Test of RTCM Version 3.1 Network RTK Correction Messages (MAC) in the Field and on Board a Ship for Uninterrupted Navigation

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BIOGRAPHY

Dan Norin graduated with a M.Sc. with emphasis on geodesy and photogrammetry from the Royal Institute of Technology in Stockholm in 1991. He has during 1991–1996 and since 2002 been working as a geodesist specialised in GNSS surveying at Lantmäteriet – the Swedish Mapping, Cadastral and Land Registration Authority. During 1996–2002, he was employed at the Stockholm City Planning Administration as an expert in mapping, surveying and geodesy.

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ABSTRACT

SWEPOS Network RTK Service is widely used in Sweden and it is working in virtual reference station mode. It has up to present not been in question to implement network RTK messages in the service. However, test measurements with the technique and discussions based on its possible advantages have taken place. One advantage would be that it is suitable for uninterrupted continuous navigation of boats, ships or other vehicles, since the technique with virtual reference station solutions introduces recalculation of the fictitious reference station. During 2012, network RTK test measurements based on network RTK messages have been performed both in field and on board a ship.

The field measurements were performed on points with known positions and receivers from Leica, Topcon and Trimble were used. The standard uncertainty in the measurements with network RTK messages was about 10 mm horizontally and a little bit less than twice as high vertically in both broadcast and automatic modes.

The measurements on board a ship were carried out on board the hydrographic survey vessel *Jacob Hägg* from the Swedish Maritime Administration. The ship made a route of approximately 130 kilometres, which lasted for approximately seven hours.

The test measurements performed with network RTK messages both in the field and on board a ship generally worked fine. Based on the measurements, it can be stated that the results from broadcast mode and automatic mode are highly correlated.

INTRODUCTION

A growing interest for RTK surveying in a network of multiple permanent reference stations for GNSS arised in the late 1990's. An effective way to distribute GNSS data in network RTK mode to a vast number of RTK users (rovers), have been through cellular telephones and mobile Internet in the standardized Radio Technical Commission for Maritime Services (RTCM) format. Network RTK surveying was pioneered by the work of Gerhard Wübbena in the German SAPOS network of permanent reference stations (Wübbena et al., 1996). A technique with area correction parameters (FKP) for ionosphere and geometry was developed.

A technique where the rover receives synthetic observations from a fictitious reference station was also developed (Vollath et.al., 2000). This Virtual Reference Station (VRS) technique has become the most widely used concept for network RTK. The network RTK software at the control centre is in this case performing the error estimation and creates the virtual reference station close to the initial location of the rover. The rover can then work in single station RTK mode.

In 1998, a Working Group of the RTCM SC-104 committee was started with Hans-Jürgen Euler from Leica Geosystems as chairman. The SAPOS approach mentioned above with area correction parameters was considered to be too model-based for a RTCM standard and instead a more observation-based system was chosen. First a system with grid-based corrections was discussed (Townsend et al., 2000). What was later to be called the Master-Auxilliary Concept (MAC) was presented in 2001 (Euler et al., 2001). Five years later these ideas formed the base of the network RTK correction messages in the RTCM standard 10403.1 (RTCM, 2007).

In network RTK messages, a group of reference stations are used and one of them is chosen as a master station. The other stations are then called auxiliary stations. Differences of the observations between the auxiliary stations and the master station are formed, the rover however can create observations for all stations and eventually ionospheric and geometric linear combinations of these are computed. The error estimation is, compared with the virtual reference station concept, moved from the network RTK software at the control centre to the rover. Network RTK messages can be used in both broadcast (static) mode and automatic modes. In broadcast mode, the master station is predetermined and in automatic mode, it will be the station closest to the rover.

The technique with network RTK messages has to some extent been overshadowed by the other ones. This situation is a bit unfair, since there are applications where network RTK messages could be a proper choice of positioning technique. An example of this is uninterrupted continuous navigation of boats, ships or other vehicles where what could be named seamless navigation is important. A moving vehicle navigating and positioning itself through the technique with virtual reference station solutions introduces recalculation of the fictitious reference station. These recalculations will lead to reinitialisations of the rover and interruptions in the navigation of the vehicle caused by these reinitialisations.

A couple of other advantages with network RTK messages would be that real physical observations are used and that two-way communication would not be needed, at least not in broadcast mode. One-way communication would open up for RTK data to be sent to the users with a broadcasting communication link, e.g. radio or (geostationary) satellite link.

The different concepts for network RTK, with special focus on network RTK messages, together with experiences from test measurements have been widely described (Takac & Zelzer, 2008, Janssen, 2009, Norin et. al., 2009, Wang et. al., 2010 and Garrido et. al., 2011).

NETWORK RTK IN SWEDEN

SWEPOS™ is the Swedish national network of permanent reference stations for GNSS (Sunna et. al., 2010) and the stations are among others used for SWEPOS Network RTK Service. The stations and the SWEPOS services are operated by Lantmäteriet – the Swedish Mapping, Cadastral and Land Registration Authority. Today (September 2012) SWEPOS consists of around 260 stations, 40 stations of the highest class (class A) and approximately 220 class B ones, see Figure 1.

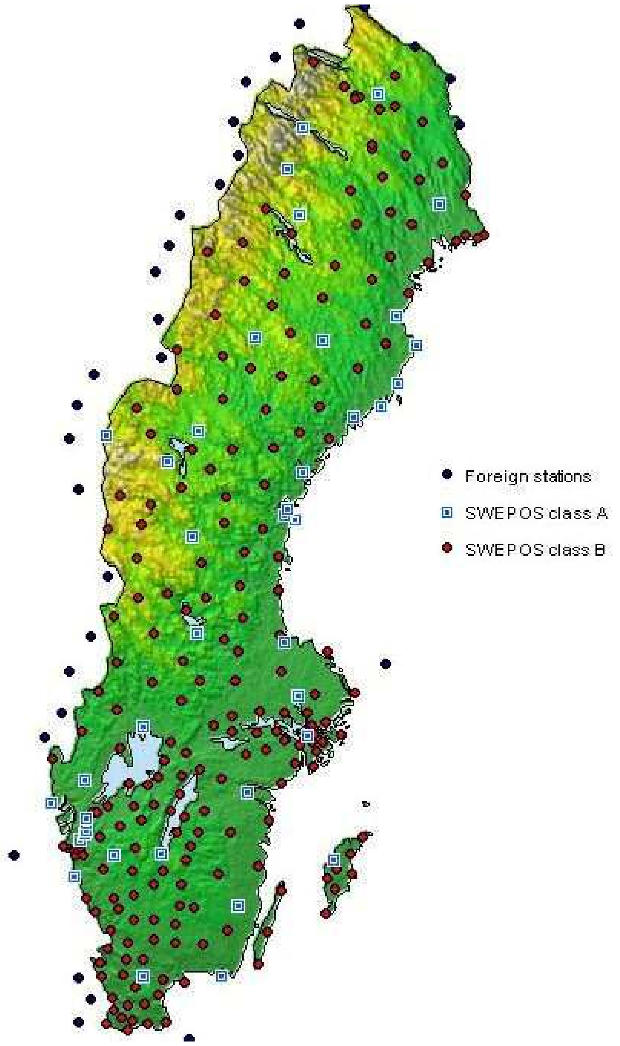

Figure 1: The SWEPOS™ network of permanent reference stations for GNSS consists of approximately 260 stations covering Sweden (September 2012) and some foreign border stations are also included in SWEPOS Network RTK Service.

The class A stations consist mainly of concrete pillars built on bedrock and they have redundant equipment for GNSS observations, communications, power supply, etc., see Figure 2. They have also been connected by precise levelling to the national precise levelling network.

Figure 2: The SWEPOS station Norrköping is an original class A station which has a new steel mast as an additional monument. Photo: Dan Norin.

Class B stations are mainly established on top of buildings for network RTK, see Figure 3. They have the same instrumentation as class A stations (dual-frequency GPS/GLONASS receivers with antennas of Dorne Margolin design), but with somewhat less redundancy.

Figure 3: The SWEPOS station Smygehamn is a station with a roof-mounted GNSS antenna mainly established for network RTK purposes belonging to Class B.

During 2011, new additional monuments have been established at the 20 original class A stations, see Figure 2. Several different designs were evaluated before finally choosing steel grid masts.

The Network RTK Service is working in virtual reference station mode with mobile Internet and GSM as the main distribution channels. It was launched in 2004 and in 2009 it reached national coverage, i.e. a national network of stations with inter-station distances of 60–70 km were finalised by that time. A densification of the network is ongoing since 2010 in order to improve the performance of the service, e.g. better measurement uncertainty and redundancy. The benefits for the users from the densifications and from the increasing number of GNSS satellites together with the influence from atmospheric disturbances have been deeply studied (Sunna et. al., 2010 and Emardson et. al., 2011). Special attention has been paid to the ionosphere, where the users since August 2011 are aided by an ionospheric monitor on the SWEPOS web-page on www.swepos.com.

The number of registered users of the network RTK service is over 2300 (September 2012), who cover a broad range of applications. Approximately 300 of the registered users have specific licences for universities and GNSS equipment dealers etc. The service has been running on GPSNet from Trimble as the network RTK software until the summer of 2012. Since the summer of 2012, the service is running on VRS3Net, also from Trimble.

It has up to present not been in question to implement network RTK messages in SWEPOS Network RTK Service. However, test measurements with the technique and discussions based on its possible advantages described in the introduction section of this paper have taken place.

FIELD MEASUREMENTS WITH NETWORK RTK MESSAGES

The first network RTK test measurements based on network RTK messages in the SWEPOS network of permanent reference stations were performed in 2008. A 14 station large sub-network was used for the measurements and they were performed in a diploma work from the University of Gävle (Johansson & Persson, 2008 and Norin et. al., 2009). The results were promising and no obvious differences in measurement uncertainty between solutions based on network RTK messages and standard virtual reference station were found. However, the receivers/firmware were of the first generation and GLONASS was by that time not implemented in network RTK messages.

Since 2008, the users of SWEPOS Network RTK Service have to very little extent asked for the possibility to use network RTK messages. One exception is the Swedish Maritime Administration. They have however managed by using the ordinary virtual reference station concept by fixing the location of the virtual reference station to the initial position, without having a recalculation of the virtual reference station after the normal five kilometres in the service. A normal procedure for them is also to manually reset the virtual reference station when suitable after a certain distance or time.

A new diploma work from the University of Gävle was performed during spring this year (2012) in order to test network RTK messages with up-to-date equipment and firmware including GLONASS (Lundell, 2012). Both field measurements with network RTK messages in broadcast and in automatic mode were performed. Also a small number of measurements based on virtual reference station solutions were performed as a comparison. A nine station large sub-network of the SWEPOS network was used for the test measurements, which were carried out on three different points with known positions named A, B and C according to Figure 4.

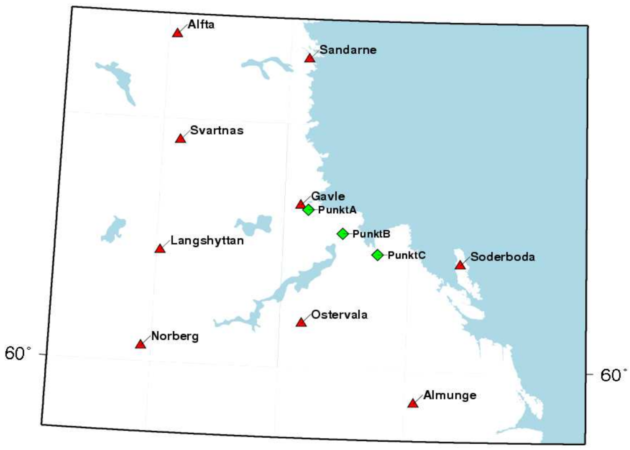

Figure 4: The field measurements with network RTK messages were performed on three points with known positions named A, B and C (green diamonds). The measurements were performed in a nine station large sub-network of the SWEPOS network (red triangles).

The GPSNet network RTK software was set up to send RTCM messages according to default settings in the software. The reference station closest to the rover was chosen as master station for measurements in automatic mode. In broadcast mode, the station called Svartnäs located in the north-west part of the sub-network was fixed as master station. This means that the distances to the master station were up to 101 kilometres. All distances from the points A, B and C to the SWEPOS stations which have been used as master stations are shown in Table 1.

Table 1: The distances from the points A, B and C to the SWEPOS stations which have been used as master stations.

Point	**Used master station and distance to each point**	
	Automatic mode	**Broadcast mode**
A	Gävle, 4 km	Svartnäs, 64 km
B	Gävle, 23 km	Svartnäs, 83 km
C	Söderboda, 37 km	Svartnäs, 101 km

Field equipment from three different manufacturers (Leica, Topcon and Trimble) was used for the measurements according to Table 2.

Table 2: The used rover equipments came from three different manufacturers.

	Leica	**Topcon**	**Trimble**
Receiver	Viva GS15	GRS-1	R8-3
Antenna	Integrated	PG-A1	Integrated
Controller	Viva CS10	Integrated	TSC3
Software in controller	Smart Worx Viva version 4.01	TopSURV version 8.2	Access version 2012.00
Network RTK messages setting	MAX	MAC	RTCM3Net
Firmware version	4.01	3.6	4.44

The measurements were carried out under varying satellite conditions between April 18th and April 30th 2012, which was a period with favourable atmospheric conditions. The measurements were done with the GNSS antennas attached to a tribrach on a tripod according to Figure 5.

Figure 5: The field measurements with network RTK messages were performed with the GNSS antennas attached to a tribrach on a tripod centred over the points. Photo: Rebecka Lundell.

The satellite cut-off angle was set to 13° above horizon. A total number of 905 measurements with network RTK messages were done evenly spread over the three points with each of the two methods (broadcast and automatic mode) and with each of the three receiver brands. Each measurement was a mean value of ten successive observations. The number of measurements based on virtual reference station solutions was limited to 25 measurements, all made on point C with the Leica receiver.

RESULTS FROM FIELD MEASUREMENTS WITH NETWORK RTK MESSAGES

The time for the initialisation of the field measurements with network RTK messages was usually in the order of 10–20 seconds. On some occasions when a fixed ambiguity solution was difficult to obtain, a reinitialisation of the rover was made after a period of time (usually two minutes). GLONASS satellites were excluded from the positioning for only a few measurements, but sometimes GLONASS satellites were not included for several measurements in a row. GLONASS satellites were excluded in totally 3–4 % of the measurements, mostly in measurements with Leica and on fewest occasions in measurements with Topcon.

Topcon had a general problem to obtain stable results with increasing distance to the master station, especially in broadcast mode. There has been no possibility to closer investigate the reason for this problem and all results from the Topcon measurements in broadcast mode has for the time being been removed.

Results in both the horizontal and vertical components from the field measurements with network RTK messages in both broadcast and automatic modes are presented in Table 3–5. Only successful measurements are included in the results. In the tables "Mean deviation" shows the mean values of the deviations from the true positions and "RMS" shows RMS values of the differences between measured and known positions.

Table 3: Mean deviations for the field measurements.

Mode	Brand	Mean deviation Horizontally (mm)	Mean deviation Vertically (mm)
Automatic	**Leica**	5	-5
	Trimble	6	-1
	Topcon	10	-18
Broadcast	**Leica**	7	5
	Trimble	5	7
VRS	**Leica**	6	-2

Table 4: Standard uncertainties for the field measurements.

Mode	Brand	Standard uncertainty Horizontally (mm)	Standard uncertainty Vertically (mm)
Automatic	**Leica**	9	20
	Trimble	9	17
	Topcon	14	21
Broadcast	**Leica**	12	16
	Trimble	10	20
VRS	**Leica**	7	11

Table 5: RMS values of the differences between measured and known positions for the field measurements.

Mode	Brand	RMS Horizontally (mm)	RMS Vertically (mm)
Automatic	**Leica**	10	20
	Trimble	11	17
	Topcon	17	27
Broadcast	**Leica**	14	17
	Trimble	12	22
VRS	**Leica**	9	11

MEASUREMENTS ON BOARD A SHIP

In order to evaluate the different RTK concepts for maritime applications, test measurements were carried out and lasted for approximately seven hours on board the hydrographic survey vessel *Jacob Hägg* from the Swedish Maritime Administration, see Figure 6. The measurements took place on June 26th 2012, a day with very calm ionosphere according to the ionospheric monitor on the SWEPOS web-page on www.swepos.com. The purpose of the measurements was to evaluate high-accuracy surveying with network RTK using network RTK messages, in both broadcast (one-way communication) and automatic mode (two-way communication).

Figure 6: The measurements on board a ship with network RTK messages were performed on *Jacob Hägg*, a vessel belonging to the Swedish Maritime Administration used for hydrographic surveying. Photo: Johan Sunna.

Three GNSS receivers logged RTK observations simultaneously. Each was connected to SWEPOS Network RTK service, transmitting RTK data over mobile Internet for network RTK messages in broadcast and automatic mode and also in virtual reference station mode respectively. The receivers were connected to a common

GNSS antenna mounted on a pole at the top of the ship. The receivers were initialised with a fixed ambiguity solution at the start and, if not required, reinitialisation was not done for any of the receivers during the test. Also a fourth GNSS receiver was connected to the GNSS antenna in order to store raw observations for post-processing. Table 6 shows the used equipments.

Table 6: GNSS receivers and RTK mode for the measurements on board the ship.

Receiver type	RTK mode
Topcon GB-3	Virtual reference station
Leica GX1230 GG	MAC, automatic mode
Leica GX1230 GG	MAC, broadcast mode
Trimble NetR9	Raw observations logged for post-processing

The services for network RTK messages were running on Trimble VRS3Net, while the virtual reference station was running on Trimble GPSNet. To be able to receive RTK data in broadcast mode, a sub-network of the SWEPOS network was set up. The sub-network consisted of eight auxiliary stations and one master station. A map of the reference stations area is shown in Figure 7.

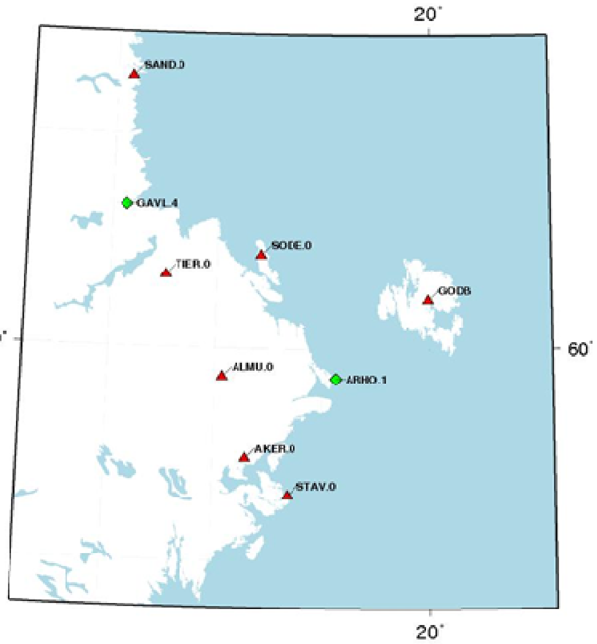

Figure 7: The sub-network of the SWEPOS network used for network RTK messages in broadcast mode. The red triangles are auxiliary stations while the green diamonds represent master stations.

The seven hour long kinematic test measurements were carried out around the island of Gräsö (lat: 60 21' 42.300" N, lon: 18 28' 6.3840" E). The approximately route length was 130 km. The weather and sea condition were good with a relative calm sea during the entire journey. The route is plotted in Figure 8 with time stamps. The coordinate axes are defined in the Swedish national coordinate system SWEREF 99 TM.

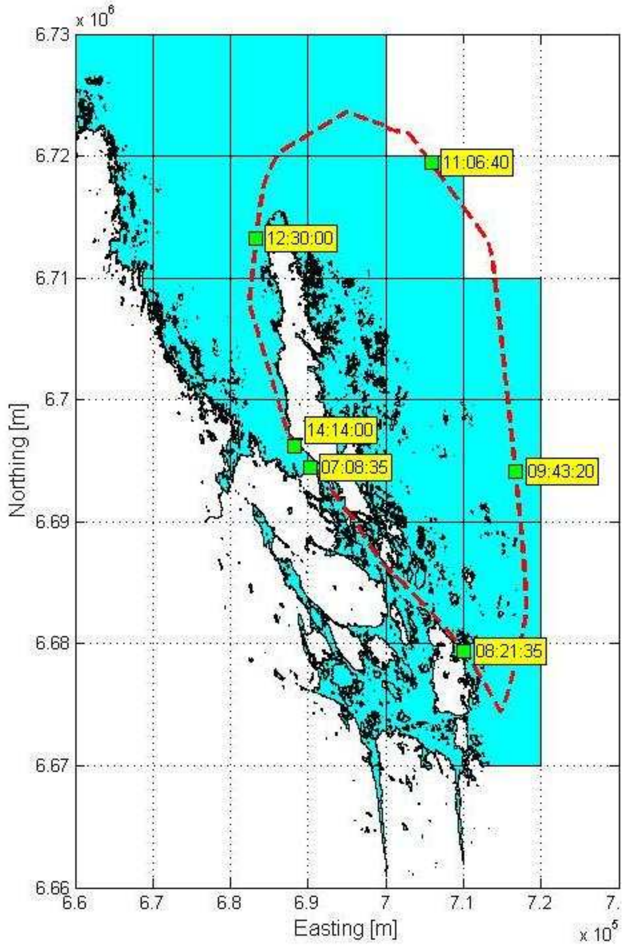

Figure 8: The test route for the measurements is illustrated by the dashed red line. The time is defined in UTC+01:00.

In Table 7 statistics from the test route are shown. Be aware of that the start-time is not the same for all three modes, there are almost 1 ½ hour between the network RTK messages in broadcast mode and the two other methods. This also leads to that the location of the virtual reference station is at the southern most part of the test route, compare with the route in Figure 8. The differences in the number of observations are due to different logging intervals.

Table 7: The table shows start times and end times (UTC+01:00) for the logging of observations together with number of observations and percent of fixed solution. In the table VRS stands for virtual reference station solution, Auto stands for network RTK messages in automatic and Broadc. stands for network RTK messages in broadcast mode.

RTK mode	Start/end times	Obser-vations	% fixed solutions
VRS	08:28:25–13:24:00	18426	-
Auto	08:30:05–13:21:55	12178	99.98
Broadc.	07:08:35–13:21:05	12590	99.97

RESULTS FROM MEASUREMENTS ON BOARD A SHIP

The observed heights were given above the ellipsoid and transformed to heights above the geoid, using the Swedish national geoid model, SWEN08_RH2000. In Figure 9, the heights for network RTK messages in broadcast and automatic mode and for virtual reference station solutions are plotted with respect to time. For the virtual reference station solution, 184 points (before 11:00) have been removed as gross errors. The paler lines are smoothed curves using a moving average filter with a sliding window of 10 observations.

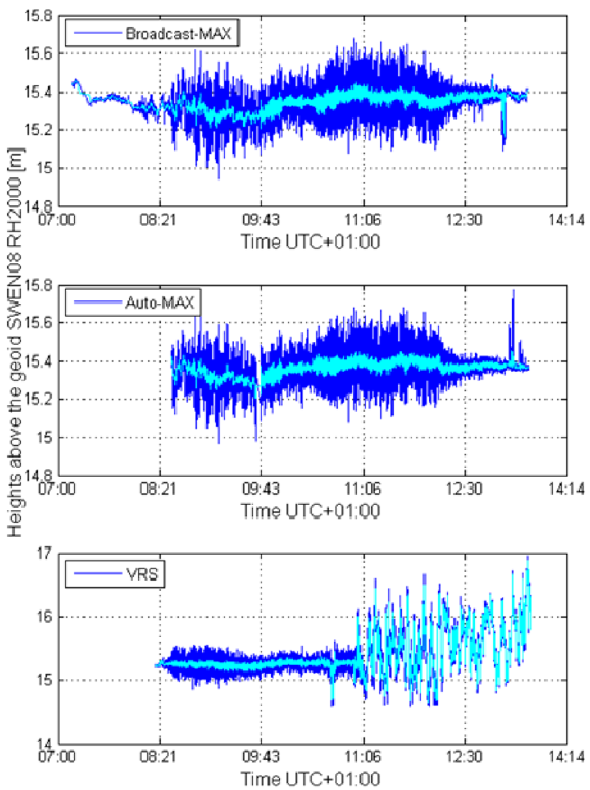

Figure 9: Heights above the geoid plotted with respect to time (UTC+01:00) for network RTK messages in broadcast and automatic mode and for virtual reference station solutions.

The smaller variations in the heights until just before 08:30 and also after approximately 12:30 are explained by a calmer sea during these periods. The reason for the calmer sea is that the ship during these periods was between the mainland and the island of Gräsö or some other smaller islands, see Figure 8.

The virtual reference station solution starts to give large variations in the heights just after 11:00. As described above, the location of the virtual reference station in the test was fixed without any reinitialisation. At just after 11:00 the ship is approximately 40 km from the virtual reference station, see Figure 10.

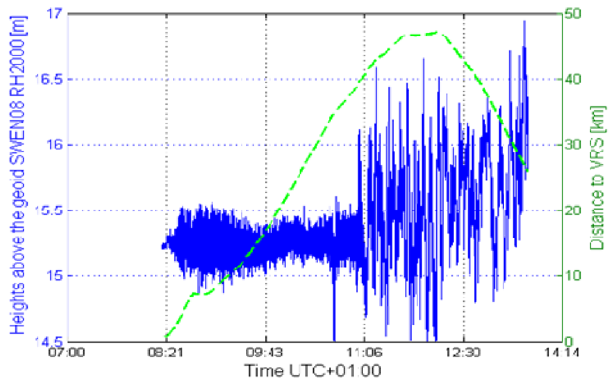

Figure 10: The figure shows heights above the geoid (blue curve, left y-axis) and distance to the virtual reference station (dashed green curve, right y-axis) with respect to time.

The logged raw observations were finally post-processed with the open-source software RTKLIB in Precise Point Positioning (PPP) kinematic mode. The calculated heights are shown in Figure 11 using both precise products from both CODE (University of Berne) and from IGS. The CODE solution, being based on products with higher rate, shows a bit smaller variations.

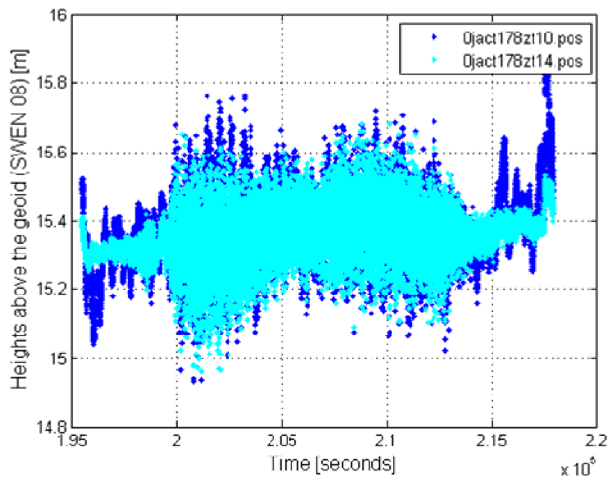

Figure 11: Heights above the geoid based on post-processing in PPP mode as a function of time (seconds) with products from IGS (0jact178zt10.pos) and from CODE (0jact178zt14.pos).

CONCLUSIONS

The test measurements performed with network RTK messages both in the field and on board a ship generally worked fine. The level of the standard uncertainties in the field measurements must be considered as very good. The few of these measurements which were performed with virtual reference station solutions were even slightly better. Previously performed test measurements with SWEPOS Network RTK Service running in virtual reference station mode have proven that these levels or even better are achievable for network RTK (Jansson, 2011 and Mårtensson et.al., 2012). This would at least be the case in densified parts of the network of reference stations and under favourable atmospheric conditions.

Based on the measurements with network RTK messages both in the field and on board a ship, it can be stated that the results from broadcast mode and automatic mode are highly correlated. By looking closely on the results, one might find that solutions in broadcast mode show slightly higher variations and that there could be a small distance dependency concerning the distance to the master station.

The conclusion for the large height variations for virtual reference station solutions when the ship is approximately 40 km from the virtual reference station is that only float solutions are obtained afterwards. There could be some limitation at this specific distance set somewhere in the system. It is actually quite remarkable that such stable values are obtained so far as up to 40 km from the virtual reference station. As earlier explained, this is not normal surveying procedure and a reinitialisation of the rover is needed for virtual reference station solutions in applications like hydrographic surveying.

ACKNOWLEDGMENTS

The authors would like to acknowledge the crew of *Jacob Hägg* for their assistance during the measurements on board the ship and the Swedish Maritime Administration for the opportunity to perform these measurements.

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