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Forsmark site investigation

A deformation analysis of the Forsmark GPS monitoring network from 2005 to 2009

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Oktober 2010

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

Abstract

The objective of the study is to identify possible movements in the bedrock within and outside the candidate area at Forsmark. Seven physically stable stations were built in the Forsmark area in the autumn of 2005. Stations were established within a ten-kilometer radius. The stations were placed in three different areas separated by regional deformation zones: NE of the Singö zone, within the candidate area, and SW of the Forsmark zone. Data have been collected in eighteen campaigns, each with a duration of about five days, from November 2005 to December 2009.

Stations consist of a stainless steel rod fixed in the bedrock on which the GPS antenna mounts. Each station has dedicated GPS equipment only used at the specific 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, whereas all other equipment is in place at the station only during the campaigns. The measurements were 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).

This report deals with altogether 18 campaigns. The first 13 campaigns were performed during the period November 2005 to August 2008. However, 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. We divided the data into periods of 24 hours with each period processed as a separate session in the Bernese post processing software, after which we analyzed the residuals to conclude that data are of the expected quality. The entire data set from four years reveals an overall contraction of the site. The displacement of individual stations appears to be the result of nonlinear motion. It should be emphasized that the observed deformations presented here are based on 18 discrete campaigns and not on continuous measurements.

Sammanfattning

Målet med aktiviteten är en kartläggning av eventuella rörelser i berggrunden kring SKB:s platsundersökningsområde i Forsmark. Under hösten 2005 etablerades totalt sju fysiskt stabila stationer inom en radie på 10 kilometer från platsundersökningsområdet. Stationerna placerades för att täcka tre områden åtskilda av regionala deformationszoner: NÖ om Singözonen, inom kandidatområdet respektive SV om Forsmarkszonen. Data har insamlats under arton kampanjer, var och en med en längd av ca fem dygn, från november 2005 till december 2009.

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 mätutrustningen på stationen under totalt fem dygn, varvid data sparas en gång per sekund under de fem dagarna. Antennen sitter kvar på en och samma station under hela projektets löptid, medan resten av utrustningen placeras ut vid varje kampanj. Det lokala nätverket utökades med närbelägna SWEPOS stationer av den typ som av Lantmäteriet har definierats som stationer med stabila fundament. Dessa stationer är Lovö, Uppsala och Mårtsbo.

Denna rapport behandlar totalt arton mätkampanjer. De tretton första kampanjerna utfördes under perioden november 2005 till augusti 2008. Aktiviteten utökades dock med ett år till att omfatta fyra år. Optimeringen av dataprocesseringen är beroende av data från hela perioden. Data delades upp i segment om 24 timmar, vardera kallad "a session", och beräknades separat från varandra i analysprogrammet Bernese. För att fastlägga att data har förväntad kvalitet analyserades residualer. Data från hela fyraårsperioden avslöjar att rörelsemönstret i berggrunden karaktäriseras av kontraktion av undersökningsområdet. Individuella punkters rörelse verkar ej vara linjär utan antyder en periodicitet på några år. Det ska framhållas att de observerade deformationerna som presenteras i denna rapport är baserade på 18 diskreta mätkampanjer och inte på kontinuerliga mätningar.

Contents

1 Introduction

This document reports data obtained from GPS deformation measurements at Forsmark, which up to and including June 2007 was one of the activities performed within the Forsmark site investigation. 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 on three geologically separate blocks. Geologists at SKB selected a set of possible sites for localization 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

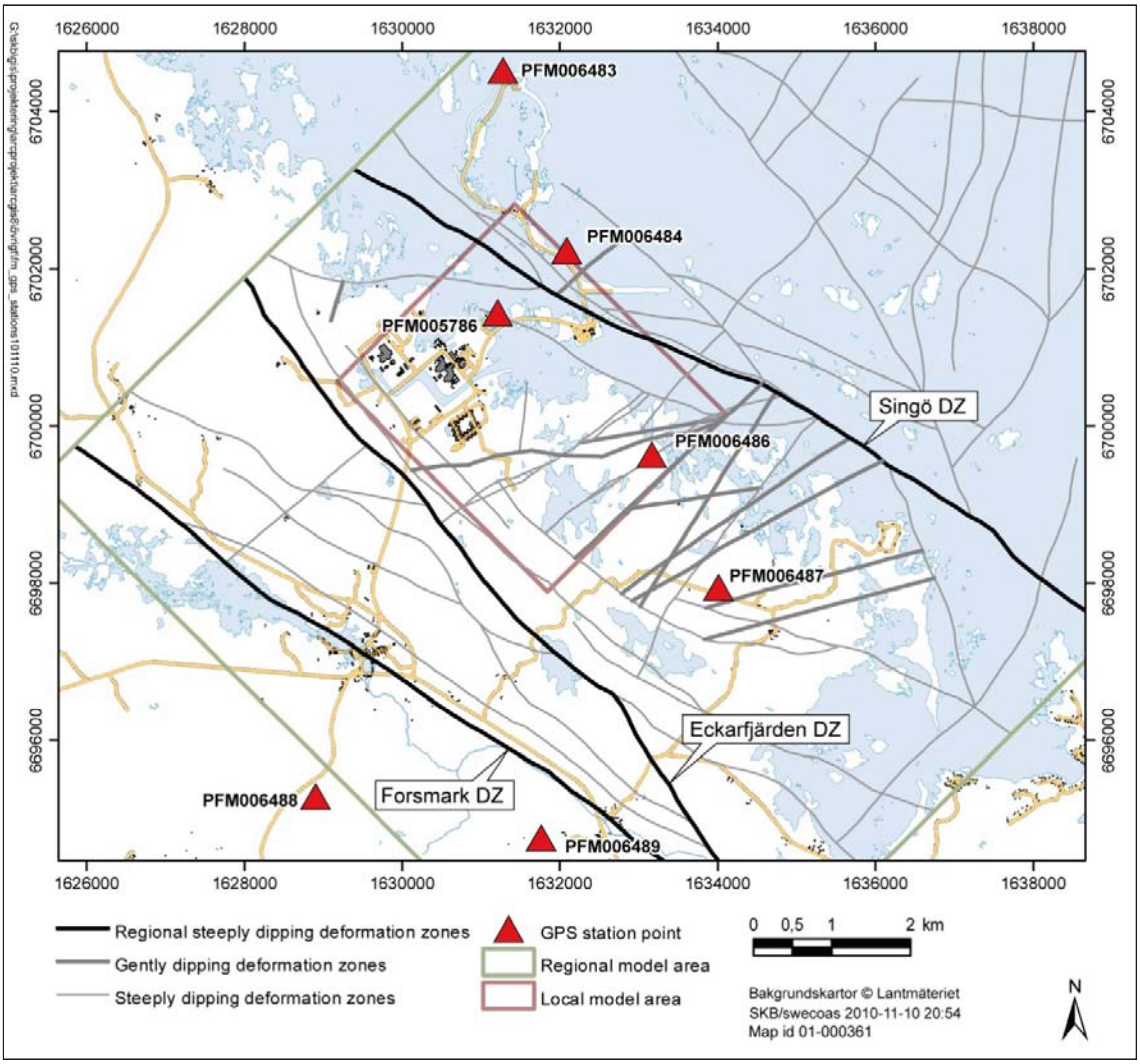

Figure 1-1. *General overview of the Forsmark site investigation area with marked station locations. The three stations PFM005786, PFM006486 and PFM006487 are located inside the tectonic lens in the investigation area. The stations PFM006483-PFM006484 are located NE of the Singö deformation zone, whereas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

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 assurance. Data were stored for use in the final deformation evaluations. This procedure was repeated in 18 campaigns with a duration of 4-5 days each between November 2005 and December 2009. The first 13 campaigns are reported in /1, 2 and 3/.

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 at an alternate site with better GPS sky.

It should be emphasized that the observed deformations presented here are based on 18 discrete campaigns and not on continuous measurements.

Table 1-1. Controlling documents 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

2 Objective and scope

The objective of this project was to define possible horizontal movements 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 used on its dedicated station at the respective campaign.

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 (an internal Lithium Ion Polymer regulated battery pack in addition to the external Lead Acid configuration) 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 at 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 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.

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.*

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 3 to 4 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. The data were successfully evaluated for quality and stored for use in the final deformation evaluations. This was repeated in 18 campaigns between November 2005 and December 2009, see Table 41. The first 13 campaigns are reported in /1, 2 and 3/. 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 additional 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.

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 the time periods for performance of all measurement campaigns at the seven stations included in the activity reported here and in previous reports /1, 2 and 3/.

Campaign	Idcode	Activity Id	Start date	Stop date
1	PFM006483	13138500	2005-11-02	2005-11-08
	PFM006484	13138501	2005-11-02	2005-11-08
	PFM006485	13138502	2005-11-02	2005-11-08
	PFM006486	13138503	2005-11-02	2005-11-08
	PFM006487	13138504	2005-11-02	2005-11-08
	PFM006488	13138505	2005-11-02	2005-11-08
	PFM006489	13138506	2005-11-02	2005-11-08
2	PFM006483	13111011	2006-01-31	2006-02-06
	PFM006484	13111012	2006-01-31	2006-02-06
	PFM006485	13111013	2006-01-31	2006-02-06
	PFM006486	13111014	2006-01-31	2006-02-06
	PFM006487	13111015	2006-01-31	2006-02-06
	PFM006488	13111016	2006-01-31	2006-02-06
	PFM006489	13111017	2006-01-31	2006-02-06
3	PFM006483	13114680	2006-03-07	2006-03-14
	PFM006484	13114681	2006-03-07	2006-03-14
	PFM006485	13114682	2006-03-07	2006-03-14
	PFM006486	13114683	2006-03-07	2006-03-14
	PFM006487	13114684	2006-03-07	2006-03-14
	PFM006488	13114685	2006-03-07	2006-03-14
	PFM006489	13114686	2006-03-07	2006-03-14
4	PFM005786	13119755	2006-05-09	2006-05-15
	PFM006483	13119756	2006-05-09	2006-05-15
	PFM006484	13119757	2006-05-09	2006-05-15
	PFM006485	13119758	2006-05-09	2006-05-15
	PFM006486	13119759	2006-05-09	2006-05-15
	PFM006487	13119760	2006-05-09	2006-05-15
	PFM006488	13119761	2006-05-09	2006-05-15
	PFM006489	13119762	2006-05-09	2006-05-15
5	PFM005786	13119763	2006-07-06	2006-07-10
	PFM006483	13119764	2006-07-06	2006-07-10
	PFM006484	13119765	2006-07-06	2006-07-10
	PFM006486	13119766	2006-07-06	2006-07-10
	PFM006487	13119767	2006-07-06	2006-07-10
	PFM006488	13119768	2006-07-06	2006-07-10
	PFM006489	13119769	2006-07-06	2006-07-10
6	PFM005786	13134251	2006-09-13	2006-09-17
	PFM006483	13134252	2006-09-13	2006-09-17
	PFM006484	13134253	2006-09-13	2006-09-17
	PFM006485	13134254	2006-09-13	2006-09-17
	PFM006486	13134255	2006-09-13	2006-09-17
	PFM006487	13134256	2006-09-13	2006-09-17
	PFM006488	13134257	2006-09-13	2006-09-17
	PFM006489	13134258	2006-09-13	2006-09-17
7	PFM005786	13151897	2007-01-18	2007-01-22
	PFM006483	13151898	2007-01-18	2007-01-22
	PFM006484	13151899	2007-01-18	2007-01-22
	PFM006486	13151900	2007-01-18	2007-01-22
	PFM006487	13151901	2007-01-18	2007-01-22
	PFM006488	13151902	2007-01-18	2007-01-22
	PFM006489	13151903	2007-01-18	2007-01-22
8	PFM005786	13165495	2007-04-25	2007-04-29
	PFM006483	13165496	2007-04-25	2007-04-29
	PFM006484	13165497	2007-04-25	2007-04-29
	PFM006486	13165498	2007-04-25	2007-04-29
	PFM006487	13165499	2007-04-25	2007-04-29
	PFM006488	13165500	2007-04-25	2007-04-29
	PFM006489	13165501	2007-04-25	2007-04-29
9	PFM005786	13169971	2007-07-09	2007-07-13
	PFM006483	13169972	2007-07-09	2007-07-13
	PFM006484	13169973	2007-07-09	2007-07-13

Campaign	Idcode	Activity Id	Start date	Stop date
	PFM006486	13169974	2007-07-09	2007-07-13
	PFM006487	13169975	2007-07-09	2007-07-13
	PFM006488	13169976	2007-07-09	2007-07-13
	PFM006489	13169977	2007-07-09	2007-07-13
10	PFM005786	13177340	2007-10-25	2007-10-29
	PFM006483	13177341	2007-10-25	2007-10-29
	PFM006484	13177342	2007-10-25	2007-10-29
	PFM006486	13177343	2007-10-25	2007-10-29
	PFM006487	13177344	2007-10-25	2007-10-29
	PFM006488	13177345	2007-10-25	2007-10-29
	PFM006489	13177346	2007-10-25	2007-10-29
11	PFM005786	13181365	2008-01-17	2008-01-21
	PFM006483	13181366	2008-01-17	2008-01-21
	PFM006484	13181367	2008-01-17	2008-01-21
	PFM006486	13181368	2008-01-17	2008-01-21
	PFM006487	13181369	2008-01-17	2008-01-21
	PFM006488	13181370	2008-01-17	2008-01-21
	PFM006489	13181371	2008-01-17	2008-01-21
12	PFM005786	13186930	2008-04-07	2008-04-10
	PFM006483	13186931	2008-04-07	2008-04-10
	PFM006484	13186932	2008-04-07	2008-04-10
	PFM006487	13186933	2008-04-07	2008-04-10
13	PFM006483	13198304	2008-08-21	2008-08-24
	PFM006484	13198305	2008-08-21	2008-08-24
	PFM006486	13198306	2008-08-21	2008-08-24
	PFM006487	13198307	2008-08-21	2008-08-24
	PFM006488	13198308	2008-08-21	2008-08-24
	PFM006489	13198309	2008-08-21	2008-08-24
14	PFM005786	13205715	2009-01-05	2009-01-09
	PFM006483	13205716	2009-01-05	2009-01-09
	PFM006484	13205717	2009-01-05	2009-01-09
	PFM006486	13205718	2009-01-05	2009-01-09
	PFM006487	13205719	2009-01-05	2009-01-09
	PFM006488	13205720	2009-01-05	2009-01-09
	PFM006489	13205721	2009-01-05	2009-01-09
15	PFM005786	13215461	2009-04-01	2009-04-05
	PFM006484	13215462	2009-04-01	2009-04-05
	PFM006486	13215463	2009-04-01	2009-04-05
	PFM006487	13215464	2009-04-01	2009-04-05
	PFM006488	13215465	2009-04-01	2009-04-05
	PFM006489	13215466	2009-04-01	2009-04-05
16	PFM005786	13234250	2009-07-08	2009-07-12
	PFM006483	13234251	2009-07-08	2009-07-12
	PFM006484	13234252	2009-07-08	2009-07-12
	PFM006486	13234253	2009-07-08	2009-07-12
	PFM006487	13234254	2009-07-08	2009-07-12
	PFM006488	13234255	2009-07-08	2009-07-12
	PFM006489	13234256	2009-07-08	2009-07-12
17	PFM005786	13241677	2009-09-17	2009-09-20
	PFM006483	13241678	2009-09-17	2009-09-20
	PFM006484	13241679	2009-09-17	2009-09-20
	PFM006486	13241680	2009-09-17	2009-09-20
	PFM006487	13241681	2009-09-17	2009-09-20
	PFM006488	13241682	2009-09-17	2009-09-20
	PFM006489	13241683	2009-09-17	2009-09-20
18	PFM005786	13243682	2009-12-04	2009-12-08
	PFM006483	13243683	2009-12-04	2009-12-08
	PFM006484	13243684	2009-12-04	2009-12-08
	PFM006486	13243685	2009-12-04	2009-12-08
	PFM006487	13243686	2009-12-04	2009-12-08
	PFM006488	13243687	2009-12-04	2009-12-08
	PFM006489	13243688	2009-12-04	2009-12-08

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 eighteen measurement campaigns, each with duration of 3-5 days, repeated approximately every three months. The antenna on every station remains on the specific station during the entire project. The GPS-systems and power supplies are employed 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 approximately 100 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 ephemerides (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 in which the known distances between the stations are 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 W 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.

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

4.5 Analysis and interpretations

The Bernese software is an 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 of 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.

5 GPS data Quality

Figure 5-1 shows the RMS-residuals from all 18 campaigns. We use these residuals in the form of root mean square (RMS) deviations from the arithmetic mean coordinates as measures of the overall quality In the processing, the station PFM006484 was kept fixed, and is therefore not included in the diagram. Station PFM006485 was closed after campaign 6.

The RMS-residuals can be considered as a measure of the error of the position of each individual station. As seen, the residuals range up to ca. 5.5 mm, with the majority in the range 1 to 3 mm.

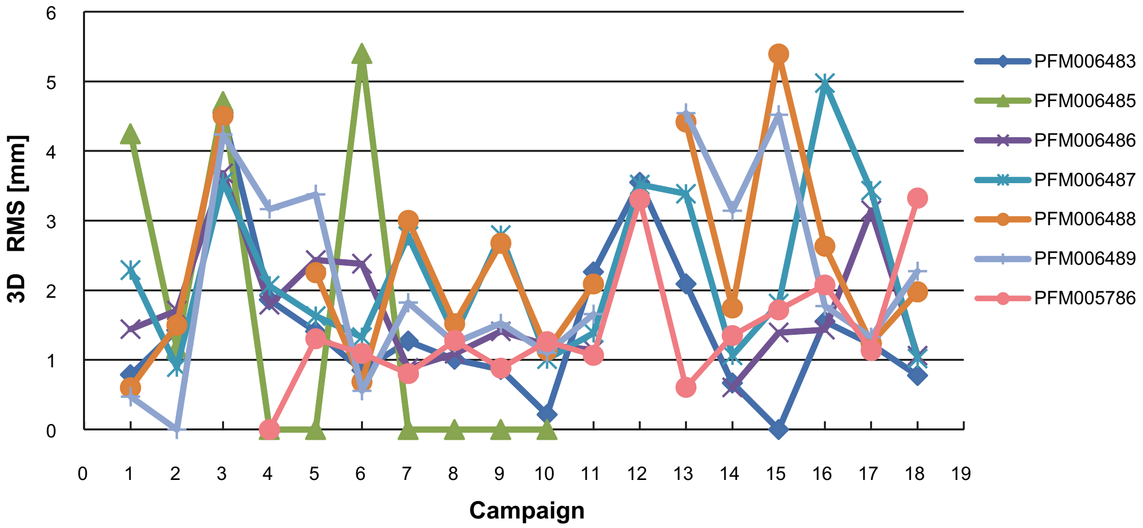

Figure 5-1. *Residuals from all campaigns in Forsmark. The residual is calculated as the RMS deviation of 24 hours simultaneous solutions from the arithmetic mean solution in three-dimensional space. The RMS results for campaigns up to that year were also published in the annual reports.*

6 Results from analysis of the entire data set from campaigns 1 through 18

Data from this activity are traceable in Sicada by the activity plan number (AP PF 400-05-056. 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 database may be revised, if needed. However, such revision of the database will not necessarily result in a revision of this report, although major data revisions are normally ensued by a revision also of the corresponding P-report. Minor revisions are normally presented as supplements, available at www.skb.se.

Each campaign yielded three consecutive 24 hours long periods of GPS observations collected at 1 second intervals with the exception of campaigns 4 and 7 that yielded two consecutive 24 hours long periods of data. Each 24 hours set of observations was processed using the Bernese GPS Software according to procedures described in Section 4.4 of this report. The Bernese software uses one observation per 30 seconds intervals.

The processing procedures include network adjustment to spread the errors across all baselines using the ADDNEQ routine. This procedure requires the coordinates of one station to be kept stationary and acts as a reference for all other stations. However, also that station can be expected to move both in the Earth-centered Earth-fixed Cartesian coordinates native to the processing and in the Swedish grid RT90-RHB70 datum.

The low frequency motions of all stations were modeled as linear displacements to estimate the motion of the reference point and therefore the entire system. A network adjustment was made to distribute all deviations from linear motion across the network and across the entire measurement period of more than four years. This function is not included in the Bernese software, and an external program was therefore written in order to calculate residuals. The network was then adjusted until a minimum was reached in the sum of the squares of all deviations from a linear motion. This resulted in a motion of the reference point (PFM006484) that had been held stationary of dX = 0.7 mm/year, dY=-0.3 mm/year, and dZ=0.3 mm/year for a total displacement of 0.82 mm/year. The adjustment reduced the sum of the residuals by a little over 2%. Table 6-1 gives the resulting linear velocity components for all points except PFM006485 which was replaced by point PFM005786 after the first few campaigns.

It should be emphasized that the errors of the estimated components of the velocities in the vertical directions are significantly higher than the errors of the velocities in the horizontal directions.

Table 6-2 lists all calculated base line lengths between successive stations, together with the estimated changes. These changes are also presented on the map in Figure 6-1. Figures 6-2a-u shows a graphical presentation of the base line changes for all 21 base lines between the seven stations. The RMS error estimates correspond to the values shown in Figure 5-1. Also shown is the linear regression line whose parameters are given in Table 6-2. The base line lengths presented in Table 6-2 and Figure 6-1 are based on geodetic length calculations, and differ from the corresponding lengths which can be calculated from the coordinates based upon the Swedish grid RT90-RHB70 datum.

Table 6-1. Estimated linear velocity components.

Station	dX mm/yr	dY mm/yr	dZ mm/yr
PFM006483	1.116	0.576	–0.864
PFM006484	0.684	–0.288	–0.288
PFM006486	–1.08	–0.972	–1.656
PFM006487	0.288	–0.864	1.404
PFM006488	0.504	0.972	0.54
PFM006489	–0.828	–0.072	–0.36
PFM005786	0.576	1.044	2.34

Table 6-2. Base line lengths and linear regression parameters.

From	to	base line at first camp [m]	change [mm/yr]	R2
PFM006483	PFM006484	2429.7806	-1.1	0.250
PFM006483	PFM006486	5243.2741	-2.3	0.646
PFM006483	PFM006487	7121.4999	-2.5	0.454
PFM006483	PFM006488	9539.1960	-2.0	0.289
PFM006483	PFM006489	9776.4689	-2.1	0.247
PFM006483	PFM005786	3079.6614	-1.7	0.269
PFM006484	PFM006486	2815.4548	-1.2	0.347
PFM006484	PFM006487	4697.3130	-1.4	0.278
PFM006484	PFM006488	7640.2039	-1.7	0.282
PFM006484	PFM006489	7478.9470	-1.3	0.173
PFM006484	PFM005786	1174.9330	-1.9	0.291
PFM006486	PFM006487	1884.7595	-0.3	0.024
PFM006486	PFM006488	6084.6024	-1.1	0.193
PFM006486	PFM006489	5067.7066	-0.3	0.014
PFM006486	PFM005786	2663.9278	-2.3	0.670
PFM006487	PFM006488	5755.2821	-1.9	0.322
PFM006487	PFM006489	3895.9832	-0.6	0.055
PFM006487	PFM005786	4478.5431	-1.8	0.303
PFM006488	PFM006489	2909.1961	-1.1	0.402
PFM006488	PFM005786	6578.1313	-0.3	0.011
PFM006489	PFM005786	6708.2742	-0.6	0.045

6.1 Summary of the results

Although the fluctuations are large in the plots of the baselines (Figure 6-2 a-u), the general trend indicates a decreasing length of the baselines. This “contraction” is particularly prominent along e.g. PFM006483-PFM006486 and PFM006486-PFM005786 (Figure 6-2b and Figure 6-2o). Furthermore, some of the baselines, e.g. PFM006484-PFM005786 and PFM6487-PFM005786, indicate a nonlinear variation in length.

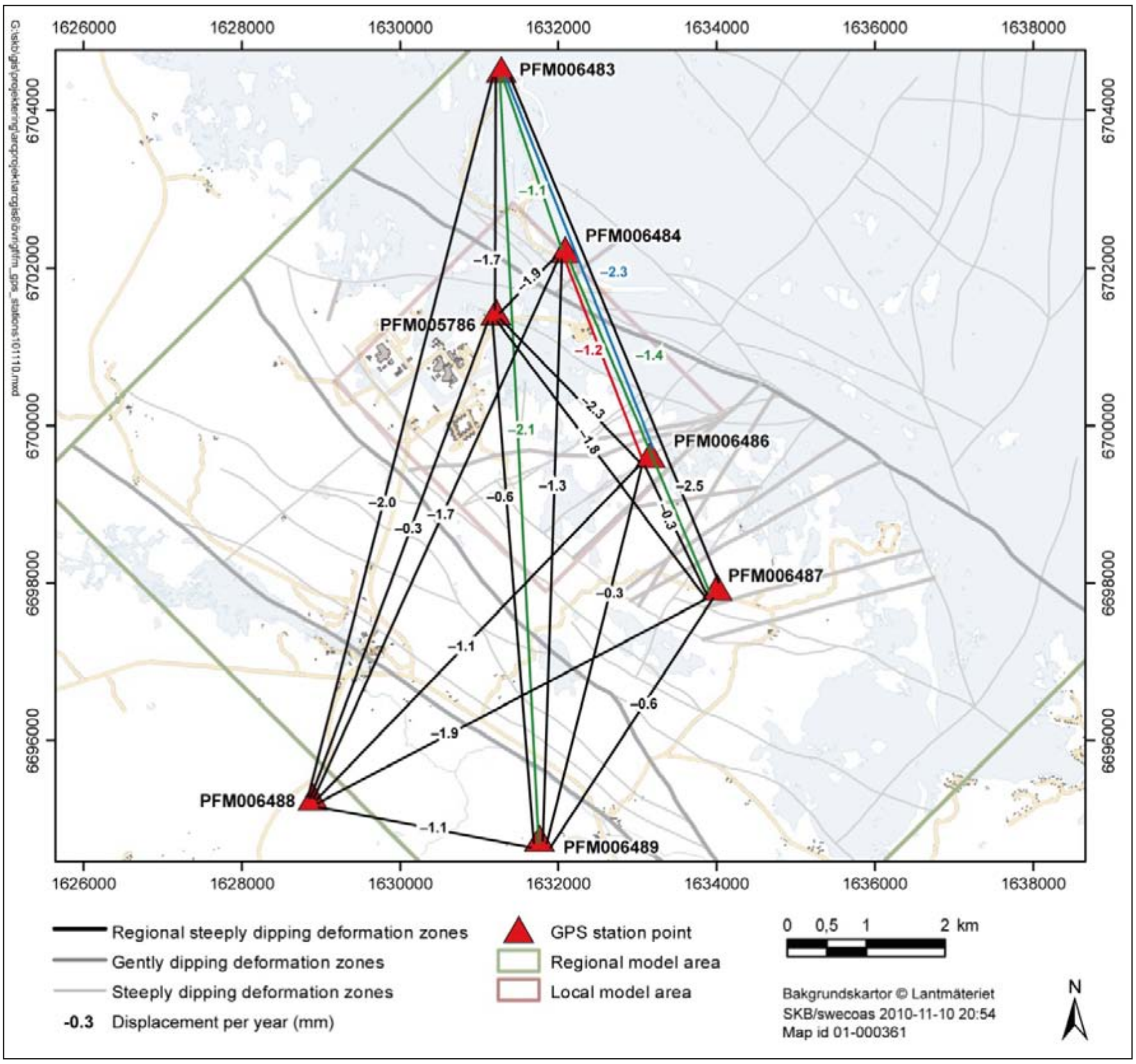

__Figure 6-1.__ Graphical presentation of the estimated annual changes of the length of the base lines, according to Table 6-2.

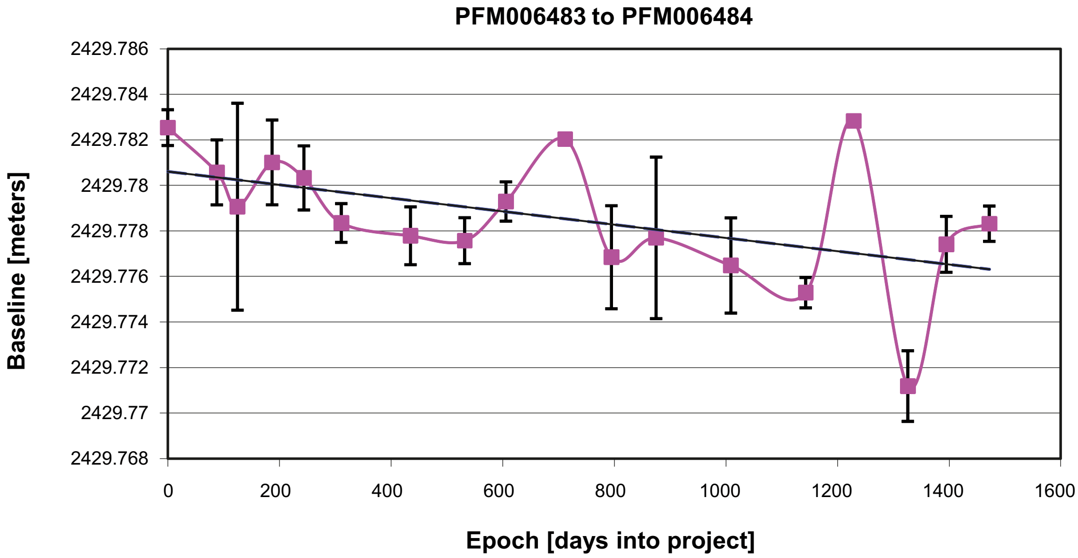

Figure 6-2a. *Variation in baseline length between stations PFM006483 and PFM006484 as a function of days into the project.*

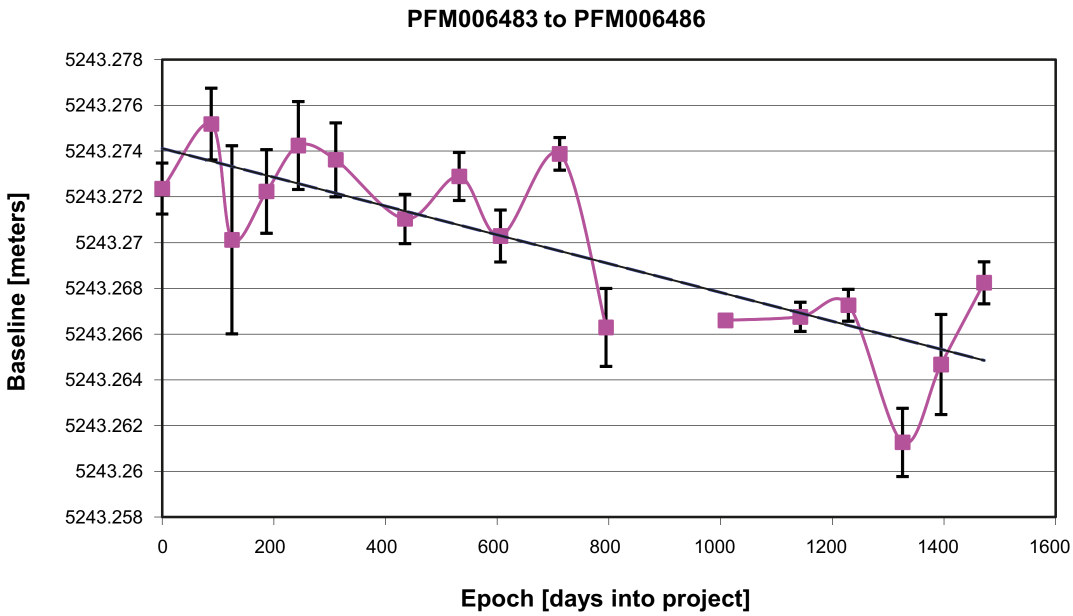

Figure 6-2b. *Variation in baseline length between stations PFM006483 and PFM006486 as a function of days into the project.*

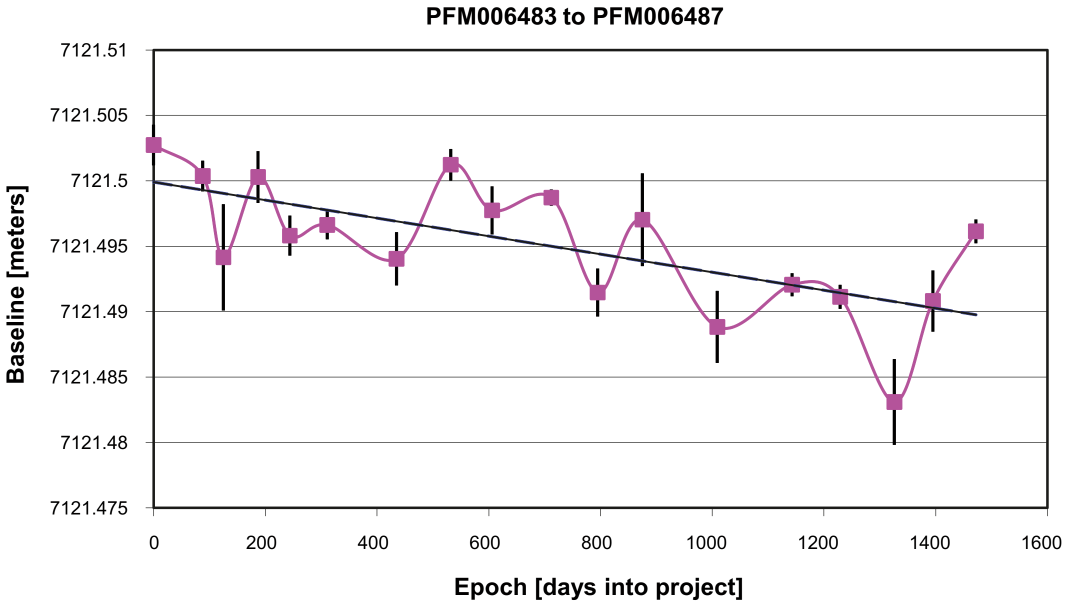

Figure 6-2c. *Variation in baseline length between stations PFM006483 and PFM006487 as a function of days into the project.*

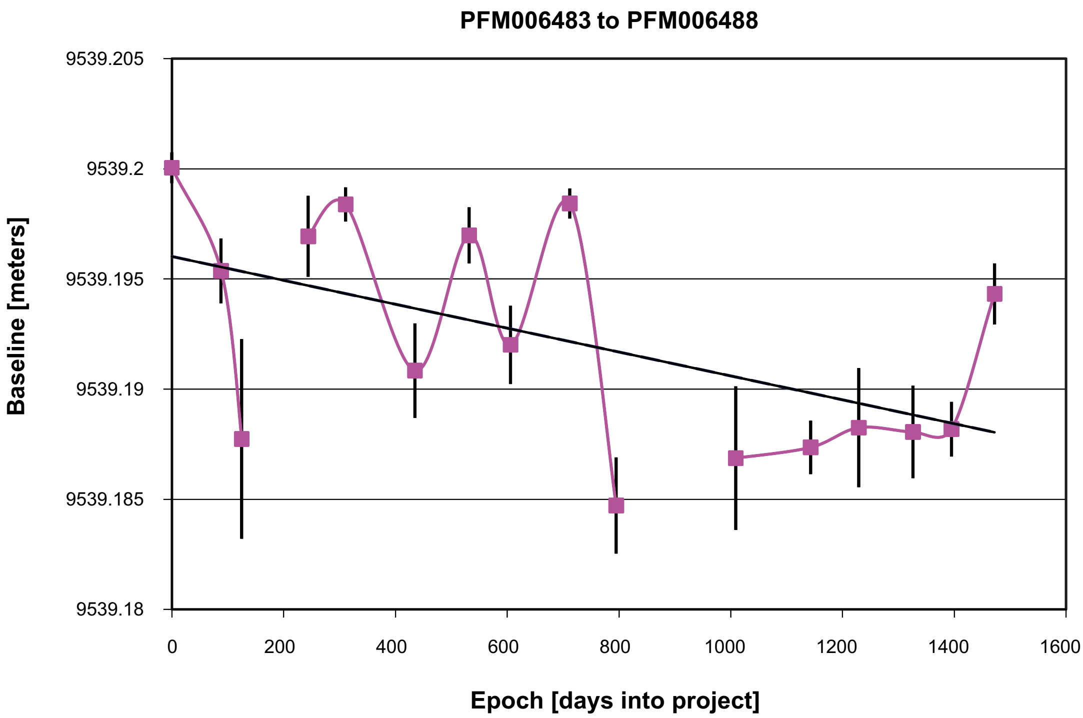

Figure 6-2d. *Variation in baseline length between stations PFM006483 and PFM006488 as a function of days into the project.*

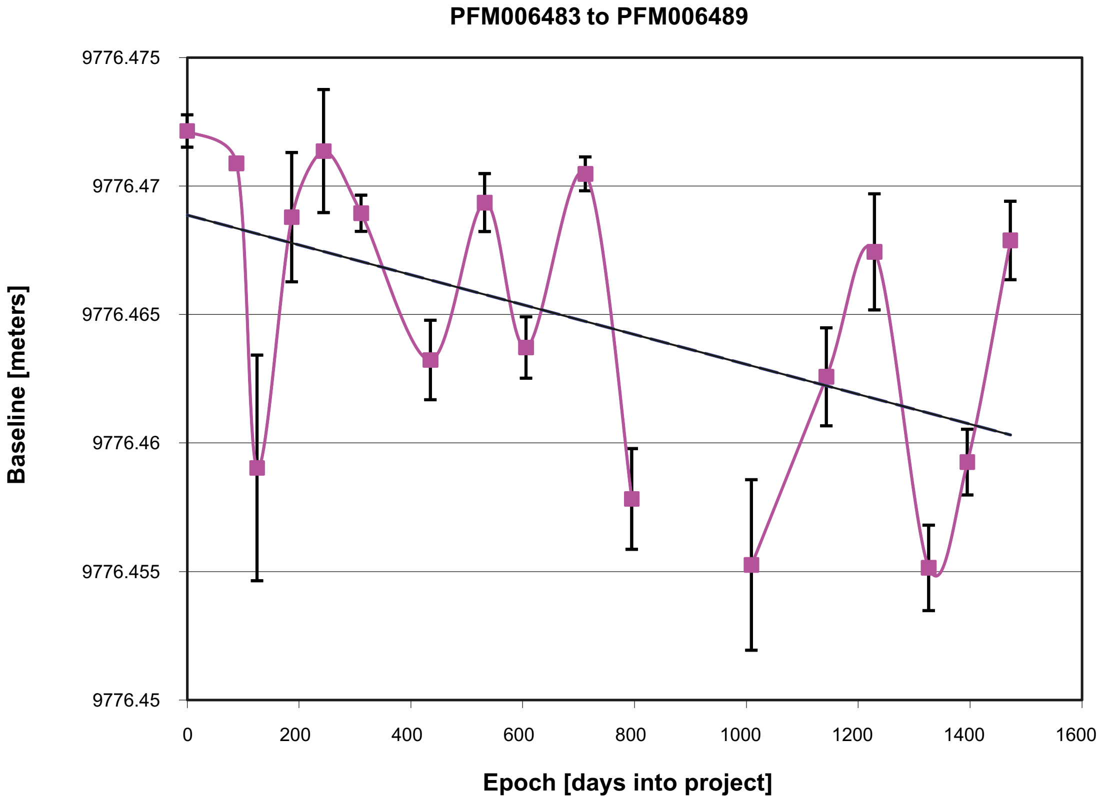

Figure 6-2e. *Variation in baseline length between stations PFM006483 and PFM006489 as a function of days into the project.*

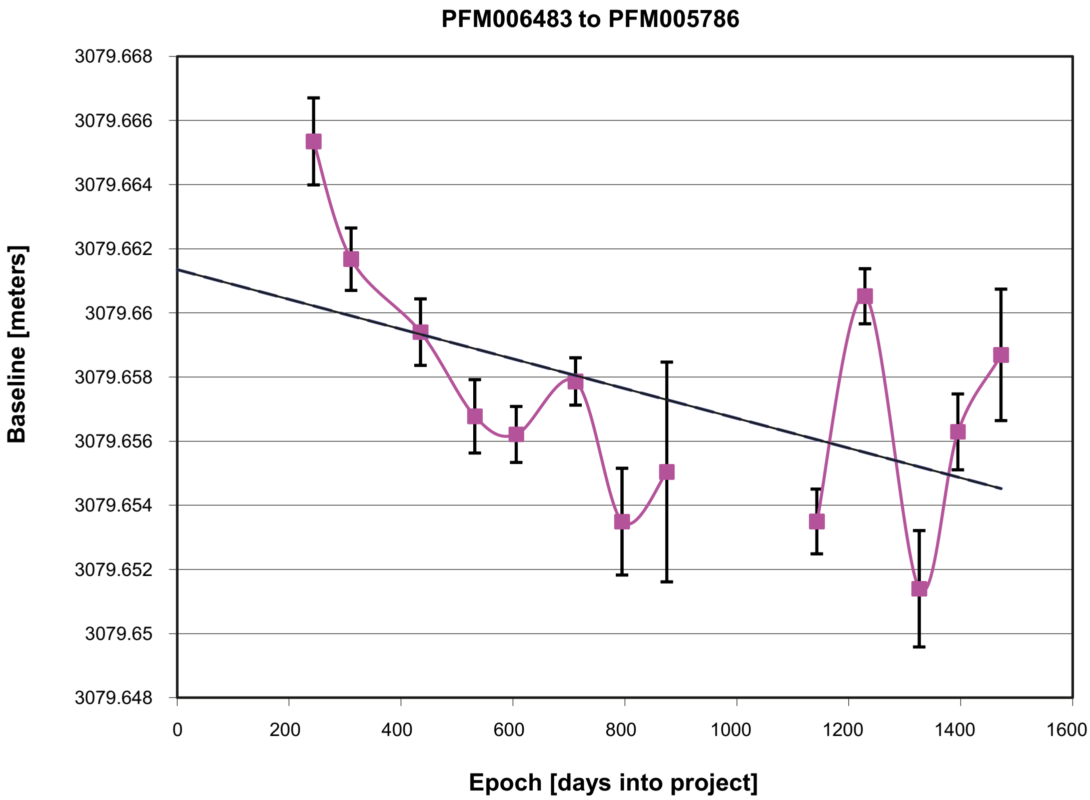

Figure 6-2f. *Variation in baseline length between stations PFM006483 and PFM005786 as a function of days into the project.*

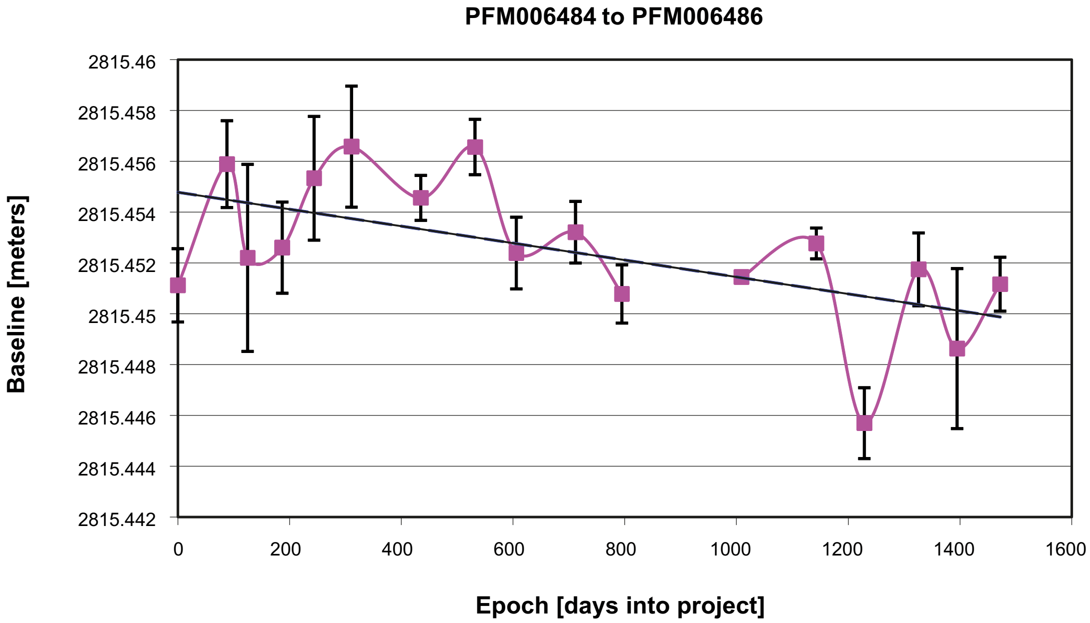

Figure 6-2g. *Variation in baseline length between stations PFM006484 and PFM006486 as a function of days into the project.*

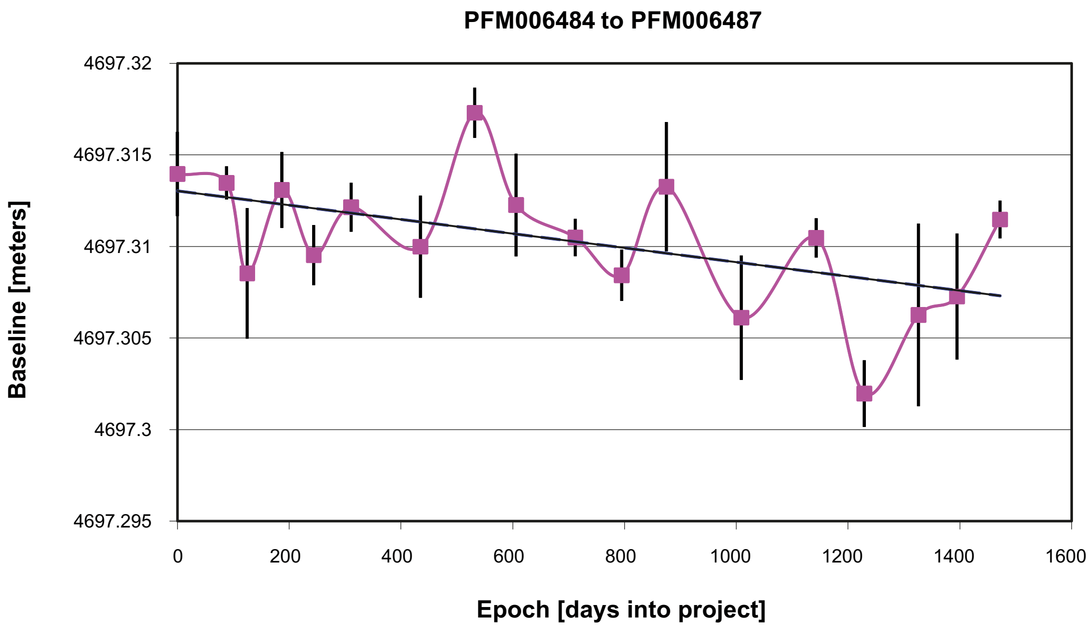

Figure 6-2h. *Variation in baseline length between stations PFM006484 and PFM006487 as a function of days into the project.*

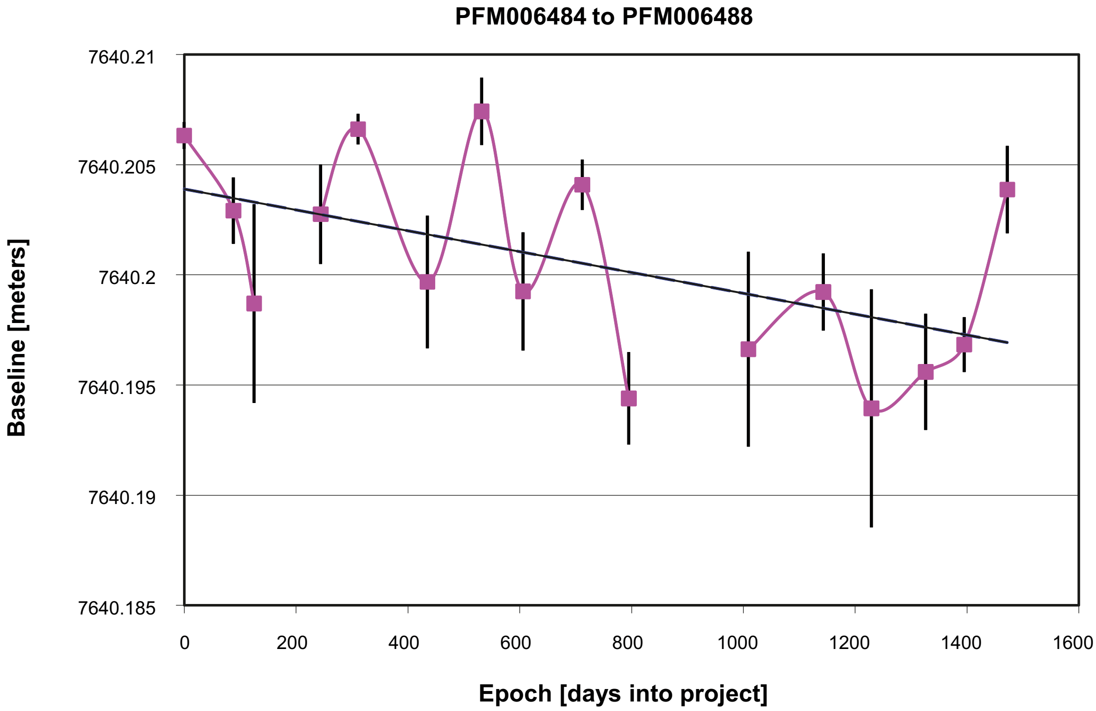

Figure 6-2i. *Variation in baseline length between stations PFM006484 and PFM006488 as a function of days into the project.*

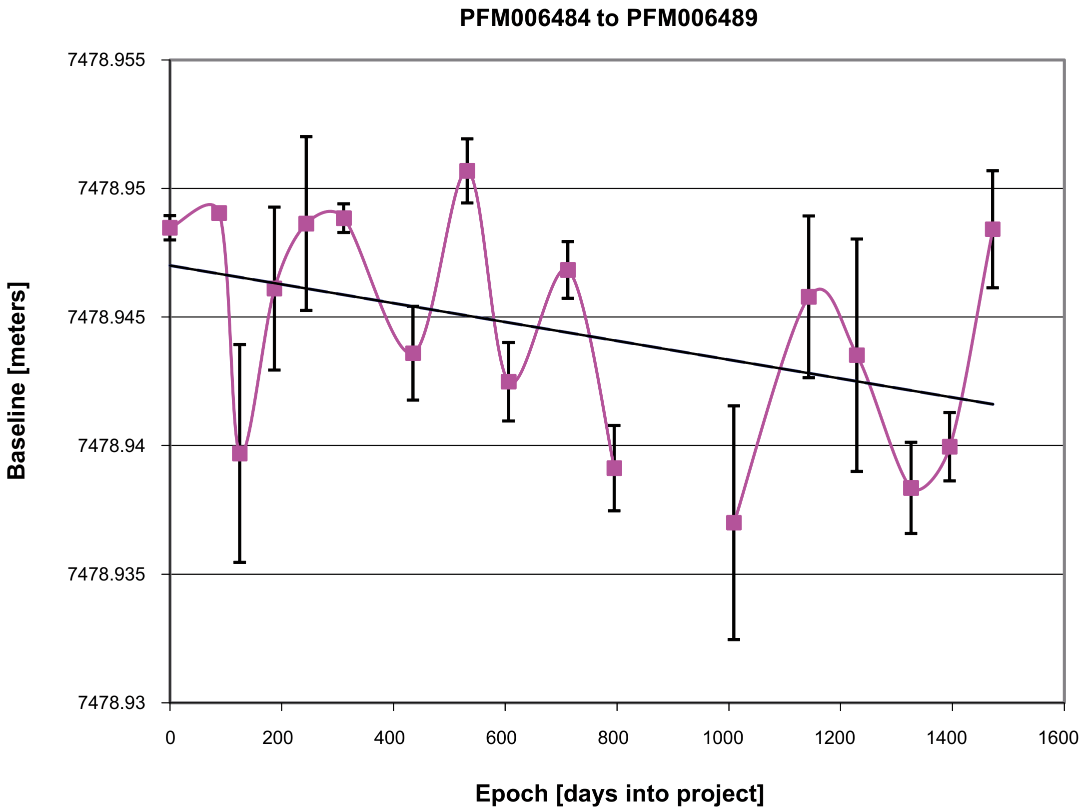

Figure 6-2j. *Variation in baseline length between stations PFM006484 and PFM006489 as a function of days into the project.*

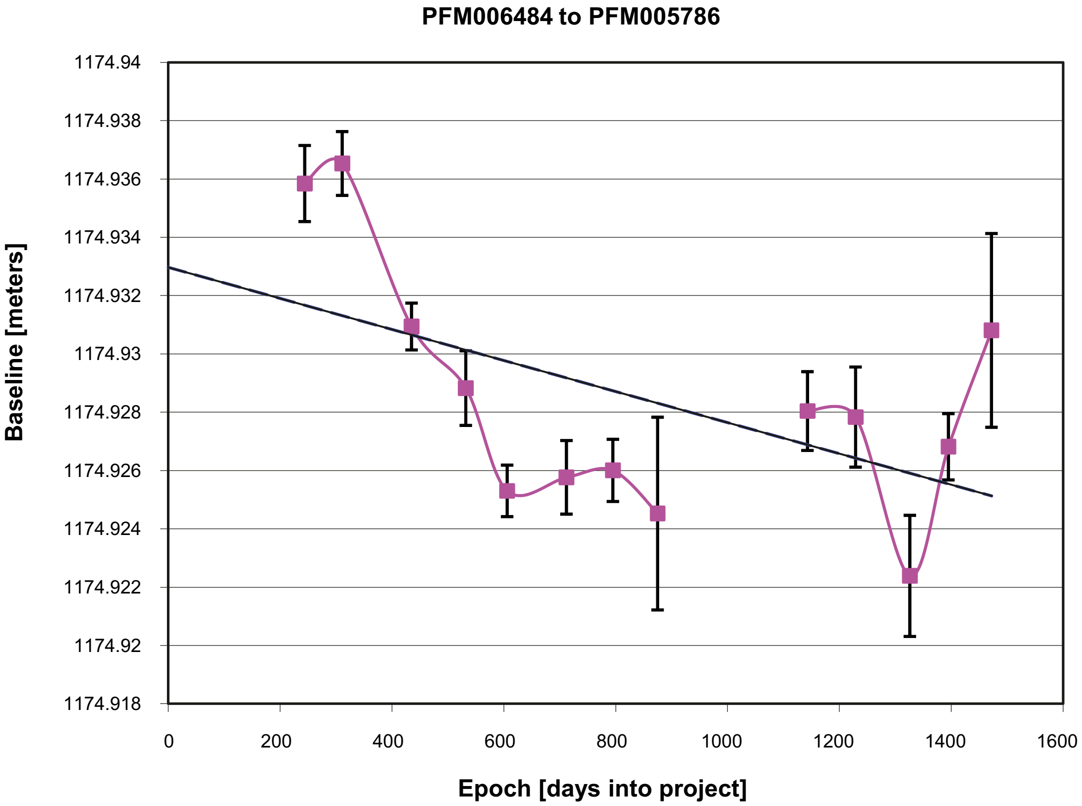

Figure 6-2k. *Variation in baseline length between stations PFM006484 and PFM005786 as a function of days into the project.*

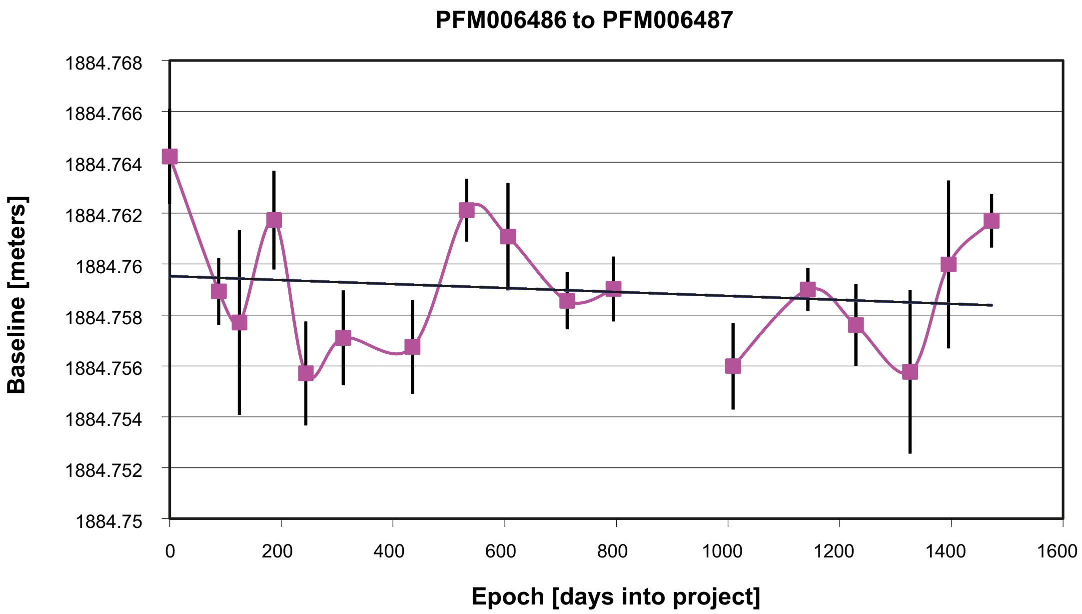

Figure 6-2l. *Variation in baseline length between stations PFM006486 and PFM006487 as a function of days into the project.*

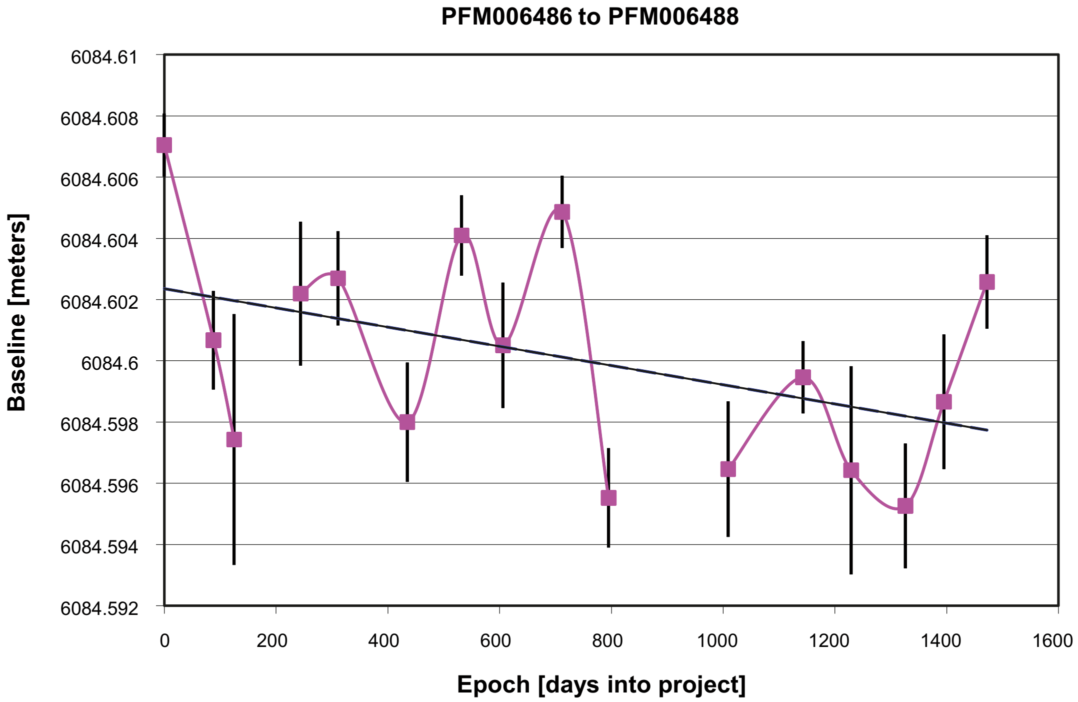

Figure 6-2m. *Variation in baseline length between stations PFM006486 and PFM006488 as a function of days into the project.*

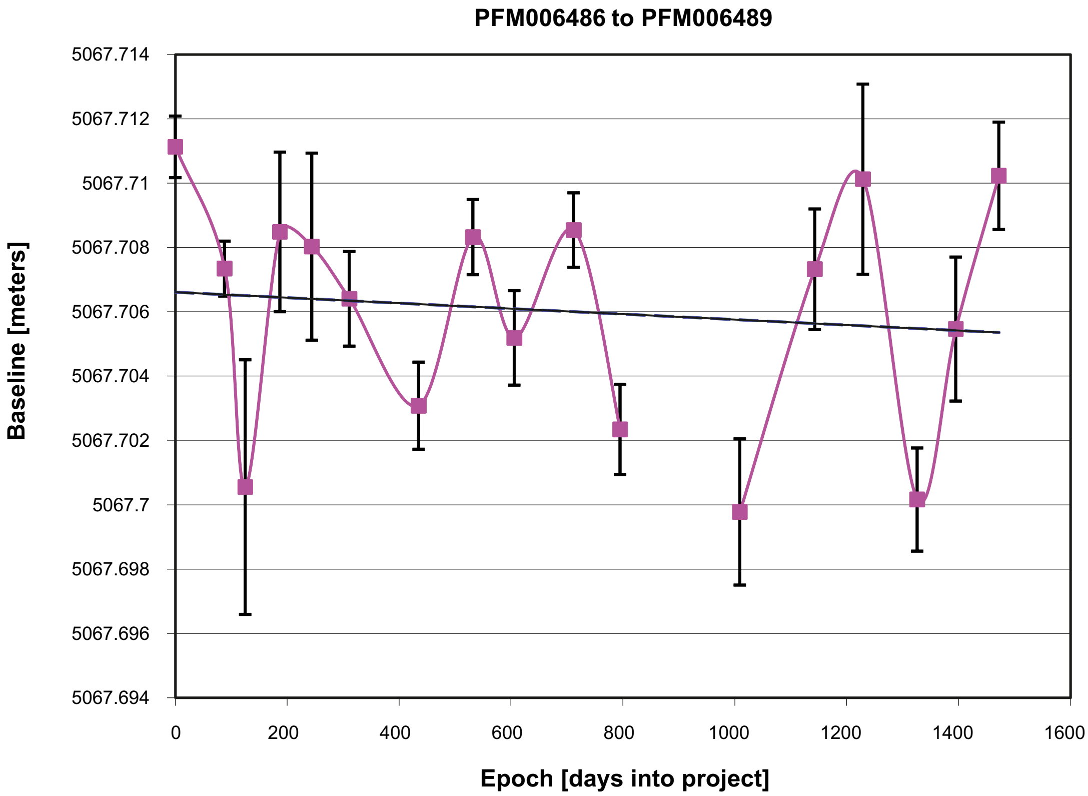

Figure 6-2n. *Variation in baseline length between stations PFM006486 and PFM006489 as a function of days into the project.*

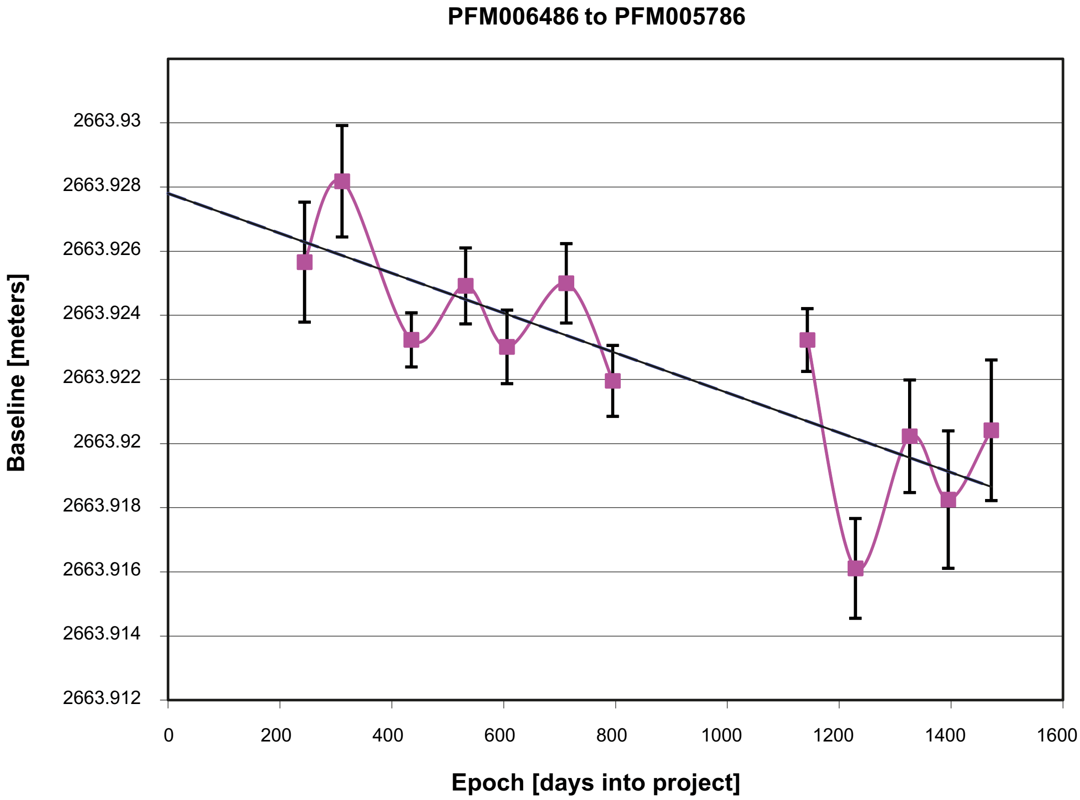

Figure 6-2o. *Variation in baseline length between stations PFM006486 and PFM005786 as a function of days into the project.*

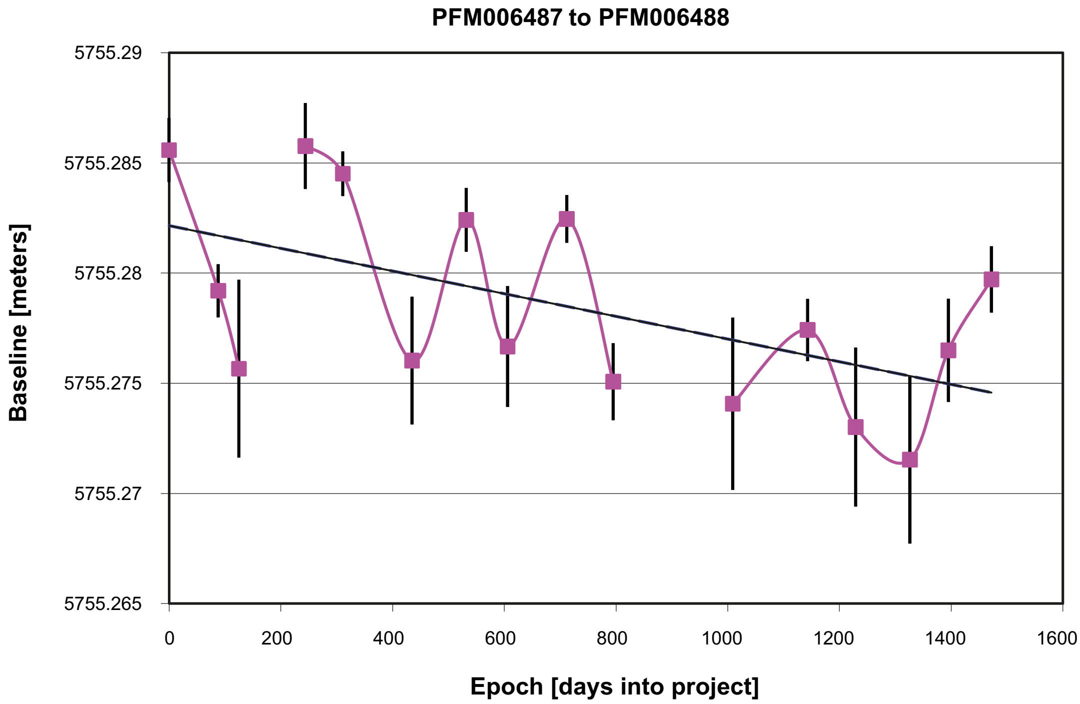

Figure 6-2p. *Variation in baseline length between stations PFM006487 and PFM006488 as a function of days into the project.*

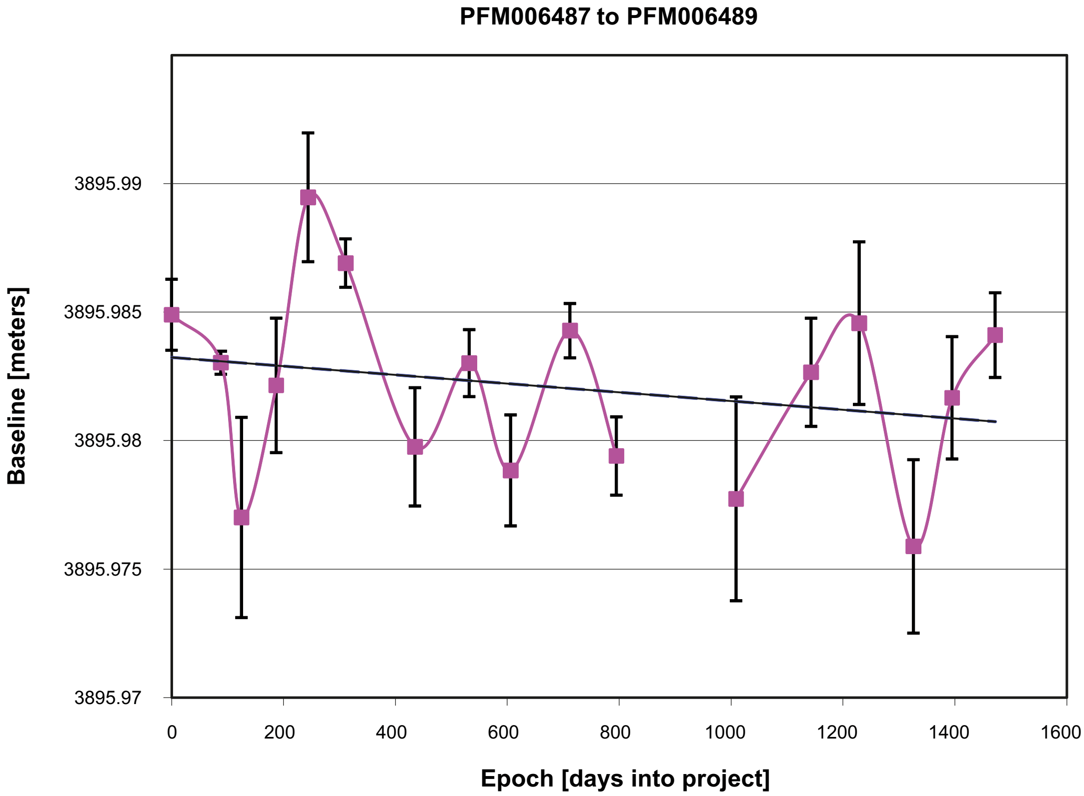

Figure 6-2q. *Variation in baseline length between stations PFM006487 and PFM006489 as a function of days into the project.*

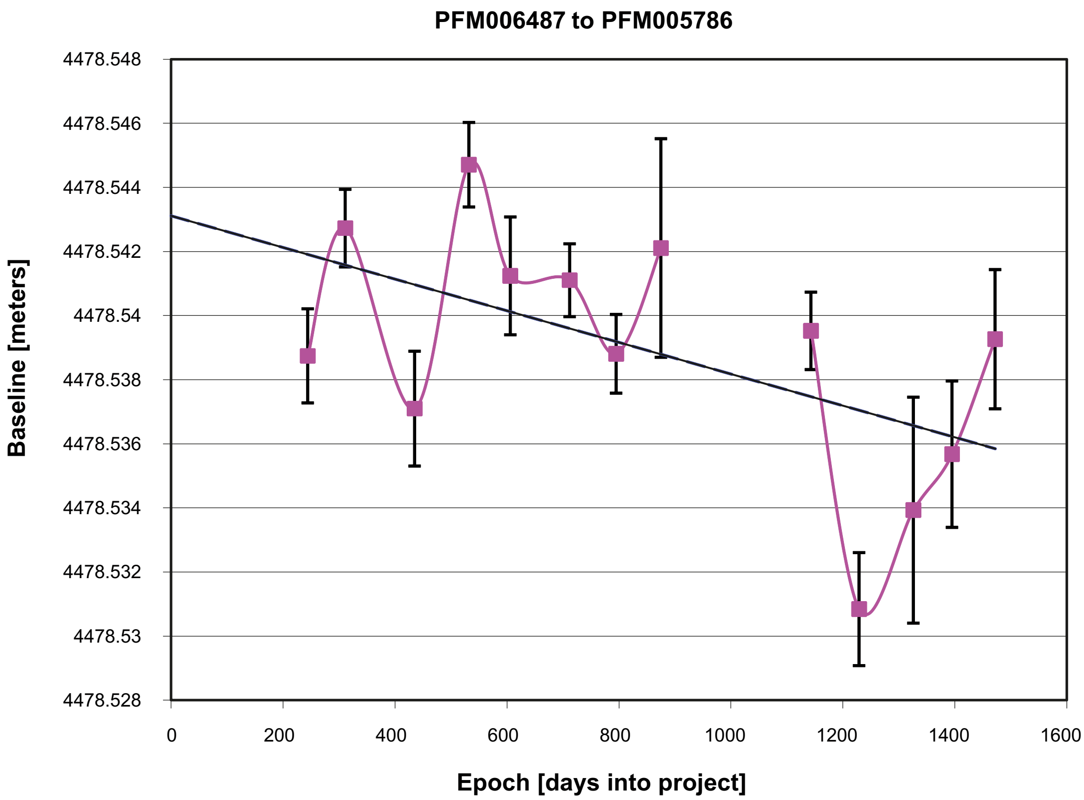

Figure 6-2r. *Variation in baseline length between stations PFM006487 and PFM005786 as a function of days into the project.*

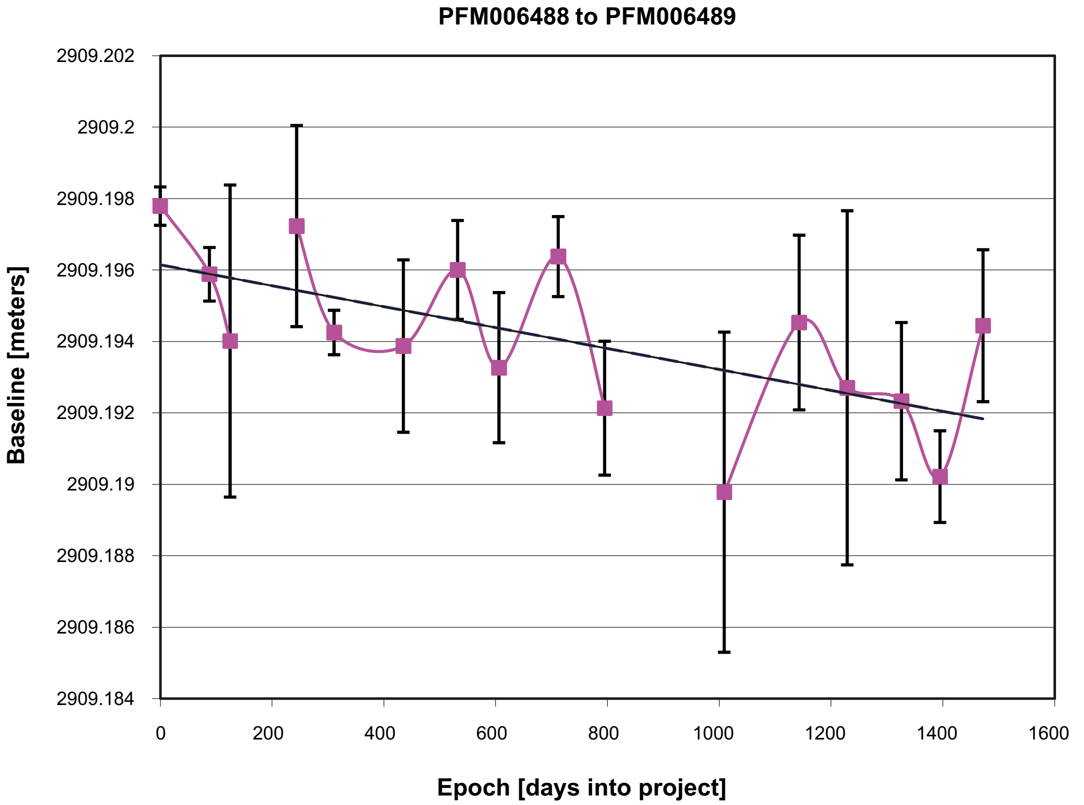

Figure 6-2s. *Variation in baseline length between stations PFM006488 and PFM006489 as a function of days into the project.*

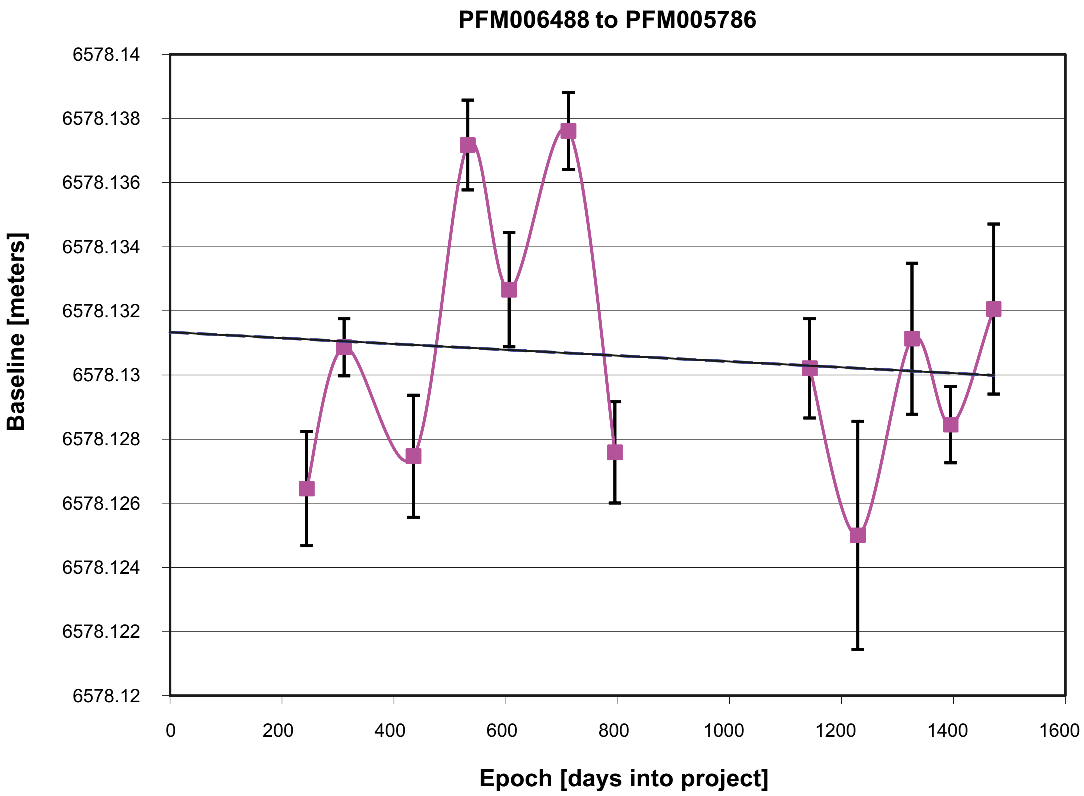

Figure 6-2t. *Variation in baseline length between stations PFM006488 and PFM005786 as a function of days into the project.*

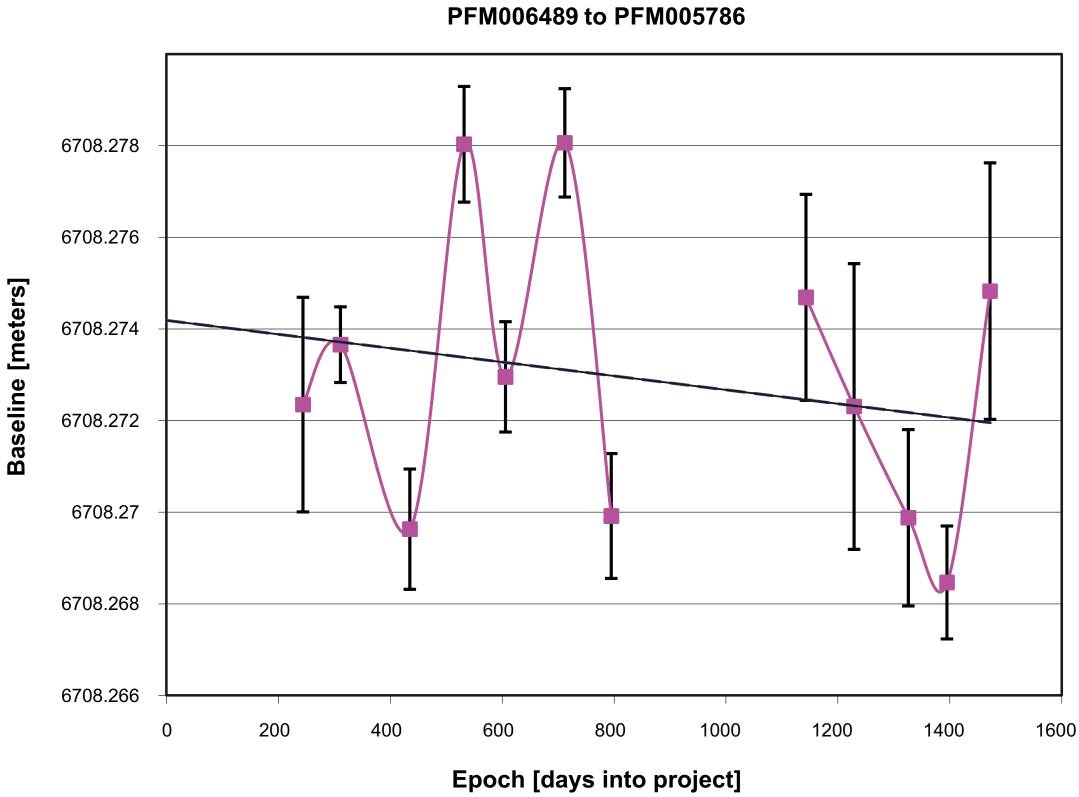

Figure 6-2u. *Variation in baseline length between stations PFM006489 and PFM005786 as a function of days into the project.*

References

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

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

/3/ **Gustafson L and Ljungberg A, 2009.** GPS deformation measurements in Forsmark. Annual report 2008. SKB P-09-27. Svensk Kärnbränslehantering AB.

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 x 150 (without radome)
- Weight: max. 4,535 g
- Consumption: 60 mA.

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

DataGrid®

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 compatible)
- 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