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Production measurements with Network RTK- Tests and analysis

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Preface

The work presented in this report is my Master's of Science project that concludes the studies at the Surveying and Mapping programme of the Royal Institute of Technology. After completing the program, I will become a civil engineer.

I would like to thank Senior Research Geodesist Bo Jonsson and Research Geodesist Christina Lilje at the Geodetic Research Division of Lantmäteriet and Professor Lars Sjöberg at the Geodesy Group of the Department of Infrastructure, Royal Institute of Technology, who have been my supervisors for the help and support given. The support of the rest of the personnel at the Geodetic Research Division and of Research Associate Milan Horemuž at the Geodesy group is also worth mentioning. They have never hesitated to answer any questions and shown a great interest in my work.

My husband, Jörgen Wahlund, deserves a special acknowledgement for the never-ending encouragement he gave when the fieldwork lasted longer than expected.

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Sara Wahlund

Abstract

GPS (Global Positioning System) is a useful tool for surveying. It may be used for determining the position with different levels of precision. The real time applications pose certain problems to high precision positioning, especially RTK (Real Time Kinematic or high precision mobile measurement in real time). Relative positioning is a technique that makes use of a reference station at a known point to model the errors. Highest possible accuracy is achieved if carrier measurement is used and the estimated errors are used for corrections of the values measured by the rover (the movable receiver). This technique is called RTK. To improve these corrections, a network of reference stations may be used to estimate spatial dependent errors such as atmospheric biases. This technique is called Network-RTK and is used in the Project Position Stockholm Mälaren.

Several tests have been made of the accuracy and precision of different RTK networks including the Position Stockholm Mälaren network. However, few investigators have tried to copy conditions during actual measurement for production purposes such as an antenna on a pole, as short observation time as possible and the possibility to detect outliers in the field. This thesis describes tests made in the Position Stockholm Mälaren net trying to simulate production conditions. Special attention was made to the initialisation times, precision and repeatability.

The results show that the precision and repeatability achieved in earlier tests also are possible to achieve during production conditions. The quality of Network-RTK is equal or better to that of single reference station RTK but the Network-RTK is more reliable due to a constant quality monitoring control centre and the possibility to use the reference stations as single-station reference stations if the network function is malfunctioning.

Sammanfattning

GPS (Global Positioning System) är ett mycket användbart verktyg för positionsbestämning. Det kan användas för att bestämma positionen med varierande noggrannhet. Att göra detta i realtid ger upphov till särskilda problem, särskilt när man använder RTK (Real Time Kinematic, eller noggrann rörlig mätning i realtid). Relativ mätning är en teknik som använder en referensstation placerad på en känd punkt för att modellera olika slags fel. Om man använder bärvågsmätning och utnyttjar dessa uppskattningar till att beräkna korrektioner till de värden som uppmätts av den rörliga mottagaren, Rovern, fås största möjliga noggrannhet och tekniken kallas RTK. Vissa av de uppskattade felen är rumsligt beroende vilket gör det möjligt att använda ett nät av referensstationer för att förbättra skattningen av dem. Denna teknik kallas NätverksRTK och används i projektet "Position Stockholm Mälaren" som har initialiserats av Lantmäteriet och involverar ett antal statliga verk, kommuner och konsulter i Mälardalen.

Det har gjorts flera tester av precision och noggrannhet i olika RTKnätverk, bl.a. i Position Stockholm Mälaren nätverket. Dessa har dock sällan försökt efterlikna förhållanden under produktionsmätning, t.ex. att bära antennen på en stång, att ha så kort observationstid som möjligt och att försöka upptäcka ”outliers” i fält. Detta examensarbete är ett försök att testa precision, noggrannhet, tillförlitlighet och initialiseringstider under mätningar som efterliknar förhållanden under detaljmätning.

Resultaten visar att den precision och noggrannhet som uppnåtts under föregående tester också är möjlig att uppnå under produktionsmätning. Kvalitén vid användning av nätverksRTK är jämförbar eller bättre än den som fås vid vanlig RTKmätning med endast en referensstation. Vidare är nätverksRTK mer tillförlitlig eftersom nätets kvalitet hela tiden övervakas av ett kontrollcenter, i detta fall SWEPOS driften. Det är möjligt att använda referensstationerna för vanlig RTKmätning inom begränsade områden om nätet av någon anledning är ur funktion.

Den mest uppenbara fördelen med nätverksRTK är dock att den tid och extra utrustning som vanligtvis krävs för att etablera en referensstation inte längre är nödvändig. Det går också att mäta med längre avstånd till referensstationerna eftersom jonosfärsfelet modelleras bättre. Nackdelen är att kommunikationskostnaden i dagsläget kan bli högre än för vanlig RTK.

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1 Introduction

Using the American satellite system GPS (Global Positioning System) is today a widespread positioning technique for different purposes. The use varies from navigation to high precision surveying with millimetre accuracy on baselines up to some kilometres. The system is built up of a space segment of at least 24 operational satellites circling the earth and a ground segment with control stations around the globe. GPS is developed and run by the U.S. Department of Defence, but it is available to both military and civilian users around the globe who have access to a GPS receiver.

Surveyors, air and marine navigators, hikers, car drivers and numerous others use GPS. However, surveyors often have higher accuracy demands. Several methods have been developed to enhance the positional quality and Network-RTK is one of the most recent approaches.

The selection of a network of reference stations in Network-RTK is used to model spatial dependent error sources. Better estimated error sources results in better corrections and improved ambiguity resolution. This makes it possible to use less reference stations to cover an area than with single station RTK.

There are several ways of estimating the errors and transferring the corrections. Each way of has a suitable transmission technique although the correction transferring may be dependent of other factors such as transferring media and number of users. The Network-RTK softwares might have the opportunity to choose a suitable correction transferring method.

The purpose of this Master’s of Science project is to study the time to initialisation and the precision/reliability of Network-RTK during conditions closely resembling conditions during measurement for production purposes, for example measurement of cartographic details or measurement for cadaster purposes. Furthermore, it was meant to study the possibility to detect outliers in the data.

Test measurements has already been made in the project Position Stockholm Mälaren as mentioned above, and also by Trimble Terrasat (former Spectra Precision), the developer of the GPS-net software used in this study. In both these studies, tripods were used and several measurements were performed on the same points without moving the antenna between the measurements. This project tries to copy the routines used when making measurements for production purposes by using an equipment carried in a backpack, an antenna on a pole and a predetermined quality figure on the GPS-receiver.

The hypothesis is that GPS measurements using the network of reference stations called Position Stockholm-Mälardalen generating corrections using the software GPS-net, has a precision and a reliability that is sufficient for a number of applications such as cadastral surveying, data capture for data bases with geographical information, machine guidance and precision navigation.

2 Measurements with GPS

There are two principle methods used in GPS to compute the distance from the satellites to the receiver, pseudorange and carrier measurements. Both methods strive to compute the distance between the satellite and the receiver. The distances to three different satellites at the same instance are necessary to compute the position of the receiver in XYZ by resection. To correct for the receiver clock error, a fourth satellite is also needed.

2.1 Pseudorange measurements

The GPS satellite transmits a coded signal, which is received by the receiver. This signal is coded. If the codes of the satellites are stored in the receiver, it is possible to generate a reference carrier, modulate it with the known code and compare the result with the received satellite signal. The two signals are correlated and the time shift needed to do this indicates the time elapsed since the signal left the satellite. By comparing the difference between transmitted and received time and multiplying this difference with the speed of light, the distance from receiver to the satellite is computed.

$$R = c\Delta t = c\Delta t(GPS) + c\Delta d = r + c\Delta d \qquad (1)$$

where R: pseudorange (distance satellite-receiver including clock bias)
c: speed of light in vacuum
Δt: time shift, difference between satellite clock reading and receiver clock reading
Δδ: clock delay ($d_R - d^S$, or receiver clock delay minus satellite clock delay)
ρ: true distance satellite-receiver (Hofmann-Wellenhof et al., 2001)

2.2 Carrier measurements

The carrier method compares the phase of the received frequency from the satellite and the constant frequency generated in the receiver, which is synchronised with the signal in the satellite. The distance between satellite and receiver also includes the unknown number of cycles between the two. This integer ambiguity, N, can be solved with different methods and is constant with time, for as long as the signal is not interrupted.

$$\Phi = \frac{1}{l} r + \frac{c}{l}\Delta d + N \qquad (2)$$

where Φ: phase observable (carrier beat phase)
λ: wavelength of the satellite carrier wave
N: number of cycles between satellite and receiver
(Hofmann-Wellenhof et al., 2001)

The pseudorange method has a precision of about three decimetres. The carrier method is the method most used for geodetic purposes since it may give a precision of three millimetres. This is under the condition that the ambiguities are resolved. The ambiguity, N, indicates number of cycles between satellite and receiver. An incorrect ambiguity resolution gives a positional error of a number of 2 decimetre-multiples in the distance to the satellite. This is the length of each cycle.

The ambiguities are only possible to solve providing the error sources are reduced. (For more about error sources see chapter 3.) This is usually done by so called relative positioning.

The idea is to compare with measurements during the same interval of time from a receiver located at a known point and there by reduce the errors. If this is done in real time by the use of radio communication between the receivers, it is called RTK, Real Time Kinematic. One may also use adjusted positions from more than one station at known points placed in a network to further improve the result. This technique is called Network-RTK and is what this paper is investigating.

There are several methods to solve the ambiguities. The traditional method is to observe for at long time and make the computations afterwards. For example, a session length of 35 to 60 minutes for a baseline of 10 km is recommended (Hoffman-Wellenhof et al., 2001) when four to six satellites are available and the ionospheric conditions are normal. This results in redundant observations and it is thereby possible to calculate the ambiguities. The more satellites, the more redundancies and the less observation time needed.

The RTK technique uses combinations of code and carrier wave measurement. This makes it possible to solve the ambiguities on a couple of minutes, depending on the distance to the reference station. This method of combining different measurements and several others not mentioned here are discussed in chapter 4, solving the ambiguities.

3 Sources of errors

3.1 Atmosphere

The signal passes through the atmosphere on its way to the antenna. If it had not been an atmosphere in between, the propagation rate would have been c, the speed of light in vacuum. However, the atmosphere contains several different kinds of particles, which affect the signal.

3.1.1 Ionosphere

The ionosphere is the atmospheric layer situated between 50 to 1300 km over the earth's surface. It contains ionising radiation, which causes the electrons to affect the propagation of the signal. The ionosphere range error is dependent on a quantity called TEC, or Total Electron Content. The TEC is, as the abbrivation indicates, the total electron content along the signal path between the satellite and the receiver. This quantity depends on the solar cycle, the season and the zenith angle of the sun. It is also larger at the poles and around the equator. This means that the ionospheric range error is variable both temporally and spatially.

The effect of the ionosphere is frequency dependent. This phenomenon may be used to calculate so-called "ionosphere free" linear combinations of the two different carrier frequencies. One of the advantages of a reference network compared with a single reference station is the possibility to model the atmospheric biases at the reference stations in real time and to interpolate them on the whole area. This is a way of reducing the ionospheric effects on the observations. See Wanninger (1999) for an evaluation of the effectiveness of reference networks in Europe under solar maximum conditions.

3.1.2 Troposphere

The troposphere is the lower part of the earth's atmosphere and its thickness is varying, up to 10 km over the poles and up to 15 km over the equator. The troposphere causes a delay on the signal, dependent on the amount of water vapour. It affects mostly the height component and may amount to 2.5 cm on a baseline of 50 km. (Sjöberg, 2000)

Unfortunately, the delay is not frequency dependent so that dual frequency differences can not be used to eliminate the effect. However, a tropospheric model, for example Hopfield (1969) or Saastamoinen (1973), may model the refraction. It may also be estimated as unknowns in an adjustment.

3.2 Satellite orbits

Knowledge of the satellite orbits is the source of knowledge of the position of the satellite in a certain moment, and from that the position of the receiver is computed. The orbits are continuously tracked and monitored by the ground segment. They are predicted and then transmitted to the satellites and broadcasted from the satellite to the receiver in the navigational message. However, there are small irregularities in the orbits for example due to malfunctioning propulsion systems of the satellites, the inhomogenity of the earth's gravity field, tidal effects from our moon and sun, solar pressure and relativistic effects, resulting in orbit biases.

The accuracy of the broadcasted orbit ephemerides is approximately 3 metres (1 sigma) (http://igscb.jpl.nasa.gov/components/prods.html). This accuracy may be improved by using so-called precise ephemerides, predicted or calculated afterwards and available from various organisations, for example International GPS Service (IGS) at http://igscb.jpl.nasa.gov/components/data.html. However, since the purpose of RTK is to obtain the position in real time, only predicted precise ephemerides loaded into the receiver in advance are applicable. Other types of ephemerides require the post calculations, which is not possible in the RTK technique.

3.3 Clock errors

There are two clocks involved in the calculation of a pseudorange (calculated distance between satellite and receiver), the satellite clock and the receiver clock. The satellite clocks are rubidium or cesium atomic clocks that are extremely stable. The receiver clocks are less expensive quartz clocks, so the clock errors in the receivers are hard to predict and therefore included as an unknown in the adjustment. The satellite clock error is monitored by the ground segment and broadcasted in the navigation message. It is also available with greater accuracy after some time from the same source as the precise ephemerides.

A widespread way of reducing errors is to use linear combinations of GPS observations, differences. The double differences (differences between two satellites and two sites, see section 4.2) cancel out the main part of the satellite and receiver clock biases. Unfortunately, it has certain disadvantages such as the increasing correlation between measurements and a doubled standard error compared to undifferenced data. Despite these disadvantages, it is still the most common method.

3.4 Multipath

Multipath is the name of the error caused by the fact that the signal may be reflected by a nearby surface before reaching the GPS antenna. This means that the direct signal and the reflected one will interfere and the measured value of carrier phase will not be correct. Multipath occurs when the antenna is situated near a reflecting surface, for example a chain-wire fence or a metallic surface. The reflections from the ground may be reduced with a so-called ground plane. Hoffman-Wellenhof et al. (2001, p. 131) observes that *“The most effective counter-measure to multipath is to avoid sites where it could be a problem.”*

3.5 Noise

If all the above mentioned errors are correctly modelled and corrections are applied to the position, it will still not be the same position measured every time. The reason for this is the random noise that is always present in the measurements. This random noise mainly contains the actual observation noise plus random constituents of multipath (especially for kinematic applications). (Hoffman- Wellenhof et al., 2001) The pseudorange noise for carrier measurements is 0.2 to 5 millimetres.

4 The ambiguities

To be able to obtain a position using carrier phase measurements with an accuracy better than two decimetres (the wavelength of a signal) it is crucial to be able to solve for the unknown ambiguities, i.e. the number of wavelengths between satellite and the receiver. It is important to eliminate as many as possible of the signal errors before attempting to solve the ambiguities, because the remaining errors will affect the solution. A quick and accurate solution will minimise initialisation time and thus speed up measurements.

4.1 Cycle Slip

The situation when the contact with a satellite is interrupted is called cycle slip. As soon as the receiver is turned on, the phase difference between satellite and receiver reference signal is observed. A counter starts and increases 1 step each time the fractional phase changes from 2π to 0. If a loss of lock occur, the counter looses track and is reinitialised. This initialisation causes a jump in the accumulated phase by an integer number of cycles. (See figure 1.) Cycle slip may be treated as an additional unknown in a static measurement and might be difficult to detect. However, there are techniques to detect and repair cycle slips in post processing. In a kinematic measurement, the receiver will have to be reinitialised if the signal is interrupted so that contact with less than four satellites remain.

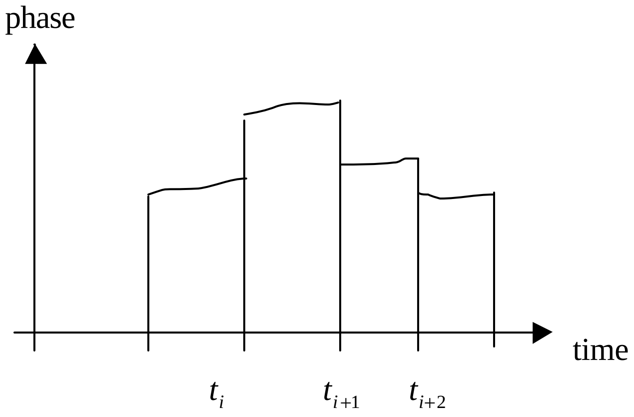

Figure 1: Phase measurement with cycle slips at t_i, t_{i+1} and ti+2. From (Sjöberg, 2000)

4.2 Double Differences

One way to get rid of the clock errors is to use double differences. A single difference is a difference between phase measurements from the same satellite to two different points. This eliminates the satellite clock bias. The resulting equation is:

$$\Phi^{j}_{AB}(t) = \frac{1}{l} r^{j}_{AB}(t) + N^{j}_{AB} + f^{j}_{AB} d_{AB}(t) \qquad (3)$$

Where f : frequency of the satellite carrier wave
t: time of observation
A and B indicate a difference between the two sites.
j indicates the satellite.

By taking the difference between two single differences of different satellites on the same two points, the receiver clock bias also cancels out. The equation of double differences looks like:

$$\Phi_{AB}^{jk}(t) = \frac{1}{l} r_{AB}^{jk}(t) + N_{AB}^{jk} \qquad (4)$$

A and B indicate a difference between the two sites
J and k indicates a difference between the two satellites

4.3 Methods for solving the ambiguities useful for RTK

There are many methods to solve the ambiguities. The ones presented below may be used for RTK solutions.

4.3.1 Linear combinations

One way to make it easier to find the ambiguities is to make linear combinations of the two different carrier waves transmitted from the satellites:

$$j = n_1 j_1 + n_2 j_2 \qquad (5)$$

where n_1 and n_2 are arbitrary constants.

There are several possible combinations with some different properties. A good combination should meet several of these criteria (Sjöberg, 2000):

a) long effective wavelength
b) the ambiguity as an integer
c) small ionosphere error in the combination
d) small effective noise

There is no combination that satisfies all these criteria, so one has to compromise. See Table 1 for a summary of different combinations in use.

A long effective wavelength simplifies the fixation of the correct ambiguity. This is also true if the ambiguity is an integer. Small errors in the observations indicate small errors in the estimations. A small effective noise is more important in RTK measurements, because it is impossible to model and correct for in the RTK-corrections.

Table 1: Examples of some linear combinations. (Sjöberg, 2000)

Symbol	**Combination**	n_1	n_2	**The effective wavelength [cm]**	**Ionosphere bias**	**Noise [mm]**
Φ_1	L1	1	0	19,0	0,78	3,0
Φ_2	L2	0	1	24,4	1,28	3,9
Φ_w	“wide lane”	1	-1	86,2	-1,00	19,4
Φ_n	“narrow lane”	1	1	10,7	+1,00	2,4
Φ_3	Ionosphere free	~9	~7	~5,4	0	10,3

It is also possible to combine data not only from two different frequencies but also from observations of code and carrier wave at the same epoch of time.

4.3.2 FARA

FARA is a method often used to determine the ambiguities, especially when the receiver is moving (or OTF, which stands for “on-the-fly”). FARA is an abbreviation for Fast Ambiguity Resolution Approach and is an algorithm that uses statistical techniques to find the most likely solution for the answer.

The method consists of four steps. (Hofmann-Wellenhof et al., 2001) First, the float carrier phase solution is computed when unknown co-ordinates of points and ambiguities are created during a network adjustment. Secondly, a search range is chosen of the real values to be tested for the correct integer value. The code solution helps in defining the range. This search range may not be too big to reduce computation time, but has to include the correct answer. When the search range is decided, the fixed integer solutions are computed for the ambiguities inside the set. Last, the solutions are tested a) using the variance-covariance matrix to see if they are statistically acceptable and b) to find which solution gives the best least-square solution and by this is judged do be the best one.

4.3.3 Long baselines

Solving the ambiguities is a difficult process, so why not use all available information? Pseudorange observations may give additional information and are often used in linear combinations with carrier observations to improve the solution. Long baselines, distances ≥ 10 km, create problem during ambiguity resolution, because the ionosphere effect increases, and this influences the solution significantly. It means that the standard error in the code observable is too big to fix all the unknowns.

This problem may be dealt with in several ways. For example Horemuž and Sjöberg (1999) proposed a method useful for baselines of up to 30 km with 15 s observation time. This method uses code observations filtered with phase observations to fix $N_{4,-5}$ and $N_{1,-1}$ and finally N_1 and N_2. $N_{i,j}$ are linear combinations of the ambiguities of the frequencies L1 and L2.

$$N_{i,j} = iN_1 + jN_2 \tag{6}$$

The RTK-network program used in this investigation does not recommend baselines longer than 35 km, probably because then the ionosphere effect creates too big problems for solving for the ambiguities. It has been shown during the Position Stockholm Mälaren project (Wiklund, 2001) that the initialisation time in the biggest triangles (with sides exceeding 70 km) is considerably longer than in the smaller triangles. This is probably due to the longer time needed to solve for the ambiguities. Still, the precision is equivalent, both for the long and short baselines.

4.3.4 “An instantaneous ambiguity resolution Procedure”

Chen (2000) suggests a method for ambiguity resolution specially adapted for reference networks. This method uses data from atmospheric models of the network area computed from adjacent epochs to fix the ambiguities. It is developed to make it possible to “keep on fixing ambiguities instantaneously (or with minimum delay) when a satellite experiences cycle-slips, a long data gap, or when a new satellite rises above the horizon.” The method has been tested using data from reference stations spaced 80 km apart and the results were promising. This author does not know if the method is used in any real application yet, but it is interesting that there is work going on, trying to develop methods for ambiguity solving with the help of the supplementary data about atmospheric biases provided by a reference network.

5 The theory of RTK

The term RTK stands for Real Time Kinematic, which means that the position is obtained in real time, even while the receiver is moving. This is possible as long as the ambiguities are solved OTF (On The Fly, or while the receiver is moving) and the receiver has continuos lock on at least four satellites, preferably more. There are several new applications that may make use of this high accuracy and moving receiver, for example road and rail measurement, machine guidance, precision navigation.

RTK is an application of relative positioning, with a moving receiver at unknown points, a so-called rover. One receiver is placed on a known point and observes simultaneously with the rover, but compares its observations with its known position. This makes it possible to compute pseudorange corrections that will be transmitted to the rover.

The corrections will increase the accuracy as long as the atmospheric biases are the same for both reference and rover. This is the case if the distance from reference to rover does not increase to far. (Usually within 20 kilometres.) If the receiver uses carrier measurement and transmits the corrections in real time, centimetre accuracy is achieved and the application is called RTK.

Possible applications of RTK are datacapture for digital elevation models, surveying of details as boundary points, water supply and sewer systems and staking out. This may be achieved with two kinds of reference stations, temporary and permanent. The differences are described below.

5.1 Temporary reference station

Temporary reference stations are the oldest and at present the most used method. It consists of a standard dual frequency receiver with the ability to calculate RTK corrections and a radio modem to transmit these corrections to the rower. It is comparably cheap to obtain, approximately a hundred thousand Swedish kronor, but the radio modem has a limited range. It is also vulnerable to theft because the occupation of the reference and the rower are seldom in line of sight to each other. Finally, it requires an additional task, namely the set-up and retrieval of the reference.

5.2 Permanent reference station

A permanent reference station excludes most of the disadvantages with a temporary reference station. It may be placed on a secure mounting, for example on the roof of a house, it may be equipped with radio antennas with greater range, and it may be operational 24 hours a day. But it is consequently more expensive to purchase; approximately twice the cost of a temporary reference station, and more complicated to establish. However, multiple users that share the costs may use it.

5.2.1 Ciceron

The service Ciceron from the firm Cartesia is an example of a permanent reference service. It uses data from the SWEPOS reference stations run by Lantmäteriverket, the National Land Survey of Sweden, and the corrections are transmitted by the DARC-channel on FM P4. DARC (DAta Radio Channel) is a channel on the usual FM radio network. Ciceron is currently operational at eight locations in Sweden, Gävle, Stockholm, Göteborg, Malmö, Hässleholm, Jönköping, Västerås and Helsingborg. It is not using network solutions. Ciceron covers an area with a radius of 10-20 km from each station.

6 The theory of Network-RTK

Network-RTK is a way of increasing the range of the RTK corrections. Since the atmospheric errors are distance dependent, the single station RTK corrections may not work on distances above 10 km or less (Vollath et al. 2000a) . This means that there will be a great number of reference stations if one intends to cover a larger area. Network-RTK models the atmospheric errors over the network area, which decreases the number of necessary reference stations. (See figure 3.) There are several theories on how to do the modelling and three main ways to transfer the corrections to the rower.

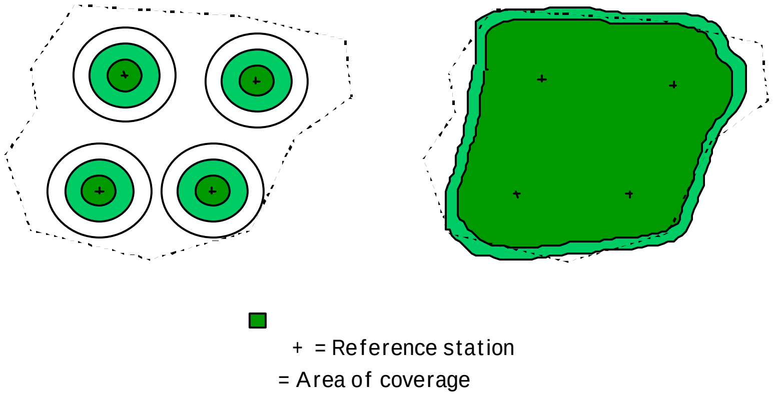

Figure 2: Areal coverage of single reference stations versus Network-RTK

A working system for Network-RTK consists of several important and complicated steps; generate the error corrections by modelling atmospheric errors, parameterisation of these corrections in a way understandable to the rover receiver, transfer of the corrections to the user and fix ambiguity resolution in real time. Each of these steps must work in a satisfactory way, independently and together, to form a working system. The parameterisation of corrections and transfer to the user will be dealt with below. Here is a short explanation of different methods to determine the corrections.

6.1 Least squares collocation

One way to determine the corrections is by least square collocation. This method has been implemented in a software at the by University of Calgary. The method relies on the possibility to determine the covariance between the errors in the reference stations before any rover measurements are made. This is done using known data such as the position of the reference receivers and received ranges from the satellites to calculate the received position errors. The covariance matrix may then be computed with a covariance function. (Raquet, 1998). When the covariance matrixes are calculated, it is possible to find the corrections at any point within the network using (Raquet and Lachapelle, 2001)

$$\hat{s} = C_{s,x} C_x^{-1} x \tag{7}$$

Where (for reference networks)

$\hat{s}$ is the signal of interest at some specified computation point within the network

$C_{s,x}$ is the cross-covariance between the corrections and the measurements

C_x is the covariance matrix of the reference stations

x is the measurement vector for the reference stations.

In a RTK network, the signal ($\hat{s}$) is the differential error between the reference receiver and the rover receiver position. The measurements (x) are all of the linearly independent double-differenced pseudorange errors from all the reference network receivers. This vector is calculated using information from the reference network. None of the terms at the right side of the equation needs information from the mobile receiver to be calculated. This means that only on-way communication may be used.

One interesting feature of least squares collocation is that it provides an additional asset; it is possible to predict network performance under different conditions knowing a covariance matrix for one set of condition. For example, what happens if there where more reference stations? This means that it is possible to evaluate the outcome of a proposed network design.

6.2 Explicit error reduction

The idea is to predict each kind of error using undifferenced data (to keep the receiver/satellite dependency). For example, the ionospheric error is modelled with a single layer model, the tropospheric error with some kind of atmosphere model and the orbits using predicted and/or broadcasted ephemerides. (Wübbena et al., 2001) To check for outliers, a short-time linear dependency may be assumed and a Kalman filter applied. The purpose is to use an error estimation method that suits the characteristics of each kind of error.

When the errors are estimated, the ideal next step would be to transfer them to the user independently. This is because they do not have the same time and spatial dependency and therefore the low-frequent errors does not have to be transferred as often as the high frequent ones. It is also possible to evaluate the global parameters as orbit and clock bias in a global network, while using a regional network for the ionospheric error and a local network for the troposphere bias. (Wübbena et al., 2001) However, today they still have to be transferred together, due to lack of a standard for transfer of each error separately.

6.3 Error parameterisation in the position domain

Raquet and Lachapelle (2001) describes three different approaches to model the errors, of which error parameterisation in the position domain is the third. The algorithm "defines a functional form for the DGPS errors in the position domain, and then uses GPS data to calculate the function coefficients." (ibid, p. 48) The idea seems to be to model the errors of the rover position, not the errors that cause the observations of the position to be wrong, like atmospheric and clock errors. The coefficients of this function are transmitted to the rover. This approach is not described in any other source this author has found, so it remains to see if it is in use in RTK softwares on the market.

6.4 Correction transferring methods

When the errors are estimated, the corrections need to be determined in a comprehensible way and transferred to the user.

6.4.1 Correction Grid

On way of transferring the corrections to the user is by using a correction grid. The corrections are distributed to a grid with chosen spatial resolution over the network area. Satellite pairs do not restrict this method. (Fotopoulos et al., 2001) The grid is transmitted to the user, thereby eliminating the need for two-way communication.

The user locates the appropriate grid cell where it is situated. The corrections are then interpolated from the closest grid nodes to the location of the user. This interpolation may result in translated corrections to a virtual reference station, (or VRS, se below) or the corrections may be used as they are. The correction grid method requires more data to be sent than the two following, but it is still within the range of modern communication techniques. (Raquet, 2001)

The grid-virtual reference station approach is used in a reference network in Japan because of the possibility to increase the number of users easily. The use of RTK services Japan for vehicle control and car navigation is supposed to increase rapidly in the near future. The same grid parameters are sent to all the users by a TV audio sub-carrier signal. They may also be accessed via Internet. The user then calculates the necessary corrections. For more information, see (Petrovski et al., 2000)

6.4.2 Correction Functions

The corrections are modelled in the form of a function of user position, for example a surface model or an inclined plane, and the coefficients of the function is sent to the user. The coefficients of the function are computed via least squares adjustment with observation equations. (Fotopoulos et al., 2001) The user then computes the corrections from its own position. This eliminates the use of two-way communication and requires less data to be sent than with the correction grid. (Raquet and Lachapelle, 2001) This is a natural approach to use with error parameterisation, but may also be used with other methods. There may however be problems if the function does not fit the error characteristics, thereby introducing additional errors. This problem is further complicated by the fact that the error characteristics are not constant, so that different kinds of functions may be more suitable at different times.

6.4.3 Virtual Reference Station

Data from the reference stations are sent to a central processing facility. Here the corrections are computed for each reference station. The user transmit its position and the corrections are interpolated from the closest reference stations to a virtual reference station (VRS) placed close to the user's position. The user interprets the received corrections as if it came from a real single reference station. (Vollath et al., 2000b)

"In this way, the user benefits from the reliability, availability and accuracy of a permanent network array, without having to invest in new processing software." (Fotopoulos and Cannon, 2001 p. 8) This means that the method works with any receiver that has RTK capabilities. However, this approach depends on two-way communication since the user has to send its approximate position to the central processing facility and then receive corrections for a virtual reference station close to this position.

7 Network-RTK today

It is recognised today that Network-RTK has several advantages. The technique strives to achieve a consistent accuracy in the whole net by making the errors less distant dependent from the reference stations. It is also possible to achieve a high reliability and availability by using multiple reference stations. If one station goes down or starts to give suspicious values, it is possible to let other stations take its place with a slight loss of accuracy comparing to if the only single reference station fails. It is easy to check the quality of corrections generated from each reference station, with the result of the others. As indicated above, it makes it possible to use larger distances between reference stations, and cover larger areas with the same amount of stations.

However, the approach has some drawbacks. The system is more complex to the single user than a standard single reference approach. It has considerably larger data transmission requirements. Both of these drawbacks may be simplified by using a central processing centre, which fetches the reference station data and computes the corrections. The virtual reference stations (VRS) further simplifies usage of the application for the surveyor in the field, since the VRS corrections are treated as corrections from a single reference station. Finally, there is one last drawback: the cost of implementing and maintaining this kind of services. The large investment that is needed makes it a candidate for co-operation between different users.

7.1 Software

There are three main programs today used in established networks all over the world. They are all under development i.e. the facts and opinions about them given below may already rapidly have changed. Still, here are some characteristics of each of them.

7.1.1 MultiRef

MultiRef is software written as a result of and during research at the Geomatics Institution of University of Calgary, Canada. Kvaerner Ship Automation in Norway has developed the software and the University of Calgary acquired it in 2000. It uses Least Squares Collocation to predict the errors and VRS to distribute them. The software is tested at numerous locations, for example for navigation in restricted waterways in Canada (Lachapelle et al., 2000) during high ionospheric activity in Brazil (Fortes et al., 2000) and for a large-scale network in Norway (Raquet et al., 2001). All these tests give promising results and have inspired to further developments in the software.

7.1.2 GNNET RTK

GNNET is a software that generates corrections for relative positioning and the RTK module is adapted for Network-RTK. It is written and sold by the company Geo++ in Garbsen, Germany. The program uses error parameterisation and distributes the errors either by VRS or by FKP. (Wübbena et al., 2001) FKP is an abbreviation of the German term for area correction parameters and they are distributed in the form of parameters of an inclined plane.

The authors of the software aim to estimate and distribute the errors separately to increase the accuracy, but since there is not RTCM standards for this yet, they have chosen the FKP or VRS computed from the FKP. The software is claimed to achieve accuracies of a few millimetres, by using antenna and mulitpath calibrations. This would make it suitable for permanent supervision of dams or bridges and other buildings. (Technical information from Geo++.)

7.1.3 VRS

VRS is not only an error distribution method but also the name of a product from Trimble (formally Spectra Precision). This software package includes the configuration RTKNet that uses VRS to provide Network-RTK corrections. The errors are modelled explicitly and interpolated within a triangular network to provide information for the calculations of VRS. Tests have been made showing an improvement by a factor of two in initialisation time and horizontal and vertical accuracy compared to standard single reference RTK. (Vollath et al., 2000a) RTKNet is the software that has been used in this study.

8 A pre-study of Network-RTK in the Stockholm area

8.1 SWEPOS

SWEPOS is a network of GPS reference stations covering Sweden operated by Lantmateriet, the National Land Survey of Sweden. The network has (May 2001) 21 stations with antenna fundaments mounted on bedrock and redundant equipment (figure 3). There are also another ten stations that are mostly located on the top of buildings and have less redundant equipment. The main task of these ten stations is to provide RTK services.

The purpose of the SWEPOS network is to:

- Provide single- and dual-frequency data for relative GPS measurements
- Provide DGPS and RTK corrections for broadcasting to real-time users
- Provide data for geophysical research
- Act as high precision control points for Swedish GPS users
- Monitor the integrity of the GPS system.
- Realise the Swedish reference system SWEREF99. (Hedling et al. 2001)

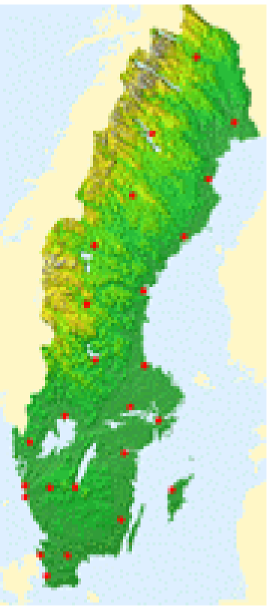

Figure 3: Map of operational SWEPOS stations

The single- and dual- frequency data is available at SWEPOS homepage (http://www.swepos.com/) and the DGPS corrections are distributed through services as Epos (Cartesia), Mobipos (Generic Mobile) and OmniSTAR (Fugro). For RTK users the Ciceron service (Cartesia) is available, providing RTK corrections computed at the closest SWEPOS station, through a DARC channel on the FM-band. Unfortunately, this only works within 20 km from the SWEPOS station and is only available on 8 locations.

8.2 The project "Position Stockholm Mälaren"

To investigate the possibility of expanding the area where RTK corrections are available, the project Position Stockholm Mälaren was started in the autumn 2000. The purpose of the project was to "survey the distance dependency of the position accuracy from the reference stations using the Network-RTK technique and if there exist any user problem". (Wiklund, 2001, translation from Swedish) The project involved the NLS, the Swedish National Rail Administration, the Swedish National Road Administration and several local authorities in the area.

To establish a local RTK network, two existing SWEPOS stations were used and four new reference stations were established. The software GPS-Network from Trimble was chosen to generate the VRS corrections, GSM was chosen as a distribution channel for the corrections and the system is managed from the SWEPOS control centre in Gävle.

Within the project approximately 1000 test measurements were carried out at known SWEREF- points. A summary of the results shows the values given in Table 2.

Table 2: Summary of the results in the project Position Stockholm-Mälaren (Wiklund, 2001)

Distance to closest reference station (km)	Largest horizontal deviation for 95% of all measure-ments (mm)	Largest horizontal deviation for all measure-ments (mm) when outliers are cancelled	Largest deviation in height for 95% of all measure-ments (mm)	Largest deviation in height for all measure-ments (mm) when outliers are cancelled	Number of outliers	Longest time to initialisation for 95% of all measurements (minutes: seconds)
0-7	17	149	34	325	1	0:33
9-15	30	76	65	110	0	1:57
18-24	40	154	84	310	10	6:12
26-29	42	148	108	168	2	4:21
34-37	46	73	116	370	7	5:45

In the conclusion of the report from the Position Stockholm Mälaren project it is indicated that “the result totally looks promising” but more studies of the possibility to detect outliers need to be done. This Master of Science project is a part of those studies.

9 The measurements in this project

The aim of our measurements was to simulate measurements for production purposes using Network-RTK. To achieve this, the following conditions were set up:

- The antenna was carried on a pole and held in the plumb line with the support of two additional poles.
- The measurements were recorded as soon as a measurement with a sigma value under the pre-set requirement of 5 cm was reached.
- Initialisation was restarted if ambiguities were not solved after five minutes.
- Reinitialisation was only made when lock was maintained with less than the four necessary satellites.

Two sites were chosen for different purposes, Gärdet with five points and the church of Litslena (called Litslena) with ten points.

Gärdet, a big former exercise field for the Swedish army in the middle of Stockholm was chosen for its excellent conditions for GPS measurements. There are no trees and therefore no obstacles for the satellites all the way around the horizon. Gärdet is also very close to the edge of the smallest triangle of the net. (See figure 4.) Before the measurements were started, it was agreed to force the program to calculate corrections from this triangle and not from the larger one on which rim Gärdet is situated. Unfortunately, this was forgotten during the vacations while the measurements were going on. But the corrections are still from one of the smaller triangles.

One also wished to compare with measurements from a site with not so ideal conditions for GPS measurements. For this purpose, the site at Litslena church outside Enköping was chosen. It consists of a parking lot by the church with a few trees and the bell tower disturbing the view to the satellites in certain angles. It is also situated approximately in the middle of the largest triangle of the net where the worst corrections should be received. This is because the error models are most weak at the point most far away from the three corners in the triangle. Litslena was chosen to make it possible to check the quality at a site far away from the reference stations and with bad satellite receiving conditions. (See figure 4.)

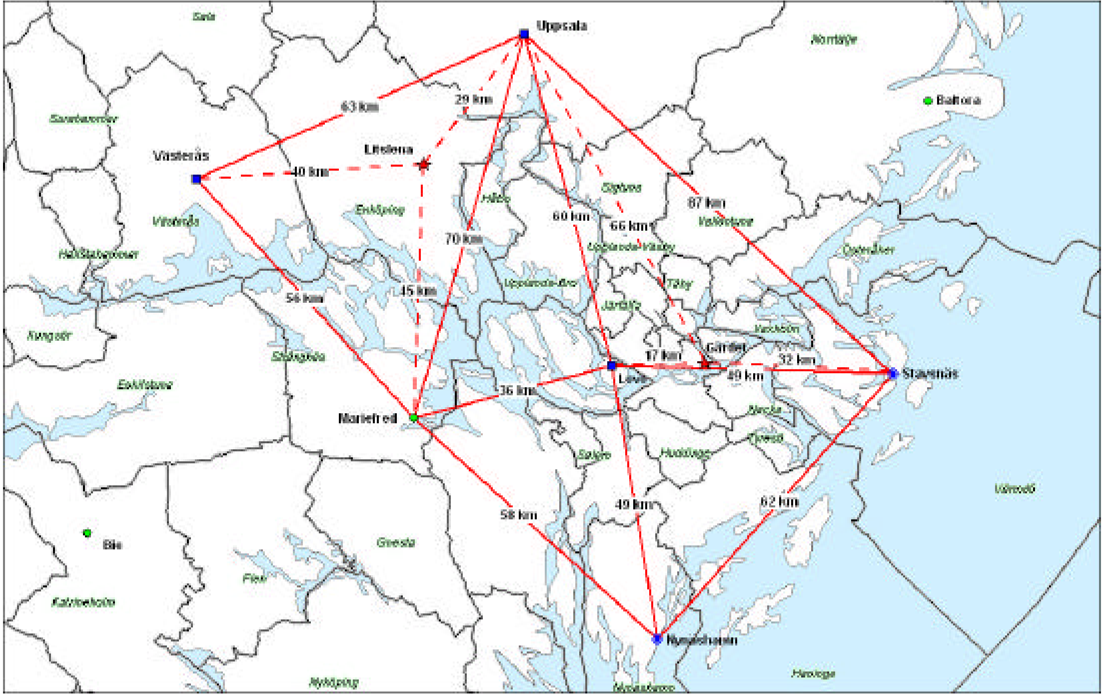

Figure 4: Map of the reference stations used for the measurements and the location of the test sites.

A loop at Litslena was planned so that the first and the last points have good conditions and the points in between are all more or less shadowed by trees and the bell tower. The point number five is most shadowed and it is also reached by passing immediately under a tree where the ambiguities almost every time are lost. The point number eight is by a metal sign and nine is right by a bus stop shelter with a metal roof which both might give mulitpath effects.

In addition to the Network-RTK measurements, the points were also measured using static GPS to achieve the best possible accuracy. These measurements were treated as the “true” value of the position of the measured point when the differences between “true” and measured values were computed.

9.1 RTK measurements

9.1.1 Method

The purpose of the measurements was to imitate measurements for production purposes. Before each series, the equipment was reinitialised to prevent correlation between the series because the receiver was using the same fix solutions. Time to fix, GDOP, estimated position quality, estimated quality of the GSM link, number of satellites and the age of the reference data was written down. (See measurement protocol in appendix.) Then the points were measured in the same order each time. If the fix solution was lost, the new values were written down and the measurements continued.

9.1.2 Equipment

A Leica SR530 GPS equipment was used including a receiver carried in a backpack, an antenna pole with horizontal level, an antenna and a GSM modem. Two additional wooden poles used to support the antenna pole at horizontation to minimise the horizontal error.

From the beginning, this examination project was also intended to include measurements with an Ashtech Z-Surveyor. These measurements had to be cut out when, after several weeks of trying, the equipment still could not be made to give reasonable results. The time assigned to measurements in this project was simply running out. This resulted in that the amount of measurements was cut down from initially intended 50*10 measurements with each instrument in Litslena and 50*5 measurements with each instrument at Gärdet to that of the Leica equipment only.

9.1.3 Measurement data and processing

The measurements were transferred to the Leica software SKI-pro. This program was used to correct erroneous point numbers and check for suspect measurements. After this work was done, the data was imported to Excel, where the analyses were done. First the difference between the measurements and the ”true” position of each point was computed. This result was in degrees, so it had to be converted to mm. Then the radial error in the plane, the standard error and some other statistical values were computed. All these calculations were made during the measurement period to make it possible to detect any suspect values.

9.2 Static measurements of the points

9.2.1 Method

The aim of the static measurements was to achieve as good values as possible given the measurement time of one day and the available equipment. At each site, two points were chosen to act as reference points for the others. These two points were measured statically for at least four hours and later computed and adjusted with respect to data from the SWEPOS stations. The remaining points were measured at least 30 minutes and adjusted with respect to the two best points in the SKI program.

9.2.2 Equipment

Ashtech Z-12 receivers were used on the two points with long occupation time and an Ashtech Z-Surveyor was moved around on the remaining points. Tripods with previously checked tribrachs were put up on the points to minimise the position error and to reduce mulitpath Ashtech Dorne Margolin antennas were utilised.

9.2.3 Measurement data and processing

The two points with longest occupation time at each site were computed using the automated computation service at the SWEPOS home page. (http://www.swepos.com/) This service uses software from the University in Bern and adjusts the result using data from the five closest SWEPOS stations. It uses CODE ephemerides to determine satellite orbits and produces a final ionosphere-free solution with, if possible fixed ambiguities. All computations are done in ITRF (International Terrestrial Reference Frame) and the result is transformed to SWEREF99 in the end. Tests show that RMS (Root-Mean-Square value) when 30 minute-observations are used is on the centimetre level. More information is available on (http://swepos.lmv.lm.se/)

The results from these computations were then treated as “true” values when the other points were computed and adjusted in the Ashtec Office Suite. In Litslena, the maximum standard deviation in the adjusted coordinates was 2,7 mm in X and Y (WGS84) and 3,9 mm in Z. In Gärdet, the maximum standard deviation was 2,9 mm in X and Y (WGS84) and 3,6 mm in Z.

10 Results

10.1 Position

The results were compiled in the form of scatter diagrams of the horizontal position and barcharts of the latitude, longitude and height deviation. The results for each observation day were also collected in special sheets. Three different measurement rounds were shown on these sheets, from the beginning, the middle and the end of the measurements that day. No significant difference in the results was shown for different time of the day, although the different days show differences in accuracy. A summary of the results is given in Table 3.

Table 3: The results

RMS (mm) (or standard deviation)	Latitude	Longitude	Ellipsoidal height
Gärdet	17	22	29
Litslena	19	22	33

The results show that these measurements with the antenna on a pole is comparable to the results from test made by the Position Stockholm-Mälaren project (Wiklund, 2001) and by the developers of the software GPS-Network. (Vollath et al., 2000a and the Trimble website) Both these tests were made with the antenna on tripods. The results from the Position Stockholm Mälaren project (Table 2) may be compared to the results of this project in Table 4.

Table 4: Summary of the results of the measurements.

Test site	Largest horizontal deviation for 95% of all measurements (mm)	Largest horizontal deviation for all measurements (mm)	Largest deviation in height for 95% of all measurements (mm)	Largest deviation in height for all measurements (mm)	Number of outliers	Longest time to initialisation for 95% of all measurements (minutes: seconds)
Gärdet	41	82	52	110	0	1:30
Litslena	50	138	68	131	0	1:25

The results achieved in the German test of RTKNet are presented with the confidence levels of 90% and 99%. These results are summarised in Table 5. To make it possible to compare these with the test results, are the results shown in Table 6 recalculated to these levels. All values are in millimetres.

Table 5: Summary of test results from German test. (From the brochure GPS-Network - The software Solution for Virtual Reference Stations.)

	Position Errors in North	Position Errors in East	Position Errors in Vertical
90%	13	9	25
99%	26	21	49

Table 6: Test results recalculated to 90% and 95% confidence levels.

	Gärdet			**Litslena**		
	Dev. Lat	Dev. Long	Dev. Height	Dev. Lat	Dev. Long	Dev. Height
90%	16	18	42	28	35	54
99%	44	41	67	48	60	88

It may be noted that the German test gives the results in north, east and vertical. This is of course not identical to the latitude, longitude and ellipsoidal height used in this report. However, a quick comparison shows that the latter figures are realistic. The lower level of the figures in the German test may be due to the fact that this test is made with 45 hours of continuous data and that it is made in Germany with probably a better satellite configuration and smaller ionosphere bias. The nearest German reference station is 32 km away.

Another issue is the handling of the RTK-data in the receiver. The receiver shall use ionosphere free data for the RTK computation, according to information from Trimble, in order to eliminate the errors from the ionospheric refraction. (Lilje, 2001) The RTK-computation in Leica uses, as far as we know, only L1 and L2-phase data. The better results of the German test may be because ionosphere free data data is used.

10.2 Time of initialisation

During the measurements, the time to initialize was also recorded. With the Leica equipment, this also includes the period of time needed for calling the control centre and establishing a connection. The time period measured starts when the “dial”-button is pushed and ends when a full fix solution is achieved.

This process sometimes took more than five minutes, and in these cases the process was restarted. This is because one may expect that during a real measurement situation, the operator will not have patience enough to wait for a possibly incorrect solution. It is often quicker to restart the process if a “bad” measurement has been recorded that make the receiver incapable to determine the ambiguities.

The times to initialisation were ordered in size and compared to the time of day, the number of visible satellites and the GDOP values. No significant relation is shown in these diagrams. This may be due to the fact that not only the time for finding the fix solution is recorded, but also the time to transfer data from the control centre. This is an unknown factor. All diagrams may be studied in the appendix.

Table 7: Comparison of time to initialisation for Gärdet and Litslena

Test site	Longest time to initialisation for 67% of all measurements (minutes:seconds)	Longest time to initialisation for 95% of all measurements (minutes:seconds)
Gärdet	1:00	1:30
Litslena	0:50	1:25

10.3 Outliers

This project was also meant to test the possibility to detect outliers. There were no outliers in the result. However, the equipment has a function that warns the operator if the measured value has a sigma value above a pre-set value. This value was set to five centimetres during the tests. The equipment indicated several times that this value was exceeded and the points were re-measured every time this happened. The fact that no outliers were detected in the measurement data after field measurement shows that the warning function works well. This function was not used during the measurements during the Project Stockholm-Mälaren. (Wiklund, 2001)

11 Analyses and discussion

It is important to recognise the limitations of this test. The measurements are only made with one brand of equipment, Leica. Wiklund (2002) has shown that there are differences between the accuracies of different equipments. The measurements were made during a limited period of time. The atmospheric conditions are, despite the corrections, affecting the results (also shown by Wiklund, 2002), and the test only reflects the conditions during the measurement period. This factor may be decreased, however, since Trimble, the manufacturer of the RTKNet software, has came out with a new release of the software claimed to reduce the distance dependency to the reference stations. This new release is currently (January 2002) installed and running in the SWEPOS control centre.

There are several factors that may have influenced the test result. Plumbing errors are always present. There is the possibility of relocated points, especially in Litslena, where some points where marked with marking nails in a gravel parking lot and others in summer-hot asphalt. Finally, the static measurements are of course not without errors, although they are treated as “true” values.

It was a pity that the Ashtech measurements had to be cut out from the project. They would have given an interesting comparison to the Leica measurements, making it possible to detect any brand differences. The difficulties with the Ashtech equipment in this project may not give reasons for bias against the brand on the whole. The particular equipment I used had been around for some years and was very well used. Further more, it consisted of several separate pieces including a custom made radio modem, connected with cords. This gives plenty of possibilities for malfunctions. On the other hand, the Leica equipment used was brand new and all the parts were built together.

Correspondence with different receiver manufacturer about the RTK function of there products (Lilje, 2001) have shown that the receivers are not ultimately configured for the RTK-Network software. Trimble Terrasat Gmb recommends the ionosphere free solution to be used, even if the baselines to the VRS are very short. Leica is presently not using the ionosphere free solution at baselines shorter than 15 km, but plan to give this option in the near future. This may improve the results for Leica equipment used for Network-RTK.

There are several interesting options that may be investigated. One may repeat the tests with the new release of the software to check if the distance dependency has decreased. One may try other brands of equipment. One may also try to increase the accuracy of the static measurements. All these possibilities would further increase the usefulness of this project.

This project has shown results that are comparable with the results in the Position Stockholm Mälaren project. This means that the precision and reliability achieved during those controlled tests are also achievable during ordinary measurement for production purposes as long as one keeps in mind the plumbing error possible when using an antenna on a pole. Furthermore, the results show that the outliers detected in the Stockholm Mälaren project are not present at production measurements.

It is, however, necessary to note that the RTK technique alone does not revolutionise detail measurement. GPS measurement always needs to be done with contact with as many satellites as possible. This may present problems when measuring in forested or urban areas. An example of this is the high number of lost satellites and thereby forced new initialisations and longer time periods to initialisation at point 5 in Litslena (see diagram 1), which has been accessed by walking under a tree. Classical measurement technique using total stations is superior during these conditions.

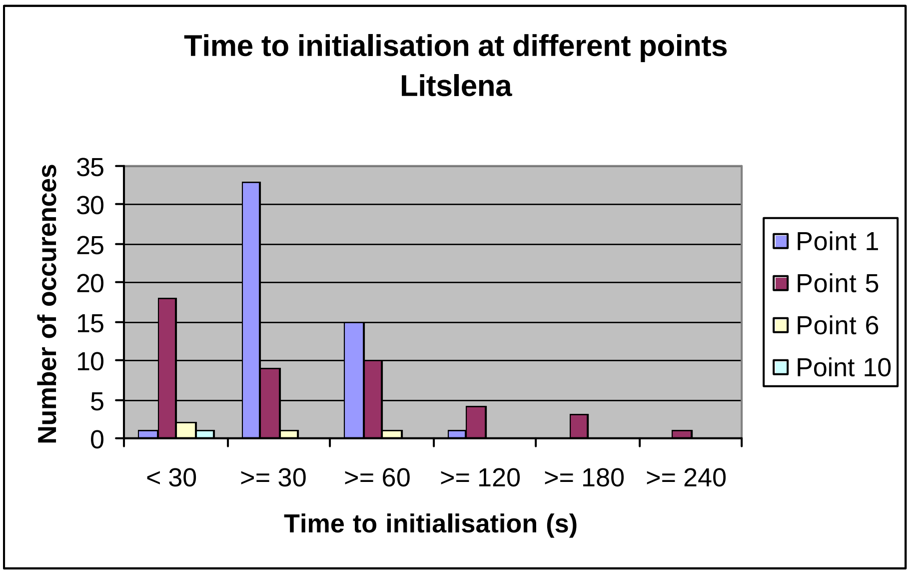

Diagram 1: Time to initialisation at different points in Litslena

Note that a reinitialisation was forced on point one, at the start of each of the 50 rounds.

A combination of GPS and conventional technique will, however, increase the efficiency dramatically and revolutionise detail measurement. Network-RTK will be one step further in this revolution since the user need only one rover (no equipment and known point for a temporary reference station) and the number of reference points on the ground can be reduced significantly. Eventually, this will save time and money.

Leica 500 technical reference manual states that the accuracy of regular RTK measurement is “around 1 to 5 cm when the ambiguities are solved.” This is the accuracy of the baseline between rover and reference. Additional positional uncertainty of the reference point and antenna pluming errors at this point will have to be added. The results of this project show a horizontal accuracy below 5 centimetres, equal to that of regular RTK. This is sufficient for the applications listed in the hypothesis.

The reliability of the RTK-network is better than of the single reference station, due to the constant monitoring of the conditions made by the control centre at SWEPOS. There is also the possibility to use the reference stations for single station RTK, if a reference station is down. This indicates reliability sufficient for the applications listed in the hypothesis.

Our hypothesis states that GPS measurements using the network of reference stations called Position Stockholm-Mälardalen generating corrections using the software GPS-net, has a precision and a reliability that is sufficient for a number of applications such as cadastral surveying, data capture for data bases with geographical information, machine guidance and precision navigation. We conclude that the hypothesis is reasonable.

12 Conclusions and Recommendations

Network-RTK is easy to use and this test shows a high reliability and an accuracy of five centimetres in the plane and thirteen decimetres in height at the 95 % level. It is a useful measuring technique as long as one is aware of the limitations of all GPS applications; possible multipath, satellites shadowed by high objects and so on. Network-RTK also requires good distribution channels for the transfer of the corrections. For applications that demand higher accuracy, other techniques are needed at present. However, there are a lot of applications that do not demand higher accuracy than this. Developments of software and the handling of RTK data in the rovers are going on to increase the accuracy.

High investment costs are needed to establish the reference net. Still, the investment costs for a network of permanent reference stations is much lower than the costs for the required number of single–RTK stations to cover the same area. This is an investment that may benefit a large number of users of the net, for several years to come. It is appropriate that the expected users of the net share the cost. The initiative taken by SWEPOS to start such a project is commendable. Network-RTK is, after all, not yet a too widespread technique. The use of GSM as correction transferring technique also adds to the costs of Network-RTK in the Stockholm-Mälaren project. This cost may be expected to lessen as new mobile data transferring techniques are introduced.

An extended network in the Stockholm-Mälardalen area went operational as a prototype service for the members of the project the 7 February 2002. (Jonsson, 2002) Similar network projects will also be established on the West Coast of Sweden and in the southern part of Sweden shortly. The software is expected to be improved during 2002 and it is interesting to evaluate improvements in accuracy and reliability. Further tests should and will be performed.

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Technical information about VRS and GPS Network from Trimble available at the website http://www.trimble.com.

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Leica 530 Technical Reference Manual.

Appendixes

Gärdet

Results collected by day of measurement

Time to initialisation

Litslena

Results collected by day of measurement

Time to initialisation

Reports in Geodesy and Geographical Information Systems from the National Land Survey of Sweden

1998:3	Lidberg M: Litteraturstudie om RTK-tekniken, ett samarbetsprojekt mellan Banverket, Lantmäteriverket och Vägverket.
1998:4	Ekman M: Jordellipsoider, geoider, koordinatsystem, höjdsystem och tyngdkraftssystem i Sverige genom tiderna
1998:5	Jansson Roland: Utstakning av fastighetsgräns i skogsmark med hjälp av GPS hos Lantmäterimyndigheten i Norrbottens län..
1999:2	Anderasson Thor-Björn Engman Linda: Multipath at the SWEPOS stations Evaluation of eccosorb, a microwave absorbing material
1999:3	Lilje Mikael: Geodesy and Surveying in the future
1999:4	Jonsson, Bo: Civil Service Interface Committee International Information Subcommittee 7 th European Meeting
1999:12	Jonsson. Bo: Proceedeings of the 13th general meeting of the nordic geodetic commission.
2000:02	Engfeldt Andreas, Jivall Lotti: Kort introduktion till GNSS
2000:03	Christina Kempe: Meodstudie för inmätning av skogsbilvägar
2000:4	Niklas Svanholm: Jämförelse av olika metoder att föra över kartdetaljer till ett nytt koordinatsystem.
2000:5	RefStrat-Stategier för referenssystem och referensnät
20001:1	Lars Engberg: Geodesi 2000 –svensk geodesiverksamhet under kommande tioårsperiod.
2001:6	Jivall, Lotti: SWEREF 99 – New ETRS 89 Coordinates in Sweden, Analysis Reoport.
2001:7	Jivall, Lidberg, Lilje, Reit: Transformationssamband mellen SWEREF 99 och RT 90/RH 70
2001:10	Andreas Rönnberg: Undersökning av tjänster för differentiell GPS
2002:1	Slutrapport för projekt Position Stockholm-Mälaren 1