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DIFFERENT METHODS AND EQUIPMENT FOR DETERMINATION OF NEW POINTS RELATIVE TO THE SWEPOS-STATIONS

A comparative study

Diploma Work by
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Gävle 1997

NATIONAL LAND SURVEY

PREFACE

SWEPOS is the Swedish national network of reference stations. When a new point is determined relative to SWEPOS by the static method, there are many adjustable factors that can influence the accuracy of the result. The purpose of this work was to compare a "standard equipment" and a "state-of-the-art equipment" and to investigate how the result depends on which method that is used and on how the equipment can handle different error sources.

The diploma work was carried out at the Geodetic Research Division (FoU-Geodesi) at the National Land Survey of Sweden (Lantmäteriverket) in Gävle. It included some field measurements, processing of the stored data and analyses of the results.

I would like to thank all nice people at the National Land Survey in general, and the personnel at the Geodetic Research Division in particular.

Thanks a lot to my instructor Jonas Ågren for his support, good advice and patience with all my questions.

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Abstract

SWEPOS is the Swedish national network of permanent reference stations, which is developed and maintained by the Geodetic Research Division (FoU-Geodesi) at the National Land Survey of Sweden (LMV) in Gävle. This study contains investigations regarding some of the factors that influence the result when new points are determined by the static method relative to the SWEPOS-stations. The purpose was to compare one typical standard equipment with a state-of-the-art equipment and to investigate how the result depends on which method that is used and on how the equipment in question can handle different error sources. As standard equipment an Ashtech Geodetic New antenna and the Geotracer GPS software, which is of the baseline type, were chosen. The state-of-the-art equipment consisted of a Dorne Margolin T antenna, that is the same type of antenna as is used at the SWEPOS stations, and the Bernese GPS software, which is of the multi-station type.

The study contains two main parts, one where the different methods and error sources are treated from a theoretical point of view, and another where the results from a number of tests are presented. The tests were made mainly to answer the following questions: How important is it to use the same antenna type as the Dorne Margolin T antennas used at the SWEPOS-stations ? How does the software affect the result ? How does the result depend on the observation time ? Do the results differ between a fixed adjustment and a free adjustment with a subsequent Helmert transformation ? How many reference stations should be utilised if the standard software is used ? The results from the tests were evaluated by comparison with very accurately determined coordinates in SWEREF 93 for the point.

The tests indicate that it is important to use the same antenna type as the ones used at the SWEPOS-stations. If different antenna types are mixed, a reliable antenna model has to be applied. It is further shown that it is possible to perform an

antenna calibration on your own, which results in a very good antenna model. The tests also indicate that it is important to use an advanced antenna model, as in the Bernese software. The last conclusion is valid both in the vertical and the horizontal components.

Another thing that could be seen from the tests is that the observation time needed for a specific accuracy is considerably lower when the Bernese software is used compared to the Geotracer case. This can partly be explained by the fact that only float solutions can be used in Geotracer in connection with long baselines. It has further been observed that longer observation times are needed when different antenna types are mixed in Geotracer, compared to when the same antenna type is used at all stations (Dorne Margolin T).

The last tests, which were performed in Geotracer, show that it does not matter if an adjustment with all stations fixed or a free adjustment with a subsequent Helmert transformation is done. It is also indicated that a fixed adjustment with four reference stations gives a similar result as with six.

Sammanfattning

SWEPOS är det svenska nätet av fasta referensstationer för GPS som utvecklas och underhålls av FoU-Geodesi vid Lantmäteriverket. Denna studie innehåller undersökningar av några av de faktorer som påverkar resultatet vid statisk bestämning av en ny punkt relativt SWEPOS. Syftet var att jämföra en GPS-standardutrustning med en specialutrustning och att undersöka hur resultatet beror av vilken metod som används och av hur utrustningen i fråga kan ta hand om olika felkällor. Som standardutrustning valdes en Ashtech Geodetic New antenn och Geotracers GPS-programvara som är ett baslinjeprogram. Specialutrustningen bestod av en Dorne Margolin T antenn, d.v.s. samma antenntyp som används på SWEPOS-stationerna, och Bern-programmet som är ett multistationsprogram.

Undersökningen innehåller två huvuddelar, en där de olika metoderna och felkällorna beskrivs teoretiskt, och en annan där resultaten från testerna presenteras. Testerna utfördes huvudsakligen för att få svar på följande frågor: Hur viktigt är det att använda samma antenntyp som används på SWEPOS-stationerna, d.v.s. Dorne Margolin T ? Hur påverkar programvaran resultatet ? Hur beror resultatet av observationstiden ? Skiljer sig resultatet mellan en fast utjämning och en fri utjämning med Helmertinpassning ? Hur många referensstationer skall användas i standardprogrammet ? Resultaten från testerna utvärderades genom att jämföra dem med mycket noggrant bestämda koordinater i SWEREF 93 för punkten.

Testerna visar att det är viktigt att använda samma typ av antenn som de som används på SWEPOS-stationerna. Om olika antenntyper blandas, måste en pålitlig antennmodell användas. Testerna visar också att det är möjligt att utföra en egen antennkalibrering, som kan resultera i en mycket bra antennmodell. Det är viktigt att programmet kan använda en avancerad antennmodell, som fallet är med Bern-programmet. Detta gäller både för vertikal- och horisontalkomponenterna.

En annan sak som kan utläsas ur testerna är att den observationstid som behövs för att uppnå en viss noggrannhet är väsentligt lägre när Bern-programmet används jämfört med Geotracer. Detta kan delvis förklaras med det faktum att endast flytlösningar kan användas i Geotracer i samband med långa baslinjer. Vidare så kan man se att längre observationstider behövs när olika antenntyper blandas i Geotracer, jämfört med när samma typ av antenn används på alla de inblandade stationerna (Dorne Margolin T).

De sista testerna, som utfördes i Geotracer, visar att det inte spelar någon roll om en utjämning med alla stationerna fasta eller en fri utjämning med Helmertinpassning används. De utvisar också att en fast utjämning med fyra referensstationer ger liknande resultat som med sex referensstationer.

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1 INTRODUCTION

To determine new points by the static method for GPS relative to a net of permanent reference stations, such as SWEPOS, has many advantages compared to working with a conventional reference net (Jivall, 1997). Among these are time savings by not having to look up the reference points and measure on them, no centring errors at the reference points and less risk for identifying the wrong point. There is also a possibility to connect to more reference points, which gives higher accuracy and higher reliability. There are reasons to believe that permanent reference stations will play a big part in position determination in the future, even for geodetic measurements with accuracy demands on the mm level. To make this possible it is a requirement to work in a modern global three dimensional system, such as SWEREF 93, which is defined by the 21 SWEPOS-stations.

Since 1994 new points are determined in SWEREF 93 by the National Land Survey in Sweden (NLS). The observations are made for 2*24 hours with a dual-frequency receiver and a *Dorne Margolin T* antenna, which is the same antenna type as is used at the SWEPOS-stations. The processing is made in the *Bernese GPS software.* This equipment will be called state-of-the-art equipment in the following.

If an ordinary user is going to determine his position relative to the SWEPOS stations by the static method, he will most probably use a typical standard equipment. In this case it will not be rational for example to use 48 hours of observations for each point, because this will be too expensive.

The purpose of the present work is to compare one typical standard equipment with the state-of-the-art equipment mentioned above. In connection with this it is investigated how the accuracy depends on which method that is used and how different error sources are taken care of in the equipment in question. It is for instance studied how important it is to use the same antenna type as the Dorne Margolin T (which is used at the SWEPOS-stations), how the troposphere influences the result, how the result depends on the observation time, how many reference stations that should be utilised if the standard equipment is used and how the results differ between a fixed adjustment and a free adjustment with a subsequent Helmert transformation.

As a standard equipment one typical commercial equipment was selected, namely an *Ashtech Z-12* receiver with an *Ashtech Geodetic New* antenna, combined with the *Geotracer GPS software 2.25* from Geotronics.

The study consists of five chapters, where the first is the introduction and the last contains a summary of the conclusions. Chapter two gives a short introduction to SWEPOS and it also presents how new points are determined in SWEREF 93 by the NLS. Chapter three deals with the different factors and error sources that affect the result from a theoretical perspective, while chapter four contains the results from the tests and the analysis of the results.

Finally, it should be mentioned that a proportionately small observation material has been used in the investigation. Therefore, this study should be seen as a first step toward a tenable methodology and as a hint to where more investigations should be made in the future.

2 SWEPOS and SWEREF 93

This chapter gives a short introduction to the SWEPOS-system and presents how new points are determined in SWEREF 93 by the National Land Survey.

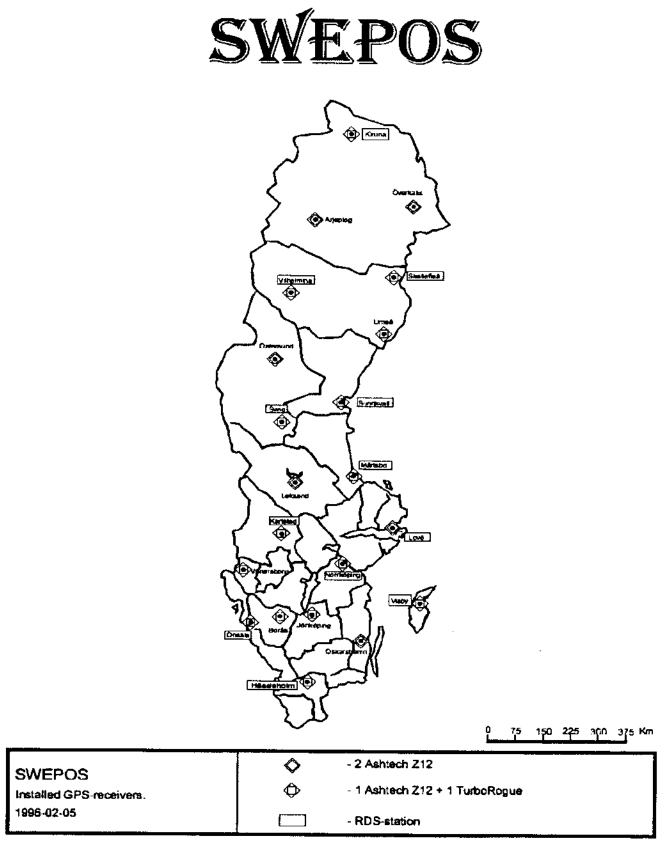
2.1 SWEPOS

SWEPOS is a national system of GPS reference stations and was established by the National Land Survey of Sweden (NLS), Onsala Space Observatory (OSO) and the project "GPS Resources in Northern Sweden". The purpose of the network is mainly to provide single- and dual-frequency data for relative GPS measurements and differential corrections for broadcasting to real-time users. It also provides data for studies of crustal dynamics. SWEPOS became operational in the summer 1993 with 20 stations spread over the country with about 200 km between them. A 21st station was located in Borås in the middle of 1995. See Hedling & Jonsson (1995) for further details.

Each station is equipped with a Dorne Margolin T (DMT) or an Ashtech "700936" antenna, with the exception for Onsala, where a Dorne Margolin B is used. Dorne Margolin T and Ashtech "700936" are practically identical antennas with the same antenna element. They have also been found to act very similar in a number of investigations (e.g. Rothacher & Mader, 1996). Therefore, Ashtech "700936" is always called Dorne Margolin T in what follows. The antennas are mounted on three meter high concrete pillars. On top of each pillar there is a stainless steel plate where the antenna is fastened. The antenna is covered by a spherical radome that is made by plexiglass, with a conical collar that is covering the top of the pillar to prevent snow from accumulating around the antenna (see Ågren, 1997a).

The coordinates of the SWEPOS stations were determined in the GPS-campaign DOSE 93 and defines the Swedish reference system SWEREF 93. This system is the Swedish densification of the European reference system EUREF 89. Like other modern geocentric systems SWEREF 93 uses the GRS 80 ellipsoid. A more thorough treatment can be found in Reit (1995).

The internal accuracy of the SWEREF 93 coordinates for the SWEPOS stations has been estimated in the daily processing of the SWEPOS network made by Dr. Jan Johansson at OSO. According to him the internal accuracy (1σ) is about 3 mm for each plane component and 4 mm for the height component (cf. Reit, 1995). This has also been confirmed by a number of tests performed by Jonas Ågren (Ågren, 1997c).



SWEPOS - the national network of permanent reference stations.

2.2 The determination of new points in SWEREF 93 made by the National Land Survey

Since 1994 other points than the SWEPOS stations have been determined in SWEREF 93 by the National Land Survey of Sweden. These points are determined relative to the eight closest SWEPOS-stations, which means that the baselines are between 50-400 km. The measurements are made with a dual-frequency receiver and a Dorne Margolin T antenna. As was mentioned in section 2.1, this is the same antenna type as is used at the SWEPOS stations.

The observation time is 2 * 24 hours. The processing is made in the *Bernese GPS Software* (see section 3.2) and is at first done separately for the two 24 hour sessions. The adjustment is made as a free adjustment with the ionosphere free linear combination and precise ephemeris from the Centre of Orbit Determination in Europe (CODE). To improve the height component, zenith tropospheric parameters are estimated. After analysing the results, the two sessions are combined to a common solution. The result is then fitted to the eight SWEPOS stations with a seven parameter Helmert transformation.

The accuracy demands for these points are very high. The accuracy (1σ) has been estimated to (Ågren, 1997c) about 5 mm for each plane component and 10 mm for the height component.

3 THEORY and METHOD

This chapter describes some of the factors that affect the result in GPS processing. Section 3.1 deals with some general factors that are important in the processing of long baselines, which are not further tested in chapter 4. Section 3.2 describes the two types of software that have been involved in the tests in the next chapter. The following sections, 3.3 - 3.5, describe the factors that have been tested and are presented in chapter 4. These factors are the influence of the antenna, the troposphere, observation time, number of reference stations and how free or fixed adjustment affect the result. How the state-of-the-art equipment (the Bernese GPS software and the DMT antenna) and the standard equipment (the Geotracer and the Ashtech antenna) differs will also be described.

3.1 General considerations regarding the methodology in connection with long baselines

To determine new points in SWEREF 93 relative to some SWEPOS stations the baselines become quite long (up to about 200 - 300 km). This means that you cannot proceed exactly in the same way as when shorter baselines are used to achieve a good result. It is important to pay attention to a number of things. In this section some general considerations that are important in connection with long baselines are discussed (cf. e.g. Harrie, 1996).

- The ionospheric path delay can not be assumed to be the same for all the receivers. To eliminate this error source the "ionosphere free" linear combination, L_3, must be used:

$$L_3 = \frac{1}{f_1^2 - f_2^2}(f_1^2 L_1 - f_2^2 L_2)$$

where L_1 and L_2 represent the phase observables expressed in meters (Rothacher et. al., 1996). Because of this it is an absolute requirement that dual-frequency receivers are used.

- The baseline error induced by errors in the orbits of the satellites are proportional to the length of the baseline. Therefore the quality of the ephemeris must be very good when long baselines are involved. Broadcast ephemeris are usually not good enough. When the highest accuracy is required, it is an advantage to use precise ephemeris. According to Rothacher et. al. (1996, p. 104), the accuracy of the CODE orbits, which are available from the SWEPOS server, are within 10 cm. In all the tests presented in chapter four, precise orbits from CODE are used.

- The visibility of the satellites should be good, since it is much harder to repair cycle slips, caused by disturbing trees and other obstacles, when the baselines become longer. Therefore, the line of sight of the new point should be almost undisturbed at elevation angles larger than 15 degrees over the horizon. At the SWEPOS stations there are no obstructions above 10 degrees.

- The accuracy of a triangulation network, such as RT 90, is generally bad over long distances. Therefore, it is a requirement to work in SWEREF 93, when long baselines are used. In what follows all the results are evaluated directly in SWEREF 93. One has to be aware, though, that as soon as the estimated position is transformed to e.g. RT 90, a loss of accuracy will result.

3.2 Software algorithms

There is a big amount of processing softwares, which have different basic principles and more or less advanced models for the calculation. One large difference between different softwares is how the carrier phase is treated. Most of them use double differences, like the Bernese and the Geotracer GPS softwares, while others use the raw phase observation. One example of the latter kind is the Gipsy software, which is of the zero difference type.

Furthermore, the software can be of the *multi station type*, which can handle two or more stations in one simultaneous adjustment, or of the *baseline type*, that only adjusts one baseline at a time. In the latter case a network adjustment has to be performed after all the baselines have been adjusted separately. A baseline software is of a more simple construction and demands less memory space in the computer. One advantage with a multi station software is that the correlation between different baselines is taken into account, which is not the case in the baseline counterpart.

In this paper two different programs are evaluated and compared, namely the Bernese and the Geotracer GPS software. Below a brief presentation is given of these two softwares.

<u>Bernese GPS Software, version 4.0</u>

This software is developed by the Astronomical Institute at the University of Bern in Switzerland. It is of the multi station type and was developed as a tool for highest accuracy requirements. It is mostly used for scientific applications and not by the common user. It has no graphic interface. The processing parameters are set in so called panels, which may be combined for almost any type of static GPS application. What is discussed later on in this report relates to how the Bernese software is used for this kind of purpose.

Geotracer GPS Software, version 2.25

Geotracer is a baseline software from Geotronics. The processing parts are developed by Terrasat and are used in some other baseline softwares as well. Geotracer consists of three main modules; the baseline processing module, the network adjustment module and the project planning module. It has a graphic and user-friendly interface where you can see your network and for example select a baseline by "clicking" on it. The mathematical algorithms are more simple and there are not at all as many parameters that can be changed as in the Bernese software. This makes it more simple for "non-professionals" to handle.

There are many differences between the two softwares. Below the most important similarities and differences are summarised.

Similarities

- Uses double differences.
- Uses triple differences to search for and repair cycle slips.
- Ionosphere-free linear combination can be used for long baselines.
- Precise ephemeris can be used. In this case from the Centre of Orbit Determination in Europe (CODE).

Differences

- Different techniques are used to solve ambiguities (section 3.2.1).
- The way of modelling the forces that influence the satellites (section 3.2.2).
- The Bernese software can use more advanced antenna models (section 3.3.3).

- The Bernese software can take care of a larger part of the tropospheric path delay (section 3.4).

3.2.1 Ambiguity resolution

It is difficult to resolve the ambiguities when long baselines are used. This is mostly due to the large influence of the ionosphere (cf. 3.1).

In *the Bernese GPS software*, a number of different methods can be used to resolve the ambiguities. For long baselines one method is to first solve the wide-lane ambiguity (n_{5kl}^{ij}), which is rather simple because of its long wavelength. When the phase observables are expressed in meters the observation equation looks like this:

$$L_{5kl}^{ij} = \rho_{kl}^{ij} + \frac{c}{f_1 - f_2} n_{5kl}^{ij}$$

The wide-lane ambiguities can then be used to solve the L1 and L2 ambiguities by means of the ionospheric-free linear combination L3 (cf. 3.1), with the following observation equation:

$$L_{3kl}^{ij} = \rho_{kl}^{ij} + c\frac{f_2}{f_1^2 - f_2^2} n_{5kl}^{ij} + \frac{c}{f_1 + f_2} n_{1kl}^{ij}$$

It is not possible to solve the ambiguities directly by means of the ionosphere-free linear combination. L_5 has to be solved first.

Thus, the ambiguity resolution is made in two steps. For each step one ambiguity at a time is solved by means of the so called Sigma strategy (Rothacher et al., 1996, p.203), which means that the estimated real-value for the ambiguity must have one integer within a certain confidence interval. Otherwise it is not resolved.

Accordingly, not all ambiguities need to be solved, just the ones that can be solved in a safe way. Because of the ionospheric path delay this is a big advantage when you have long baselines.

In *the Geotracer software*, the ambiguities are solved with a FARA-like method (Fast Ambiguity Resolution Approach). This means that all the ambiguities are solved simultaneously by testing different combinations of integers around the real value estimates. One advantage of this method is that it is very fast. One drawback is that either all or none of the ambiguities are solved. The Geotracer software is not adapted to solve ambiguities for long baselines (30 - 40 km or longer), which means that you are forced to use a float solution where the ionosphere-free linear combination is used. Accordingly float solutions were used in the Geotracer software in this investigation. Fix and float solutions differ very little when longer observation times are used (Rothacher et.al., 1996, fig. 15.1). The shorter the observation time, the worse the float solution becomes. One question is how long the observation time has to be to get a float solution that is good and reliable. Investigations regarding this are found in section 4.5.

3.2.2 Ephemeris

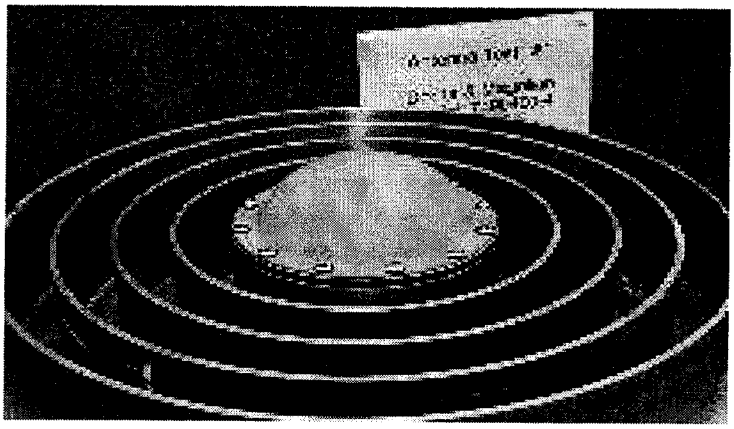
The Bernese software uses more advanced models than Geotracer for the forces that act on the satellite. This makes it possible to calculate the orbit of the satellite in a better way. In "Precise Ephemeris" there is only one observation every 15 minutes. The processing software calculates an orbit that fits to these observations as good as possible. This can be made in a better way in the Bernese software, but this difference is not that important in this case (Ågren, 1997c).

3.3 Antennas

When a new point is determined relative to the SWEPOS-stations, it is important to be aware of the influence of antenna related errors, which is one of the largest error sources today. In the tests presented in chapter four, two different antenna types were used at the new point, namely Dorne Margolin T, which is also used at SWEPOS, and Ashtech Geodetic New. In section 3.3.1 and 3.3.2 these antennas are presented. Section 3.3.3 contains a general discussion of antenna related errors and of the phase centre variations (PCV) of the GPS antenna.

3.3.1 Dorne Margolin T

Dorne Margolin T is manufactured by Turbo Rouge. It is an antenna of the type Choke Ring which means that there are some steel rings on the ground plane around the antenna centre. This antenna is considered to be very good and it is used as reference antenna in the antenna calibration made by Rothacher and Mader (1996). This antenna type is also used at the SWEPOS-stations.



Dorne Margolin T

3.3.2 Ashtech Geodetic New

One of the largest producers of antennas is Ashtech. The type that was included in this investigation is the "Ashtech Geodetic III" with the model number 700718.A. This antenna is also known as "Ashtech Geodetic New" or "The Whopper". It has a 14.5 inch groundplane and includes a little compass.

Ashtech Geodetic New

3.3.3 Antenna related errors and the phase centre variations of the antenna

The GPS signals reaches the antenna from different directions and the position of the antenna phase centre depends on these directions. This dependency on the direction is called the phase centre variations (PCV) of the antenna. The location of the electric centre is usually different for different types of antennas, but it can also differ for different examples of the same type. The centre for a given antenna type differs between L1 and L2 and for satellites on different azimuths and latitudes. The phase centre variations for one antenna can be modelled by an offset vector relative to the antenna reference point (ARP). This offset vector is used to specify the mean antenna phase centre for L1 and L2. In addition to these, parameters can be set to model the dependence on the elevation and azimuth (Rothacher et.al., 1995).

There are some differences between the Bernese software and Geotracer in how the phase centre variations of the antenna can be modelled. In *the Bernese software* there is a possibility to use both the mean value offset vectors and parameters which describe azimuth and elevation dependencies of the antenna. The following model is used both for L1 and L2, where α is the azimuth and z the zenith distance of a satellite seen from a certain station (Rothacher et. al., 1996, Ch. 17.2)

$$\Delta\phi(\alpha,z)=\Delta\phi'(\alpha,z)-\Delta\phi_0+\Delta r\cdot e$$

$\Delta\phi$ is the correction which is added to the distance between the satellite and the receiver in the observation equation for the zero difference. The partially linear function $\Delta\phi'$ models the elevation and azimuth dependency of the antenna and this is the one to be estimated for different antennas. The vector Δr defines the position of the mean antenna phase centre offset for the current frequency with respect to the antenna reference point (ARP) and the vector e denotes the unit vector in the direction antenna to satellite. $\Delta\phi_0$ is an arbitrary constant which is eliminated when double differences are formed.

In *the Geotracer software* it is only possible to model the phase centre offsets for L1 and L2 in the vertical component. These offsets have to be specified in the GPS.INI file.

When two antennas with different phase centre variations are mixed, an error in the relative position will result. This error is usually larger in the vertical than in the plane components. A difference in the elevation dependent phase centre variations between the two antennas may also disturb the estimation of zenith tropospheric parameters (see section 3.4). As can be seen in Ågren (1997a) this may result in a systematic error in the height component, which can be as large as 10 cm (cf. the results in section 4.3).

The best way to proceed is to use the same antenna type at all stations, because the error caused by different PCV disappears if the two samples of the type in question are similar enough. However, if you do not use the same type of antenna, it is a good idea to calibrate the two types relative to each other. It is common that values published by the antenna manufacturers are not compatible with each other. To achieve a good height it is therefore better to use the result from an antenna calibration. The question is how good result you get with a calibrated antenna, compared to when the same type of antennas are used. There are published antenna models, for example Rothacher & Mader (1996). You can either use one of these, or do your own antenna calibration. In section 4.3 some tests are presented where both these strategies are tested. In this case the Ashtech Geodetic New antenna is mixed with the Dorne Margolin T antennas at the SWEPOS station. There is also a description of how an antenna calibration can be performed.

3.4 The Troposphere

The lowest part of the atmosphere, up to about 40 km of height, is called the troposphere. The propagation of the radio waves in the troposphere is, unlike in the ionosphere, frequency independent. Consequently, the tropospheric refraction can not be eliminated by dual frequency combinations.

The troposphere can be divided into a dry and a wet component. The dry part results from the dry atmosphere. The wet part is the one nearest the earth surface (<11 km) and results from the water vapour in the atmosphere. About 90% of the tropospheric refraction arise from the dry part and about 10% from the wet part.

The tropospheric path delay can be described in the following way:

$$\Delta^{Trop} = 10^{-6}\int N_{dry}^{Trop}\,ds + 10^{-6}\int N_{wet}^{Trop}\,ds$$

$N_{dry/wet}^{Trop}$ = refractivity for the dry and wet part respectively.

Most of the tropospheric path delay can be calculated by a standard tropospheric model, e.g. Saastamoinen or Hopfield (Hoffmann-Wellenhof, 1994). They use standard values for temperature, atmospheric pressure and content of water vapour. This is mostly better than to observe these quantities by yourself. The part that is left, not accounted for by the standard model, causes two types of errors; error in scale and error in relative height. This part is mostly caused by the wet part of the atmosphere and varies with time and place. One could say that it varies in the same way that the weather varies. The risk of having a different amount of water vapour is, of course, increased the longer baseline you have. It can be neglected if the baseline is shorter than five kilometres. With baselines from some tenths of kilometres and more, the uncorrected part of the tropospheric path delay can give a height error of several centimetres.

In *the Bernese software*, zenith tropospheric parameters may be estimated in the least square adjustment to model the difference between the standard model and the real atmosphere. One parameter is introduced , for example every third hour, for all the stations involved. Two stations for 24 hours means 16 parameters. A great deal of both the errors above can be reduced in this way. To estimate a zenith tropospheric parameter means that one parameter is used to describe the delay in the zenith direction. After this a so called mapping function is used to describe the delay for satellites at other elevations. (Rothacher et.al., 1996)

Mapping function; $f(z) = \frac{1}{\cos z}$ (z = zenith distance)

One disadvantage of this method is that the estimation easy gets disturbed by elevation dependent errors caused by different antenna types or radomes etc. To make it possible to use zenith tropospheric parameters, the supply of a good antenna model is very important when different types of antennas are mixed. Otherwise there is a risk of getting a systematic height error.

In *the Geotracer software* one can estimate a parameter called "tropospheric scaling". As was mentioned above, the part of the tropospheric error that is left after the standard model has been applied, induces an error in the scale of the baseline and in the relative height of the involved stations. Thus, in *Geotracer* you can introduce a scalefactor into the adjustment, which may reduce a big part of the scale error, but not the relative height error. This means that the reliability of the height component for the baseline length in question should be questioned when this method is used. The scale error caused by the troposphere becomes very small in our case, which means that the use of this option is limited for this investigation (Ågren J, 1997c).

The influence of the tropospheric errors have been studied and are presented in section 4.4.

3.5 Method

There are many further factors that may affect the result when new points are determined in SWEREF 93 relative to the SWEPOS-stations. Some of them have been tested in this investigation and are briefly presented below.

3.5.1 Observation time

To get a good solution with the current length of the baselines it is very important to observe the same satellites for a long time. Some of the error sources described above are also likely to be reduced when the observation time becomes longer, for instance the influence of the troposphere. For a long observation time the difference in the troposphere between the beginning and the end of the session can be quite big, and the result arises from a "mean troposphere". If the observation time is shorter, the troposphere may influence the result more. A similar effect results if different antenna types are mixed and no advanced antenna model is used, but only the vertical offset for L1 and L2 (Geotracer). The vertical offsets are usually estimated during at least 24 hours, using all possible satellite configurations. For a shorter observation time only some of the configurations are present, which will increase the error. All this means that the observation time needed depends on how different error sources can be taken care of in the software. Therefore, it can be suspected that the observation time that is necessary is shorter in the Bernese software than in Geotracer.

Another circumstance, which supports the fact that longer observation time is needed when Geotracer is used, is that this software only is able to produce float solutions for long baselines. The difference between the fix and the float solutions becomes smaller when longer observation time is used (Rothacher et. al., 1996, fig. 15.1).

To have short observation times means that the measurements and processing get faster. The question is how long observation time you need to get a reliable solution. This is studied and discussed in section 4.5.

3.5.2 Number of reference stations

The position of a point is determined relative to a number of reference stations. When a new point is determined in SWEREF 93 by the National Land Survey, eight SWEPOS stations are used in the Bernese software (see section 2.2). One reason for the large number of stations in this case is that the reliability is increased. It is thus possible to detect problems with specific stations. Here it should also be mentioned that the accuracy does not depend very much on the baseline length, when the baselines are longer than 50 -100 km (Ågren, 1997c).

Theoretically, at least three stations are required to eliminate the major part of the scale and rotation errors in the network, which may be caused by bad ephemeris or arise from the fact that SWEREF 93 not quite agrees with ITRF 94, in which the precise ephemeris are given.

For an ordinary user, who owns a standard equipment, it is an advantage if fewer reference stations have to be used, because this makes the processing more simple. Therefore, tests have been made of how the accuracy depends on the number of reference stations in the case when the Geotracer software is used, see section 4.7.

3.5.3 Adjustment

In the Geotracer software there is the possibility to either do an adjustment were all SWEPOS-stations are held fixed or a free adjustment with a following Helmert transformation. Results of these two adjustment methods are presented and compared in section 4.6.

4 PRACTICAL TESTS

In this chapter the results from a number of tests are presented and evaluated. As was mentioned in the introduction, the purpose of this work is to compare one standard equipment with a state-of-the-art equipment and to investigate how the result depends on which method that is used and on how the equipment in question can handle different error sources (cf. chapter 1). As standard equipment an Ashtech Geodetic New antenna and the Geotracer GPS software 2.25 were chosen. The state-of-the-art equipment consisted of a Dorne Margolin T antenna and the Bernese GPS software 4.0. The tests were mostly performed in both of the softwares.

The tests were made mainly to answer the following questions.

- *Comparison of the softwares.* How does the result differ when the processing is made in the Bernese and the Geotracer softwares respectively ?
- *Antennas.* How important is it to use the same antenna type as is used at the SWEPOS stations? How is the result affected if different antenna types are mixed? In what extent is it possible to overcome this problem by antenna calibration ?
- *Tropospheric refraction.* What influence does the troposphere have on the estimated height component ? How important is it to use a software that is able to estimate zenith tropospheric parameters ?
- *Observation time.* How short observation time can you have and still get a reliable and accurate solution ? How does the observation time needed depend on how different error sources are treated in the software and on if a fix (Bernese) or a float solution (Geotracer) is used ?
- *Adjustment.* How does an adjustment with all SWEPOS-station fixed differ from a free adjustment followed by a Helmert transformation ? (Only Geotracer.)

- *Number of reference stations*. How does the accuracy depend on the number of reference stations used ? (Only Geotracer.)

4.1 Test procedure

Data from two GPS **campaigns** were used for all the tests.

1. **Session 3380 and 3390**. Performed at the point SIB1 at Mårtsbo test field between 9.48 A.M. on the third of December and 9.48 A.M. on the fifth of December 1996. A Dorne Margolin T (DMT) antenna and an Ashtech Z-XII receiver were used.
2. **Session 3410 and 3420**. Performed at the point SIB1 at Mårtsbo test field between 10.34 A.M. on the sixth of December and 10.34 A.M. on the eighth of December 1996. An Ashtech Geodetic New (AGN) antenna and an Ashtech Z-XII receiver were used.

In both the campaigns, the centring was made with an optical precision plummet to minimise the centring errors. The observation interval was 30 seconds and the cut off angle 15 degrees.

In **the Bernese software** the processing was made in the same way as when new points are determined in SWEREF 93 by the National Land Survey (cf. section 2.2), just changing the parameters for the current topic. The eight closest SWEPOS-stations, with the exception of Mårtsbo were used in all tests.

As mentioned in section 3.2.1, **the Geotracer software** is not suited to solve ambiguities for long baselines, which means that a float solution with the ionosphere-free linear combination (Lc) had to be used. The processing was made with precise ephemeris and with the six closest SWEPOS-stations, except for Mårtsbo (when nothing else is mentioned, cf. section 4.7). A network adjustment was performed with the SWEPOS stations held fixed (when nothing else is mentioned, cf. section 4.6). For the weighting the estimated 3*3 variance-covariance matrix of the baseline processing was used. All the processing in the Geotracer were made this way, only changing the parameters that were interesting for the current test. When nothing is mentioned in the description of a particular test, it is understood that the processing has been made in the way described here.

Evaluation of the results

It is difficult to evaluate the accuracy of points determined by the GPS-technique. The estimated standard deviations from the least square adjustment are as a rule too optimistic, which can be explained by the presence of systematic errors. This can also be expressed by saying that the observations usually are correlated with each other and not statistically independent, as is presupposed by the least square theory. Thus, it is not suitable to use the estimated standard deviations from the least square adjustment to evaluate the accuracy of different methods.

The best way to evaluate the accuracy in this investigation is to use a reference point which has been determined with a more accurate method, than the ones studied. In our case we used the point SIB 1 situated about 100 meters from the SWEPOS-station in Mårtsbo. Because this point participates in the precision network in Mårtsbo, it is determined at the mm-level (1σ) relative to the SWEPOS-station in Mårtsbo. Taking the internal accuracy of SWEPOS into account (cf. section 2.1), the following accuracy (1σ) in SWEREF 93 can be estimated for SIB 1 relative to the surrounding SWEPOS stations (not Mårtsbo):

North; 3 mm

East; 3 mm

Up; 4 mm

The following mathematical expressions were used to evaluate the results, where the SWEREF 93 coordinates for the SIB 1 station are designated as true.

Deviation (ε)	$= L - L_{true}$	(test value - true value)
RMS	$= \sqrt{\frac{\Sigma\varepsilon^2}{n}}$	(Root Mean Square)
Std. dev.	$= \sqrt{\frac{\Sigma(L - \bar{L})^2}{n-1}}$	(Standard deviation)
Mean	$= \frac{\Sigma\varepsilon_i}{n}$	(mean deviation from true value)
Max	$= \max(abs(\varepsilon))$	(maximum absolute deviation from true value)

When the result from 24 hour sessions are presented, only the deviations (ε) in each component are given.

When SIB1 is determined relative to the surrounding SWEPOS stations, the difference between the known and the estimated coordinates for SIB1 will be influenced both by errors in the SWEREF 93 coordinates for SIB 1 and by errors in the method used to determine this point. Both these errors will be reflected in the RMS-values above.

As can be seen above, the coordinates for the SIB 1 station have been designated as true, even though this is not the case. However, if the technique to be evaluated has significantly larger RMS values than the estimated accuracy for SIB 1 above, this assumption will be valid for all practical purposes. One has to be aware, though, that if two methods have very small RMS-values it is not possible to say which one is most correct.

One circumstance that one should have in mind when evaluating this investigation is the limited data selection. These tests should therefore be seen as a pointer toward a tenable strategy, but it is difficult to draw any statistically reliable conclusions.

4.2 Comparison Bernese / Geotracer

To see if there are any differences in the results between the two softwares, two 24-hour sessions were processed in both the softwares. Data from the campaign with a Dorne Margolin T antenna (campaign 1 in section 4.1) were used to avoid antenna related errors. The processing was made with tropospheric parameters relative to eight SWEPOS-stations in the Bernese software. In the Geotracer software, six stations were used and, as was mentioned in section 3.2.1, this software is only able to produce a float solution for the current baseline lengths.

Unit: [mm]	Deviation from known coordinates		
Session	Horizontal - North	Horizontal - East	Vertical
	Bernese		
3380	2	0	0
3390	4	-1	2
	Geotracer		
3380	7	6	5
3390	8	-2	3

Table 4.21 DMT. 24-hour sessions in the Bernese and the Geotracer softwares respectively.

The results in table 4.21 are slightly better with Bernese than with Geotracer, but they indicate that the results from the two softwares seem to be comparable. It is a little bit surprising that the vertical component in the results from Geotracer is that good, considering the influence of the troposphere. This indicates that the tropospheric conditions were very favourable during the campaign in question. For some rather rare days the influence for a 24 hours session may be as large as 5 to 10 cm when no zenith tropospheric parameters are used (Ågren. 1997 c). More tests regarding the troposphere can be found in section 4.4 and 4.5. From the results in table 4.21 it can also be seen that the plane components are very good in Geotracer, even though a float solution had to be used. However, as was mentioned in section 3.2.1, the results with a float solution will probably be worse when shorter observation time is used, compared to when a fix solution is used. Tests about this are presented in section 4.5.

4.3 Mixing of antennas and antenna calibration

The meaning of the tests presented in this section is to find out what happens if you mix antennas of different types. As was said in section 3.3.3, the best thing to do is to apply an antenna model from a calibration, where the different antennas have been calibrated relative to each other. There are published antenna models, such as Rothacher and Mader (1996). It is also possible to make your own antenna calibration. To see how these two approaches differ from each other, an antenna calibration was performed, where the current antenna type (AGN) was calibrated relative to the antenna type that is used at the SWEPOS stations (DMT). These antenna types were presented in section 3.3. After that it was tested whether the result differed between the model just estimated and the model from Rothacher and Mader.

Antenna calibration

There are two independent methods of making an antenna calibration (Rothacher et.al., 1995):

- *The anechoic chamber test*, where the phase pattern of a single GPS antenna is measured. One transmitting antenna is kept fixed while the antenna that is going to be calibrated is mounted on a positioner and rotated around two independent axes. The test antenna gets signals for various azimuth values from -90 to +90 degrees. The location of the centre of rotation with respect to ARP (Antenna Reference Point) can then be determined.
- *Determination of phase centre corrections from processing GPS data* taken on short baselines. A large number of antennas can be calibrated at the same time on a test field.

The latter of these methods was used in the antenna calibration campaign on the 16-17 of January 1997, which was made on a test field with points very accurately determined relative to each other in the horizontal components. This test field lies about 100 m from the point SIB1. Two Ashtech Geodetic New and one Dorne Margolin T were placed on tripods about ten meters from each other. The height differences between the points on the ground were levelled and the centring was made with newly calibrated tribrachs. Three observers measured the antenna heights independently of each other and the mean values were calculated. The processing was performed in the Bernese GPS software. The Dorne Margolin T antenna, with the model that is usually used in the Bernese software (Rothacher & Mader, 1996), was used as reference antenna.

First, the vertical and plane components in the offset vector (Δr) for the Ashtech antenna type were estimated relative to the reference antenna. Then parameters for the elevation dependent phase centre variations were estimated. A partially linear function $\Delta\phi'(z)$ (only elevation dependent, not azimuth dependent) was used in this step, see section 3.3.3. This estimation was performed by using the former estimated offset vector.

The antenna model that was made could now be compared with the Ashtech Geodetic New antenna model made by Rothacher and Mader. They were named as follows:

AM1	Antenna Model 1. Rothacher and Mader. Both phase centre offsets and parameters for the elevation dependence.
AM2	Antenna Model 2. Rothacher and Mader. Only phase centre offsets.
AM3	Antenna Model 3. Estimated in this investigation. Both phase centre offsets and parameters for the elevation dependence.
AM4	Antenna Model 4. Estimated in this investigation. Only phase centre offsets.

Antenna comparison

To find out the differences between the antenna models above they were tested in the two softwares. In these tests a different sample of the same model (Ashtech Geodetic New) was used compared to the ones utilised in the calibration.

Bernese

Two 24 hour sessions with the Ashtech Geodetic New antenna (campaign 2, section 4.1) were processed with each antenna model in the Bernese GPS software relative to eight SWEPOS stations (equipped with DMT:s), using tropospheric parameters and fix solutions.

Deviation from known coordinates				
Unit: [mm]	Session	Horizontal North	Horizontal East	Vertical
AM1	3410	-10	-3	35
	3420	-10	-2	32
AM2	3410	-10	-3	83
	3420	-10	-2	81
AM3	3410	-5	-1	5
	3420	-5	0	2
AM4	3410	-5	-1	102
	3420	-5	0	100

Table 4.31 Bernese, AGN, 24-hour sessions with different antenna models.

The following can be noticed from the results in table 4.31:

- The antenna models which only have offset values, AM2 and AM4, gives vertical values that exceed the "true" height with up to 10 centimetres. As was mentioned in section 3.3.3, the same thing could be seen in earlier investigations made by the National Land Survey. In Ågren (1997a) this effect is studied more thoroughly.

- AM1, which should be very good, shows vertical deviations that are 30 mm higher than with AM3. This indicates that the estimated model is better than the model by Rothacher & Mader in this case. The reason for this is unknown. The AM1 model is also a little bit worse in the plane coordinates.
- The best result is achieved when the AM3 model is used. In this case the result is comparable to when the Dorne Margolin T antenna is used (see table 4.21).

Geotracer

The same sessions as in the previous test were then processed in the Geotracer software with the vertical offsets from AM1 and AM3 respectively. As mentioned in section 3.3.3, you are only able to model the phase centre offsets for L1 and L2 in the vertical component. The processing was made relative to six SWEPOS stations (not Mårtsbo), equipped with DMT antennas (cf. chapter 4.1).

Some problems occurred when sessions that passed over a change of GPS week were processed. That is why only the first half of session 3420 was processed.

Deviation from known coordinates				
Unit: [mm]	Session	Horizontal - North	Horizontal - East	Vertical
AM1 (Offset param.)	3410	11	10	-30
	3420 (12h)	4	15	-42
AM3 (Offset param.)	3410	11	10	-11
	3420 (12h)	4	15	-23

Table 4.32 Geotracer, AGN, 24-hour sessions with different antenna models.

Of course the deviation in the plane coordinates are the same for both the antenna models (only vertical offsets). If the result in table 4.32 is compared with the result in the Dorne Margolin T case (see table 4.21), it can bee seen that the plane components are significantly worse when the Ashtech Geodetic New antenna is used. The vertical components are a little bit closer to the "known" coordinates with AM3. However, it is not possible to expect a result as good as with the Bernese software, since no zenith tropospheric parameters can be estimated in Geotracer (cf. section 4.4). Instead the results in table 4.32 should be compared to the case when no zenith tropospheric parameters are estimated, see table 4.41. If table 4.32 and 4.41 (AGN, NO Trop. par.) are studied it can be seen that the result seems a little bit worse in the Geotracer case, which is probably due to the simpler antenna model, where no parameters for the elevation dependence of the phase centre are used. This difference can, however, be explained by other factors than the antenna model.

From the results above the following conclusions can be drawn, keeping in mind that a rather small data selection was used in the tests:

- It is very important to use a good antenna model, with parameters that describe the elevation dependence of the phase centre, if zenith tropospheric parameters are to be estimated in a successful way.
- In this test, the model from the antenna calibration performed, yielded a very good result. But the fact that the model from Rothacher and Mader are rather bad, shows that there are problems in making an antenna calibration in a reliable way. There is always the risk that the calibration is disturbed by multipath and other errors, which will result in a systematic error when the antenna model is used in practice. The most reliable way to proceed is to use the same antenna type at all involved stations.
- The result becomes better with an advanced antenna model (Bernese) compared to a simpler one (Geotracer). For instance, in the Bernese software the plane components can be calibrated and modelled, but this is not the case in Geotracer. In the latter software the plane coordinates are clearly worse when

the Ashtech Geodetic New antenna is used, compared to the Dorne Margolin T case (no mixing of antennas). This shows that also the plane coordinates can be affected when different antenna types are mixed.

If different antenna types are mixed and shorter observation times are used, the errors are probable to be larger if not an advanced antenna model is used (cf. section 3.5.1). Tests with shorter observation times are presented and analysed in section 4.5.

Because AM3 gave the best result in the tests above, it was decided to use this model in the following investigations. In the Geotracer software only the vertical offset components are used in what follows.

4.4 The troposphere

In section 3.3 the troposphere was treated from a theoretical perspective. In this chapter some tests are presented, which were made to find out how the vertical component is affected when the processing is made with and without zenith tropospheric parameters in the Bernese software. As was mentioned in section 3.3, the estimation of zenith tropospheric parameters is made to reduce both the scale error and the relative height error induced by the troposphere. In the Geotracer software, it is only possible to estimate a scale factor, using the option "tropospheric scaling", which will only reduce the scale error, but not the relative height error. A minor test regarding the latter approach is also presented in this section (Geotracer).

Only tests made with long observation times will be presented in this section. If 24 hour sessions are used, the difference in the troposphere between the beginning and the end of the session can be quite big, and the results arise from a "mean troposphere". If the observation time is shorter, the troposphere may influence the result more. Tests regarding shorter observation times are presented in section 4.5.

Bernese

These tests were performed both with a Dorne Margolin T and an Ashtech Geodetic New antenna. The DMT data were taken from session 3380 and 3390 (cf. campaign 1, section 4.1). The processing was performed in the Bernese software in an ordinary way, first with tropospheric parameters and then without. As a comparison the same processing was made with session 3410 and 3420 where an AGN antenna was used (cf. campaign 2, section 4.1). The processing was performed with the antenna model AM3, which has been shown to be very good in section 4.3. Table 4.41 shows the results from processing with and without tropospheric parameters respectively.

Unit: [mm]		Deviation from known coordinates			
Antenna (ant.mod)	Trop. param.	Session	Horizontal North	Horizontal East	Vertical
DMT	YES	3380	2	0	0
		3390	4	-1	2
	NO	3380	2	0	-4
		3390	2	-1	-15
AGN (AM3)	YES	3410	-5	-1	5
		3420	-5	0	2
	NO	3410	-7	-1	-4
		3420	-5	-1	12

Table 4.41 Bernese, DMT and AGN, 24-hour sessions with and without tropospheric parameters.

From the results in table 4.41, one can see that the vertical component differs up to 17 mm depending on if zenith tropospheric parameters are estimated or not. The results are clearly better in the former case. As expected, the horizontal components are practically the same in the two cases. It can further be seen that the results are very similar with the AGN as with the DMT antenna, which confirms that the used antenna model is very good.

From this test, we can only conclude that the result becomes better when zenith tropospheric parameters are estimated, compared to when only the standard model is used. It is not possible to say how large the influence of the troposphere is when no tropospheric parameters are estimated. We can only say that the influence of the troposphere apparently is rather small at these four 24-hour sessions. Other days the height error induced by the troposphere has been found to be much larger (Ågren, 1997c) when no tropospheric parameters are used.

Geotracer and Dorne Margolin T

This test was made to see how the result is affected when the ”tropospheric scaling” option is used in Geotracer. Data from the DMT antenna sessions 3380 and 3390 (cf. section 4.1) were used to avoid antenna related errors. The results in table 4.42 come from 8-hour float solutions. To be able to solve the normal equation system when a scale factor is estimated, weights must be put on the scale parameter. In Geotracer this is done by giving a reasonably large value of the error in the standard model (see section 3.4) in percent. Considering that the total influence of the troposphere is as large as approximately 2,0-2,5 meters in the zenith direction, a value of 2 % was chosen in the tests presented in table 4.42.

Unit: [mm]	Horizontal - North				Horizontal - East				Vertical			
Tropospheric scaling	RMS	Std. dev.	Mean	Max	RMS	Std dev.	Mean	Max	RMS	Std. dev.	Mean	Max
NO	5	1	4	6	6	5	-3	13	18	19	-4	37
YES (2 %)	6	1	6	8	5	5	-2	8	21	23	2	39

Table 4.42 Geotracer, DMT, 8-hour sessions.

In this test it is not possible to see any significant difference between if a scale factor is estimated or not. As was mentioned in section 3.4, the most problematic error in this context is the relative height error, which is not likely to be reduced in a significant way by the estimation of a scale factor.

4.5 Observation time

The tests presented in this section were meant to show how short observation time you can have and still get a good and reliable solution (cf. section 3.5.1). Another question, which the tests were made to answer, is how the observation time needed depends on how different error sources are handled in the software that is used. The result is for instance probable to be affected more by the troposphere and antenna related errors if a simpler software (Geotracer) is used, compared to if a more advanced one is utilised (Bernese). Another factor that will affect the choice of observation time, is whether the software in question can produce a fix solution at the current baseline length. As has been pointed out many times above, only float solutions can be produced by Geotracer in this context. The difference between a float and a fix solution becomes larger when the observation time gets shorter (see section 3.2.1 and 3.5.1).

The test have been performed both with the Dorne Margolin T (DMT) and the Ashtech Geodetic New (AGN), using both the Bernese and the Geotracer softwares. The observations with a DMT antenna were taken from the two 24-hour sessions at the point SIB1 between the 3rd and 5th of December 1996 (cf. campaign 1, section 4.1), and the AGN antenna observations were taken from the data between the 6th and 8th in the same month (cf. campaign 2, section 4.1). These sessions were then split up into eight-, four-, two- and one-hour sessions.

Bernese

The processing was performed in the Bernese GPS software both with and without tropospheric parameters respectively. As usual, eight SWEPOS stations equipped with DMT antennas were used (not Mårtsbo).

Unit: [mm]			Horizontal - North				Horizontal - East				Vertical			
Antenna (ant.mod)	Trop. param.	Obs. time [hours]	RMS	Std. dev.	Mean	Max	RMS	Std dev.	Mean	Max	RMS	Std. dev.	Mean	Max
DMT	YES	**8**	3	2	3	6	1	1	-1	2	4	4	0	6
		4	3	2	3	6	2	2	-1	3	5	7	0	10
		2	4	2	3	8	2	1	-1	4	9	9	-1	22
		1	6	5	3	14	14	14	0	60	26	26	-2	113
DMT	NO	**8**	3	2	2	5	1	1	-1	2	12	7	-10	22
		4	4	2	3	7	2	2	-1	3	14	12	-11	31
		2	4	3	3	10	2	1	-1	4	15	11	-11	34
AGN (AM3)	YES	**8**	6	1	-6	7	1	1	-1	3	5	3	4	7
		4	6	1	-5	7	2	2	-1	3	7	7	4	14
		2	5	2	-5	8	3	3	-1	13	8	9	1	19
AGN (AM3)	NO	**8**	5	1	-5	7	2	1	-2	3	17	19	3	32
		4	5	2	-5	7	2	1	-2	4	19	20	2	34
		2	5	2	-5	8	4	3	-2	13	19	20	1	37

Table 4.51 Processing in the Bernese software with different session lengths.

The results in table 4.51 shows that the results in the horizontal components are very good even for such short observation times as 2 hours, with RMS values less or around 5 mm. The maximum errors are mostly below 10 mm.

In the vertical component, the result is very good for the 8, 4 and 2 hour sessions when zenith tropospheric parameters are estimated. The RMS-values are below 10 mm, although the maximum deviations becomes larger, the shorter the observation time gets. In the cases when no tropospheric parameters are used, the RMS values increase to 15 - 20 mm. The maximum values also become larger, with a maximum of 37 mm. It must be kept in mind, though, that the tropospheric conditions were quite nice during the time span used for all these tests (see section

4.4). Other days the height component might be much worse in the case no zenith tropospheric parameters are estimated.

For the one hour sessions the quality of the results decreases. However, the large maximum deviations in table 4.51, occur during time spans with only four satellites and high PDoP values. In these bad intervals, only a few of the ambiguities could be solved, which explains the large maximum deviations.

In table 4.51 it can also be seen that the results are excellent when the AGN antenna is used. This confirms the conclusion in section 4.3 that the model resulting from the antenna calibration is very good.

At large, the results presented in table 4.51 are very promising. If one uses a Dorne Margolin T antenna or another antenna type, which has been very carefully calibrated, these tests show that only two hours of observation might be enough to achieve a very good solution, with RMS values below 10 mm in all three components. This, however, presupposes that an advanced software like the Bernese is used, which has the possibility to estimate tropospheric parameters and to use advanced antenna models. One further requirement is of course that the antenna model that is used is reliable.

Here it must be pointed out that these conclusions have been drawn from only 96 hours of observations. To confirm or refute these results, more extensive tests have to be made under various conditions.

Geotracer

The Geotracer software is not able to produce a fix solution with this length of the baselines (see section 3.2.1). Accordingly the results in table 4.52 are float solutions, processed in the way described in section 4.1:

Unit: [mm]			Horizontal - North				Horizontal - East				Vertical			
Antenna (ant.mod)	Trop. param.	Obs. time [hours]	RMS	Std. dev.	Mean	Max	RMS	Std dev.	Mean	Max	RMS	Std. dev.	Mean	Max
DMT	NO	**8**	5	1	4	6	6	5	-3	13	18	19	-4	37
		4	5	2	5	8	7	7	-3	12	18	19	-1	36
		2	8	6	5	18	15	15	-1	25	28	29	0	62
AGN	NO	**8**	8	9	-2	10	10	10	-4	15	30	34	-6	37
(Offset param. From AM3.)		**4**	7	8	-1	18	16	17	3	29	29	30	-9	57

Table 4.52 Processing in the Geotracer software with different session lengths.

The first thing that can be noticed in table 4.52 is that the results are significantly better when the Dorne Margolin T antenna is used. This conclusion is most valid in the horizontal component, since the influence of the troposphere is a likely reason for the worse result in the vertical component. This indicates that a good antenna model is required to achieve a good result also in the horizontal components when different antenna types are mixed.

If table 4.52 is compared to table 4.51, it can be seen that the results are considerably more promising when the Bernese software is used. This can be explained by the fact that only float solutions can be used in Geotracer, by the more elaborate antenna model in Bernese and by the fact that zenith tropospheric parameters can be estimated in Bernese. Of course, there are a number of other factors that may also explain this result, e.g. different processing strategies.

The results in table 4.52 show that when Geotracer is used an observation time of at least 4 hours is required in combination with a Dorne Margolin T antenna to achieve a solution with a RMS-value below 10 mm in each horizontal component. It is difficult to say anything about the height component, because of the rather nice tropospheric conditions during the time in question (cf. section 4.4). If different antenna types are mixed, the result in the horizontal component depends on how similar the antenna type at the new point is to the Dorne Margolin T antennas at the SWEPOS-stations. This is so, since it is not possible to model the horizontal components in the antenna model in Geotracer. In our case, at least 8 hours is needed with AGN, to achieve a good and reliable solution, with RMS values in the horizontal components below 10 mm.

The most important conclusions that can be drawn from the tests presented in this section can now be summarised:

- When the *Bernese Software* is used, it is possible to achieve a solution with an RMS-value less than 10 mm in all three components with as short observation time as 2 hours. This requires that zenith tropospheric parameters are estimated and that a Dorne Margolin T antenna is used. Another possibility is that another antenna type is utilised that has been very carefully calibrated relative to a DMT and that an advanced antenna model is used.
- Longer observation times are required in the *Geotracer* case to achieve good results in the horizontal components. When a Dorne Margolin T antenna is used, at least 4 hours is required to get a RMS-value below 10 mm in each horizontal component. In the case another antenna type is used (AGN) one has to use 8 hours to get a similar result. These results can partly be explained by the fact that only float solutions can be used in Geotracer and also by the simpler antenna model in this software.
- Because no zenith tropospheric parameters can be estimated in Geotracer, it is difficult to say very much about the vertical component. For the tests presented in this section, RMS-values between 15 and 30 mm are typical. The result will depend, though, on the tropospheric conditions, which might vary quite heavily both in time and place.

As before it must be kept in mind that a rather small data selection was used in the tests. To corroborate the results, more tests have to be made.

4.6 Adjustment

This test was made in the Geotracer software to find out if there is any difference in the results between performing a fixed network adjustment or a free adjustment with a following Helmert transformation, see section 3.5.3. The data was taken from campaign 1 (cf. section 4.1), where a Dorne Margolin T antenna was used. In the fixed adjustment, all the SWEPOS stations were held fixed. In the free adjustment, only the station in Sundsvall was fixed. In the latter case all baseline combinations were computed before the network adjustment. Table 4.61 shows the results from the 24-hour sessions and table 4.62 from the 8-hour sessions.

Deviation from known coordinates				
Unit: [mm]	Session	Horizontal - North	Horizontal - East	Vertical
Fixed adjustment	3380	7	6	5
	3390	8	-2	3
Free adjustment + Helmert transformation	3380	3	8	5
	3390	7	2	-8

Table 4.61 Geotracer, DMT, 24-hour sessions.

Unit: [mm]	Horizontal - North				Horizontal - East				Vertical			
Adjustment	RMS	Std. dev.	Mean	Max	RMS	Std dev.	Mean	Max	RMS	Std. dev.	Mean	Max
Fixed	5	1	4	6	6	5	-3	13	18	19	-4	37
Free + Helmert	4	1	4	5	5	5	1	8	11	10	-6	25

Table 4.62 Geotracer, DMT, 8-hour sessions.

The results in table 4.61 and 4.62 show that there is no significant difference between the two adjustment methods, even though the result seems to be a little bit better with a free adjustment in the 8-hour sessions, but in the 24-hours session the other adjustment method is better in the vertical component.

Thus, it can be concluded that both methods are comparable. Considering that a fixed adjustment is easier to perform, it should be preferred by the user.

4.7 Number of reference stations

The tests in this section were made to show how the accuracy depends on how many reference stations that are used, see section 3.5.2. This was tested by determining SIB 1 relative to two, four and six SWEPOS-stations. In the case with two reference stations, two different combinations of stations were chosen to see how this affects the result. The data from campaign 1 was used in the processing (cf. section 4.1). Table 4.71 shows the results from the 24-hour sessions and table 4.72 from the corresponding 8-hour sessions.

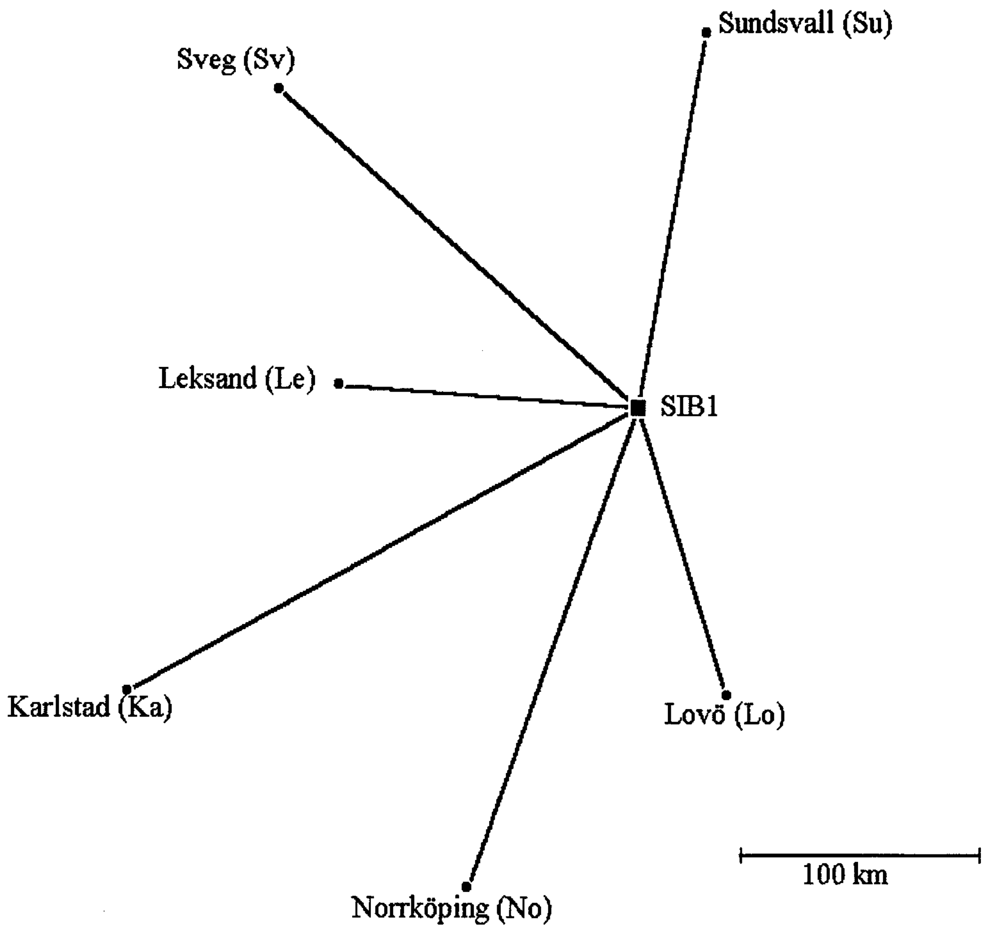


Fig. 4.71 The SWEPOS-stations that were used in the processing in the Geotracer. SIB1 is located in Mårtsbo, 10 km south of Gävle.

Deviation from known coordinates				
Unit: [mm]	Session	Horizontal - North	Horizontal - East	Vertical
6 (Sv,Su,Le,Lo,Ka,No)	3380	7	6	5
	3390	8	-2	3
4 (Sv,Su,Le,Lo)	3380	10	8	5
	3390	11	2	2
2 (Su,No)	3380	4	15	5
	3390	8	0	-13
2 (Su,Le)	3380	10	17	9
	3390	18	3	4

Table 4.71 Geotracer, DMT, 24-hour sessions.

Unit: [mm]	Horizontal - North				Horizontal - East				Vertical			
Reference stations	RMS	Std. dev.	Mean	Max	RMS	Std dev.	Mean	Max	RMS	Std. dev.	Mean	Max
6 (Sv,Su,Le, Lo,Ka,No)	5	1	4	6	6	5	-3	13	18	19	-4	37
4 (Sv,Su,Le,Lo)	8	1	8	10	5	6	0	8	16	18	2	32
2 (Su,No)	2	2	1	3	4	4	-2	7	17	13	-11	29
2 (Su,Le)	11	1	11	12	6	6	2	10	24	25	8	37

Table 4.72 Geotracer, DMT, 8-hour sessions.

In this test, the result is roughly similar, independently of how many reference stations that are used, even though the result with two stations seems to vary a little bit more depending on which stations that are used. It is interesting that the result in the two station case is as good as it is, because the scale and rotation errors in the whole network are not completely eliminated with only two reference stations. Significant errors because of this can not be observed here, with this small observation selection, but under other circumstances it could be dangerous to use only two stations.

From this we can conclude that to use six or four reference stations seems to be comparable. The processing is easier with four stations, but there are more redundant observations with six and it is easier to see if any of the reference stations is of bad quality. The tests also indicate that the result can be very good when only two SWEPOS stations are used, but in this case the reliability is very low and a significant part of the scale and rotation errors can, in unfortunate cases, still be left.

5 CONCLUSIONS

This work is meant to be a first step toward a tenable methodology in how to determine new points relative to the SWEPOS stations in an easy and reliable way with a typical standard equipment. The main purpose of the study is to compare one standard equipment with a state-of-the-art equipment and to investigate how the result depends on which method that is used and on how the equipment can handle different error sources. The two equipments have been tested with different antenna models, observation times, adjustment methods and number of reference stations, and with and without tropospheric parameters respectively. Below the most important conclusions are summarised. See chapter 3 and 4 for details.

The fact that Geotracer only is able to produce a float solution does not affect the result much if the observation time is long. When two 24 hour sessions with Dorne Margolin T antennas, which is the same antenna type as is used at the SWEPOS stations, were processed in both the softwares, the results seemed to be comparable, even though they were slightly better in the Bernese case.

The tests have shown quite clear that the best results are achieved when the same antenna type is used at all involved stations (DMT). When different antenna types are mixed (DMT and AGN), the results were better with the advanced antenna model that is used in Bernese compared to a simpler one, like the one in Geotracer. This conclusion is valid both in the horizontal and the vertical components. Of course this requires that a model from a good and reliable antenna calibration is available.

The antenna model from the antenna calibration made in this investigation, generated results comparable to using a Dorne Margolin T antenna, when an advanced antenna model was used in Bernese. The results with this model were clearly better than with the model from Rothacher & Mader. That the latter model was bad, shows that there might be problems in making an antenna calibration in a reliable way. There is always a risk that the calibration is disturbed by multipath and other errors, which will result in a systematic error when the antenna model is used in practice. However, the tests have shown that it is possible to make a good antenna calibration on your own.

With a Dorne Margolin T antenna, or another antenna type that has been very carefully calibrated, the tests show that only two hours observation time might be enough to achieve a very good solution, with RMS values below 10 mm in all three components. This presupposes that an advanced software like Bernese is used, which has the possibility to estimate zenith tropospheric parameters and to use advanced antenna models.

The tests also indicate that a longer observation time is required when the *Geotracer* software is used (compared to Bernese) to achieve good results in the horizontal components. With a Dorne Margolin T antenna, at least four hours are required to get an RMS-value below 10 mm in each horizontal component. In the case another antenna type is used (AGN), the tests show that eight hours are needed to get a similar result. That longer observation times are needed in Geotracer compared to Bernese, can partly be explained by the fact that only float solutions can be used in Geotracer and also by the simpler antenna model in that software.

Because no zenith tropospheric parameters can be estimated in Geotracer, it is difficult to say very much about the vertical component. In the tests RMS-values between 15 and 30 mm were typical. Other tests have shown, though, that the tropospheric conditions were quite favourable during the test campaigns. It is therefore hard to say anything general about the quality of the vertical component when the Geotracer software is used. The result will depend on the tropospheric conditions, which might vary quite heavily both in time and place.

The tests have further shown that a fixed adjustment is comparable to a free adjustment with a subsequent Helmert transformation in the case when the standard software from Geotracer is used. Because a fixed adjustment is easier to perform it should therefore be preferred by the user.

To use six or four reference stations in the adjustment seems also to be comparable when the standard equipment (Geotracer) is used. It is easier and faster to use four but six will give more redundant observations and it is easier to detect if any of the reference stations is of bad quality.

It must finally be pointed out that a proportionately small observation material, only 96 hours, has been used in this investigation. Therefore, the study should be seen as a first step toward a tenable methodology and more extensive tests have to be made under various conditions to confirm or refute the results in these tests.

Other factors that should be interesting to study in further investigations are how various site obstructions affect the result, how good the initial coordinates in the adjustment must be and how the baselines should be weighted in the network adjustment. Further studies are also required where other typical standard equipments are investigated.

6 ABBREVIATIONS

AGN	Ashtech Geodetic New antenna
AM1, AM2, AM3, AM4	Antenna Model (NR)
ARP	Antenna Reference Point
CODE	Centre of Orbit Determination in Europe
DMT	Dorne Margolin T antenna
DOSE 93	Dynamics Of the Solid Earth 1993
EUREF 89	European REFerence frame 1989
FARA	Fast Ambiguity Resolution Approach
GPS	Global Positioning System
GRS 80	Geodetic Reference System 1980
IGS	International GPS Geodynamics Service
LMV	Lantmäteriverket
NLS	National Land Survey
NOAA	National Oceanic and Atmospheric Adm.
OSO	Onsala Space Observatory
PCV	Phase Centre Variations
RMS	Root Mean Square
SWEREF 93	SWEdish REFerence frame 1993

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