Improving RTK positioning with SWEPOS™ – lessons from theory and practice

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Abstract
Established during the 1990s, SWEPOS™ is a network of over 200 permanent GNSS reference stations that fulfils a wide range of production and scientific purposes. The largest volume of production GNSS measurements in SWEPOS is carried out with network-RTK technique, which was first introduced in Sweden in 2002. Regional densification of the original sparse SWEPOS network through successive establishment projects has since then led to nation-wide coverage of the network-RTK service, with 1500+ registered users. Typical applications are detail and cadastral surveying, and in recent years also within building and construction (e.g. machine guidance).

A current trend in SWEPOS development has been small or local densifications of the national RTK network, mainly aimed at large-scale construction projects that require high-precision positioning services, around-the-clock availability and rigorous monitoring. But there also seem to be consensus among a broader group of SWEPOS users that similar services are required in order to fully utilize the network-RTK technique. The height quality of positioning seems to be a key concern for many users.

More in-depth studies of network-RTK technique in Sweden were carried out during 2008-2010, in an effort to assess present and future possibilities to meet such demands. The main areas of interest in these studies were:

- Modernization of the GNSS, including Galileo and Compass
- Different levels of SWEPOS network densification – e.g. in-between station distances of 35km or 10km, in comparison with present 70km
- The upcoming solar maximum, with increasing ionospheric activity

This paper summarizes how these factors are expected to affect positioning with network RTK technique, and describes how both user input and theoretical considerations have spurred ongoing efforts to modernize the SWEPOS infrastructure.

1. Introduction

SWEPOS is a network of approximately 200 permanent GPS/GLONASS reference stations. The first stages of this geodetic infrastructure were established in the early 1990s. Operation, maintenance and development of SWEPOS are presently the responsibilities of Lantmäteriet (the Swedish Mapping, Cadastral and Land registration authority).

The largest volume of production measurements in SWEPOS is carried out with the nation-wide network-RTK service. The number of users has rapidly increased since the introduction of the service in 2004, with more than 1500 registered users today (Feb. 2011). The users represent a broad spectrum of disciplines, from cadastral surveying to machine guidance. The rapid increase of users has also lead to an increasing demand for an around-the-clock availability and reliability of the positioning services.

To keep quality standards at a high level, the development of SWEPOS is carried out in co-operation with the users. In recent customer surveys, many users are specifically asking for lower vertical positioning uncertainty. The results from several studies of network RTK technique, most notably the "CLOSE" projects (Emardson et al. 2009a and c), have suggested that this primarily will be achieved by densification of the present SWEPOS network. This paper presents the ongoing efforts of SWEPOS infrastructure modernization, in order to meet user demand and to be prepared for future satellite systems and the upcoming solar maximum.

2. The SWEPOS network

The Swedish GNSS reference station network has been developed in different stages to be able to meet the requests on better positioning uncertainty, reliability and availability. In this chapter a brief description is presented on the development and services provided by SWEPOS.

2.1 Different stages of development

The Swedish geodetic infrastructure for GNSS measurements has been developed in stages to meet current demands on better positioning uncertainty, reliability and availability from the user community. The original SWEPOS network was established in the early 1990s, with a control centre facility and 21 "Class A" stations with an average in-between-station distance of 200 km. Class A stations are built on solid bedrock with a Dorne Margolin antenna installed on a 3 meter high concrete pillar, see figure 1. Due to winter conditions in Sweden the pillar is heated electrically to hold a constant temperature of approximately 15^{o} C. These stations also have redundant equipment, and are able to run for approximately 48 hours if the power breaks down. The original sparse network of 21 class A stations can be regarded as the backbone for the present SWEPOS network and realizes the Swedish three-dimensional reference frame SWEREF 99.

Real-time GNSS positioning at cm-level, became possible with the development of network-RTK technique. Based on the experiences and results from a number of pre-study projects carried out during the years 1999-2002, regional production RTK networks projects were established in three major urban areas in Sweden in close co-operation with local partners such as municipalities, local Lantmäteriet offices, private surveying companies etc. The purpose of these projects was to evaluate network-RTK for different production applications and to quantify typical rover position uncertainty. They also included basic GNSS training for beginners and user conferences with focus on introducing the concept of network-RTK (Jonsson et al. 2006).

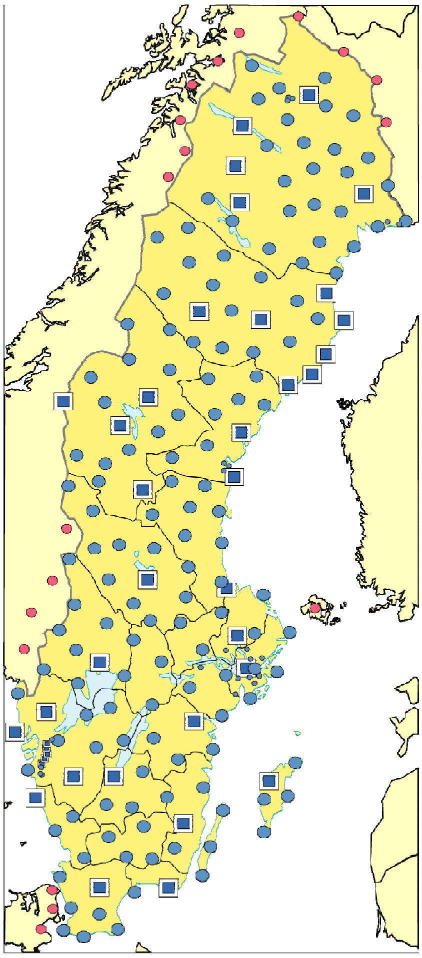

Fig. 1. Current SWEPOS network and a number of bordering Norwegian, Danish and Finnish stations (red dots) that are used in SWEPOS Network-RTK Service. Blue squares are stations of Class A type. Blue dots are stations of Class B type, established mainly for network-RTK purposes.

The SWEPOS Network-RTK service was launched in 2004, starting with the RTK project networks already in place, and extending regionally step-by-step through similar projects during the next few years. The full-scale densification of the original sparse SWEPOS network was completed in 2009, and the present nation-wide GNSS reference station network has an average in-between station distance of 70 km (see figure 1).

The bulk of the newly established stations are so called Class B stations, with less stringent requirements in terms of monument stability and equipment redundancy. These stations are typically located at public buildings (e.g. municipality offices, schools and hospitals), with the benefit of faster establishment and easier access.

2.2 Positioning services provided by Lantmäteriet

Lantmäteriet is offering a number of services based on the data from the SWEPOS reference station network:

- Quality checked RINEX data through www/ftp
- A web-based automatic computation service (cm-level post-processing)
- The DGPS-service EPOS (operated by the Swedish company Teracom)
- Network-RTK and Network-DGPS services (cm-level and dm-level in real-time)

The popular network-RTK service is based on the VRS-concept (Virtual Reference Station). Real-time correction data is distributed in the RTCM format via two-way GSM/GPRS communication between control centre and end users. The network-RTK service also includes a number of Norwegian, Danish and Finnish stations in the border regions, see figure 1. Users of the service receives positions in the SWEREF 99 reference frame and can expect a rover position uncertainty (1σ) of 15mm in the horizontal component and 25mm in the vertical component (i.e. ellipsoid height), given that recommendations for best practise is followed (e.g. Norin et al., 2006). A high quality geoid model is also available for those users that require positions in the national height system RH 2000.

2.3 Project adaptation and user requests

SWEPOS development during the recent 5-year period has seen the increasing demand for flexible and tailor-made positioning solutions, mainly aimed at large-scale construction projects. One example of this concept is the project services set up for the construction of new parallel-running double track railway and four-lane highway north of Gothenburg, which is the largest ongoing construction project above ground in Sweden (see figure 2). A number of benefits come with this solution, e.g.

- Several alternatives for distribution of RTK correction data to users in the project area, e.g. one-way radio communication of corrections for a fixed VRS position.
- Lower expected positioning uncertainties (10mm horizontally and 15mm vertically at 1-sigma) because of the short in-between stations distances of 10-15 km.
- A 24/7 quality control of the distributed data using separate monitoring stations, i.e. SWEPOS stations configured as permanent rovers.
- GNSS positioning can be used more extensively throughout the building process, leading to increased overall productivity

- The project owner “supplies” the contractors with *one* positioning infrastructure for planning, building and post-production verification.

The trends from project adaptation have been further corroborated by a survey carried out by questionnaire in early 2008. Lantmäteriet received approximately 400 answers from the 900 organizations that subscribes to the network-RTK service. A majority of the users were satisfied with the general performance of the service, and close to 50% of the organizations could perform all their positioning with network-RTK. However, more than 40% of the users requested improvements of vertical position uncertainties in order to fully benefit from the use of network-RTK, notably for machine guidance and for staking out building elements. The SWEPOS users also rely on high availability and performance and expect to be notified immediately in case of operation failures.

Fig. 2. Project adapted reference stations (blue dots) set up for an infrastructure project north of Gothenburg. The in-between-station distances are 10-15 km.

3 Assessment of the quality of Network-RTK

To evaluate the quality of RTK positioning with SWEPOS, both empirical and theoretical studies have been carried out. This chapter summarizes the results from these studies.

All errors in this chapter are presented as 1σ. For a detailed presentation of CLOSE I and II, see Emardson et al. (2009a, 2011).

3.1 Empirical studies (2002-2007)

Numerous field studies of network-RTK have previously been conducted as part of the SWEPOS establishment projects and diploma works. These studies have included controlled test measurements in order to verify the technique and to quantify some measures of position uncertainty. The measurement strategy has generally been to keep the rover centred over a number of geodetic points with well determined coordinates in SWEREF 99, using a tripod, and to perform repeated initialisations. This has been done with different brands of RTK equipment and under varying conditions.

A tendency towards decreasing rover positioning uncertainty with network-RTK can be seen over this period; from 15-20mm horizontally and 25-30mm vertically in the early studies, to corresponding numbers of 10-15mm and 20-25mm at present. These numbers have been confirmed through other studies over these years, and is most likely explained by a combination of factors: modernization of equipment on both the service provider and the end-user sides (e.g. GNSS antennas with better multipath reduction), better modelling of atmospheric errors in the network-RTK software, and steadily decreasing ionosphere disturbances as we have moved further away from the latest solar maximum.

3.2 The CLOSE projects (2008-2010)

The so called “CLOSE-RTK” projects were initiated by Lantmäteriet, SP Technical Research Institute of Sweden and Chalmers University of Technology. They investigated the state of network-RTK technique in Sweden, specifically in relation to expected positioning quality. The two main projects were:

- CLOSE I - current and future network-RTK with SWEPOS (Emardson et al., 2009a)
- CLOSE II - network-RTK in Sweden during high solar activity (Emardson et al., 2011)

The CLOSE I project aimed to quantify different error sources - such as ionosphere, troposphere and local effects - and how they affect the achievable uncertainty level for network-RTK positioning. This investigation was based on empirical data from the SWEPOS network. The resulting “error budget” from contributing error sources was based on the assumption of rover L1 processing, with in-between station distances of 70 km and the use of reference data from six surrounding reference stations. The errors in the vertical and horizontal rover position were then estimated via error propagation, and evaluated through comparison with real-time measurements using the SWEPOS network-RTK service. The comparison confirmed that the estimated rover position errors from the "error budget" come reasonably close to actual network-RTK measurements.

CLOSE I estimated the total vertical position uncertainty to 27 mm, using current network-RTK (in-between-station distance of 70 km) under “nominal” conditions. This is in agreement with the results from previous empirical studies (see 3.1).

The contributions from the major error sources that affect the vertical position uncertainty are summarized in figure 3. With standard L1 processing, it is obvious that the error contribution from ionosphere and troposphere dominates. The study therefore included other linear combinations, such as L3 and the new suggested L_0, with different combined effects of the error sources.

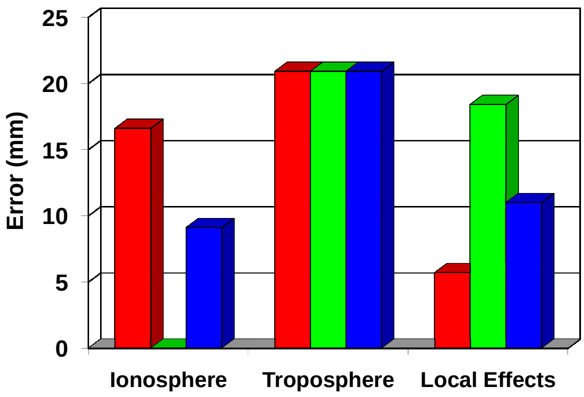

Fig. 3. Vertical error contribution from the three major error sources, for L1 (red), L3 (green) and the novel L_0 (blue) (Emardson et al., 2009b).

The expected future quality of network-RTK in Sweden considering different development scenarios of space and ground infrastructure was also investigated. The main scenarios were as follows:

(1) Current SWEPOS network (70 km) and current GNSS constellation
(2) Current SWEPOS network and future GNSS constellation
(3) Future SWEPOS network (~35 km) and current GNSS constellation
(4) Future SWEPOS network and future GNSS constellation

The effect of these scenarios is summarized in figure 4. In conclusion, the rover position uncertainties can be expected to decrease by a factor 2 from today, both for the horizontal and vertical component, given the proposed changes in GNSS constellation (GPS, GLONASS, Galileo and COMPASS) *and* a densification of the current SWEPOS network to average in-between station distances of 35 km

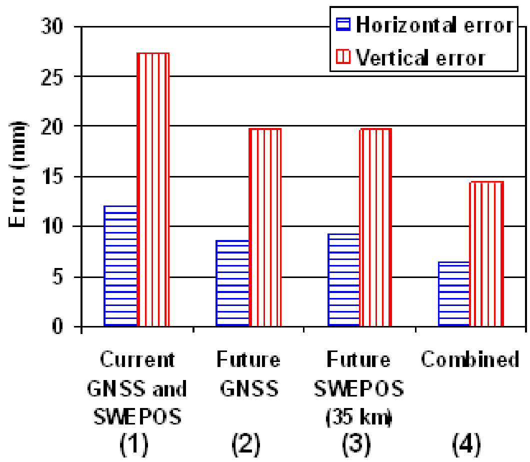

Fig. 4. Horizontal and vertical positioning errors, with current and future GNSS constellations. (Emardson et al. 2009b).

In order to prepare a robust GNSS infrastructure that can function during adverse conditions, an important question is the upcoming solar maximum and to what degree it will affect measurements with network-RTK. The CLOSE II project studied SWEPOS data from the time of the previous solar maximum, specifically from three locations in northern, middle and southern Sweden, and how the ionospheric influence contributed to network-RTK measurements errors. During the previous solar maximum (around year 2002) the distances between the reference stations in Sweden were larger than the today standard 70 km. Therefore estimated errors at the test sites were scaled to correspond to the present 70 km in-between station distances. The assumptions and processing strategies were otherwise similar to CLOSE I.

The ability of GNSS receivers to fix integer ambiguities is a key issue for cm-level positioning in real time. This was specifically studied in CLOSE II, using RTK corrections that were manipulated with different grades of ionospheric variability before rover ambiguity resolution. With variability below 10 mm the rover was able to fix the ambiguities in more than 90% of the cases, but this number decreased rapidly with increasing ionospheric variability (Emardsson et al. 2011).

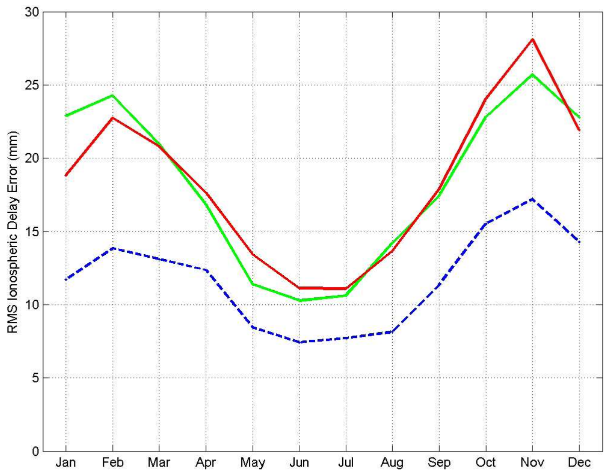

Fig. 5. The variation of the ionospheric delay during a year. The blue dashed line represent northern, the green line middle and the red line southern Sweden (Emardson et al. 2011).

Another important conclusion from the study was that different geographic regions must be studied in order to present a “true” picture. Ionospheric effects in the northern part of Sweden may not be relevant for a user in the southern part of Sweden. The variation of the ionospheric delay during one year for the different geographic regions can be seen in figure 5. The results show that this closely correlates with the positioning error contribution from the ionosphere which, on average, is larger for the northern part of Sweden (typically two thirds of the total vertical positioning error). The data from the previous solar cycle maximum also revealed that the most problematic time for GNSS measurements occurs during night time.

4 Improving positioning with SWEPOS

The experiences from the project adapted services and the overall user demand (see chapter 2.3) have driven the initial efforts to improve RTK positioning with SWEPOS. The CLOSE projects on the other hand, have given a clear indication of what a modernized SWEPOS infrastructure should look like in order to achieve that. As an example, a densification of the current network, together with future satellite systems, reduces the position uncertainty by a factor 2.

The current goal is to establish 40 new reference stations each year over the next five years, which will result in a densified network covering most of Sweden. User statistics have been used to identify the most active regions, where the first establishment efforts will be focused. Densification is presently under way in the following regions:

- Metropolitan Stockholm
- Skåne and the Öresund region (southernmost Sweden)
- West Sweden including Gothenburg.

In metropolitan Stockholm 10 new stations was established during 2010, in co-operation with local municipalities, and over 20 stations are now in progress in the western and southern regions. The average in-between station distances will here be at, or below, 35 km - as recommended by the CLOSE studies. The vertical positioning uncertainty with network-RTK can therefore be expected to decrease to 20 mm, making this technique more feasible for new user groups. A side-effect of the densification is that it will provide redundancy for the network in cases of station failure.

To keep track with development in ground and space segments, an upgrade of SWEPOS equipment (including GNSS antennas and receivers) is in progress. This will ensure full compatibility with new or coming satellite systems and radio signals (e.g. L2C, L5, GLONASS third frequency) as well as better redundancy. Network-RTK software from the major GNSS manufacturers will be evaluated during 2011, based on the experiences over the years of running a large-scale RTK network. Consideration is also given to issues concerning compatibility between different brands of GNSS equipment and network-RTK software. Lantmäteriet will work in co-operation with the GNSS manufactures in these matters, for a solution that will benefit SWEPOS users.

Other development projects are also in progress, which will improve the quality of the real-time positioning services. For example, an ionospheric monitor will be available on the SWEPOS web site, which will allow users to track the ionospheric activity and the expected quality of positioning for a given location within the network. An SMS message service is today included in the network-RTK service, and additional monitoring stations has been established for the national service.

5 Conclusions

The ongoing quality assessment of the SWEPOS Network-RTK services provides valuable information about the error sources and how they affect positioning. Results from the CLOSE projects and similar studies will continue to guide the development of SWEPOS to meet the demands of the user community.

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