Development of the Project Adapted Network-RTK in Sweden – A review and the future plan

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Key words: RTK, Network-RTK, Geodetic infrastructure, GNSS

SUMMARY

Trafikverket, The Swedish Transport Administration is respectively responsible for long-term planning of the transport system for all types of traffic, as well as for building, operating and maintaining public roads and railways. Digitalisation is in focus on their research and innovation program for the period of 2019 – 2024. The field of geodesy serves a central role in the digitalisation process by bringing digital and physical reality together. This is valid for all the stages in the facility lifetime: from early planning to construction and maintenance of the infrastructure. With a robust future-proof geodetic infrastructure adapted to the Swedish Transport Administration's daily activities, digitisation and more efficient use of resources and reduced environmental impact are made possible as a result.

This paper covers a review of the development of Project Adapted Network-RTK, a concept of how to establish and use a new generation of geodetic infrastructure, the design and building process. The concept has developed by the Swedish Transport Administration and been in use since 2006. Today the concept is used as a de facto standard for large and complex projects on a national level.

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1. BACKGROUND

Trafikverket[1], The Swedish Transport Administration is responsible for the long-term planning of the transport system for all types of traffic, as well as for building, operating and maintaining public roads and railways.

All design and construction contracts, within the responsibility of the Swedish Transport Administration, is based on public procurement. Each project has its own budget and its own timetable. To win the contracts, all players act on an open market and they constantly need to look for more efficient production methods. From a surveying perspective, the early adapters of the Global Positioning System (GPS) gained an advantage over those who used traditional surveying methods. This became especially clear in the middle of the 1990th with the RTK-technology (Real-Time-Kinematic). With RTK, sensor technology and the development of digital models, the first machine guidance systems came quite rapidly. In Sweden, the application of the new production process was a need to survive in the market.

In absence of N-RTK

In the early stages of the use of RTK, consultants and contractors established their own local reference stations as a base for the RTK-measurements. The reference stations, or the active realisation of the reference system, served often only the needs of the single user or company at a working site. Data from the reference stations were distributed by local radio transmitters with limited range on open frequencies. When the assignment was ended, the reference station was removed from the site. This solution worked fine on sites where only one party was present. In more urban areas where several actors work within the same working site or at adjacent sites, there was a competition for the frequency space for the distribution of the RTK data. In some cases, the surveyors did not know which reference station they used or in other words, they did not know which active realisation of the reference system they used. A further problem occurred, when several parties worked within the same working site and used their own reference stations. In this case, there were different active realisations of the reference frame within the same project. Moreover, using the single base stations are subject to distance-dependent biases.

[1] https://www.trafikverket.se/en/startpage/

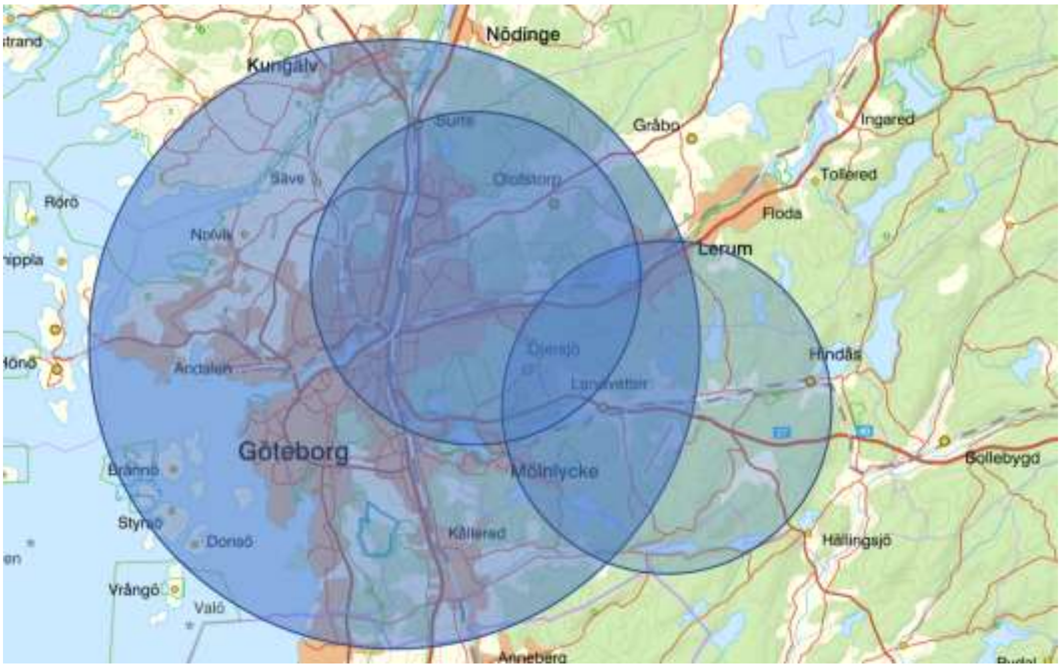

Figure 1, Theoretical example of radio distribution in an area, where several local reference stations were in use simultaneously and transmitting data corrections. ©Lantmäteriet.

N-RTK

A solution to overcome the abovementioned limitations was to develop a network of GPS reference stations located in a wide geographic area. The technique is largely referred to as Network-RTK (N-RTK), where the reference stations are interconnected and a user inside the network needs only a single GPS receiver (rover) to estimate the coordinate of its location. The network provides the users with the correction information, which are transmitted to the rover by a communication link in real-time. One of the major challenges in the N-RTK is the network configuration, where the distance between reference stations and the rovers is better not to exceed 100 km (Wübbena & Willgalis, 2001) as it would be difficult to resolve the ambiguity. Moreover, the number of reference stations in the vicinity of a rover is of importance as the increased redundancy of reference stations, in principle, improves the accuracy of positioning and guarantees the availability of the network in case of operation failure of any reference station.

Swepos

In Sweden, the RTK measurements can be performed based on the Swedish national network of permanent stations (Swepos[2]), which is in operation since 1998 and run by Lantmäteriet (the National Surveying and Mapping Authority of Sweden). The initial design of the Swepos provides a 70 km distance between adjacent reference stations on a national scale (today is 35 km), where the data corrections are distributed via GSM from the control centre (Jonsson, Hedling, & Wiklund, 2003). Swepos consisting of the software Trimble Pivot Platform (TPP).

[2] https://Swepos.lantmateriet.se

2. PROJECT ADAPTED NETWORK RTK (PA-NRTK)

2.1 Feasibility study, Concept development

The Swedish Transport Administration started in 2005 to investigate the contractors' solutions to streamline the production efficiency, provided by a combination of 3D-models, machine guidance and GNSS technology. They also identified that a solution was required to the problem that occurred in projects and regions, where each contractor establishes its own RTK-surveying system.

A research project was started by the Swedish Transport Administration in 2006 to seek a solution to the problems raised concerning RTK-surveying. The basic philosophy to suggest a future solution was not only to influence the users' measurement choice but to ensure the existence of the required infrastructure in the place for the users to easily choose their best-measuring methods. Several criteria have been defined to reach a future solution. The solution would provide the conditions for modern production methods, would eliminate the problems related to the radio communications in the project site and guarantee that the same reference stations will be in use over the projected timespan. Moreover, the solution would be introduced on a national scale with backwards compatibility, where the previously defined quality criteria, i.e. precision, reliability and availability, needed in an infrastructure project would not be violated.

A number of user groups have been identified and the focus placed on their requirements to further develop the research project. The user groups can be divided into three categories: the individual projects, the Swedish Transport Administration in general and the society. Each individual project needs an accessible geodetic infrastructure, which fulfils the requirements of both clients and users. The Swedish Transport Administration requires defining standardised conditions for small and large projects, and the society is in need of a forum to exchange data and share the infrastructures.

Addressing the requirements, a solution could be developed from the risk management perspective. The purpose of risk management is to ensure the efficiency of the RTK-surveying system where the system is continuously in operation, is capable to deliver the corrections and is reliable enough for a user to obtain (at least) a similar uncertainty as by using RTK based on a local reference station. The risks are divided into four groups: general risks, system suppliers, project risks and users. The general risks include external factors such as satellite systems, atmospheric effects and other parameters that affect the results where the users cannot influence. System suppliers address the hard- and software in the positioning systems as well as the necessary data communication between reference stations, control centre and users. The project risks describe the concerns of the Swedish Transport Administration in each individual project and with contractors. The user's risks are directly connected to the individual users of the system.

By considering all the conceivable risks, a developed concept is introduced within the PA-NRTK. The concept consists of a complete solution for the RTK-surveying and its post-processing estimations. Furthermore, the concept describes the station establishment routines, system operation, handbooks for users and instructions for the documentation between the Swedish Transport Administration and the contractors. The establishment of the passive networks that enables applying the traditional surveying methods is also included in the concept.

To achieve a national scale RTK-surveying system, a collaboration was started with the National Surveying and Mapping Authority of Sweden (Lantmäteriet), who had established the Swepos network by 70 km distances between reference stations by that time. One of the main concerns in this research project was to determine the optimal distance between the reference stations as well as designing an optimal network configuration for the RTK-surveys in the projects with longitudinal expansions. Emardson and Jarlemark (2011) proposed an optimal network configuration where the distance between reference stations is 10 km and the distance to the reference line along the project corridor should be kept as short as possible to fulfil the precision criterion of the network.

Two methods are developed in this project to switch over from the traditional methods to the satellite-based techniques: a method based on the static GNSS measurement, and another one based on the real-time GNSS measurements. The static method is developed on the basis of the Bernese GNSS software (Dach, 2015) and enables the users to post-process their measurements via a web GNSS automated post-processing service belonging to Lantmäteriet. The users have the possibility to upload their RINEX files in the web service and receive the results in form of estimated coordinates with uncertainty and a post-processing summary. The service uses the closest reference stations within a radius of about 20 km from the measuring point. A detailed workflow and a review of the quality requirements are explained in Malmborg (2011). The second method uses the RTK measurements to establish a total station. The method of real-time updated free station (abbreviated as RUFRIS) uses the RTK coordinates of several common points to estimate the coordinates and orientation of the total station. The optimal number of common points to be simultaneously measured by both total station and RTK is 10 to 30 points for acquiring reasonable establishment precision and reliability (Horemuz & Andersson, 2011). The concept is explained in Andersson (2012) and further studies conducted to analyse the correlation (Horemuz, 2011a) and the reliability criterion (Horemuz, 2011b). The RUFRIS method is also evaluated to be used in height determination when there is low accessibility to benchmarks in projects. A standard deviation of about 7 mm is estimated for the determination of heights by using this method if a modified geoid model is available (Alizadeh-Khameneh, Jensen, Horemuz, & Andersson, 2017).

Monitoring routine for the transmission of the radio signals is developed in this research project. The monitoring stations are established as RTK receivers, where they continuously receive the radio-transmitted corrections. In addition, the ambiguity is resolved by every minute. Therefore, one could monitor when and how the fixed solution is obtained. These results are continuously reported on a website for the users.

The final solution for the PA-NRTK addresses the densification and configuration of the Swepos network, where the reference stations are located at a distance of 10-12 km from each other. The reference stations are equipped with full redundancy in all components except the

GNSS antenna. Every station is equipped with dual GNSS receivers, double data links to the control centre and dual communication interfaces to the users. Both electric power and batteries are in an off-the-grid operation. Data corrections are distributed to the users both via mobile internet and by a local UHF radio signal. The control centre is also equipped with dual operating servers and a disaster recovery system. Moreover, the satellite signals, data communication from reference stations, the position of the reference stations and the local radio signal distribution are all monitored in the control centre. Transmission of the data correction via radio signals is continuously monitored at the monitoring stations and 24/7 support is available.

The PA-NRTK services are free of charge for the project members. From a user perspective, a user account is required to get access. By registration, the users provide the service with their contact information including e-mail address and cell phone number (SMS) to receive notifications.

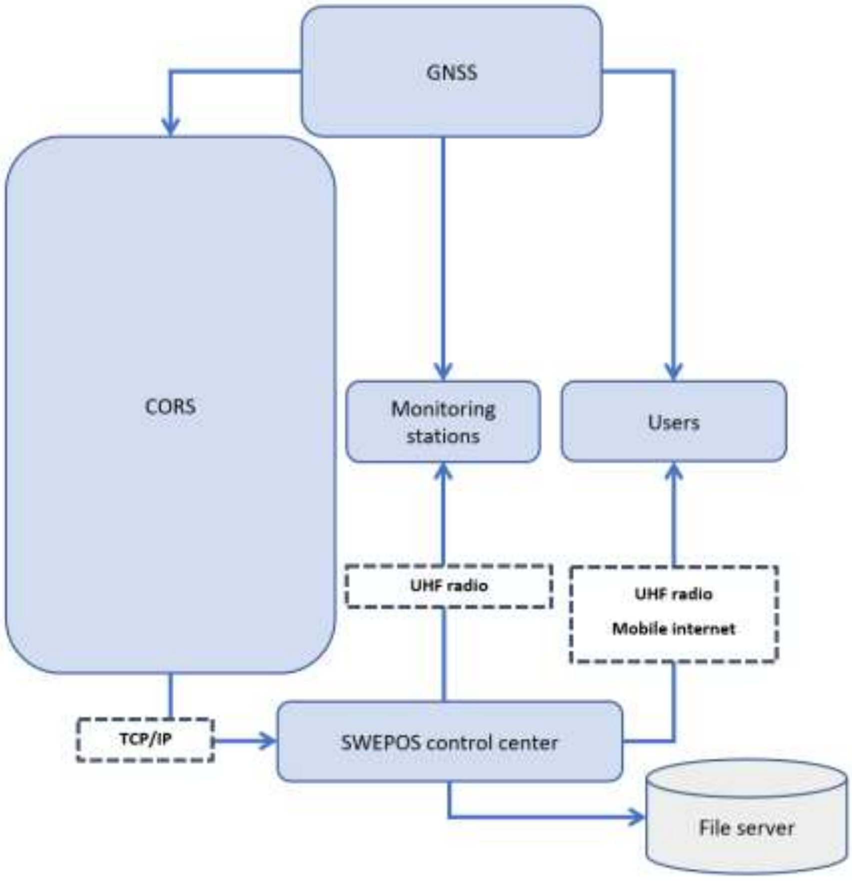

Figure 2, System overview PA-NRTK (Swepos) implementation.

The active and passive realisation of the coordinate system is always controlled before running the PA-NRTK services at known points both horizontally and vertically by the RTK- and the static GNSS-survey. Besides, local geoid models can be developed as needed.

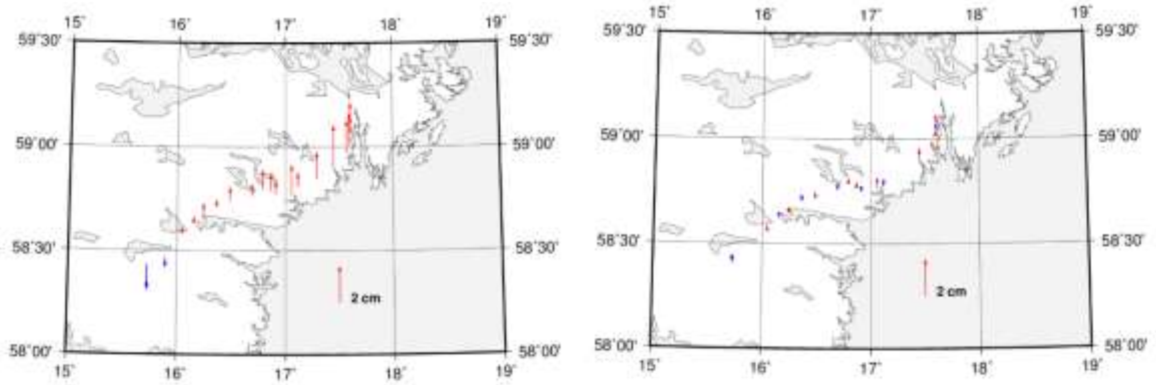

Figure 3, Left figure presents the systematic residuals between the static GNSS surveying and levelling by using the national geoid model (SWEN08). The residuals are reduced in the right figure by using a local geoid model (SWEN-OSTL). The figure is adapted from Ågren & Ohlsson (2016).

2.2 Review of SIL1.0 (Stomnät i Luften 1.0)

To evaluate the PA-NRTK on a larger scale, a pilot project (BViV: Bana Väg i Väst) had started by the Swedish Transport Administration. The project corridor was extended from Gothenburg to Trollhättan for about 75 km. A new double-track railroad and a four-lane motorway were to be constructed in the BViV. The project area was located along the Göta river and was known for its poor soil condition. The construction started in 2006 and took until 2012 when the road and railroad between the two cities were completely built.

A PA-NRTK was established for the BViV according to the specifications, consisting of an active and a passive realisation of the project's reference system. The active realisation was based on the Swepos 70 km network with further 9 reference stations. The location of the reference stations is shown in **Figure *4***. All hardware used in the reference stations are equipped with full redundancy and can be remotely controlled from the control centre. Moreover, a dual communication channel is provided between the reference stations and the control centre by both mobile internet and fixed telecommunications. The distribution of the RTK-corrections to the users is preliminary carried on via UHF-radio, where each radio broadcasting station has a fixed Virtual Reference Station (VRS). In addition, the mobile internet can also be used to increase redundancy. The UHF radio corrections are always controlled in real-time at the project's established monitoring stations. It is worth mentioning that the active realisation provides 24/7 support for the project members. Besides, a passive realisation of the reference system can also be utilised to ensure the possibility of using the traditional surveying methods. The required control points in a traditional geodetic network are horizontally established as pair of points with inter distance of about 3 km. To deal with the project's height, benchmarks are set with a 1 km distance from each other.
The relation between the active and the passive reference systems are controlled before starting a PA-NRTK. To improve the accuracy of the height measurements with the GNSS, a local and tailored geoid model was developed for the project by Lantmäteriet. The obtained uncertainties in the PA-NRTK is shown in **Table *1*** (Hederos, 2011).

Table 1, Uncertainties of RTK-survey and post-processing service.

Coordinate estimation method	Uncertainty (1σ)	
	2D [mm]	1D [mm]
RTK	11	13
Post possessing service	8	11

Figure 4, The Swepos network in the project area was densified by further 9 new reference stations in two stages for the PA-NRTK: Marieholm-Älvängen, and Älvängen-Trollhättan. The yellow triangles in the figure represent the Swepos stations when the project started. © Trafikverket.

Several interviews were made to document the practical experiences of the PA-NRTK users and to collect feedback. The participants in these interviews were project managers, surveying engineers, construction managers, machine operators, instrument and system suppliers, as well as surveyors at adjacent municipalities. The prevalent questions in the interviews were about the economy, productivity, contract-related questions and regulations. The outcome of the interviews is summarised by Andersson (2013), where the major benefit of the PA-NRTK in providing a similar surveying condition for all the user groups is clearly emphasised. The previously mentioned problems, where users were establishing their own single base RTK in a project area, are solved by using the PA-NRTK, which makes it easier for the users to collaborate. Another feedback is to highlight the importance of a geodetic infrastructure in an early stage of the project, which provides a clear strategy for positioning through the projected timespan. Moreover, according to the interviews, the production efficiency is increased by using machine guidance, where it enables the surveyors to concentrate on quality control instead of traditional stakeout. The PA-NRTK introduces even more flexibility to work in shifts, as GNSS and machine guidance can be used independently from the daylight at the workplaces. At the start of BViV in 2006, there were only a few machines equipped with machine guidance systems, while almost all machines were using the system in the end 6 years later.

From the financial point of view, the total savings of the project is calculable. The cost estimations showed that about 3.2 million Euros are saved for establishing and maintaining a geodetic network along the project corridor. The major saving is made at the contractor, by combining the PA-NRTK, 3D models of the construction to be built and machine guidance system. The savings related to increased production efficiency are estimated to 32 million Euros.

3. NEW RESEARCH PROJECT

The Swedish Transport Administration are in the middle of a digitalisation process. From 2015 and on, it was decided that all new investments should be based on BIM (Building Information Models). The digitalisation process puts focus on geodata and the relation to the geodetic reference systems. In recent decades, the Swedish Transport Administration has shown, through both types of research and in real projects, that there are large economic and environmental benefits with the modern implementation of the geodetic reference systems based on GNSS in combination with the use of 3D-models and machine guidance. Technological development within all three of these areas goes very fast. To ensure the concept of PA-NRTK is kept as modern as possible and that it fulfils future needs from the users, Swedish Transport Administration has started a three-year research project started in 2019, Stomnät i Luften 2.0 (SIL2.0). The project is a continuation of the earlier research project (SIL1.0) but is also based on experience from risk management carried out at each establishment of PA-NRTK and from the use in real projects. SIL2.0 initiated by Swedish Transport Administration but there are several organisations involved in doing research within the project: Lantmäteriet, the research institute of Sweden (RISE), the KTH Royal Institute of Technology and the consultant company WSP. SIL2.0 consists of several activities and are explained more in detail below.

New satellite systems and updated satellite signals
A lot is going on with the field of GNSS that need to be addressed within the implementation of PA-NRTK. PA-NRTK is designed for the two GNSS with Full Operational Capability, GPS and GLONASS. In near future, they will be accomplished by both the European Galileo and the Chinese BeiDou. Besides that, the new GNSS becomes available, the existing is under constant development. New frequencies, code structures, redesign of ground control and so forth. All these changes will change the conditions for the PA-NRTK concept. The aim with activity on new satellite systems and updated satellite signals is to ensure that PA-NRTK stays as a modern and robust geodetic infrastructure gaining all the benefits from the improved GNSS.

Strategy for establishment and operation of PA-NRTK
A common reference system simplifies the exchange of geodata between different user groups from early planning, design within the building process. A common reference system is a necessity when implementing BIM in an organisation as Swedish Transport Administration.

One of the advantages of the PA-NRTK concept is the direct link to the Swedish reference system, SWEREF99, realised by the reference stations in the Swepos. The direct link to the national reference system is also one of the challenges when applying PA-NRTK in local construction projects. All changes applied on a national level in Swepos will directly influence each PA-NRTK system, i.e. software updates, new hardware in the reference stations, implementation of new antenna models, or as in February this year when a new realisation of SWEREF99 was made, resulting in new coordinates for all stations Figure 6 show a time series from the daily monitoring of the reference station Botsmark in the northern part of Sweden. Each numbered vertical line represents some action taken at Swepos at a national level that influences the users of the PA-NRTK systems.

Within Swedish Transport Administration, each construction projects acts as solitaires with their own budget, duration and responsibility for the realisation of geodetic reference systems. Large projects are usually those that establish PA-NRTK and bear the cost for the operation of the systems. Surrounding projects uses the same infrastructure directly or indirectly since the reference stations in PA-NRTK is a part of the national Swepos-system. There is a risk that a large project, when it ends, de-establish its PA-NRTK system, with the consequence that all the surrounding projects being directly influenced.

The purpose of activity within the establishment and operation of PA-NRTK is to find a common strategy for establishment, operation and de-establishment and to create a platform for the exchange of experience between projects with PA-NRTK.

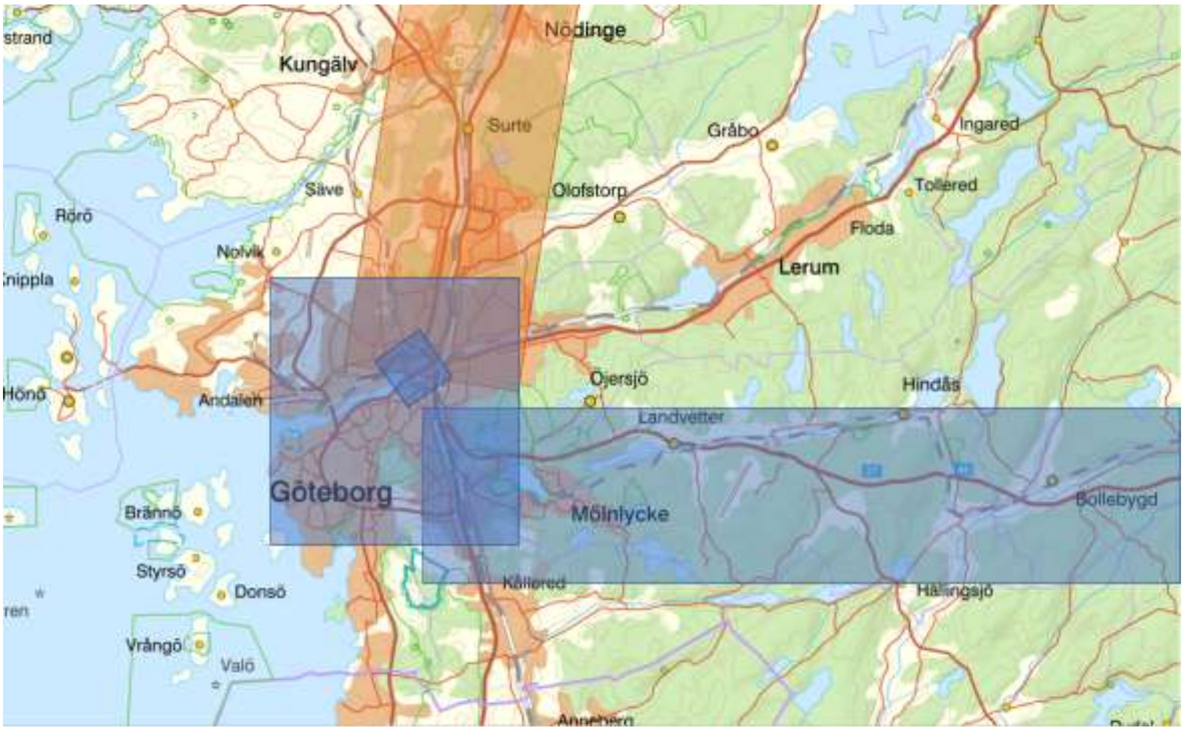

Figure 5, Within the Gothenburg area, there are several projects with PA-NRTK systems in use. The red area in the north is the pilot project for PA-NRTK (Bana Väg i Väst), in which 5 of 9 stations were removed when ended in 2012. ©Lantmäteriet.

Routines for monitoring the reference stations

Swepos is classifying their reference stations into two categories: class A and B. The class A stations are used to realise the reference system SWEREF99. These stations are placed on solid bedrock with specially designed pillars for the GNSS-antennas to ensure their stability. The class B stations, on the other hand, are placed on top of buildings. These are easier to establish but are not as stable as the class A stations. Most of the reference stations in a PA-NRTK system is of the class B type.

A basic assumption in the Swepos-network is that the reference stations are stable over time and known their coordinates known. This assumption does not hold if the GNSS-antenna for some reason is accidentally moved or if there are some seasonal effects, as shown in **Figure 6**.

Lantmäteriet monitors the coordinates in the Swepos reference stations, both in real-time and on daily basis. The real-time monitoring is done in the TPP software used in the control centre of the system and the daily monitoring based on 24h data processed in the Bernese software. The sensitivity in the real-time monitoring is proximally 10-15cm and in the postprocessing less than a centimetre. The real-time monitoring will directly give a response to the large displacements but the postprocessing will give a response after at least 24 hours. The users on the other hand want the information as soon as possible to ensure the result in the field. SIL2.0 focus to find alternative methods to determine and verify the stability of the reference stations are investigated to minimise the risk for the users.

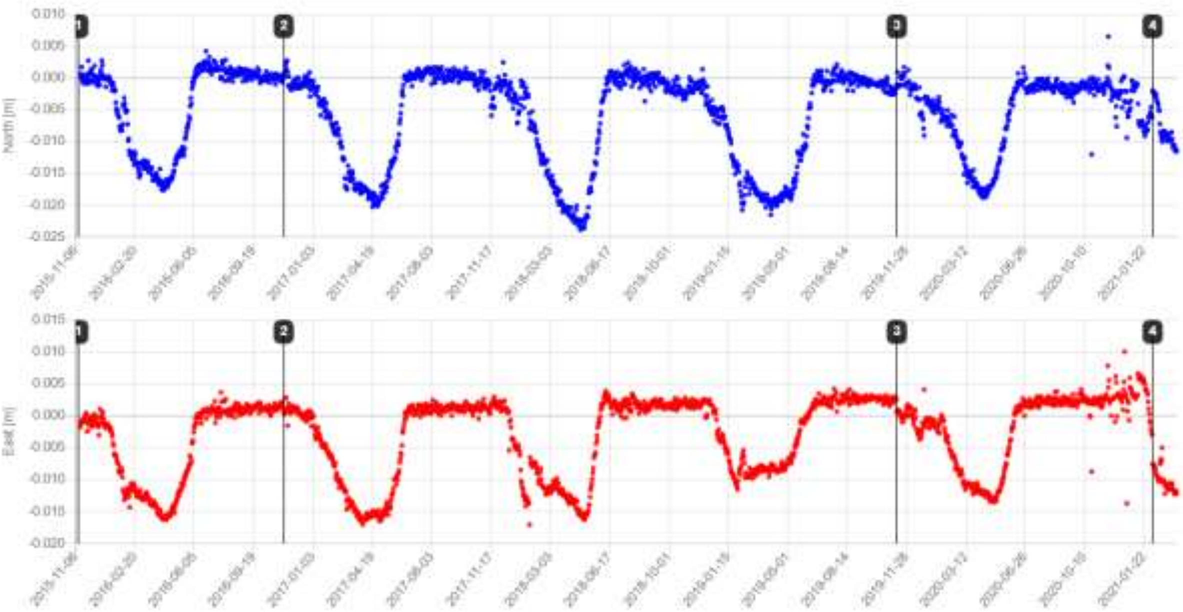

Figure 6, An extreme but clear example of the seasonal motion pattern in Northing and Easting at station Botsmark, a class B station, in the north of Sweden. The coordinates come from the daily monitoring of the reference stations. Each box with a number represents an action that affects the coordinates of the station (change of hardware at the station, new land lift models, computational settings, etc.).

Further development of the postprocessing service
Within the concept of PA-NRTK, there is an Automated Post-processing Service. Each project with PA-NRTK gets its Automated Post-processing Service available on a WWW/FTP server in RINEX-format. The user logs in to a webpage at Swepos selects the actual project and uploads the RINEX-file. Before the computation is started, a quality check is performed to make sure that all input needed for the computation is in the RINEX-file. After quality control, the computation process can be started. A few minutes later the user gets an email with the results.

The current version of the Automated Post-processing Service has some limitations when it comes to practical use. One is that it only can process RINEX-data at time. This limitation makes it impossible to ensure the local connection between adjacent points measured in the same session. Further, the current version of the portal lacks the opportunity to include existing passive points as reference points in the processing which leads to difficulty in securing the relation between existing passive geodetic networks and new ones.

The activity around the development of the postprocessing service will focus on: how to include more GNSS into the service, how to incorporate observations from points with known coordinates, if we can give some advice to the users on how to treat the seasonal variation, and finally if it is possible of an automated review of the results from the service.

Distribution of corrections
PA-NRTK is based on full redundancy in all hardware, software, communication and electrical power supply. RTK-corrections are distributed to the user both via Mobil Internet and UHF-radio. Radio has been used ever since the first project and is still the main channel for distribution. The reason for this is that it is both reliable and stable. Mobile internet has shown to be vulnerable during rush hours and in areas with poor coverage. However, UHF poses also problems, especially in urban areas with many projects with different duration time, i.e. the surroundings around Gothenburg in **Figure 5**. The number of frequencies for data distribution on UHF is limited and the project that is first in place chooses data format (or version of RTCM). Redundancy and availability key concepts when trying to find an alternative to the current channels for the distribution of corrections.

Next solar maximum and its effects on Ionospheric effects
All GNSS measurements are affected by the actual electron density when the signal is passing through the atmosphere. The number of free electrons that influences the GNSS-signal varies both spatial and temporal. The aim of this activity within SiL2.0 is to predict what we could expect for the PA-NRTK users in the approaching solar maximum period that expected to occur in 2025. Theoretical studies, as well as simulations, will be a part of the work.

User contact and information channels
From a user perspective, information about the actual status of the Swepos is critical. It is a question of integrity for the user. To increase the integrity are some tools built into the PA-NRTK concept and in the Swepos-system. In critical situations, the user gets information by e-mail and SMS. These messages are sent when something happens to the system that will

influence the positioning performance at the user side. Beside these quick communication channels, there is also the Swepos-homepage, where users with a user account can log in and get access to information about: the actual status of the reference stations, upcoming service windows, monitoring stations and an ionosphere monitor. On the webpage, there are also some tools for planning GNSS-campaigns. For the users in the Swedish Transport Administration projects, it is not very convenient to access the information directly through the Swepos general webpage since there is simply too much information. To make the information available user focus are put into the SIL2.0 project to study how this could be done. As a starting point prototypes of project-specific portals are on the agenda.

Detection and identification of spoofing and jammers
At a typical modern construction site, today (2021) is about 90% of the building process is based on GNSS. This makes the sites very sensitive and vulnerable to disturbances of any kind. With the loss of GNSS, one must use traditional surveying methods instead resulting in increased costs and probably extended timetables etc. An obvious risk is that could cause a disturbance in the production is spoofing or jamming of the GNSS-signal. Previously in SIL1.0, the risk has been identified and routines developed at the Swepos system level, how to act in case of suspected disturbances. In the SIL2.0 project, the question is raised again, this time to increase knowledge about how spoofing and jamming will affect the users and further to investigate different methods to identify the sources causing the disturbance in the field.

Installation of GNSS equipment on construction machinery
Based on a basic assumption that all systematic errors related to the satellite systems, the atmosphere, and the receiver clock are eliminated by the corrections from the network-RTK system and by double differencing the observations at the VRS and the rover. The remaining error source will be found surrounding the antenna at the rover. This activity will focus on the installation of GNSS equipment on construction machinery.

New Positioning methods
The PA-NRTK concept is based on a traditional RTK-measurement with the use of VRS. In the future, there might be several other positioning methods in use besides RTK, like Precise Point Positioning (PPP). The purpose of this activity is to study alternative GNSS positioning methods and how to use them in or combine them with PA-NRTK.

Positioning systems for autonomous construction vehicles
One experience from the pilot project with PA-NRTK (2006-2012) was that it is the combination of 3D-models, machine guidance, and GNSS that makes it possible to increase productivity with cost savings as one of the real benefits. The next generation of construction machinery is on its way, electrified and with autonomous driving.
A part of SIL2.0 focuses on the next-generation construction sites and what type of geodetic infrastructure is needed.

Local geoid models
Geoid models are needed to be able to measure heights with GNSS in the same reference system as traditional levelling. The accuracy of heights that are determined with GNSS

depends both on the uncertainty of the coordinate estimates in the receiver and the uncertainty of the geoid model. In Sweden, there is a national geoid model SWEN17_RH2000 based on the gravimetric geoid model NKG2015 adapted to the national circumstances. The model has a standard uncertainty of 8 – 10 mm (Kempe & Ågren, 2018) on a national level. At each new project with PA-NRTK the relation between GNSS and levelled benchmarks are studied. If needed local geoid models are determined to reduce systematic errors. A PhD, student at KTH Royal Institute of Technology in Stockholm investigates routines on how to update the national geoid model with information from the local projects.

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Johan Vium Andersson has been working at WSP since 1994. He has been involved in developing the concept of PA-NRTK since the start of 2005. He got his PhD at the Division of Geodesy at KTH Royal Institute of Technology in Stockholm in 2008. His research was focusing on GNSS and monitoring applications. He has a focus on the practical application of geodesy and research interest in the area of geodetic surveying, geodetic infrastructure, satellite positioning and InSAR.

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