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Test and Evaluation of SWEPOS Automated Processing Service

Diploma work by
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Preface

This is an MSc thesis from the Division of Geodesy, Royal Institute of Technology (KTH), Stockholm. The work informing this thesis has been conducted at Lantmäteriet (the National Land Survey of Sweden) during the period October 2004 – March 2005.

Gävle, September 2007

Jesper Ivarsson

Abstract

For seven years ago there was an automated processing service for SWEPOS and GPS post-processing of static observations established at Lantmäteriet (the National Land Survey) in Gävle, Sweden. SWEPOS is a multipurpose network of permanent reference stations for GNSS observations in Sweden. The service is used by those who do not want to compute statically measured GPS positions by themselves and is meant for positioning separate points (on centimetre level) using SWEPOS stations placed nearby. A new version of the software used in the service will be introduced in the beginning of 2008.

The accuracy for the computed position is estimated when the user compares received quality parameters with given guidelines. Exactly what these parameters denote is defined in the study. The guidelines have been determined using the processing service on a small number of points where the conditions have been excellent, i.e. a clear view and use of choke-ring antennas.

The aim of this study is to produce guidelines for the quality parameters based on measured points that are not so ideal in a GPS perspective and where regular geodetic GPS antennas have been used. GPS data of three hours observations from a total number of 34 points have been computed in a copy of the processing service. The output quality parameters from the process have comprised the core in the study: these were used in all calculations and comparisons.

The recommendations drawn from the study are based upon the results from the calculations. The accuracy for the calculated positions, expressed as RMS values for the distribution around the true values, is 19 mm horizontally and 37 mm vertically. When points that had been considered to be bad or less good concerning the sight conditions towards the satellites (vegetation etc.) were excluded, the values went down to around 15 mm and 30 mm. This was also the case when points with a low fraction of resolved ambiguities were excluded.

The results from the study vary a lot, but recommendations for a guideline were brought out as follows:

- The average of the fractions of resolved ambiguities of all baselines is more than 50 %.
- The RMS of the multi-station solution is less than 3 mm.
- The standard deviation of unit weight of the Helmert fit on known SWEREF 99 positions is less than 10 mm.
- The lowest fraction of resolved ambiguities for any baseline is more than 30 %.

Sammanfattning

En tjänst för SWEPOS på Lantmäteriet i Gävle för automatisk beräkning av statiska GPS-observationer upprättades för sju år sedan (SWEPOS Beräkningstjänst). SWEPOS är ett nätverk (med flera användningsområden) av fasta referensstationer för GNSS-observationer i Sverige. Beräkningstjänsten används av dem som inte vill beräkna statiskt mätta GPS-positioner själva. Tjänsten är avsedd till att positionsbestämma enskilda punkter (på centimeternivå) genom användning av SWEPOS-stationerna närmast punkten. En ny version av det beräkningsprogram som används i tjänsten kommer att införas i början av 2008.

Noggrannheten för den beräknade positionen uppskattas genom en jämförelse av erhållna kvalitetsparametrar mot givna riktlinjer. Exakt vad dessa parametrar anger är definierat i rapporten. Riktlinjerna har bestämts genom användning av tjänsten på ett fåtal antal punkter där förutsättningarna har varit utmärkta dvs. klar sikt och där choke-ring-antenner har använts.

Syftet med studien var att ta fram riktlinjer för kvalitetsparametrar utgående ifrån mätta punkter som inte är idealiska sett från ett GPS-perspektiv och där vanliga GPS-antenner har använts. GPS-data med en observationstid på tre timmar ifrån ett totalt antal av 34 punkter har beräknats i en kopia av beräkningstjänsten. De kvalitetsparametrar som kommit ut ur beräkningarna har varit grunden för studierna. Dessa användes i alla beräkningar och jämförelser.

Rekommendationer dragna ifrån arbetet är grundade på resultaten från beräkningarna. Noggrannheten för de beräknade positionerna uttryckt som RMS-värde för spridningen runt det sanna värdet var 19 mm horisontellt och 37 mm vertikalt. När punkter som ansågs vara dåliga eller mindre bra med avseende på sikten vid punkten mot satelliterna (vegetation etc.) var avlägsnade, sjönk värdena ner till omkring 15 mm och 30 mm respektive. Detta var också fallet där punkter med låg andel av lösta periodobekanta var avlägsnade.

Resultaten från studien varierar stort, men rekommendationer för riktlinjer blev uppsatta enligt följande:

- Medelvärde för andelen lösta periodobekanta för alla baslinjer är mer än 50 %.
- RMS i slutlig fixlösning är mindre än 3 mm.
- Grundmedelfelet i Helmerttransformationen till SWEREF 99 är mindre än 10 mm.
- Lägsta värde för andelen lösta periodobekanta för alla baslinjer är mer än 30 %.

Test and Evaluation of SWEPOS Automated Processing Service

Test and Evaluation of SWEPOS Automated Processing Service

1 Introduction

This report starts with presenting the background and the purpose of the study. After that theory regarding GPS and theory concerning the Bernese GPS Software are given. The part of the automated processing service that was used in the work is described. In the method section, the gathering and selecting of data are described, and also how the processing of the data and the analyzing were done. In the end the result is presented and discussed, as well as some conclusions.

1.1 Background

Seven years ago Lantmäteriet established an automated processing service for GPS post-processing of static observations. The service is based on a nationwide net of permanent reference stations called SWEPOS. The users are those who do not want to compute for the statically measured GPS points on their own. The service refers to determining single points towards close SWEPOS stations on a centimetre level.

After sending the GPS data to the automated processing service, it will be processed and the result will be sent back to the user, including a number of quality parameters to evaluate the quality of the point computed. To make this evaluation possible, guidelines have been set for some of the quality parameters to verify that the result is satisfactory.

The automated processing service has been tested on a number of stations during circumstances that have been very good, with a clear view and with the use of Dorne Margolin antennas (choke-ring antennas). The result from the testing has been associated with the quality parameters and forms the basis of guidelines that currently are in use. The proposal was to study the quality parameters and the directive for these more extensively. The quality parameters and the current guidelines for them are described and explained in Section 2.2.1.

1.2 Purpose

The aim of this thesis was to investigate the quality parameters that are in use today and evaluate the parameters from another perspective through circumstances that were not used in earlier studies. To be certain of obtaining reliable accuracy in determining the position, the study should be able to offer guidelines for the different quality parameters. The purpose was also that the user should receive a clear indication of the quality obtained.

1.3 Earlier Studies

An initial evaluation of the processing service was done in 2001 (Kempe, 2001 and Kempe & Jivall, 2002) and supports the present thesis. This earlier study can be found on www.swepos.com. The previous study of the quality parameters to evaluate the quality of the result was set up in a somewhat different way and also approached differently to some extent. This earlier study is what the quality parameters currently in use are based on.

1.4 Restrictions

The set of GPS points has been restricted to the available points at Lantmäteriet. The points have been chosen from the available description (a description of the point's location) that can be found in the geodetic archive. The varieties of point locations and antenna types have also been limited to the data that was available.

The theory part concentrates on what is central for this thesis and gives some explanation for basic GPS theory.

2 Theory

2.1 Reference system

A geodetic coordinate system aims to define a position of a point on the earth's surface. Geodetic coordinates are one way to describe the position. Depending on the location on earth, different reference ellipsoids can be used for different reference systems. A position on earth can be defined in more than one coordinate system. There are several ways to describe the relation between different coordinate systems. Normally a seven parameter transformation is used, where three parameters are shifts along the geocentric axis's X, Y and Z, three parameters are rotations around these axis's and the seventh parameter is a scale factor.

The International Terrestrial Reference System (ITRS) is a global spatial reference system, which is realized under the name International Terrestrial Reference Frame (ITRF). ITRF has come out and has been prepared through a compilation of international global frames. It is a geocentric system that can define the centre of mass for the whole Earth, including oceans and atmosphere. Since the first ITRF 89 there have been repeated recalculations and modifications at an interval of a couple of years. The different ITRF have been obtained by combinations of individual ITRF solutions using observations from different space techniques as GPS, VLBI, SLR, LLR and DORIS.

The World Geodetic System, WGS 84 is a global reference frame which since 1994 is based on ITRS. It has been constructed by the Americans for real time positioning with GPS. If the position is defined only with data from GPS satellites it will come out in the global reference frame WGS 84. To reach high accuracy the GPS data should be combined with data from points on the ground, for example points in the SWEPOS network. The position will then be expressed in the same reference frame as the ground based points are given in. In Sweden the reference frame SWEREF 99 is used for this purpose. There is no proper or correct realisation of WGS 84 in Sweden. WGS 84 and SWEREF 99 differ with a couple of decimetres. In the most applications of GPS in Sweden the two systems are considered the same.

2.1.1 SWEREF 99

Currently SWEREF 99 is the valid realisation of the European reference system ETRS 89 in Sweden. The preparation went on for a number of years at Lantmäteriet. There is an older version called SWEREF 93 that is now out of date and not used since SWEREF 99 got introduced in 2001. The deviation between SWEREF 99 and SWEREF

93 is 5 to 6 cm. SWEREF 99 was realised from 49 permanent reference stations in the Nordic countries including 25 SWEPOS stations, where 21 have become fundamental sites for the Swedish ETRS 89 realisation.

SWEREF 99 uses the ellipsoid GRS 1980 with the parameters:

- Semi-major axis (a) 6 378 137 m
- Flattening (f) 1/298.257222101

2.2 SWEPOS

SWEPOS is a national network of permanent reference stations for GNSS in Sweden. SWEPOS is operated by Lantmäteriet and has 154 stations in the network. The main purpose of SWEPOS is to supply GNSS data for many different kinds of applications and demands for accuracy. This means constant surveillance of the whole system and providing raw data for post processing. SWEPOS also gives data for meteorological studies and other scientific investigations.

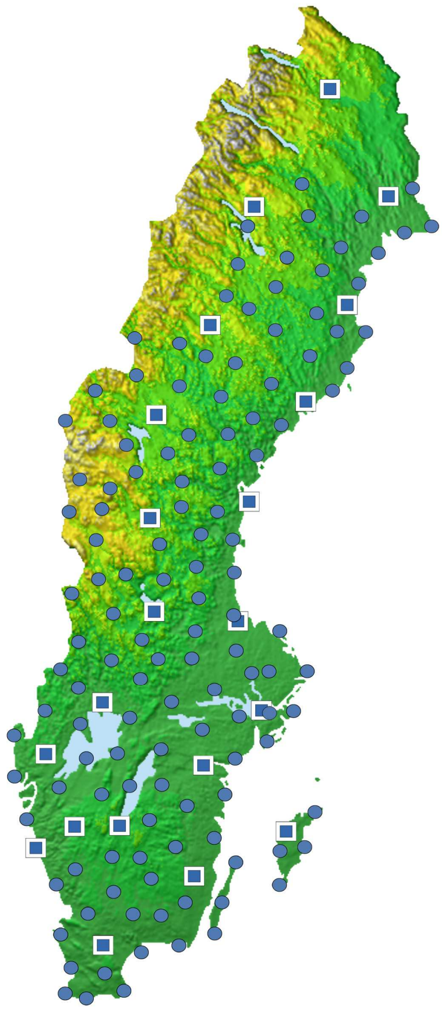

Figure 2.1 *Map over the SWEPOS stations. Squares show fundamental stations all in class A and dots are stations mainly constructed for network RTK purposes where the main part is in class B.*

All the stations are connected with TCP/IP connections through permanent land lines to the SWEPOS control centre at Lantmäteriet. There are 21 fundamental reference stations all in class A with high status (see Figure 2.1). The antennas for these stations are mounted on pillars made out of concrete and are placed on solid bedrock. The pillars are often placed at high altitudes to prevent obstacles from affecting communication from satellites at low elevation. Complete network adjustments of all the SWEPOS stations are made every day.

Each station has a GNSS receiver that gathers GPS and GLONASS data on frequencies L1 and L2. The accuracy of the position on centimetre level is achieved by using the Bernese GPS Software for post-processing. Data for post-processing is store on servers that can be reached by the users via an FTP server. FTP stands for File Transfer Protocol and is the language used for file transfer from computer to computer across the Internet.

The rest of the SWEPOS reference stations are mainly constructed for network RTK purposes where the main part is in class B. The SWEPOS Network RTK Service has more than 900 users. They have their antennas mainly mounted on buildings and the equipment, as telecommunication and power supply inside the building, which could be a school or a public building.

2.2.1 The automated processing service

An automated processing service has been developed to smooth the progress of post-processing for the users of SWEPOS. The system of the service has been put together at Lantmäteriet in Sweden. It has been operational since autumn 2000 and for easy access and fast delivery it uses the Internet for transferring data to the user. The user can either upload his data with a RINEX file through FTP or at SWEPOS website (www.swepos.com). The result from the post-processing is then sent by email to the user. During 2005 there were 219 subscribers on the service and 230 single day users, who submitted 2153 observation files.

The RINEX file that is sent from the user to the service has to include static dual-frequency GPS observation data. The data must be sampled in a 30-second interval and be in the same 24-hour period. This means the data cannot proceed over midnight. If it is sampled in a higher frequency the data will be reduced to a 30-second interval. The file that arrives at the automated processing service for post-processing will first be placed in a queue. When ready it will be inspected to fit the given criteria for processing.

The service consists of a number of components. When the RINEX file is ready to be processed it is sent to an initialisation procedure, where all the necessary data including SWEPOS data, ephemeris data and earth orientation parameters are gathered and a script is put together that starts the processing. The header in the RINEX file is read through and based on the information the corresponding SWEPOS data from the five closest fundamental SWEPOS stations, matching ephemeris data and earth orientation parameters are chosen. At first official post-processed ephemeris data is selected and if it is not available rapidly, post-processed ephemeris or predicted ephemeris data is selected. The gathered data is stored in an archive of zipped files to minimize the storing space, but also to simplify transportation.

The Centre of Orbit Determination in Europe (CODE) provides ephemeris and earth orientation parameters to the processing. The data is based on observations from tracking stations of the International GNSS Service (IGS). IGS works as a global support for post processing of GNSS data and has around 350 stations, which are the basis for the calculation of precise ephemeris, clock corrections, atmospheric data and earth orientation parameters. The solutions from calculations of the IGS network are also an important part of the realization and maintenance of the international reference system, ITRS.

All the computations are then made in a programme called the Bernese GPS Software (see Section 2.6). It usually takes around 10 minutes for the programme to complete the computations. The result, including a number of quality parameters, is put together in a text file and sent back to the user. To make it possible for the user to evaluate the result, guidelines for three of the quality parameters to verify that the result is satisfactory have been set in an initial evaluation done in 2001 (Kempe, 2001 and Kempe & Jivall, 2002). A satisfactory result means that a standard deviation of approximately 1 cm per planar component and 1.5-2 cm in height for a Dorne Margolin T antenna (choke-ring antenna) is achieved - somewhat higher for other antennas. The guidelines are:

- The average of the fractions of resolved ambiguities of all baselines is more than 30 %.
- The RMS of the multi-station solution is less than 3 mm. The Bernese GPS is a multi-station software, which means that all baselines are solved in the same adjustment.
- The standard deviation of unit weight of the Helmert fit on known SWEREF 99 positions is less than 10 mm.

2.3 RINEX: The Receiver-Independent Exchange Format

The RINEX format was presented in 1989 and was accepted as the recommended GPS data exchange format to use. The GPS observables in a receiver are defined in different ways depending on what kind of receiver is used. To process data from different receivers the exchange format RINEX has been designed to convert between the different formats. RINEX stands for Receiver INdependent EXchange format and indicates that the data format is independent of receiver type. Today the RINEX format could be considered to be the standard exchange and transferring format of GPS data.

The GNSS data for post-processing that SWEPOS supplies is only in RINEX format, but can be set to different log intervals. The RINEX files are available for both single and dual frequency data files.

The file consists of a header section with information about e.g. receiver and antenna type, approximate position and types of observables with time intervals. The file also has additional information for post-processing of the data. Beneath the header come the observables.

The file name is labelled after station code, day of year and the two digit year of the first observation epoch in the file. The last letter in the file name tells us if it is an observation or a navigation file. The RINEX file uses the ASCII format. The Bernese GPS Software runs much faster with binary files and therefore it transfers the RINEX observation files into Bernese binary format.

Today RINEX exists in version 2.11, but a new RINEX version 3.00 has also been formed. The main reasons for a modification are the upcoming Galileo and the enhanced GPS with new frequencies and observation types.

2.4 GPS

The navigation system GPS (Global Positioning System) was launched in 1973 by the U. S. Department of Defence (DOD). The system was designed to be used by the U. S. military, but became accessible for civilians and is probably the most known and used system for navigation, positioning and geodetic measurements in use today.

The navigation system is divided into different segments: the space segment, the control segment and the user segment.

The space segment consists of the satellites. The supposed GPS constellation is 24 satellites that orbit the earth for approximately 12 hours. Often there are more than 24 operational satellites as new ones are launched to replace older ones. Today there are 30 operational satellites. There are 6 orbital planes with an inclination angle of 55 degrees with respect to the equatorial plane. The average altitude of the satellites is around 20,200 km. This constellation provides the user with 5-8 satellites visible from any point on earth. The satellites transmit on two frequencies, L1 and L2, with the frequencies 1575.42 MHz and 1227.60 MHz respectively.

The control segment is the tracking stations located all around the world. The master control is located in Colorado Springs. The stations are constantly tracking data from the satellites. The data i.e. ephemeris and clock corrections, is computed at the master control and then sent back to the satellites for upgrading.

The user segment is any kind of GPS receiver. The receivers use the signal from the satellites to compute position, velocity and time estimates.

The basic theory for positioning with GPS is to determine the distance between satellite and receiver. Since the velocity of the signal is known (speed of light) the distance can be determined by computing the time it takes from the satellite to reach the receiver. The position of the satellite when sending out the signal can be computed from out of the satellite message. When the distances to 3 satellites are known the three-dimensional receiver position can be determined. In reality a fourth satellite is needed due to poor synchronization between satellite and receiver clocks.

There are two ways to determine the position using satellites: absolute and relative positioning. In absolute positioning only one receiver is used and mostly it is used in navigation in real time. In relative positioning there are two or more receivers measuring at the same time to one or more satellites. In this way a receiver works as a reference with known coordinates and corrections can be computed.

2.5 Sources of Errors

Errors that affect the accuracy of the positioning negatively are problems that always have to be considered in the GPS field. Many of the errors can be reduced or even eliminated, but there is still no error-free solution existing today. However, there are a vast number of mathematical methods that improve the result in a significant way.

2.5.1 Satellite errors

The GPS satellites hold four very precise atomic clocks each. Although they are close to perfect, clock bias exists and the clock may contribute to small errors. The satellites orbit and their distribution over the point has a major effect on the accuracy of the positioning. A larger distribution means better accuracy. A way to measure the quality of this is the dilution of precision, the so-called DOP-value.

2.5.2 Signal propagation

The atmosphere affects the signal from the satellite. The signal propagates a bit differently through the journey from the satellite down to the receiver. A longer journey affects the signal even more and therefore the elevation angle is important for achieving the desired quality. Usually the cut off angle is set from 10 to 15 degrees.

The atmosphere can be divided into the ionosphere and the troposphere. These two affect the signal in different ways. The troposphere is the part of the atmosphere that reaches from the earth's surface up to a height of about 10 km. The troposphere can further be divided into a wet and dry part, where the wet part is water vapour closer to the earth's surface and other moisture. The wet part is only 10 % of the troposphere, but nevertheless a bigger problem to adjust for. The dry part is usually modelled with a standard model. The troposphere delay primarily causes error vertically, which can add up to 2.5 cm on a baseline of 50 km. Phase and code measurements are affected in the same way.

The ionosphere reaches from about 50 km and up to 1000 km above the earth's surface. With longer baselines one has to consider the activity in the ionosphere. In the ionosphere the refraction can be eliminated to large extend through a linear combination of L1 and L2 since it is frequency-dependent.

2.5.3 Receiver errors

The GPS receiver has a quartz clock and is not as precise as the clocks in the satellites. Clock bias in the receiver clock has to be considered. The electrical centre (phase centre) of the antenna must also be defined. The position of the geometric antenna centre and the antenna phase centre do not coincide. There are two effects that have to be considered: the offset and the variation depending on the elevation and azimuth of the received satellite signal of the antenna phase centre. The offset can usually be determined as a constant, but the antenna phase centre variation is more difficult to determine. It is important to determine this variation as well as possible to minimize the error. This variation is typically around a couple of centimetres and if handled correctly errors would not exceed some millimetres.

Multipath is when the signal does not reach the receiver directly, but first gets to the antenna after a reflection from i.e. an immediate building or a blank surface. Small elevation angles lead to greater errors in these cases. Multipath makes measurements in a dense area of constructions or obstacles hard to accomplish. Using a choke-ring antenna can reduce the error.

2.5.4 Satellite configuration

It is important that the satellites used in the measurement have an acceptable geometric configuration among themselves. The satellites have to be well spread over the sky to achieve a good configuration. On the other hand signals from satellites with a low elevation above the horizon affect the quality of the signal negatively and consequently also the accuracy of the measurement. Usually satellites below an elevation of 10-15 degrees are filtered and not used in the computation. The elevation mask is arbitrary and can be set to whatever is desired.

The DOP value (Dilution of Precision) is a measure for the satellite configuration's contribution to the uncertainty when determining the position. Therefore a DOP value can be calculated for each specific satellite configuration. The DOP value changes as the satellites changes position. A lower DOP value means a better configuration. The satellite configuration cannot be altered for the benefit of the GPS user, although it can be forecast so that it may be considered in the planning of a survey. A forecast is provided at the SWEPOS website.

A number of different DOP-values are used:

- GDOP (Geometric DOP)
- PDOP (Positional DOP)
- TDOP (Time DOP)
- HDOP (Horizontal DOP)
- VDOP (Vertical DOP)

2.6 The Bernese GPS Software

The program, Bernese GPS Software used for the processing has been developed at the University of Bern in Switzerland (http://www.bernese.unibe.ch/index.html). The Bernese programme is designed for easy installation on a range of different computer platforms and the software consists of more than a hundred FORTRAN programmes. These programmes are automatically executed one by one during the process and the user does not have to execute them manually.

The version of the software used in the processing service is 4.2 and runs in the DOS environment. A new version, 5.0, was released in 2004 and it will in the beginning of 2008 replace version 4.2 in the processing service. The processing service works through a programme developed by Lantmäteriet called MBerini from Windows. The standard Bernese GPS Software is changed somewhat to suit the processing service.

Once the Bernese GPS Software is started it goes through a number of steps automatically:

- The data is converted to the format of the Bernese software. Also the sampling interval will be reduced when necessary to 30 seconds.
- From the CODE ephemeris the satellite orbits will be determined where the position of the satellites is given every 15 minutes.

- Clock correction of the receiver is determined. This is done epoch by epoch, through determination of the absolute position.
- Baselines from the point to be calculated to the five closest fundamental SWEPOS stations are formed and differences of the phase observations are computed.
- A triple difference solution is done and cycle slips are fixed. Also poor observation data is excluded.
- To get better approximate coordinates for the point a first double difference solution is done.
- Cycle ambiguities are determined and the Quasi Ionosphere – Free algorithm (QIF) strategy is used.
- Troposphere parameters are used and the final solution is a simultaneous adjustment of the five baselines.
- A similarity transformation from the current ITRF epoch to SWEREF 99 based on the five used SWEPOS stations is done.

2.6.1 Ambiguity resolution strategies

In the Bernese GPS Software there are four ambiguity resolution strategies implemented, which are called ROUND, SIGMA, SEARCH and QIF. When choosing strategies, there are different aspects that have to be taken into account, such as length of baseline and length of session. In the case of longer baselines around 200 kilometres it is vital to use both L1 and L2 frequencies to solve for the ionospheric delay.

The Quasi Ionosphere-Free algorithm (QIF) strategy uses both frequencies L1 and L2 when resolving the ambiguities, and consequently both frequencies are required. It is recommended to resolve ambiguities, which leads to higher efficiency in the process. Different algorithms use different combinations of the L1 and L2 observations. Recommended strategy for longer sessions and medium length of baseline (10 – 100 km) is the QIF strategy; therefore this strategy is used in the Bernese GPS Software in the SWEPOS Automated Processing Service. The SEARCH strategy is recommended for short sessions and short baselines. For very short baselines (up to several kilometres) the ambiguities may be resolved independently on L1 and L2 using the SIGMA algorithm.

2.7 Bernese Processing Engine

The Bernese Processing Engine (BPE) was made to simplify the data processing in the Bernese GPS Software and for the automation of processing permanent GPS networks. The automated process in the programme can be viewed as a chart underneath (see Figure 2.1). Permanent networks as the base for a processing service are used more and more in many regions of the world as for SWEPOS Automated Processing Service.

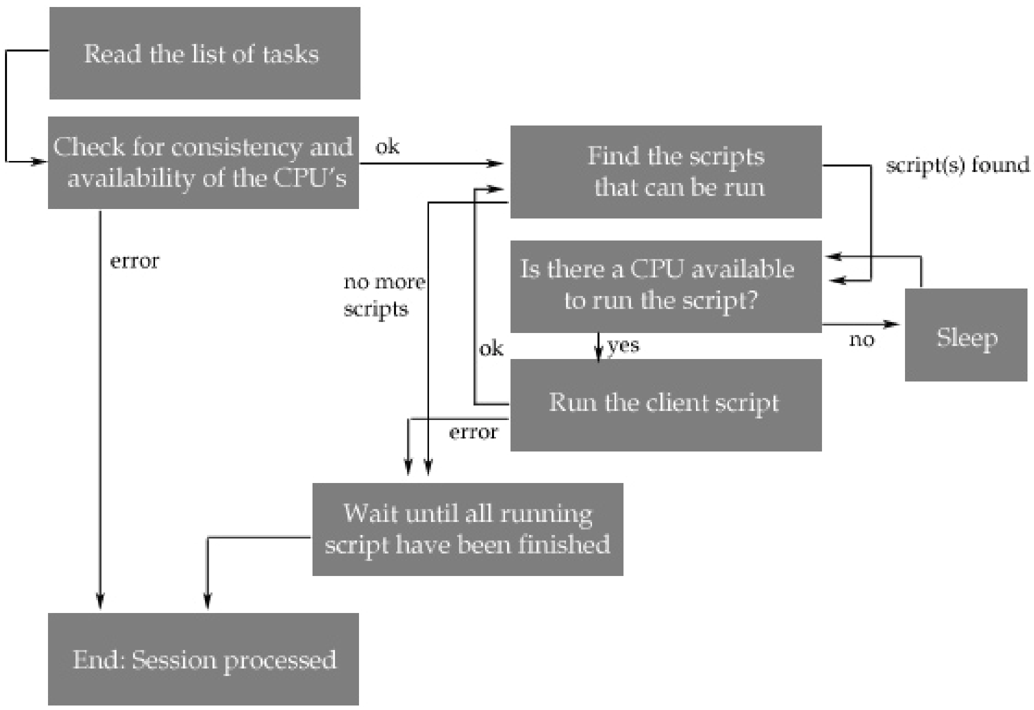

Figure 2.1 *Example of a Process Control Script flow chart.*

3 Method

The methods and the structure of the work for this project will be explained here, as will the certain conditions for the project and the methods for the processing of GPS data along with the methods for analyzing the processed data. The GPS data that have been processed come from previously performed measurements on points with known positions.

3.1 Introductory work

For the processing of the GPS data, the Bernese GPS Software together with the SWEPOS Automated Processing Service was used. To be able to use the programme without disturbing the operative processing service, it was installed with everything necessary for the processing service to run on a local computer. In this way a copy of the processing service could be used on the local computer. In order to structure all the data and to use formulas to compute statistics about the computed positions, a suitable program was needed. It was quickly decided to use Microsoft Excel for these evaluations and analyses. It has been used in earlier research projects at Lantmäteriet and was considered to be suitable also for this project.

To make the work of the study easier, everything needed was brought to the local computer. All data were structured in the computer and consisted of:

- GPS data from points with known positions
- GPS data for the SWEPOS stations
- Ephemeris data
- Earth orientation parameters
- Values of antenna dimensions
- Antenna models with the phase centre variations for the used antennas.

All GPS data were processed on this local computer. After establishing this copy of the processing service and some tests had been made, the system was set up and ready for computing the data.

The GPS data from the points with known positions come from measurements performed in a project at Lantmäteriet called RIX 95. RIX 95 is a GPS densification of the national geodetic network. It makes it possible to establish transformation parameters between local and national reference frames. The intention with the project is also to facilitate the exchange of geographical information and a rational use of GPS.

According to a report called “RIX 95-projektet” from Lantmäteriet of how the RIX 95 points have been established, they have been set up through static measurements with at least 45 minutes of observation time, in order to have a fixed solution on L1. The centring and the height of the antennas were verified using redundancy. The accuracy of the points has been improved by network adjustment with lots of baselines. It is a solid network, which is connected to the very accurately determined so-called SWEREF points.

The positions that were computed with the processing service have been compared with the official positions for the RIX 95 points. These official positions are found in the geodetic archive at Lantmäteriet and descend from the official RIX 95 evaluation. These official positions are also considered to be the true coordinates without errors, though they probably have a standard error on centimetre level in SWEREF 99.

3.2 Selection and range

Different criteria for the GPS data were put together for what was to be included in the data set. When putting the criteria together for measurement to be in the data set the argument was not to have the best conditions, but a range between poor and good. With this in mind the different criteria of a measurement for a point had to be defined. Length of measurement, instrument as antenna and receiver model and the condition at location were some of the considerable things that influenced the measurement. The limitations and boundaries for these factors had to be determined individually.

- The quality of the points regarding the sight conditions towards the satellites is found together with the positions in the geodetic archive and is given in four classes depending on how many obstacles there are around the points. The four classes are poor, less good, good and very good conditions. This quality classification was done during the survey of RIX 95.
- The observation time for the GPS data was set to the same for all points in the data set, namely three hours. This length was considered to be a reasonable choice in respect of the time it takes to attain a fair accuracy. Points measured longer than that were shorten down to three hours in the RINEX file.
- The epochs for the GPS data to be computed were recorded and logged in the RINEX file in a time interval of 15 seconds. In the processing service, an epoch interval of 30 seconds is used.
- The equipment used was different for each measured point. It was desirable to get a diverse set of used equipment. The receiver could be of any kind. More important was the choice of antenna. The different antennas used for the data set were defined to be of a typical kind. This is explained more in Section 3.3.1

- The measurements had to be on both GPS frequencies (L1 and L2), as this is required for the processing in the processing service.
- The geographical location in Sweden for each point and also the distance to the closest SWEPOS station were taken into account, but the geographical location in Sweden was not used during the evaluation of the results. All points no matter the location were brought into the data set.
- The range of the years for the observations of the computed GPS data went from 1997 to 2002. This was also taken into account, but was not used during the evaluation of the results.

The data to be computed were arranged in a folder structure based on the quality regarding the sight conditions for the points and on what equipment that was used. The points for the data set were selected out of these parameters. The aim was to get an as wide-ranging data set based on these parameters as possible.

3.3 Data acquisition

3.3.1 Equipment

Different antenna types were used in the measurements. The spread of different antennas did not end up so diverse as first supposed. In fact the antennas used all come from the same brand name with a variation in model. These were mainly different types of Ashtech models (see Figure 3.1). These types of antennas would be considered to be somewhat typical in the kind of measurements that have been done (static measurements). It was desirable to not use antennas of choke-ring type, since the aim was to gather measurements with not the best possible settings.

Figure 3.1 *Antenna models ASH700228B and ASH700700 used in RIX 95.*

3.3.2 Data gathering

When gathering the data, the aim was to get as many measurements as possible for the data set. With a large quantity of data as sample for the study, a pattern in deviation and/or the outcome of the analyses would easier be noticed. It also increases the possibility to locate errors.

All data was gathered from archived measurements at Lantmäteriet. Most of these are structured in zip-files after geographical location. There were a lot of zip-files to choose from at first. How they were measured and under what circumstances could not be found out about until the zip-file containing the RINEX file was unpacked and looked through. The information about measured time and equipment used was found in the header of the RINEX file as mentioned in Section 2.3.

Complete GPS data for the SWEPOS stations, ephemeris data and earth orientation parameters for the periods of the measurements were gathered from the archives at the SWEPOS control centre. This was a very time-consuming task to perform.

3.4 Data processing

The study has been divided into major parts such as the sight conditions for the measured points for comparison and all the steps in the data processing, and also finally studying the result and analysing the comparison.

The sight conditions for the measured points were investigated more thoroughly compared to earlier studies. The data was classified based on time, sight conditions for the points, geographical location and equipment. The time and the geographical location were however not used during the evaluation of the results. So this was all structured in a system of folders and for every point measured each one was placed in the arrangement of folders according to Figure 3.2.

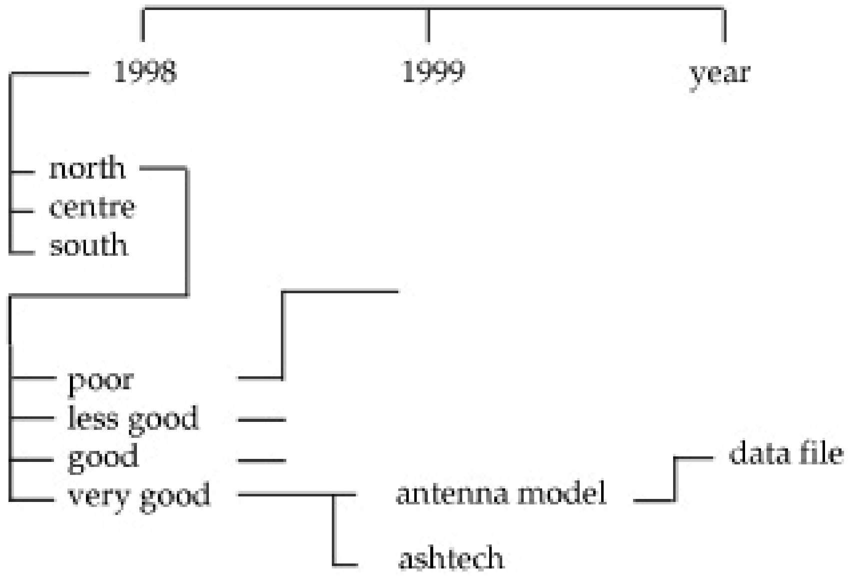

Figure 3.2 *Folder structure for the GPS data from the measured points.*

Every point has a number for identification. Each point has information and meta data such as the nearest surroundings around the point's location and a detailed description of how to find it. In this information a judgment of the point's situation may be found. This information about the points was to be found in the geodetic archive at Lantmäteriet.

The measured points were taken one by one from the structure and then run one at a time with the Bernese GPS Software in the copy of the processing service.

The processing was carried out as follows:

- All of the GPS data for the SWEPOS stations, precise ephemeris data and the earth orientation parameters were collected from separate servers where data for post-processing is stored. This data was brought to the local computer and re-structured in folders in a way that it would be able to work at the processing. The GPS data for the SWEPOS stations was at first split in several files over a twenty-four hours interval. These files were converted and put together into one single file for each day.
- In the header of the RINEX file for the points to be computed the used antenna type is given and also the antenna height. The

antenna type must be correctly given in order for the correct antenna model with the phase centre variations to be used. The given antenna height was measured in the field, but not to the Antenna Reference Point (ARP), which corresponds to the bottom of the antenna. To get the correct antenna height to ARP, the given value had to be recalculated.

- A start up file was made containing general information about the person responsible, date of issue and, most important, what RINEX file was to be processed. The start up file was run in a programme called MBerini. The MBirini program works as an execution programme for the Bernese GPS Software in the processing service when running in Windows environment.
- The RINEX file together with indispensable data as precise ephemeris was run through the Bernese GPS Software. The processing was done under surveillance and had to be verified as free from errors and programme failures, although the programme itself would notify system errors.
- The results of the process appear in several folders including files with all the information about the process. Comprehensive results are presented in a number of text files.

The elevation cut-off angle for the satellites is set to 15 degrees. The programme also makes an additional computation with an elevation mask set to 25 degrees, which makes it possible to verify the satellite elevation dependence on the result. The programme requires at least four satellites for an epoch to be processed.

The calculated coordinates from the Bernese GPS Software were extracted from a text file with the results and imported into Microsoft Excel to be evaluated as a first step in the study. From two text files with results there were also some quality parameters attached. The quality parameters used from these files were:

- The average of the fractions of resolved ambiguities of all baselines.
- The RMS of the multi-station solution. The Bernese GPS Software is a multi-station software which means that all baselines are solved in the same adjustment.
- The standard deviation of unit weight of the Helmert fit on known SWEREF 99 positions.
- RMS of the residuals per component (north, east and up) in the Helmert fit on known SWEREF 99 positions.
- The fraction of resolved ambiguities for each of the five baselines to the five SWEPOS stations (especially the fraction of resolved ambiguities for the baseline with the lowest fraction of resolved ambiguities).

- Distance to the closest SWEPOS station.

Note that the three first quality parameters are those which today have a guideline for the evaluation of the result according to Section 2.2.1.

For each calculated point the deviation from the known position was computed in the two plane dimensions and in height. The deviations in latitude and longitude in plane were calculated in seconds (Δlat_{sec} and $\Delta long_{sec}$) and had to be converted to millimetres (Δlat_{mm} and $\Delta long_{mm}$) according to the formulas below. For the height it was not necessary, as it was already given in metres.

$\Delta lat_{sec} \cdot 30{,}9 = \Delta lat_{mm}$

$\Delta long_{sec} \cdot 30{,}9 \cdot \cos(lat_{degr}) = \Delta long_{mm}$

With increasing latitude the distance between the lengths of degrees in longitude decreases which leads to the difference in longitude given in millimetres and is shown in the formula above.

No coordinate transformations had to be made because the coordinates were already given in SWEREF 99, which was the reference system used throughout the whole project.

The programme GTRANS is a programme with functions to store information about coordinate systems and coordinate transformations of all sorts that occur within Geodesy. It is a tool to transfer coordinates from one reference system to another. The GTRANS programme was useful for the coordinate transformations between Cartesian and Geodetic coordinates that was done after the processing.

A total number of 34 points were calculated. GPS data from more points had been prepared, but a hard disc crash in the computer used made it impossible to calculate more points.

3.5 Method of analysis

Every point that has been processed was brought one by one to Microsoft Excel, where all of the statistical analyses were made. From the comparison of the known and calculated coordinates the deviation and some standard error propagation could be computed. As true values in this study the official positions for the RIX 95 points have been used, though they probably have a standard error on centimetre level in SWEREF 99 as described in Section 3.1.

To study the error for each point two types of statistical analysis were applicable, such as error in location and error in distribution. To show the error in location the mean deviation was computed and to show the error in distribution both values for precision and accuracy were computed.

The mean deviation shows the mean value of the deviations from the true values (errors) for all measurements. This deviation should be as small as possible if no systematic errors occur and with a larger amount of measurements an approach towards zero should be noticeable. The mean deviation (m) has been computed as:

$$m = \frac{\sum \varepsilon}{n} \tag{3.1}$$

Here ε denotes the error (the deviation between calculated and true value), while n denotes the number of measurements.

The precision is calculated as standard deviation (s) and shows the distribution around the mean value of the measurements:

$$s = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}} \tag{3.2}$$

The accuracy describes the distribution around the true value and is calculated as an RMS value.

$$\hat{s} = \sqrt{\frac{\sum \varepsilon^2}{n}} \tag{3.3}$$

Even though the precision is good the accuracy can still be poor, which indicates systematic errors. To check if a systematic error is significant, the mean deviation (m, formula 3.1) can be compared with the standard error of the mean deviation (s_m, formula 3.5). A systematic error can be detected if the mean deviation is larger than the standard error of the mean deviation on a certain risk level (α) and with a certain testing power (β) according to the t-distribution; $t_{\alpha/2}(n\text{-}1)+t_{1\text{-}\beta}(n\text{-}1)$. In this study, a risk level of 5 % and a testing power of 80 % have been used.

$$m > (\mathrm{t}_{\alpha/2}(n-1) + \mathrm{t}_{1-\beta}(n-1)) \cdot s_m \tag{3.4}$$

$$s_m = \frac{s}{\sqrt{n}} \tag{3.5}$$

The measurement deviations between calculated and known positions of the points were sorted on a scale from the lowest to the highest value. At first the highest value was selected from all of the measurements, which means 100 % of the data set. After that the highest value for 68 and 95 % of the data set were of interest. So the remaining values of the highest deviation (above 68 % and 95 % respectively) are excluded in the 68 % and 95 % values.

4 Results

In this chapter the results are presented. The data set of 34 measurements on RIX 95 points with known positions are used in the comparison between calculated and known positions. All of the positions are based on horizontal coordinates as latitude and longitude and height above ellipsoid in SWEREF 99. The known and the calculated positions are found in Appendix 1. The calculated points and the comparisons are presented graphically in the form of tables and diagrams. They are presented in different diagrams of distribution and deviations. Results in planar coordinates and height have been separated in the diagrams, but computations in 3D have also been made and are represented in the results as well.

4.1 Results of processed and calculated coordinates

The deviations between calculated and known positions give the error for each point and are presented in Table 4.1. They are calculated as described above in Section 3.4. Some quality parameters from the Bernese GPS Software from the calculations are presented in Tables 4.2 and 4.3.

__Table 4.1__ Error in mm (difference between calculated and known position).

Error in mm					
Point number	**North**	**East**	**Plane**	**Height**	**3D**
1	3	8	9	-26	27
2	11	5	11	-14	18
3	19	-3	19	22	29
4	21	3	21	-10	23
5	-10	9	13	-7	15
6	30	23	38	-141	146
7	31	-40	51	2	51
8	-5	7	8	-12	15
9	2	4	4	3	5
10	12	14	18	-20	27
11	-12	-3	12	47	49
12	6	-10	12	-21	24
13	-9	8	12	0	12
14	-2	8	9	-6	10
15	11	8	13	10	17
16	-3	-22	22	-4	23
17	-1	31	31	-38	49
18	-11	2	11	-64	65
19	-15	-4	15	17	23
20	16	1	16	-14	21
21	-4	2	4	-21	21
22	6	9	11	-22	25
23	-16	-7	17	-6	18
24	2	45	45	1	45
25	3	10	11	96	97
26	7	7	10	-17	20
27	24	15	29	-7	29
28	2	10	10	-65	66
29	7	-1	7	19	20
30	11	4	12	-9	15
31	9	-3	10	-16	19
32	2	-4	5	3	6
33	20	3	20	-15	25
34	-7	-3	8	5	9

Table 4.2 *Some quality parameters from the calculations. Closest distance shows the distance from the point to the closest SWEPOS station. The fraction of resolved ambiguities for each of the five baselines (Amb1-Amb5) and the average of the fractions of resolved ambiguities of all baselines (Average Amb) are also indicated. The lowest fraction of resolved ambiguities out of the baselines was also selected and placed in a separate column (Lowest Amb). There are no quality parameters present for point number 5 (indicated by -).*

Point number	Closest distance (km)	Amb 1	Amb 2	Amb 3	Amb 4	Amb 5	Lowest Amb	Average Amb
1	68.3	57.9	78.6	76.9	64.7	75	57.9	69.6
2	82.0	83.3	91.7	76.9	83.3	83.3	76.9	83.6
3	24.8	54.5	72.7	63.6	70	60	54.5	64.2
4	60.3	72.7	53.8	72.7	53.8	-	53.8	62.5
5	-	-	-	-	-	-	-	-
6	85.1	18.2	41.7	41.7	50	-	18.2	38.3
7	57.7	72.7	63.6	45.5	27.3	-	27.3	52.3
8	53.9	57.9	61.1	52.6	80	83.3	52.6	67
9	44.5	66.7	75	69.2	75	66.7	66.7	70.5
10	50.5	61.5	76.9	61.5	92.3	69.2	61.5	72.3
11	29.5	55.6	55.6	55.6	77.8	50	50	59.1
12	29.7	63.6	30.8	58.3	61.5	75	30.8	57.4
13	51.0	72.7	70	50	70	70	50	66.7
14	87.2	87.5	75	100	75	75	75	82.5
15	59.4	75	75	62.5	77.8	55.6	55.6	69
16	55.0	60	60	60	54.5	0	0	48
17	24.3	22.2	87.5	77.8	22.2		22.2	51.4
18	42.5	61.5	83.3	91.7	83.3	83.3	61.5	80.3
19	81.5	90.9	81.8	73.3	90.9	72.7	72.7	81.4
20	69.8	70	70	80	75	70	70	72.9
21	60.5	100	80	80	78.6	80	78.6	83.3
22	50.8	77.8	80	77.8	100	77.8	77.8	82.6
23	49.9	16.7	23.1	0	8.3	25	0	16.4
24	39.6	0	0	0	0	0	0	0
25	74.0	88.9	77.8	88.9	88.9	87.5	77.8	86.4
26	71.7	54.5	55.6	54.5	70	55.6	54.5	58
27	102.7	84.6	76.9	76.9	92.9	92.3	76.9	84.8
28	90.9	81.8	80	80	90.9	90.9	80	84.9
29	67.2	56.3	53.3	60	60	-	53.3	57.4
30	61.6	95.5	90.9	90.5	86.4	86.4	86.4	89.9
31	80.4	58.8	61.1	47.4	70.6	58.8	47.4	59.1
32	68.0	80	77.8	70.6	81.3	70.6	70.6	75.9
33	84.0	80	92.3	85.7	80	78.6	78.6	83.1
34	46.6	93.8	85.7	93.3	80	80	80	86.7

Table 4.3 *Some quality parameters from the Bernese GPS Software from the calculations such as RMS values of the multi-station solution, the standard deviation of unit weight of the Helmert fit on known SWEREF 99 positions and the RMS of the residuals per component (north, east and up) in the Helmert fit on known SWEREF 99 positions. For point number 1, 2 and 5 there are mainly no quality parameters present (indicated by -). All values are given in millimetres.*

Point	RMS of the multi-station solution	Standard deviation of unit weight of the Helmert fit	RMS of the residuals in the Helmert fit		
			North	East	Up
1	2.5	-	-	-	-
2	1.9	-	-	-	-
3	2.1	9.8	4.8	6.4	11.3
4	1.8	6.9	2.5	3.7	8.6
5	-	-	-	-	-
6	2.1	10.8	6.4	11.6	7.4
7	2.8	38.7	19.3	43.9	26.5
8	1.8	4	2.9	1.3	4.7
9	2	2	1.6	1.5	1.8
10	1.6	1.5	1.6	1.3	0.6
11	1.8	3.8	3.3	3.3	2.7
12	2.4	16.9	7.7	17.7	14.1
13	1.9	4.6	2.8	5.4	2.3
14	1.9	5.7	3.4	1.1	7.3
15	1.7	7.4	1	1.4	10.3
16	1.8	18.1	14.1	19.7	8.1
17	1.9	20.5	9.5	22.2	10.8
18	2	6.4	2.5	6.8	5.5
19	2	10.1	6	4.4	12.2
20	1.8	3	3.5	2	1.3
21	2	9.2	5.4	3.7	11.2
22	2.2	4	1.9	2.3	4.8
23	2.2	26.1	8.7	8.1	35
24	2.8	44.1	19.9	44	39.5
25	2	4.1	1.3	1	5.6
26	1.4	1.6	1.1	1.2	1.6
27	1.6	3.8	1.4	1	5.1
28	1.5	4.7	1.8	1	6.4
29	1.8	3.3	2.1	3.2	2.8
30	1.7	6.1	2.3	2.2	8.1
31	1.7	4	1.5	1.6	5.2
32	1.7	1.4	1	0.9	1.5
33	2	1.7	2	1.4	0.4
34	1.9	4.4	3.7	4.8	1.8

4.2 Quality distribution

The points were arranged and classified after the quality of the points regarding the sight conditions towards the satellites. Here the quality refers to the location of the point. This means satellite configuration and atmospheric affects are not taken into account. As mentioned in Section 3.2, the quality is given in four classes depending on how many obstacles there are around the points.

In Tables 4.4, 4.5 and 4.6 the results with respect to the quality of the points are presented as mean deviations from the true values (m, formula 3.1), as standard deviations (s, formula 3.2) and as RMS values of the errors ($\hat{s}$, formula 3.3).

To check if a systematic error is significant, it is also of interest to calculate the standard errors of the mean deviation (s_m, formula 3.5). The standard errors of the mean deviation are presented for all measurements in Table 4.7. Since the check is one-dimensional, the values are given in latitude, longitude and height.

Table 4.4 *Quality distribution in plane. The quality of the points regarding the sight conditions towards the satellites is given in four classes depending on how much obstacles there are around the points. The four classes are poor (0), less good (1), good (2) and very good (3) conditions. The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors ($\hat{s}$, formula 3.3) are also shown. All values are given in millimetres.*

Plane						
Quality	**Number**	**68 %**	**95 %**	**m**	**s**	**$\hat{s}$**
All	34	16.1	40.1	6.2	18.6	19.4
0	1	44.6	44.6	44.6	-	44.6
1	3	16.9	34.7	20.5	16.4	24.5
2	18	15.5	33	4.0	19.0	18.9
3	7	10.8	22.7	5.3	13.8	13.8
Unknown	5	15.4	20.5	3.6	16.9	15.6

Table 4.5 *Quality distribution in height. The quality of the points regarding the sight conditions towards the satellites is given in four classes depending on how much obstacles there are around the points. The four classes are poor (0), less good (1), good (2) and very good (3) conditions. The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres..*

Height						
Quality	**Number**	**68 %**	**95 %**	**m**	**s**	**ŝ**
All	34	20.1	74.3	-9.7	36.2	37.0
0	1	1.0	1.0	1.0	-	1.0
1	3	22.0	122.4	-57.3	72.5	82.4
2	18	19.2	43.8	-0.9	28.5	27.7
3	7	19.8	64.7	-26.0	27.6	36.4
Unknown	5	15.0	40.8	8.0	25.8	24.4

Table 4.6 *Quality distribution in 3D. The quality of the points regarding the sight conditions towards the satellites is given in four classes depending on how much obstacles there are around the points. The four classes are poor (0), less good (1), good (2) and very good (3) conditions. The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres.*

3D						
Quality	**Number**	**68 %**	**95 %**	**m**	**s**	**ŝ**
All	34	-	-	11.5	40.7	41.7
0	1	44.7	44.7	44.7	-	44.7
1	3	26.1	127.3	60.9	74.3	86.0
2	18	25.1	55.4	4.1	34.2	34.5
3	7	27.5	65.5	26.5	30.8	39.0
Unknown	5	25.7	43.8	8.8	30.9	29.0

Table 4.7 *Standard errors of the mean deviation (s_m, formula 3.5) and minimum detectable errors on 5 % risk level (α) and with a testing power (β) of 80 % according to the t-distribution (($t_{\alpha/2}(n-1)+t_{1-\beta}(n-1))s_m$, formula 3.4) for all 34 measurements. For 34 measurements $t_{\alpha/2}(n-1)$ is 2.04 and $t_{1-\beta}(n-1)$ is 0.85. It is of interest to calculate these values to be able to check if a systematic error is significant. Mean deviations from the true values (m, formula 3.1) and standard deviations (s, formula 3.2) are also shown. All values are given in millimetres.*

	m	s	s_m	$(t_{\alpha/2}(n-1)+t_{1-\beta}(n-1))s_m$
Latitude	4.8	12.3	2.1	6.1
Longitude	4.0	14.0	2.4	6.9
Height	-9.7	36.2	6.2	17.9

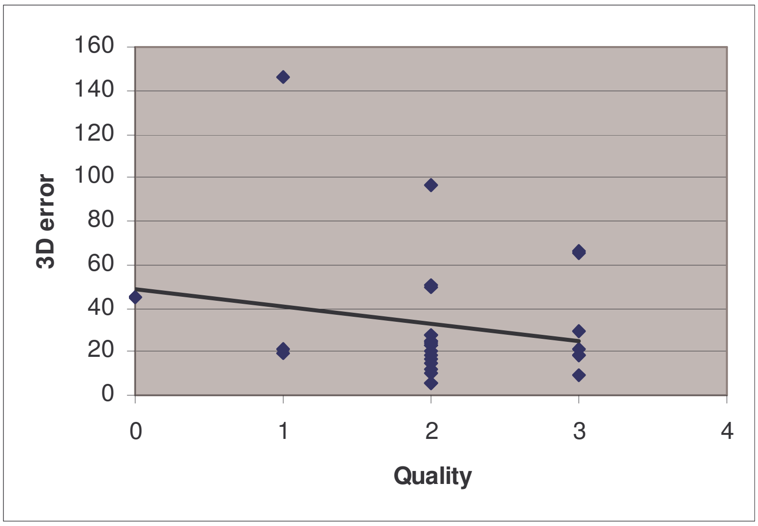

Figure 4.1 *Distribution of quality (described in Section 3.2) in 3D.*

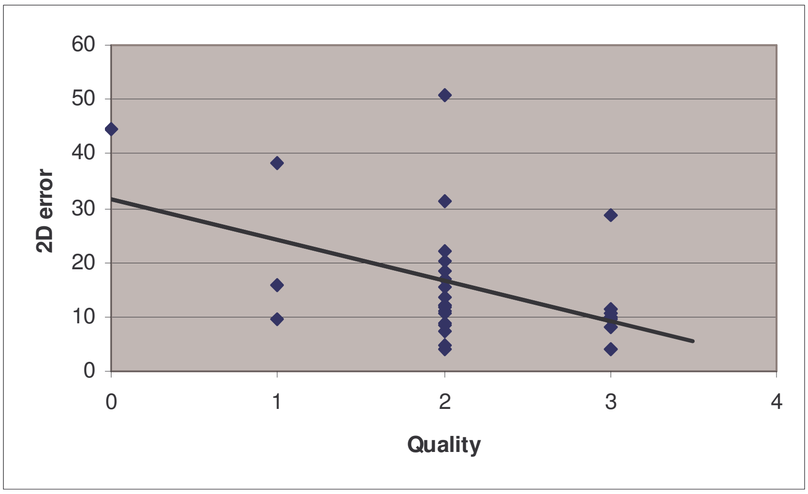

Figure 4.2 *Distribution of quality (described in Section 3.2) in plane.*

4.3 Lowest fraction of resolved ambiguities distribution

In Tables 4.8, 4.9 and 4.10 the results with respect to the lowest fraction of resolved ambiguities out of the baselines are presented as mean deviations from the true values (m, formula 3.1), as standard deviations (s, formula 3.2) and as RMS values of the errors ($\hat{s}$, formula 3.3).

Table 4.8 *Distribution of lowest* ***fraction of resolved*** *ambiguities in plane (2D plane). The lowest fraction of resolved ambiguities is given in four classes (Amb). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors ($\hat{s}$, formula 3.3) are also shown. All values are given in millimetres.*

Amb (%)	Number	68 %	95 %	m	s	$\hat{s}$
All	33	15.1	33.45	6.4	18.6	19.5
0 – 30	6	38.6	49.2	8.9	38.2	36.0
30 – 50	2	10.7	11.8	10.2	5.5	10.9
50 – 70	12	12.2	19.8	5.8	12.3	13.1
70 – 100	13	11.8	23.2	6.7	12.6	13.9

Table 4.9 *Distribution of lowest* ***fraction of resolved*** *ambiguities in height. The lowest fraction of resolved ambiguities is given in four classes (Amb). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors ($\hat{s}$, formula 3.3) are also shown. All values are given in millimetres.*

Amb (%)	Number	68 %	95 %	m	s	$\hat{s}$
All	33	19.4	75.9	-10	36.8	37.5
0 – 30	6	8.6	110.1	-31	55.9	59.7
30 – 50	2	17.8	20.5	-18	3.5	18.7
50 – 70	12	20.3	53.8	-4	28.1	27.2
70 – 100	13	16.7	75.9	-4	35.7	34.5

Table 4.10 *Distribution of lowest* ***fraction of resolved*** *ambiguities in 3D. The lowest fraction of resolved ambiguities is given in four classes (Amb). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres.*

Amb (%)	Number	68 %	95 %	m	s	ŝ
All	33	25	76.9	11.7	41.3	42.3
0 – 30	6	49.2	117.5	32.3	67.7	69.7
30 – 50	2	20.8	23.5	21.1	6.6	21.6
50 – 70	12	27.0	55.4	7.0	30.7	30.2
70 – 100	13	24.7	76.9	7.8	37.8	37.2

4.4 Average of fractions of resolved ambiguities distribution

In tables 4.11, 4.12 and 4.13 the results with respect to the average of the fractions of resolved ambiguities of all baselines are presented as mean deviations from the true values (m, formula 3.1), as standard deviations (s, formula 3.2) and as RMS values of the errors (ŝ, formula 3.3).

Table 4.11 *Distribution of average of fractions of resolved ambiguities in plane (2D plane). The average of the fractions of resolved ambiguities is given in four classes (Amb). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres.*

Amb (%)	Number	68 %	95 %	m	s	ŝ
All	33	16.4	40.5	6.5	18.6	19.5
0 – 30	2	27.1	42.2	20.1	38.4	33.8
30 – 50	2	27.8	36.4	13.5	39.8	31.2
50 – 70	13	12.8	38.0	6.9	19.9	20.4
70 – 100	16	11.9	21.8	6.5	12.4	13.6

Table 4.12 *Distribution of average of fractions of resolved ambiguities in height. The average of the fractions of resolved ambiguities is given in four classes (Amb). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres.*

Amb (%)	Number	68 %	95 %	m	s	ŝ
All	33	20.4	75.9	-10	36.8	37.5
0 - 30	2	2.8	5.5	-3	5.0	4.3
30 - 50	2	53.3	127.3	-73	96.9	99.7
50 - 70	13	20.7	41.1	-3	23.1	22.4
70 - 100	16	19.6	71.2	-8	35.5	35.3

Table 4.13 *Distribution of average of fractions of resolved ambiguities in 3D. The average of the fractions of resolved ambiguities is given in four classes (Amb). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres.*

Amb (%)	Number	68 %	95 %	m	s	ŝ
All	33	27.0	76.8	11.7	41.3	42.3
0 -30	2	27.7	42.3	20.3	38.7	34.1
30 - 50	2	67.3	133.7	73.7	104.7	104.5
50 - 70	13	26.5	49.7	7.5	30.5	30.2
70 - 100	16	25.0	72.2	10.5	37.6	37.9

4.5 Standard deviations of unit weight of the Helmert fit distribution

In tables 4.14, 4.15 and 4.16 the results with respect to the standard deviations of unit weight of the Helmert fit on known SWEREF 99 positions are presented as mean deviations from the true values (m, formula 3.1), as standard deviations (s, formula 3.2) and as RMS values of the errors (ŝ, formula 3.3).

Table 4.14 *Distribution of standard deviations of unit weight of the Helmert fit in plane (2D plane). The average of the standard deviations of unit weight of the Helmert fit is given in four classes (S_0). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres.*

S_0 (mm)	Number	68 %	95 %	m	s	ŝ
All	31	17.1	41.2	6.3	19.3	20.0
0 - 5	16	11.9	21.8	6.7	12.0	13.4
5 - 10	7	12.8	20.3	7.4	12.7	13.8
10 - 15	2	23.3	35.7	12.3	37.3	29.1
15 <	6	32.1	49.2	3.4	35.8	32.9

Table 4.15 *Distribution of standard deviations of unit weight of the Helmert fit in height. The average of the standard deviations of unit weight of the Helmert fit is given in four classes (S_0). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres.*

S_0 (mm)	Number	68 %	95 %	m	s	ŝ
All	31	21.1	79.0	-9.1	37.8	38.3
0 - 5	16	18.8	71.2	-0.9	34.7	33.6
5 - 10	7	18.4	53.9	-11.1	27.3	27.6
10 - 15	2	61.6	128.6	-62.0	111.7	100.4
15<	6	6.6	33	-11.0	15.6	18.0

Table 4.16 *Distribution of standard deviations of unit weight of the Helmert fit in 3D. The average of the standard deviations of unit weight of the Helmert fit is given in four classes (S_0). The 68 % and 95 % values show the deviations from the true values for 68 % and 95 % of the measurements. Mean deviations from the true values (m, formula 3.1), standard deviations (s, formula 3.2) and RMS values of the errors (ŝ, formula 3.3) are also shown. All values are given in millimetres.*

S_0 (mm)	Number	68 %	95 %	m	s	ŝ
All	31	27.2	80.0	11.1	42.5	43.2
0 - 5	16	25.0	72.2	6.8	36.7	36.2
5 - 10	7	22.5	52.4	13.3	30.1	30.9
10 - 15	2	67.3	133.7	63.2	117.8	104.6
15<	6	45.3	50.4	11.5	39.0	37.5

5 Discussion

The purpose of this thesis was to study the quality parameters that are attached to the result from the SWEPOS Automated Processing Service and the guidelines for these that are in use today, based on some other conditions than those of earlier studies. The present study and its results were not as extensive as first aimed for, but the purpose of the thesis has been accomplished in the sense that some conclusions can be outlined.

The aim was to get an as wide-ranging data set as possible, based on the factors given in Section 3.2. This turned out to be a quite challenging task. The several points that fit the conditions turned out to have the same set up and exact same settings, which was not what was desired. However, this had to be overlooked to get as many points as possible. Not only did it take a great amount of time to get a point ready for processing, but also to find one that fit the conditions that were set up. It is also clear that the local circumstances around the points influence the distribution of errors in different ways.

If the amount of points for the data set may be said to be poor, it is due to a computer breakdown that led to that the copy of the automated processing service was not able to be recovered. Moreover, this also put a stop in the gathering of data and the processing of more data. This may be considered something of a failure, and certainly an unsatisfying, aspect of the study.

What receiver type that was used for every point was not taken into consideration. Comparing receiver types with respect to seeing how they affect the quality would most likely have reduced the number of points in the data set even more.

5.1 Comparison

The automated processing service should use observation times over at least an hour in its present setup and recommended is at least two hours. All of the observations used in the study had an observation time of three hours. The observation time should therefore not contribute or have very little influence on the result.

In the quality distribution a clear correlation could be observed. It is easier to observe this when only 68 % of all measurements are given. Here larger errors have been left out and one can see the tendencies in the range of deviation correlates clearly. What can be observed is that points with the quality class 3 regarding the sight conditions towards the satellites (which means very good) have much better result in plane than the quality classes 1 and 2. In height, points with the quality classes 2 and 3 have better results than quality class 1. The deviation could also be seen in the figures (showing the distribution of quality) where the inclination of the regression line shows how the measurements for each quality are distributed (see Figure 4.2). The classification of the points that was taken from the geodetic archive has been one-sided, and it has been up to each observer to decide the quality class for each point. In this subjective classification one might have thought it would be difficult to see a difference with respect to the quality.

The values in Table 4.7 were studied to check for minimum detectable systematic errors. The results for latitude, longitude and height were listed separately. There is no detectable significant systematic error since the mean deviations from the true values (m, formula 3.1) are smaller in all dimensions than the standard errors of the mean deviation on a 5 % risk level (α) and with a testing power (β) of 80 % according to the t-distribution; $t_{\alpha/2}(n-1)+t_{1-\beta}(n-1)s_m$ (formula 3.4). For latitude a mean deviation (m, formula 3.1) of 4.8 mm is compared with 6.1 mm, for longitude a mean deviation of 4.0 mm is compared with 6.9 mm and in height is a mean deviation of 9.7 mm compared with 17.9 mm.

It is however possible that there could be a slight systematic effect in the errors, since the values are rather close to each other, especially in latitude. By studying Table 4.1 it is noticed that the largest errors have both negative and positive values, so the mean deviations would not be so much affected if the largest errors would be removed. The reasons for the possible slight systematic distribution are difficult to determine, but could be found in uncertainties concerning the used GPS antennas and in the known positions.

Studying Table 4.1 and 4.2 and observing the distance to the closest SWEPOS station can draw the conclusion that there is no instant relation between the distance and the values for error in deviation.

It is difficult to say anything about the RMS of the multi-station solution, which is less than 3 mm for all computed points. If the threshold parameter is set to a value below 3 mm, many of the measurements with satisfying result would be excluded. This means that this parameter says little about the quality.

Many measurements with large errors are closely related to the fraction of resolved ambiguities. Most of these measurements are in the interval where less than half of the ambiguities have been resolved.

When studying the quality distribution in Tables 4.8-4.10, sorted on lowest fraction of resolved ambiguities, there is a relation for accuracy values (RMS values of the errors ($\hat{s}$, formula 3.3) etc.) for a fraction of resolved ambiguities over and fewer than 30 %. Accuracy values for a fraction of resolved ambiguities over 30 % are much better than for fewer than 30 %. There is the same result for accuracy values (RMS values of the errors ($\hat{s}$, formula 3.3) etc.) sorted on average of fractions of resolved ambiguities (Table 4.11-4.13), but with a threshold value of

50 %. The share of resolved ambiguities is considered to be a good method to determine and measure the quality. As well as a measurement can still have a satisfying quality, even if one SWEPOS station provides a bad ambiguity resolution or is lost. The average of fractions of resolved ambiguities gives a better measure of the quality than the lowest fraction of resolved ambiguities.

In the interval from 70 to 100 % for the average of fractions of resolved ambiguities, the standard deviation (s, formula 3.2) is close to 10 mm in plane, which shows satisfying quality. With over 50 % ambiguities resolved the error increases a bit and the standard deviation is closer to 20 mm in plane.

When studying the Tables 4.14-4.16, the distribution of standard deviations of unit weight of the Helmert fit (S_0), the accuracy values tend to increase considerably when S_0 exceeds 10 mm in plane.

6 Conclusions and recommendations

This chapter outlines a summary of the main conclusions made in this report. A more detailed discussion could be read in Chapter 5. The conclusions are based on the number of measurements that have been made, which are quite limited. Therefore no guarantees that every conclusion is one hundred percent accurate can be given. The conclusions can be summarized as follows:

- There is, as said in the comparison in Section 5.1, no direct indication of a dependency on the distance from the calculated point to the closest SWEPOS station.
- The classification of the quality around the point site showed that there was a relation between the size of the error and a specified class of quality for the point. The accuracy for the calculated positions expressed as an RMS value for the spread around the true values ($\hat{s}$, formula 3.3) was 19 mm horizontally and 37 mm vertically. When points that had been considered to be bad or less good concerning the GPS suitability (vegetation etc.) were excluded, the values dropped to around 15 mm and 30 mm respectively. This was also the case if points with low ambiguity resolution rate were excluded.
- There was a small but noticeable difference between points that had an average above 50 % of resolved ambiguities and values above 70 % out of the 34 points that were calculated. A more significant difference is seen between 30 % and 50 % of resolved ambiguities. In the existing guidelines (see Section 2.2.1), a value of 30 % is given as a threshold today, but since only 2 points in this study got a value between 30 and 50 %, the conclusion from this study that 50 % is a better value is based on very little data.
- With over 50 % of ambiguities resolved the standard deviation (s, formula 3.2) in plane is a bit less than 20 mm in plane.
- The guidelines in Section 2.2.1 say that a satisfactory result would be a standard deviation of approximately 1 cm per planar component and 1.5-2 cm in height. The results in the study shows upon a standard deviation (s, formula 3.2) close to 1 cm in plane, when over 70 % of the ambiguities are resolved. When comparing, the result meets the limit for the earlier given guidelines here. For lower values and in height the accuracy in this study does not fully meet the guidelines and the reasons could be that ordinary antennas were used, that the points had more obstacles around them and that old data with uncertainties concerning antennas were used.

Overall, the conclusion for the whole study is that the results are close to the present guidelines that are in use today. As shown from the tables the results between points differ a lot. What this shows is that a larger amount of material plays a great part in the whole process of making correct conclusions. The amount of ambiguities resolved was close related to the quality of the results. The recommendations drawn from this study concerning the guidelines for the three quality parameters that today are in use (see Section 2.2.1), would be:

- For the first quality parameter (the average of the fractions of resolved ambiguities), the value more than 30% can be raised to more than 50%.
- For the second quality parameter (the RMS of the multi-station solution), the value less than 3 mm is a good value.
- For the third parameter (the standard deviation of unit weight of the Helmert fit on known SWEREF 99 positions), the value less than 10 mm is a good value.

A recommendation from this study is also to add a fourth quality parameter to the guidelines, namely the lowest fraction of resolved ambiguities for any baseline and the recommendation is that:

- The lowest fraction of resolved ambiguities for any baseline is more than 30%.

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Appendix 1 Known positions

Point	Point number	Latitude	Longitude	Height (ellipsoid)
1	7956390	58 54 10.06360	15 13 55.56975	147.777
2	7945990	58 50 40.91647	14 55 6.40096	124.882
3	108111	59 7 52.25693	17 40 7.24597	99.287
4	798410	58 48 8.77857	17 40 27.35122	43.227
5	195611,1	63 24 22.92806	14 57 10.89954	467.034
6	7452190	56 28 55.55115	15 5 55.09916	166.897
7	7346590	56 14 5.83117	14 36 40.80922	114.318
8	7464390	56 35 7.57814	16 6 49.37949	58.465
9	7466490	56 40 45.93371	16 11 7.40134	59.812
10	7465590	56 37 51.84398	16 14 .18324	38.057
11	7469190	56 48 9.63223	15 56 1.81798	135.329
12	7550990	56 50 17.82656	15 44 32.17053	197.052
13	7467890	56 42 47.56333	16 31 54.31815	75.509
14	7368790	56 18 55.30561	16 24 6.46550	32.452
15	7453890	56 33 16.59285	15 42 55.14052	135.598
16	7456690	56 39 12.33392	15 30 .13904	182.818
17	7554790	57 1 5.88503	15 36 20.18536	225.834
18	7552490	56 55 48.86008	15 20 33.89559	281.117
19	7447890	56 42 6.75766	14 50 10.15177	180.75
20	7456190	56 39 49.98833	15 7 4.79187	176.561
21	7458290	56 45 6.38554	15 11 10.34602	181.693
22	7552290	56 55 52.77916	15 11 49.75846	292.407
23	7556290	57 7 3.78500	15 10 43.19879	247.622
24	7557490	57 9 15.12312	15 21 50.17766	287.295
25	7547590	57 8 45.59366	14 35 27.10979	250.385
26	7547591	57 10 40.47404	14 37 24.99252	244.237
27	2075390	63 48 44.34040	17 8 35.04072	294.131
28	1969890	63 32 32.53813	16 40 5.39749	218.31
29	1962290	63 12 47.84089	16 5 53.34319	255.13
30	1855491	62 55 2.35113	15 14 16.26581	332.239
31	1850590	62 40 30.46885	15 20 7.68853	433.597
32	1853190	62 50 11.26598	15 0 22.79235	351.378
33	1851690	62 44 21.20790	15 27 7.50308	377.274
34	1858090	63 1 28.33642	14 51 49.45894	372.004

These are the known coordinates in SWEREF 99 and are presented in latitude, longitude and height over ellipsoid. The points are sorted with respect to quality in ascending order, starting with the less good quality.

Appendix 2 Calculated positions

Point	Point number	Latitude	Longitude	Height (ellipsoid)
1	7956390	58 54 10.06369	15 13 55.57027	147.751
2	7945990	58 50 40.91681	14 55 6.40125	124.868
3	108111	59 7 52.25754	17 40 7.24575	99.309
4	798410	58 48 8.77925	17 40 27.35138	43.217
5	195611	63 24 22.92775	14 57 10.90018	467.027
6	7452190	56 28 55.55213	15 5 55.10052	166.756
7	7346590	56 14 5.83218	14 36 40.80689	114.32
8	7464390	56 35 7.57799	16 6 49.37990	58.453
9	7466490	56 40 45.93377	16 11 7.40156	59.815
10	7465590	56 37 51.84438	16 14 .18404	38.037
11	7469190	56 48 9.63184	15 56 1.81781	135.376
12	7550990	56 50 17.82677	15 44 32.16993	197.031
13	7467890	56 42 47.56303	16 31 54.31861	75.509
14	7368790	56 18 55.30556	16 24 6.46599	32.446
15	7453890	56 33 16.59320	15 42 55.14099	135.608
16	7456690	56 39 12.33381	15 30 .13775	182.814
17	7554790	57 1 5.88501	15 36 20.18722	225.796
18	7552490	56 55 48.85974	15 20 33.89570	281.053
19	7447890	56 42 6.75718	14 50 10.15153	180.767
20	7456190	56 39 49.98884	15 7 4.79195	176.547
21	7458290	56 45 6.38542	15 11 10.34613	181.672
22	7552290	56 55 52.77937	15 11 49.75898	292.385
23	7556290	57 7 3.78449	15 10 43.19840	247.616
24	7557490	57 9 15.12320	15 21 50.18032	287.296
25	7547590	57 8 45.59375	14 35 27.11041	250.481
26	7547591	57 10 40.47427	14 37 24.99291	244.22
27	2075390	63 48 44.34118	17 8 35.04184	294.124
28	1969890	63 32 32.53820	16 40 5.39820	218.245
29	1962290	63 12 47.84113	16 5 53.34313	255.149
30	1855491	62 55 2.35149	15 14 16.26608	332.23
31	1850590	62 40 30.46915	15 20 7.68833	433.581
32	1853190	62 50 11.26604	15 0 22.79204	351.381
33	1851690	62 44 21.20855	15 27 7.50331	377.259
34	1858090	63 1 28.33618	14 51 49.45873	372.009

The table shows the calculated positions as described earlier in Section 3.4.

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