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Forsmark site investigation

GPS deformation measurements in Forsmark

Annual report 2008

Lars Gustafson, Annika Ljungberg
Caliterra AB

May 2009

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Keywords: GPS, Deformation, AP PF 400-05-056, Forsmark.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

Data in SKB's database can be changed for different reasons. Minor changes in SKB's database will not necessarily result in a revised report. Data revisions may also be presented as supplements, available at www.skb.se.

A pdf version of this document can be downloaded from www.skb.se.

Abstract

The objective is to identify possible movements in the bedrock within and outside the candidate area in Forsmark for a repository of spent nuclear fuel. Seven thermally and physically stable stations were built in the Forsmark area in the autumn of 2005. Stations were established within a ten-kilometre radius. The stations were placed in three different geologic areas: NE of the Singö zone, within the candidate area and SW of the Forsmark zone.

Stations consist of a stainless steal rod fixed in the bedrock on which the GPS antenna mounts. Each station has dedicated GPS equipment only used at that site. Sets consist of a GPS receiver collecting raw GPS data and a choke ring antenna linked to the receiver using a coaxial cable. The receivers and antennas are dual frequency high precision geodetic grade.

During each campaign the GPS receiver saves a reading every second for the duration of the five days campaign. The antennas remain mounted on the stations during the entire project (four years) while all other equipment is in place at the station only during the campaigns. The measurements will also be related to the SWEPOS network stations Lovö, Uppsala and Mårtsbo that are defined as stations with stable fundaments by the National Land Survey of Sweden (Lantmäteriet). There will be fifteen campaigns in total. This report describes the first thirteen campaigns from November 2005 to August 2008.

The number of campaigns has been extended by adding a fourth year to the project. Optimization of the data processing depends on the properties of the entire data set comprising a period of four years. Our objective in this report is to establish the data quality. We divided the data into periods of 24 hours with each period processed separately in the Bernese post processing software. We analyzed the residuals to conclude that data are of the expected quality. The entire data set from four years is needed to reveal any motion.

Sammanfattning

Målet med projektet är en kartering av eventuella rörelser i berggrunden kring SKB:s platsundersökningsområde i Forsmark. Under hösten 2005 etablerades totalt sju stationer inom en radie på 10 kilometer från platsundersökningsområdet. Stationerna placerades för att täcka tre tektoniska områden: NÖ om Singözonen, inom kandidatområdet och SV om Forsmarkszonen.

Stationerna består av en metallstav fixerad i berget på vilken en GPS-antenn är fastmonterad. Varje station har en egen dedicerad GPS-utrustning bestående av en GPS-mottagare och en separat chokering antenn. Både mottagaren och antennen är av geodetisk kvalitet.

Under varje kampanj finns utrustningen på stationen under totalt fem dygn. Utrustning sparar data varje sekund under de fem dagarna. Antennen sitter kvar på en och samma station under hela mätperioden. Resten av utrustningen placeras ut vid varje kampanj. Det lokala nätverket utökas med närbelägna SWEPOS stationer. Vi använder oss endast av SWEPOS stationer som har definierats av Lantmäteriet som stationer med stabila fundament. Dessa stationer är Lovö, Uppsala och Mårtsbo. Denna rapport behandlar de tretton första kampanjerna som utfördes under perioden november 2005 till augusti 2008.

Aktiviteten har utökats med ett år till att omfatta fyra år. Optimeringen av dataprocesseringen är beroende av data från hela perioden. Vårt mål med denna delrapport är att beskriva kvaliteten på data. Data delas upp i segment om 24 timmar vardera och beräknas separat från varandra i analysprogrammet Bernese. Vi analyserar residualer för att fastlägga att data har förväntad kvalitet. Data från hela fyraårsperioden behövs för att eventuella rörelser i berggrunden ska kunna påvisas.

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1 Introduction

This document reports data obtained from GPS deformation measurements in Forsmark, which up to and including June 2007 was one of the activities performed within the site investigation at Forsmark. After June 2007 the activity is part of a programme for long-term observations (monitoring) of geological parameters and ecological objects included in a project denominated “Platsprojekt Forsmark”. The work was carried out in accordance with activity plan AP PF 400-05-056, which refers to method description SKB MD 133.003, see Table 1-1. The activity plan and method description are SKB internal documents.

Base stations were established in three geologically separate blocks. Geologists at SKB selected a set of possible sites for localisation of GPS stations, based on geological considerations. These were evaluated for suitability to high precision GPS measurements, and seven sites were selected within these areas accounting for GPS sky visibility, nearby manmade or natural reflectors and the ability to firmly anchor a station to the bedrock. Seven stations were built on the selected sites in August 2005 and their positions surveyed. Figure 1-1 gives an overview of station placement. Dual frequency (L1 and L2 bands) GPS code- and carrier-phase raw data were collected and evaluated for quality. Data were stored for use in the final deformation evaluations. This procedure was repeated in thirteen five days long campaigns between November 2005 and August 2008. The first ten campaigns are already reported in /1 and 2/.

Data were in general found to be of good quality, although during the first three campaigns data from one station may not have been equally good as from the other six stations due to nearby vegetation. A new station was therefore built in May 2006 prior to the fourth campaign as an alternate site with better GPS sky.

Table 1-1. Controlling document for performance of the activity.

Activity plan	**Number**	**Version**
Deformationsmätningar med GPS i Forsmark	AP PF 400-05-056	1.0
Method Description		
Deformationsmätningar med GPS	133.003	1.0

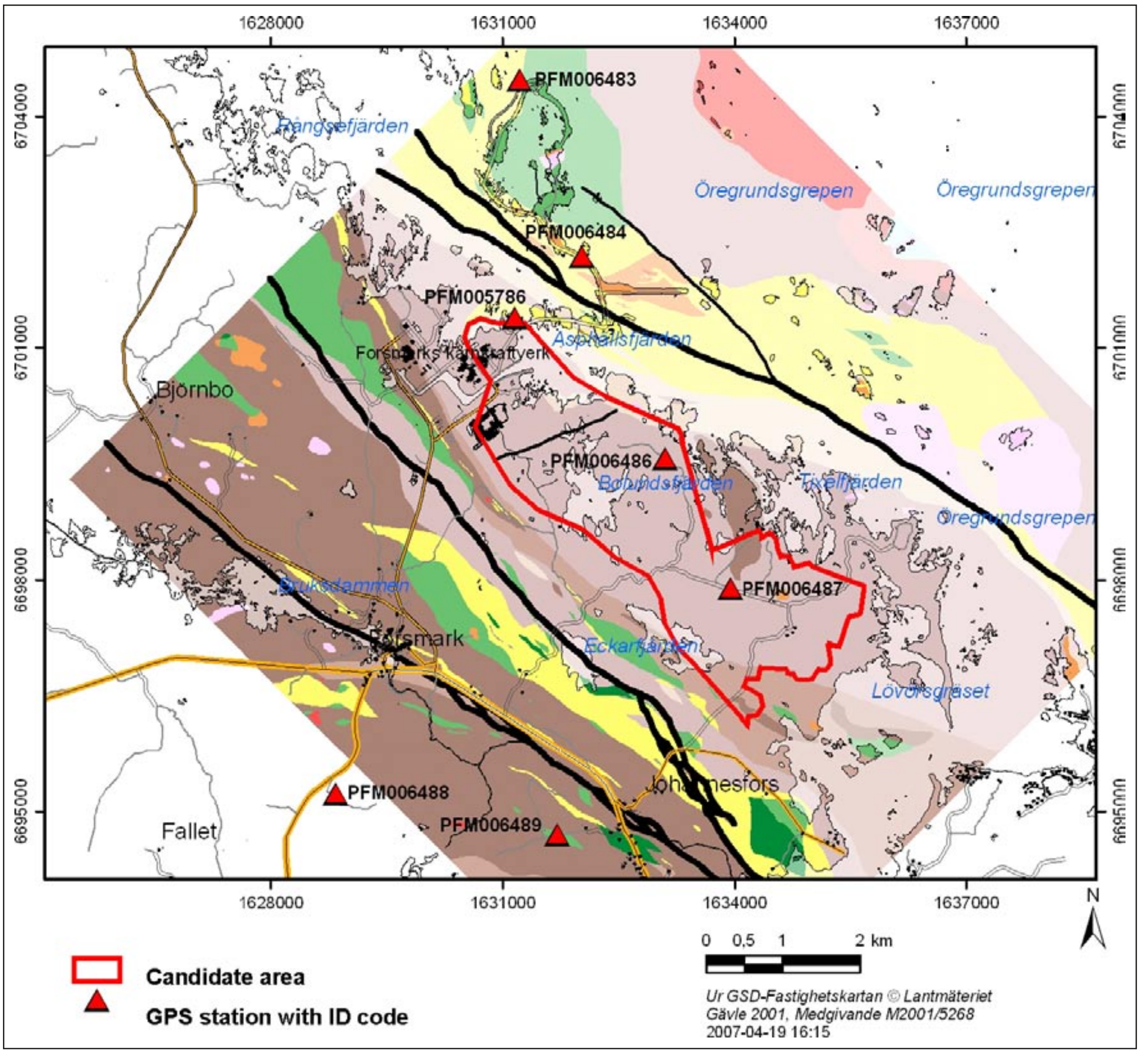

Figure 1-1. *General overview of the Forsmark site investigation area with marked station locations and the candidate area outlined in red. The three stations PFM005786, PFM006486 and PFM006487 are located inside the tectonic lens in the investigation area. The stations PFM006483-PFM006484 are located NE of the Singö zone, and the stations PFM006488-PFM006489 are located SW of the Forsmark zone.*

2 Objective and scope

The objective of this project is to define possible horizontal movements (exceeding approximately one millimetre per year) in the bedrock in the Forsmark area. The study focuses on the Forsmark candidate site, an adjacent area to the NE separated by the Singö zone and an area to the SW, similarly separated by the Forsmark zone. Possible motion of these geologically separated areas will be related to the larger scale motion of the surrounding area using data from existing GPS stations operated by SWEPOS[1].

[1] SWEPOS is a national network of fixed GPS reference stations, operated by the National Land Survey of Sweden (Lantmäteriet).

3 Equipment

3.1 Description of equipment/interpretation tools

The surveying equipment used in this project is a set of carrier phase dual frequency geodetic grade GPS systems capable of yielding state-of-the-art accuracy. The GPS receiver is a Toughman, manufactured by DataGrid Inc. (see Appendix 1), customized with 128 Mb extended memory and improved temperature tolerance. All receiver functions are designed to the 40°C to +70°C temperature range, thus extending the interval indicated in the specification sheet in Appendix 1. The antennas are choke ring GPS L1 and L2 survey grade antennas of model AT2775-43 manufactured by AeroAntenna Technology Inc. (see Figure 3-1 and Appendix 1). Each station has the antenna permanently mounted on a mechanically and thermally stable fundament. To anchor the fundament, every site was drilled with an 18 mm drill bit. A 25 cm long threaded 5/8-inch diameter metal rod was inserted in the holes to a depth of 15 cm. The rod height above the ground is 10 to 12 cm. A two-component anchor paste curing totally after 24 hours was used.

The station fundaments were built several weeks before the antennas were permanently mounted on them. All stations are equipped with the same model and version number hardware and software combination. The receiver mounted just below the antenna (also seen in Figure 3-1) is removed for safe storage between measurements. Each receiver is marked and will be used on its dedicated station at the respective campaign.

Figure 3-1. *Sample station with choke ring antenna and GPS receiver mounted to the lower left. The station in this picture is PFM006489 but all sites have identical hardware (and firmware). They are mounted on a short steel rod anchored in the rock for good mechanical and thermal stability. However, the low mounts increase the demand on the GPS environment. The antenna radome and pin are designed to protect the active components of the antenna and discourage birds and other small animals from lodging on the antenna. A second cover provides additional protection between measurement campaigns.*

All GPS receivers are equipped with internal power regulators and conditioners and can operate for up to 8 hours using internal batteries. An external power supply consisting of a lead acid battery/ solar panel combination (not shown) extends this operating time practically indefinitely. The arrangement with power accumulated in two separate systems allows for reliable operation even at times when the temperature may dip below normal operating temperature for the lead acid batteries.

All equipment is dedicated to this project and is not used for any other activity for the duration of the project. The Bernese post processing software package (version 5.0) is an advanced software for GPS-post processing developed by the astronomical institute of the University of Bern, Switzerland.

Calibration data for the antenna make and type phase centre is part of the processing software. Antennas are fixed in place to eliminate geometric errors related to antenna orientation and cantering in the displacement data, thereby eliminating a significant potential error source and the corresponding need for calibration. The GPS receivers produce phase measurements in code phase and carrier phase. Since these all refer to a single clock (the GPS TCXO or Temperature Compensated Crystal Oscillators), the GPS receivers require no calibration. The data processing double difference technique eliminates any error due to clock differences from one receiver to another. Hence, not either clock drift needs calibration.

The largest remaining errors are probably related to site conditions. GPS station sites must have clear sky in all directions and as close to the horizon as possible. Nearby electric conductors should be avoided. More detailed site studies with data gathering for a full period of 24 hours may be used as acceptance tests in questionable locations. In our study one such site passed our initial study but did not yield equally good data in subsequent campaigns presumably due to changes in nearby vegetation and or soil moisture. An alternative site has been established and data were subsequently collected on the original as well as on the new site. Since we perform displacement measurements rather than absolute position measurements, one may consider the comparison measurements to be calibrations in the sense that remaining differences are attributable to stochastic errors such as phase noise. A measure of the displacement should therefore be retrievable using standard statistical analysis methods.

Manufacturer’s data sheets are presented in Appendix 1.

4 Execution

4.1 General

The methods used in this project are in accordance with the method description SKB MD 133.003.

Our first task was to evaluate a set of GPS station placement areas proposed by SKB for suitability as high precision GPS station sites. Station sites within the three areas proposed by SKB were selected accounting for GPS sky visibility, nearby manmade or natural reflectors and the ability to firmly anchor the station to the bedrock. Seven stations with mechanically and thermally stable fundaments were built in August 2005.

Dual frequency (L1 and L2) GPS code- and carrier-phase raw data were typically collected from these stations at 1-second intervals in campaigns of 4 to 4.5 days. The data collected during each campaign are processed in the Bernese post processing software package and evaluated for quality and self-consistency. The results including preliminary coordinates are presented in an "EG180 – Point surveying Session" file. Final optimization of the data processing is dependent on the total dataset, so we view currently calculated positions as preliminary. Our aim is to collect data of known good quality in this phase of the investigation.

The data were successfully evaluated for quality and stored for use in the final deformation evaluations. This was repeated in ten campaigns between November 2005 and August 2008, see Table 4-1. The first ten campaigns are already reported in /1 and 2/. However, quality checking also revealed that one station (PFM006485) might have produced data of lower quality than the other six during the first three campaigns. This is believed to be due to sky disturbances possibly due to nearby vegetation. An additionnal station (PFM005786) was established in May 2006 as an alternative site with better GPS sky view. Data were successfully collected at most of the stations during the following campaigns, except for some malfunctions of solar panels etc in campaigns 12 and 13. All original results are stored in the primary database Sicada, and are traceable by the activity plan number.

Figure 1-1 shows a general overview of station placements within and outside the candidate area. Two stations were placed NE of the Singö zone, two stations SW of the Forsmark zone and three stations within the candidate area.

A dedicated GPS set consisting of receiver and choke ring antenna is used at each of the seven stations during each measurement campaign. The antennas are permanently mounted to minimize mechanical errors (see Figure 3-1) whereas the GPS receivers and power supplies (lead-acid battery and solar panel combination) were securely stored between campaigns. A cover also protects each station between campaigns. After the cover is removed and the GPS with its power supply is deployed (only two cables to connect), the receiver is turned "on" and data are automatically stored in the internal flash memory until they are retrieved at the end of the campaign. The equipment is then restored to its protected inter-campaign state and the data are processed and evaluated for quality.

Table 4-1. Activity log listing all the activities at all the stations reported here and in previous reports /1 and 2/.

Campaign	Idcode	Activity ID	Start Date	Stop Date
1	PFM006483	13138500	2005-11-02 00:00	2005-11-08 00:00
	PFM006484	13138501	2005-11-02 00:00	2005-11-08 00:00
	PFM006485	13138502	2005-11-02 00:00	2005-11-08 00:00
	PFM006486	13138503	2005-11-02 00:00	2005-11-08 00:00
	PFM006487	13138504	2005-11-02 00:00	2005-11-08 00:00
	PFM006488	13138505	2005-11-02 00:00	2005-11-08 00:00
	PFM006489	13138506	2005-11-02 00:00	2005-11-08 00:00
2	PFM006483	13111011	2006-01-31 00:00	2006-02-06 00:00
	PFM006484	13111012	2006-01-31 00:00	2006-02-06 00:00
	PFM006485	13111013	2006-01-31 00:00	2006-02-06 00:00
	PFM006486	13111014	2006-01-31 00:00	2006-02-06 00:00
	PFM006487	13111015	2006-01-31 00:00	2006-02-06 00:00
	PFM006488	13111016	2006-01-31 00:00	2006-02-06 00:00
	PFM006489	13111017	2006-01-31 00:00	2006-02-06 00:00
3	PFM006483	13114680	2006-03-07 00:00	2006-03-14 00:00
	PFM006484	13114681	2006-03-07 00:00	2006-03-14 00:00
	PFM006485	13114682	2006-03-07 00:00	2006-03-14 00:00
	PFM006486	13114683	2006-03-07 00:00	2006-03-14 00:00
	PFM006487	13114684	2006-03-07 00:00	2006-03-14 00:00
	PFM006488	13114685	2006-03-07 00:00	2006-03-14 00:00
	PFM006489	13114686	2006-03-07 00:00	2006-03-14 00:00
4	PFM006483	13119756	2006-05-09 00:00	2006-05-15 00:00
	PFM006484	13119757	2006-05-09 00:00	2006-05-15 00:00
	PFM006485	13119758	2006-05-09 00:00	2006-05-15 00:00
	PFM006486	13119759	2006-05-09 00:00	2006-05-15 00:00
	PFM006487	13119760	2006-05-09 00:00	2006-05-15 00:00
	PFM006489	13119762	2006-05-09 00:00	2006-05-15 00:00
5	PFM005786	13119763	2006-07-06 00:00	2006-07-10 00:00
	PFM006483	13119764	2006-07-06 00:00	2006-07-10 00:00
	PFM006484	13119765	2006-07-06 00:00	2006-07-10 00:00
	PFM006486	13119766	2006-07-06 00:00	2006-07-10 00:00
	PFM006487	13119767	2006-07-06 00:00	2006-07-10 00:00
	PFM006488	13119768	2006-07-06 00:00	2006-07-10 00:00
	PFM006489	13119769	2006-07-06 00:00	2006-07-10 00:00
6	PFM005786	13134251	2006-09-13 00:00	2006-09-17 00:00
	PFM006483	13134252	2006-09-13 00:00	2006-09-17 00:00
	PFM006484	13134253	2006-09-13 00:00	2006-09-17 00:00
	PFM006485	13134254	2006-09-13 00:00	2006-09-17 00:00
	PFM006486	13134255	2006-09-13 00:00	2006-09-17 00:00
	PFM006487	13134256	2006-09-13 00:00	2006-09-17 00:00
	PFM006488	13134257	2006-09-13 00:00	2006-09-17 00:00
	PFM006489	13134258	2006-09-13 00:00	2006-09-17 00:00
7	PFM005786	13151897	2007-01-18 00:00	2007-01-22 00:00
	PFM006483	13151898	2007-01-18 00:00	2007-01-22 00:00
	PFM006484	13151899	2007-01-18 00:00	2007-01-22 00:00
	PFM006486	13151900	2007-01-18 00:00	2007-01-22 00:00
	PFM006487	13151901	2007-01-18 00:00	2007-01-22 00:00
	PFM006488	13151902	2007-01-18 00:00	2007-01-22 00:00
	PFM006489	13151903	2007-01-18 00:00	2007-01-22 00:00
8	PFM005786	13165495	2007-04-25 00:00	2007-04-29 00:00
	PFM006483	13165496	2007-04-25 00:00	2007-04-29 00:00
	PFM006484	13165497	2007-04-25 00:00	2007-04-29 00:00
	PFM006486	13165498	2007-04-25 00:00	2007-04-29 00:00
	PFM006487	13165499	2007-04-25 00:00	2007-04-29 00:00

Campaign	Idcode	Activity ID	Start Date	Stop Date
	PFM006488	13165500	2007-04-25 00:00	2007-04-29 00:00
	PFM006489	13165501	2007-04-25 00:00	2007-04-29 00:00
9	PFM005786	13169971	2007-07-09 00:00	2007-07-13 00:00
	PFM006483	13169972	2007-07-09 00:00	2007-07-13 00:00
	PFM006484	13169973	2007-07-09 00:00	2007-07-13 00:00
	PFM006486	13169974	2007-07-09 00:00	2007-07-13 00:00
	PFM006487	13169975	2007-07-09 00:00	2007-07-13 00:00
	PFM006488	13169976	2007-07-09 00:00	2007-07-13 00:00
	PFM006489	13169977	2007-07-09 00:00	2007-07-13 00:00
10	PFM005786	13177340	2007-10-25 00:00	2007-10-29 00:00
	PFM006483	13177341	2007-10-25 00:00	2007-10-29 00:00
	PFM006484	13177342	2007-10-25 00:00	2007-10-29 00:00
	PFM006486	13177343	2007-10-25 00:00	2007-10-29 00:00
	PFM006487	13177344	2007-10-25 00:00	2007-10-29 00:00
	PFM006488	13177345	2007-10-25 00:00	2007-10-29 00:00
	PFM006489	13177346	2007-10-25 00:00	2007-10-29 00:00
11	PFM005786	13181365	2008-01-17 00:00	2008-01-21 00:00
	PFM006483	13181366	2008-01-17 00:00	2008-01-21 00:00
	PFM006484	13181367	2008-01-17 00:00	2008-01-21 00:00
	PFM006486	13181368	2008-01-17 00:00	2008-01-21 00:00
	PFM006487	13181369	2008-01-17 00:00	2008-01-21 00:00
	PFM006488	13181370	2008-01-17 00:00	2008-01-21 00:00
	PFM006489	13181371	2008-01-17 00:00	2008-01-21 00:00
12	PFM005786	13186930	2008-04-07 00:00	2008-04-10 00:00
	PFM006483	13186931	2008-04-07 00:00	2008-04-10 00:00
	PFM006484	13186932	2008-04-07 00:00	2008-04-10 00:00
	PFM006487	13186933	2008-04-07 00:00	2008-04-10 00:00
13	PFM006483	13198304	2008-08-21 00:00	2008-08-24 00:00
	PFM006484	13198305	2008-08-21 00:00	2008-08-24 00:00
	PFM006486	13198306	2008-08-21 00:00	2008-08-24 00:00
	PFM006487	13198307	2008-08-21 00:00	2008-08-24 00:00
	PFM006488	13198308	2008-08-21 00:00	2008-08-24 00:00
	PFM006489	13198309	2008-08-21 00:00	2008-08-24 00:00

4.2 Preparations

A functional test was made on a standard site with well-known coordinates. All components were found to function properly.

4.3 Execution of field work

The technique used is briefly described below in connection to the results presented. For detailed descriptions the reader is referred to the method descriptions.

A network of GPS stations was established. GPS data were collected in thirteen measurement campaigns, each with a duration of 5 days, repeated approximately every three months. The antenna on every station remains on that station during the entire project. The GPS-systems and power supplies are deployed only during measurement campaigns.

Every station includes:

- One geodetic survey grade dual frequency receiver with 128 MB internal memory to store all data during the session.
- Choke ring geodetic survey grade dual frequency antenna.
- Cables, backup battery and solar panels.

The equipment is used on the same location and the choke ring antennas remain fixed on the respective stations during the entire project. This prevents errors caused by displacements or any asymmetries in the antennas or other equipment. The GPS receivers are collected after a total of 120 hours of survey and data are uploaded to a laptop/desktop computer for analysis and storage.

4.4 Data handling/post processing

Raw GPS data (code and carrier phase in the L1-band and carrier phase from the L2-band along with "housekeeping data" on satellite functions and the GPS receivers) are collected directly by onboard controllers sealed inside the GPS receiver box. The onboard controller stores data at one-second intervals on a 128 MB internal and similarly sealed solid-state flash memory chip rated for "industrial" use.

After retrieval of the GPS receivers, their data are uploaded to a computer and processed for quality control using the Bernese software package. Coordinates are calculated for three separate periods of 24 hours using the Bernese software and are checked for consistency. Before processing the data we wait for precise ephemeredes (trajectories of the satellites) to post process at the highest accuracy. The precise ephemerides are available approximately two weeks after the measurements.

After post processing, a network adjustment is made with ADDNEQ routine in the software package were the known distance between the stations is used to increase the accuracy. The stations in the network are related to three SWEPOS stations with stable fundaments (see photography in Figure 4-1), Lovö, Uppsala, and Mårtsbo, by including them in the network. Coordinate conversions from Earth-centered Earth-fixed Cartesian coordinates to the Swedish grid RT90-RHB70 coordinates were made in two steps: from earth-centered coordinates to WGS 84 in Geotrans V2.2.3 by the US Army Topographic Engineering center (Geospatial Information Division and National Imagery and Mapping Agency Exploitation Tools Division) and from WGS 84 to RT90 2.5 G V and RHB70 in G-trans 3.1, upgraded in 2007 to G-trans 3.6 by the National Land Survey of Sweden (Lantmäteriet).

The results are entered in an "EG180 – Point surveying Session" file and delivered to the Sicada database. All raw files and results are also saved both by SKB and Caliterra AB.

4.5 Analyses and interpretations

The Bernese software an is advanced software for post processing of GPS-data, developed by the astronomical institute at the University of Bern, Switzerland. It performs ranging data differencing to minimize or eliminate the dominating ranging errors. This is a standard technique used in all high precision GPS work. The main difference between the Bernese software and other standard software packages is in the great control over processing parameters offered in the Bernese software suite along with academically credited and partly peer-reviewed methods and documentation. The great control over processing parameters allows the operator to optimize processing and retrieve information about error sources while the transparency allows proper statistical interpretation.

4.6 Nonconformities

There are no reported nonconformities. The project runs according to the activity plan and will be completed within one year from now.

Figure 4-1. *The SWEPOS reference station in Uppsala.*

5 Results

All original results are stored in the primary database Sicada and are traceable by the activity plan number AP PF 400-05-056. Original data from the reported activity are stored in the primary database Sicada. Only data in databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major revisions entail a revision of the P-report. Minor revisions are normally presented as supplements, available at www.skb.se.

Our aim is to determine if the data collected are of the expected quality. There are several ways to estimate quality. A discussion of this issue is found in /3/. With similar methods and conditions the findings in /3/ are probably the most relevant to this specific investigation. Most strikingly, the authors found that formal errors that are estimated as part of the Bernese post processing are optimistic. Instead they used the residuals from the arithmetic mean of coordinate positions as a more realistic measure.

Our findings concerning error estimates are in agreement with /3/, and we therefore include deviations that are not accounted for in the formal errors reported by the Bernese software.

We use these residuals in the form of root mean square (RMS) deviations from the arithmetic mean coordinates as measures of the overall quality. Horizontal errors are significantly lower than errors in the vertical direction. We decided to compare the residual in three-dimensional (3D) space for compactness and as a quality measure of the entire data set. This measure is used to make a direct comparison between our results and those reported in /4/ to determine if the data sets are of similar quality.

In /3/ the authors discuss optimization of post processing and averaging. Figure 5-1 is compiled from residuals reported in /3/ after final processing, in which only L1 ranging data are used. These therefore represent a measure of the quality of the data set after optimization of the processing. We have not settled on an optimization scheme, since we intend to use the same settings and averaging techniques at all epochs to avoid systematic bias. We therefore need to evaluate the full data set for optimization. Specifically there is a real possibility that ionospheric stability will degrade in coming years and may force reliance on L1/L2 data combinations despite the higher phase noise than in L1 alone. Averaging techniques may reduce the effect of the phase noise depending on ionospheric stability across a campaign.

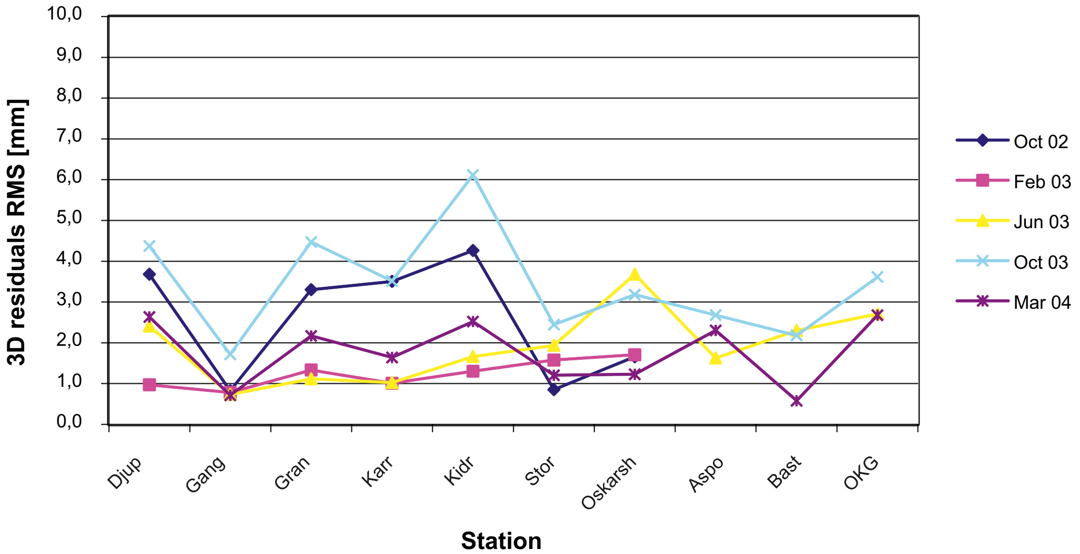

***Figure 5-1.** Residuals in three-dimensional space from the arithmetic mean solution compiled from a study at Oskarshamn /2/, based upon 24 hours simultaneous solutions.*

Figure 5-2 and Figure 5-3 show residuals in our data computed similarly as the residuals by /2/ shown in Figure 5-1, except that the processing and averaging of our data are not optimized. Figure 5-2 compiles the results from the first six campaigns, Figure 5-3 for the four campaigns in 2007 and Figure 5-4 for the campaigns in 2008. Further, our results are based on all data (including L1 and L2 combinations) as compact measures of overall data quality. We consider the results as a "worst case" processing and averaging, acknowledging that this leaves room for improvement. We also note that we have a significantly larger data set for Forsmark (we captured one record per second, whereas the data reported in /2/ are collected every 15 seconds). With this larger data set we may want to use the median as a better estimate than the arithmetic mean, along with more advanced averaging with digital filters to reduce the effect of noise in the carrier phase determinations and to retrieve the wanted low frequency displacement terms. This may allow us to make better use of especially the L2 data.

Figures 5-2, 5-3 and 5-4 thus summarize the quality of all data from the thirteen first campaigns, including L1 and L2 ranging using standard or default settings in the Bernese post processing software (no optimizations). In some campaigns no residuals are shown for some of the points. This is due to the fact that the data collection time was shorter than for the other campaigns, and thus did not allow daily residuals to be computed similarly to /2/ for those locations. However, we note that residuals at the other locations are typical values. The overall conclusion is that the figure shows comparable residuals to those seen in Figure 5-1. We can therefore expect results of similar or better quality than in /2/, assuming that the data in the remaining time of the project are of the same quality as those for the first three years.

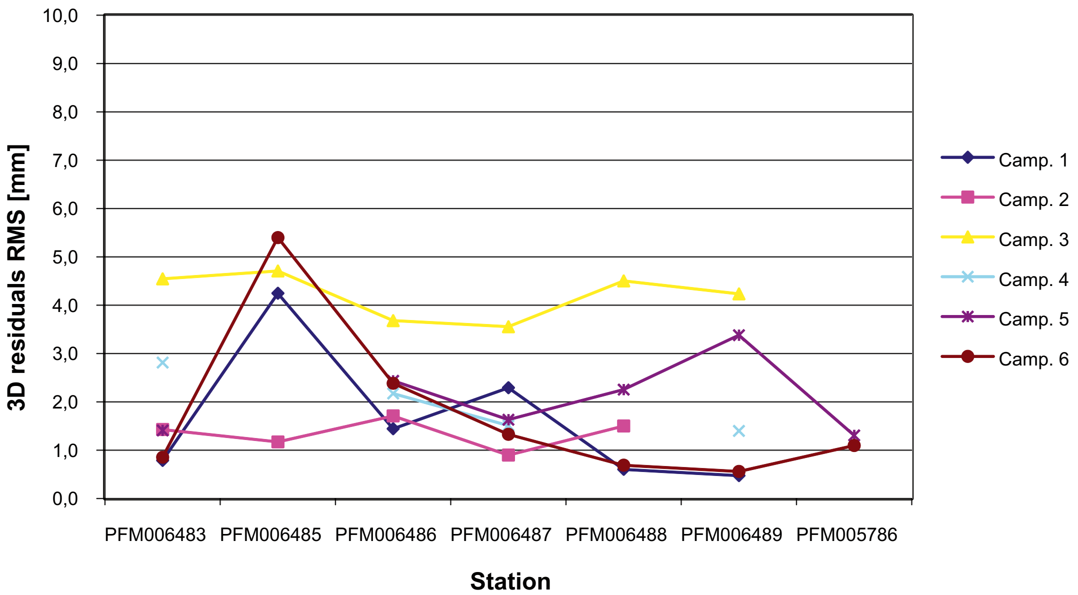

Figure 5-2. *Residuals from the on-going study at Forsmark in three-dimensional space from the arithmetic mean solution from 24 hours simultaneous solutions for the data from the first six campaigns, reported in /1/.*

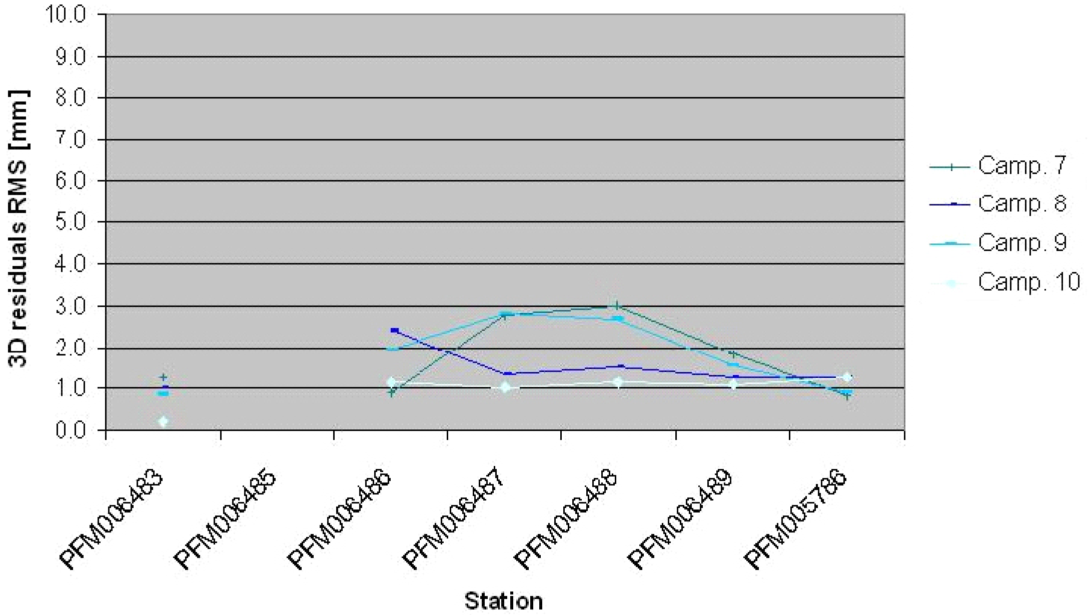

Figure 5-3. *Residuals from the 2007 campaigns in Forsmark in three-dimensional space from the arithmetic mean solution from 24 hours simultaneous solutions for the data reported in this report.*

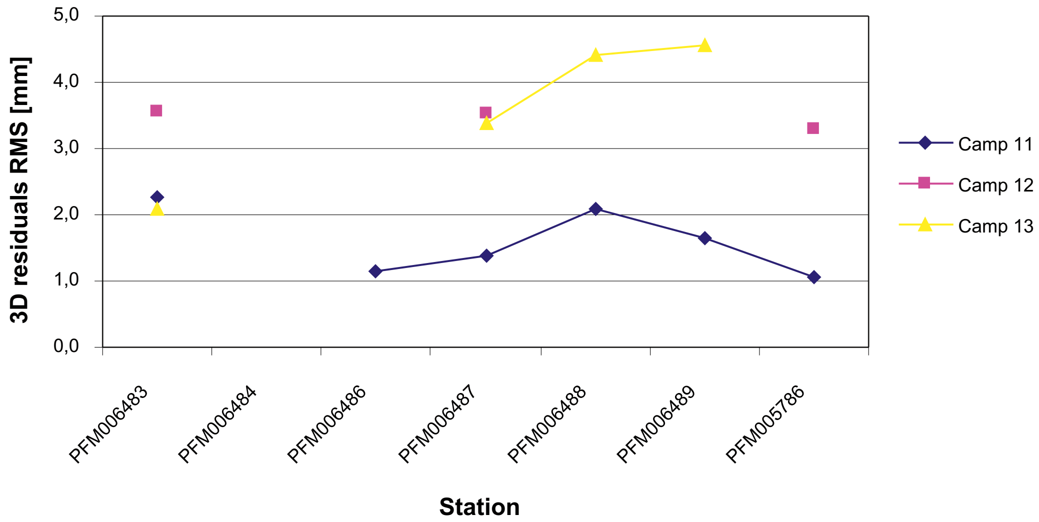

Figure 5-4. *Residuals from the 2008 campaigns in Forsmark in three-dimensional space from the arithmetic mean solution from 24 hours simultaneous solutions for the data reported in this report.*

6 Summary and discussions

A network of stable stations with good anchoring into the rock and good GPS sky was established in three tectonically different areas in Forsmark. Data from the first, second and third year are found to be of good quality. Final processing will depend especially on the quality of the data obtained in the last year. We will therefore only settle on an optimized processing technique once the quality of the entire data set is known.

We may note that during this project the probability for solar activity affecting the ionosphere is expected to be low. However, significant solar activity can occur at any time during the solar cycle. It is therefore prudent not to settle on a processing optimization technique until the entire record has been collected and evaluated. However, it could be concluded (in Chapter 5) that the data quality from the first two of the three years is good.

Even though the sun is in a "quiet" phase, sudden ionospheric disturbances, caused by solar outbursts, struck the Earth on December 6, 2006. In addition to disturbing the ionosphere, the disturbances produced what are possibly the strongest emissions ever observed at a frequency (1.4 GHz) near the L1 waveband used by GPS satellites. Dale Gary, director of Owens Valley Solar Array (OVSA), one of the leading research facilities for studies of the sun's impact upon earth, commented /5/:

> "The Sun is supposed to be at the minimum phase of its 11-year cycle. Nevertheless, the disruption lasted more than an hour, produced a record amount of radio noise, and caused massive disruptions of Global Positioning Satellite (GPS) receivers world wide."

Such disturbances cannot be reliably predicted with sufficient accuracy, but our campaigns are sufficiently long to allow collection of adequate data, even if a disturbance compromises a portion of the campaign.

References

/1/ **Gustafson L, Ljungberg A, 2007**. GPS deformation measurements in Forsmark. Annual report 2006. SKB P-07-89. Svensk Kärnbränslehantering AB.

/2/ **Gustafson L, Ljungberg A, 2008**. GPS deformation measurements in Forsmark. Annual report 2007. SKB P-08-49. Svensk Kärnbränslehantering AB.

/3/ **Sjöberg L E, Pan M, Asenjo E, 2004**. A deformation analysis of the Äspö GPS monitoring network from 2000 to 2004. SKB P-04-196. Svensk Kärnbränslehantering AB.

/4/ **Sjöberg L E, Pan M, Asenjo E, 2002**. An analysis of the Äspö crustal motion-monitoring network observed by GPS in 2000, 2001 and 2002. SKB R-02-33. Svensk Kärnbränslehantering AB.

/5/ **Weinstein Sheryl, 2006.** EurekAlert (New Jersey Institute of Technology) URL: http://www.eurekalert.org/pub_releases/2006-12/njio-nsp121506.php

Appendix 1

Specifications

AeroAntenna

Choke Ring Antenna AT2775-43
High-precision dual frequency choke ring GPS antenna

The choke ring antenna AT2775-43 from AeroAntenna is a high-quality dual frequency antenna with choke ring and radome, ideal for stationary long-time measurements.

Options

- Amplification (gain) ± 2 dB: 00 (passive), 12 dB (30 mA), 26 dB (60 mA), 36 dB (60 mA), others on request
- Input voltage: 00 (passive), 5 VDC, 5–18 VDC, others on request
- HF-connector: TNC female, BNC female, N-Type female, others on request

with or without radome

Applications

- GPS Reference Stations
- GPS deformation monitoring

Specifications

- Frequency: 1,227 ± 10 MHz, 1,575 ± 10 MHz
- Polarization: right hand circular
- Axial ratio: max. 3 dB
- Noise figure: max. 2,5 dB
- Impedance: 50 Ohm
- VSWR: < 2.0 : 1
- Band rejection: 35 dB
- Finish: Polyurethan Enamel
- Choke Ring: Aluminium
- Designed to: DO-160

Dimensions and Consumption

- Dimensions in mm: Ø 379,4×150 (without radome)
- Weight: max. 4,535 g
- Consumption: 60 mA.

Lat: N 29 39 42.318
Lon: W 82 19 36.863

Toughman Product Specifications

GPS Receiver:
- 28 parallel-channel GPS L1/L2 receiver
- 2 channels can be used for SBAS support of WAAS, EGNOS and MSAS
- Position update rate: 1 to 10 Hz
- Real time DGPS code phase, fallback to 2D/3D DGPS and L1/L2 standalone positioning modes
- Carrier phase post-processing
- Cold start: 120 seconds
- Warm start: 33 seconds
- Re-acquisition time: 1 second typical

Features:
- 32 MB Flash Memory non-volatile data storage
- 2 Serial input/output ports (configurable, NMEA 0183 compatble)
- 1 A/D Input +/- 5V 16 bit ADC
- Rechargeable Lithium-ion Polymer battery, 10 hours continuous operation
- Internal battery charger accepts 10 to 28 VDC
- Visual status indicators
  - Low Battery
  - Charging
  - Satellite Count
  - Valid Position
- Audio alarm for Invalid Position

Physical Characteristics:
- Powder coated aluminum enclosure
- Meets IP65 Rating
- Operating temperature: -20°C to 60°C
- Dimensions 20 cm x 8.5 cm x 3.5 cm (7 7/8" x 3¼" x 1 3/8")
- Weight: <600 grams (1 lb 5 oz)

Antenna:
- L1/L2, Geodetic Survey Grade
- Weight: <300 grams (10.5 oz)

DataGrid, Inc.
1022 NW 2nd Street
Gainesville, Florida 32601
(866) 318-GRID
(352) 371-3128 FAX
www.datagridinc.com

D9001

Typical Accuracy:
- Real time differential
  - Dynamic (WAAS, EGNOS) 2 meter
- Post-processing
  - Static +/- 0.5 cm + 1ppm RMS
  - Dynamic
- RTK +/- 1 cm + 1ppm RMS (Accuracy will vary depending on baseline range of radio)*

GeoID Software:
- Windows Operating System
- Import and Export RINEX files
- Automatic and advanced post-processing
- Static and kinematic modes
- Imports data from data collectors
- GeoMapper Software

Optional Upgrades:
- Wireless Bluetooth Communications

* RTK performance is provided by optional DataGrid CSTRTK software run on an external PocketPC

Authorized Representative