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Lars E Sjöberg, Ming Pan, Erick Asenjo

Royal Institute of Technology,
Department of Infrastructure

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Abstract

During a period of 20 months a feasibility study was performed in using the satellite system GPS for detecting possible crustal “creep” deformations of the order of 1 mm/yr in candidate regions for long-term disposal of nuclear waste. Precise GPS positions were collected 3 times/year at 6 epochs in a small test network at Äspö near Oskarshamn in the south east of Sweden. Although the measurements were deteriorated by some extreme ionosphere activities, and the GPS equipment was not ideal, the analysis shows that the method works well. By extending the period of observations to several years the investigated technique should be an excellent tool for monitoring possible crustal “creep” motions with high precision and reliability.

Sammanfattning

En förstudie med att använda mätningar med satellitsystemet GPS för att mäta möjliga deformationer, kryprörelser, längs med möjliga aktiva förkastningslinjer har utförts under en tid av 20 månader i ett testnät vid Äspö nära Oskarshamn. Syftet med mätningarna var att testa om GPS-tekniken är användbar för fortsatta mätningar av deformationer runt möjliga förkastningszoner i de kommuner som blir föremål för undersökningar av en lämplig plats för ett djupförvar av använt kärnbränsle. GPS- nätverket, bestående av 7 mätpunkter, är lokaliserat över ett område på ca 15 x 15 km^2, på ömse sidor om två förkastningszoner, med möjliga krypdeformationer, som övertvärar området vid Mederhult. GPS-punkterna utgörs av ståldubbar fastgjutna direkt i berget och GPS-antenner är monterade direkt på ståldubbarna med "forced centring", dvs repeterbart utan centreringsfel.

GPS-mätningarna upprepades 3 gånger per år, eller under 6 perioder mellan juni 2000 och februari 2002. Vid varje mättillfälle fastsattes GPS-antenner och mottagare anslöts vid samtliga 7 mätpunkterna under minst 48 timmar. Dessutom användes GPS-data från närmaste SWEPOS station belägen i Oskarshamn som referens för beräkningarna. I huvudsak genomfördes mätningarna utan problem.

Bernese GPS version 4.2 mjukvara användes för att genomföra beräkningarna. Först genomfördes beräkningarna för respektive period för att beräkna lägeskoordinaterna och längden på baslinjerna. Koordinaternas standardavvikelse blev i storleksordningen 1 mm. Baslinjeförändringarna blev mindre än 1 mm/år med undantag för den långa baslinjen till SWEPOS station i Oskarshamn vilken uppgick till 2 mm/år. Men eftersom motsvarande standardavvikelse var i storleksordningen mellan 0.5 och 1 mm/år är de uppskattade baslinjehastigheterna inte av betydelse utan hypotesen om noll-hastighet håller. Ytterligare data från framtida GPS-kampanjer kan ändra eller bekräfta denna slutsats.

Mätningarna har genomförts under en period av tidvis stora jonosfäriska störningar. GPS-utrustningen har inte varit helt idealisk för ändamålet. Trots detta tyder mätresultatet på att metoden fungerar tillfredsställande. Som slutsats beaktande de speciella problemen med jonosfäriska störningar som inte kunde undvikas och att den totala observationsperioden bara var 20 månader kan vi visa att den aktuella GPS-tekniken ger en mycket hög noggrannhet i position och genom att mätningarna upprepas vid många tillfällen (3 ggr/år), kan positionsförändringar om ca 1 mm/år bestämmas efter 2–3 års mätningar. Precisionen och tillförlitligheten ökar ytterligare om mätningarna utsträcks till flera år. Metoden kan därför användas för övervakning av eventuella små rörelser i berggrunden.

Summary

A feasibility study of using GPS technology for monitoring possible crustal “creep” motions as part of the long-term site investigations for the decision on site location of nuclear waste disposal has been carried out in an established test network near Oskarshamn in the south east of Sweden. The network, consisting of 7 points, is located in an approximate area of 15 x 15 km^2, and two possibly active faults in the crust cross the area. The points are realized by steel pegs, installed and cemented into boreholes in the bedrock, and the GPS antennas are mounted directly on top of the steel pegs by so-called forced centring, i.e. repeatedly without any centring bias.

The GPS data were measured 3 times per year, or in total at 6 epochs, between June 2000 and February 2002. At each epoch GPS receivers occupied all 7 sites for at least 48 hours of measurement. In addition, data from the nearest SWEPOS GPS station at Oskarshamn was used as a reference for the analysis. In general the observations performed well without many problems.

The Bernese GPS software version 4.2 was used to adjust the data. First, the adjustment was performed epoch by epoch to determine site coordinates and baseline lengths. The achieved coordinate standard error is of the order of 1 mm. The baseline evolutions were found to be less than 1 mm/yr, except for the long baseline to the SWEPOS station, which reached 2 mm/yr. However, as the corresponding standard errors are of the order of 0.5 and 1 mm/yr, respectively, the estimated baseline velocities are not significant, but the hypothesis of zero-velocities holds. Further data from future GPS campaigns may change or confirm this conclusion.

Second, the GPS software was used to merge the epoch-wise results into final site coordinates and their temporal variations.

A special theoretical investigation by linear regression was carried out to estimate a scale factor of the formal standard errors of coordinates and their temporal changes provided by the Bernese software. It was concluded that a scale factor of about 10 is appropriate. Using this scale factor the estimated standard errors of site velocities vary between 0.4 and 0.8 mm/yr, and Student t-tests on estimated coordinate shifts versus their standard errors satisfy the hypothesis of no crustal motion within the investigated period of time.

The following special problems during the test should be notified. First, the data were collected during a period of extreme sun spot activity, leading to some likely ionosphere biases. Second, it was not possible, as was planned, to use exactly the same GPS antenna at each site and observation epoch. This problem may have led to some eccentricity biases and enlarged standard errors of estimated site velocities. This problem should be easy to solve in an operational application of the method.

Finally, we have carried out a simple theoretical comparison of site velocity standard errors between our monitoring technique by epoch-wise campaigns and continuous GPS data collection with 3-day averaging of data. The result is that the standard error of the latter method is approximately 6 times smaller, independent of total period of observation. If the epoch-wise technique is extended to one observation campaign/month, this

ratio decreases to 3. However, the estimated advantage of the continuous monitoring technique might be too optimistic, as we have not considered the likely correlation among such data.

In conclusion, considering the special problems discussed above that could be avoided in an operational monitoring network, and that the total observation period was only 20 months, we think that we have proved that our technique can be an excellent tool in monitoring any site motion of the order of 1 mm/yr within 2–3 years of epoch-wise observation campaigns. The precision and reliability of the method will, of course, increase even further with time.

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1 Introduction

By the Swedish Nuclear Fuel and Waste Management Company (SKB) the Swedish government has decided to investigate various locations for possible long-term disposal of nuclear waste. These site investigations, which will run for many years, will include the monitoring of the stability of the crust by employing the satellite Global Positioning System (GPS) technology. In order to investigate the suitability and capacity of such a method, SKB has contracted the geodesy group of the Royal Institute of Technology (KTH) in Stockholm to establish and measure a small deformation network near the Äspö Hard Rock Laboratory near Oskarshamn in the south east of Sweden. The goal of the observation technique is to admit the detection of any point motions larger than 1 mm/yr after 2–3 years of data collection. This report evaluates the results of the pre-study.

1.1 GPS observation errors and their reductions

There are a number of error sources in GPS observations. In GPS navigation one uses the code observable with a fundamental wavelength of 300 m for the generally available C/A code. As a rule-of-thumb the noise level is about 1/100 of the wavelength of the signal, which becomes 3 m in the present case. Such a noise would be too imprecise for our application. Instead geodetic GPS receivers use the phases of the 19 and 24-cm carrier wavelengths on L1 and L2, respectively, as the primary observables. This corresponds to a noise level of about 2-mm for the raw observable. As explained below, the observable that is used in the final network adjustment is the double difference of phase observations, corresponding to a random error of about 4-mm. In the case of static observations (which applies to our deformation measurements), the noise level is diminished even further in the average by carrying out the observations for at least 48 hours.

The raw phase observation is a function of the distance from the satellite to the observation point. If the satellite positions were known, three such distances, if correctly determined, would be sufficient for intersecting the position of the observer in three-dimensional space (i.e. three observations suffice to determine three coordinates). The low noise discussed above would not greatly harm such a solution, provided that the geometry of the satellites versus the receiver is good.

Unfortunately, there are a number of systematic error sources that deteriorate this otherwise excellent observation scheme. These comprise the uncertainties of satellite position and clock, the velocity of the signal in the atmosphere, multipath of signal, satellite azimuth and elevation dependent antenna phase centre, eccentric position of antenna, hardware delay of signal and receiver clock instability. All GPS softwares utilize standard atmospheric models to estimate the signal delay in the ionosphere and troposphere. A standard trick to reduce (or even eliminate some) error sources is to take differences between the simultaneous observations from two GPS receivers and two satellites, which observable is called a double difference. This concerns the clock errors, satellite positions and atmospheric errors.

For some of these systematic errors, such as the errors by the atmosphere, the systematic error reduction by this difference observable is dependent on the baseline length between the receivers. Most annoying for baselines longer than, say, 15 km is the signal delay caused by the ionosphere. (For the most precise applications the ionosphere effect might be significant also for shorter ranges.) A ionosphere bias can be eliminated by the so-called ionosphere-free linear combination (L3) of the L1 and L2 phase observations at the price of 3.6 times increased noise level. For shorter baselines it must therefore be judged if the use of L3 is worth this price. Usually, this is not the case.

The positions of the GPS satellites are nowadays very well predicted by the International GPS Service, which provides orbital information to the user.

Multipath is reduced if the observation site is selected with care in an open space without reflecting surfaces in the surrounding. Also, the most advanced choke-ring antennas efficiently reduce multipath.
Antenna phase centre variation can be controlled by individual calibration of each antenna.

For precise deformation analyses it is important that the error caused by an eccentric positioning of the antenna is eliminated by so-called forced centring.

The carrier phase observations cannot be fully explored unless the integer phase ambiguities (i.e. the numbers of full cycles of the satellite-to-receiver ranges) have been determined. Noisy and biased data will inevitably impair the possibility of fixing the ambiguity, and if caution is not taken, the wrong ambiguity might be fixed. As the carrier wavelength is about 20 cm, each erroneous cycle corresponds to an erroneous satellite-to-receiver observation of this magnitude. For precise GPS positioning it is therefore a necessity to reliably fix the integer ambiguities. However, in the case of static observations for sessions of several hours of duration with baselines not exceeding, say, 15 km and good observation conditions, there should be no problem to meet the demands.

1.2 The design of the established GPS network

A GPS network consisting of 7 steel benchmarks fixed in the bedrock was established close to Äspö. The network is located across two possibly active faults near Oskarshamn /SKB, 2000/, within an area of the order of 15×15 km^2 (see Figure1-1). Each point consists of a steal peg with screws cemented directly into the bedrock (see Figures 1-2 and 1-3), and a GPS antenna can be installed on the peg (see Figure1-4). The main advantage of this method is that the position of the antenna will be fixed to the rock in an economic way without a possible eccentricity error. However, as the antenna phase centre is located only about 10 cm above the ground, two problems may deteriorate the GPS observations. The first one is that grass and small bushes close to the antennas will directly disturb the satellite signals. Although bushes and trees near to the sites were cut down and checked for each observation campaign, some vegetation always remains and

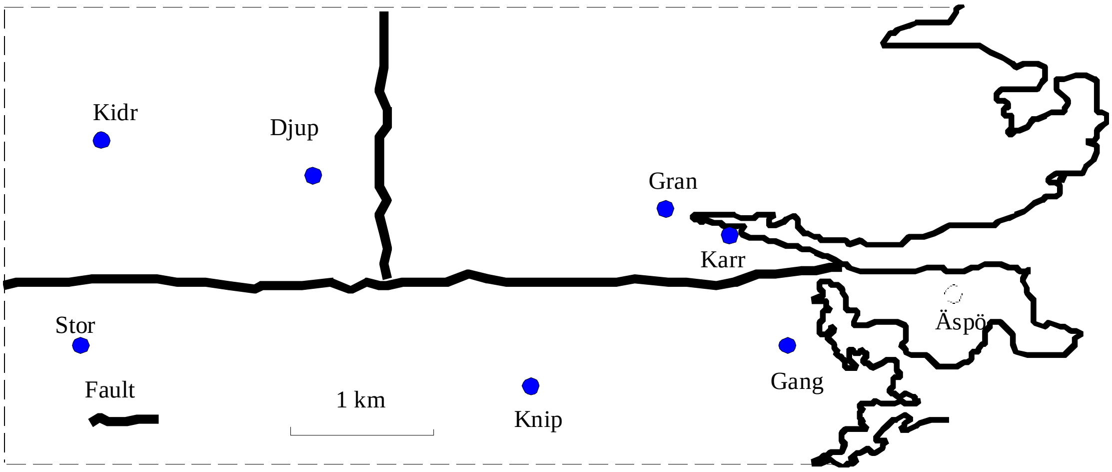

***Figure 1-1.** The Äspö GPS monitoring network with two possible active faults.*

***Figure 1-2.** The steel components used to install an antenna on the ground.*

Figure 1-3. *The steel screw components fixed to the rock.*

Figure 1-4. *The chokering antenna with a Trimble GPS receiver at site Knip in June 2000.*

prevents full visibility of satellites (see Figure1-4). The second problem is multipath as discussed in Sec.1.2. To diminish these bad effects Dorne Margolin chokering antennas were used (see Figure1-4), instead of the ordinary Trimble Compact L1/L2 GP antennas. Some experiments have shown that such antennas may efficiently reduce the noise from the multipath effects /Jaldehag et al., 1996 and Vermeer, 1997/. In addition, the chokering antennas (Dorne Margolin T) are also used at the national SWEPOS stations, which allow us to avoid an antenna-mixing problem with possible bias when also employing such data (see below Sec. 2.2).

2 GPS observations

The GPS data to be used in this analysis consists of six epoch GPS campaigns as well as data from the SWEPOS station at Oskarshamn. This chapter describes the data.

2.1 The six GPS campaigns from 2000 to 2002

Six GPS campaigns were carried out between 2000 and 2002, each for three days, namely 27–29 of June and 26–28 of September in 2000, 16–18 of January 12–16 of June and 16–19 of October in 2001 and 20–22 February in 2002. The measurements were recorded at 15-second intervals for a total of 50 hours at each site with Trimble 4000 SSE GPS receivers. As memory capacities of receivers were not so large, the data had to be transferred from the receivers to personal field computers after about eight hours of measurements.

As a precaution to antenna location biases the antenna serial numbers were recorded at every site. In this way one would be able to use the same antenna at each site during each GPS campaign. Unfortunately, as KTH is not in the position of the needed type of precise GPS antennas, these had to be on loan for each campaign. As a result, it was not always possible to get the same set of antennas.

Surface measurements of temperature, pressure and relative humidity were not recorded during the campaigns, as long experience has proved that such information does not improve the results.

Generally, the measurements were successful, but the following exceptions should be noticed:

- In the June campaign of 2000 one receiver at site Knip was damaged and stopped functioning by heavy rain. A spare receiver was installed after some time.

- In the June campaign of 2001 the chokering antenna at site Gang failed to get the satellite signal (see Figure 2-1) and the original Trimble Compact L1/L2 GP antenna had to be used to measure about 48 hours. After that, an extra 24-hour observation session was arranged for four sites (Knip, Djup, Karr, and Gang) using chokering antennas.

- In February 2002 the receiver at site Karr (Figure 2-2) somehow slipped down on the rock (maybe by animals), and as a result, the power was disconnected and ca. eight hours of data was not recorded.

- On 22nd February 2002, at the end of the last GPS campaign, a strong snowstorm stroke a major part of Sweden (Figure 2-3). The GPS measurements were cut down about one hour.

Figure 2-1. *The chokering antenna failed to work at the site Gang in June 2001.*

Figure 2-2. *The receiver at the site Karr in the February campaign of 2002 was knocked down somehow and it lost eight-hour data.*

Figure 2-3. *The approaching storm at Oskarshamn on 22nd February 2002.*

2.2 SWEPOS

In 1991 the National Land Survey of Sweden in co-operation with Onsala Space Observatory, Chalmers University of Technology started to build up the Swedish network of permanent reference stations (SWEPOS) /Hedling and Jonsson, 1995/. The first six test stations were successfully operating in 1992, and today the continuously operating network consists of 25 SWEPOS stations unified throughout Sweden. The major application include geophysical research (measuring three-dimensional crustal rates of deformation at continental scale with sub-mm per year resolution as well as geodesy (establishment and maintenance of reference system) and rapid positioning in real-time for surveying and navigation with an accuracy of about 1 m, and in the future the CICERON service is expected to provide even better accuracy.

The nearest SWEPOS station Oskarshamn (see Figure 2-4), close to the Äspö network, was used in our processing in order to get excellent a priori co-ordinates in the International Terrestrial Reference Frame (ITRF). The Terrestrial Frame Section of International Earth Rotation Service is in charge of producing and maintaining the ITR System (ITRS). The coordinates and their velocities of the ITRF reference stations are calculated by precise space geodetic techniques, such as Very Long Base Interferometry, Satellite Laser Ranging, Lunar Laser Ranging and GPS, to optimise the realisation of the ITRS, which is then called the ITRF /Sillard and Boucher, 2001/. The working reference system of an individual analysis is generally conventionally defined in such a system. In this way the motion of the Äspö network can be analysed relative to the SWEPOS station (Oskarshamn) defined in the ITRF.

Figure 2.4. *The SWEPOS station Oskarshamn with a chokering antenna.*

3 General description of the processing method

As described above, the chosen strategy for GPS observation is epoch-wise campaigns. Primarily, the GPS observations of the Äspö GPS network were also processed epoch by epoch. Hence, the data was adjusted by the new version 4.2 of the Bernese GPS software /Hugentobler et al., 2001/. As the network consists of seven sites about 5 km apart within an area of 15×15 km^2 approximate size, and the SWEPOS station Oskarshamn is about 60 km away from the network, two methods were used for the computations, namely the standard techniques for short or long baselines, respectively. The major guidelines on how we dealt with the data are briefly described below:

- First, the coordinates of station Knip was determined by adjusting the observations from the long baseline Oskarshamn to Knip by keeping Oskarshamn fixed to its ITRF97 /Boucher et al., 1999/ coordinates provided by SWEPOS. The primary measurement was the L3 ionosphere-free linear combination dual frequency phase observable.
- Second, station Knip was kept fixed for the Äspö network, and daily solutions were processed using L1 phase observations /Hugentobler et al., 2001/.
- 10° elevation mask was used, and all available observations were recorded at 15-sec observation rate.
- Correlations between the baselines were correctly modelled.
- The "geometry-free" linear phase combination

$$L_4 = L_1 - L_2 \tag{1}$$

was used for the estimation of a regional ionosphere model. [Notice that L_4 is independent of receiver clocks and geometry (orbits, station coordinates); Rothacher et al., /1996/. It only contains the ionosphere delay and the initial phase ambiguity.] From the L_4 observations the following observation equations were processed [Eq. (13.9a) of Hugentobler et al., 2001]:

$$L_4 = -a\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)F_I(z)E(\beta, s) + B_4 \tag{2}$$

where L_4 is in units of metres, a is a constant, f_1 and f_2 are the frequencies of the carriers L_1 and L_2, $F_I(z)$ is a mapping function (considered as known) evaluated at the zenith distance z, B_4 is a constant bias and $E(\beta, s)$ is the vertical Total Electron Content (TEC) as a function of geographic or geomagnetic latitude β and sun-fixed longitudes.

The regional TEC model, that was applied in the vicinity of one or more dual-frequency stations, was represented by the power series /Eq. (13.10) of Hugentobler et al., 2001/:

$$E(\beta, s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{m_{max}} E_{nm} (\beta - \beta_0)^n (\lambda - \lambda_0)^m, \qquad (3)$$

where n_{max} and m_{max} are the maximum degrees of the two-dimensional Taylor series expansion in latitude β and in longitude λ, respectively, β_0, and λ_0 are the coordinates of the origin of the development, and E_{nm} are the unknown TEC coefficients of the Taylor series to be estimated in the local model.

For example, on 18th January 2001 a regional ionosphere model was estimated for the Äspö network with n_{max} and m_{max} set to 1 with the following result:

$E_{00} = 1.0598 \pm 0.0061$ $E_{01} = 0.3357 \pm 0.0017$

$E_{10} = -0.3511 \pm 0.0026$ $E_{11} = -0.0495 \pm 0.0013$.

Once these parameters have been estimated, the ionosphere delay $\delta\rho^i{}_{ion}$ for the observation carrier L_i can be estimated by the formula /Spilker, 1978/:

$$\delta\rho^i{}_{ion} = -41 E(\beta, s) / (f_i \cos Z), \qquad (4)$$

where Z is zenith distance at the so-called ionosphere point.

- Precise GPS satellite ephemerides were used, offered by the International GPS Geodynamics Service (IGS) in the ITRF97 system for the 2000 and 2001 campaigns, but for the 2002 campaign ITRF00 was offered. The precise orbits of the 2002 campaign were transferred from ITRF00 to ITRF97 at the observation epoch using a seven-parameter Helmert transformation.

- The phase ambiguities were resolved independently on L1 and L2 phase observations using the SIGMA algorithm for short baselines, and for the long baselines from Oskarshamn to the network the Quasi ionosphere-Free (QIF) strategy was used.

- The data was processed session by session (or day by day), and normal equations (NEQ) of all the sessions were stored. Then, the results were combined to obtain final solutions of the campaign, using the combination program ADDNEQ and calculating repeatablities of estimated coordinates as internal accuracy of the campaigns.

- Site velocities of the Äspö network were estimated using the ADDNEQ program, and only horizontal velocities were solved. (The total time span of 20 months was too short to solve for the vertical component.)

A set of reference values of a standard atmosphere at sea level was used in the Saastamoinen’s /1973/ model for troposphere corrections. Naturally, the standard model can not describe actual meteorological conditions. Additional troposphere parameters, troposphere zenith delays, were estimated together with the other parameters. One absolute and three relative parameters, both with an a priori accuracy of 5 cm, were included per station and session for each campaign. Estimation of tropospheric zenith path delays was carried out in 6-hour intervals for the network and 4 hours intervals for the Knip-Oskarshamn baseline.

In order to save computer time, the normal equations of each session were stored. Then, all sessions were combined to get a final campaign solution. This was done in the program ADDNEQ. In addition to the above-described parameters, the previously fixed parameters could be estimated as well. The program ADDNEQ only uses the stored normal equations without taking care of the original observations. This program may simplify and considerably accelerate the calculations.

4 Results of network adjustments

In processing the GPS carrier phase observation data, the coordinates of one station is usually held fixed (as known) in the ITRF system [as precise orbits were used in the ITRF system provided by the International GPS Geodynamics Service (IGS)]. Deviation of the coordinates from their true values may introduce errors to the calculated baseline components. The standard method to determine the coordinates of a fixed station of a network is by so-called single point positioning (i.e. point determination by a single receiver) with an accuracy of several metres, which is not sufficient for our purpose. Fortunately, one way out of this problem is to connect the fixed station to a reference station (in this case Oskarshamn, controlled by SWEPOS). The coordinates of the Oskarshamn station are listed in Table 4-1 in the ITRF96 system offered by SWEPOS. As the precise ephemerides were used, offered by (IGS) in the ITRF97 system, the coordinates of the Oskarshamn station had to be transferred from ITRF96 to ITRF97 at the observation epoch using a seven-parameter transformation.

Table 4-1. The coordinates of the reference station offered by SWEPOS at the epoch 1999.3 in the ITRF96 system.

Station	X(m)	Y(m)	Z(m)
Oskarshamn	3341339.982	957912.421	5330003.341

As mentioned above, L_1 double difference phase data was used for the relatively short baselines within the network. The regional ionosphere model (3) was used to correct for the ionosphere delays. For the long baseline from Knip to Oskarshamn, the L_3 combination was processed separately.

The data were processed as day-by-day sessions, and normal equations (NEQ) of all the sessions were stored. After that, the results were combined to a final solution of each campaign, using the combination program ADDNEQ.

As baseline lengths of the network are only about 5 km, except of the baseline from Oskarshamn to the rest of the network (about 60 km), in general, about 95% of the ambiguities were resolved. Some ambiguities could not be resolved due to satellite signals destroyed by trees, multipath, or ionosphere activity. The ionosphere activity is strongly correlated with the sunspot activity, and the solar activity may be characterised by an 11-year cycle. The most recent ionosphere maximum occurred in 1989/1990, and the ionosphere activity was also rather strong during our observation campaigns, reaching a new maximum at the end of 2001 as was expected (see Figure 4-1). There is thus a risk that the increased ionosphere activity has considerably affected our observation results.

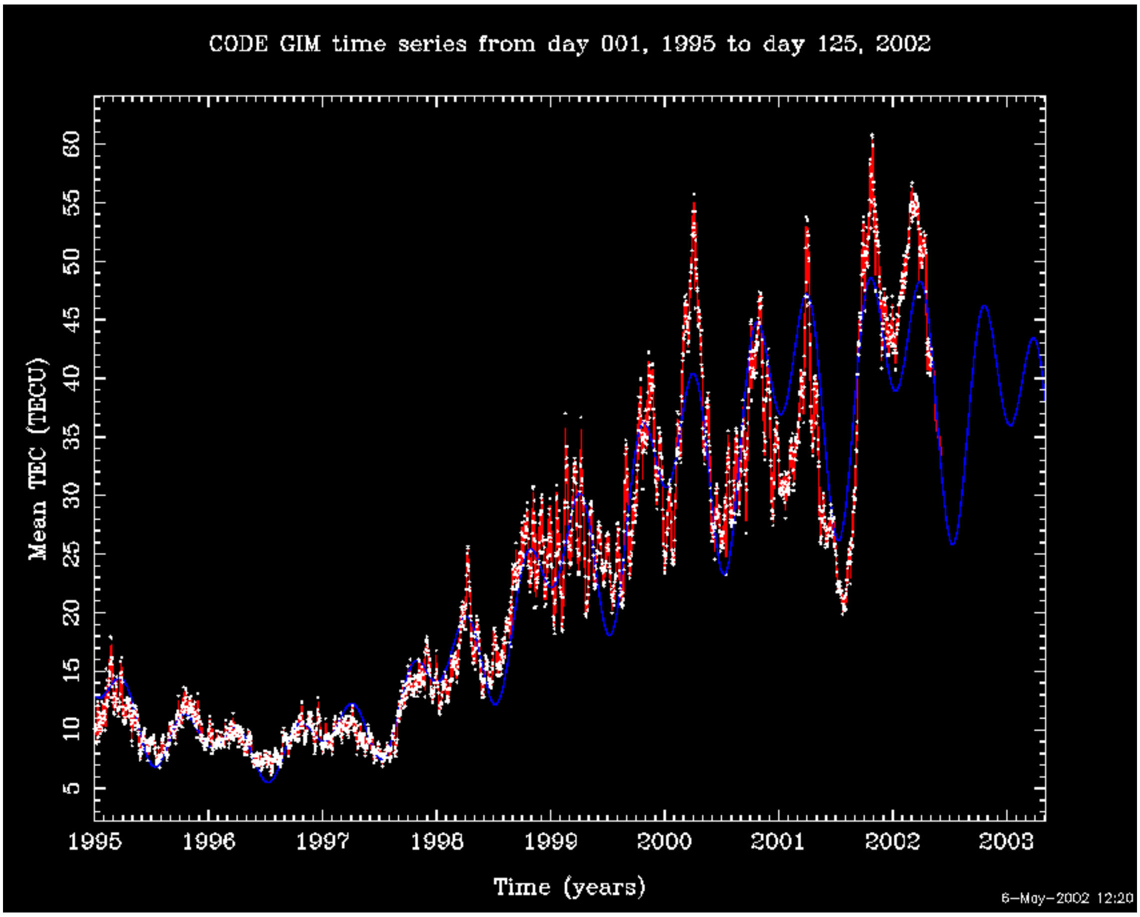

Figure 4-1. *The ionosphere activity in units of TEC for the period 1995–2003 (from IGS). Note: red line represents the real ionosphere activity and green line is the predicted activity. 1 TEC = 10^{16} electrons per m^2.*

4.1 Internal precisions of campaigns

One way to assess the quality of the overall solution is to estimate coordinate repeatabilities (or standard errors), which show internal consistencies that can better reflect the real GPS precisions than the standard errors obtained directly in the network adjustments. Then the results of the site coordinates for each individual epoch campaign are compared with the combined solution from all epochs. The coordinate repeatabilities (as unweighted standard errors) in the local north-east-up coordinate system are given in Tables from 4–2 to 4–7 in units of mm. Station Knip is kept fixed in these solutions. The tables show that horizontal precision is about 1 mm with a maximum of 1.6 mm (site Karr in June 2000). The vertical precision is about 3 mm with a maximum of 7 mm (site Stor in June 2001). Hence, as one would expect, the vertical precision is worse than for the horizontal component. (The reasons are that the vertical components are much more affected by the variable influences of the troposphere, and of the satellite configuration with satellites only 10° and higher above geographic horizon.

Taking a closer look at the result, one can see that the repeatabilities of the campaigns during 2000 are somewhat worse than those of 2001 and 2002. See e.g. coordinate repeatablities. The standard errors of the campaigns in 2000 were about 2 mm, but about 1.5 mm for the remaining campaigns. Much more bad data was deleted from the 2000 campaigns in comparison with the 2001 and 2002 data.

The precision of the longest baseline from Knip to Oskarshamn was almost the same as those of the short baselines of the Äspö network (see Tables 4-2 to 4-7), although the baseline is about 60 km long and estimated by the ionosphere-free linear combination L_3. It is likely that there are some un-modelled ionosphere biases in the estimates by the regional models (3)+(4).

The chokering antenna at site Gang failed to work in the June campaign 2001, and the original Trimble Compact L1/L2 GP antenna was then used to measure the remaining 48 hours. After that a new 24-hour observation session was arranged for the four sites Knip, Djup, Karr, and Gang using chokering antennas. A comparison of the internal precisions obtained for the original and chokering antennas at site Gang is listed in Table 4-8. As one would expect, the table reveals that the precision by the chokering antenna is better than by the original antenna. There is also some significant systematic differences between the coordinates determined by the two types of antennas (estimated to 1, 18, and 33 mm in the N-S, W-E and Up directions, respectively), which we refer to the problem of mixing different type of antennas. Hence, the simplest way out of this problem is to delete all observations with the original Trimble Compact antenna.

Despite of some observation problems, as described in Sec. 2.1 that eight hours of data were lost at site Karr in the February campaign of 2002, and site Gang measured only 24 hours in the June campaign of 2001 due to failure of the chokering antenna, the estimated precisions were not affected by these data losses. We assume that this positive experience is due to the short baselines of the Äspö network (See Tables 4-5 and 4-7).

Table 4-2. Coordinate repeatabilities (standard errors) for the June campaign in 2000 with respect to fixed station Knip.

Station	N–S (mm)	E–W (mm)	Up (mm)	No. of sessions
Gran	1.1	0.8	2.8	3
Djup	1.0	0.2	3.6	3
Gang	1.2	0.3	1.7	3
Karr	1.6	0.8	2.8	3
Kidr	1.2	0.2	1.8	3
Oskarshamn	0.4	0.6	1.7	3
Stor	0.9	1.0	2.5	3

Table 4-3. Coordinate precisions (std. errors) for the September campaign in 2000 with respect to fixed station Knip.

Station	N–S (mm)	E–W (mm)	Up (mm)	No. of sessions
Gran	1.6	0.2	1.9	3
Djup	1.3	0.3	3.6	3
Gang	0.3	0.2	1.3	3
Karr	1.2	0.3	2.5	3
Kidr	1.2	0.4	2.3	3
Oskarshamn	1.5	0.2	3.8	3
Stor	1.6	0.5	0.5	3

Table 4-4. Coordinate std. errors for the January campaign in 2001 with respect to fixed station Knip.

Station	N–S (mm)	E–W (mm)	Up (mm)	No. of sessions
Gran	0.7	0.3	1.4	3
Djup	0.0	0.1	2.1	3
Gang	0.2	0.1	1.0	3
Karr	0.6	0.2	1.5	3
Kidr	0.2	0.1	2.4	3
Oskarshamn	0.4	0.2	3.9	3
Stor	0.7	0.5	2.4	3

Table 4-5. Coordinate std. errors for the June campaign in 2001 with respect to fixed station Knip.

Station	N–S (mm)	E–W (mm)	Up (mm)	No. of sessions
Gran	0.7	0.2	2.0	3
Djup	1.4	0.5	2.3	5
Gang	0.9	0.2	1.9	2
Karr	0.8	0.6	2.8	5
Kidr	1.5	0.6	5.2	3
Oskarshamn	1.4	1.4	6.9	5
Stor	0.4	0.8	7.0	3

Table 4-6. Coordinate std. errors for the October campaign in 2001 with respect to fixed station Knip.

Station	N–S (mm)	E–W (mm)	Up (mm)	No. of sessions
Gran	0.7	0.3	2.2	4
Djup	0.8	0.5	0.6	4
Gang	0.4	0.2	3.3	4
Karr	0.6	0.3	3.7	4
Kidr	0.7	0.6	1.1	4
Oskarshamn	1.8	0.6	3.8	4
Stor	0.8	0.8	1.2	4

Table 4-7. Coordinate precisions (std. errors) for the February campaign in 2002 with respect to fixed station Knip.

Station	N–S (mm)	E–W (mm)	Up (mm)	No. of sessions
Gran	0.1	0.1	2.1	3
Djup	0.2	0.2	1.7	3
Gang	0.3	0.1	3.5	3
Karr	0.7	0.2	0.8	3
Kidr	0.2	0.3	2.1	3
Oskarshamn	1.1	0.7	2.8	3
Stor	0.0	0.2	1.3	3

Table 4-8. Internal precision using the original and chokering antennas at (std. errors) site Gang in June 2001.

Antenna	N–S	E–W	Up	Sessions
Original	1.2	0.6	4.6	3
Chokering	0.9	0.2	1.9	2

4.2 Preliminary analysis of combined GPS solutions

In the last section the internal precisions were analysed. However, such an analysis tell you nothing about the absolute accuracy of point determination, but merely gives you the scatter among the observations within one observation campaign. We will now assume that there are no internal motions among the stations of our network, but the total network may move as a solid block. The velocity model of the ITRF97 will be used to propagate all epoch solutions to a common epoch (2001.0). By comparing the solutions for coordinates of these individual solutions, we get an idea about the accuracy of theses solutions under the assumption of no internal motions within the network.

The differences from a combined solution of all six individual campaign solutions are listed in Table 4-9. In general, the standard errors among horizontal coordinates are of the order of 1–2 mm, while the vertical errors are larger. In particular, the large vertical error of site Djup is remarkable. This might be due to some local, site related temporal changes of position, but the problem must be further studied. Fortunately, we will only analyse horizontal velocities in this report, due to the limited 20-month span of data. Thus we conclude that any possible un-modelled biases of the adjustment model, such as relative horizontal deformations among the sites of the network, are limited to the order of 1–2 mm.

Table 4-9. The coordinate differences from the mean values of the six campaigns transformed to the common epoch (2001.0) using the velocity model of the ITRF97. Unit: mm.

Station	Comp.	Std. error	2000.6	2000.9	2001.1	2001.6	2001.10	2002.2
Djup	North	1.4	-0.5	0.4	-1.8	-1.2	1.4	1.6
	East	0.7	0.4	0.0	-0.3	-0.3	-1.0	1.2
	Up	15.9	-15.1	-16.3	-11.9	14.0	14.4	15.0
Gang	North	0.7	0.5	0.0	-0.7	0.9	-1.0	0.3
	East	0.4	0.2	-0.2	-0.5	-0.3	0.4	0.4
	Up	2.2	2.1	-3.5	1.6	-1.9	1.3	0.4
Karr	North	0.5	0.0	0.8	-0.2	-0.3	-0.7	0.4
	East	0.6	1.2	-0.5	-0.3	-0.1	-0.4	0.0
	Up	1.6	-0.5	-1.0	-0.1	3.1	0.0	1.6
Kidr	North	1.3	1.6	0.1	-1.2	-1.8	1.1	0.2
	East	1.1	0.9	1.0	0.6	0.0	-2.0	0.5
	Up	2.9	-2.8	-2.8	-1.2	0.5	1.4	4.9
Gran	North	0.7	0.2	0.2	-1.3	0.8	-0.2	0.3
	East	0.7	0.4	0.3	0.9	-1.0	-0.2	-0.4
	Up	2.4	-0.4	0.8	1.7	2.7	-0.6	4.1
Stor	North	0.9	0.4	0.4	0.1	-1.4	-0.8	1.2
	East	1.1	0.9	0.8	-0.6	-1.0	-1.2	1.2
	Up	4.0	-2.0	-1.0	8.0	-2.6	-1.7	-0.7
Oskarshamn	North	2.2	-0.4	-2.1	0.9	-0.1	-2.0	3.7
	East	1.2	-0.9	-0.8	0.7	-0.3	-0.7	2.1
	Up	2.8	-3.9	1.6	0.9	-1.2	-1.7	4.2

5 Baseline length evolution

This chapter is devoted to the analysis of the temporal changes of horizontal baselines of the network. We start to derive a simple theory for estimating the linear change of the baseline (or coordinate) with time from epoch-wise data. Then we apply the theory to estimate the expected accuracy of an analysis of achieved data. Next we apply the theory to the real data, and finally we discuss the expected result for continuous observation with permanent GPS stations.

5.1 Theory: Linear regression of station/baseline velocities

Let the observation equations

$$y_i - \varepsilon_i = a + bt_i \;\; ; \;\; i = 1, \cdots, n \tag{5}$$

represent the temporal evolution of a coordinate or baseline. Here y_i is the observation with the random observation error ε_i, observed at epoch t_i and totally n times. The constants a and b are the unknowns of the equation, where a is the coordinate/baseline at time $t_i = 0$, while b is the coordinate change with time. All the observation equations can be expressed by the matrix equation

$$AX = L - \varepsilon , \tag{6a}$$

where

$$A^T = \begin{bmatrix} 1 & 1 & \ldots & 1 \\ t_1 & t_2 & \ldots & t_n \end{bmatrix} \quad , \qquad X = \begin{bmatrix} a \\ b \end{bmatrix} , \tag{6b}$$

$$L^T = \begin{bmatrix} y_1 & y_2 & \ldots & y_n \end{bmatrix} \tag{6c}$$

and

$$\varepsilon^T = \begin{bmatrix} \varepsilon_1 & \varepsilon_2 & \ldots & \varepsilon_n \end{bmatrix} \; . \tag{6d}$$

Here superscript T denotes the transpose of the matrix. If we assume that all observation errors are random and uncorrelated with expectation zero, the least stuares solution of the system (6) becomes /Bjerhammar, 1973; Sjöberg, 1984; see also Sjöberg, 1982, pp. 19–22/:

$$\hat{X} = \begin{bmatrix} \hat{a} \\ \hat{b} \end{bmatrix} = (A^T A)^{-1} A^T L = \begin{bmatrix} n & \sum_{i=1}^{n} t_i \\ \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} t_i^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} t_i y_i \end{bmatrix} , \tag{7a}$$

with the covariance matrix

$$Q_{\hat{X}\hat{X}} = \sigma_0^2 (A^T A)^{-1} = \sigma_0^2 \begin{bmatrix} n & \sum_{i=1}^{n} t_i \\ \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} t_i^2 \end{bmatrix}^{-1}, \qquad (7b)$$

where σ_0^2 is the so-called variance of unit weight, which can be estimated by the formula

$$\hat{\sigma}_0^2 = \frac{\sum_{i=1}^{n} (y_i - \hat{a} - \hat{b} t_i)^2}{n - 2} \qquad (8)$$

If t_i is substituted by $\Delta t_i = t_i - t_0$, where t_0 is the mean epoch of the total time interval, it implies that $\sum_{i=1}^{m} \Delta t_i = 0$, and Eqs. (7a) and (7b) can be simplified to

$$\hat{X} = \begin{bmatrix} \hat{a} \\ \hat{b} \end{bmatrix} = \begin{bmatrix} \frac{1}{n} \sum_{i=1}^{n} y_i \\ \frac{\sum_{i=1}^{n} \Delta t_i y_i}{\sum_{i=1}^{n} (\Delta t_i)^2} \end{bmatrix} \qquad (9)$$

and

$$Q_{\hat{X}\hat{X}} = \hat{\sigma}_0^2 \begin{bmatrix} n^{-1} & 0 \\ 0 & \left[\sum_{i=1}^{n} (\Delta t_i)^2 \right]^{-1} \end{bmatrix} \qquad (10)$$

Of particular interest to our study are the standard errors of the estimated coordinate (a) and its temporal change (b) obtained from Eq. (10):

$$\hat{\sigma}_{\hat{a}} = \frac{\hat{\sigma}_0}{\sqrt{n}} \qquad (11a)$$

and

$$\hat{\sigma}_{\hat{b}} = \frac{\hat{\sigma}_0}{\sqrt{\sum_{i=1}^{n} (\Delta t_i)^2}}; \qquad (11b)$$

As one would expect, these formulas show that

- The precisions increase with the number of observations and the total time span.
- $\hat{\sigma}_a$ and $\hat{\sigma}_b$ are proportional to the standard error $\hat{\sigma}_0$ of the GPS measurements.

5.2 Expected precision of the Äspö network on a long-time basis

The results of the previous section can be applied to derive expected precision values of the coordinates and site velocities of the network. Equations (11 a, b) give all relations of interest. In the real case we have seen that the Äspö network has a precision (σ_0) of a single coordinate estimation of ± 1.0 mm (with a maximum of ±1.5 mm) and ± 4.0 mm for the horizontal and vertical components, respectively (see Tables 4-2 to 4-7), and the frequency of measurements were three times per year. Inserting these figures into Eqs. (11a,b) one obtains the results of Table 5-1 for observation periods of 2 to 5 years. If one requires that the standard error of $\hat{b}$ should be within 0.3 mm/yr, this goal is reached already after two years of observations, if the standard error of the GPS observations (σ_0) is 1 mm. If the accuracy of the resulting coordinate of a GPS campaign is of the order of 1.5 mm (the worst case in the Äspö network), it takes 3 years to reach the goal. However, if the vertical motion is to be estimated with the achieved precision 4 mm for the vertical coordinate, 5 years of observation are needed.

Comparing the time evolutions of the standard errors for coordinate estimation and velocity estimation ($\hat{\sigma}_a$ and $\hat{\sigma}_b$) of Table 5-1, one can see that the latter decreases more rapidly with time than the former. As we are particularly interested in the precision of the estimated baseline or coordinate change with time, this is a good experience.

Table 5-1. Expected precisions of the velocities and coordinates/baselines after 2 to 5 years of observation period with different data qualities σ_0. n is number of epochs.

		σ_b (mm/yr)			σ_a (mm)		
Yr	n	σ_0 (mm)			σ_0 (mm)		
		1	1.5	4	1	1.5	4
2	7	0.31	0.47	1.26	0.41	0.61	1.63
3	10	0.18	0.27	0.71	0.33	0.50	1.33
4	13	0.12	0.18	0.47	0.29	0.43	1.15
5	16	0.09	0.13	0.34	0.26	0.39	1.03

However, the above results are based on the assumptions that the observations are free from gross and systematic errors, and that the observations are uncorrelated and with equal variance. In order to check that these assumptions are fulfilled one needs additional data. That is, to reliably check the results, data must be collected over a longer period of time than shown in Table 5-1.

5.3 Bernese results for baseline length evolutions

The temporal changes of each baseline can be estimated from the results of the epoch-wise adjustments by the Bernese software module ADDNEQ. The results of the baseline lengths and the associated velocities are given in Figures 5-1 to 5-7. The figures show that the baseline lengths from Knip to Gran, Karr, Gang, and Stor change about –0.5 to +0.3 mm/yr. The baselines from Knip to Djup, Kidr, and Oskarshamn differ from the previous group by baseline evolutions of 0.9, 1.1 and -1.8 mm/yr, respectively. Here it is notable that the two sites Djup and Kidr belong to the same block (see Figure1-1). If we check the Figures 5-1, 5-5 and 5-7 carefully, the data shows that the residuals of the baseline lengths Knip-Djup and Knip-Kidr jumped from -0.7 and -1.2 mm to plus +1.7 and 2.2 mm, respectively, in the October campaign 2001. If these data are deleted, their baseline length evolutions become those of Figure 5-8. Then the velocities of the baseline lengths decrease from about 1 mm/yr to 0.3 mm/yr. In a similar way the baseline length residual Knip-Oskarshamn suddenly changed from plus 2.2 mm to minus -3.9 mm in the February 2002 campaign (see Figure 5-7). If this out-lying data is deleted, the estimate of the baseline length with time changes from -1.8 mm/yr to 0.3 mm/yr. From Figure 4-1 we can see that at both events (October 2001 and February 2002) there are extreme ionosphere activities. Consequently, one may suspect that un-modelled ionosphere biases caused the outlying residuals of these baselines.

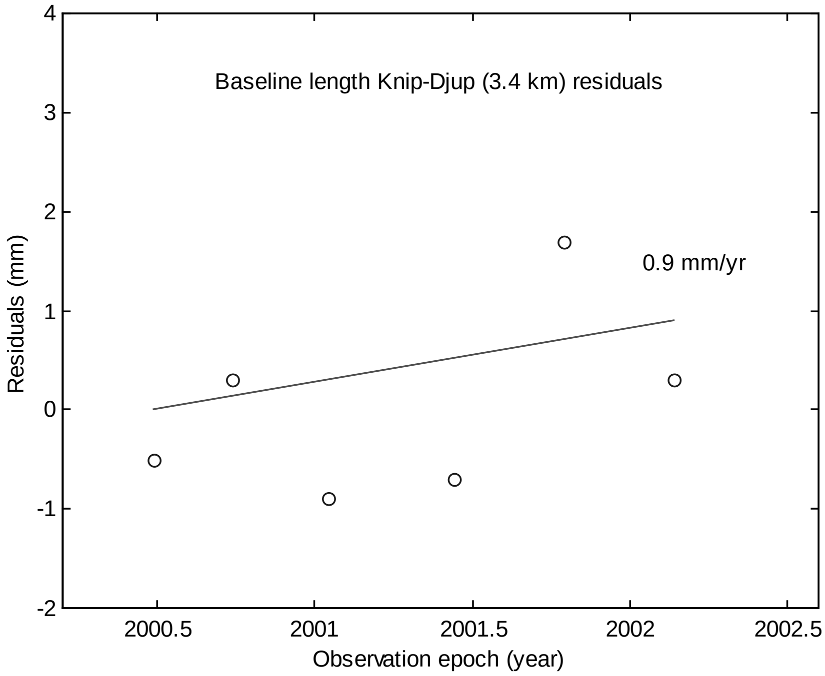

Figure 5-1. *The residuals of the baseline length Knip-Djup and the velocity value.*

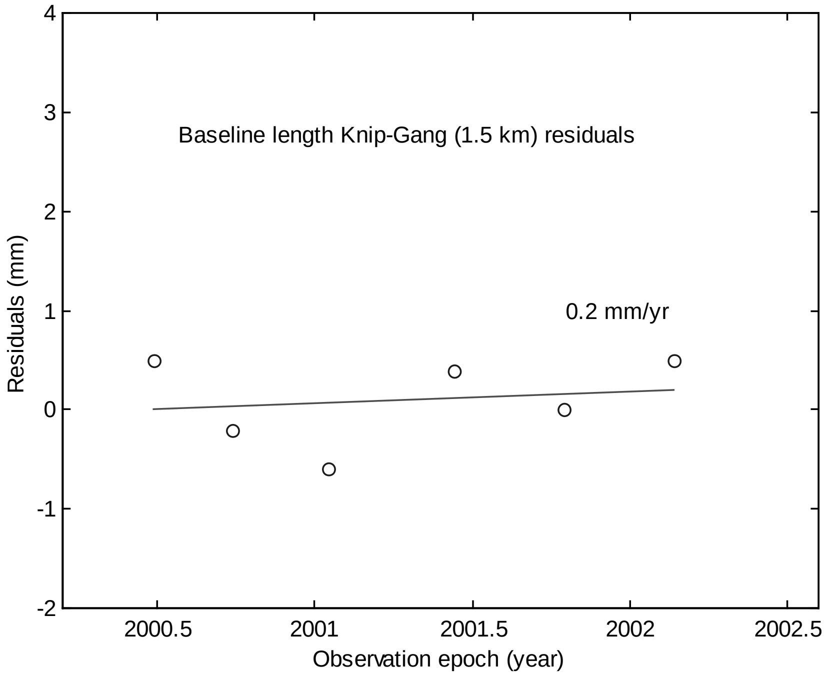

Figure 5-2. *The residuals of the baseline length Knip-Gang and the velocity value.*

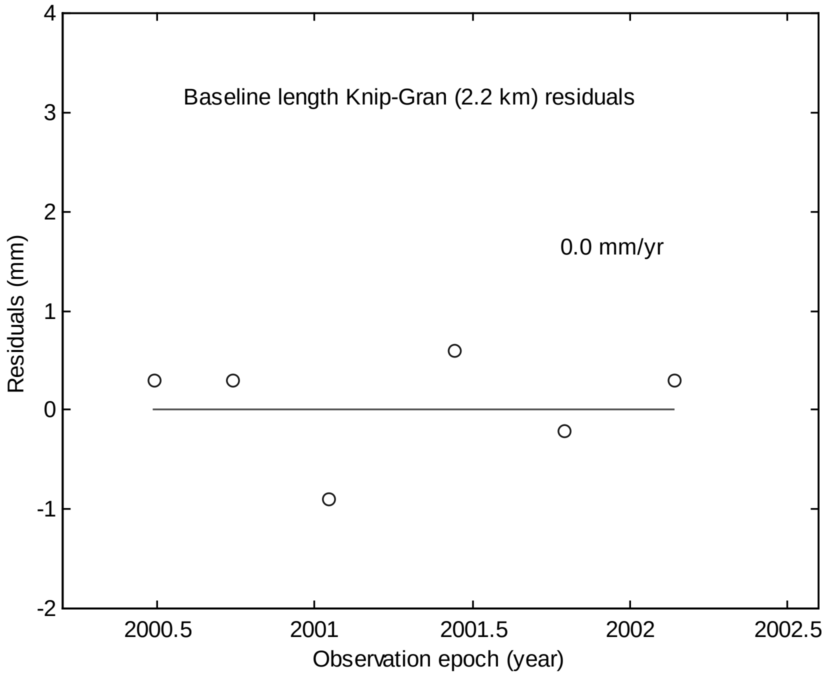

Figure 5-3. *The residuals of the baseline length Knip-Gran and the velocity value.*

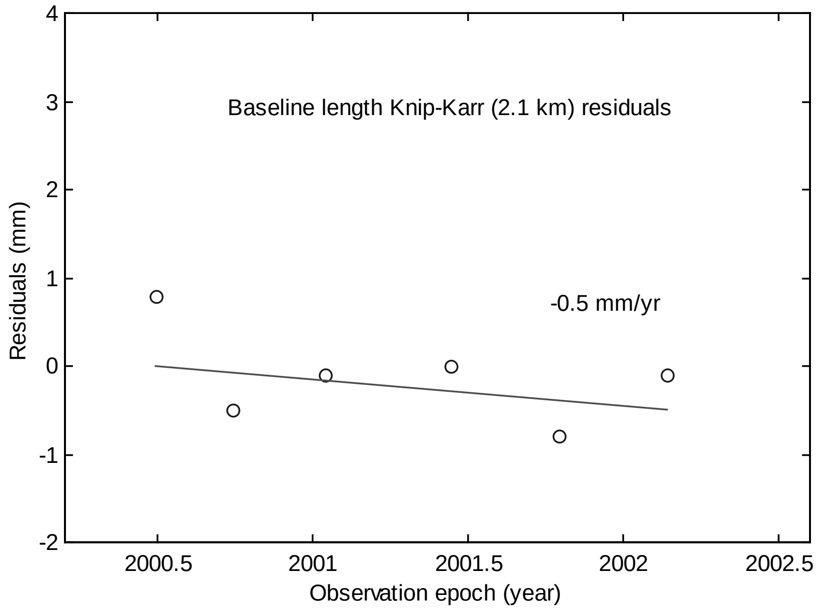

Figure 5-4. The residuals of the baseline length Knip-Karr and the velocity value.

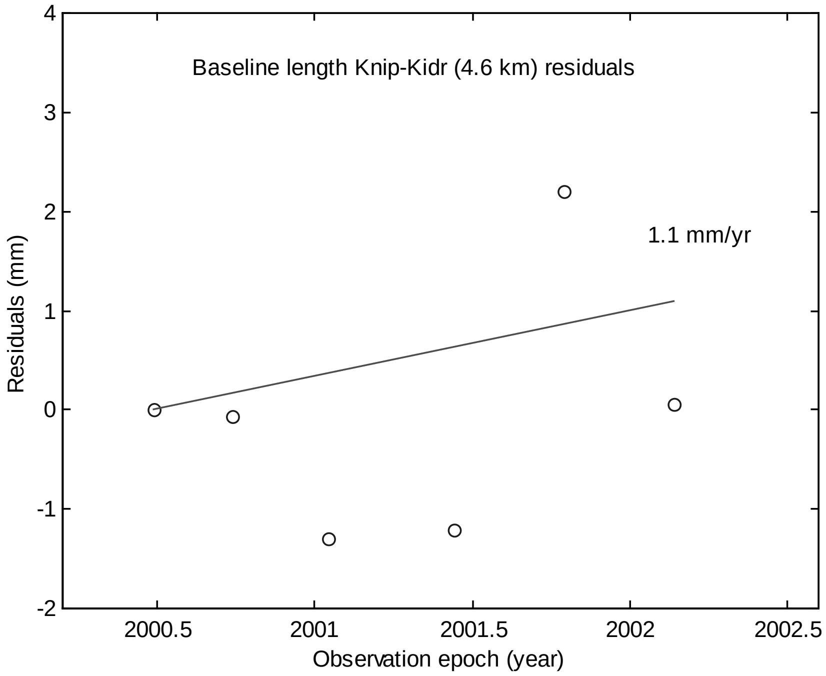

Figure 5-5. The residuals of the baseline length Knip-Kidr and the velocity value.

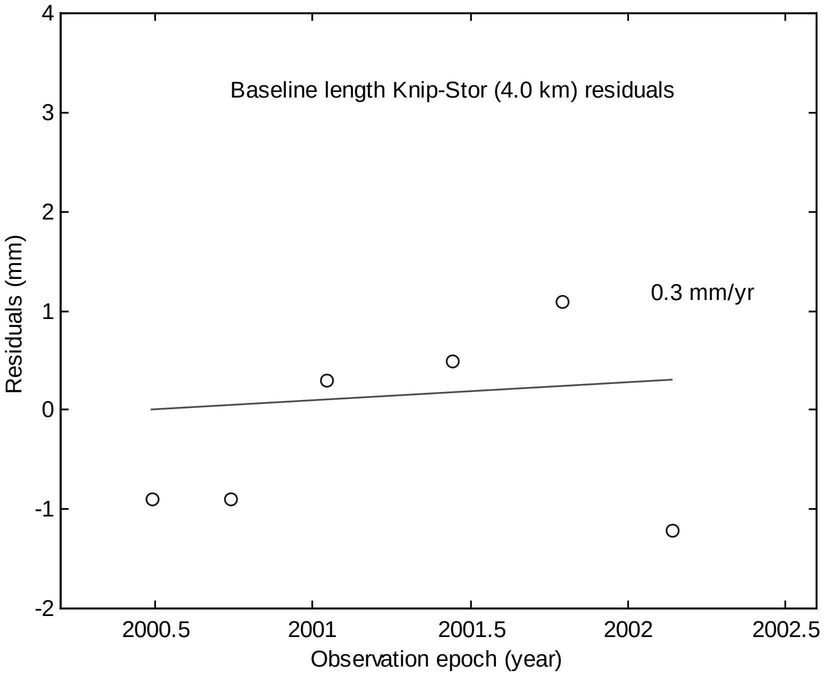

Figure 5-6. *The residuals of the baseline length Knip-Stor and the velocity value.*

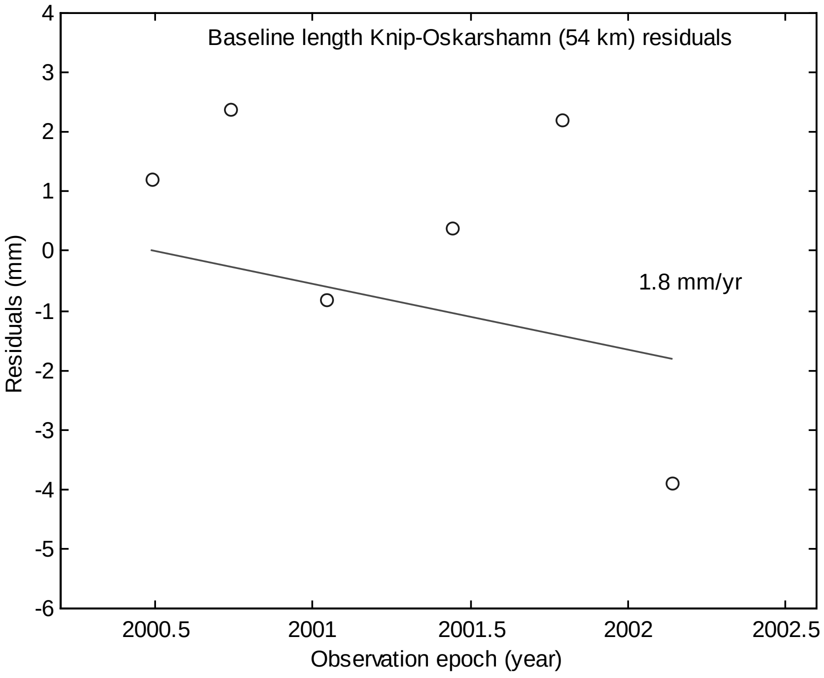

Figure 5-7. *The residuals of the baseline length Knip-Oskarshamn and the velocity value.*

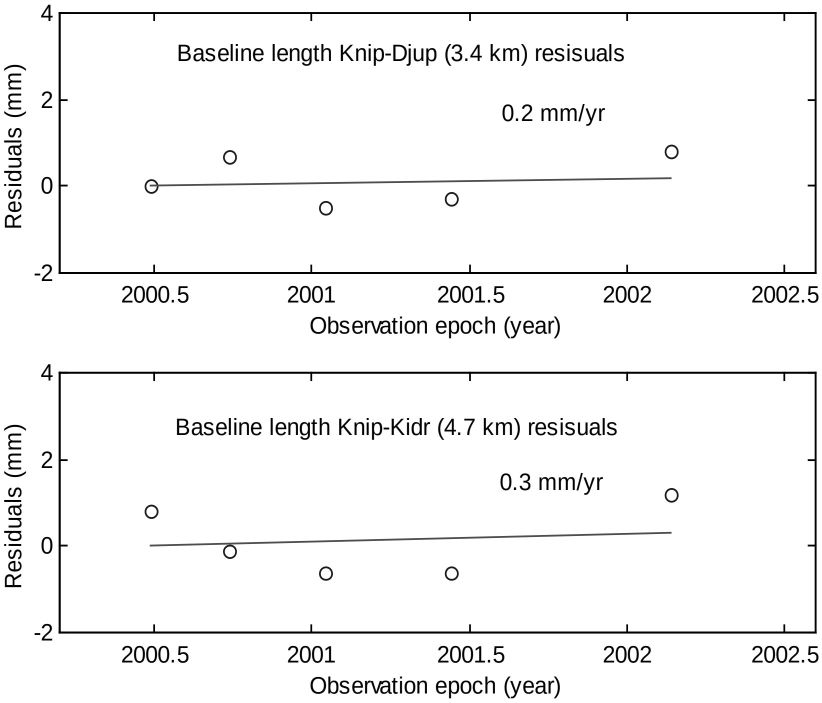

Figure 5-8. *The residuals of the baseline length Knip-Djup and the estimated velocity without using the data of October 2001.*

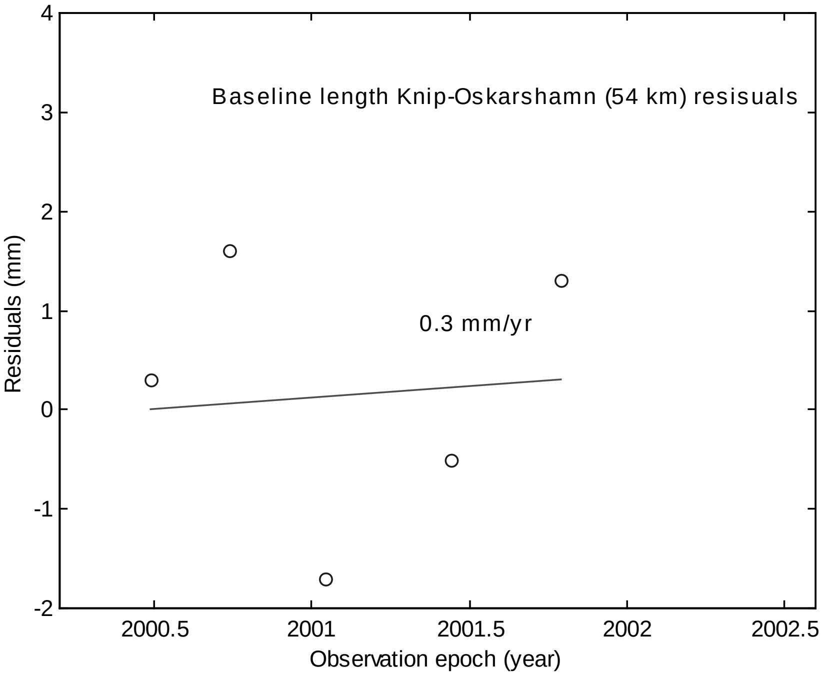

Figure 5-9*. The residuals of the baseline length Knip-Oskarshamn and the estimated velocity without using the data of February 2002.*

5.4 Epoch-wise versus continuous GPS campaigns

If we assume that the GPS data is recorded continuously, it is reasonable to compile the data, say, into 3-day averages. Also in this case Eqs. (11a,b) can be used to estimate the resulting standard errors of coordinate (or baseline length) and its change with time. However, for a large data set with equal time intervals (ΔT), it is useful to simplify the previous equations as follows.

In general it holds that $\Delta t_i = (i - 1 - \frac{n-1}{2})\Delta T$, and for an odd number of (n) epochs one obtains

$$\sum_{i=1}^{n} (\Delta t_i)^2 = (\Delta T)^2 S(\frac{n-1}{2}) \tag{12a}$$

where

$$S(\frac{n-1}{2}) = 2\sum_{i=1}^{\frac{n-1}{2}} (i-1)^2 = \frac{n(n^2-1)}{12} \tag{12b}$$

If the number of epochs is even, it follows that

$$\sum_{i=1}^{n} (\Delta t_i)^2 = 2\sum_{i=1}^{\frac{n}{2}} (\Delta t_i)^2 = \frac{(\Delta T)^2}{2}\sum_{i=1}^{\frac{n}{2}} (2i-1)^2 = \frac{(\Delta T)^2}{2}[S(n-1) - 4(S(\frac{n-2}{2})] \tag{13a}$$

where

$$S(m) = 1^2 + 2^2 + ... + m^2 = \frac{m(m+1)(2m+1)}{6} \tag{13b}$$

Let us now compare the velocity standard errors for velocity estimates of epoch-wise strategy with 3 epochs per year and continuous observations with 3-day mean values of data. In both cases the result is given by Eqs. (11b) and (12a,b) with ΔT set to 1/3 and 1/120, respectively. In the former case the standard error after y years (with m_e = 3y+1 epoch campaigns) becomes

$$\sigma_{b_{ep}} = \frac{6\sqrt{3}\sigma_0}{\sqrt{m_e(m_e{}^2 - 1)}}, \tag{14}$$

while in the case of permanent observations with m_p = 120y+1 epoch campaigns one obtains

$$\sigma_{b_{perm}} = \frac{240\sqrt{3}\sigma_0}{\sqrt{m_p(m_p^2 - 1)}} \tag{15}$$

Hence, the approximate ratio between the two standard errors becomes after some year

$$\sigma_{b_{ep}} / \sigma_{b_{perm}} \approx 2\sqrt{10} \approx 6.1 \tag{16}$$

i.e. the standard error of the permanent strategy is six times smaller than in the epoch-wise strategy (see also Table 5-2). The ratio decreases to 3 if the epoch-wise campaigns are repeated every month. However, it is reasonable to assume that the ratio becomes even smaller, if we consider that the continuous data is probably much more correlated than the epoch-wise collection of data.

Table 5-2. Expected precisions of the velocities and coordinates/baselines after 2 to 5 years continuous observation period with different data qualities (σ_0).

		σ_b (mm/yr)			σ_a (mm)		
Yr	n	σ_0 (mm)			σ_0 (mm)		
		1	1.5	4	1	1.5	4
2	241	0.06	0.08	0.22	0.06	0.09	0.25
3	361	0.03	0.05	0.12	0.05	0.08	0.21
4	481	0.02	0.03	0.08	0.04	0.07	0.18
5	601	0.01	0.02	0.06	0.04	0.06	0.16

5.5 Linear regression versus Bernese software results for baseline evolutions

It is well known that GPS software frequently overestimates standard errors of estimated coordinates and coordinate changes with time. The main reason for this problem is that the GPS adjustment includes an overwhelming amount of GPS observations, which in the strict sense are correlated. However, the correlation is frequently neglected in the adjustment; a shortcoming that should hardly or little affect the estimation of coordinates and velocities, but standard errors of these parameters may be very significantly affected. This conclusion stems from the fact that the least squares estimates of parameters are still unbiased (but not optimal with least variances) when the correlations are neglected, but the estimates of standard errors of the parameters are biased. /Cf. e.g. Sjöberg, 1981; Persson, 1981/ This section will investigate whether simple linear regression of the epoch-wise results can be used to improve the standard errors of the outcome of total adjustment by Bernese. The idea is that the very few data, well separated in time, from the results of the epoch-wise adjustments of a baseline, are mutually free from significant correlations, and therefore suitable for the estimation of standard errors or a scale factor to the standard errors achieved by the Bernese software adjustment.

The simple linear regression technique employs the Eqs. (8), (9) and (11a,b) for the epoch-wise baseline estimation from station Knip to the rest of the network stations as observations (y_i). See also Figures 5-1 to 5-7. The results of these computations are shown in Table 5-3, columns 2-4. Column 2 shows that the standard error of an epoch-wise determination of a baseline by GPS is about 1 mm, except for the long baseline from Knip to Oskarshamn, which standard error reaches 2 mm. Column 4 shows the temporal changes of the baseline lengths: except for the long baseline to Oskarshamn, they are all within 1 mm/yr. Moreover, as their standard errors are close to, or even bigger than, the estimates of velocities, the latter quantities cannot be considered significantly different from zero.

Finally, in column 5 we list the result of baseline length velocities with standard errors estimated by the Bernese software. The velocities agree rather well with the linear regression, while the standard errors are, as expected from our discussion above, unrealistically small. From these results we are tempted to conclude, that the Bernese software standard errors should be scaled up by, at least, a factor 10. Other investigators using the Bernese software under different conditions (mainly for global applications; see the next chapter) set this scale factor of the formal standard error to 7.

Table 5-3. Comparison of baseline length parameter estimates by linear regression of epoch-wise solutions and joint Bernese software multi-epoch solution. The standard errors are computed by Eqs. (8), (9) and (11a,b).

	Linear regression			**Bernese results**
Baseline	**Standard error of unit weight (σ_0) (mm)**	$\pm\sigma_a$ **(mm)**	**b**$\pm\sigma_b$ **(mm/yr)**	$b\pm\sigma_b$ **(mm)**
Knip-Djup	0.97	± 0.96	0.81 ± 0.69	0.90 ± 0.02
Knip-Gang	0.46	± 0.45	0.22 ± 0.32	0.20 ± 0.03
Knip-Gran	0.58	± 0.58	0.00 ± 0.41	0.00 ± 0.03
Knip-Karr	0.54	± 0.53	-0.36 ± 0.38	-0.50 ± 0.03
Knip-Kidr	1.31	± 1.31	0.98 ± 0.93	1.10 ± 0.02
Knip-Stor	1.03	± 1.00	0.35 ± 0.72	0.30 ± 0.03
Knip-Oskarshamn	2.17	± 2.15	-2.08 ± 1.53	-1.80 ± 0.04

6 Estimation of the site velocities of the network

The site velocities of the network were processed in a local topocentric coordinate system with respect to site Knip. The estimated coordinates of all six campaigns are assumed to have the same standard error of unit weight σ_o (see Tables 4-2 to 4-7) and to be uncorrelated. The principal results of the data analysis are the site velocities being computed together with the mean site coordinates in the program ADDNEQ. The network Äspö and the baseline length Knip-Oskarshamn were adjusted separately. In both adjustments a free velocity estimation of the site horizontal components was performed with a big a priori sigma (e.g. 999.99 mm/yr). The velocities of the vertical components of the sites were not solved, as there is not a sufficiently long time span of data for this purpose.

The final 6-campaign solution containing the velocity estimates within ITRF97 is shown in Table 6-1 and Figure 6-1. The formal precision of the velocity estimation of the adjustment of all campaigns are too optimistic due to the fact the software neglects the small but existing correlations among the huge number of GPS data. The standard errors and error-ellipses have therefore been scaled up by a factor 10 to represent approximately the accuracy from all the campaigns. This factor yields a standard error fairly in agreement with our regression analysis (Sec. 5.5), but slightly worse than the expected precisions (Sec. 5.2 and Table 5-1). It differs also slightly from the scale factor 7 proposed e.g. by Becker et al. /2000/ and Fridez /2002/, but their conclusions were drawn from global GPS network adjustments.

To judge whether the estimated velocities are significant or not, a Student's t-test can be used /see e.g. Koch, 1999/. The t-statistic based on the observations:

$$t = \frac{\hat{b}}{\hat{\sigma}_b}, \tag{17}$$

where $\hat{b}$ and $\hat{\sigma}_b$ are the estimated velocity and its precision, respectively, is compared to its theoretical value $t_{\alpha/2}(n-2)$ given by the t-distribution, where n is the number of observation epochs and α is the chosen risk level (5%). Our null-hypothesis (H_0) is that there is no motion, i.e. $H_0 : b = 0$. The t-values are listed in the second last column of Table 6-1, which should be compared with $t_{5\%}(4) = 2.7$. If $|t| \le t_\alpha$, then H_0 is accepted, otherwise H_0 is rejected.

The result of the tests is given in the last column of the table. Two sites (Kidr and Oskarshamn) do not pass the test. Also site Djup is near to fail the test. However, as mentioned above (Section 7.3), the data of the sites Djup and Kidr in October 2001 and the site Oskarshamn in February 2002 were suspected as outliers, possibly contaminated by ionosphere bias. If these data are deleted, the new velocity estimates and t-tests for these sites are presented in Table 6-2 and Figure 6-2. Then the velocity estimates changed from 1.3, 1.4 and -1.8 mm/yr to 0.8, 1.3 and 0.6 mm/yr, respectively, and the null hypothesis is accepted for all sites.

Table 6-1. Site displacement rates of the Äspö network relative to the fixed site Knip with the standard error rescaled by a factor 10.

Site	Rate (mm/yr)	Precision (mm/yt)	Azimuth	t=Rate/ precision	H_0 accepted
Djup	1.35	0.50	2°	2.7	Yes
Kidr	1.44	0.50	267°	2.9	No
Gran	0.67	0.42	290°	1.6	Yes
Karr	0.48	0.57	221°	0.8	Yes
Gang	0.41	0.50	136°	0.8	Yes
Stor	0.36	0.50	303°	0.7	Yes
Oskarshamn t distribution (5%) : 2.8	1.8	0.50	37°	3.6	No

Table 6-2. Displacement for three sites (Djup, Kidr, and Oskarshamn) with only 5 GPS campaigns with the Standard error rescaled by a factor 10. For the sites (Djup and Kidr) and Oskarhamn without using the data of the campaigns of October 2001 and February 2002, respectively.

Site	Rate (mm/yr)	Precision (mm/yt)	Azimuth	t=Rate/ precision	H_0 accepted
Djup	0.85	0.50	29°	1.7	Yes
Kidr	1.29	0.50	229°	2.6	Yes
Oskarshamn t distribution (5%) : 3.1	0.58	0.80	164°	0.7	Yes

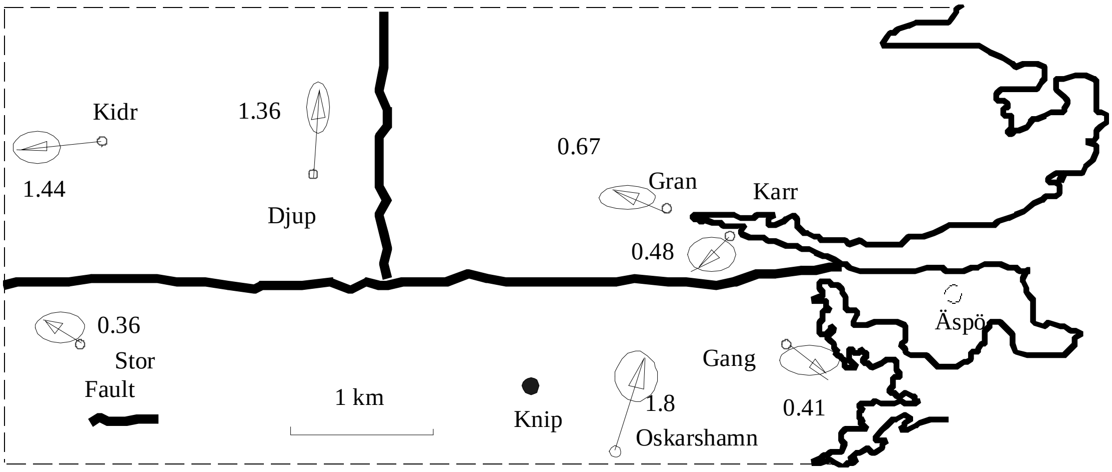

Figure 6-1. The site motion rates in mm/yr of the Äspö network derived using all data from 6 campaigns relative to the fixed site Knip. The formal error ellipses were rescaled by a factor 10 for a better approximation of the accuracy.

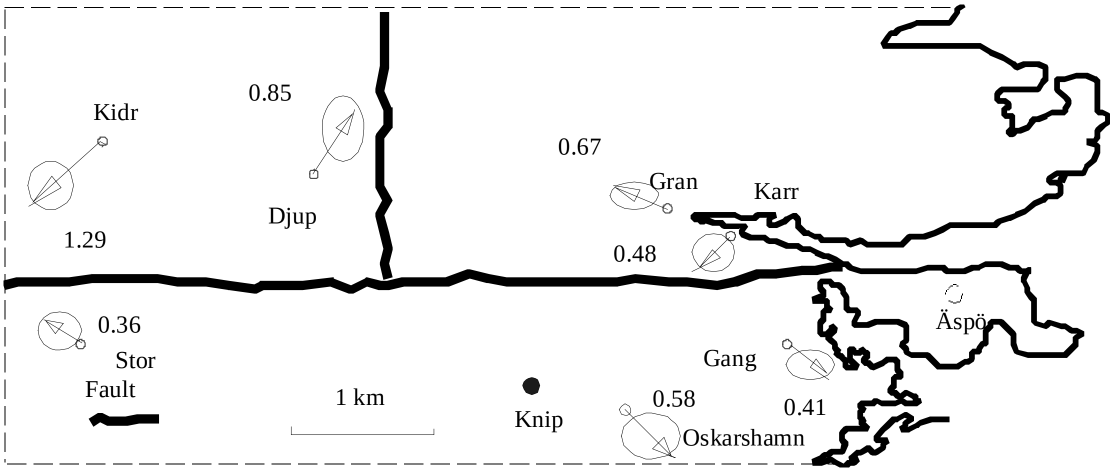

Figure 6-2. *Rates of motions in mm/yr. The sites Gran, Karr, Gang and Stor were computed using data from all 6 campaigns, while for the 3 sites Djup, Kidr and Oskarshamn only 5 campaigns were used. The formal error ellipses were rescaled by a factor 10 for a better approximation of the accuracy.*

7 Conclusions and final remarks

Our simple, linear regression analysis of the temporal changes of baseline lengths (Section 5.5) shows that the standard errors of temporal changes by the Bernese software should be scaled up by a factor of at least 10. There is an obvious over-estimation of the quality of parameters of the Bernese software. This stems from the fact that the tremendous amount of GPS data is not properly adjusted with consideration to correlations among the data. These correlations will probably not significantly affect the estimated parameters, but they will considerably change the estimated standard errors.

When considering the baseline and coordinate results from the six campaigns, some outlying data can be traced to correlations with dramatic ionosphere effects, which are likely to have caused biased results. If these outlying data is omitted from the analysis, we may conclude that no significant crustal motions occurred during the observation period (at the 5% risk level).

We find also that the standard errors of coordinate velocities are usually somewhat bigger than their theoretical estimates. This result may partly be due to the ionosphere biases and the changes of GPS antennas between campaigns, but also other systematic error sources might prevail. Longer observation periods are needed to control such gross and systematic error resources.

Nevertheless we believe that the pre-study has proven that the analysis of this type of precise epoch GPS campaigns is a powerful tool for monitoring crustal deformations. We have also shown, that the gain in accuracy of employing the alternative strategy of a permanent monitoring network is not very significant.

Finally, we like to propose an improved method for combining dual frequency GPS data not available in current GPS softwares. By using the so-called Best Linear Unbiased Etimator (BLUE) of the satellite-to-receiver range as a combination of the L1 and L2 observables as well as an a priori estimate of the ionosphere bias (e.g. zero for short baselines) the best ionosphere-free observation for the network adjustment is always obtained, independent on baseline length /Sjöberg, 2002; cf. also Sjöberg 1999/. However, such a refined method necessitates some software development before application.

References

Becker M, Reinhart E, Nordin S B, Angemann D, Michel C, Reigber C, 2000. Improving the velocity field in South and south-east Asia: The third round of GEODYSSEA. Earth Planets Space, 52, pp. 721–726.

Bjerhammar A, 1973. Theory of errors and generalized matrix inverses. Elsevier Scientific Publishing Co., Amsterdam, London, New York.

Boucher C, Altamimi Z, Sillard P, 1999. The 1997 International Terrestrial Reference Technical note No. 27, Observatories de Paris.

Fridez P, 2002. A private communication. Astronomical Institute University of Berne.

Hedling G, Jonsson B, 1995. SWEPOS-A Swedish Network of Reference Stations for GPS. LMV-rapport 1995:15, Gävle, Sweden.

Hugentobler U, Schaer S, Fridez P (Ed.), 2001. Bernese GPS Software, version 4.2, Astronomical Institute University of Berne, February 2001.

Jaldehag R T K, Johansson J M, Rönnäng B O, Elosegui P, Davis J L, Shapiro I I, Neil E, 1996. Geodesy using the Swedish permanent GPS network: Effects of signal scattering on estimates of relative site positions. J. Geophys. Res., Vol. 101, N0. B8.

Koch K R, 1999. Parameter Estimation and Hypothesis Testing in Linear Models, Second updated and enlarged Edition. Springer-Verlag, Berlin, Heidelberg.

Persson C-G, 1981. On the estimation of variance components in linear models and related problems. The Royal Institute of Technology, Department of Geodesy, Stockholm (Doctoral Dissertation).

Rothacher M, Mervart L, Beutler G, Brockhamn E, Fankhauser S, Gurtner W, Johnsson J, Schaer S, Springer T, Weber R, 1996. Manual for Bernese GPS Softerware Version 4.0. Astronomical Institute University of Berne.

Saastamoinen J J, 1973. Contributions of the theory of atmosphere refraction. Bull. Geod.-, 107(1), 13–34

Sillard P, Boucher C, 2001. A review of algebraic constrints in terrestrial reference frame datum definition. J Geod., 75, 63–73.

Sjöberg L E, 1981. Direct mean versus weighted mean of correlated data. Survey Review, Vol. 26, No. 199, pp. 3–10.

Sjöberg L E, 1982. Singular versus regular adjustment of gravity networks for various observation strategies. The Department of Geodesy Report No. 15, University of Uppsala.

Sjöberg L E, 1984. General matrix calculus, adjustment and variance-covariance component estimation. In B. Harsson (Ed.): Optimization of Geodetic operations, Lecture Notes, Nordiska Forskarkurser 12/1984, Norges Geografiske Oppmåling Publ. No. 3/1984, pp. 7–69.

Sjöberg L E, 1999. Unbiased vs biased estimation of GPS phase ambiguities from dual-requency phase and code observables. J Geod.,73, 118–124.

Sjöberg L E, 2002. The BLUE of the GPS double difference satellite-to-receiver range for precise positioning. Accepted by Zeitschrift für Vermessungsvesen.

SKB, 2000. Förstudie Oskarshamn, slutrapport. Svensk Kärnbränslehantering AB.

Spilker J, 1978. GPS Signal Structure and Performance Characteristics, Navigation: The Journal of the Institute of Navigation, Washington, Vol. 25, No. 2 pp.121–146.

Vermeer M, 1997. Use of the global positioning system for geodynamic research in Finland. In geodetic applications of GPS. Lecture notes for Nordic autumn school organised By the Nordic Geodetic Commission. Bo Jonsson (Ed.): LMV-rapport 1997:16, Gävle, pp.217–234.