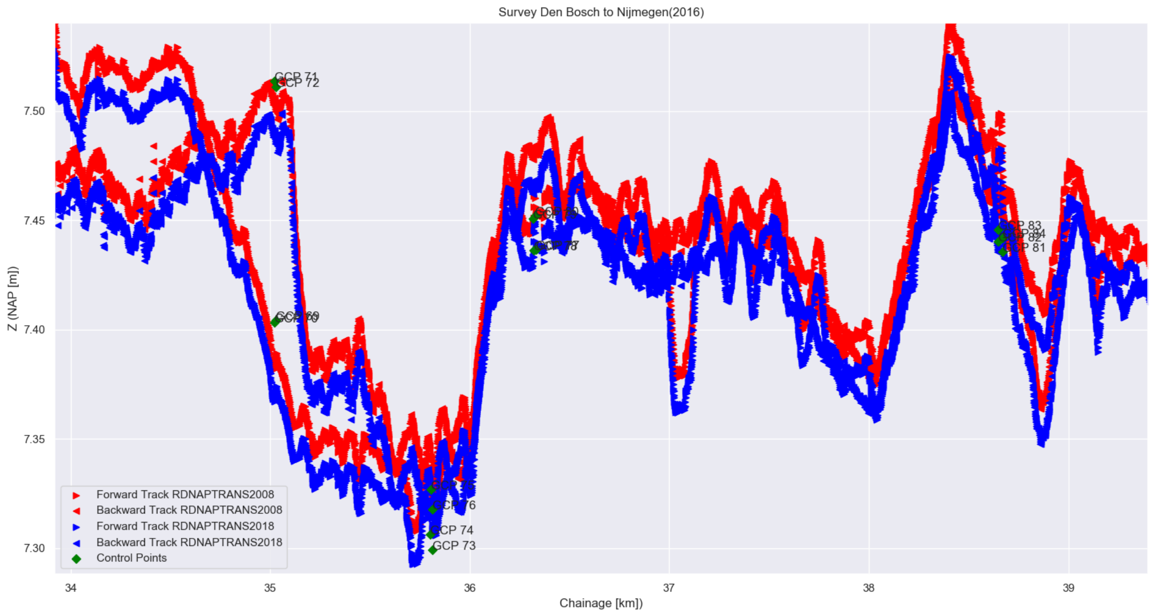

Figure 4.6: RILA tracks with Z elevation with respect to chainage and the elevations of the ground control points in *green*

A zoomed area of the plot for GCP 109 to GCP 112 can be found in Figure 4.7 where the control points (almost) coincide with the heights obtained using RDNAPTRANS2018. GCPs which would show an offset of maximum of $2cm$ when comparing the levelled benchmarks and the RILA heights now show an offset of $0.4 - 0.7cm$ for the mentioned GCPs upon using RDNAPTRANS2018. This is found to be the case for majority of the ground control points where the RILA survey and the levelling survey was done for same railway track.

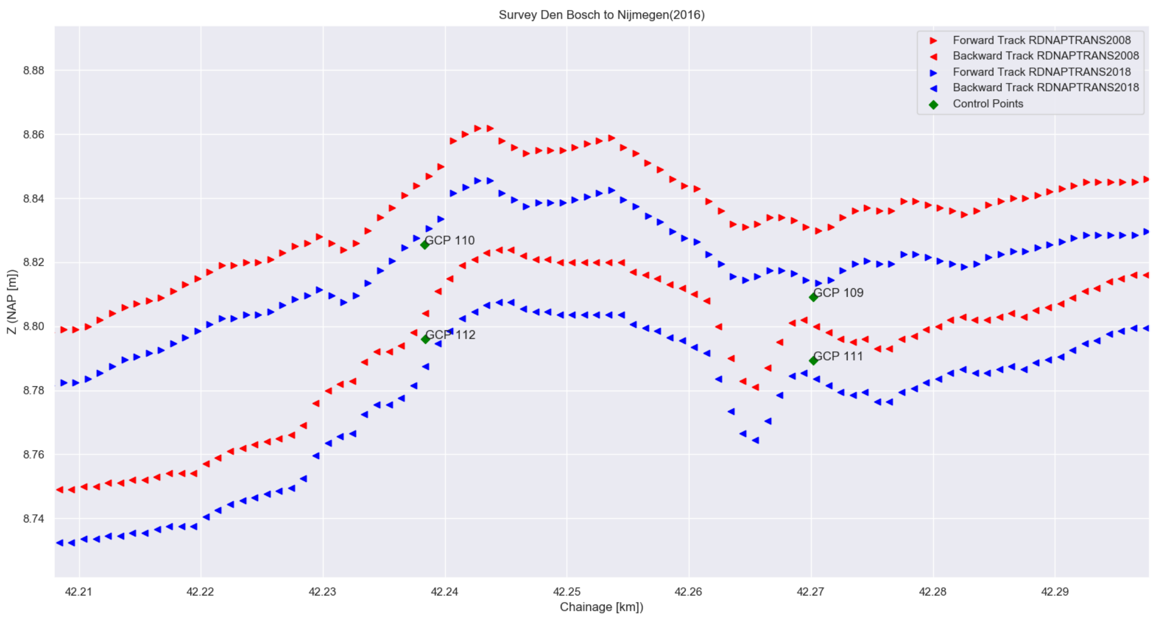

Figure 4.7: Zoom section for GCP 109 to GCP 112 with Z elevation with respect to chainage and the elevations of the ground control points in *green*

In Figure 4.8, where some of the ground control points measured are not surveyed by RILA track, it was observed upon looking at the height profiles for this in Figure 4.9 the mileage/chainage is not

Figure 4.8: Ground control points locations on the track in a zoomed section

the best function to interpret these heights. Moreover, just using the X and Y coordinates to plot these heights is not the ideal solution in general since there can be two or more values for just one X or Y coordinate. Hence it becomes of utmost importance to make sure the area measured is based on the geographical position rather than chainage concept.

Therefore, the RILA measured heights were extracted based on their geographical location and closest to the ground control point. However, this does not help in getting rid of the ground control points which are not on the same location as the RILA survey and results into outliers being used as assessment, this is resolved in Section 4.2. After obtaining these points, the height differences are calculated for both RDNAPTRANS2008 and RDNAPTRANS2018 and plotted as a function of the X coordinate for visualisation purposes in Figure 4.10, where the height difference upon RDNAPTRANS2008 show a mean height difference of $1.2cm$ which is reduced to $-0.36cm$ making use of RDNAPTRANS2018 showing a better fit. The distribution plot for these height differences can be found in Figure 4.11. The areas where the observed height difference was more than $20cm$ was found to be the area where the distance between the GCP and RILA point was also large. Therefore it is advised to come out with a strategy in order to get rid of these outliers where the GCP and RILA surveyed point do not coincide.

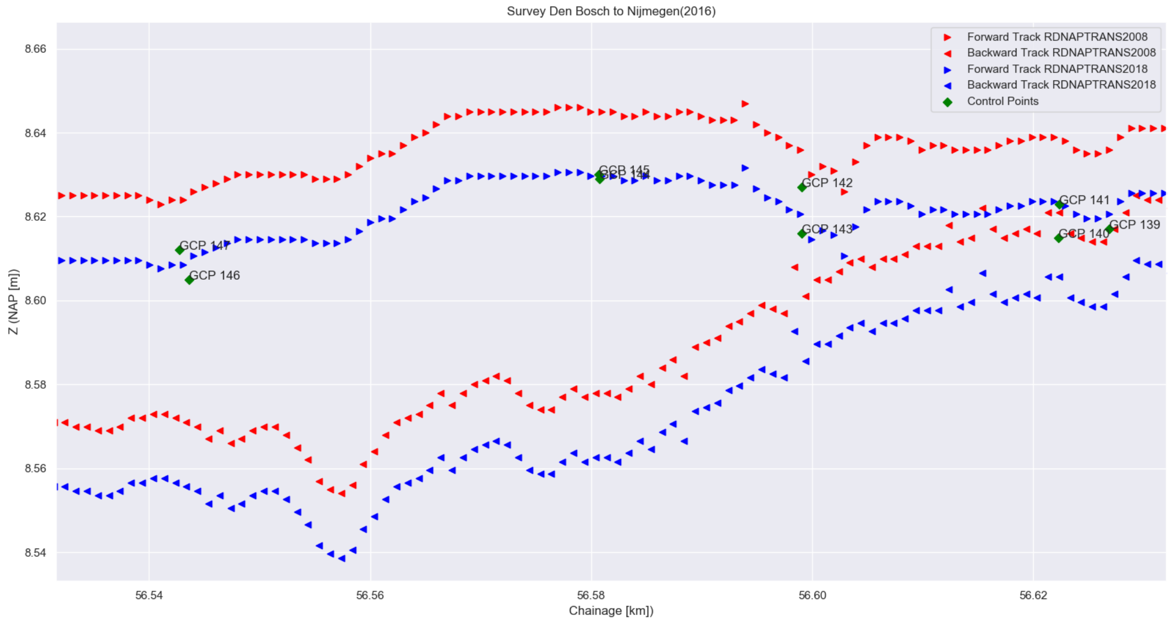

Figure 4.9: Zoom section for GCP 139 to GCP 147 with Z elevation with respect to chainage and the elevations of the ground control points in *green*

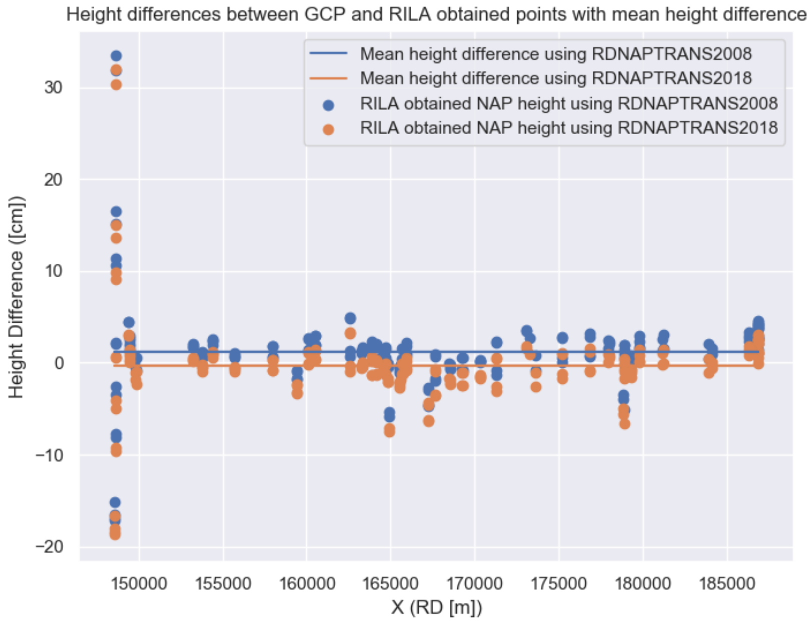

Figure 4.10: Height differences between GCP and RILA points along with mean height differences for RDNAPTRANS2008 and RDNAPTRANS2018

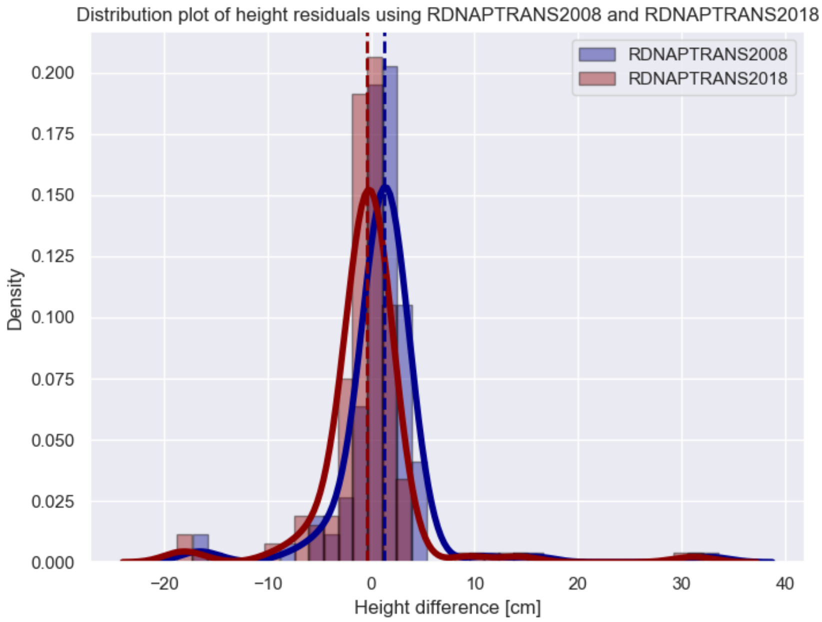

Figure 4.11: Distribution plot of the height differences using RDNAPTRANS2008 and RDNAPTRANS2018

4.2. Outliers Removal Strategy

4.2.1. Introduction

In order to assess and understand the differences in the two heights obtained via levelling and GNSS-IMU derived NAP heights after applying RDNAPTRANS2018, it is required getting hold of a good set of validation measurements points which can be considered reliable, by removing the identified outliers from the levelling measurements.

4.2.2. Nearest Neighbour Search

In Figure4.8, it was found that the location of the levelling measurements were not aligned with the track center-line, which results into comparing the heights of two different locations due to lack of accessibility (for example, comparing next-to-next railway tracks or pavement next to track). Upon inspecting the aerial imagery it was found that the track surveyed by RILA and the track levelled were indeed different for this area close to Wijchen as shown in Figure 4.12 where the blue points are the RILA observed heights and red points are levelled heights.

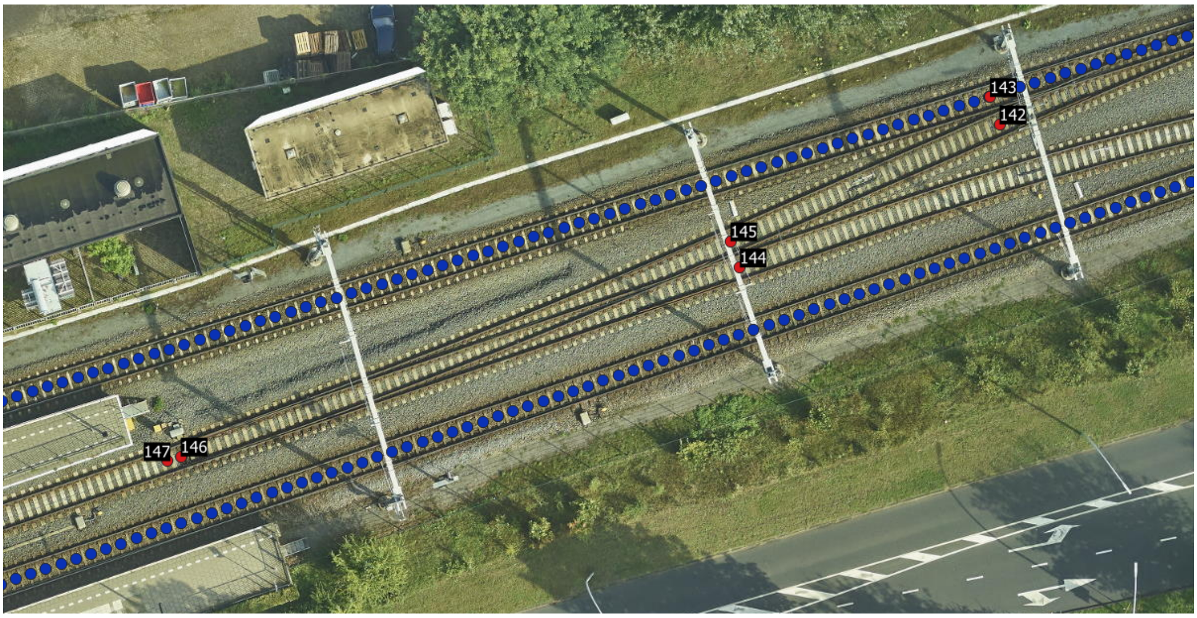

Figure 4.12: Aerial imagery obtained from ProRail *luchtfoto* showing different area surveyed by RILA and Levelling team where blue points are the RILA observed heights and red points are the levelled heights

Due to the higher density of RILA observations (every meter) resulting in 82,136 data points and only 189 levelling points, it was ideal to store the RILA observations only for these 189 levelling benchmarks. However, as shown not all the levelling benchmark lie on the RILA track line. In order to resolve this issue, the nearest neighbour algorithm was applied to get hold of 189 points from the RILA measurements. The nearest neighbor (NN) search problem is defined as follows:

Theorem 4.1: Given a set S of points in a space M and a query point $q \in M$, find the closest point in S to q.

As can be seen in Figure 4.13, for the following set S of points, the NN search algorithm aims to find the point in S closes to q. Since RILA observes points at every 1 meter, the following algorithm can be constrained by setting a maximum distance of 1 meter and making use of two nearest neighbours. See Figure 4.14 where the two nearest neighbours for the ground control point measurement (in yellow) is found for a maximum distance of 1 meter in red.

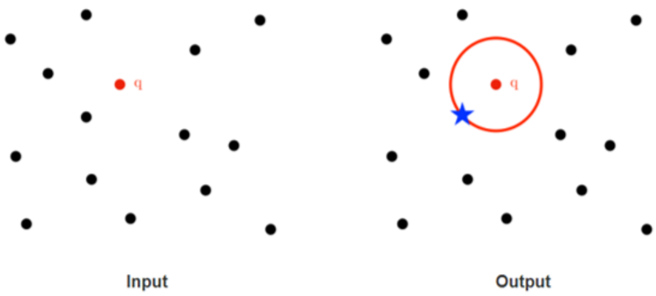

Figure 4.13: Nearest Neighbour Search Algorithm

Upon obtaining these two nearest neighbours, a linear interpolation is applied in order to extract the value for RILA observed height at the ground control point location. The interpolation error is proportional to first derivative of topography however, the topographic/terrain effect in this case can be excluded since the tracks do not change upon such a short distance of 1 meter. The result of this strategy resulted in exclusion of 54 levelling points where the levelled benchmark and the RILA observation referred to two different tracks.

The mean height difference observed is $\mu = 0.4931cm$ with standard deviation of $\sigma = 1.535cm$. It

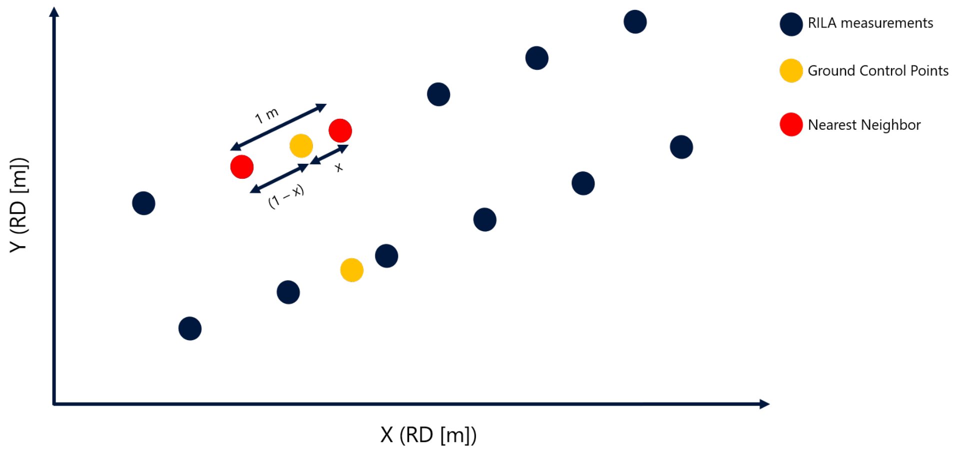

Figure 4.14: Finding the two nearest neighbour for the ground control points measurements

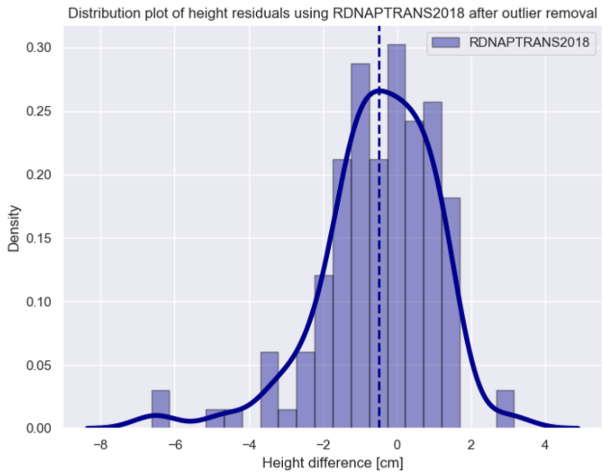

Figure 4.15: Distribution plot for the height residuals after outlier removal with mean height difference of 5 mm

can be seen from the distribution plot in Figure 4.15 that there are a very few values where the height differences is more than $4cm$. After a conditional check this was found to be at a train crossing where the maximum height difference were found. In order to assess these quantities, the next strategy is applied where the connection to the NAP network is investigated.

4.2.3. Connection to the NAP network

The terrestrial survey was connected to both NAP and PMG. PMG (*dutch: Primaire Meetkundige Grondslag*), just like the NAP is a network of benchmarks surveyed by ProRail for the track maintenance and performance. When connecting both NAP and PMG benchmarks in the survey adjustment, it was found, that standard deviations of the measured points were much higher. Therefore the elevations of the train crossings were calculated in three scenarios: with reference to NAP height system, PMG points, and PMG & NAP combined. However, from previous research done at Fugro, it was found that there is a significant discrepancy between NAP and PMG. The difference can be both positive and negative and the median/mean values are around zero indicating that we are not looking at a fixed bias. The two networks do not connect to a sufficient level of accuracy to be used simultaneously for the high absolute accuracy requirements. For this research, the points were connected to the second order NAP levelling network, measured five years before the date of RILA acquisition (2016).

In Figure 4.16, the NAP benchmarks (shown as black stars) which are connected by the levelling done by the Fugro team (shown as purple dots). Since all these benchmark points are from the levelling campaign of 2011, it was decided to not remove any of these control since none of these points are connected to over 10 years old benchmarks. There could still be some deformation in the following 5 years, but for this research the effect of those are neglected since they are expected to be in couple of mm for the survey area. However, if these GCP, were connected to benchmarks much older than 10 years, it is highly advisable to perform this check since over that period, due to natural activities like deformation, the heights can differ, and include biases in the validation dataset.

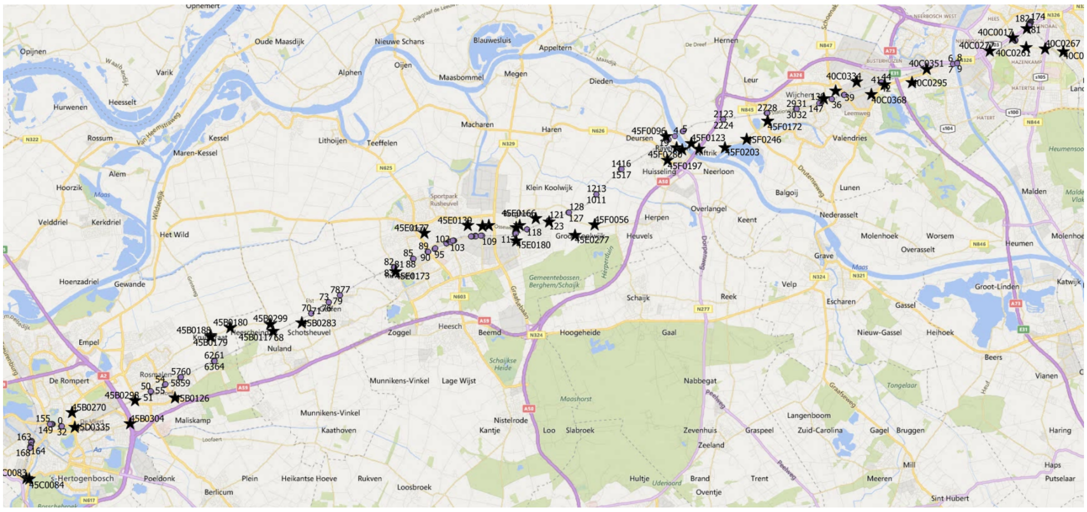

Figure 4.16: Street view of the NAP benchmarks (in black stars) which were connected to the terrestrial surveying team

4.2.4. Manual Inspection

Since the ground control points were measured at the train crossings, switches and bridges, a manual inspection of these points is required especially in areas such as train crossings where discrepancies can be found due to the fact that railbar is very much covered by the material of the crossing and during the point cloud processing which can include non-precise values. This can also be investigated as the maximum height difference is observed at these train crossings. After looking at the drone imagery from ProRail *luchtfoto* along with the railhead scan from the rail striper data of RILA, 10 GCPs were removed from the dataset, where the railbar is covered by the material from level crossing.

Finally, now these 125 GCPs hold a value to be used as validation measurement against the RILA data set. In Figure 4.17, the obtained RILA height and the validation measurement point can be visualised. However, the errors associated with these individual sources of heights need to be found. This can be done by obtaining the error budget accounting for all the errors during the computation of these heights.

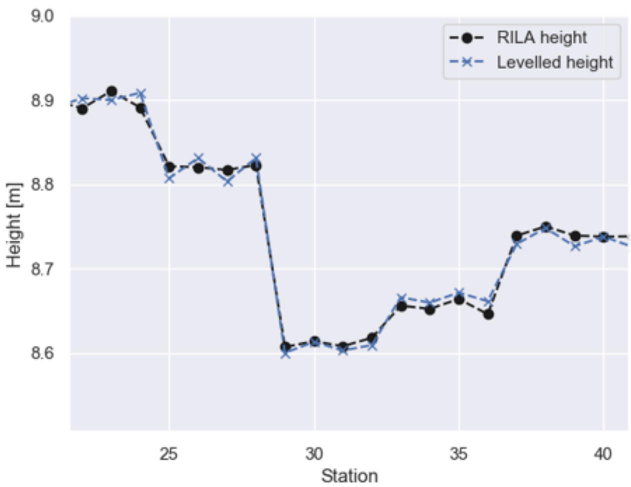

Figure 4.17: RILA derived NAP height and the levelled height

The distribution plot for these 125 GCP's can be found in Figure 4.18 where when compared to the distribution plot after outlier removal strategy, the mean height difference is $\mu = -0.30cm$ with standard deviation of $\sigma = 1.1cm$ which was originally $\mu = 0.5cm$ with standard deviation of $\sigma = 1.5cm$

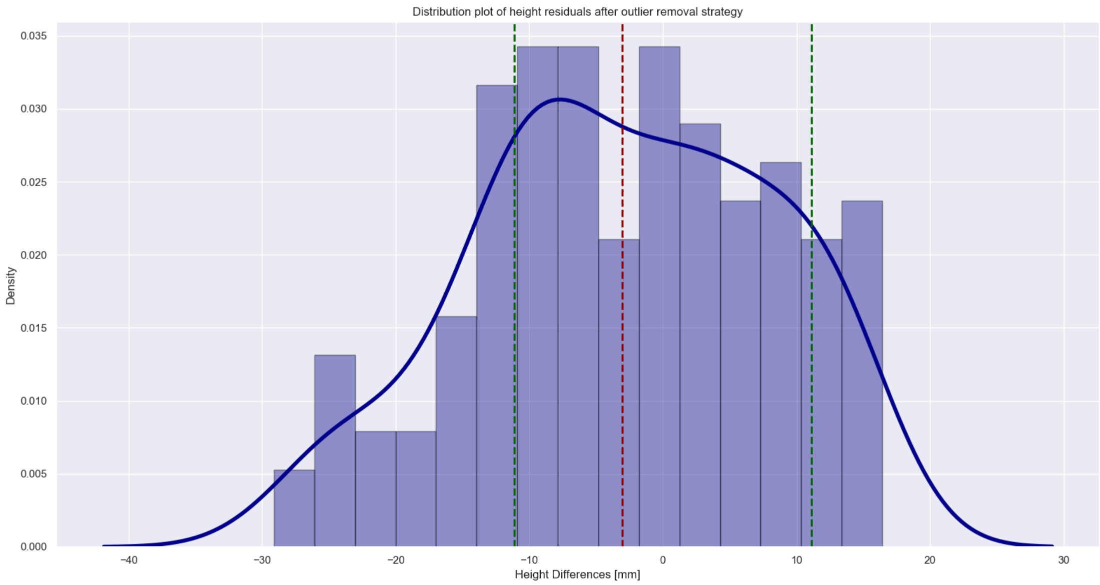

Figure 4.18: Distribution plot of height residuals once the outlier removal strategy has taken place. The mean height difference now observed is $3.0mm$

In Table 4.1 statistics of the differences between the gravimetric quasi-geoid undulations and GPS levelling ($h - H - N$) are presented.

Mean [cm]	-0.30
Min [cm]	-2.91
Max [cm]	1.64
Std. [cm]	1.12

Table 4.1: Statistics of differences between the gravimetric geoid undulations and GPS levelling

4.3. Total Error Budget

4.3.1. Introduction

In order to understand the reliability of the RILA measurements upon comparing them to levelling heights, all the uncertainties associated with these measurements need to be taken into account. This is done by preparing a total error budget and estimating these uncertainties.
The best way to represent these heights for the collected GNSS heights from RILA (h_{RILA}), levelling height (H_N) and the geoid height (here representated as N), they can be written for their combined adjustment as:

$$H_N = h_{RILA} - N \tag{4.1}$$

and the matrix notation can be written as

$$H_N = \begin{bmatrix} I & -I \end{bmatrix} \begin{bmatrix} h_{RILA} \\ N \end{bmatrix} \tag{4.2}$$

The uncertainties coming for the normal heights derived from RILA and the quasi-geoid model after applying the variance propogation law can be written as:

$$C_{H_N} = \begin{bmatrix} I & -I \end{bmatrix} \begin{bmatrix} C_{h_{RILA}} & 0 \\ 0 & C_N \end{bmatrix} \begin{bmatrix} I & -I \end{bmatrix}^T = C_{h_{RILA}} + C_N \tag{4.3}$$

where $C_{h_{RILA}}$ is a diagonal matrix since it was not possible to reconstruct the covariances of the GPS and the levelled heights. The variances used were derived from the results of the trajectory processing in a loosely-couple approach with GNSS-IMU (see Wang et al., 2017 for detailed explaination of this approach), along with combined errors from the LiDAR measurements to derive the center track information. However, C_N is a full variance-covariance matrix of gravimetric quasi-geoid[1], provided by D.C. Slobbe from the quasi-geoid analysis Slobbe et al., 2019.

The

4.3.2. Error Budget

The accuracy of the ellipsoidal height h and normal height H_N depends on the observation procedure and the precision of the measurements, while the accuracy of the N component depend on several factor such as errors associated with the acquisition of gravity data, reprocessing of the GNSS/Levelling heights, etc. (Kasenda, 2009). The results of these estimations can be found in Figure 4.19 where on the horizontal axis are the GCPs ID, and on the vertical axis is the height difference observed and the uncertainties associated are plotted as the error bars. It was found, that the highest uncertainties in the total error budget come from the RILA measurements, due to the uncertainties coming from GNSS-IMU sensors. The error obtained from the levelling campaign are then smaller than RILA error after connecting to NAP benchmarks and in the order of $3-5mm$. Finally, the quantitative gravimetric quasi-geoid error (without the innovation function) are somewhat in same magnitude of each other and the smallest, since the area is not that different during this 40km stretch of railway track.

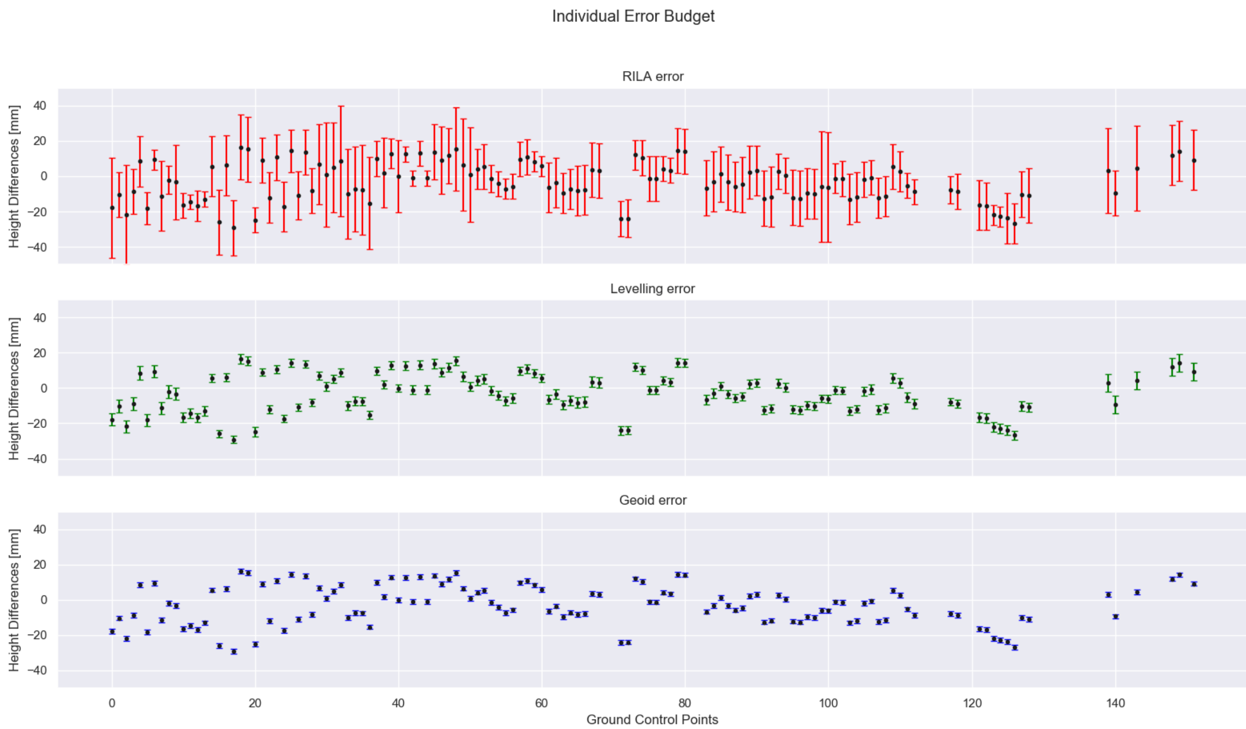

Figure 4.19: Individual error budget plotted for each GCP and the height difference for: RILA, Levelling and NLGEO2018 gravimetric quasi-geoid

Figure 4.20 shows the the total error budget part consisting of all the uncertainties coming from these three techniques for the height difference observed. The most notable error is observed at the

[1]This doesn't include the innovation function and computed based on GNSS data of 5mm precision (1σ) and 2-4mm (1σ) levelling data.

train stations such as Den Bosch, Oss and Nijmegen. This is quite expected since the RILA measurements have poor GNSS reception at these areas and rely mostly on IMU as a feedback to improve the positioning. It can be observed that the height differences at these locations is also of the highest magnitude along with some train crossings.

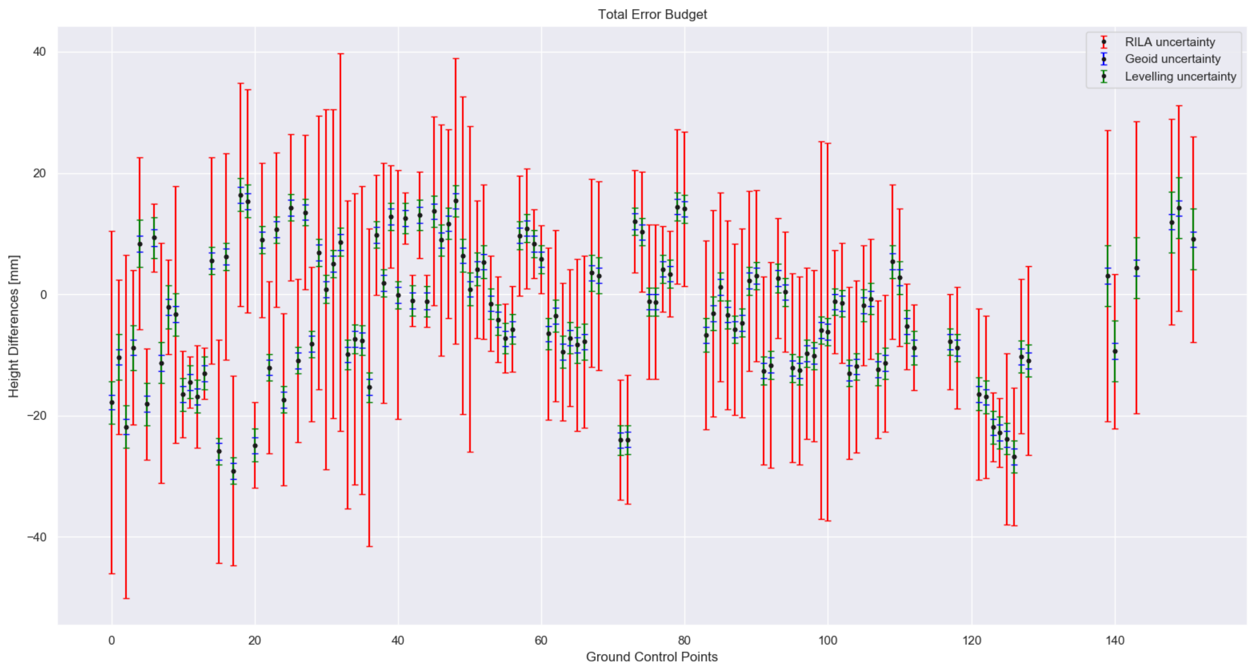

Figure 4.20: Total error budget plotted for each GCP and the height difference. Uncertainties from RILA seem to show the most influence.

In Table 4.2, the minimum, maximum and the mean value of each component is shown along with the the total comprised error from these three components.

Error Source	**Min [mm]**	**Max [mm]**	**Mean [mm]**
RILA	4.25	31.15	14.07
Levelling	2.2	5.0	2.65
Quasi-Geoid	1.24	1.34	1.29
Total Error	5.10	31.25	14.44

Table 4.2: Statistics of the individual error source and the total error budget

Furthermore in order to understand the spatial correlation of these height differences from the RILA system and the levelled NAP height, a variogram is used. A variogram is used to display the variability between data points as a function of distance. The experimental variogram, representing source data, in this case these are the height differences from the RILA observed height and the NAP height, are then fit to different types of variogram models such as spherical, gaussian or experimental.

This is done so that the data, which were sampled at discreet units, can be modelled as a continuous function, and the value for any unknown point at any distance can be interpolated. The experimental variogram and the fitted variogram can be found in Figure 4.21. The distance where the model first flattens out is known as the range (depicted as r in the figure). Sample locations separated by distances closer than the range are spatially autocorrelated, whereas locations farther apart than the range are not. The value that the variogram model attains at the range (the value on the y-axis) is called the sill (depicted as s in the figure). The maximum distance for the variogram calculation is defined as the maximum distance in the dataset divided by 2. The figure makes use of 40 point pairs for fitting purposes. Since all these point pairs are very close to each other, due to the location of the GCP (for example, 2 or 4 times at one level crossing). From the Figure. 4.21 it can be found that the sill is almost the same for all these observations at around $2.70km$, however the range is different for spherical model at $1.9km$. This shows that the the height differences show a correlation only for a short distance of maximum about 2.5km for the spherical model.

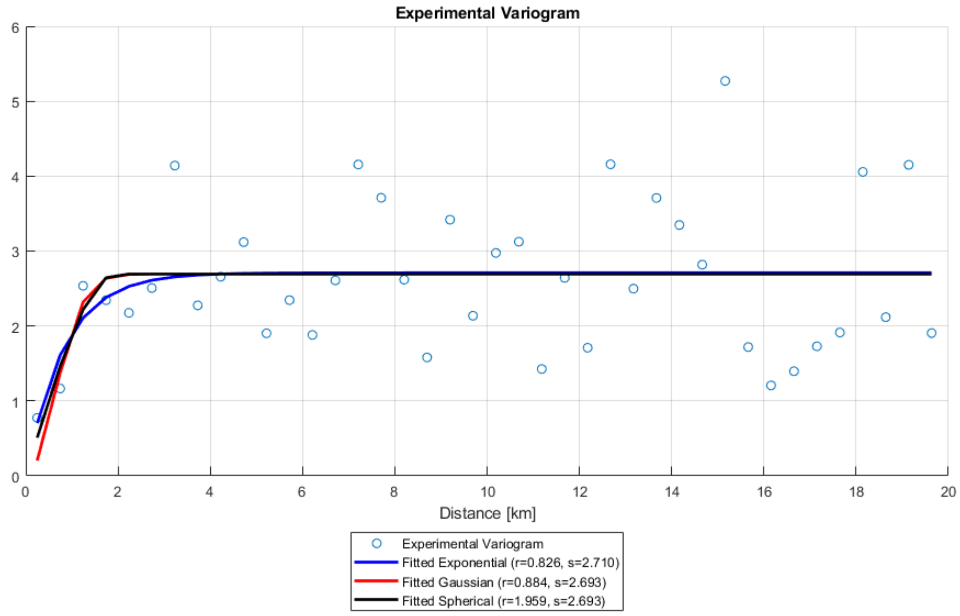

Figure 4.21: Variogram (cm^2) for the differences in RILA observed heights and NAP heights

Comparing the variogram computed in this research to the semi-variogram computed by Slobbe et al., 2019, in Figure 4.22, the gamma-variances reach a higher plateau at a rather short distance of only 1-2km compared to the one observed in Slobbe et al., 2019. This is due to the fact that the GNSS/IMU data from the RILA observed heights consists of higher uncertainties than the terrestrial GNSS receivers used in computing NLGEO2018 gravimetric quasi-geoid

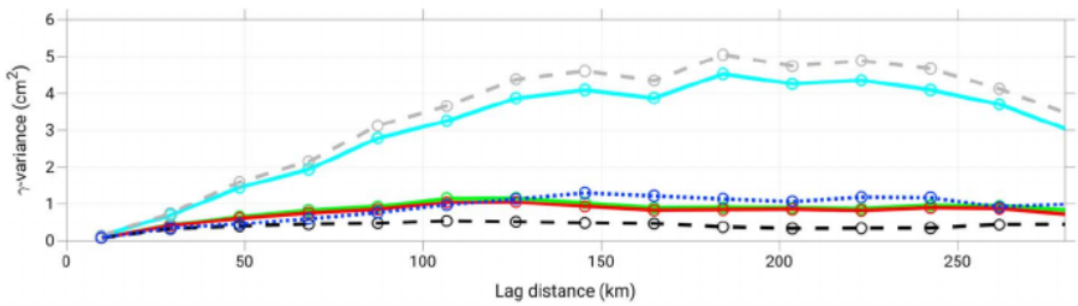

Figure 4.22: Variogram (cm^2) of the differences between geometric and gravimetric height anomalies at the GPS/leveling stations in the Netherlands for NLGEO2018 in dashedblack line (Slobbe et al., 2019)

In order to get a better insight on these height differences with the total error, a hypothesis test can be performed for the relative error of these height differences. This is defined as:

$$\text{Relative Error} = \frac{\text{Height Difference Observed}}{\sigma_{total}} \tag{4.4}$$

This holds true if it can be assumed that the height difference is normally distributed with zero mean and standard deviation of σ_{total}, Since the relative error is normally distributed with a standard normal

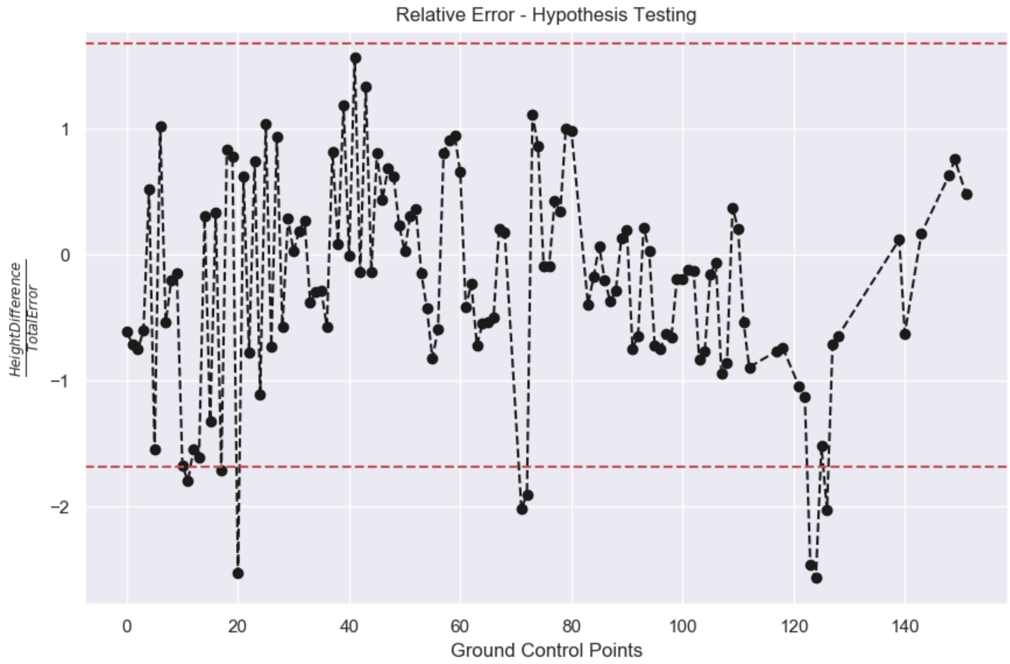

Figure 4.23: Relative Error defined as fraction of the height difference and the total error. ±2σ value plotted in red

distribution, then it can be seen how often the relative error is outside the 95% (2σ) confidence interval which is similar to w-test hypothesis testing. The result of this can be seen in Figure 4.23. Since the relative error is defined as the fraction of height difference over total error, for areas where the height difference is zero or close to zero, the value for the relative error will also be zero, and not dependent on the total error. A value of one or closer would indicate that the height difference and the total error accounted for are of the same order. The 2σ values was calculated which was found to be 1.68 and plotted in the same graph. Higher than the following threshold indicates that the difference observed is much higher than the total error accounted for. The average value of significance observed over these height differences is -0.22 with a maximum of 1.57 . Since the majority of these points are between 0 and 1 this indicates that for any height difference observed at those points, the error budget is able to explain the height differences or the difference in height is small compared to the error.

As for the GCP's where the relative error observed was more than 2σ, it is beneficial to inspect them in order to understand the height differences. The following GCP with the set-threshold were then exported to be visualised using satellite imagery. The GCP and the aerial imagery can be found in Figure 4.24 to Figure 4.25

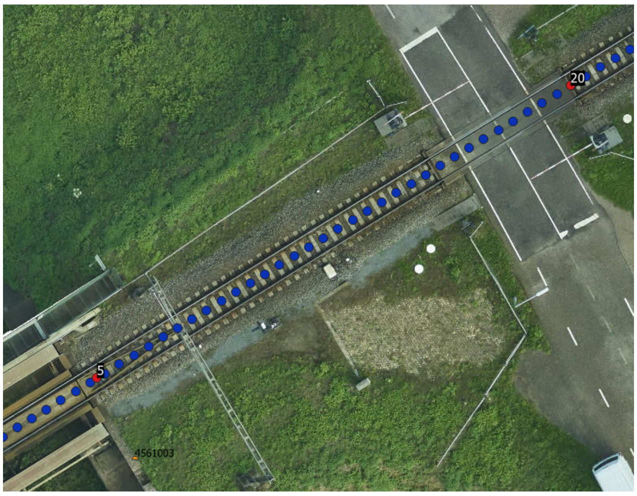

Figure 4.24: Location of GCP 5 and GCP 20 on aerial imagery

As seen in Figure 4.24 GCP 5 and GCP 20 both are one of the GCP separated by ≈ 32 meters where GCP 5 is on one of the switches and GCP 20 is on the train level crossing. The heights observed from RILA and the levelling measurements can be seen in Table 4.3 along with the height differences. The relative height difference observed i.e.,

$$\Delta H_{5-20} = (H_{RILA5} - H_{RILA20}) - (H_{Levelling5} - H_{Levelling20}) = (0.3036 - 0.2969) = 6.7mm \quad (4.5)$$

GCP	H$_{RILA}$ [m]	H$_{Levelling}$ [m]	Height Difference [mm]
5	13.24238	13.2605	-18.1195
20	12.93867	12.9636	-24.9058

Table 4.3: Significance of the height differences for GCP 5 and GCP 20

A similar strategy was also applied for GCPs which showed a large height difference in the heights, namely GCP 14 and 16 along with GCP 15 and 17 observed at the level crossing (See Figure 4.25).

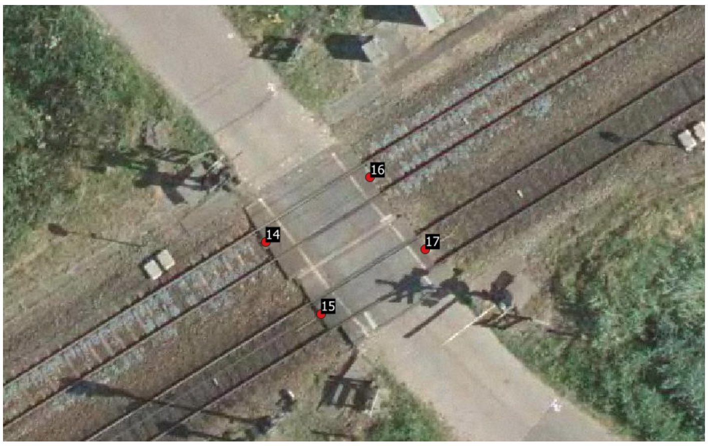

Figure 4.25: Locations of GCP 14 to 17 on aerial imagery from 2016 at the train crossing

$$\Delta H_{14-16} = (H_{RILA14} - H_{RILA16}) - (H_{Levelling14} - H_{Levelling16}) = |(0.0083 - 0.0089)| = 0.6mm \quad (4.6)$$

For the ground control points next to each other or seperated by small distance (GCP 14 and 16), the height difference observed is 5.6 and 6.2mm respectively, however the relative height difference is

GCP	**H**$_{RILA}$ **[m]**	**H**$_{Levelling}$ **[m]**	**Height Difference [mm]**
14	8.1956	8.19	5.6
16	8.1873	8.1811	6.2

GCP	**H**$_{RILA}$ **[m]**	**H**$_{Levelling}$ **[m]**	**Height Difference [mm]**
15	8.1870	8.2129	-25.9
17	8.1804	8.2095	29.1

in sub-mm. This indicates a systematic bias in the two systems since the quasi-geoid doesn't change in such a small distance.

$$\Delta H_{15-17} = (H_{RILA15} - H_{RILA17}) - (H_{Levelling15} - H_{Levelling17}) = |(0.0066 - 0.0034)| = 3.2mm \quad (4.7)$$

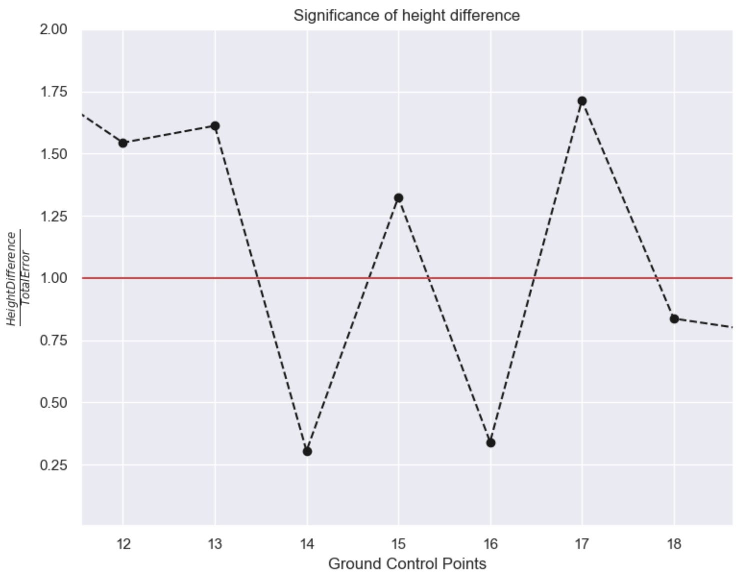

Figure 4.26: Significance of height differences observed for GCP 14 to 17

The same is found for GCP 15 and 17, where the height difference between RILA and levelled measurements is 3cm, the relative height difference observed is 3.2mm. In Figure 4.26, the significance for these heights obtained can be found showing low value of significance for GCP 14 and 16, but high significance of error for GCP 15 and 17. This makes sense, since the height difference is rather huge for these two heights while the total error remains the same for all four GCP.

4.4. Summary

In this chapter, impact of using RDNAPTRANS2018 was shown over RDNAPTRANS2008, and validating that indeed it shows a better connection to purelly levelled NAP heights. The result of this was the so-called *updated heights* which were then used to analyse with the GCP measured in the same duration, and get hold of good set of validation points. Finally, an error analysis was performed which included constructing a total error budget and doing variogram analysis followed by a w-test hypothesis to check for relative variation in the heights obtained at the GCP.

5

Conclusions and Recommendations

This thesis provides an important bridge to understand the impact of the new quasi-geoid and RDNAPTRANS2018 transformation model to derive NAP heights using GNSS heights obtained from the Fugro train mounted system RILA. The findings from the literature review and the analysis help in answering the research questions and sub-questions introduced in Chapter 1.

5.1. Conclusions

The following sub-research questions are answered based on the findings throughout this research:

> **What is the impact of RDNAPTRANS2018 on the quality of GNSS derived NAP heights compared to RDNAPTRANS2008? Do the differences between leveling- and GNSS/leveling-derived NAP heights improve? What is the variation in height from point to point in relative and absolute?**

The transformation model RDNAPTRANS2008 is based on NLGEO2004 quasi-geoid, while the new transformation model RDNAPTRANS2018 is based on newer quasi-geoid NLGEO2018 along with innovation function with a precision of 5mm. The idea behind the new RDNAPTRANS2018 is to allow an accurate conversion of GNSS derived heights to NAP heights. It was found upon using RDNAPTRANS2008, that there was a misfit of about **1.3 - 1.9 cm** upon comparing RILA derived heights to NAP heights. However, this comparison was done without taking into account the individual error sources from all height types i.e., NAP, GNSS/IMU and the geoid itself. After applying the new transformation model into these old heights, the new heights were found to be lower than the old heights. It was also found that the NAP heights recorded during that time were also lower than the heights recorded by GNSS-IMU system using RDNAPTRANS2008. Hence, the (new) heights obtained by RDNAPTRANS2018 show an offset of about **0.4 to 0.7** cm at 95% of the benchmarks. Furthermore, a statistical analysis of these showed, the height difference upon using RDNAPTRANS2008 show a mean height difference of 1.2cm which was reduced to −0.36cm. Comparing this to the misfit observed with RDNAPTRANS2008, it was concluded that just the application of the new RDNAPTRANS2018 shows a better (and closer) connection of RILA derived heights to purely levelled NAP heights.

In order to answer the relative variation within the dataset, for the ground control points next to each other or separated by small distance , the relative height difference was calculated from RILA derived height and levelled NAP height. This relative height difference was found for majority of the dataset in sub-mm or maximum of $6mm$. This indicates a systematic bias in the RILA derived height since the quasi-geoid doesn't change in such a small distance.

> **Which validation points (ground control points) can be used and what kind of outlier removal strategy is to be applied in order to get hold of good set of points which are reliable?**

In order to do this assessment, a large number of validation points (ground control points) is required to assess the quality of the heights from old and new RDNAPTRANS models. Since RILA derived heights are much higher rate of observation (the whole survey), compared to the 189 levelling points (which are only at switches, crossings or bridges), it was ideal to store the observed RILA height only for these 189 levelling benchmarks. Firstly, it was revealed that not all the levelling benchmark points lie on the same point where RILA derived height was acquired. In order to resolve this issue, nearest neighbour algorithm was applied to get hold of a set of points from the RILA measurements which are within the distance of 1 meter of the levelling point. Following this a manual inspection based on the satellite and drone imagery during the acquisition was done to make sure certain discrepancies found at certain points were removed. The result from this was a set of 125 validation points which hold a value to be used as a validation measurement. Following this, the mean height differences between the ground control points and the RILA heights was reduced from $-0.36cm$ to $-0.30cm$. An offset of $6mm$ in the total uncertainty.

What are the contributors in the total error budget used in this assessment including RILA derived GNSS height, levelling and quasi-geoid height using RDNAPTRANS2018?

In order to understand the reliability of these RILA measurements upon comparing them to levelled heights, all the uncertainties associated with these measurements need to be taken into account. Hence a total error budget is need to be designed accounting for the uncertainties coming from all individual error sources which in this case are: RILA derived height (h_{RILA}), geoid height (N) and the levelling height (H_N). The accuracy of the parameters h_{RILA} and H_N depends on the observation procedure and the precision of the measurements, while the accuracy of the N component depend on several factor such as errors associated with the gravity data, re-processing of GNSS/Leveling, and grid resolution. It was found that the highest uncertainties comes from GNSS-IMU sensors of the RILA system ranging from 4mm to 30mm uncertainty and the least from the gravimetric quasi-geoid in order of 1.2mm to 1.3mm. There was also uncertainty in the range of 2.2mm to 5mm in the validation dataset from the surveying using levelling and total station respectively. The most notable error is observed at the train stations such as Den Bosch, Oss and Nijmegen. This is quite expected since the RILA measurements have poor GNSS reception at these areas and rely mostly on IMU as a feedback to improve the positioning. Moreover, certain level-crossings showed a higher error due to the fact that the rail head is covered by the material of the level-crossing, and the rail-head detection in this area was not satisfactory.
Finally, after answering all these sub-research question, the final research question can be answered:

What is the impact of using RDNAPTRANS2018 on the accuracy of the NAP heights obtained with Fugro train mounted RILA system upon comparing them to validation data from Ground Control Points?

One of goal throughout this research was to reduce the number of terrestrial surveying done by ProRail at railway tracks which are not only time consuming and expensive but also imposes a dangerous threat to the surveyors. Upon the previous work done by Fugro, a misfit in the height of the order of $1.3-1.9cm$ were found in the NAP heights and GPS-derived NAP heights. The idea with the new NLGEO2018 quasi geoid is that this model allows a more accurate conversion of GNSS derived heights to NAP heights with a precision of $0.7cm$ making levelling at some areas even obsolete. However in order to determine these areas where levelling can be skipped all together to limit the number of validation data, the total error budget is important to assess, since this gives the uncertainties coming from all individual error sources like GNSS height processed by RILA, levelling and geoid. It was found that areas where GNSS-IMU performs badly like in stations, tunnels and areas with high vegetation the height obtained at those control points had the highest uncertainty (even exceeding $20mm$) making comparison with the levelled NAP heights meaningless. However, areas such as switches where train changes its track and bridges showed the best fit upon comparing these heights. At certain level crossings where the survey was done the height differences observed are somewhat of larger magnitude than expected. This was found as a result of the material of level crossing interfering in the processing of center line using RILA height.

5.2. Recommendations

Based on the above stated conclusions and throughout the whole research stage, the following recommendations are being suggested which can improve the results in this research.

A deep analysis of the accuracy of RILA measurement device especially at certain locations

It was found that at certain areas, where the rail tracks are not much visible by the LiDAR scanner on the RILA system (such as train crossings) seem to show the highest mismatch when comparing RILA derived orthometric height and levelled height. Upon taking the relative difference of two points on the same RILA track the relative height difference observed was less than 1mm. This indicates that there is a systematic bias since upon taking this relative height difference, the errors from geoid are cancelled out. Hence, a deep analysis based on the LiDAR points observed at these areas is required to further improve the accuracy with which RILA measurements can improve the connection to levelled NAP heights..

Fitting the geoid to a new set of accurate GNSS heights

The NLGEO2018 geoid was fit to a set of points for which both an accurate GNSS height and a NAP height were available based on the previous 84 GNSS/Levelling points. However, this dataset is more than twenty years old and thus had to be transformed to the current ETRS89 system. Besides this, Rijkswaterstaat lacks a good validation dataset and hence plans to start a new measurement campaign to obtain a new accurate set. Without such a dataset it is difficult to assess how well RDNAPTRAN2018 can transform GNSS heights to NAP for the whole Netherlands. The current research shows a good connection and can be further improved, by improving the quality of RDNAPTRANS2018 by making use of more GNSS/Levelling points over much larger domain. Despite this being a time consuming process, doing so could further improve the uncertainty with the quasi-geoid and inturn RDNAPTRANS procedure.

Levelling points at areas of high vegetation, train stations, tunnels and subways

It was found that RILA derived heights, just like any other GNSS heights are affected upon areas such as high forestation or inside areas like train stations or tunnels due to lack of GNSS reception or/and multipath bound error. This results in higher standard deviation observed in the measurements and as a result of which influences the total error budget, resulting in comparing the RILA derived height and levelled NAP height meaningless. Even with a use of higher quality geoid a reliable NAP height cannot be derived at these location and hence levelling would be the only suitable approach to derive NAP heights, which could be used as an input in the RILA derived heights for corrections.

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