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Analysis of 20 years of GPS data from SWEREF consolidation points

– using BERNESE and GAMIT-GLOBK software

Lotti Jivall[1], Faramarz Nilfouroushan[1,2], Naim Al Munaizel[1]

[1]Lantmäteriet, [2]University of Gävle

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Naim Al Munaizel[1]

[1]Lantmäteriet, [2]University of Gävle

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Preface

This report is a result of the efforts of many individuals, too many to list, who have contributed in one way or another in the establishment of the SWEREF 99 reference frame and its maintenance since 1999. All individuals are greatly acknowledged who contributed to the development of the concept of SWEREF consolidation points, planning, field reconnaissance, establishment of the benchmarks, GNSS measurements, documentation, preceding processing and analysis.

The report documents the first aggregative analysis of the repeated measurements of the 300 so-called consolidation points ("försäkringspunkter" in Swedish). It first reviews the SWEREF 99 reference frame and its importance for geodetic infrastructure and then all data collection, reprocessing and analysis are explained. The results of consistent processing of 20 years of GPS data from consolidation points, using two scientific software in parallel – the Bernese and the GAMIT-GLOBK software packages – are presented and compared to the original processing and to each other.

The stability of SWEREF 99 over time was evaluated on a general level by estimating the uncertainties based on repeated measurements and by performing trend analysis on all points with at least three observations. Points, for which our statistical testing indicates trends, and points with degraded quality were identified.

The main part of the GNSS-analysis in terms of reprocessing was performed already in 2017-2018 based on data up to 2017. After this the uncertainty and trend analysis started. Meanwhile results from the regular operational processing got available and was included in the analysis. The latest uncertainty and trend analysis based on the original/operational processing was performed in 2022 and is presented in the appendices.

The results of this work will be used in the future planning of consolidation point measurements and as a basis for the computation of the SWEREF 99 component of coming geoid models. Every year about 50 consolidation points are measured, where the main part will add another observation to the time series, and new analyses will follow. We hope that the developed methods and strategies, presented in the work reported here, will be useful also for the future analysis of consolidation points.

September 2022

Lotti Jivall | Faramarz Nilfouroushan | Naim Al Munaizel

lotti.jivall@lm.se | faramarz.nilfouroushan@lm.se | naim.al.munazel@lm.se

Abstract

The SWEREF 99 national geodetic reference frame has been used in Sweden since 2007 and it was adopted by EUREF in 2000 as the national realisation of ETRS89 in Sweden [Jivall and Lidberg, 2000]. The **SWEREF 99 reference frame is defined by an active approach** through the 21 original (fundamental) SWEPOS GNSS stations, hence relying on positioning services such as the network real time kinematic (NRTK) and post processing services. The SWEREF 99 coordinates are assumed to be fixed in time and no temporal variations are expected. However, the stability of the stations and their coordinates can be altered due to equipment change or software as well as local movements at the reference stations.

To be able to check all alterations mentioned above and having a backup national network of GNSS points, approximately **300 passive so-called consolidation points** are used. The consolidation points are a subset (the main part) of the so-called SWEREF points established from 1996 and onwards. All 300 points are remeasured with static GNSS for 2x24 hours using choke ring antennas on a yearly basis with 50 points each year. The original data processing was done with the Bernese GNSS software in a regular basis and the reprocessing was carried out with both the Bernese and the GAMIT-GLOBK software packages during 2017-2018.

The **resulting coordinates in SWEREF 99 from GAMIT and Bernese processing are equal at 1–2 mm level for the horizontal and 4 mm for the vertical components (1 sigma)** when using almost the same models and processing strategy. The result from the original processing, which partly is based on other models and parameters, differs slightly more for the north component compared to the reprocessing results (RMS of 2 mm compared to 1 mm).

Our analysis both of Bernese and GAMIT results shows that **the standard uncertainties for a single SWEREF 99 coordinate determination (with 2x24 hrs observation) is about 2 mm for the horizontal components and 6 mm in height.** It is interesting to note that the coordinate repeatability is on the same level also for the original processing, where we have differences in models and parameters used during the years. This indicates that **our concept for determining SWEREF 99 coordinates has worked well on the mentioned uncertainty level**.

We performed trend analysis and statistical tests for the points having minimum three observations to investigate the stability of the estimated SWEREF 99 coordinates. The low rate of redundancy (just one redundant observation in case of three observations) was a problem so a **modified version of the F-test was developed** which gave good agreement with visual interpretation of the time series. This strategy showed that **about 10% of the points had trends (with notable movements), but we should be aware of the low redundancy.** With more observations in the future, we can determine trends more reliably.

We will continue to analyse the point coordinate repeatability and trends when we get more data. Further on, some reprocessing is needed to be compatible with the SWEREF 99 update 2021 at SWEPOS. We will also study the effect of using different satellite systems and finally prepare for the publication of updated coordinates in the Digital Geodetic Archive (DGA) provided by Lantmäteriet.

Sammanfattning

Det nationella referenssystemet SWEREF 99, som accepterades av EUREF som en nationell ETRS89-realisering år 2000, har använts som officiellt referenssystem i Sverige sedan 2007. **SWEREF 99 är aktivt definierat baserad på SWEPOS fundamentalstationer.** För åtkomst till systemet är användare därmed hänvisade till tjänster såsom SWEPOS nätverks-RTK och SWEPOS beräkningstjänst. SWEREF 99-koordinaterna betraktas som statiska och förväntas inte variera med tiden. Däremot kan SWEPOS stationernas koordinater ändras vid förändringar på stationerna, t.ex. antennbyten, eller p.g.a. lokala rörelser.

För att ha kontroll på effekten vid koordinatbestämning av sådana förändringar på stationerna används **300 passiva försäkringspunkter,** vilka även kan betraktas som ett passivt komplement till SWEPOS. Försäkringspunkterna är till största delen identiska med de SWEREF-punkter som etablerades under RIX 95-projektet från 1996 och framåt. Försäkringspunkterna mäts 2x24 timmar med chokering-antenner enligt ett rullande schema med 50 punkter per år och återbesök efter 6 år. Ursprungligen beräknades punkterna med det så kallade Bern-programmet (Bernese GNSS software). Under 2017–2018 har dessutom konsistenta omberäkningar gjorts med både Bern-programmet och GAMIT-GLOBK.

De resulterande koordinaterna från GAMIT respektive Bern-programmet stämmer överens på 1–2 mm i plan och 4 mm i höjd på 1-sigma-nivån när i stort sett samma beräkningsstrategi och modeller används. Den ursprungliga beräkningen, vilken delvis är baserad på andra modeller och inställningar, avviker något mer i nordkomponenten jämfört med omberäkningarna (RMS på 2 mm istället för 1 mm).

Vår analys av såväl Bern- som GAMIT-beräkningarna visar att **standardosäkerheten för en enskild punktbestämning (2x24 timmar) ligger på ungefär 2 mm per plankomponent och 6 mm i höjd.** Intressant att notera är att de ursprungliga beräkningarna inte är sämre trots varierande beräknings-inställningar och modeller. Det indikerar att **vårt koncept för att bestämma nya SWEREF 99-koordinater har fungerat väl på den tidigare nämnda osäkerhetsnivån**.

För att undersöka stabiliteten hos punkternas koordinater gjordes trend-analys och statistiska tester av de punkter som hade minst tre observationer (år). Den låga andelen överbestämningar (endast en överbestämning vid tre observationer) gav problem med ett standard F-test. Istället togs en modifierad strategi fram som gav ett urval av punkter som bättre stämde överens med visuell tolkning av tidserierna. Enligt denna strategi uppvisade ungefär **10% av punkterna trender (med märkbar rörelse), men med tanke på den låg andelen överbestämningar är det förstås ett osäkert resultat**. Med fler observationer kommer trenderna att kunna bestämmas med större säkerhet.

Vi kommer att fortsätta att analysera osäkerheter och trender när tidserierna på försäkringspunkterna fylls på. Delar av materialet behöver räknas om med anledning av uppdateringen av SWEREF 99-koordinaterna på SWEPOS-stationerna 2021. Vidare föreslår vi studier av olika satellitsystems påverkan vid försäkringspunktsbestämning och förberedelser för att publicera koordinaterna i DGA, Digitalt geodetiskt arkiv, som tillhandahålls av Lantmäteriet.

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1 Introduction

1.1 The actively defined national reference frame SWEREF 99

The national geodetic reference frame of Sweden, SWEREF 99, was adopted in 2000 by EUREF as the realization of ETRS89 in Sweden [Jivall and Lidberg, 2000]. It was officially introduced in 2001 as a national reference frame and replaced the former national reference frame, RT 90, in 2007. Since then, a lot of efforts have been undertaken to introduce the system in all other Swedish organisations (including the 290 municipalities).

SWEREF 99 is defined by an active approach through the 21 original (fundamental) SWEPOS stations [Ågren and Engberg, 2010], hence relying on positioning services like the SWEPOS network RTK and SWEPOS post processing services. The SWEREF 99 coordinates are assumed to be fixed over time and no temporal variations are expected. However, the stability of the SWEPOS stations and their coordinates can be altered due to equipment or software changes as well as local movements at the reference stations. We try to compensate for coordinate shifts at the SWEPOS stations introduced by (mainly antenna related) equipment and model changes, but each change will still introduce some uncertainties.

1.2 300 passive consolidation points

To be able to check the effect of all alterations mentioned above and having a backup (or passive) national network of GNSS points, approximately 300 so-called consolidation points distributed all over Sweden are used and remeasured on regular basis (Figure 1). The consolidation points form a subset (main part) of the so-called SWEREF points established from 1996 and onwards [Ågren and Engberg, 2010] in the so-called RIX 95 project [Lantmäteriet, 2015]. All consolidation points are passive points which are remeasured in campaign-mode surveys. Most of the points are marked directly on either bedrock (49%) or on boulders (42%), usually using a steel bolt. Markers of iron, brass or copper are also common. A few points are monumented with pillars. In this study we have also included some other points and observations which have been measured in the same way as the SWEREF and consolidation points. We designate all these points as SWEREF 99 class 1 points. It should also be mentioned that large part of the SWEREF 99 class 1 points have been levelled forming a GNSS-levelling data set for aligning and improving geoid models. A part of the processing reported here (data up to 2016) was used to define the SWEREF 99 component in the fit of the SWEN17_RH2000 geoid model to SWEREF 99 and RH 2000 [Ågren, 2017], [Jivall, 2017]. In the last few years efforts are made to increase the number of GNSS-levelling points both by adding new points and by replacing existing consolidation points that cannot be levelled.

In the data processing, each consolidation point is individually connected to the closest 6-8 fundamental SWEPOS stations, hence minimising the effect of land uplift and common mode errors. They are remeasured with static GNSS for 2x24 hours using Dorne Margolin choke ring antennas on a yearly basis with 50 points each year (Figure 2). The yearly-based measurements of 50 points from a total of 300 points means each point is remeasured every 6 years. This set of repeated measurements does not only help to better analyse the GNSS observations, but also to better investigate the temporal and spatial stability of the points. Moreover, unstable points potentially help to spot such local deformation zones in Sweden.

The original (operational) data processing was carried out in connection to the measurements using the Bernese GNSS software and the reprocessing of the data was done using both the Bernese GNSS software and the GAMIT-GLOBK software in parallel during 2017-2018.

The outcomes from the processing and analysis reported here are used to better explore and understand the stability of the SWEREF 99 reference frame after two decades and to estimate the uncertainty of this measurement method/strategy.

Figure 1: Distribution of the SWEREF 99 class 1 points and number of measurements visualised by different size of coloured circles, for the period 1993-2017.

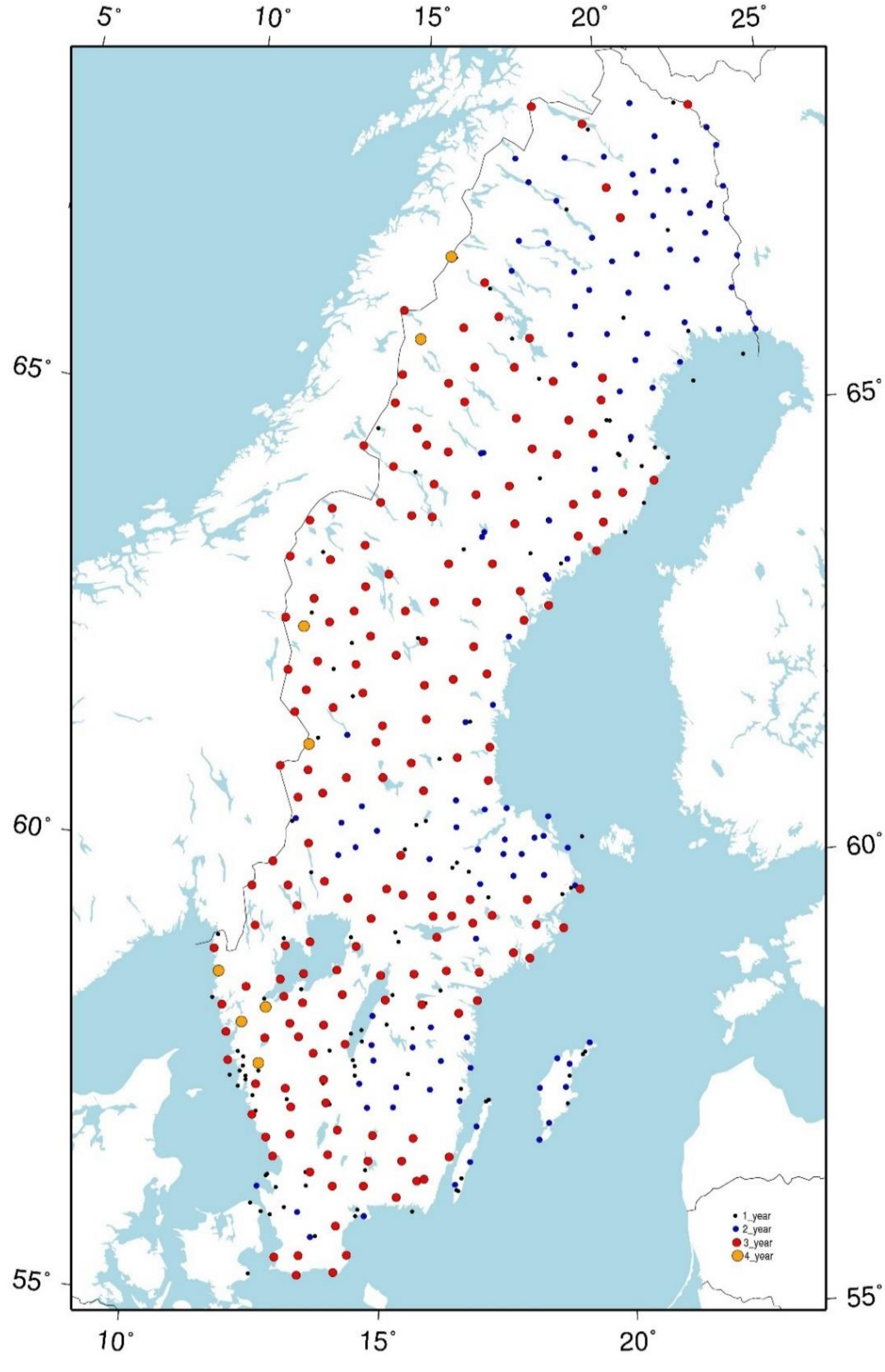
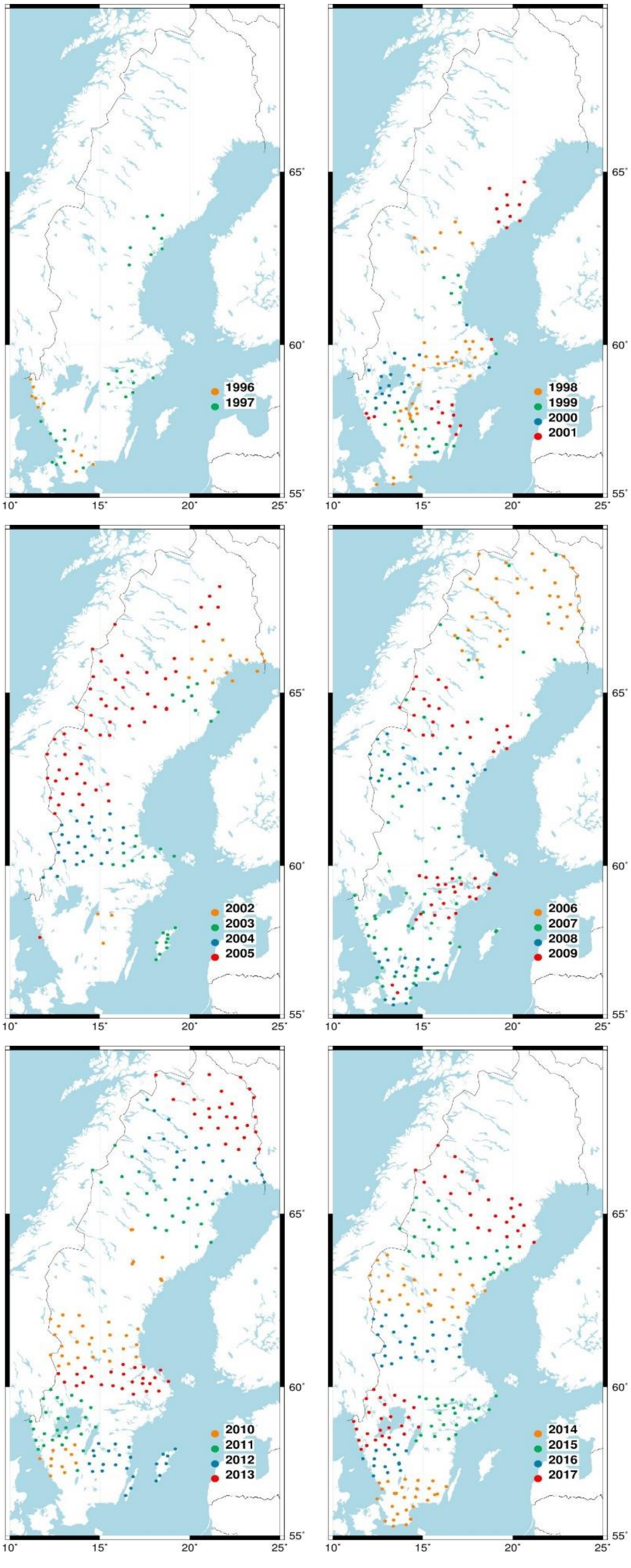


Figure 2: Maps of SWEREF 99 class 1 point locations measured in the years 1996-2017.



1.3 Study questions

The analysis and the report address the following questions:

- What is the standard uncertainty for a single SWEREF 99 class 1 point coordinate determination (2x24 hours)? How are the standard uncertainties statistically distributed?
- How consistent are the results between different software (Bernese and GAMIT) and between different processing options? Does the consistent reprocessing have a better repeatability than the original processing, where the options have varied over time?
- Do we have consolidation points with unstable coordinates (temporal change)? Are the points with changing coordinates localised in some areas? Are there any systematic trends? Could the trends be interpreted as a drift of the reference frame or are they rather a question of local movements?
- Which environmental factors do affect the measurements?

2 GNSS Measurements

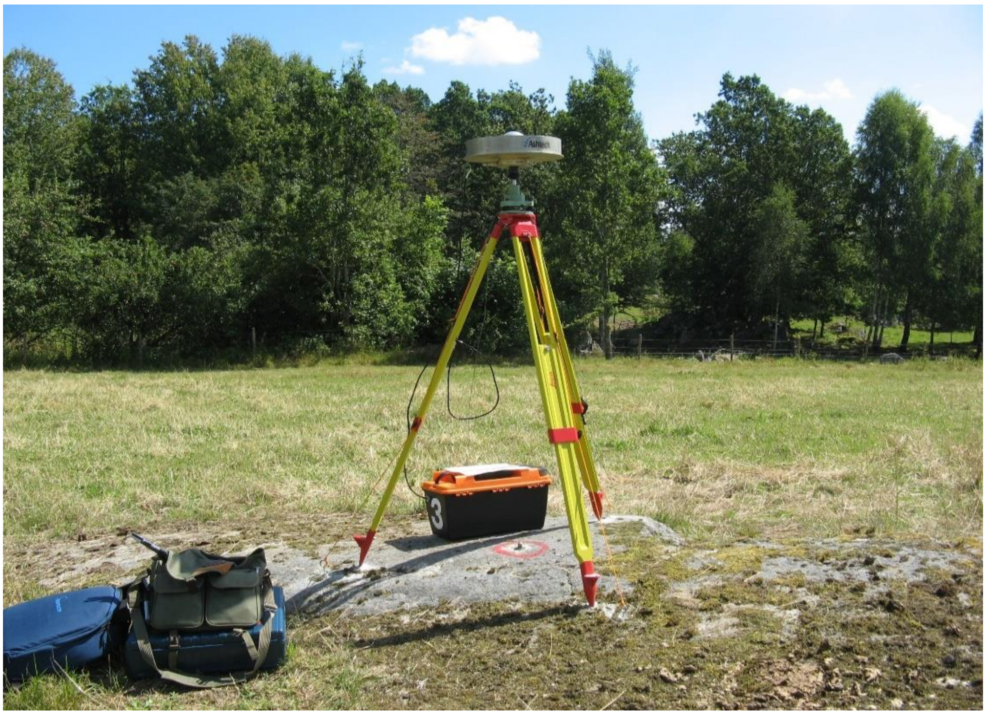
2.1 RIX 95, GNSS-levelling and consolidation points

The measurements of the so-called SWEREF points were performed in the RIX 95 project (1996-2006). In 2007 the focus was to get additional points with GNSS-levelling for the SWEN08-geoid model; about 50 levelling benchmarks were determined as SWEREF 99 class 1 using the same measurement strategy. Starting 2008, repeated measurements are made on the 300 selected consolidation points.

There were also similar GNSS point determinations made from 1995 to summer 1996, but they could not be considered as SWEREF 99 class 1. The reason is that unmodelled glass fibre radomes, with a quite large impact on the GPS-signals, were used on the SWEPOS stations during this time. The height component was degraded as troposphere parameters could not be solved for in a reliable way [Ågren, 1997].

Data collection was carried out with geodetic GNSS receivers (GPS-receivers used up to year 2016) and choke ring antennas on tripods (Figure 3). The antennas were not individually calibrated, hence type calibrations had to be used in the processing. First from 2020 individually calibrated antennas were used for the measurements. Many of the earlier used antennas have later (end of 2019) been sent for individual calibration.

Figure 3: GNSS-observation at point 734958.



2.2 Two sessions with independent setups

The GNSS antenna was levelled, oriented toward the north and centred on the markers. A new independent setup (with a different antenna height) was made for each 24-hour observation session to provide redundancy also for the centring and antenna height measurement. The antenna height was measured before and after each session with two independent methods, i.e., vertical measurement with a “height hook” or slope measurement with either a rod or a folding rule in inches and mm.

The starting time for the GNSS observations was not at 00.00 UTC, i.e., the 24-hour sessions were crossing the UTC daily boundaries and was different for each observation point. The reason for this was to make the field work more efficient, but did cause some extra work for data processing, especially for GAMIT which is reported later in this document.

3 Data processing

The data processing was carried out both with the Bernese GNSS Software and GAMIT-GLOBK software using similar processing strategy. The input observation files were 2x24-hours RINEX files for each point, which first were processed separately, and in the end combined. We used IGS final products and kept orbits fixed. The alignment to SWEREF 99 was made pointwise by Helmert transformations (7-parameter) normally using 6-8 close by fundamental stations in SWEREF 99 as fitting points. To improve the fit, a land uplift model was used to remove the approximated land uplift between the observation epoch and the reference epoch at 1999.5 prior to the fit. In the following we present some background on the antenna models and land uplift models used. Furthermore, both software and the different processing sets are described.

3.1 From relative to absolute antenna PCV models

The most important model change in the original (operational) processing setup between different time periods is the change of antenna models.

The GNSS observations refer to the electrical phase centre of the antenna, which is neither a single point, nor a stable point. It varies with the direction to the satellite (elevation and azimuth), and the frequency of the observed signal. Antenna models are used to model the phase centre variations with respect to a fixed physical point on the antenna, the antenna reference point (ARP).

There are two calibration methods to determine antenna models: relative and absolute. In relative calibration, one antenna is set as reference antenna (e.g., the choke ring antenna AOAD/M_T) and all antenna offsets and phase centre variations are computed with respect to that reference antenna [Mader, 1999]. This can introduce a bias if the reference antenna itself is object to phase centre variations.

The other type is absolute calibration. In this one, all antenna offsets and phase centre variations are absolutely determined and are independent of any reference antenna. The calibration could be performed either by a robot, that moves the antenna to receive the satellite signals in different orientations [Wübbena G. 2000] or [Billich. and Mader. 2010], or in an anechoic chamber with synthetic GNSS-signals [Görres et al., 2006].

Absolute antenna models were introduced into the products of the International GNSS Service (IGS) in 2006 compiled in the igs05.atx table and updated in 2011 to the igs08.atx table and once again in 2017 to the igs14.atx table.

Iga05.atx was never used for the operational work of Lantmäteriet (SWEREF and SWEPOS applications). Absolute antenna models were first introduced in 2012 with the igs08.atx models and in 2019 igs14.atx was introduced for the operational work at Lantmäteriet. In connection to the introduction of the new antenna models in services and applications, the coordinates of all SWEPOS stations and other stations used in the SWEPOS services were corrected to be valid for the new antenna models [Jivall, 2012] and [Lilje and Jivall, 2019].

3.2 Land uplift models

The land uplift from the postglacial rebound deforms the land both in horizontal and vertical and introduces systematic movements between epochs. For epochs close to the reference epoch of SWEREF 99, the differences in regional areas could simply be handled with the 6- or 7-parameter Helmert transformations, but with increasing time, the differences to the reference epoch 1999.5 needed to be corrected for in order to keep the precision in the fit to SWEREF 99.

Correction using a land uplift model was introduced into the processing setup from year 2004. This year just the height component was corrected using the NKG2005LU_abs model. [Ågren and Svensson, 2007]. It is the same model as used for RH 2000 converted to absolute uplift.

From year 2005 also the horizontal components were corrected for, using the model NKG_RF03vel [Lantmäteriet, 2006]. The horizontal components origin from a GIA model by [Milne et al. 2001] that has been transformed to ITRF2000.

From 2016 a non-official model, internally called NKG2016, has been used for the processing of consolidation points. The up-component is the NKG2016LU_abs [Vestøl et al. 2019] and the horizontal components are based on the GIA-model NKG2016GIA_prel0907 [Häkli et al. 2019] transformed to ITRF2008.

A new land uplift model has recently been developed, NKG_RF17vel [Häkli et al. 2020] and was introduced for SWEREF and SWEPOS applications in 2021, i.e., after the time periods included in this report. This model is composed by NKG2016LU_abs in vertical (same as for NKG2016 above) and the horizontal components origin from the GIA-model NKG2016GIA_prel0907 (same as for NKG2016 above), which in this case has been transformed to ITRF2014 and been improved with least-square collocation to model the remaining differences between GNSS and GIA velocities.

3.3 Bernese GNSS Software

Bernese GNSS Software, is as scientific, high-precision, multi-GNSS data processing software developed at the Astronomical Institute of the University of Bern (AIUB). It is used e.g., by CODE (Center for Orbit Determination in Europe) for its international (IGS) and European (EUREF/EPN) activities [Dach et al. 2015].

The Bernese GNSS Software has been used both for the definition and the maintenance of SWEREF 99, as well as for many other ETRS 89 realisations in Europe. Bernese is also the dominating software in the analysis of the EPN (EUREF Permanent Network); 14 out of 16 analysis centres use the Bernese software.

The Bernese GNSS Software is used in the SWEPOS post processing service [Jivall et.al. 2016] and in the NKG GNSS AC [Lahtinen et.al. 2018]. The accurate access to and maintenance of SWEREF 99 is therefore tightly connected to the Bernese GNSS Software. By using the same software with mainly the same options, it has been possible to keep a high precision.

3.3.1 Bernese, original processing

The original processing has been carried out since early data collection and therefore different versions of the Bernese GNSS software and input models/setups have been used throughout the last two decades. The most important options are listed here:

- GPS only
- Final IGS-products from CODE, fixed orbits
- Bernese software, version 4.0, 4.2, 5.2
- Antenna Model: igs_01.atx (relative), igs08.atx, igs14.atx
- Elevation cut-off-angle: 15˚, 10˚ and elevation dependent weighting
- Tropospheric mapping function: 1/cosz, Niell and GMF
- Tropospheric zenith delays every 2 hours and partly daily gradients
- Land uplift model: No model, NKG2005LU_abs, NKGRF03vel, NKG2016

Initially version 4.0 with 15˚ cut-off and 1/cos(z) as tropospheric mapping function was used. From 2000 the software was upgraded to version 4.2, but the important options were kept. This processing setup is consistent with the setup used for processing the SWEREF 99-campaign (defining the SWEREF 99 frame).

In 2004, the vertical land lift model NKG2005LU_abs was introduced and in 2005 the horizontal components were also considered by introducing NKG_RF03vel.

From year 2007, the earlier semi-manual session wise processing was replaced with processing using SWEPOS post processing service (which is based on the Bernese GNSS Software). At the same time the version of the Bernese was changed to 5.0 and a number of parameters were adjusted after thorough testing and comparison to the old processing strategy [Lilje, Jivall, 2008]. The mapping function 1/cos(z) was replaced with Niell mapping functions (dry and wet).

The elevation cut-off was changed from 15˚ to 10˚ with elevation dependent weighting from 2008. (The comparison between cut-off angles is also included in the testing mentioned above).

Version 5.2 with the GMF-mapping function was introduced for the processing of year 2013 and onwards. At the same time absolute antenna models (igs08.atx) were introduced. The data from 2012 were processed with both relative and absolute antenna models as a test [Lilje 2013] but the results with the relative antenna models were considered as final.

In 2016 the NKG_RF03vel land uplift model was replaced with the intermediate model internally called NKG2016. The different options used for the processing of different years are summarised in Table 1.

The closest 6-8 fundamental SWEPOS stations were included in the processing together with the data from each SWEREF 99 class 1-point. Additional foreign stations with defining SWEREF 99 coordinates were added if it was found necessary to avoid extrapolation. The foreign stations used in Denmark, Norway and Finland corresponds to the fundamental SWEPOS-stations and are more than just the EPN-stations. (From 2013, when SWEPOS post processing service was updated, additional class A-stations were included in the processing but not used for the alignment.)

Table 1: Different options used in the original (operational) processing for different years of measurements.

Year of measurement	Bernese version	Antenna model	Elevation cut-off	Trop. mapping function	Deformation model
1996-1999	4.0	relative	15°	1/cosz	none
2000-2003	4.2	relative	15°	1/cosz	none
2004	4.2	relative	15°	1/cosz	NKG2005LU_abs
2005-2006	4.2	relative	15°	1/cosz	NKG_RF03vel
2007-2012	5.0	relative	10°	Niell	NKG_RF03vel
2013-2015	5.2	igs08.atx	10°	GMF	NKG_RF03vel
2016-2019	5.2	igs08.atx	10°	GMF	NKG2016
2020	5.2	igs14.atx	10°	GMF	NKG_RF17vel

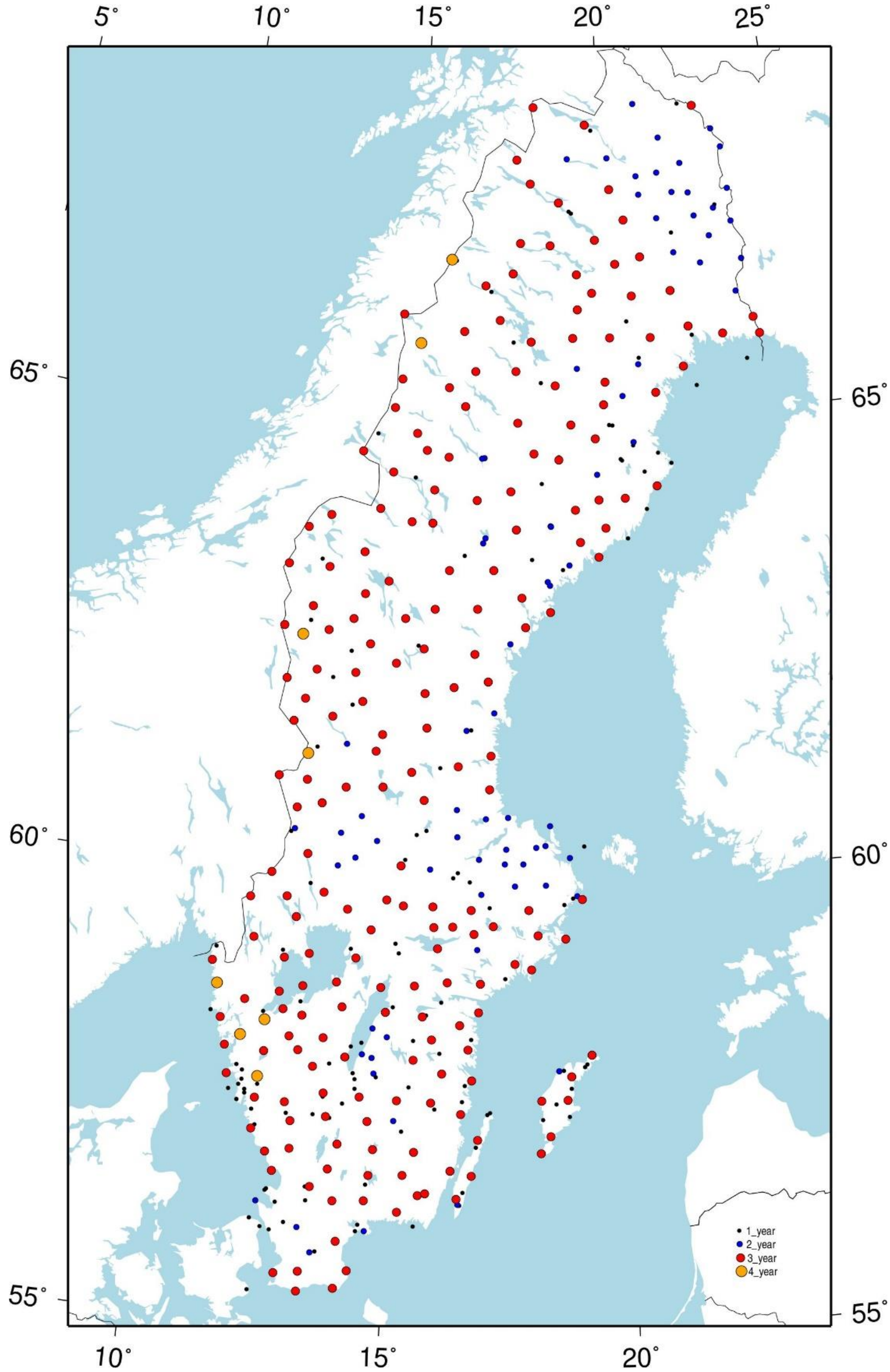
The sessions were first computed individually, and then the session wise normal equations were combined with the program ADDNEQ (part of the Bernese software) and finally fitted to SWEREF 99.

The results from this processing form the "**Bernese original**" data set.

A few point coordinates in the data set "Bernese original" were additionally collected from other campaigns (DOSE93A, NORDREF94 and EUVN97), where each point has been fitted by Helmert fit to the closest SWEPOS stations in the same way as other SWEREF/consolidation-points. The first two campaigns were actually processed by Onsala Space Observatory using the GIPSY software [JPL, 2018]. The reason for adding them to this data set is that those coordinates have been used as SWEREF 99 class 1 coordinates in e.g., the RIX 95-project, hence been considered as SWEREF-points. Besides, it was useful to have some early observations in the analysis of repeated observations and trend analysis.

Before the final trend analysis, also the results from observations made in 2018 were added to the "Bernese original" data set. The new data set was called "**Bernese original 2018**" and has more points with observations from at least three different years (Figure 4).

Figure 4: Distribution of the SWEREF 99 class 1 points and number of measurements visualised by different size of coloured circles, for the period 1993-2018.



3.3.2 Bernese, reprocessing

To produce a consistent set of results, input processing parameters and models were the same as for the Bernese original processing of the years 2016-2019. All the data collected between 1996 and 2015 were reprocessed with version 5.2 of the Bernese GNSS software.

The results of the reprocessing constitute together with the original (operational) results from 2016 and 2017 the data set "**Bernese Repro**" with the following main parameters/models:

- GPS only
- Final IGS-products from CODE, fixed orbits
- Igs08.atx absolute antenna models
- Multistation processing
- 10° elevation cut off angle (with elevation dependent weighting)
- Tropospheric mapping function: GMF
- Tropospheric zenith delays every 2 hours and daily gradients
- The NKG2016 land uplift model

3.4 GAMIT-GLOBK

Similar to the Bernese Software, GAMIT-GLOK software is also a high-precision software for GNSS data processing and analysis. GAMIT can estimate the relative positions of ground stations (baselines or networks) and satellite orbits, earth orientation parameters and tropospheric zenith delays, using GNSS phase data.

GLOBK uses Kalman filter method to constrain and combine geodetic (e.g., GPS and GLONASS) solutions. The software has been developed by MIT, Scripps Institution of Oceanography and Harvard University and is freely available for education and scientific applications [Herring et al., 2008] and http://geoweb.mit.edu/gg/)

3.4.1 Reprocessing with GAMIT-GLOBK

To increase the reliability of the results and check with another scientific software, we also processed the data with GAMIT-GLOBK software (version 10.61). We carried out a consistent reprocessing for the years 1998-2017 using the following options:

- GPS only
- Final IGS-products
- igs08-atx absolute antenna models, fixed orbits
- Baseline processing
- 10° elevation cut off angle (Elevation- and azimuth-dependent model, AZEL option)
- Tropospheric mapping function: GMF
- Tropospheric zenith delays every 2 hours and daily gradients
- The NKG2016 land uplift model

The results from this processing form the "**GAMIT repro**" data set.

For GAMIT, we had to take two extra steps for reprocessing. Firstly, GAMIT only works with 4-char ID station names and does not accept long names as Bernese does. Therefore, 6-7 characters (digits) ID assigned to each point was shortened to 4-char ID to make it readable for GAMIT. To do so, mostly first two characters were removed, and the rest were kept as the same as original but sometimes because of duplication the last character was exchanged by a letter, e.g., A, B. For example, point names 156588, 186588 and 266588 were shortened as 6588, 658A and 658B respectively for GAMIT. We made a translation file which helps finding the point names (IDs) in both Bernese and GAMIT solution files and make it possible to compare the results for the same points.

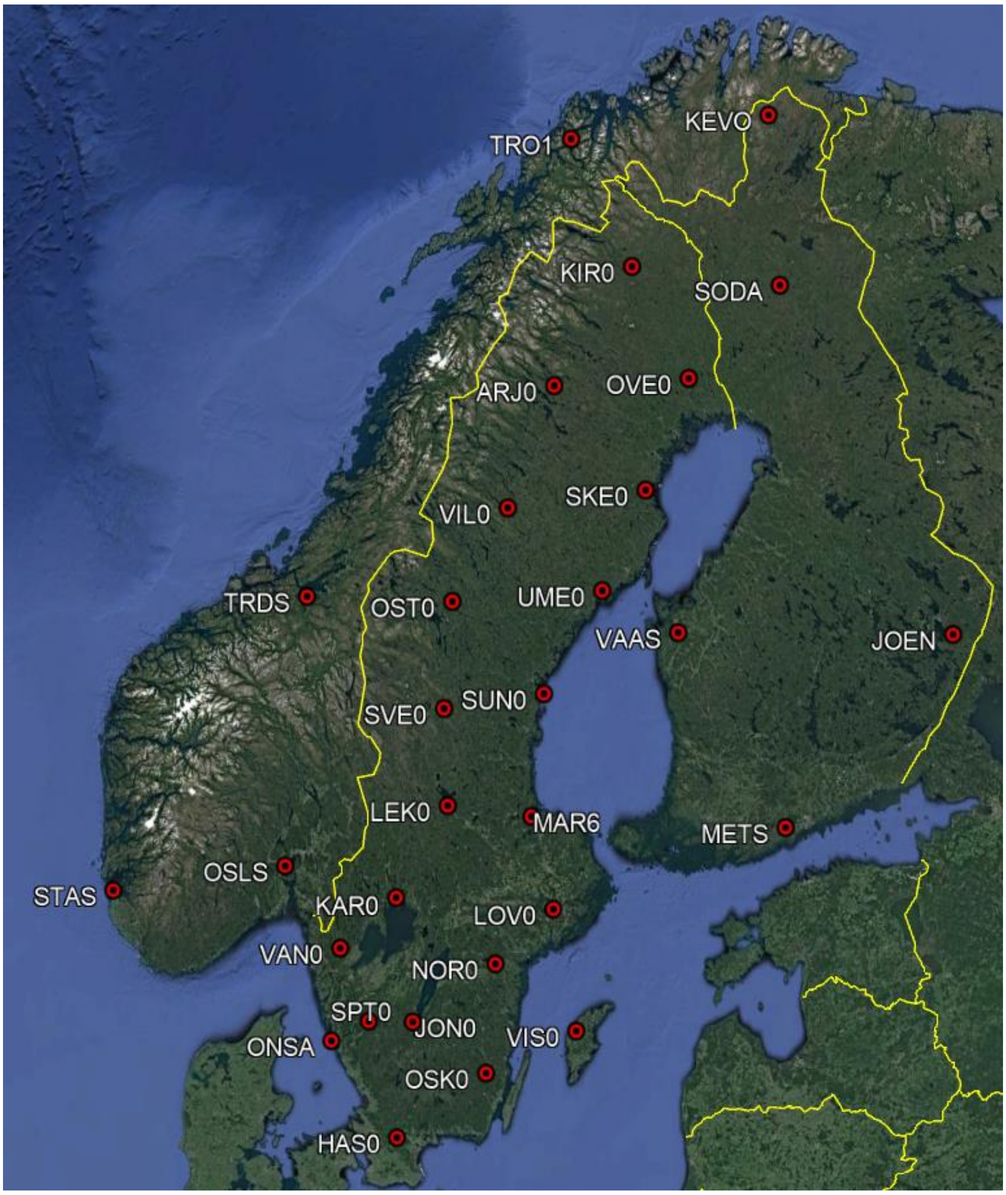
The other thing that needed extra preparation was the handling of the nonstandard observation sessions spanning across UTC daily boundaries (00-24 UTC). To do so, in GAMIT, we had to define the starting time for each session and each point and combine the broadcast orbits as well as the precise IGS orbits for the two consecutive days in which the observation session had taken place. (This had to be done also for the Bernese, but in our case SWEPOS post processing service did this preparation.)

All SWEPOS fundamental stations and all available EPN stations in Norway and Finland were used in the daily solutions for each SWEREF point (Figure 5). This is the main difference to the strategy used for the Bernese, where just the closest stations were included. The idea for the different processing strategy in GAMIT, i.e., using more reference stations in daily solution than Bernese, was to form regional networks and make it possible to determine the velocity field (in ITRF) in the future when we have more data collected.

For GAMIT, loosely constrained daily solutions were processed first for each point and session and then the GLOBK was used for the reference frame realization. The following EPN stations were used for the reference frame realization in ITRF2008: JOEN, SODA, METS, VAAS, KIR0, SKE0, TRO1, VIS0, MAR6, VIL0, SPT0, ONSA, OSLS, TRDS, STAS. The SWEREF 99 coordinates were estimated pointwise by Helmert transformations (7-parameter) of daily coordinates solutions using minimum five close by fundamental stations in SWEREF 99 as fitting points. The final combined coordinates for each year and point were computed as a plain average of the two session wise determinations.

Hence, the processing with GAMIT-GLOBK resulted in two sets of coordinates for each point and year, both in ITRF2008 and in SWEREF 99.

Figure 5: Google Earth map shows the reference stations in Sweden, Norway and Finland which were used in GAMIT daily solutions



4 Quality of observations and results

4.1 Quality parameters

The GPS-processing of each point and session was evaluated by studying the following quality parameters:

- Available observations
- Resolved ambiguities
- Difference between fix and float solution
- Elevation cut-off test 10° - 25°
- RMS in the Helmert fit to SWEREF 99
- Coordinate differences between sessions

A low ratio of observations indicates either problems with the receiver or that there are obstacles around the point, e.g., trees. The ratio is calculated by TEQC [Estey 1999] by comparing the number of available observations with the number of expected observations at a certain position and elevation cutoff-angle.

A high ambiguity resolution success rate would indicate a good and reliable solution. The rate is dependent on the ambiguity resolution strategy used and whether some ambiguities are not even tried to be solved, e.g., due to possible quarter cycle biases. A small difference between the fixed and float solution would further confirm the reliability of the solution, i.e., that the ambiguities have been fixed to the correct integers.

In the elevation cut-off test (ECT) two solutions with different cut-off angles are compared, hence elevation dependent errors would give larger differences in height. This could be useful to detect problems with the used antenna model or the measurement environment.

The fit to SWEREF 99 indicates how well the coordinates could be determined in SWEREF 99. A bad Helmert fit could either depend on a bad GNSS-solution, non-valid coordinates for the reference stations or deficiencies in the land uplift model or a combination of these.

The coordinate difference between the 24-hours sessions gives a direct measure of the uncertainty. Here problems with the centring or the antenna height measurement could be revealed as a new setup was done between sessions.

4.2 Analysis of quality parameters for Bernese Repro 2018

The quality measurements for the processing set “**Bernese repro 2018**” (Bernese Repro + 2018 from the operational processing) were compiled and compared to some standard limits. Two sets of limits were used: one set with earlier defined limits for normal values and one set for extra degraded quality (Table 2).

Table 2: Limits used for the analysis of quality measures from the Bernese Repro data set.

Quality measure	Limit – normal	Limit – extra degraded
Ambiguity resolution	> 85%	< 60%
Available observations	> 95%	< 80%
Data screening	< 2%	
Elevation cut-off test (ECT) (U)	< 20 mm	
Differences between fixed and float solution (N, E, U)	< 10, 10, 10 mm	
Helmert fit (N, E, U)	< 2, 2, 4 mm	> 3, 3, 5 mm
Differences between sessions (N, E, U)	< 5, 5, 10 mm	

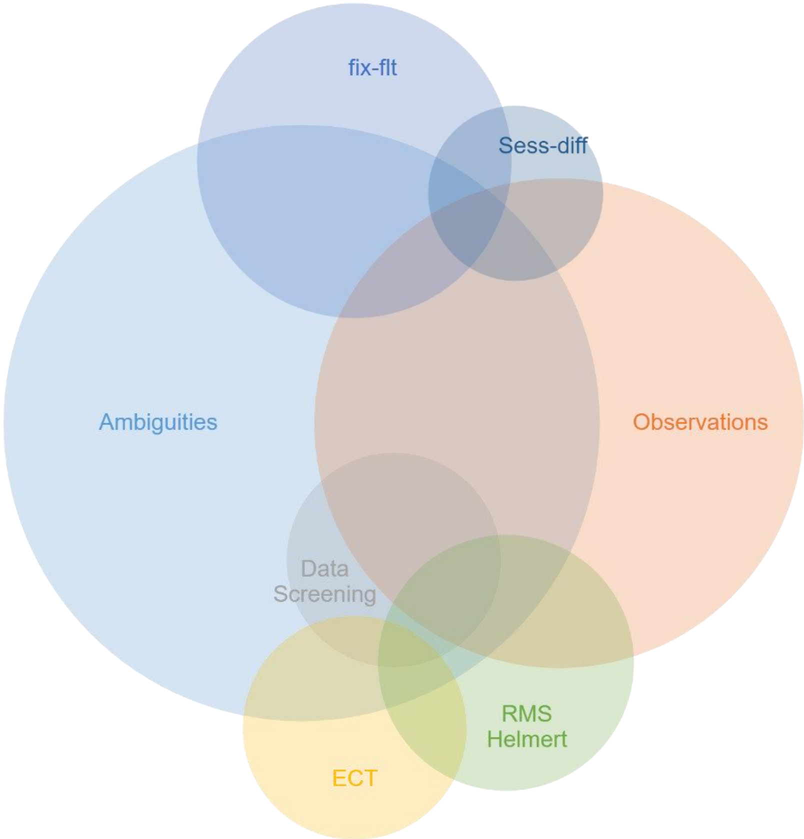
In total we have 916 point-determinations in the data set. 495 (54%) exceeds at least one of the limits for normal measurements (for at least one session). This is of course a very high ratio of point-determinations not fulfilling all the limits. From those 495 determinations, 63% are failing on the ambiguity resolution and 37% on the number of available observations in any of the two sessions, see Table 3 and Figure 6. 22% are failing on both the ambiguity resolution and number of available observations, i.e., 59% (22/37) of the determinations with low number of observations do also have a low ambiguity resolution rate.

Further, 24% of the Helmert fits of the combined solution exceed the values in at least one component. The ratios of the other failed quality measures are lower, although there are quite many determinations also with a difference between fixed and float solution exceeding 1 cm.

Table 3: Share of determinations exceeding the individual limits from the 495 determinations, which failed on at least one of the limits for normal quality (Table 2).

Quality measure	Amb	Obs	Data Scr	ECT	fix-flt	Helmert fit	Sess-diff
Ambiguities	**63%**	22%	7%	5%	13%	12%	3%
Observations	22%	**37%**	5%	3%	4%	6%	2%
Data screening	7%	5%	**8%**	2%	3%	2%	1%
ECT	5%	3%	2%	**12%**	2%	2%	1%
fix-flt	13%	4%	3%	2%	**21%**	8%	2%
Helmert fit	12%	6%	2%	2%	8%	**24%**	1%
Sess-diff	3%	2%	1%	1%	2%	1%	**5%**

Figure 6: Venn diagram showing the quality measures failing on at least one of the limits for normal values (Table 2) for the 495 point determinations.



Venn diagram where "Ambiguities" and "Observations" are the two dominating quality measures.

However, when checking the repeatability between years for these 495 solutions, we can conclude that many of them still look normal, despite the failed quality measures. Therefore, we decided to loosen the limits (Table 2) to find the most problematic determinations with extra degraded quality. 61 determinations (7 %, 51 points) were defined as problematic, mainly failing on low ambiguity resolution success rate, see Table 4.

Table 4: Share of determinations exceeding the individual limits from the 61 determinations that failed on at least one of the limits for extra degraded quality in Table 2.

Parameter	Ambiguities	Observations	Helmert fit
Ambiguities	**61%**	7%	0%
Observations	7%	**21%**	5%
Helmert fit	0%	5%	**20%**

Each of these determinations were examined by inspecting the solution, the field protocols, photographs and by comparison to determinations from other years. Unfortunately, we do not have photographs of the points and their surrounding environments for the measurements before 2008. Therefore, it was difficult to analyse the reasons for the low quality of the early measurements, except for some cases with hinting comments in the field protocols.

Based on this examination we concluded that 33 of the suggested problematic determinations (corresponding to 32 points) were ok, but two of the points would probably not be useful in the future because of growing surrounding trees. It means that we in the end defined 28 determinations (concerning 19 points) as problematic with degraded quality.

By checking the results, we found that there are different reasons for the low quality of the measurements for some points. Among others, we can mention point locations in the forests or near the power lines and/or observations in bad weather.

4.3 Examples of problematic points

In the following, we will illustrate some examples of these problematic points determinations, which failed on the limits for extra degraded quality:

Figure 7: The station 153178 in 2010.

The first example is the observations for the point 153178 (Figure 7) in 2010, located near an iron fence. We got low ambiguity resolution, for the first session 42.6% and for the second session 44.3%. The differences to the result from 2004 were 5, 3 and 29 mm in north, east and up, respectively. The point was replaced with 153179 already in 2010.

The point was included in the SWEN17 GNSS-levelling data set, but the observations from 2010 was excluded (only measurements from 2004 were used).

Figure 8: Station 198168 in 2010.

Before the measurements in 2010, there was a big metal fish monument built near (over) the point 198168, and that was the last year for measurements of that point (Figure 8). We got low ambiguity resolution, 37.4%, in the first session but it was higher for the second session, 77.5%. However, the coordinate difference in SWEREF 99 for two different measurements in 1997 and 2010, was just around 3 mm in horizontal and 5 mm in vertical. The point has been replaced with 1982591.

Figure 9: Station 239198 in 2017.

For the point number 239198 from 2017, which is located directly under the power lines, we got very low number of observations for the second session (31%). (Figure 9). The point has been replaced with 230108.

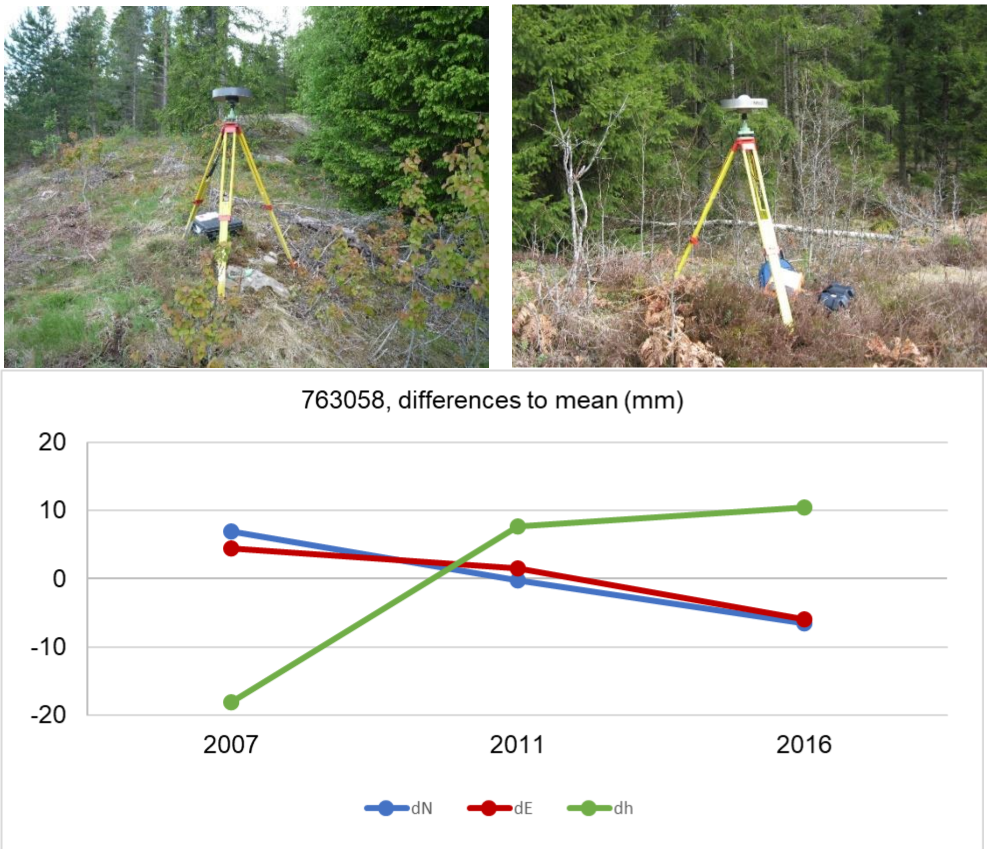
Figure 10: Station 240668 from 2012.

The point 240668 (Figure 10) was measured twice, in the years 2002 and 2012. For both measurements we got low ambiguity resolution (52.6–59.3%). Perhaps the reason was the presence of some tall trees south of the point. We decided to replace this point with a new one (240868) in 2018.

Figure 11: Station 743318 in 2014.

The point 743318 (Figure 11) was measured three times; in 1996, 2008 and 2014. The ambiguity resolution for the two sessions was (96% and 97%), (43.3% and 44.9%), (46.9% and 52.5%) in 1996, 2008 and 2014 respectively. We do not have pictures of the measurements from 1996, but we can at least be quite sure that the trees were shorter at that time. The point has been replaced with 742588.

Figure 12: The station 763058 in 2011 (top left) and 2016 (top right). The lower graph shows the SWEREF 99 coordinate variations from the mean in 3 sets of measurements in 2007, 2011 and 2016 (unit: m.). As shown in this graph, the height component is very different in 2007 compared to the two other measurements.



The point 763058 (Figure 12) was measured three times and we got the following results:

- 2007: ambiguity resolution for the 1st and 2nd sessions 76.3% and 71.2%; number of observations 75% in both sessions; the RMS of vertical component after Helmert transformations was 6.7 mm.
- 2011: ambiguity resolution for the 1st and 2nd sessions 65.0% and 54.8%; number of observations 80% and 82%; the RMS of vertical component after Helmert transformations was 4.2 mm.
- 2016: ambiguity resolution for the 1st and 2nd sessions 46.4% and 48.1%; number of observations 78% and 79%; the RMS of vertical component after Helmert transformations was 1.2 mm.

We note that the ambiguity resolution decreased with time due to the growth of trees beside the point, which would degrade the solution. On the other hand, we can see that also the RMS in the Helmert fit also decreased with time, which is an improvement. The larger RMS-values in the Helmert fit for the earlier years can partly be explained by the fact that the SWEPOS's igs08.atx compatible coordinates used in the Bernese Repro for earlier periods have been reconstructed afterwards from newer coordinates. The corresponding RMS values from the original processing are lower (3.0 mm for 1997 and 1.6 mm for 2011), but still a bit larger than for the last measurement. We should also have in mind that the RMS in the Helmert fit mainly tells how well the SWEPOS stations fit, just if we have very bad or missing data the baselines to SWEPOS will be considerably affected. In this case only 75% of the observations are available in 2007 which explains the higher RMS for this year.

The point has been replaced with two points (763028 and 763398) in 2018.

5 Analysis based on coordinate comparisons

The coordinates from each point, year and processing set (Bernese original, Bernese repro and GAMIT repro) were compared and analysed in three different ways:

- Each common point/year were compared between the processing sets, with the aim to investigate the consistency between the results from different software and when using different options.
- For each processing set, the repeatability between the years was estimated for each point with the goal to estimate general uncertainty values for this type of point determination.
- For each processing set, trend analysis and velocity estimation were performed for points with at least three yearly solutions, with the aim to identify moving points and to investigate if we can see any systematic trends in SWEREF 99 in any areas.

5.1 Comparison between different processing sets

The three sets of processing results (Bernese original, Bernese repro and GAMIT repro) were compared for each point and year. The RMS of the differences for each component was estimated and listed in Table 5. Note that the time span of yearly determinations is not the same, e.g., the last two years 2016-2017 are just processed once with the Bernese software and are therefore not included in the comparison between the Bernese original processing and the Bernese reprocessing. On the other hand, there are two more years in the beginning of the time period for this comparison, which is not included in the comparison with GAMIT.

Table 5: RMS of coordinate differences between the different processing in mm.

Differences	Years	# points	RMS_N	RMS_E	RMS_U
Bernese repro - Bernese original	1996-2015	754	2.4	1.4	4.3
Bernese repro – GAMIT repro	1998-2017	810	1.2	1.3	4.0

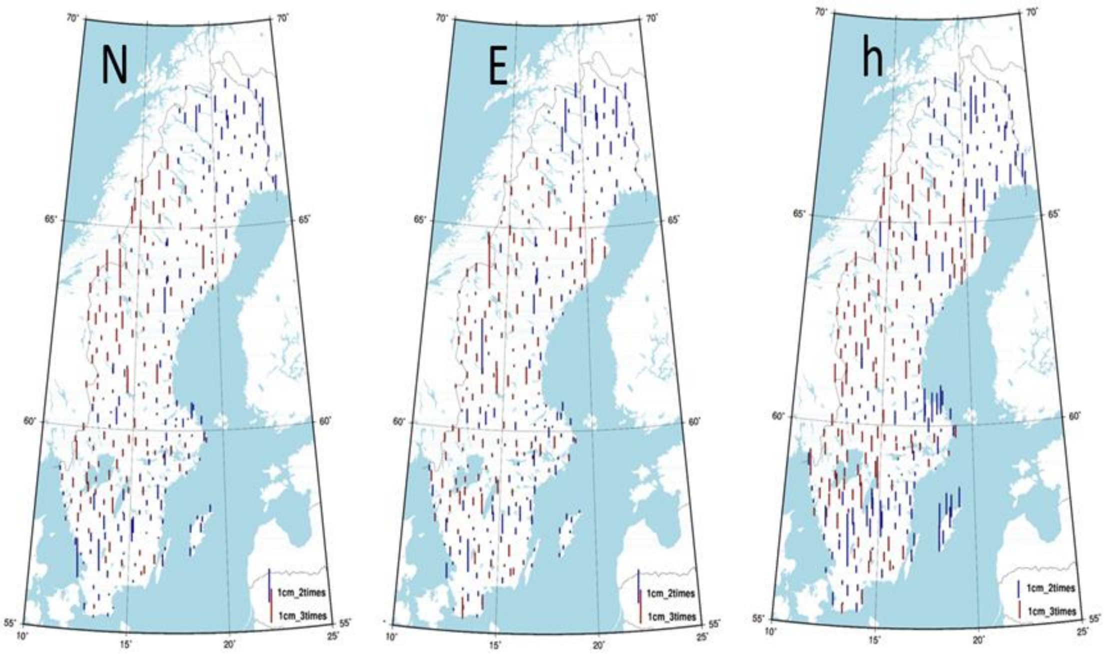
As expected, the reprocessing results show a slightly better agreement (mainly in the north component) than the one between the original processing and the reprocessing. Clearly, using the same models (especially antenna models) and the same processing strategy yields more homogenous results. However, it is interesting to note that even the original processing and the reprocessing with Bernese does not show a big difference, only on mm level.

The agreement between the two software, Bernese and GAMIT, is of the same size (mm-level) as in an earlier comparison between the two software [Jivall and Nilfouroushan, 2019].

5.2 Standard uncertainties based on repeated point coordinates

Repeated measurements were used to estimate the general uncertainty for a single SWEREF 99 class 1 determination (2x24 hours). The standard uncertainties for each point and processing set were first computed. Figure 13 shows the uncertainties for the GAMIT processing as an example and we can see that both the larger and the smaller uncertainties are quite well distributed over the country.

Figure 13: The standard uncertainty of the estimated coordinates in SWEREF 99 for each component (measured 2 or 3 times, results of GAMIT).



The general (combined) standard uncertainties were computed based on the concept of pooled standard deviations (Formula 1 and Table 6).

$$s_{pooled} = \sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2+\cdots+(n_k-1)s_k^2}{n_1+n_1+\cdots+ n_k-k}} \tag{1}$$

where

n_i = *number of measurements for point i*
s_i = *standard deviation for point i*

There are two values presented for the Bernese original processing, one including the year 2018 and one including data just up to 2017, the latter being more compatible with the two reprocessing data sets.

The estimated general standard uncertainties for a 2x24 hour measurement from the different processing sets are very close to each other, just over 2 mm for each horizontal component and 6-7 mm in height.

The standard uncertainty for the height is slightly larger for GAMIT, which possibly can be explained by the fact that more efforts were made with Bernese to find the optimal local Helmert fit for each point. It is interesting to note that the repeatability is not worse for the original processing with the Bernese than for the reprocessed coordinates, although processing options and antenna models vary between different years and that the observation time span is larger.

Table 6: Estimated general standard uncertainties for different components based on repeated measurements.

All available repeated points (except 3 unstable points). Unit: mm							
Analysis	# 2 times	# 3 times	# 4 times	SN	SE	SU	Time span
Bernese original 2018	76	211	8	2.2	2.5	6.2	1994-2018
Bernese original	115	169	8	2.2	2.4	6.1	1994-2017
Bernese repro	126	157	4	2.4	2.4	6.0	1996-2017
GAMIT	144	139	2	2.5	2.4	6.9	1998-2017

Three points with very clear and large movements were excluded from the general uncertainty estimation, see Figure 14 - Figure 16. Those three points would have influenced the estimated uncertainties too much and the idea here is to estimate the uncertainty of the measurement method and not the stability of the points.

In principle all moving (unstable) points should have been excluded but testing to exclude other points with movements (smaller than the mentioned three worst cases) did not have much impact on the pooled standard uncertainties, so they remained in the data set. None of the three excluded points are marked in bedrock.

The distribution of the standard uncertainties was also studied for each processing set, see Figure 17. Supposing the measurements (2x24 hours) are normally distributed, then we can expect the standard deviations to be distributed according to the Chi-squared distribution (if first normalised, squared and multiplied by their degrees of freedom). The shares in % of the standard deviations that are below 1, 2 and 3 times the general standard uncertainty, estimated for each processing set, were compared to the Chi-squared distribution (Table 7). We can conclude that the distribution agrees well with the theoretical Chi-squared distribution. There are slightly more standard deviations below 1-time and slightly less below 3-times the general standard uncertainty for all components and processing sets.

Figure 14: Unstable station excluded from the estimation of general standard uncertainties. Gällivare (280218) is marked with steel bolt in boulder.

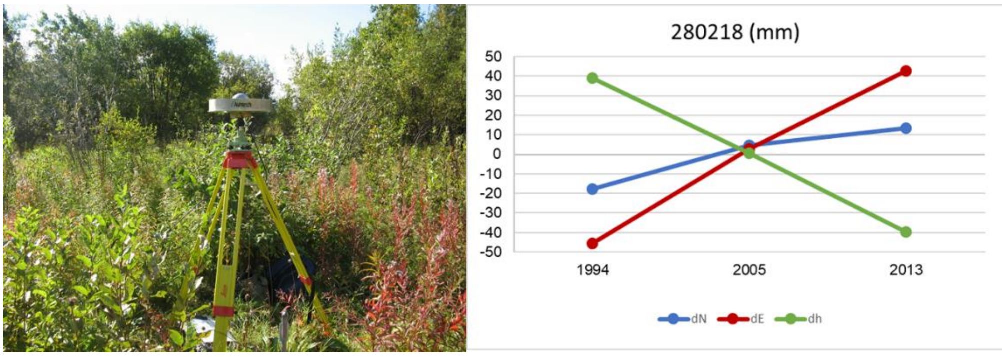


Figure 15: Unstable stations excluded from the estimation of general standard uncertainties. Kaxås (194918) is marked with steel bolt in boulder.

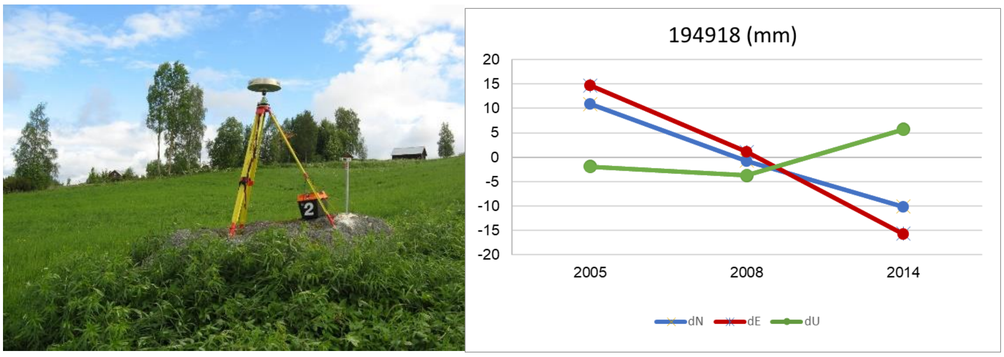


Figure 16: Unstable station excluded from the estimation of general standard uncertainties. Junosuando (281978) is marked with a steelbar in a pipe driven down to bedrock.

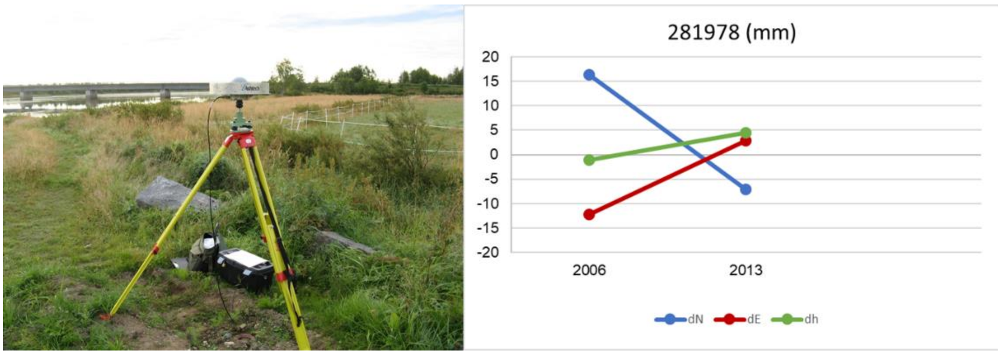


Figure 17: Distribution of the standard deviations for Bernese original (1993-2018), Bernese repro (1996-2017), Gamit repro (1998-2017).

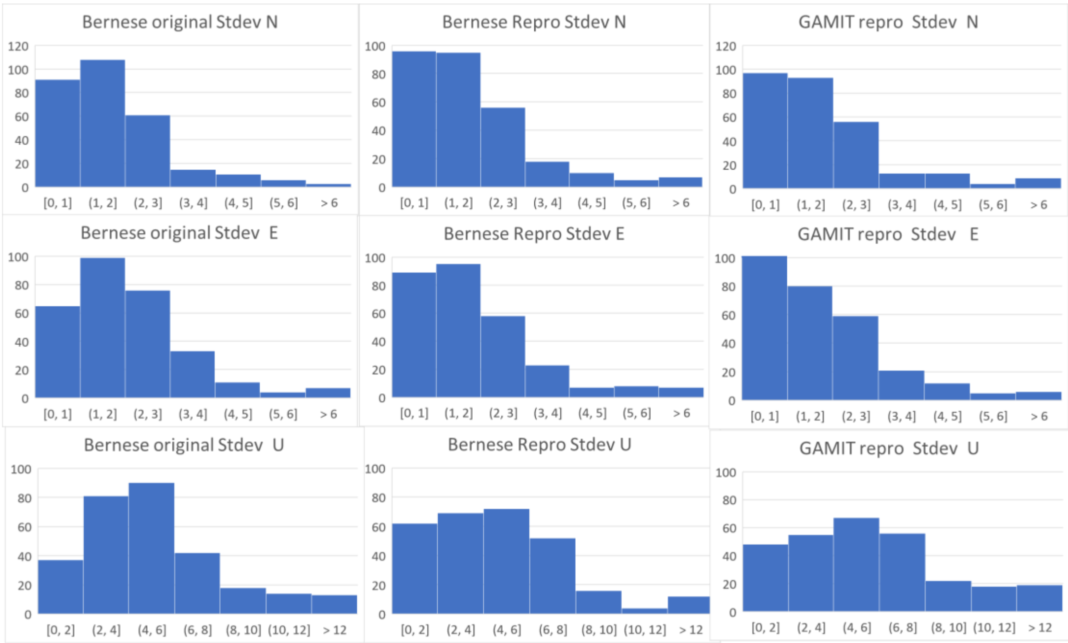


Table 7: Distribution of the standard deviations compared to theoretical values in the Chi-squared distribution (degree of freedom in an interval from 1 to 3, i.e., corresponding to 2-4 repeated measurements).

Distribution of standard deviations: share below n x pooled stdev (%)									
Processing set	**< pooled stdev**			**< 2 x pooled stdev**			**< 3 x pooled stdev**		
component	**N**	**E**	**U**	**N**	**E**	**U**	**N**	**E**	**U**
Bernese original 2018	72	72	72	95	96	97	99	99	100
Bernese original	73	70	72	95	95	97	99	99	100
Bernese repro	77	73	71	96	95	96	99	99	99
GAMIT	76	75	68	95	96	95	99	99	99
Chi-squared distribution	60.8-68.3%			95.4-99.3%			99.7-100 %		

5.3 Trend analysis

The estimated SWEREF 99 coordinates obtained from several measurements in different years are expected to be stable over time. If not, either the point is moving, the GPS-solutions are not good enough or we might have some systematic degradation of SWEREF 99 over time. Such degradation can be caused by deficiencies in the land uplift model in combination with uncertainties in the coordinate updates that are done due to new equipment and new antenna models at the defining SWEPOS stations and corresponding foreign stations.

The ideal case is that there shouldn't be any significant trend in the SWEREF 99 coordinate time series, and this hypothesis is statistically tested by F-test for all points that have at least three repeated measurements. The test was applied to the simple linear regression model. With just three or four measurements the redundancy is low, and the F-test does not always give expected result.

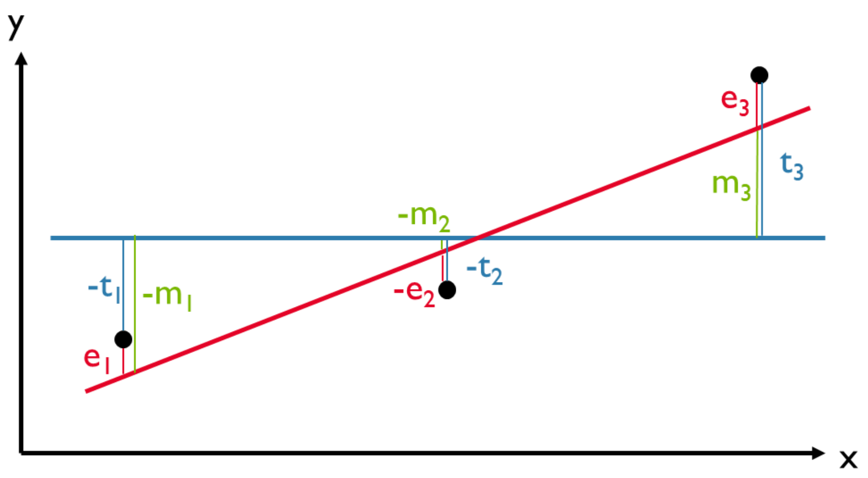
With more repeated measurements in the future, the standard F-test will probably perform better, but for the present data set, we needed to make some modifications of the test to get reasonable output and still have an objective method to find the points with possible trends.

Several alternatives of F-tests with different modifications were performed. The tests were initially performed on all processing sets and finally further developed based on the “Bernese original 2018” (1993-2018) data set, where we have the highest number of points measured three or more times. This new strategy was then applied to the other data sets as well.

5.3.1 Linear regression

The linear regression defines the best fitting straight line to a set of observations according to the method of least squares, where the sum of the squared errors is minimised, see Figure 18 and formula 2.

Figure 18: Linear regression model. Differences that can be defined: e = error = observation minus model, t = total error = observation minus average, m = model variation = model minus average.



$$y = vx + b \quad (2)$$

y = coordinate
v = velocity
x = time
b = bias, interception with the y-axis

The sum of squares for the quantities defined in Figure 18, e (error = observation - model), t (total error = observation - average) and m (model error = model - average), and their corresponding degrees of freedoms are defined according to the formulas below (3) and form the basis for the F-tests.

$$SSE = \sum_{i=1}^{n} {e_i}^2 \qquad SST = \sum_{i=1}^{n} {t_i}^2 \qquad SSM = \sum_{i=1}^{n} {m_i}^2$$

$$SST = SSM + SSE \tag{3}$$

$DFE = n - 2$ *(= degrees of freedom for SSE)*

$DFT = n - 1$ *(= degrees of freedom for SST)*

$DFM = 1$ *(= degrees of freedom for SSM)*

5.3.2 F-tests

We want to test the null hypothesis, stating that the coordinates are stable, and we have no significant trend, i.e., v= 0 in formula 2. This is done by comparing the variances when using the full model, (including velocity) and the reduced model (based on an average). Three different F-tests were evaluated (based on different F-ratios):

Standard F-test using the standard deviation from each linear regression. The differences between the variance from the full and the reduced models is compared to the full model. This is the most common way to perform F-test for linear regression.

$$\frac{(SST - SSE)/(DFT - DFE)}{SSE/DFE} = \frac{SSM}{SSE/(n-2)} \in F(1, n-2) \tag{4}$$

Alternative F-test 1, same as the standard F-test, but here the variance from the reduced model is directly compared to the variance of the full model, i.e., SSM is replaced with SST. This ratio might be more intuitive as we directly compare the two alternative models, but this ratio is strictly not F-distributed, as the nominator and denominator are correlated with each other.

$$\frac{SST/DFT}{SSE/DFE} = \frac{SST/(n-1)}{SSE/(n-2)} \in F(n-1, n-2) \tag{5}$$

Alternative F-test 2, same as the standard F-test but using standard deviations based on all points (general standard uncertainties based on pooled standard deviations, Table 6) instead of values estimated from each linear regression. The idea is to increase the power in the test as the degrees of freedom increases.

$$\frac{SSM}{stdev^2} \in F(1,\ DFpool)\ ,\ stdev = pooled\ standard\ deviation \quad (6)$$

5.3.3 Testing of different strategies to find significant velocities

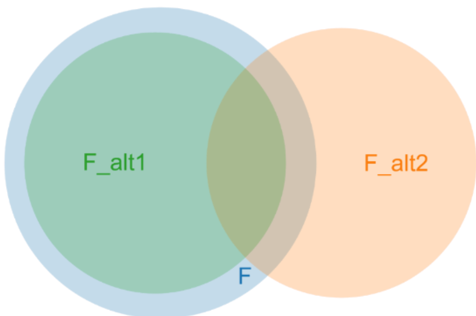
The three F-ratios above (in formula 4-6) were computed for each point and data set. Based on the F-ratios the probability to have a smaller F-value than the computed, under the condition of the null hypothesis (no trend), was determined. We decided to set the limit for significance at 95% probability, which means that we with 5% risk level can reject the null hypothesis and conclude that we have a significant trend.

The points found to have a significant trend on the 95% level, in the different data sets and using different F-tests, were studied and compared to each other. A summary of the result is found in Table 8 and Figure 19.

Table 8: Summary of the significant trends found when using different F-tests.

Ratio of points with significant trends (%)				
F-test	Bern org -2018	Bern org -2017	Bern rep -2017	GAMIT rep -2017
Number of points with 3 obs	221	179	162	142
F_standard	20%	19%	17%	18%
F_alt1	14%	13%	15%	8%
F_alt2	15%	17%	17%	17%
(F ∩ F_alt1)/F_alt1	100%	100%	100%	100%
(F ∩ F_alt2)/F_alt2	30%	23%	18%	25%

Figure 19: Venn diagram visualising the number of significant trends defined by different F-tests for the dataset Bernese original 2018 (1993-2018).



First, we can conclude that the ratios are quite similar for all processing sets. About 20% of the points were found to have significant trends with the standard F-test, up to 5% less with the alternative F-test 2 and even less with the alternative F-test 1. We can also note that all the points found with the alternative F-test 1 also were found with the standard F-test. The alternative F-test 2 suggests different trends than the other two F-tests, just 20-30% of the points are common between the standard F-test and the alternative F-test 2. Further on, the rates are very low for GAMIT in the alternative F-test 1, but this can be explained by the fact that many points were just below the 95%-limit in this case.

We looked through the time series plots from the “Bernese original 2018” (1993–2018) data set for the points that were found to have significant trends only in either the standard F-test or the alternative F-test 2. In Figure 21 – Figure 20 some examples are shown, where the standard F-test identified significant trends, but not the alternative F-test 2. We see that the standard F-test also gives trends with very small velocities when the observations are very close to forming a straight line.

Figure 21: Significant trends in the north-component (N, blue) with the standard F-test.

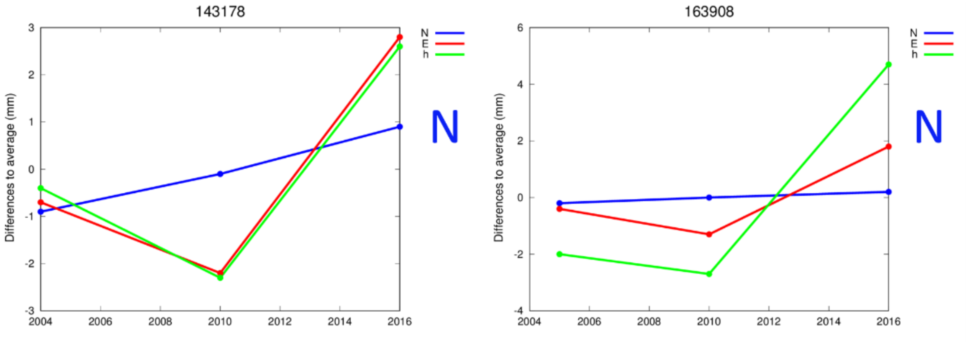


Figure 22: Significant trends in the east-component (E, red) with the standard F-test.

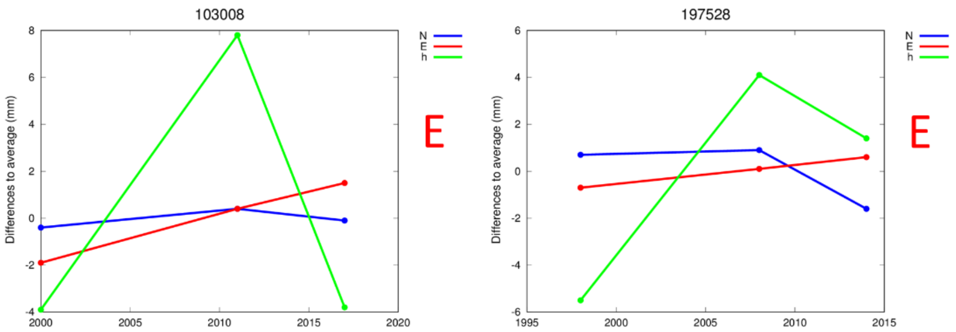
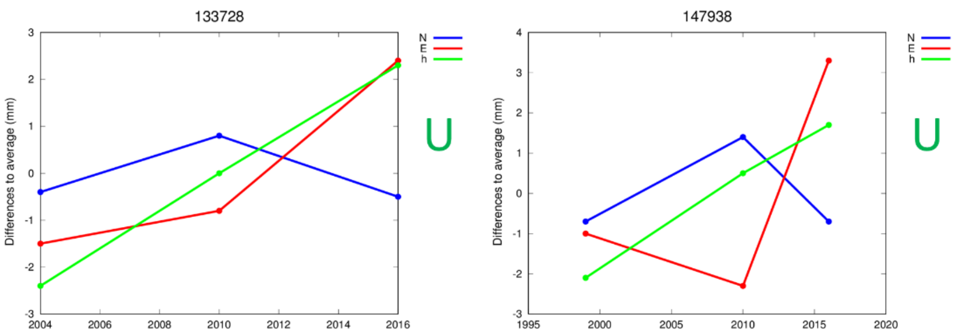


Figure 20: Significant trends in the up-component (U, green) with the standard F-test.



The alternative F-test 2 on the other hand, which is based on the general standard uncertainties, identified all large trends as significant, irrespective of how close to a straight line the observations are. Figure 23 shows some points with large trends where we suspect a physical movement, whereas in Figure 24, the large trends are mainly caused by large uncertainties.

Figure 23: Significant trends in the alternative F-test 2, where we from a visual inspection could expect real movements.

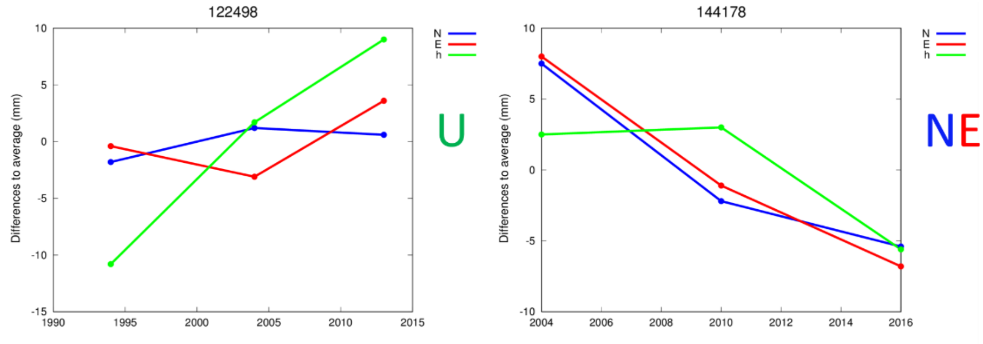
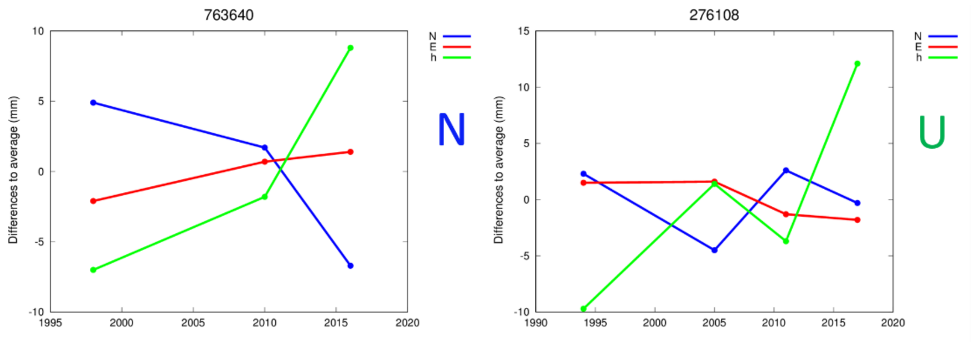


Figure 24:Significant trends in the alternative F-test 2 where the variations are very large, which we suspect to be caused by bad GPS-solutions.



To conclude, the standard F-test points out also quite many small trends and does at the same time miss some of the large (but not perfectly clear) trends. The outcome from the alternative F-test 2, based on the general standard uncertainties, include all large trends but not the small ones, just as desired. But it does also include some questionable trends which rather could be explained by large variations between the repeated measurements.

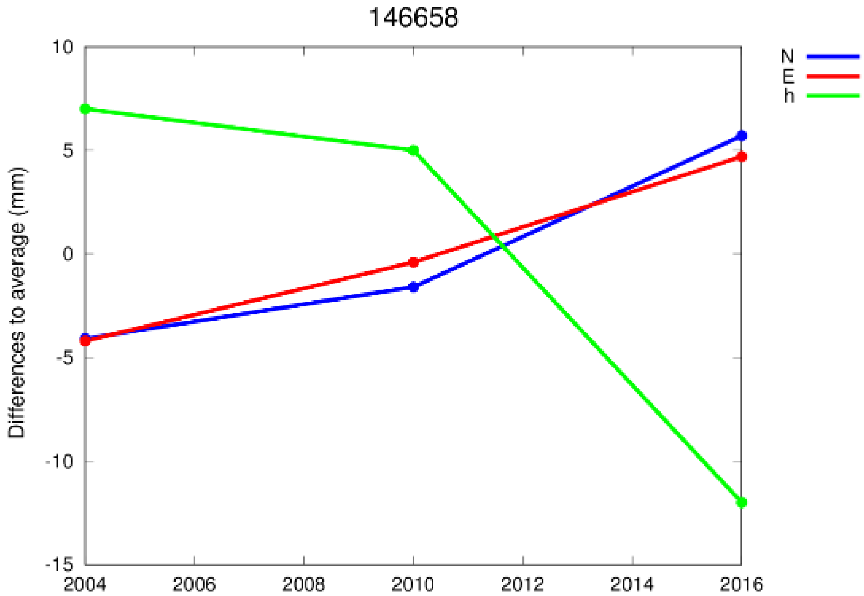
The question is how to modify the tests to obtain more reasonable selection of significant trends. Two main options were considered, either starting from the standard F-test or from the alternative F-test 2. The alternative F-test 1 was not considered anymore as it resulted in a subset of the points already identified using the standard F-test, and it suffers from the same drawbacks as the standard F-test. Besides, this test is not theoretically correct because of the correlation between the nominator and denominator in the F-ratio.

5.3.3.1 Modification of the standard F-test

The standard F-test could be modified in the following way. The small irrelevant trends could be avoided by just including points which have a large standard deviation between the repeated observations. To include also the large relevant trends, which are not perfectly on a line, the significance could be decreased from 95% to maybe 80-90%.

We tried first to match all points having the 10% largest standard deviations with the points that have a significant trend in any component according to a standard F-test on 90% confidence level. However, then we got also matches between large trends in one component and large standard deviations in another. The matching was therefore repeated for each component and the points with a significant trend in any component were counted as points with a trend. 15 points were identified in this way (compared to the original 44 ones). When looking through the time series we noted that the 90% significance level still required the observations to be very close to forming a straight line. Figure 25 shows a point where just the east component and not the north component is identified as having a significant trend. Looking at this one and a few other examples we decided to decrease the significance level to 80%. This gave 12 new components and 6 new points, so in total 21 points of 221 points were identified with a significant trend using the limits 80% F-test and 10% largest standard deviation. The time series of the selected points were visually inspected and almost all points seem reasonable to classify as having trends. As desired, the very small trends are not included anymore and the large trends which are not perfectly aligned to a straight line are included.

Figure 25: The East component (E) was identified as having a significant trend but not the north component (N) with the limits 90% in the F-test and 10% largest standard deviations.



5.3.3.3 Modification of the alternative F-test 2

The other option is to start from the alternative F-test 2. In this case we need to reject the trends with large variations and an option is to reject points with degraded quality measures in the processing, as we think the reason for the large variations is degraded quality of the GPS-solutions. Fortunately, we had a list available where we had identified bad points based on the extra degraded quality measures (see limits in Table 2) in the Bernese Repro data set and an additional manual inspection of the results and pictures of the points. Five of the 33 points were excluded because of bad quality according to this list, i.e., 28 points with significant trends remain. As there were more points and observations in the Bernese original 2018 (1993-2018) data set compared to the Bernese Repro (1996-2017) data set, all points were not fully checked/filtered out in the check for bad quality. It means that we may still have some points with large variations in the outcome from this modified test. We checked the availability of the quality information for the 33 points with significant trends from the alternative F-test 2 and it turned out that all points have quality information, but for six points there was just quality information for two determinations.

To fully use this method the quality measures from each processing set should be analysed and points/sessions with degraded quality measures should be listed. The results and quality measures from the early years of the original processing is not as easily accessible as the later years and the Bernese Repro, so it would need quite much work to compile. Furthermore, some of the quality parameters are quite dependent on the processing strategy used (e.g., ambiguity resolution strategy and elevation cut-off) which differs over time in the original processing set.

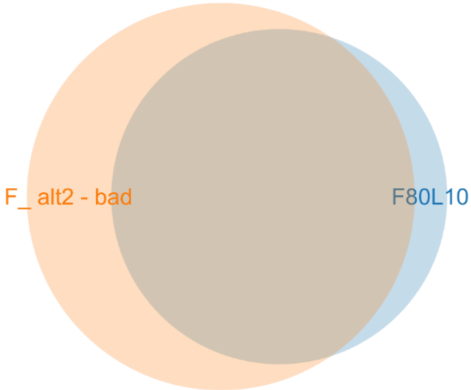
5.3.3.4 Comparison between the two modified strategies and conclusion

The set of points identified having significant trends with the two modified strategies, were compared to each other. We can see in Figure 26 that the overlap between the two sets of points is quite good and much better than between the two original F-tests (Figure 19). 21 points were identified with the modified standard F-test (F80L10) and 28 with the modified alternative F-test 2 (F_alt2-bad). 19 points were common between the two sets. It was expected to get more points with the modified alternative F-test 2 strategy as we have some points (58) for which we did not have a list with degraded points/sessions, that possible could have been excluded.

We looked through the times series of the additional 9 points selected by the modified F-test 2 and all those points do indeed have questionable trends with large variations between observations.

There are two points that are only included in the set from the modified standard F-test and they both are on the limit to be defined as significant.

Figure 26: Venn diagram visualising the number of stations with significant trends found by using the two modified F-tests. F80L10 refers to 80% confidence level in the standard F-test in combination with the 10% largest rms-values of the repeatability between years. F_alt2-bad refers to the alternative F-test 2 (95% confidence level) excluding the points with bad quality measures from the processing.



To conclude, we have found a strategy – standard F-test (80% confidence level) in combination with a condition on the standard deviation between repeated measurements (10% largest), called F80L10, that gives both a reasonable selection of points with significant trends (compared to visual inspection of the time series) and agrees well with the alternative strategy (F-test with general uncertainties and rejection of points with degraded quality from the processing, called F_alt2-bad.)

The alternative strategy (F_alt2-bad) was not an option to be used in the end, as we do not have the quality measures from the data processing compiled from all processing sets, but the available quality measures were useful to verify the chosen strategy.

5.3.4 Comparison between processing sets

The chosen strategy, F80L10, was also applied to the Bernese Repro and GAMIT Repro processing sets.

The identified points in each processing set were compared to the other sets (Table 9 and Figure 27).

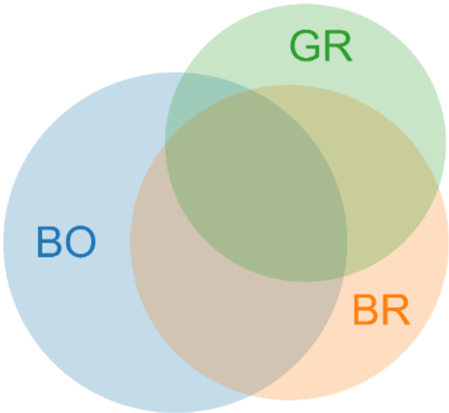
There were 21, 18 and 14 points with significant trends found in the "Bernese original 2018", "Bernese Repro" and "GAMIT Repro", respectively. But we should also note that the number of analysed points, i.e., points with at least three measurements, differs between the sets; "Bernese original 2018" has 221, "Bernese Repro" 162 and "GAMIT Repro" 142. The number of points with significant trends corresponds to approximately 10% for each set. There are six points that are common between all sets: 101368, 144178, 146658, 194918, 203728 and 210448.

Table 9: Number of points with significant trends between the processing sets. BO= Bernese original 2018, BR=Bernese Repro, GR=GAMIT Repro.

No. common points			
	BO	BR	GR
BO	**21**	11	6
BR	11	**18**	9
GR	6	9	**14**

No. points only in combination			
	BO	BR	GR
BO	**10**	5	0
BR	5	**4**	3
GR	0	3	**5**

Figure 27: Venn diagram visualising the number of points with significant trends and the overlap between sets.



As "Bernese original 2018" includes in principle all measurements with SWEREF 99 class 1 determinations up to 2018, which the other sets don't, it is quite natural that there are quite many points with trends just in the Bernese original (10). However, we see also many points only in either GAMIT (5), Bernese Repro (4), or a combination of the two (3). The statistics for these points were studied and we can note the following:

- The points present only in Bernese Repro are close to the limits for Bernese Repro and Bernese original. See an example of a point in Figure 28.
- The points just in GAMIT Repro are close to the limits either for GAMIT Repro or Bernese Repro or both. One point has a fourth observation in Bernese original, which is not at all in line with the other three. Bernese original has in general slightly larger variations than the other sets. See example in Figure 29.
- 6-7 of the 10 points only in Bernese original do not have three observations in Bernese Repro and GAMIT Repro. For the other 3-4 points the F-test and/or standard deviations are close to the limit for all sets.

Example

Figure 28: Example of a point (724218) with a significant trend only in Bernese Repro, east component = red line.

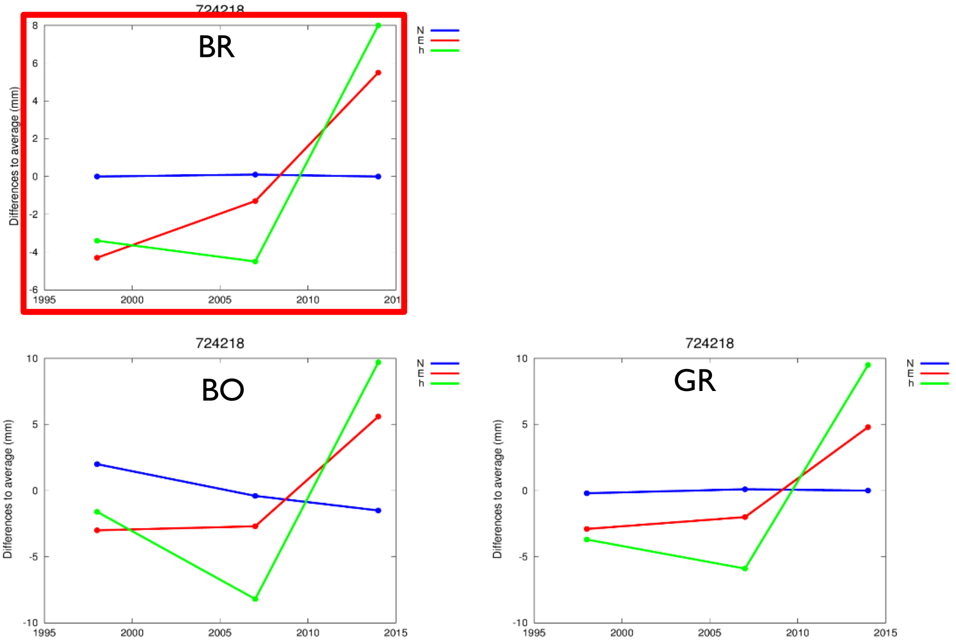
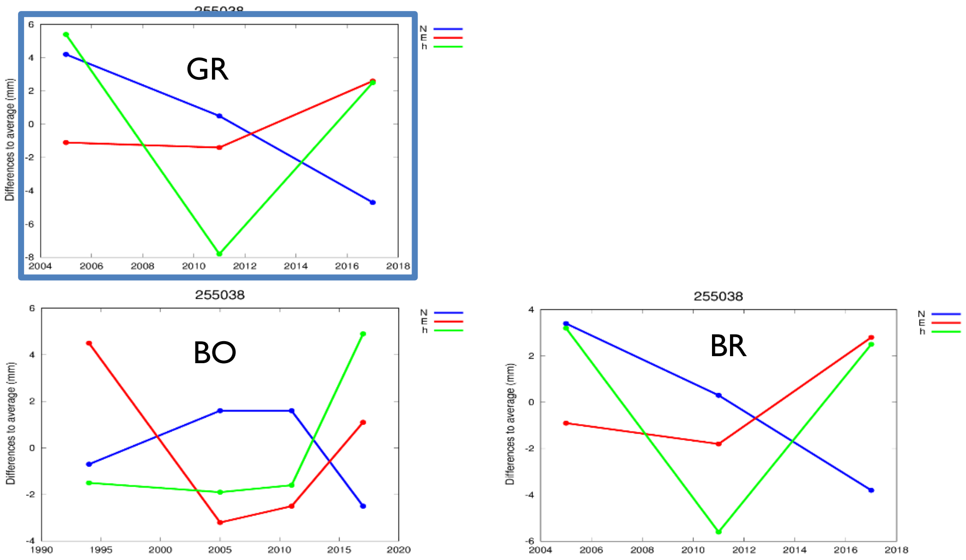


Figure 29: Example of a point (255038) with a significant trend only in GAMIT repro, north component = blue line.



To conclude, the point trends that are significant in only one of the processing sets are usually close to the limits for defining significance, or not included, in the other sets. There are also some cases with more observations in one or two of the sets. The situation is similar for points that are significant in two but not in the third set.

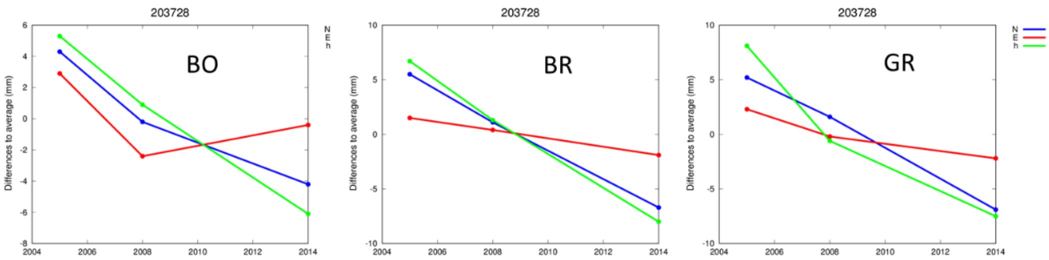
The computed velocities for the six points common between the processing sets were compared to each other (Table 10). Only differences between those velocities considered as significant (according to the F80L10-strategy) are presented.

Table 10:Velocity differences (mm/yr) between the processing sets for the six common points.

	GR-BR			BR-BO			BO-GR		
Point	dvN	dvE	dvU	dvN	dvE	dvU	dvN	dvE	dvU
101368	0.0			-0.1			0.1		
144178	0.1	0.1		-0.1	-0.1		0.0	-0.1	
146658	0.2	0.1		0.0	0.0		-0.1	-0.1	
194918	0.0	-0.2		-0.3	0.0		0.3	0.2	
203728	0.0			-0.4			0.5		
210448		0.1			0.1			-0.2	

Most differences are very small, up to 0.2 mm/yr, which corresponds to 4 mm in 20 years. The largest difference is found for the point 203728 where the Bernese original differ 0.45 mm/yr, which corresponds to 4 mm over a time span of 9 years (Figure 30).

Figure 30: Point 203728 for which the Bernese original differ almost 0.5 mm/yr in the north component (blue) from the other processing sets.



Velocity differences for the points common between just two processing sets (Table 11) are on the same level as for the six common points. The two reprocessing sets (BR and GR) are closer to each other than the original processing (BO).

Table 11: Velocity differences (mm/yr) between two processing sets.

GR-BR				BR-BO			
Point	dvN	dvE	dvU	Point	dvN	dvE	dvU
101368		-0.1		186588	-0.1	0.1	
144178	-0.1			188108			-0.6
146658	0.5			219028	-0.2		
				723988		-0.1	
				790278	-0.1		

5.3.5 Graphical presentation of the significant velocities

The velocities found significant for each processing set were finally plotted on a map to investigate if there are any systematic trends or if the moving points are concentrated to some certain areas (Figure 31 – Figure 33). The non-significant velocities were set to zero, which explains why we have some horizontal velocities only in one of the components.

We should remember that the main part of the velocities is based on only three observations and the presented trends should be understood as an indication of possible trends, and not as well determined trends.

The possible explanation for those trends can be either local deformation and/or residuals of the land uplift model and/or computational effects such as lack of good or enough close-by stations for Helmert transformations from ITRF to SWEREF 99.

The largest velocities are probably caused by unstable stations. The large horizontal velocity north west of Östersund/Storsjön is the point Kaxås (194918) and the one with large velocity both in horizontal and vertical in the far north is Gällivare (280218), both identified as moving stations already before the trend analysis and rejected from the computation of the general standard uncertainties, see Section 5.2 and Figure 14.

The third rejcected station (Junosuando 281978) is not included in the trend analysis as it just has two measurements. Gällivare (280218) is not included in the trend analysis of the two reprocessing sets as we have not included the results from 2018 there.

If we should comment on the geographical distribution of points with a trend, there is a slight overweight for the northern part of Sweden. It could either be that we have more unstable points there or that the point determination there suffers more from deficiencies in the reference frame and the used land uplift models.

In the trend map from the original processing, we do not see any systematic trend in any areas, but from the two reprocessing sets, we see some correlation between the horizontal vectors in some areas.

Figure 31: Significant velocities found in the "Bernese original 2018" processing set, which includes repeated observations in the period 1993-2018. All the stations included in the trend analysis (at least three observations) are shown in the map (small black dots). Horizontal velocities are shown in green and vertical red (upwards) or blue(downwards).

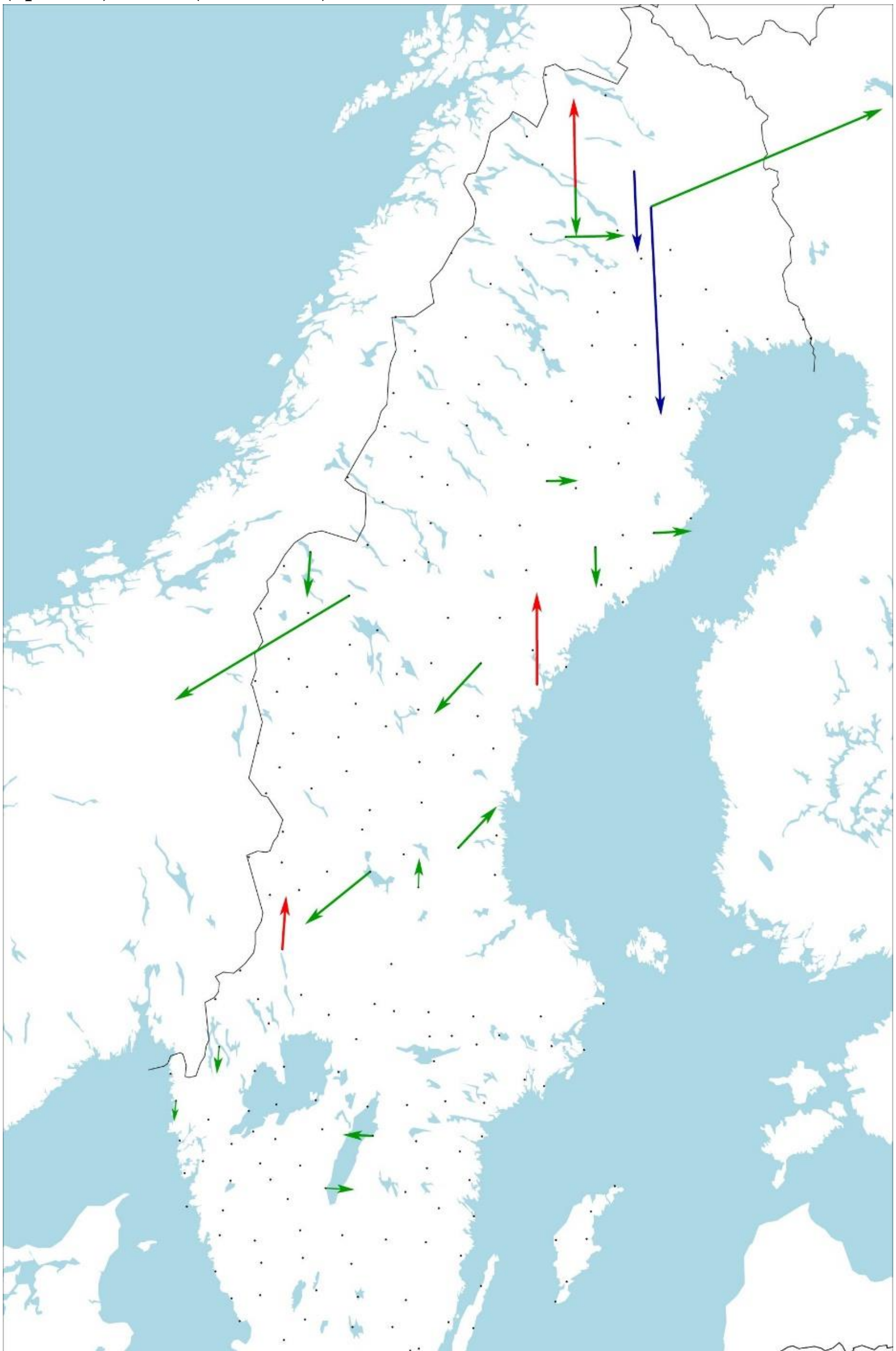


Figure 32: Significant velocities found in the Bernese reprocessing set, which includes repeated observations in the period 1996-2017. All the points included in the trend analysis (at least three observations) are shown in the map (small black dots). Horizontal velocities are shown in green and vertical red (upwards) or blue (downwards).

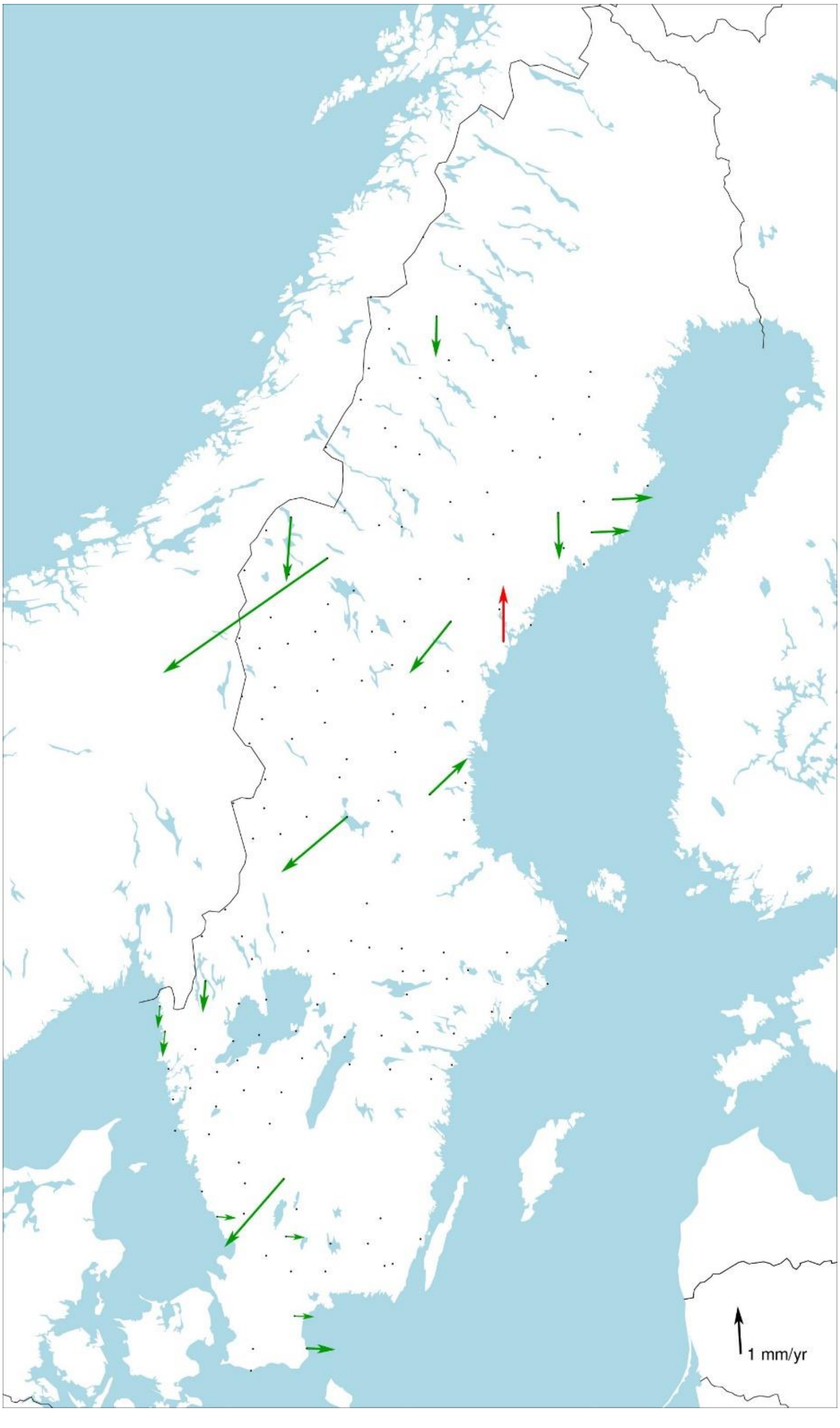
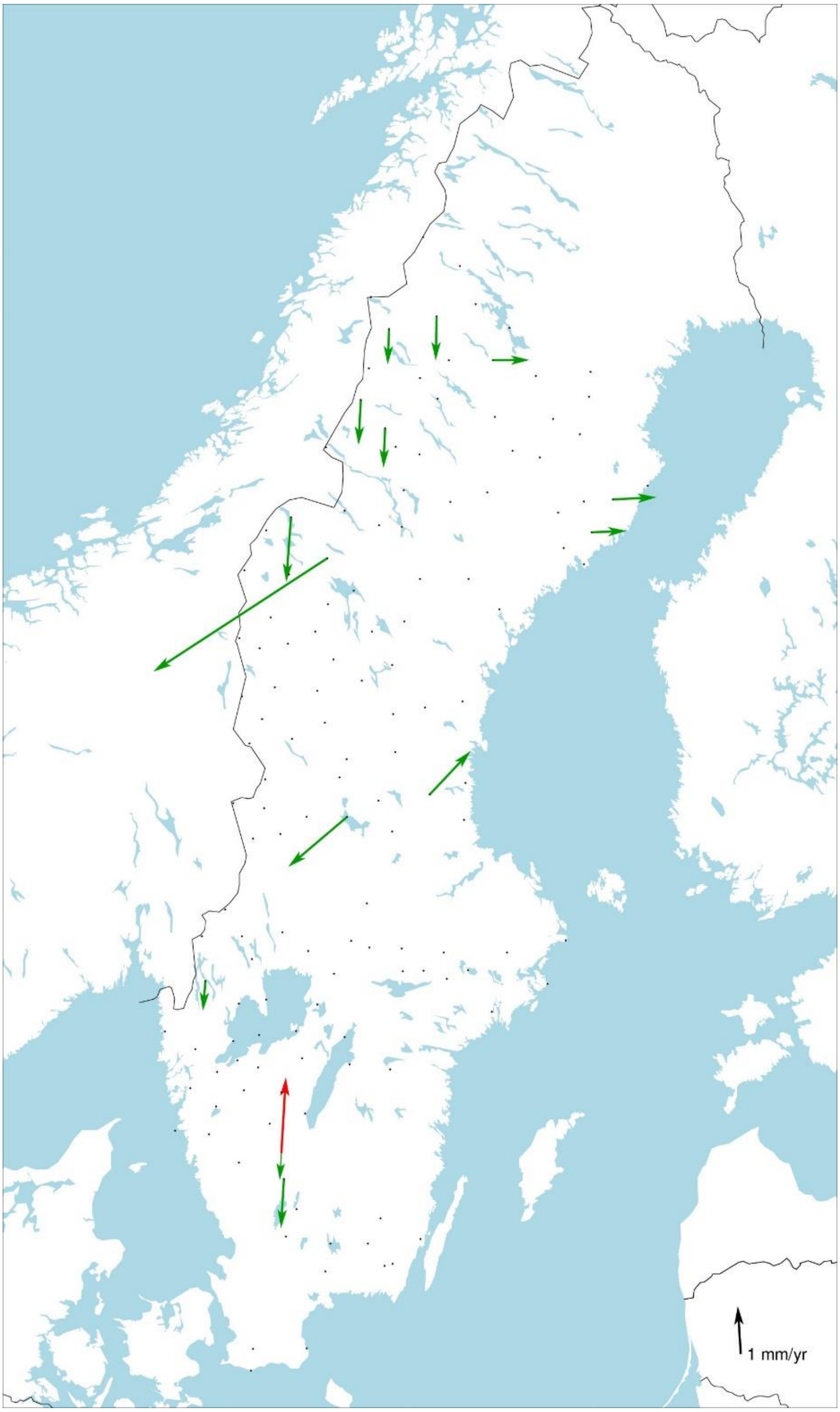


Figure 33: Significant velocities found in the GAMIT reprocessing set, which includes repeated observations in the period 1998-2017. All the points included in the trend analysis (at least three observations) are shown in the map (small black dots). Horizontal velocities are shown in green and vertical red (upwards) or blue (downwards).



6 Additional testing

6.1 Comparison between using GPS only and GPS + GLONASS

All analyses so far reported are based on only GPS-data. From 2017 also GLONASS data are available in the RINEX-files. The data from the years 2017 to 2020 have been processed both with and without GLONASS as a basis for an analysis of the effect of adding GLONASS.

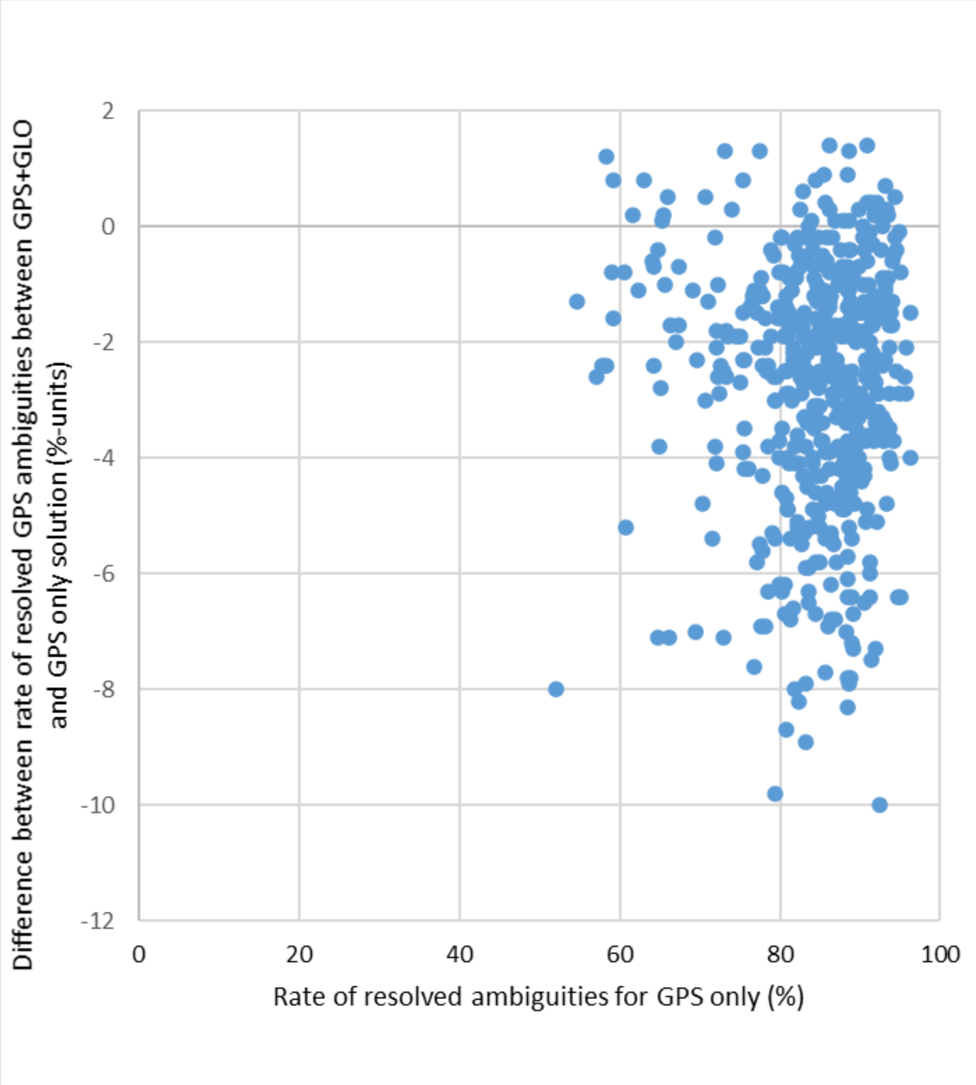
When studying the quality parameters, it is obvious that the ambiguity resolution success rate is much lower when using GLONASS, both for GLONASS and consequently also the total rate for both GPS and GLONASS ambiguities. We decided therefore to check if also the GPS-ambiguity resolution success rate was decreased when GLONASS was added. In some earlier tests the GPS ambiguity resolution success rate was improved when GLONASS was added, even though the total rate decreased.

We did also analyse the coordinate differences between the final coordinates from each data set (GPS only or GPS+GLONASS) and tried to correlate the largest differences with the quality parameters. Finally, also the differences between the two sessions for each point and each data set were analysed to see whether GPS only or GPS + GLONASS performed better.

6.1.1 Lower rate of resolved GPS ambiguities in the GPS + GLONASS solution

In total we have 251 points measured during those four years. The mean ambiguity resolution success rate for the GPS only solution was 82.1%, 79.5% for GPS in the GPS + GLONASS (GPS+GLO) solution and 37.9% for GLONASS (in the GPS+GLO solution). The differences in GPS ambiguity resolution success rate are within 10%, where the GPS only solution has the higher rates for the main part of solutions, see Figure 34. We cannot see any correlation between the difference and the rate itself.

Figure 34: Difference in rate of resolved GPS ambiguities (GPS+GLO minus GPS) as function of the rate of resolved GPS-ambiguities. Each session is plotted (2x251 points). Data from 2017-2020.



6.1.2 Minor differences in final coordinates

The coordinate differences between using GPS or GPS+GLO were calculated for each point and summarised in Table 12. The RMS of all differences were around 1, 1 and 2 mm in north, east and up, which can be considered as small in comparison to the general standard uncertainty for this type of point determination, which is 2, 2 and 6 mm in north, east and up. The maximum differences were 3, 3 and 8 mm in north, east and up. The point with the largest difference in height was 219978 in 2017, where just 50% GPS ambiguities were resolved. The point with the largest difference in horizontal was 262591 (observed in 2018), which is partly obstructed by a small hut. The mentioned points are pictured in Figure 35.

Table 12: **Coordinate differences between using GPS or GPS+GLO.**

	RMS (mm)			Max (absolute) (mm)		
Year	dN	dE	dU	dN	dE	dU
2017	1.1	1.1	2.4	2.6	2.6	7.8
2018	0.8	0.7	1.9	3.4	1.8	5.9
2019	0.9	0.9	1.7	2.6	2.3	4.5
2020	1.0	1.2	2.5	2.8	2.7	6.8
2017-20	**1.0**	**1.0**	**2.1**	3.4	2.7	7.8

Figure 35: Left: View to south-west from 219978. Right: View to north from 262591.

6.1.3 Correlation between large coordinate differences and degraded quality

All point determinations with differences exceeding 2, 2 and 4 mm in north, east and up (i.e., two times the RMS of 1, 1 and 2 mm) were analysed with respect to the quality measures of each determination. Just rate of resolved ambiguities and number of observations were considered, as these are the most usual reasons for defining bad quality. The idea was to see if the "large" differences could be explained by inferior surveying conditions, thus seen in the quality parameters from the processing. In total there were 32point determinations exceeding the coordinate difference limits mentioned above. 27 and 2 of them exceed the limits for normal quality and extra degraded quality (Table 2), respectively. This means that 84% of the 32 point determinations exceed the limit for normal values and 6% are considered having extra degraded quality.

For the Bernese repro 2018 dataset (1996-2018) the corresponding (considering ambiguities and observations) share of point determinations exceeding the limit for normal values is 42% and the share of point determinations exceeding the limit for extra degraded quality is 5%. It seems that the subset with larger coordinate differences between GPS and GPS+GLO have the same share of point determinations with extra degraded quality, but more point determinations exceeding the normal values, compared to the Bernese repro 2018 dataset (see further section 4). However, the time periods are different, 2017-2020 for the analysis between GPS and GPS+GLO and 1997-2018 for the Bernese repro 2018 dataset so it might also be that the quality measures have degraded with time.

For a more fair comparison, we made the same comparisons again for the Bernese repro 2018 dataset just for the time period 2017-2019 (we did not have the quality information compiled for 2020). For the time period 2017-2019 there were 24 point determinations exceeding the coordinate limits of 2, 2 and 4 mm in north, east and up. Of those, 16 determinations were exceeding the normal quality limits and 1 was exceeding the limit for extra degraded quality. This means that 67% of the determinations exceed the limit for normal values and 4% are considered having extra degraded quality. Corresponding values from the full repro data set for these years (2017-2019) are 55% and 7%. This comparison shows that the share of point determinations exceeding the normal quality limits is larger in the data set with large coordinate differences between GPS and GPS+GLO than in the total data set for corresponding years, but the difference is quite small if we take into account that one point determination corresponds to 4% of the smaller data set.

Anyway, it indicates that there is a correlation of the coordinate difference with the degraded quality in the processing, which probably is caused by inferior surveying conditions at the points. We have seen above that the point determinations with the largest coordinate differences also had quite bad surveying conditions. We should however remember that the difference between GPS and GPS+GLO on a general level (1, 1 and 2 mm) is minor compared to the general standard uncertainty for this type of point determination (2, 2 and 6 mm).

6.1.4 Smaller differences between sessions for GPS only

From the tests reported above, we can just see that there are small differences between the GPS and the GPS+GLO solutions, but which one is the better?

One absolute quality measure, that would be directly linked to the uncertainty, is the difference between the two sessions of each point determination. RMS values of the differences between sessions were computed for each year and totally for the four years for both the GPS- and the GPS+GLO-solutions, see Table 13. The differences are taken from the combination and are therefore not dependent on the reference system alignment of each session from SWEPOS post processing service.

Table 13: Differences between session 1 and session 2 expressed as RMS in mm.

	GPS			GPS+GLO		
Year	**RMSdN**	**RMSdE**	**RMSdU**	**RMSdN**	**RMSdE**	**RMSdU**
2017	1.5	1.0	5.0	1.6	1.4	6.3
2018	1.1	0.9	2.9	1.3	1.3	3.5
2019	1.3	1.1	3.2	1.5	1.7	3.8
2020	1.5	1.7	4.9	1.8	2.2	5.1
2017-2020	**1.4**	**1.2**	**4.0**	**1.5**	**1.7**	**4.6**

The differences are on the level 1-2 mm for the horizontal components and 4-5 mm in height, so they are somewhere between the differences between using GPS or GPS+GLO and the general standard uncertainties. The differences are slightly larger for the GPS+GLO-solutions, both in horizontal and in height and for all four years. Further on we see that the differences are larger in east than in north which probably is related to the degraded ambiguity resolution when GLONASS is used.

A possible reason for the slightly inferior results – concerning both the differences between sessions and the ambiguity resolution – when GLONASS is included could be lack of true GLONASS calibrations for some of the used antennas. The antennas used on the field points (SWEREF 99 class 1) have just corrections based on GPS and in some case just copied values from AOAD/M_T for the years 2017-18. For the years 2019-20 both true GPS and GLO corrections are available for the field measurements, but some of the SWEPOS stations still had true values just for GPS, and calibrations just based on a few individual antennas. The situation was a bit better in 2020 when igs14.atx was used, then it was just one antenna type on SWEPOS that only had GPS-corrections. In Table 13 we can see that the differences between the RMS values are pretty similar throughout the years. If the deficiencies in the antenna models would be the only explanation for the slightly degraded results when GLONASS is included, then we would expect that 2019 and especially 2020 would have smaller differences than the other years. Of course, we can see that 2017 has slightly larger and 2020 slightly smaller height differences, so the antenna models might be part of the explanation but there are also other factors affecting the result.

7 Discussion

7.1 Antennas and antenna PCV models

As we mentioned in section 3.1 different antenna models were used in the data processing with the Bernese software. For original processing, igs_01.atx (relative) was used up to 2012 and thereafter igs08.atx (absolute) models. For reprocessing with the Bernese GNSS Software, the igs08.atx model was consistently used for all years.

The change of antenna models from relative igs_01.atx to absolute igs08.atx introduced coordinate shifts. The size of those shifts is dependent on type of antenna and type of GNSS-solution. For the antenna types used on SWEPOS fundamental stations and for the field measurements of the SWEREF 99 class 1 points – AOAD/M_T and Ashtech or Javad versions of Dorne Margolin choke ring antennas – the shift varies between 0 and 5 mm in height when using the ionosphere free linear combination and solving parameters for the troposphere delay.

7.1.1 SWEPOS station coordinates corrected for new antenna PCV

The SWEREF 99 coordinates of the SWEPOS stations have been corrected for the shifts introduced when the igs08.atx antenna table was implemented in SWEPOS. It means that the effect on the SWEREF 99 class 1 points will only be dependent on the used antenna at this point (and not on the antenna models for the SWEPOS stations). If an antenna type, whose antenna model remained unchanged from igs_01.atx to igs08.atx, e.g., an JNSCR_C146-22-1 or JAVRINGANT_DM, was used for the measurement of the SWEREF 99 class 1 point, there should in theory not be any difference if igs_01.atx with the original SWEREF 99 coordinates or the igs08.atx with the updated SWEREF 99 coordinates were used. For the Ashtech-choke ring antennas a difference of 3-5 mm in height could be expected between solutions based on the different antenna model tables.

7.1.2 Coordinate differences on the same level as between individuals

The coordinate differences when using antenna models in either igs_01.atx or igs08.atx are on the same level as individual variations between antennas of the same type and a bit less than the standard uncertainty for the SWEREF 99 class 1 point determination. The small differences from the antenna models are hidden in the noise of the measurements. This is probably the reason why we see the same uncertainty level for the original processing, where we have both relative (igs_01.atx) and absolute antenna models (igs08.atx), as for the two repro solutions, where consistent antenna models have been used.

We shall also remember that we have not used the same antenna individuals and not even the same type of antenna for the repeated measurements at each point. If an accurate determination of deformation would have been the main objective, then it could have been beneficial to use the same antenna individual for each re-visit of a point and in that way eliminate or at least reduce the antenna dependent errors. However, our main objective was to determine points in SWEREF 99 between SWEPOS fundamental stations and to monitor the whole “SWEREF 99 calculation system” including changes of antenna models, satellite signals, SWEPOS equipment etc. By using different antennas for the repeated measurements, we will also get more realistic uncertainty estimations for this type of measurements, as also the antenna uncertainties are included.

7.1.3 Possible to reprocess with individual antenna models

The processing presented in this report has been conducted with type calibrations but many of the antennas have been individually calibrated afterwards. The differences between individual antennas could be reduced by reprocessing with individual models in the future. However, it is not sure that the standard uncertainties really will decrease if there are other errors that are more dominant. There are also some doubts if the individual antenna models always are more accurate than the type values. In case the individual variations are small, the result from the averaging of the type models might be better.

It is important to consider the used antenna models when analysing the results of the processing. For example, the conclusions from the comparisons when including GLONASS (section 6.1) might be different if other antenna models with true corrections from calibration for all signals and antenna types had been used instead of sometimes copied values from GPS or from another antenna type, which was the case for some antennas in igs08.atx.

7.2 Degraded quality with time of the Helmert fits

The alignment to SWEREF 99 is made with a three-dimensional Helmert transformation to the closest fundamental SWEPOS stations or foreign stations that also are defining stations for SWEREF 99. To improve the fit, the GNSS-solution that includes the SWEREF 99 class 1 point, is first reduced from the observation epoch to the epoch of SWEREF 99 (1999.5) with a land uplift model (see section 3.2) before the Helmert fit.

The selection of reference stations used for the fit is usually the 6-8 closest fundamental SWEPOS stations and possibly additional foreign stations. In case of the Bernese solutions (both repro and the original) the final selection of reference stations for the alignment to SWEREF 99 is made manually. (The Helmert fits for the GAMIT processing were made with a more automated approach.) It happens sometimes, and more frequently in the last years, that some stations do not fit perfectly and need to be excluded from the fit. For some stations, mainly in the north, we have had residuals in the order of 5 mm in horizontal and 10 mm in height, which is quite high in comparison to the normal RMS of 1-2 mm per component.

One reason could be that there have been equipment changes and the coordinates have not been perfectly corrected for the change. Especially for stations in the outskirts (normally foreign stations) there are sometimes problems to calculate a good correction because of the extrapolation. Another reason is that the land uplift model does not model the real deformation between the observation epoch and 1999.5, either because of deficiencies in the model or because of local movements at some stations (not following the long wave pattern from GIA). Skellefteå (SKEL.0) is such a station where we have had problems to get a good fit for the horizontal components the last decade. The station is close to the land uplift maximum and might suffer from local movements.

Some stations have been determined with extrapolation. This is usually not a problem if the fit is good and the extrapolation is limited. However, the larger residuals in northern Sweden in combination with extrapolation has increased the uncertainties of the point determinations, e.g., along the boundary to Norway.

The fit to SWEREF 99 has been degraded with time because of the two reasons mentioned above – deficiencies in the land uplift model (which get more pronounced with an increased time span) and uncertainties introduced in connection to equipment changes (more changes are done with time). But we can also see in the reprocessing that we sometimes do not get the same level of fit for the early years as we originally did. This can be explained by the fact that we for the reprocessing had to compute coordinates compatible with igs08.atx for old time intervals of some reference stations, which especially if we were dependent on foreign stations introduced additional uncertainties.

7.3 Problematic points

For some points and time intervals the data are degraded and not usable for accurate coordinate determination with the aim to control the stability of the reference frame. In connection to the analysis of the Bernese solutions 1993-2018 we concluded that about 3% of the point determinations were not reliable because of degraded quality. The reason for the degraded quality could usually be found in the environment of the point – it could be obstructions in form of trees, fences or power lines, but it could also be connected to bad (space) weather.

There are several quality parameters from the analysis of the data, but we find it hard to define limits for acceptable values that will result in useful and reliable coordinates. The quality parameters will also to some extent be dependent on details in the processing options and models and may therefore vary with time (in case of the original/operational processing). When the limits defined for normal values were applied to data from the early years, the main part (54%) of the point determinations failed on at least one of the limits. Therefore, more loose limits (i.e., what we called “extra degraded quality” in this report) were defined, but also when applying those limits we found many point determinations to be ok when we checked the point repeatability and inspected the environment, even though the quality measures were out of bounds.

It would of course have been nice to have limits to sort out unusable processing results from further analysis (like trend analysis), but unfortunately, we have not been able to reach this vision without rejecting too many usable point determinations. Therefore, we have included also questionable point determinations in the further analysis of repeatability and trends and first in the end, with all information available, tried to define bad/unusable point determinations and points.

Another type of problematic points are points which are not stable. By checking the marker foundation and pictures of the points with significant trends we found a few unstable points.

In case we have identified problems with the point environment or point stability, the point has been replaced with a new one for the future repeated measurements.

7.4 Local deformation

7.4.1 Deformation at the reference stations

All deformations at the reference stations (SWEPOS fundamental stations and corresponding foreign stations) that are not included in the used land uplift models will show up as large residuals in the Helmert fit to SWEREF 99 and will also have a small impact on the determination of the SWEREF 99 class 1 points. As mentioned above this problem is mainly occurring in northern Sweden and the possible deformation seen on the reference stations is quite small. The residuals after 15-20 years are up to 5 mm horizontally and 10 mm vertically, so the impact on the SWEREF 99 class 1 points will be much smaller as we normally perform the Helmert fit using 6-8 stations. In case of fewer reference stations and with extrapolation, the impact on the SWEREF 99 class 1 point determination may be significant.

7.4.2 Significant trends

The possible local deformation at the SWEREF 99 class 1 points could be found by the trend analysis of the repeated measurements. When we searched for significant trends, we found 21, 17 and 14 points in the “Bernese original 2018”, “Bernese Repro” and “GAMIT Repro”, respectively. The number of analysed points – points with at least three measurements – differ between the data sets; but the share of points with significant trends correspond to approximately 10% for each set. There are six points that are common between all sets and the points that differ between the sets (if available in all sets) are in most cases close to the limits for significance, so we can conclude that the different processing sets give similar trend results.

However, an identified trend may also have other explanations than local deformation, especially if we consider that our trend analysis is mainly based on time series with just three observations. Growing trees, other changing conditions around the point or bad data quality may also be the cause of a trend.

Only for the largest trends (> 2-3 cm over 10-20 years) we can be quite sure that there was a physical movement. There were three such points and we believe that the movement is due to unstable markers rather than a trend that is representative for a larger area. In the graphical presentation of the trends, we could for the two reprocessing data sets see some indication of systematics between close by points, but it could also be caused by other error sources as mentioned above. For the original Bernese processing data set we see no such systematics of the trends.

8 Conclusions

8.1 Good agreement between Bernese and GAMIT

The processing results (compared for each point/year) from GAMIT and Bernese are equal at about 1-2 mm level for horizontal and 4 mm for vertical components (1 sigma, see Table 5) when using the same models and processing strategy. The original processing, which partly is based on other models and parameters, differs slightly more for the north component (2.4 mm, 1 sigma), but is also very similar. It means that it is possible to use also GAMIT for determination of SWEREF 99 coordinates if we use the same processing strategy.

8.2 Standard uncertainty for a single SWEREF 99 class 1 determination

Our analysis both from processing with Bernese (repro and original) and GAMIT (repro) shows that **the standard uncertainties for a single SWEREF 99 class 1 determination (2x24 hrs) is about 2 mm for the horizontal components and 6-7 mm in height**. The standard uncertainty for the height is slightly larger for GAMIT compared to the two Bernese data sets. It can possibly be explained by the fact that more efforts were made with the Bernese to find the optimal local Helmert fit for each point. It is also interesting to note that the repeatability of the original Bernese processing is not worse than from the reprocessing, although the longer time span and that processing options and models vary over time.

The good repeatability for the original processing shows that **the concept of determining new SWEREF 99 coordinates has resulted in a stable frame on the mentioned uncertainty level**. It also means that we can use the original processing for the trend analysis and do not need to perform consistent reprocessing.

8.3 Trend analysis adapted to the low redundancy

We performed trend analysis and statistical tests to investigate the stability of the estimated SWEREF 99 coordinates. Points with minimum three observations were analysed. The main part of those had just three observations, there were only a few points with four observations. The **very low redundancy** gave undesired result from the standard F-test on 95% significant level – some trends that were very small but with the observations being very close to forming a straight line were found significant, while some large trends were missed. Some alternative F-tests were also performed, but none of them provide a reasonable set of significant trends (according to visual inspection of the time series). The agreement between the different F-tests were also not good.

We tried to develop a test better suited for our data by modifying two of the F-tests. The modified F-tests gave a better agreement between the two tests and – most important – better agreement with intuitive expectation (and avoiding the weaknesses mentioned above).

8.4 Significant trends for 10% of the points

The finally chosen strategy, which is based on the combination of 80% significance level of a standard F-test and the 10% largest RMS values of the repeatability between years, pointed out 21 points with significant trends from the Bernese original 1993-2018 data set. This corresponds to about 10% of the analysed points. When this strategy was applied to the other data sets similar results were achieved. The points that were categorised differently (significant/non-significant trends) between the data sets were in most case close to the limits for having significant trends.

The two largest velocities – for the points Kaxås (194918) and Gällivare (280218) – were both identified as moving points already before the trend analysis. In those cases we are quite convinced that we have local instability of the markers.

The significant trends were also plotted on a map for each data set to see if there were any systematic trends in some areas or if the moving points are concentrated to some certain areas. In the trend map from the original processing (up to 2018), we do not see any systematic trend in any areas, but from the two reprocessing data sets and in the additional analysis based on the original processing with data up to 2019 (Appendix 1), we see some correlation between the horizontal vectors in some areas.

Concerning the **geographical distribution of points with a trend there is a slight overweight for the northern part of Sweden.** It could either be that we have more unstable points there or that the point determination there suffers more from deficiencies in the reference frame and the used land uplift models.

However, we should keep in mind that the trend analysis mainly is based on only three observations, which does not give much redundancy and hence **the results might change when more observations are added to the point wise time series**.

In fact, when writing these conclusions, we do have results from two more years (Appendix 1 and 2). With data up to 2020, there are 29 points that have got a fourth observation compared to the earlier presented data up to 2018. Three points changed classification with the additional observation, but for 90% of the points this fourth observation confirms the earlier classification concerning significant/non-significant trend.

9 Future work

9.1 Continue to study the repeatability and perform trend analysis

From 2008 to 2019 the consolidation points have been remeasured every 6 years, which means that in principle all points have got three observations after the measurements in 2019. From 2020 the strategy changed a bit to give priority to GNSS-points that also are levelled. The aim is to get a more useful set of points that also support future geoid determinations. This means that some old consolidation points are replaced by new levelled points and new time series will be started. [Alfredsson et al. 2019]. When the completing of the GNSS-levelling data set is finalised, a new decision will be taken on which points are to be classified as consolidation points and will be included in the future repeated measurements. The GNSS-measurements for the GNSS-levelling data set are planned to be finalised in 2024 and additional levelling in 2028.

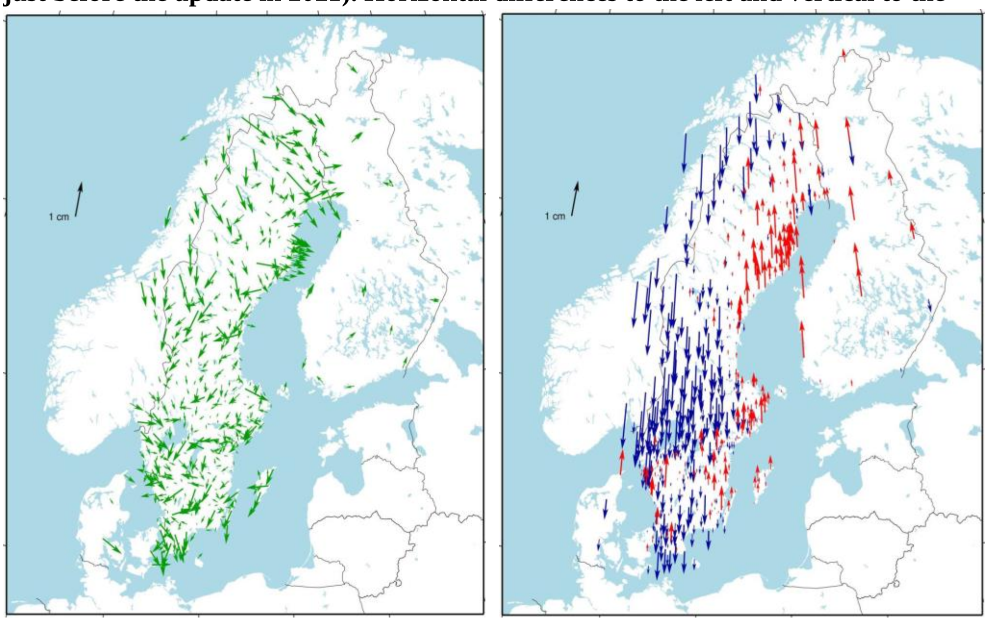
As long as we continue to perform repeated measurements, we should also continue to analyse the repeatability and the trends. In the main text of this report we have included measurements up to 2018, but before finalising the report, we added the analysis including measurements up to 2019 and furthermore 2020, see Appendix 1 and 2. With data from year 2019 we can perform trend analysis on "all" consolidation points, at least we have points in all areas of Sweden with a minimum of three observations. 2020 is the last year before the update of SWEREF 99 on the SWEPOS stations – see section 9.2 – so this year conclude the analysis based on the original SWEREF 99. The strategy for trend analysis developed in this report was used for the additional analysis reported in the Appendices. In the future when we have more observations on all points, the standard F-test might be useful to identify the trends.

For the future it would be useful with a yearly repeatability and trend analysis. The selection of points to be included in this analysis should also be considered. Preferably just consolidation points should be included and not the old campaigns from the 1990s. Eventually, the first measurements, which were not fully compatible with the SWEREF 99 class 1-point determinations, get less interesting.

9.2 Reprocessing following the SWEREF 99 update 2021

While working with this report, the coordinates of all SWEPOS stations and other permanent GNSS-stations defining SWEREF 99, have been adjusted to comply with present GNSS-observations and models, resulting in SWEREF 99, update 2021 [Jivall, Lilje, 2023]. The update was introduced in the SWEPOS-services February 7, 2021. The maximum systematic difference to the earlier coordinates is about 1 cm in height in Värmland-Dalarna and 4 mm in east in the north-west of Sweden – see Figure 36.

Figure 36: Coordinate differences (old - new) at the SWEPOS stations (at an epoch just before the update in 2021). Horizontal differences to the left and vertical to the



To avoid systematic differences between the active realisation of SWEREF 99 through SWEPOS and the passive control network of SWEREF 99 class 1 points, the latter need to be re-calculated using the new updated coordinates on the SWEPOS stations and foreign defining stations. Of course, coordinates valid for each observation epoch have to be used. (Updated coordinates of the defining stations have been calculated for different time intervals, depending on equipment changes at the stations.)

As it is a huge work to reprocess everything and the main part of the points are regularly remeasured (every 6 years), we ask ourselves how much of the data really need to be reprocessed. All data back to 1993? Or maybe 1996? Do we need to reprocess the campaigns like DOSE93A, NORDREF94 and EUVN97? Or is it enough to re-reprocess only the latest years? If so, how many years?

We can conclude that we need to have new coordinates (compatible with the SWEREF 99 update 2021 at SWEPOS) for all points that are and have been available to the users through the Digital Geodetic Archive (DGA) (see section 9.4.) and for all points we want to use for the GNSS-levelling part in the coming geoid models. Furthermore, we would like to continue to make trend analysis and study the time series of the consolidation points. However, we think it is not necessary to reprocess all observations for the trend analysis, the earlier observations can be corrected if there is at least one common observation (year) with both old and new coordinates.

9.2.1 Recommendations for the reprocessing

- Define the list of the points that should be reprocessed:
  - All SWEREF 99 class 1 points already available in DGA
  - Additional levelled SWEREF 99 class 1 points, new or used for SWEN17
- Only the latest measurement for each point needs to be reprocessed (except some cases where the latest measurement is affected by growing trees or similar). Start to reprocess the observations of the latest six years (2016-2021). Then reprocess the rest of points in the list of points mentioned above.
- Options compatible with the SWEREF 99 update 2021 should be used for the reprocessing. SWEREF 99 update 2021 was processed with GPS + GLONASS + Galileo using 3° cut-off, Vienna mapping function, NKG_RF17vel and igs14.atx. SWEPOS post processing service, which is used for the processing of the SWEREF 99 class 1 points, was updated accordingly in connection to the introduction of SWEREF 99 update 2021, but the present version is not able to process Galileo. This means that the reprocessing will be based on only GPS + GLONASS, but we see no major issue with this as we have seen that the contribution from Galileo is minor for the SWEPOS stations and this type of processing with daily solutions [Jivall, Lilje, 2023]. Furthermore, SWEPOS post processing service uses Global mapping function (GMF) instead of Vienna mapping function (VMF). This should not cause any problems either as we have seen that the systematic coordinate differences between VMF and GMF are small on the SWEPOS stations, below 1 mm in height, according to a test on the Swedish sub-network of NKG GNSS AC [Jivall 2016].

9.3 Include other satellite systems besides GPS

All analyses in this report, besides the testing in section 6.1, are based on only GPS-data. From 2017 also other data from satellite systems (at least GLONASS and Galileo) are available in the RINEX-files. In section 6.1 a comparison between results from GPS only and GPS+GLONASS observations for the period 2017-2020 is presented. It shows that the difference on a general level is small – RMS of 1, 1 and 2 mm in north, east and up. It also reveals better results for the GPS only solutions in form of ambiguity resolution and repeatability (between the two sessions of each determination). This is maybe a bit surprising but could possibly be explained by lack of true GLONASS calibrations for some of the used antennas. It is therefore interesting to continue to study the effect of including different satellite systems with the use of new antenna models.

A renewal of SWEPOS post processing service – including possibilities to process multi GNSS-data in RINEX3 format – is under planning. It will be based on a new version of the Bernese Software, version 5.4. When this new version of SWEPOS post processing service is available, more tests with multi-GNSS processing of the

SWEREF 99 class 1 points can be performed. The plan is to use multi GNSS solutions for the future operational processing.

9.4 User access through DGA

The national geodetic points are available with point descriptions and their coordinates/heights in the Digital Geodetic Archive (DGA) at Lantmäteriet.

The official SWEREF 99 coordinates for the SWEREF 99 class 1 points are still (2022) the result from the determination in the RIX 95-project, which was kept fixed in adjustment of the densified RIX 95-points. In this way the official coordinates of the SWEREF 99 class 1 points are consistent with the results from the RIX 95-project, which have been used for transformations from local systems to SWEREF 99 and as reference for local control networks. On the other hand, if we include also later observations and compute an average for each point, more accurate and reliable positions could be computed. Such averaging based on measurements from several years have been done for the definition of the SWEREF 99 component of the SWEN17-geoid model.

The update of the SWEREF 99 coordinates on the SWEPOS stations in 2021 has also increased the difference between the realisation of SWEREF 99 based on the SWEPOS stations on one hand, and the realisation based on the passive network on the other hand.

Before updating the information in DGA with new coordinates on the SWEREF 99 class 1 points (thus making them available to the users) there are several questions that need to be addressed and decided upon.

- Which coordinates should be considered as official? Based on which processing? Based on a single observation or on an average of several observations (years)?
- How to handle and give access also to previously official coordinates?
- How to handle the consolidation points (the main sub-set of the SWEREF 99 class 1 points)? Which points are/have been consolidation points and for which time interval?

9.5 Summary – future work

The desired future work can be summed up with the following actions:

- Continue to analyse repeatability and trends for the consolidation points using the methods outlined in this report.
- Reprocess all points that have been available to the users or have been/will be used for geoid modelling so they will be compatible with the SWEREF 99 update 2021 at SWEPOS. It is enough to reprocess one observation (two sessions/one year) for each point. Preferrable the latest observation will be used if there is not any problem with this one. We have decided to start to process years 2016-2021 with the same strategy as was used for the SWEREF 99 update 2021.
- Renew SWEPOS post processing service to include possibilities to process multi GNSS-data from RINEX3.

- Continue to study the effect of using different satellite systems.
- Compute and decide official coordinates for the SWEREF 99 class 1 points.
- Make the coordinates available in DGA – possibly together with previously official coordinates. Make necessary changes of DGA to allow the handling of different generations of official coordinates.
- Define the set of consolidation points and their validity time.

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The maps in the report were generated using the Generic Mapping Tool (GMT) [Wessel et al. 2013], except Figure 5, which is from Google Earth. The Venn diagrams were generated with tools from https://westeurope.displayr.com/. Finally, we would also like to thank our colleagues at the department of Geodetic Infrastructure, who came with valuable comments and suggestions on the report.

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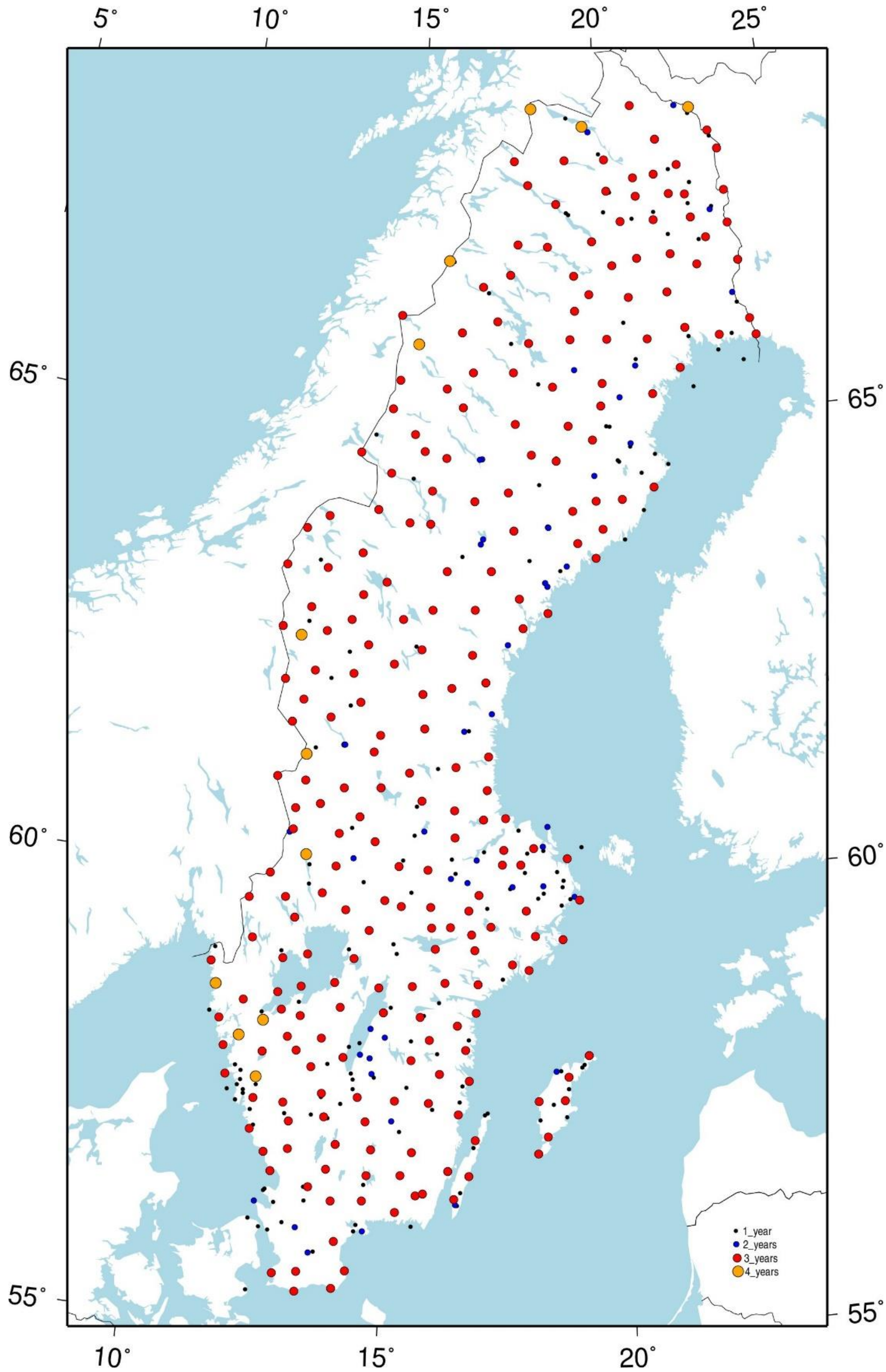
Appendix 1: Bernese original 1993 – 2019

Here we have applied the strategies outlined in the report on the original coordinates processed each year from 1993 to 2019. 2019 was the first year when the SWEREF 99 class 1 points in all parts of Sweden were covered with three observations (years) – see Figure 37.

Figure 37: Distribution of the SWEREF 99 class 1 points and number of measurements visualised by different size of coloured circles, for the period 1993-2019.

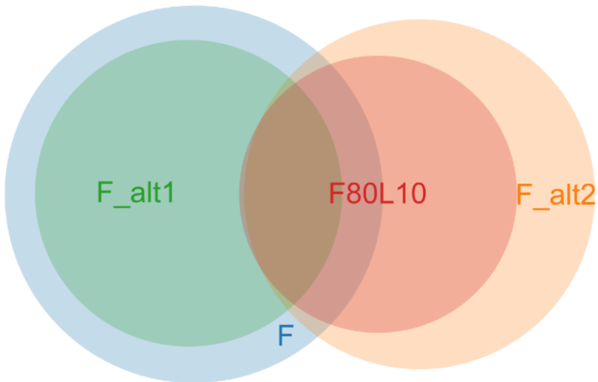


In total 258 points are measured at least three times (246 three times and 12 four times). One point (107218) was excluded from the trend analysis as the last measurement were affected by a fence, so trend analysis was performed for 257 points.

The estimated general pooled standard uncertainty is 2.3, 2.6 and 6.1 mm for north, east and up, which corresponds well to the earlier results based on data up to 2018.

We performed trend analysis according to the strategies outlined in the report. The outcomes from the three first F-tests (standard-F-test, F-test alternative 1 and F-test alternative 2 – see section 5.3.2) and the final F80L10-strategy (see section 5.3.3.1) are presented in Figure 38. It is interesting to note that the points selected by the modified standard F-test (F80L10) is a subset of the points selected by the F-test alternative 2. The relation between the first three F-tests is similar to the results based on data up to 2018.

Figure 38: Comparison between F-tests based on data up to 2019.



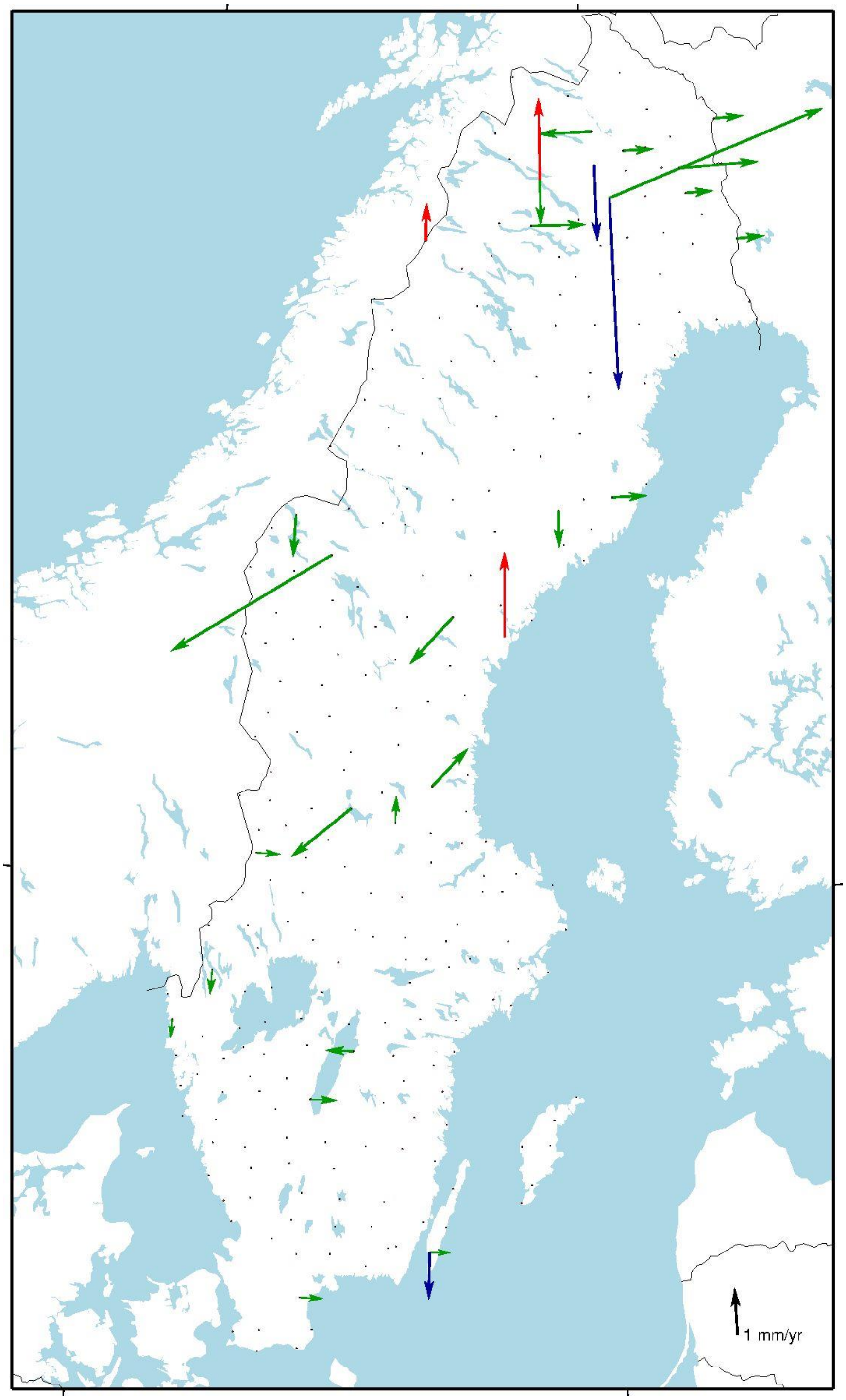
To finally select points with significant trends, we used the F80L10-strategy (80% confidence level in the standard F-test in combination with the 10% largest RMS-values of the repeatability between years). 27 points were defined as having significant trends with this strategy. This corresponds to 10% of the analysed points.

The significant trends are plotted in Figure 39. The non-significant velocities were set to zero, which explains why we have some horizontal velocities present only in one of the components.

We should remember that the main part of the velocities is based on only three observations and the presented trends should be understood as an indication of possible trends, and not as well determined trends.

In contrast to the analysis based on data up to 2018, we can now see a systematic trend in the northeast of Sweden. (This area was not covered with three observations before 2019.) If this trend depends on local movements, deficiencies in the land up-lift model, uncertainties in the alignment to SWEREF 99 or a combination of those reasons is not clear when we write this report. However, we think it is due to uncertainties in the SWEREF 99-realisation and the land up-lift model rather than local movements. When determining point coordinates in this area we either have to extrapolate or rely on foreign stations.

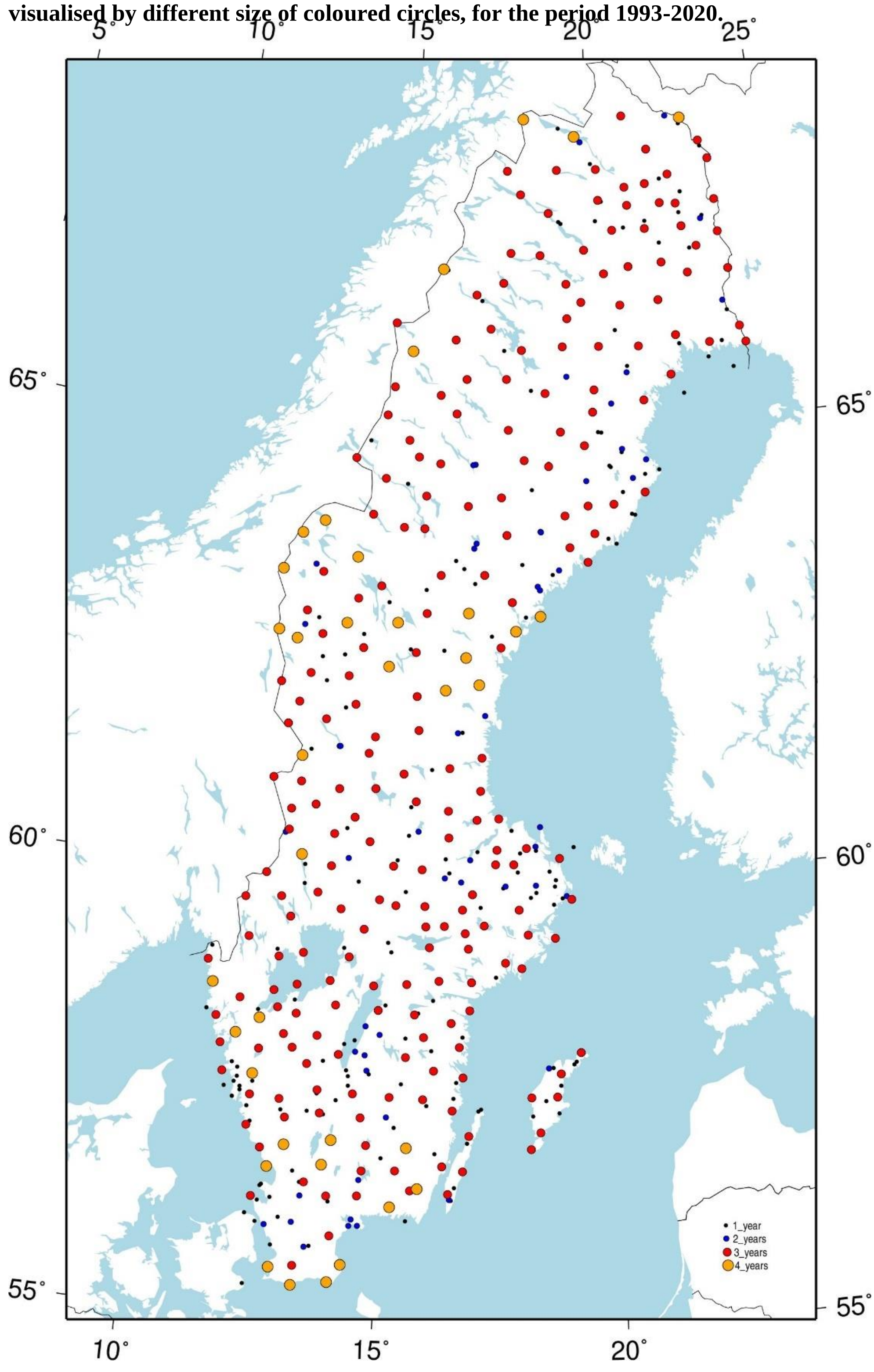
Figure 39: Significant velocities found in the Bernese original processing set 1993-2019. All the stations included in the trend analysis (with at least three observations) are shown in the map (small black dots). Horizontal velocities are shown in green and vertical red (upwards) or blue (downwards).



Appendix 2: Bernese original 1993 – 2020

Here we have applied the strategies outlined in the report on the original coordinates processed each year from 1993 to 2020. 2020 was the last year before the SWEREF 99 update 2021 was implemented (see section 9.2). The point distribution and number of occupations are shown in Figure 40.

Figure 40: Distribution of the SWEREF 99 class 1 points and number of measurements visualised by different size of coloured circles, for the period 1993-2020.

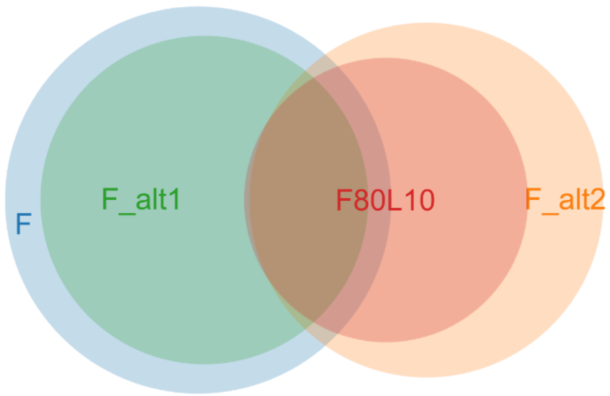


In total 260 points are measured at least three times (223 three times and 37 four times). One point (107218) was excluded from the trend analysis as the last measurement were affected by a fence, so the trend analysis was performed for 259 points.

The estimated general pooled standard uncertainty is 2.3, 2.6 and 6.3 mm for north, east and up, which corresponds well to the earlier results based on data up to 2018. The standard uncertainty is slightly larger in up which might be explained by the fact that we introduced another antenna model table – igs14.atx – for the year 2020.

We performed trend analysis according to the strategies outlined in the report. The outcomes from the three first F-tests (standard-F-test, F-test alternative 1 and F-test alternative 2 – see section 5.3.2) and the final F80L10-strategy (see section 5.3.3.1) are presented in Figure 41. It is interesting to note that the points selected by the modified standard F-test (F80L10) is a subset of the points selected by the F-test alternative 2. The relation between the first three F-tests is similar to the results based on data up to 2018.

Figure 41: Comparison between the F-tests based on data up to 2020.



To finally select points with significant trends, we used the F80L10-strategy (80% confidence level in the standard F-test in combination with the 10% largest RMS-values in the repeatability between years). 27 points were defined as having significant trends with this strategy. This corresponds to 10% of the analysed points.

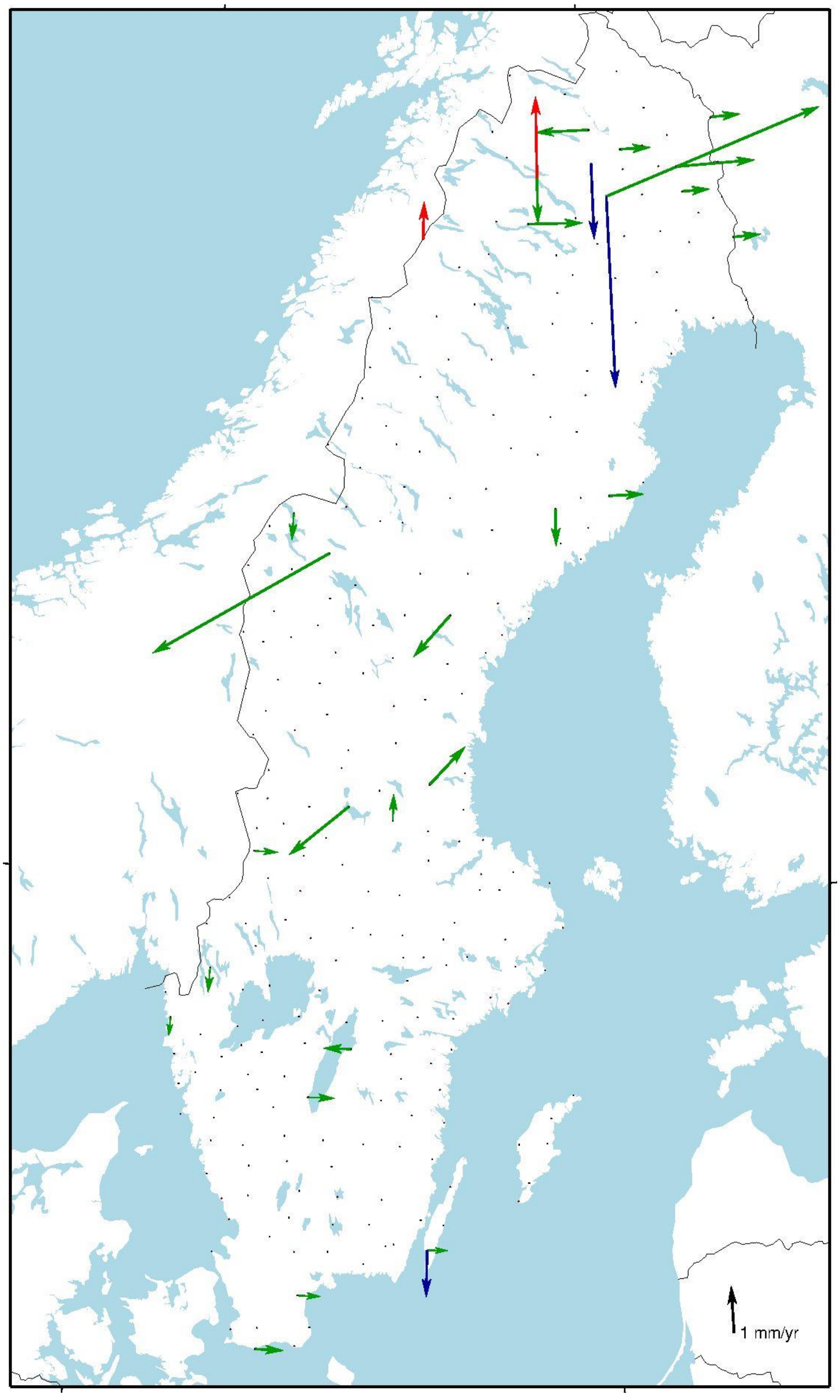
The significant trends are plotted in Figure 42. The non-significant velocities were set to zero, which explains why we have some horizontal velocities present only in one of the components.

We should remember that the main part of the velocities is based on only three observations and the presented trends should be understood as an indication of possible trends, and not as well determined trends.

Just as in the analysis based on data up to 2019, we see a systematic trend in the northeast of Sweden. (This area was not covered with three observations before 2019.)

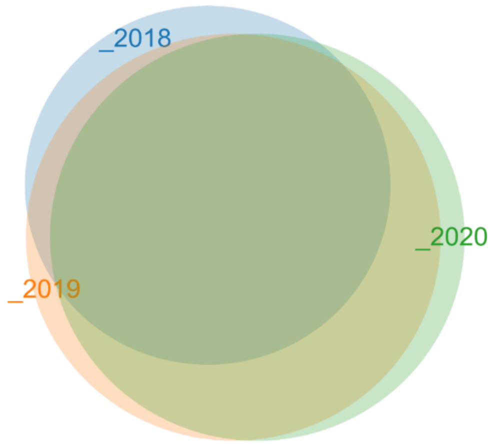
If this trend depends on local movements, deficiencies in the land up-lift model, uncertainties in the alignment to SWEREF 99 or a combination of those reasons is not clear when we write this report. However, we think it is due to uncertainties in the SWEREF 99-realisation and the land up-lift model rather than local movements. When determining point coordinates in this area we either have to extrapolate or rely on foreign stations.

Figure 42: Significant velocities found in the Bernese original processing set 1993-2020. All the stations included in the trend analysis (with at least three observations) are shown in the map (small black dots). Horizontal velocities are shown in green and vertical red (upwards) or blue(downwards).



Finally, we compared the set of selected significant trends between the data sets up to 2018, 2019 and 2020, respectively. The overlap between the significant trends is shown in Figure 43 and Table 14. Just as expected there are more trends in the data sets ending 2019 and 2020 than the one ending 2018 (as there are more points with at least three observations), but it is interesting to study the points that are only included in either 2018 or 2019.

Figure 43: Overlap between significant trends in the data sets from 1993 to 2018, 2019 and 2020, respectively.



There are two points that have significant trends only in the data set up to 2018. The point 122498 has got one more observation (four observations) in the data sets up to 2019 and 2020 and this latest observation is not in line with the other three that form a significant trend in the data set up to 2018, see Figure 44. The point 228418 has a standard deviation which is just below the 10% limit in the data set up to 2019 and 2020, but just above in the data set up to 2018. The situation is similar for the point 276108.

There are two points whose trends are classified (significant/not significant) differently between the data sets up to 2019 and 2020. For 188108 the situation is similar to 122498. The fourth observation added in 2020 is not in line with the earlier so significant trend in height, see Figure 45. For 712788 the trend in east gets significant when the observation for 2020 is added, see Figure 46.

It is not strange that the classification can differ when a fourth observation is added. In this data we have three such cases and we have in total 29 points that got a fourth observation between 2018 and 2020. This means that only 10% had changed classification, and the other 90% got their classification confirmed by the fourth observation.

In addition, there were two points (228418 and 276108) which were classified differently although the observations remained the same. It depends on the limit for the 10% largest standard deviations – those limits differ depending on the data set and these two points were close to the limits.

Table 14: Points with significant trends in the data sets from 1993 to 2018, 2019 and 2020, respectively.

	Significant trend			**Number of observations**		
Point	**_2018**	**_2019**	**_2020**	**_2018**	**_2019**	**_2020**
101368	yes	yes	yes	3	3	3
122498	yes	no	no	3	4	4
132058	no	yes	yes	2	3	3
135878	yes	yes	yes	3	3	3
144178	yes	yes	yes	3	3	3
146658	yes	yes	yes	3	3	3
186588	yes	yes	yes	3	3	4
188108	yes	yes	no	3	3	4
194918	yes	yes	yes	3	3	4
203728	yes	yes	yes	3	3	4
210448	yes	yes	yes	3	3	3
219028	yes	yes	yes	3	3	3
228418	yes	no	no	3	3	3
273308	no	yes	yes	2	3	3
276108	no	yes	yes	4	4	4
278548	yes	yes	yes	3	3	3
280218	yes	yes	yes	3	3	3
281398	no	yes	yes	2	3	3
281978	no	yes	yes	2	3	3
288558	yes	yes	yes	3	3	3
289988	yes	yes	yes	3	3	3
290348	no	yes	yes	2	3	3
299778	no	yes	yes	2	3	3
302148	no	yes	yes	2	3	3
712788	no	no	yes	3	3	4
723988	yes	yes	yes	3	3	3
746070	yes	yes	yes	3	3	3
773591	yes	yes	yes	3	3	3
784698	yes	yes	yes	3	3	3
790278	yes	yes	yes	4	4	4

Figure 44: The SWEREF 99 class 1 point 122498, which was found to have a significant trend in height in the data set up to 2018 (left) but not in the data sets including year 2019 (right).

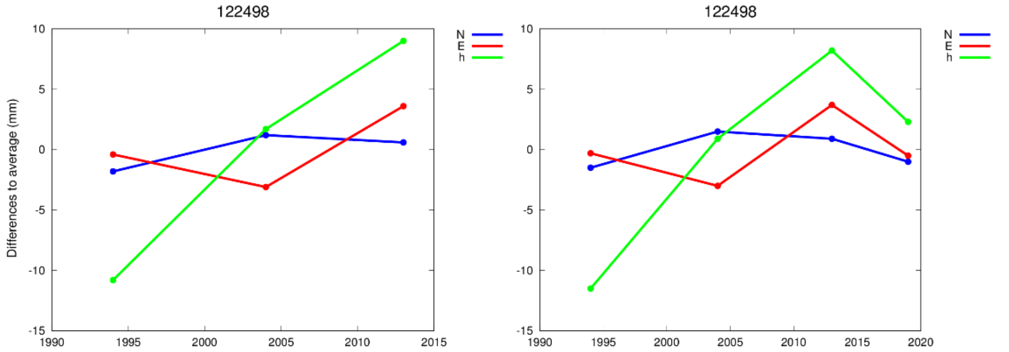


Figure 45: The SWEREF 99 class 1 point 188108, which was found to have a significant trend in height in the data set up to 2019 (left) but not in the data sets including year 2020 (right).

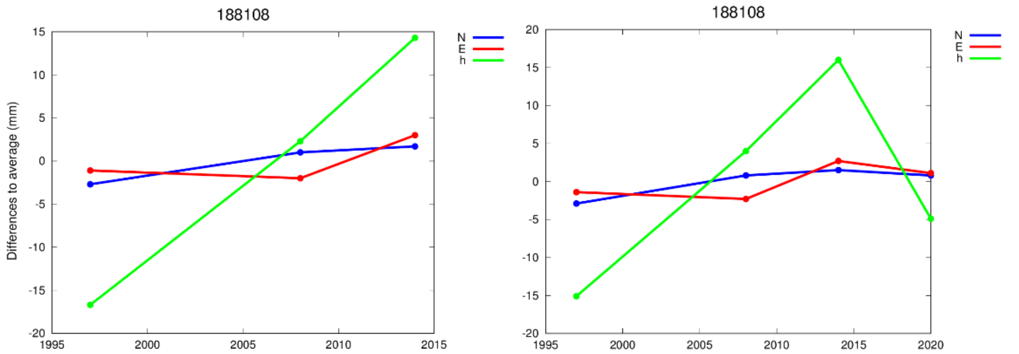
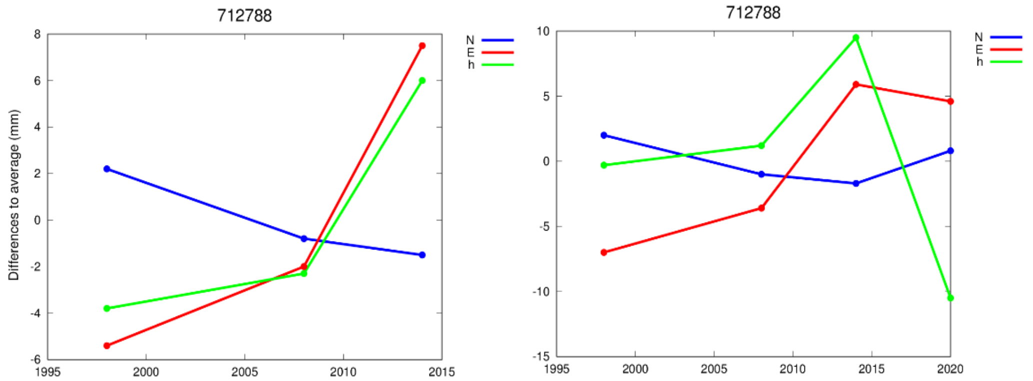


Figure 46: The SWEREF 99 class 1 point 712788, which was found to have a significant trend in east in the data set up to 2020 (right) but not in the data sets without 2020 (left).



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LANTMÄTERIET

801 82 Gävle Phone 0771 - 63 63 63 E-mail lantmateriet@lm.se
Internet: www.lantmateriet.se