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– using the Bernese and GAMIT-GLOBK Software Packages

Lotti Jivall[1] & Faramarz Nilfouroushan[1,2]

[1]Lantmäteriet, [2]University of Gävle

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[1]Lantmäteriet, [2]University of Gävle

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Abstract

For about 20 years, the fundamental pillar stations in SWEPOS® network (the Swedish Permanent GNSS network) have been used as the carrier of the Swedish national reference frame, SWEREF 99, and used as control points for several geodetic and geodynamic studies. Today, each pillar station has a close-by truss mast station, mostly in 10 meters distance. Switching from pillar-based network to mast-based network (with stations equipped with more modern receivers and calibrated antennas), as reference network, need careful analysis, for example, comparing solutions from these networks.

In this study, we use both the Bernese GNSS Software (BSW) and GAMIT-GLOBK software and process the same data set with almost the same processing strategy and compare the results. Our solutions and their comparisons show that BSW has slightly lower rate of resolved integer ambiguities for the mast-based network compared to the pillar-based network (3-4 percentage points for the selected 14 SWEREF points and 1-2 percentage points for all SWEREF points (50) processed in this study). For GAMIT-GLOBK, we don't see any significant difference in the rate of resolved integer ambiguities between the network types.

Furthermore, the comparison of resulting coordinates between the two software, show a very good compliance for the pillar-based network (on average at the 1 mm level for the horizontal components and 2 mm for the height component), but for the mast-based network there is 3-4 mm systematic difference in the height component.

The good compliance between the GAMIT-GLOBK and BSW solutions for the pillar network, makes it possible to use results also from GAMIT-GLOBK for coordinate determination of SWEREF points.

The systematic height difference between the two software solutions for the mast-based network, as well as slightly degraded quality measures mainly for BSW, indicate that there are some problems with the mast stations that need further investigation.

Sammanfattning

Pelarna på SWEPOS fundamentalstationer har använts som bärare av det nationella referenssystemet SWEREF 99 och för olika geodetiska och geodynamiska studier under ungefär 20 år. Idag har alla fundamentalstationer i SWEPOS® (det nationella nätet av fasta referensstationer för GNSS), två monument som oftast ligger inom 10 m, dels den ursprungliga pelaren, dels en nyare fackverksmast.

Att gå över från det pelarbaserade nätet till det nya mastbaserade nätet (med stationer som är utrustade med mer moderna mottagare och individkalibrerade antenner), som referensnät, kräver en noggrann analys, med t.ex. jämförelse av lösningar från de båda näten.

I den här studien använder vi både Bernese GNSS Software (BSW) och GAMIT-GLOBK för beräkning av samma data-set med i stort sett samma beräkningsstrategi och gör jämförelser mellan olika lösningar. Våra jämförelser visar att BSW har något lägre andel lösta periodobekanta för det mastbaserade nätet jämfört med det pelarbaserade nätet (3–4 procentenheter för de utvalda 14 stationerna och 1–2 procentenheter för alla SWEREF-punkter inkluderade i studien (50 stycken). Med GAMIT-GLOBK kan vi inte konstatera någon signifikant skillnad vad gäller lösningen av periodobekanta mellan nättyperna.

Vidare visar jämförelsen av slutliga koordinater en mycket bra överensstämmelse mellan de olika programvarorna för de pelarbaserade näten (i medeltal 1 mm för de horisontella komponenterna och 2 mm i höjd), men för de mastbaserade näten finns det en systematisk skillnad på 3–4 mm i höjd.

Den goda överensstämmelsen för de pelarbaserade näten möjliggör användning av GAMIT-GLOBK för SWEREF-punktbestämning.

Den systematiska höjdskillnaden mellan programvarorna för det mastbaserade nätet, såväl som något degraderade kvalitetstal för framförallt BSW, indikerar att det fortfarande finns problem med mast-stationerna som kräver ytterligare undersökningar.

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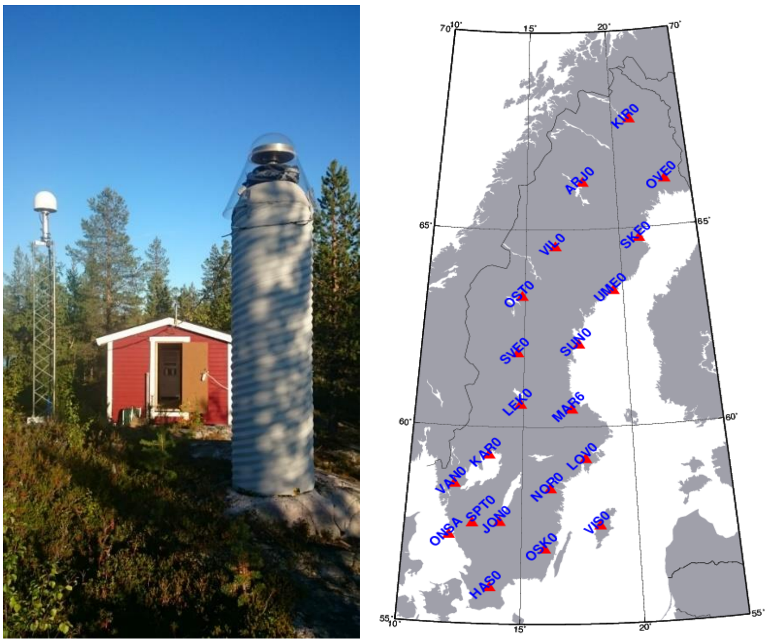
Mast-based versus Pillar-based Networks for Coordinate Estimation of SWEREF Points

1 Background

For about two decades, the 21 fundamental pillar stations of SWEPOS® (the Swedish Permanent GNSS network) have been used as the carrier of the Swedish national reference frame, SWEREF 99. So far these pillars, equipped with standard Dorne Margolin choke ring antennas, have been used as reference points for different geodetic and geodynamic studies (e.g. Johansson et al., 2002; Lidberg et al., 2007). To keep continuous measurements of these long-lived pillar stations and at the same time modernise the SWEPOS network, new truss mast stations have been installed at the same sites, equipped with modern and individually calibrated antennas and radomes, capable of tracking all new GNSS satellites (*Figure 1*).

Figure 1: *Left: Example of the pillar (ARJ0) and nearby truss mast (ARJ6) stations. Right: Distribution of SWEPOS fundamental pillar stations.*



All 21 mast stations at the fundamental sites, except one, were installed in 2011 (ONS1 was installed in January 2012). The close-by truss mast stations are mostly within 10 meters distance from the pillars and at approximately the same height. They are equipped with individual calibrated Leica 3D choke ring antennas with belonging radome (LEIAR25.R3, LEIT). The plan was to let the masts take over the role as carrier of SWEREF 99, i.e. to be used as reference stations for high precision determination of SWEREF 99 coordinates.

The highest class of SWEREF 99 points, after the SWEPOS stations are the so called SWEREF points, which are determined with 2*24 hours GNSS observation using modern receivers and standard Dorne Margolin Choke Ring antennas. Lately, the main part of the SWEREF points, are also so-called consolidation points (försäkringspunkter in Swedish). A special version of SWEPOS Processing Service [Jivall et al., 2016] is used for the processing. SWEPOS Processing Service process each station separately and calculates SWEREF 99 coordinates by connection to the five closest SWEPOS stations. In the special version for SWEREF-point calculation, more SWEPOS stations and stations abroad defining SWEREF 99, could be used for the constraint.

A first test with SWEPOS Processing service using the SWEPOS mast-stations instead of pillars as referenced stations, revealed a degraded performance of the mast-stations in terms of resolved ambiguities [Lilje, 2013]. This was most significant for short observations times and for stations with bad quality data, but it was also seen for SWEREF points. SWEPOS Processing service was at that time based on version 5.0 of the Bernese GNSS Software [Dach et al., 2015].

To investigate this further, a study was made using GAMIT-GLOBK [Herring et al., 2015] solutions for different networks, e.g. pillar-based, mast-based and combined mast- and pillar-based network of the fundamental stations of SWEPOS [Nilfouroushan et al., 2016]. Ambiguity resolution and daily repeatability were studied. The comparison between pillar and mast stations showed similar time series for different horizontal and vertical components and their normalised rms (nrms) and weighted rms (wmrs) were almost equal. The wide-lane (WL) ambiguity resolutions for the mast-based and pillar-based networks were high and mostly between 90-95%. The combined network resolved more ambiguities and rose up to 95-99%.

As the study by Nilfouroushan et. al. (2016), using GAMIT-GLOBK software did not confirm the problems we had experienced earlier with SWEPOS processing service, it was decided to make a new study of the special case of determining coordinates of SWEREF points to figure out if it still was a problem with masts as reference stations. For this new study, all GPS observations of SWEREF points collected in 2*24 hours sessions in 2012 were processed and analysed using SWEPOS Processing Service, based on the Bernese GNSS software (BSW) version 5.2. Later, for simplicity, a smaller set of 14 points (28 sessions) was used for comparison and processed with GAMIT-GLOBK. For both software, similarly, networks of 6-8 SWEPOS mast or pillar stations as reference points and one SWEREF point was processed. The final coordinates in SWEREF 99 and different quality measures from each network/day/software were compared.

2 Test with BSW

Until now all SWEREF points have been determined using BSW (the Bernese GNSS Software). Since 2008 SWEPOS Post Processing Service [Jivall et al., 2016] is used for the processing of each session.

In this study, firstly, all SWEREF points measured in 2012 were analysed, i.e. 100 (2x50) solutions. The idea was to use the same dataset where we had seen problems before [Lilje, 2013]. The SWEREF-version of SWEPOS processing service defines baselines between the SWEREF point and the six closest fundamental SWEPOS stations. In addition, other SWEPOS class A stations closer than the third closest fundamental station, are also included. No stations abroad in neighbor countries were added manually. The processing strategy is characterised by the following options: 10° elevation cut-off, ZDT-parameters estimated every hour using GMF-mapping function, CODE-products and type antenna models from IGS for all stations except the fundamental mast-stations, where individual calibrated PCV from Geo++ are used (i.e. the same antenna models as in EPN (epn08_atx).

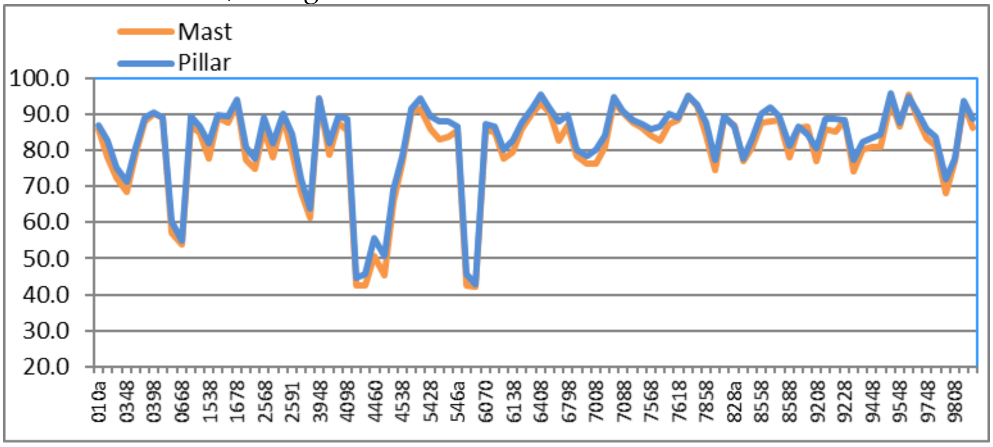
The final alignment to SWEREF 99 is made through either a 6- or 7-parameter Helmert fit after reduction for the land-uplift effect using the NKG_RF03vel-model [Nørbech et al., 2008]. In this fit just the fundamental stations are used.

The original version of SWEPOS post processing service for SWEREF points uses the pillars as reference stations. Therefore, an alternative version was set up using the masts instead. The 100 daily observation files were run both with the original version using the pillars as reference and the test version with the masts. Resolved ambiguities, differences between the two sessions at each station and other quality measures were analysed. It turned out that in some cases, the selection of SWEPOS-sites was slightly different between the pillar-based and mast-based computations, because the data for the mast station at Borås (BORA.7) was missing.

When comparing all 100 daily solutions, in general 2.2 percentage points less ambiguities were resolved in the mast-based networks compared to the pillars-based ones (

Figure 2). If just considering the solutions with the same SWEPOS stations (62) then 2 percentage points less ambiguities are resolved for the masts. If just considering solutions without additional stations and without Borås (12), the value is 1.5 percentage points.

Figure 2: *Ambiguity resolution in % for the 100 stations/sessions (shown in horizontal axis) using BSW.*



A comparison of the coordinate differences between the two daily sessions at each station, revealed a slightly better performance for the pillar-solutions in which the rms of differences were 2.8 mm for the pillars and 4.1 mm for the masts. Neglecting one outlier (16 mm for the masts and 9 mm for the pillars) gives 2.5 mm for the pillars and 3.4 mm for the masts. Final computed coordinates differ in general approximately 0.5 mm for the horizontal components and 3 mm in height component (expressed as rms) between using pillar-based and mast-based networks.

The rms of the height component in the Helmert fit is usually slightly lower for the pillars compared to the masts (0.5-0.7 mm lower). The comparison of different solutions using different processing parameters in BSW (10° fix, 10° float, 10° no-trop, 25°) are sometimes too large to show any numbers in the comparison made by COMPAR (a module in BSW to compare the coordinate differences between several datasets/solutions) for the mast-solutions, but this is not a problem for the pillar solutions.

Altogether, the mast-based solutions show slightly degraded results compared to the pillar-based solutions, but the differences are small.

3 Test with GAMIT-GLOBK

The processing of SWEREF points in GAMIT-GLOBK is not as straight forward as in SWEPOS processing service, because the routine way of GAMIT processing is using 24 hours data starting from 0 till 24 (GMT), but our observations had different starting time each day and the observation sessions were crossing the midnight. As such, before processing, broadcast and precise satellite orbits of the two consecutive days had to be combined and processing sessions based on different observation sessions for different SWEREF points had to be defined individually. Therefore, to simplify the comparison, a small number of stations/sessions (14 stations in 28 days, each station 2*24 hours) were selected for the analysis. The selection was based on solutions without Borås – see above – and with the largest differences in resolved ambiguities. The differences in ambiguity resolution were between 3.3 and 4.6 percentage points (lower for masts than pillars) in the BSW processing.

To compare the mast-based and pillar-based network solutions in both GAMIT-GLOBK and BSW, the same set of SWEPOS reference stations were used in both software. In GAMIT daily processing, the standard (type) IGS receiver antenna phase centre models were used for both mast-based and pillar-based networks. However, to make the GAMIT solutions similar to BSW, the available individual calibrated phase centre antenna models from GEO++ were also used for the mast stations. The solutions from BSW and GAMIT with individually calibrated antenna models for the mast stations are presented here and the solutions of GAMIT with standard IGS antenna models are considered for future analysis.

For daily processing with GAMIT, after modification of the orbits and defining processing sessions based on the observation sessions, the routine way of GAMIT processing was used, i.e. using 13 tropospheric parameters per day (every 2 hours), azimuth/elevation (AZEL) dependent antenna models and 10° cut-off angle (similar to BSW). As recommended for local and regional scale network processing, baseline mode (in which no orbit is estimated) was used. The average wide lane (WL) and narrow lane (NL) ambiguity resolutions of the loosely GAMIT-GLOBK solutions for each session, for both mast-based and pillar-based networks, were extracted and plotted (*Figure 3* and *Figure 4*).

The loosely GAMIT solutions for each mast and pillar network (h-files) were introduced into the GLOBK software and using generalised constraints in which the residuals of reference sites are minimised and using only 3 translations. The final coordinates for each 24-hours session and for each mast-based or pillar-based network were estimated in ITRF2008 reference frame [Altamimi et al., 2012].

Figure 3: *Wide lane (WL) ambiguity resolutions (in %) for each 24 hours session (including only 1 unknown point (shown in horizontal axis) and 5-8 reference mast or pillar stations).*

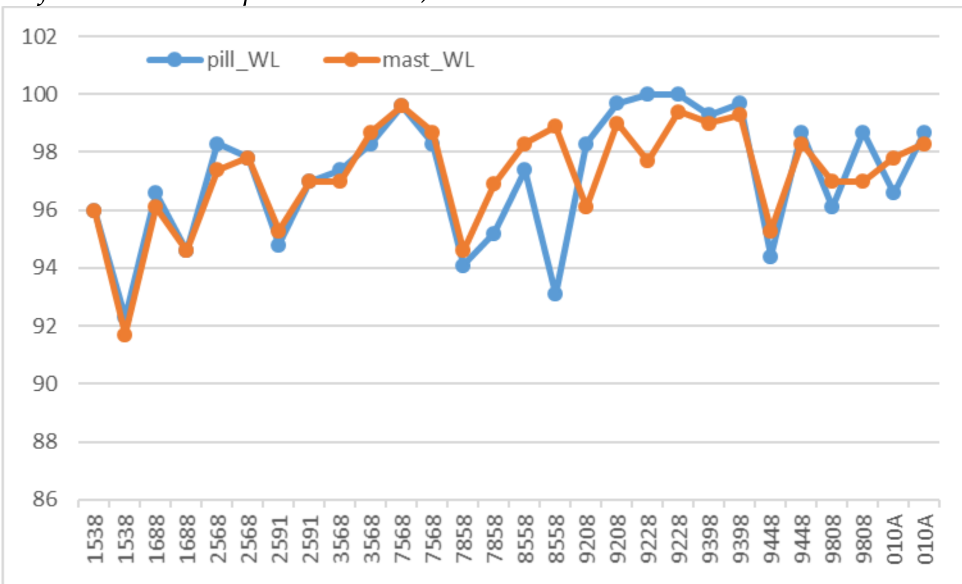
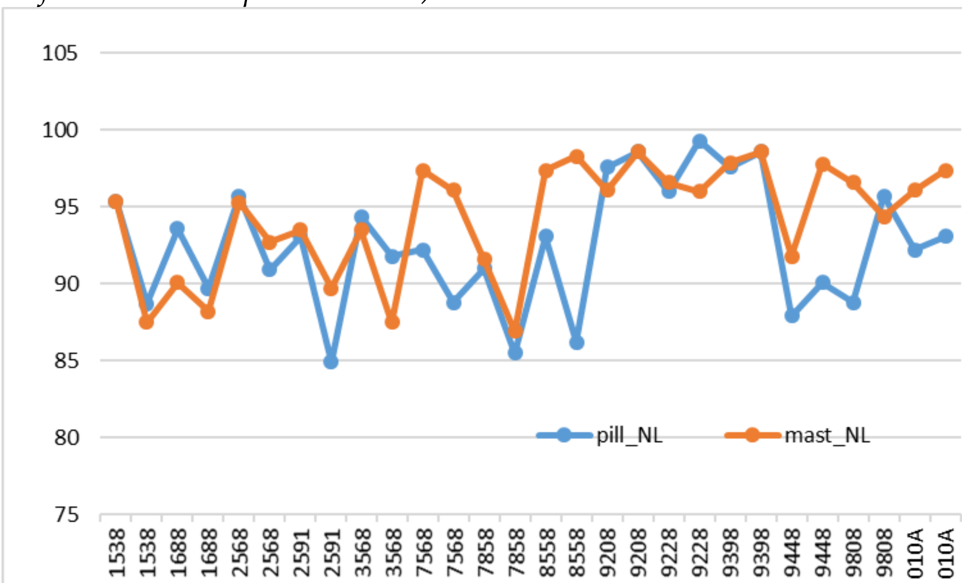


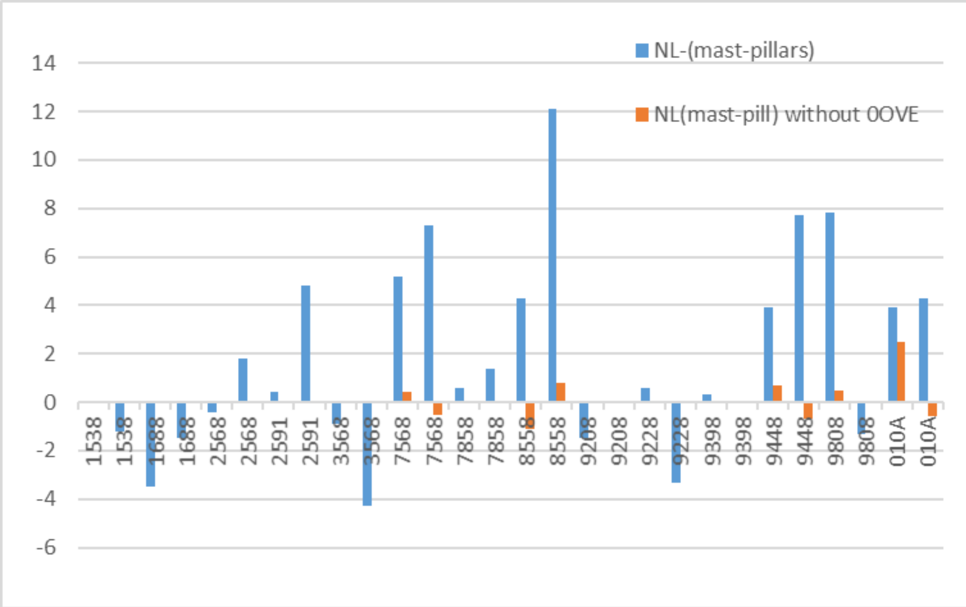
Figure 4: *Narrow lane (NL) ambiguity resolutions (in %) for each 24 hours session (including only 1 unknown point (shown in horizontal axis) and 5-8 reference mast or pillar stations).*



The Överkalix station (0OVE) was not behaving well in some days for the pillar-based network and we noticed that the ambiguity resolutions could be significantly improved by deleting that station from the solutions (*Figure 5*).

After removing the problematic station (0OVE) from the pillar-based network, the performance of the NL ambiguity resolution is almost equal for both network types (pillar-based and mast-based).

__Figure 5:__ The difference between mast-based and pillar-based network solutions; narrow lane (NL) ambiguity resolutions (in %) are compared here with and without Överkalix (0OVE) station. It shows clearly that the two solutions were almost identical in terms of NL % when the problematic station (0OVE) was not included in the solutions.



4 Comparison of Coordinates between BSW and GAMIT-GLOBK Solutions

In order to compare the final coordinates in SWEREF 99, the ITRF2008 coordinates generated by GAMIT-GLOBK were aligned to SWEREF 99 using the same strategy as in the SWEPOS Processing Service, i.e. first reduction for the land uplift to epoch 1999.5 with the velocity model NKG_RF03VEL [see Nørbech et al., 2008 for details] and then Helmert fits to the fundamental SWEPOS stations in SWEREF 99. BSW version 5.2 was used for this alignment. Both 6-parameter (3 translations and 3 rotations) and 7-parameter (3 translations, 3 rotations and scale) Helmert transformation were carried out. In the normal routines for SWEREF point processing both 6- and 7-parameter Helmert transformations are produced and finally there is a user decision for each SWEREF point which one to use. Here we have analysed the results from both.

4.1 Quality of the Helmert fits

First the quality of the Helmert fits to SWEREF 99 were analysed using the different options: pillars or masts, 6 or 7 parameters, BSW or GAMIT-GLOBK. The RMS of the residuals in the Helmert fits are summarised in *Table 1*. The analysis is based on the same 28 files both for GAMIT-GLOBK and BSW.

Table 1: *The RMS of residuals in Helmert fits from ITRF2008 to SWEREF 99. Unit: mm.*

Helmert fit to SWEREF 99							
		BSW			GAMIT-GLOBK		
Network type	**# par**	**rms N**	**rms E**	**rms U**	**rms N**	**rms E**	**rms U**
Pillar-based	6	5.7	1.7	2.6	5.3	2.5	3.6
Pillar-based	7	2.8	1.9	2.6	2.3	2.1	3.6
Mast-based	6	5.8	1.6	3.2	5.5	1.5	3.1
Mast-based	7	3.2	1.9	3.2	3.1	1.9	3.1

The 7-parameter fits give lower rms than the 6-parameter fits, i.e. the fittings are better, especially in the north component. This is expected as the scale also takes up deficiencies in the land uplift model and is most obvious for stations in the north. Comparing the solutions with masts or pillars the results are on the same level and equal good. BSW seems to perform slightly better with the pillar-based network and GAMIT-GLOBK with the mast-based network. Also, in the comparison between the two software, there is no significant difference. For pillar-based network BSW might be a bit better having slightly lower rms, but the difference is small.

4.2 Coordinate Differences between Sessions

Each SWEREF point is determined in two 24-hours sessions. In *Table 2* the rms of the differences of the 14 SWEREF points are summarised. Maximum differences (absolute values) are available in *Table 3*.

Table 2*: The RMS of differences between the two 24-hours sessions for the 14 points. Unit: mm.*

Rms of differences between sessions							
		BSW			GAMIT-GLOBK		
Network type	**# par**	**rms N**	**rms E**	**rms U**	**rms N**	**rms E**	**rms U**
Pillar-based	6	1.2	1.2	3.3	1.0	1.3	2.8
Pillar-based	7	1.2	1.2	3.3	1.1	1.3	2.8
Mast-based	6	1.2	1.1	5.6	1.3	1.4	4.1
Mast-based	7	1.3	1.2	5.6	1.4	1.4	4.1

Table 3: *Maximum differences between the two 24-hours sessions for the 14 points. Unit: mm.*

Maximum differences between sessions							
		BSW			GAMIT-GLOBK		
Network type	**# par**	**rms N**	**rms E**	**rms U**	**rms N**	**rms E**	**rms U**
Pillar-based	6	2.5	2.9	9.1	2.5	3.2	4.8
Pillar-based	7	2.5	2.9	9.1	2.5	3.5	4.8
Mast-based	6	2.4	2.5	15.9	3.1	3.1	10.0
Mast-based	7	2.4	2.5	15.9	3.2	3.6	10.0

The pillars yield smaller differences between sessions, both in general (expressed as rms) and as maximum values. In the same way GAMIT-GLOBK performs slightly better than BSW. The results from 6 and 7 parameters are in this case the same.

4.3 Final Coordinate Comparison

Finally, the calculated SWEREF 99 coordinates for each SWEREF point and session were compared between the two software. Summaries of the coordinate differences are presented in *Table 4* (rms of differences) and *Table* 5 (maximum differences).

Table 4: Coordinate differences in SWEREF 99 between GAMIT-GLOBK and BSW, expressed as rms. Unit: mm.

Rms of differences, GAMIT- BSW				
Network	**# par**	**rms N**	**rms E**	**rms U**
Pillar-based	6	0.6	0.7	2.1
Pillar-based	7	0.8	1.0	2.1
Mast-based	6	0.8	1.2	4.3
Mast-based	7	0.8	1.2	4.3

***Table 5**: Maximum coordinate differences in SWEREF 99 between GAMIT-GLOBK and BSW. Unit: mm.*

Maximum differences, GAMIT- BSW				
Network	**# par**	**rms N**	**rms E**	**rms U**
Pillar-based	6	1.5	1.5	4.7
Pillar-based	7	1.7	2.3	4.6
Mast-based	6	1.9	3.1	8.0
Mast-based	7	2.0	3.1	8.0

The average differences expressed as rms in computed SWEREF 99 coordinates between GAMIT-GLOBK and BSW are for both network types approximately 1 mm in horizontal (*Table 4*). But in height component the differences are lower for the pillar-based network (rms 2 mm) compared to the mast-based network (rms 4 mm). *Table 5* shows that the max differences in height component between BSW and GAMIT-GLOBK are as high as 4.7 mm for the pillar-based network and 8 mm for the mast-based network. This means BSW and GAMIT-GLOBK solutions are mainly different in height component and for mast-based network. There is a systematic height difference for SWEREF points determined from the mast-based network. SWEREF points determined using GAMIT-GLOBK are approximately 3.5 mm lower than BSW solutions, when the mast network is used, see *Table 6*, where the full list of the differences between the resulting SWEREF 99 coordinates (based on 7-parameter Helmert fits) from the two software is presented. The differences between the 6- and 7-parameter results are negligible.

Additional comparisons were also made between the ITRF2008-coordinates for each station/session from the two software. The comparison was made by Helmert fittings with 3- and 7-parameters. The 3-parameter fits would be most relevant as just constraints on translations have been made both for GAMIT-GLOBK and BSW. The average residuals in the 3-parameter fits were 0.7, 0.6, 1.9 mm for the pillar-based network and 0.8, 0.7, 2.7 mm for the mast-based network, i.e. slightly better agreement for the pillar-based network.

Table 6: *Coordinate differences between GAMIT-GLOBK and BSW for each processed file (station/session). Unit: mm.*

Input file	Pillar network 7-par			Mast network 7-par		
	N	E	U	N	E	U
010a1810.12o	1.1	2.0	-2.9	0.9	-0.8	-4.3
010a1820.12o	1.1	2.3	-3.8	0.1	0.0	-4.0
15382700.12o	0.2	1.1	0.2	0.9	1.5	-1.5
15382710.12o	0.3	-0.1	-1.2	0.5	1.0	-3.0
16882160.12o	1.2	-0.6	0.6	1.0	-0.2	-1.6
16882170.12o	-0.2	-0.5	-1.0	0.2	0.1	-5.1
25682140.12o	1.4	1.7	1.0	1.9	1.1	-4.9
25682150.12o	-0.6	0.6	-3.5	-0.1	-1.0	-6.0
25912140.12o	0.3	0.2	-0.7	0.8	-0.4	-5.9
25912150.12o	0.5	-0.4	-0.7	1.0	-1.5	-3.4
35682140.12o	-0.4	-0.3	-1.4	0.1	-1.0	-5.9
35682150.12o	-1.3	-0.6	3.7	-2.0	-0.2	0.0
75681830.12o	0.1	1.4	-4.6	-0.4	0.7	-7.1
75681840.12o	0.3	0.7	-1.0	-0.2	0.6	-5.6
78582190.12o	-0.2	0.1	1.1	-0.2	-1.3	-2.1
78582200.12o	0.5	-0.2	-1.7	1.2	-3.1	-8.0
85581780.12o	0.9	1.0	1.8	0.1	0.9	0.8
85581790.12o	1.3	0.9	3.8	-0.5	0.9	2.3
92082180.12o	0.7	0.5	1.8	0.1	1.2	-1.1
92082190.12o	0.4	0.3	-0.7	-0.2	1.6	-2.9
92281040.12o	-0.3	0.1	1.8	-0.4	0.3	-6.8
92281050.12o	-0.5	-0.3	2.0	0.0	0.2	-3.4
93982180.12o	0.3	0.5	1.4	0.6	0.7	-2.4
93982190.12o	0.3	0.2	1.3	0.3	1.2	-1.6
94481810.12o	1.7	0.5	-0.7	0.6	-3.0	-1.0
94481820.12o	1.4	1.0	-0.6	1.0	-1.8	-2.5
98081820.12o	0.1	1.9	-2.3	0.4	0.1	-5.6
98081830.12o	0.5	0.7	0.9	1.2	-0.8	-4.6
rms	**0.8**	**1.0**	**2.1**	**0.8**	**1.2**	**4.3**
absmax	**1.7**	**2.3**	**4.6**	**2.0**	**3.1**	**8.0**
average	**0.4**	**0.5**	**-0.2**	**0.3**	**-0.1**	**-3.5**
stdav	**0.7**	**0.8**	**2.1**	**0.7**	**1.2**	**2.5**

5 Discussion and Conclusions

Our GAMIT-GLOBK and BSW solutions and their comparisons show that the pillar-based network results agree better between the two software (on average at the 1 mm level in horizontal components and 2 mm in height) while the coordinates resulting from mast-based network differ at about 4 mm level in height. The GAMIT-GLOBK solutions give approximately 3.5 mm lower heights than BSW when using the mast-based network. The reason for this has not been identified. No such systematic is seen for the pillar-based network or in the horizontal components.

BSW has slightly lower rate of resolved ambiguities for the mast-based network compared to the pillar-based network (3-4 percentage points for the selected 14 SWEREF points and 1-2 percentage points for all SWEREF points (50) processed in this study). For GAMIT-GLOBK the rate of resolved ambiguities is almost equal for both network types.

BSW has been used for the originally definition of SWEREF 99 and for all coordinate calculation of SWEREF points until now. Using the same software with mainly the same options during the years, has ensured a consistent reference frame.

The good compliance between GAMIT-GLOBK and BSW solutions for the pillar-based network makes it possible to use results also from GAMIT-GLOBK for coordinate determination of SWEREF-points, for example for defining SWEREF 99 heights on GPS-levelling points for the establishment of the new geoid model SWEN17_RH2000 [Jivall, 2017].

As stated before, the mast-based networks have larger differences in height component between the different software solutions. The difference between sessions are also slightly larger for the mast-based network compared to the pillar-based network for both software. The main difference between the mast-based and pillar-based network solutions are antenna types and antenna models; Standard Dorne Margolin choke ring antennas (AOAD/M_T or copies) and type (standard) IGS antenna models are used for the pillar-based network, but Leica 3D choke ring antennas with belonging radomes (LEIAR25.R3, LEIT) with individual calibrated antenna models for the mast network.

We do not feel confident to start using the mast stations as defining reference stations in SWEREF 99. The possible problems with the mast stations need further investigation.

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LANTMÄTERIET

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