Geometry of reference stations in Network RTK

Milan HOREMUŽ, Amin ALIZADEH-KHAMENEH, Johan Vium ANDERSSON, Sara WAHLUND, Sweden

Key words: Network RTK, VRS solution, simulation model, network geometry, user uncertainty

SUMMARY

Using the Global Navigation Satellite System (GNSS) surveying methods give the users an advantage over the other traditional methods, where for instance, measurements between points with longer distances can be performed with no line of sight. Furthermore, the GNSS technology, through its real-time applications, can provide a basis for more efficient data collection and product automation, e.g., machine guidance. Nowadays, users do not need to have deep theoretical knowledge of GNSS to survey. They only expect a reliable and precise estimation of coordinates from the surveying instruments and GNSS services. It is the system providers, who face challenges to ensure a reliable delivery with consistent quality to the users and are, therefore, in need of planning tools and models to operate more efficient services. The developed simulation model in this paper provides an overview of uncertainties for the network Real Time Kinematic (RTK) measurements and investigates the effect of network geometry on users' precision. Besides, the model is used to study the possible deterioration in users' precision if any reference station in the network stops working. This information provides a theoretical basis for densification strategies and evaluates if any reference station is more important than the others to maintain consistent quality in the network.

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1. BACKGROUND

The number of applications and users of precise Global Navigation Satellite System (GNSS) measurements has been increasing steadily in recent years. In Sweden, most of the users rely on the positioning infrastructure and services provided by Lantmäteriet (The Swedish Mapping, Cadastral and Land Registration Authority). The positioning infrastructure is based on more than 450 Continuously Operating Reference Stations (CORS) distributed all over the country and the services include post processing, network Real Time Kinematic (RTK) and Differential GNSS (DGNSS). The network RTK service (SWEPOS) is based on the Trimble Virtual Reference Station (VRS) software (Vollath et al., 2000). The users are provided with corrections in form of a synthetic reference station (VRS) located near the user. The VRS data are corrected by a combined ionospheric, tropospheric, and orbital correction computed on a number of closest CORS and interpolated for the VRS location. The user's receiver computes its position by processing baseline towards the VRS.

One of the users' challenges in using this service is their unawareness of the status of the CORS, which are used to determine the users' position. For instance, any interruptions or delays in the dataflow between the reference stations and the VRS-processing centre impose a higher uncertainty on the user's estimated position. Moreover, the distribution of CORS in network RTK and their effect on the positioning precision is usually unclear for the users.

The goal of this paper is to consider the observation domain corrections, namely the concept of a VRS and create a model to analyse the effect of the reference stations' geometry on the positioning precision of a rover. The developed model is also used to study the uncertainty on a roving receiver in some practical situations. The results can be used both by the users of a network RTK service or by decision-makers when an optimal network configuration is to be designed or the network is to be densified.

The paper is a continuation of the previously published paper in FIG working week 2021, where the development of the project-adapted network RTK in Sweden has been discussed in detail, see Andersson et al. (2021).

2. NETWORK RTK: A REVIEW

Due to the effect of systematic errors in raw GNSS observations, a roving receiver should operate at a short distance from a reference station, which may restrict its use in practice. A network of GNSS reference stations instead of a single reference station can efficiently model or eliminate the systematic errors in the region and thus provide a possibility to increase the distance between the rover and the reference station. Furthermore, a more reliable network RTK system and a shorter RTK initialisation time can be achieved (Landau et al., 2002). Vollath et al. (2002) compared the cumulative time-to-initialise for different receivers using the single- and network-based RTK, where the single-based RTK results show the worst initialisation times. In addition, establishing and maintaining of a network RTK is expected to economically be more efficient comparing to single-based RTK measurements in complex projects. Today, several network RTK solutions for estimating and modelling the GNSS systematic errors and distributing the corrections to roving receivers are in use in the market including, for instance, MAC, VRS, i-MAX and FKP. Previous studies investigated the differences between these solutions in sufficient detail, see for instance Takac & Zelzer (2008) and Edwards et al. (2010). More detailed studies have been conducted by, for instance, Janssen (2009) to compare the VRS and MAC principles and Landau et al. (2003), where they reviewed FKP and other broadcast solutions and performed a comparison with the VRS technique. These studies showed that the solutions are in principle very similar to each other, but they are different in the way of parametrisation of the distributed corrections.

Moreover, the densification (distance between the CORS) and the geometric configuration of the reference stations are of importance for the positioning precision of the network RTK. A problem can occur in sparse networks, where a longer distance exists between a rover and the nearest reference station. Integer ambiguity resolution could then be a challenge due to the increasing effect of systematic errors, which yields imprecise and unreliable results (Rizos et al., 2003). A more detailed study is conducted by Janssen & Haasdyk (2011) using the Australian CORS networks (see for instance Janssen, et al., 2016), where they highlighted the superiority of network RTK compared to the single-based RTK and concluded that the longer inter-CORS distances might significantly degrade the precision and accuracy of the network RTK.

The concept of geometry in network RTK is, for instance, studied by Grejner-Brzezinska et al. (2005), where different solutions (single- and multi-baselines) have been tested in networks with short-, medium- and long-range reference station separations. They concluded that a network with shorter baselines (30-40 km) is required to achieve a sub-centimetre accuracy.

The efficiency of the network RTK with shorter inter-distances is also confirmed in other studies by Dardanelli & Pipitone (2021), where they compared different CORS geometries by using different RTK solutions, i.e., VRS, FKP as well as corrections from the nearest and the furthest stations. Using the full network of CORS with different geometric configurations, the obtained precision from the VRS, FKP and the nearest corrections are similar. However, the FKP solution apparently achieves higher precisions in networks with limited geometric configuration, where for instance several CORS are out of order, or the inter-distances are longer.

In Sweden, a series of studies on network RTK has been conducted by the Swedish Transport Administration (Trafikverket) to create a national strategy for RTK-based surveying in construction projects. Based on the results of several research projects, where an optimal configuration of reference stations (Emardson & Jarlemark, 2011) and measurement accuracy in network RTK (Emardson et al., 2009) are investigated, the national CORS network of Sweden (SWEPOS) has been densified so the distance between the reference stations is currently about 35 km.

The SWEPOS network is densified on an occasional basis for large and complex infrastructure projects, where precise and reliable surveying and machine guidance is in demand. A Project-Adapted Network RTK (PA-NRTK) service is then provided in the area, where the distances between the reference stations are about 10-12 km. An increased redundancy of equipment at reference stations, e.g., receivers, power supply, enhanced communication and increased monitoring of the service are provided for PA-NRTK. For more details on the concept of PA-NRTK, see for instance Andersson et al. (2021). The expected precision for an RTK-user in the field with respect to different densification grades is also studied by Alizadeh-Khameneh et al. (2022).

Lantmäteriet has provided the users with some information about the expected uncertainty using the SWEPOS service for the RTK measurements. The expected positioning uncertainties, published in their handbook (HMK), are provided corresponding to different densification of the reference stations in the area, i.e., 70 km, 35 km and PA-NRTK (10 km), where an uncertainty of about 18, 10 and 7 mm is expected for horizontal positioning (within 68% confidence level), respectively. An uncertainty of about 30, 18 and 10 mm is also desirable for height measurements in the networks with the abovementioned densifications (HMK, 2021).

2.1 VRS concept

The basic principle of VRS is illustrated in Figure 1. Using phase observations from reference stations A, B and C, the following undifferenced phase observation equation can be written as (Hofmann-Wellenhof et al., 2008):

$$\begin{aligned}\varphi_i^s(t) &= \rho_i^s(t) + \lambda N_i^s(t_0) + \Delta_i^s(t) + \varepsilon_i^s(t)\\ \Delta_i^s(t) &= T_i^s(t) - I_i^s(t) + O_i^s(t)\end{aligned} \tag{1}$$

where φ_i^S is the phase observation between satellite S and receiver i with $i = A, B, C$. Furthermore, ρ is geometrical distance, λ is wavelength, N represents phase ambiguity and ε contains the noise and multipath errors. Tropospheric, ionospheric, and orbital errors are given by T, I and O, respectively. Since the coordinates of the reference stations are known, the ambiguities as well as the term $\Delta_A^s(t)$ can be computed for each reference station.

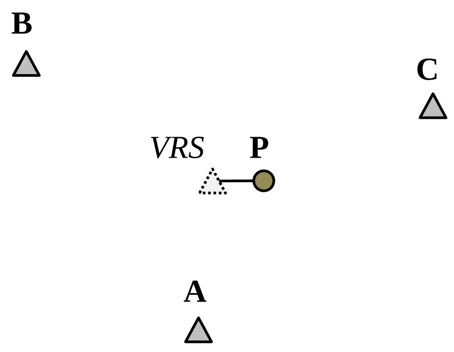


Figure 1. Basic principle of Virtual Reference Station (VRS). GNSS observations at VRS are computed from actual observations at reference points A, B and C for a location close to point P. Coordinates of P are determined by a single-baseline solution.

The phase observation for VRS at location V can be computed as

$$\varphi_V^s(t) = \varphi_A^s(t) + \rho_V^s(t) - \rho_A^s(t) + \Delta_V^s(t) \tag{2}$$

where $\Delta_V^s(t)$ is computed by an interpolation, using $\Delta_A^s(t)$ computed on all reference stations. There are different interpolation methods; here we consider weighted linear interpolation, which is used in Trimble's software (Landau et al., 2002):

$$\Delta_V^s(t) = \frac{\sum p_i \Delta_i^s(t)}{\sum p_i} \qquad i = A, B, C, ... \tag{3}$$

where p_i is the weight of Δ_i^s, which depends on the distance between VRS and reference station i. The weight is greater if VRS is located near a reference station, since $\Delta_i^s(t) \approx \Delta_V^s(t)$ and it decreases as the distance increases since the difference $\left|\Delta_i^s(t) - \Delta_V^s(t)\right|$ will increase. The difference increases mainly due to the residual ionospheric and tropospheric errors, therefore the standard uncertainty in Δ_i^s can be computed as

$$u(\Delta_i^s) = \sqrt{u^2(iono) + u^2(tropo)} \tag{4}$$

where $u(iono)$ and $u(tropo)$ are computed using the distance-dependant uncertainties introduced in Emardson et al. (2009)

$$u(tropo) = \sqrt{\mathrm{C}\,(d_i)^{\alpha}} \qquad u(iono) = \sqrt{\beta\, d_i} \tag{5}$$

with $\mathrm{C} = 5.57 \times 10^{-9}$, $\alpha = 0.9$, $\beta = 6 \times 10^{-10}$ and d_i is the distance between point P and reference station i. The weights p_i in Eq. (3) is obtained from

$$p_i = \frac{1}{u^2\left(\Delta_i^s\right)} \tag{6}$$

and the standard uncertainty for Δ_V^s is computed as

$$u\left(\Delta_V^s\right)=\frac{1}{\sqrt{\sum p_i}} \tag{7}$$

The standard uncertainty of a VRS phase observation is:

$$u(\varphi_V)=\sqrt{u^2(\varphi)+u^2(\Delta_V^s)} \tag{8}$$

where $u(\varphi)$ is the standard uncertainty of phase observations (including local effects) at the reference stations as well as at point P. In our computations, an empirical value of 6 mm is considered for $u(\varphi)$.

2.2 GNSS error budget

The accuracy of the VRS solution in network RTK is limited by the distance-dependant errors from orbit, ionosphere, and troposphere as well as station dependant influences like multipath and antenna phase centre variations. Satellite clock and orbit errors are almost completely cancelled using the network RTK corrections. However, the effect of orbit errors in RTK with single reference station is not negligible and is in the order of a few millimetres for baseline length over 10 km (Emardson et al., 2009).

The ionospheric delay as a function of elevation angles, daily mean value of vertical TEC and distances between the reference stations is experimentally investigated by Emardson et al. (2009) in Sweden. They also studied both hydrostatic and wet tropospheric delays. The hydrostatic part is a height dependant, and its effect can be neglected in geographical areas with smaller topographical variations. On contrary, the wet delay has a significant effect on GNSS applications. Equation (5) expresses the tropospheric and ionospheric delays as a function of the distance between the rover and reference station in network RTK. These values are also depicted in Figure 2.

Moreover, the satellite geometry and redundancy in the number of available satellites at the surveying moment is crucial to obtain a precise result. With more satellite systems in operation, the risk of having poor satellite configuration has decreased, but there are still some periods around the clock with poor satellite distribution in the user's sky-view, which results in higher Dilution of Precision (DOP). Also, physical obstacles can affect the DOP value, for instance, surveying in the vicinity of high buildings or under tree canopies may impose higher uncertainties on the GNSS measurements. The total error graph in Figure 2 is drawn by considering a common value for the horizontal DOP (here is 2).

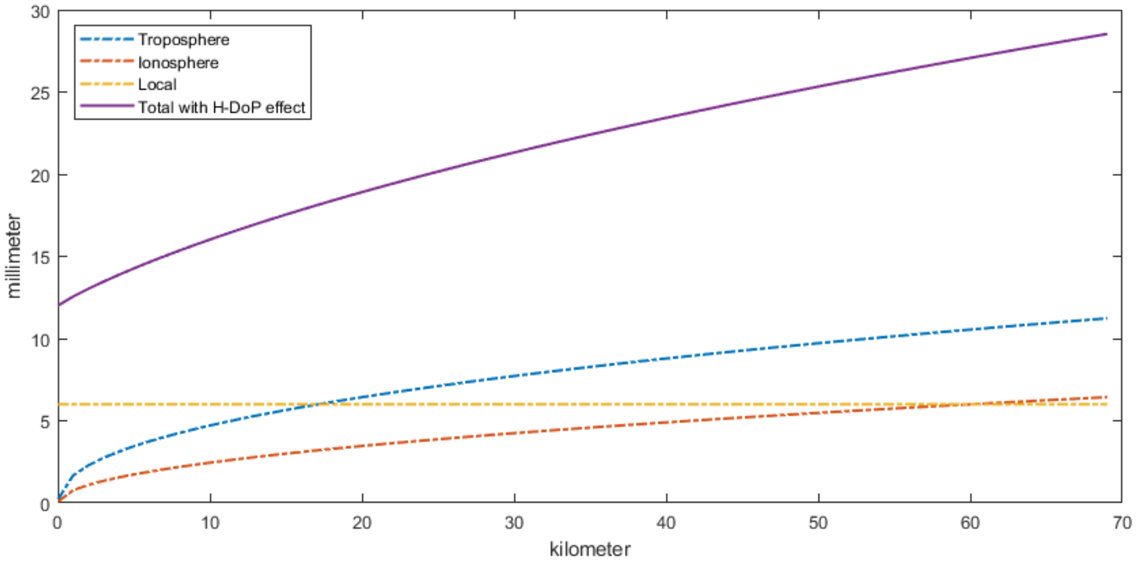


Figure 2. Distance-dependant (e.g., ionosphere and troposphere) and station-dependant (e.g., multipath and receiver noise) errors in GNSS measurements.

2.3 Simulation of precision in network RTK

The expected horizontal precision for the SWEPOS network in Sweden is simulated according to the abovementioned methodology with some assumptions as follows:

- Satellite configuration with PDOP = 2
- Distance dependant weighting of the phase observations according to Eqs. (4), (5) and Figure 2.
- Grid size over the whole country with 1 x 1 kilometre size. For each grid point, the horizontal precision is computed using the 6 nearest Swepos stations.

Figure 3 (a) illustrates the simulation results in the whole SWEPOS network, where the lowest uncertainty of about 5 mm belongs to the locations in the vicinity of the reference stations (dark blue colours in the figure). As could be expected, the uncertainties increase by the distance from the reference stations as they are computed using the distance dependant weighting algorithm (VRS solution). The colour bar in the figure has a unit of mm and is scaled from 5 mm for the dark blue colour to 15 mm for the yellow colour. The vertical uncertainty is illustrated in Figure 3 (b), with almost twice more uncertainties as it is expected from GNSS measurements.

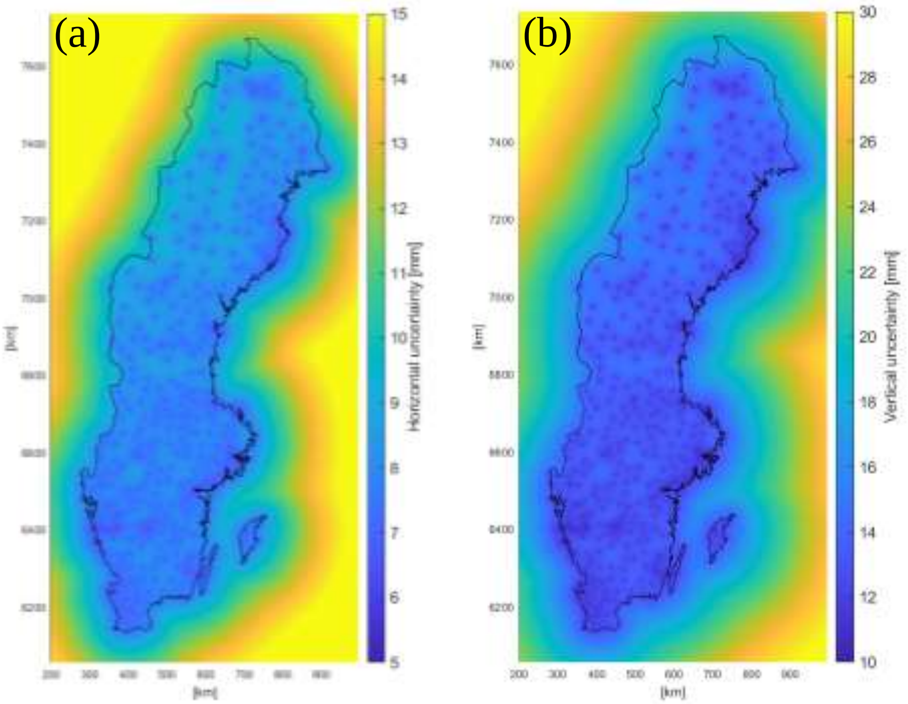
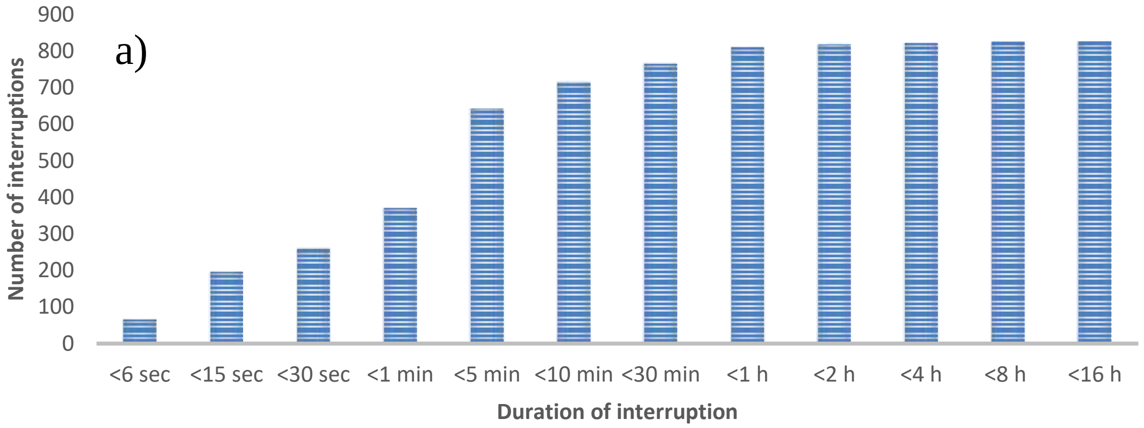


Figure 3. Expected horizontal (a) and vertical (b) uncertainties for RTK measurements using the network RTK service from SWEPOS in Sweden (a VRS solution). The colour bar has a unit of mm.

3. DISRUPTION ON REFERENCE STATIONS

A variety of factors may lead to a disruption to the reference stations, from both intentional human interaction to random noises and malfunctioning instruments. These factors (for instance, change or removal of antenna, damage to instrument, failure in telecommunication, power outage, etc.) may introduce a discontinuity and/or change in collected and transmitted data. Analysing the time series of data can be considered the main method to detect the possible disruptions on reference stations, which are usually observable as gaps or jumps in the series. Recently, several attempts have been made to automate the monitoring and detection of offsets (Egan, 2019).

A detailed investigation has been performed in this paper to scrutinise a sample dataset from SWEPOS, which is collected from 35 reference stations in a period from February to October 2022. The reference stations belong to a PA-NRTK service and are in operation in the Norrbotniabana project (see the next section for more information about the project). The data is classified to show the occurred interruptions/disruptions in the reference stations, Figure 4. It can be seen in the figure (a) that almost half of the interruptions had a duration of less than 1 minute, which is probably because of an abrupt change in the communication between the reference station and the processing-centre. It is also realised that about 30% of the whole sample belongs to interruptions with a duration of 1 to 5 min. According to the supplier, the reference station is removed from the network processor if there is no observation within one minute from that station. Therefore, longer interruptions in observations might change the order of involved reference stations in the processing stage that will influence the user.



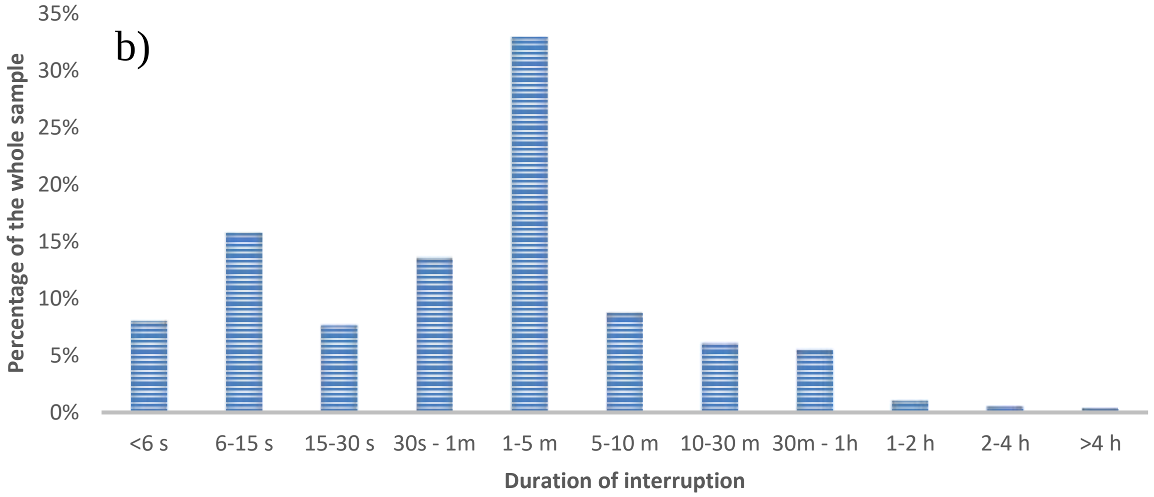


Figure 4. Interruptions in SWEPOS reference stations in Norrbotniabana project for the period from February to October 2022.

3.1 Case study

The developed model in this study can be even used to simulate the effect of temporary station outages in network RTK for the users. The following are two practical case studies in Sweden, where the simulation model is used to both evaluate the positioning uncertainty in the areas and investigate the densification feasibility considering the possible station outages.

3.1.1 Norrbotniabana (NBB)

The Norrbotniabana project is an about 270 km railway project in the North of Sweden, which is going to be built between Umeå and Luleå to enable much safer, faster, and more sustainable travel and transport in this region. To guarantee precise and reliable surveying and machine steering infrastructure, a PA-NRTK service is provided for this project. The developed simulation algorithm described in this paper was used to evaluate the precision of the network RTK in the area and also investigate the consequences of possible disruption or withdrawal of active reference stations.

The project area is divided into northern and southern parts, where the southern part has already been densified with respect to the PA-NRTK with about 10 km distances between the stations, Figure 5 (a). However, the distribution of reference stations in the northern part follows the national 35 km densification. Our developed model was applied to this area to evaluate the horizontal uncertainty after densification. The simulation shows an average 20% improvement after the densification, Figure 5 (b). Further analysis was performed to inspect the effect of station outage on the measurement precision of a random user. To this purpose, 4 test points (TP1-4) have been distributed evenly within the project area to see the effect of each surrounding reference station on the precision of these points, Figure 5 (c).

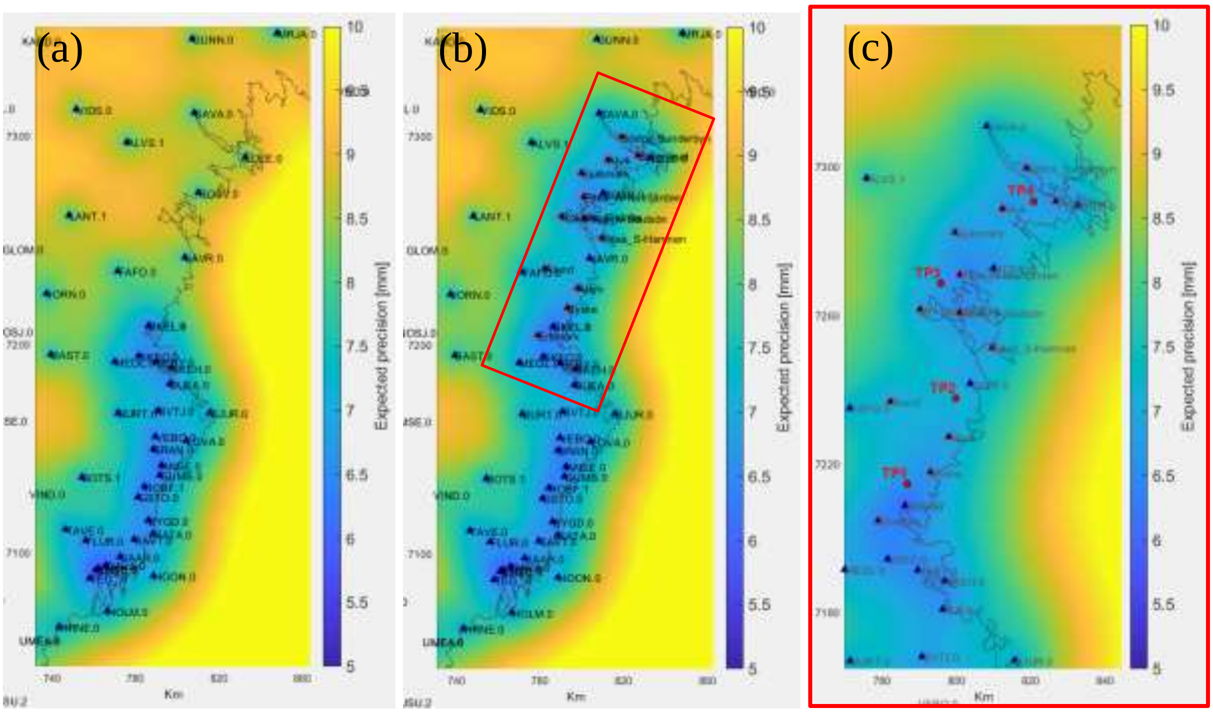


Figure 5. SWEPOS reference stations in the NBB project area: (a): a partially densified network in the south, (b): complete densification of the project corridor according to the PA-NRTK concept and (c): a zoomed view over the northern part of the NBB project, where the test points (TP1-4 red circles) show the location of a random network RTK user.

Figure 6 presents the numerical results for the test points. It is clear in the figure that the absence of the nearest reference stations has the most influence insofar as the precision can be deteriorated by 7%. It can also be understood from the graph for TP2 that station JAVR.0 has the highest effect on this station and thus is more important. Redundancy for this station (backup) can ensure the quality of the network in case JAVR.0 stops functioning. However, due to a dense distribution of reference network for the PA-NRTK service, the temporary outage of the stations is not very sensitive as there is another reference station, which can be easily substituted in the processor. This would be more challenging in sparse networks or in case more stations simultaneously stop functioning.

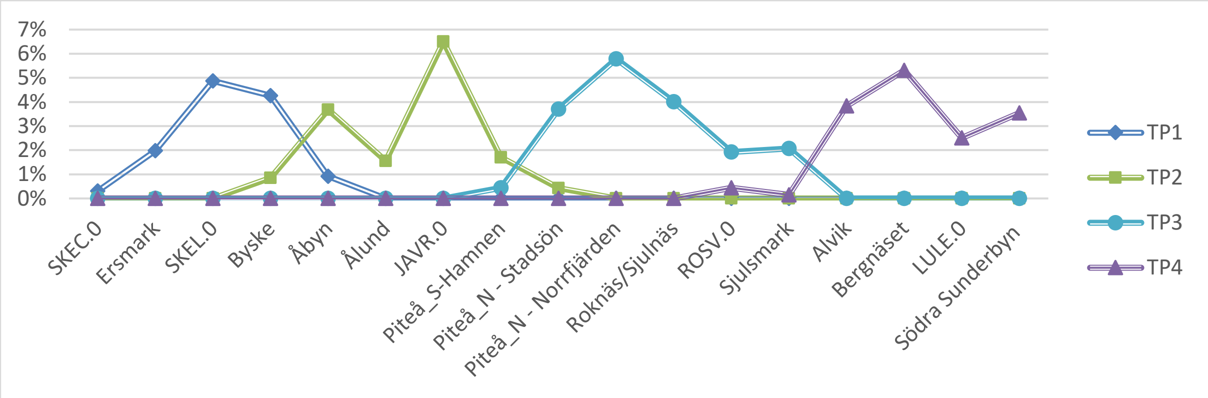


Figure 6. Deterioration of measurement precision for a random user (TP1-4) by the absence of nearby reference stations in the area.

3.1.2 Four Tracks Uppsala

The Four Tracks Uppsala project is planned to expand the railway between Uppsala and Stockholm. The current double-track in this route has already reached its maximum traffic capacity and therefore the number of tracks is planned to be doubled to facilitate transportation. Geodetic infrastructures are improved and densified in the area to provide better surveying conditions and also a common platform to share data from the planning step to execution.

A similar study as NBB is performed to evaluate the uncertainty of RTK measurements in the area, where the four-track Uppsala is going to be constructed. The goal is to verify whether establishing new reference stations in the area can help with the improvement of surveying and machine steering precision. An improvement of about 15% is achieved from the results, see Figure 7 (a) and (b). Two test points have been chosen in the area (Figure 7 (c)) to numerically evaluate the effect of reference stations on the precision of the network RTK. The test points resemble random users who perform RTK measurements. Table 1 represents numerical values for the precision of the test points when one of the surrounding reference points is out of service. Once again, the effect of the nearest reference station can be highlighted, where for instance, Knivsta and Sävja, which are the two nearest reference stations to the TP2, have the highest influence on this point. The results show that both reference stations have almost an identical effect, which is indicated a redundancy in the network as well.

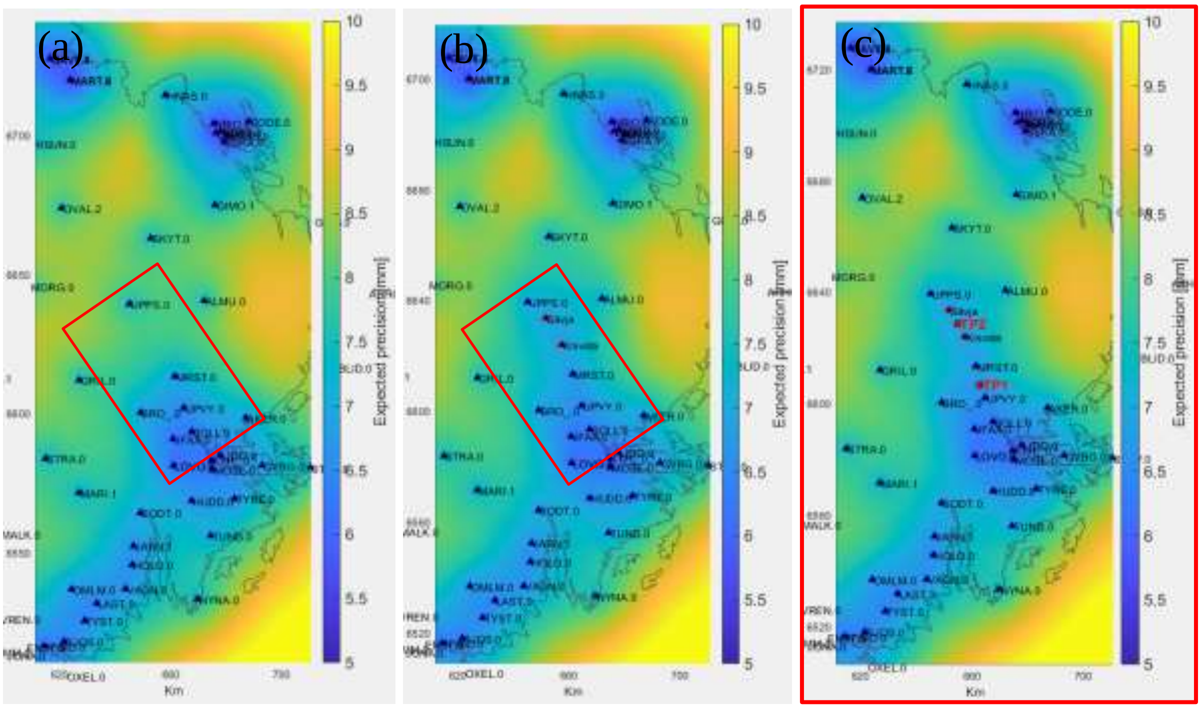


Figure 7. SWEPOS reference stations in the area for the Four Tracks Uppsala project: (a): project corridor before densification, (b): after densification according to the PA-NRTK concept and (c): a zoomed view over the project corridor, where the test points (red circles) show the location of a random network RTK user (TP1-2).

Table 1. Deterioration of measurement precision for a random user on TP1-2 by the absence of a nearby reference station in the area.

	All in operation	UPVY.0	BRO_.0	MRST.0	Knivsta	Sävja	UPPS.0	ALMU.0
TP1	0,007 [m]	5%	3%	5%	1%	0%	0%	0%
TP2	0,007 [m]	0%	0%	3%	7%	7%	3%	1%

3.2 Outage of the nearest reference station

Thus far, the role of reference stations in preserving network precision has been discussed. It is shown in Table 1 that the removal of a reference station can influence the precision of nearby points, albeit with a minor effect. This is, however, true if the measurement is performed in a densified network. Figure 8 illustrates the influence of the nearest reference station in the whole SWEPOS network. The deterioration of precision in the areas with a sparse network can be up to 30% (corresponding to a loss of about 4 mm in precision) when the nearest reference station is out of order, and the next nearest reference station is used instead. A zoomed view over the NBB project area is also provided in Figure 8. Due to more densified reference stations in the southern part of the project, an outage of the nearest station has no significant effect on the precision of the user; the reference stations are located close to each other and therefore the network has enough redundancy even in the absence of the nearest station to the user's point. On the contrary, a 35 km network is in operation for the northern part of the project. An outage of the nearest reference station can have a relatively significant effect on the user's precision as the second nearest station is located at a further distance from the user.

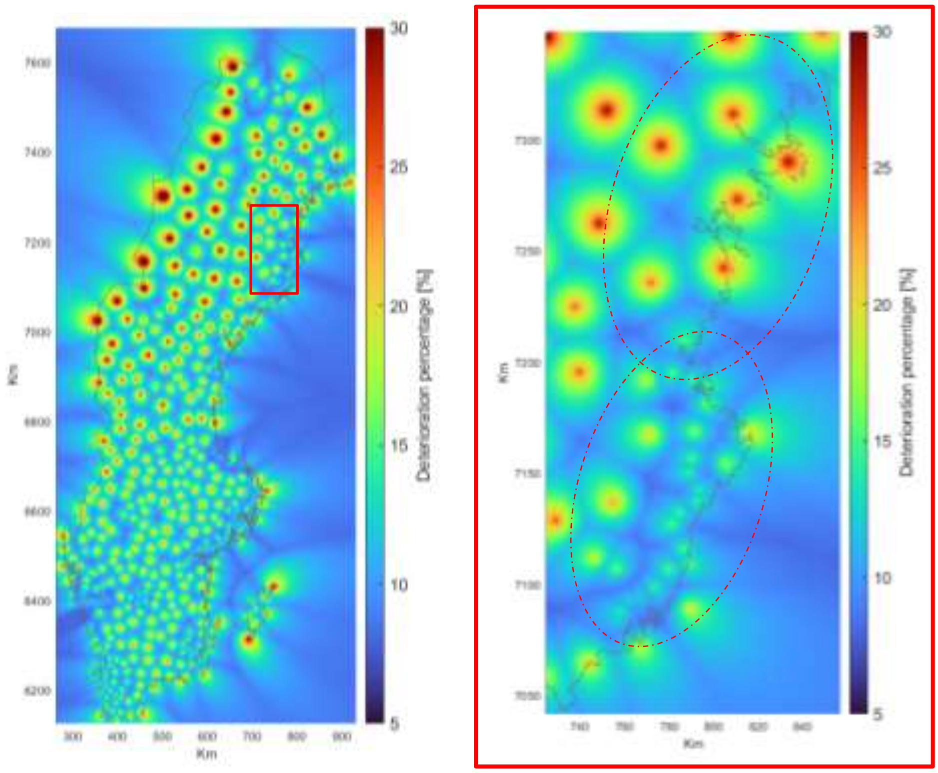


Figure 8. Deterioration of measurement precision using the network RTK, when the nearest reference station is out of service. On the right: a zoomed overview from the NBB project area, where the densification of reference stations in the northern and southern parts are 35 and 10 km, respectively.

4. CONCLUSION

Influence of reference stations' geometry on positioning uncertainty in network RTK was studied in this paper. For this purpose, a simulation model was developed based on the VRS concept and applied to the SWEPOS network with different densification grades. The purpose of this investigation is to provide service suppliers with a theoretical basis for densification strategy as well as to provide a tool for evaluation of expected positioning uncertainties for existing configurations and considering outages on one or more CORS.

We can conclude that the geometry of reference points does not significantly influence the positional uncertainty of new points determined by NRTK GNSS observations. It does not matter if the points are distributed along a line or if they form triangles or other regular polygons. Considering normal conditions (satellite geometry, multipath, atmosphere, etc.) the expected positioning precision for a NRTK user depends mainly on the proximity to the nearest reference station. which is in line with the experience that short GNSS baselines and low DOP give the best positioning precision. This finding is important mainly for the densification of the existing network: the best strategy is to place a new reference station close to the area of interest. However, this does not mean that regular or symmetric distribution of reference stations is meaningless; on contrary, it gives an optimal coverage of larger geographic areas using a minimum number of reference stations.

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BIOGRAPHICAL NOTES

Milan Horemuž is associate professor in geodesy at KTH Royal Institute of Technology in Stockholm, where he has been working since 1996. He received his PhD degree in geodesy at the Slovak Technical University in Bratislava in 1996. His research and teaching are in area of precise satellite positioning and its combination with other sensors, geodetic surveying, and laser scanning.

Amin Alizadeh-Khameneh has joined the WSP Group in 2016. He defended his PhD at the Division of Geodesy and Satellite Positioning at KTH Royal Institute of Technology, where he focused on the optimal design and optimisation of the geodetic GNSS-based networks. After the disputation, he has been involved in several projects and research studies related to, for instance, applied geodesy, sensor technique, etc at WSP Sweden.

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.

Sara Wahlund has received her Master of Science in Civil Engineering with a major in Surveying at KTH Royal Institute of Technology in 2002 and has since then worked with practical applications of GNSS surveying. Sara joined WSP in 2011 and has been involved in establishing several PA-NRTK projects as a consultant for Trafikverket.

CONTACTS

Milan Horemuž
KTH Royal Institute of Technology
Teknikringen 10B
Stockholm
SWEDEN
Tel. +46733790630
Email: milan.horemuz@abe.kth.se

Amin Alizadeh-Khameneh
WSP Geographic Information and Asset Management
Arenavägen 7
Stockholm
SWEDEN
Tel. +46721480756
Email: amin.alizadeh.khameneh@wsp.com

Johan Vium Andersson
WSP Geographic Information and Asset Management
Arenavägen 7
Stockholm
SWEDEN
Tel. +46705364156
Email: johan.vium@wsp.com

Sara Wahlund
Department of Geographical Information West
Ullevigatan 19
Gothenburg
SWEDEN
Tel. +46705947500
Email: sara.wahlund@wsp.com