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– GEODETIC REPORT

Activity Report: Contributions from Lantmäteriet to the InSAR-Sweden Project

Faramarz Nilfouroushan[1,2], Nureldin Gido[1], Per-Anders Olsson[1], Chrishan Puwakpitiya Gedara[1]

[1] Department of Geodetic Infrastructure, Lantmäteriet, Gävle, Sweden
[2] Department of Computer and Geospatial Sciences, University of Gävle, Sweden

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Authors: Faramarz Nilfouroushan, Nureldin Gido, Per-Anders Olsson, Chrishan Puwakpitiya Gedara

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Summary

The two-year Swedish Ground Motion Service (InSAR-Sweden) project was started in 2021 and made a collaboration between the Geological Survey of Norway (NGU) and several Swedish organizations, including Lantmäteriet. During the project, the InSAR-based ground motion service has been developed by NGU using Sentinel-1 data (2015–2021) and the Persistent Scatterer Interferometry (PSI) technique and is freely available for interested users. There were different working groups in the project and Lantmäteriet has contributed mostly to working group WP#3 which is the "validation of deformation data".

We used the PSI results of previous studies for Uppsala and Gävle cities to validate the newly launched InSAR-Sweden ground motion service. We compared the deformation localization and Line of Sight (LOS) displacement time series at some deforming locations. Although the number and acquisition dates of Sentinel-1 data and the parameters used for PSI processing differ between Uppsala, Gävle and InSAR-Sweden, the cross-checked results demonstrate good agreement between corresponding studies regarding the localization and rate of subsidence in those two cities over a period of five years.

During the project, Lantmäteriet installed several types of radar corner reflectors (CR) in different locations in Sweden. These corner reflectors are passive devices which provide precise measurement points and can be installed at desired locations. These devices can be used to measure temporal LOS changes and consequently the ground movements precisely using the InSAR technique. The plan is to continue and complement the national geodetic infrastructure with at least 20 passive reflectors which are collocated with permanent GNSS stations and/or tide gauges. Among others, these co-located permanent GNSS stations and corner reflectors can potentially contribute to the development and validation of the national (InSAR-Sweden) and European ground motion (EGMS) services. Moreover, the co-location helps to transform the relative ground motions estimated with InSAR to an absolute geodetic reference frame.

In this activity report, we provide a brief introduction to SAR corner reflectors and their applications, and we explain our progress in installing such reflectors in Sweden. We also present our preliminary results from our data analysis. Moreover, we explain our cross-checking of the results obtained from InSAR-Sweden with the InSAR-based studies conducted for Uppsala and Gävle cities.

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1. Introduction

The interest in using Interferometric Synthetic Aperture Radar (InSAR) for ground motion monitoring is rapidly increasing, thanks to the Copernicus Sentinel-1 satellites which cover relatively large areas with a 12-days revisit time. The ground motion of many locations, especially urban areas around the world have been studied using Sentinel-1 data and the rate and localization or distribution of ground deformation have been reported. For Sweden, for example, Fryksten and Nilfouroushan (2019) and Gido et al. (2020) studied the active ground subsidence in Uppsala and Gävle cities using the Sentinel-1 data collected between 2015–2020. Today, fortunately, we have the nationwide ground motion service of Sweden (https://insar.rymdstyrelsen.se) covering almost the entire country, providing free and accessible ground motion data useful for many applications including land subsidence, landslides, and infrastructure health monitoring.

Since 2019, Lantmäteriet, the Swedish mapping, cadastral and land registration authority, has been actively involved and contributed to the initiation and implementation of the InSAR-based ground motion service of Sweden (hereafter called InSAR-Sweden) and has mostly contributed to the work package WP#3, i.e., "Validation of deformation data" for the InSAR-Sweden project ("Utvärdering och nyttoanalys av rikstäckande InSAR-tjänst" in Swedish) which was granted in 2020. In addition, before and during the project Lantmäteriet has been developing new geodetic infrastructure in Sweden using InSAR reflectors/transponders which have different applications including calibration of the InSAR-based products in future.

This report, which reflects Lantmäteriets' activity and contributions to the InSAR-Sweden project, consists of five sections: the first one shortly introduces corner reflectors, different types and designs and applications and continues with our activity for designs and installations of such reflectors in Sweden. Such corner reflectors have different applications for example for deformation monitoring and geodetic infrastructure maintenance in Sweden. The second section is about the validation and cross-checking of the InSAR-Sweden PSI-based (Permanent Scatterers Interferometry) results with the ones previously published for two cities in Sweden i.e., Uppsala city (Fryksten and Nilfouroushan, 2019) and Gävle city (Gido et al., 2020). In the third section, discussion and conclusions are presented and then, in the fourth section, we list the Lantmäteriet activity for the project-related presentations at national and international conferences/meetings/workshops independently or together with co-workers of the project. In the end, plans and thoughts for the future are presented.

Lantmäteriet has also participated in an activity related to atmospheric corrections study for the project, a collaboration with researchers at the Chalmers University of Technology. That contribution isn't reported here but is included in the Chalmers University of Technology's technical report.

2. Development of geodetic infrastructure in Sweden using SAR corner reflectors

In this section, firstly the SAR corner reflectors and their applications are introduced and then continued with the corner reflector types and the ones which have been designed and tested for installations by Lantmäteriet. The progress in the installation of corner reflectors in Sweden is reported and the preliminary data analysis for a couple of reflectors is presented.

2.1. Coherent radar targets and artificial corner reflectors

Persistent Scatterers (PS) are coherent radar targets that can be distinguished in all SAR images and have a relatively steady phase history. For example, roads, bridges, bare rocks, buildings, and towers are examples of scatterers (reflectors) that are visible and can be tracked in SAR images and monitored over time. The PS points do not exist everywhere, and the number and density of PS points are lower in vegetated, forested, and low-reflectivity areas (Crosetto et al. 2016). The lifetime of a PS point sometimes is limited, for example, due to the re-pavement of a street or destroying a building in which consequently the object (PS) acts as a reflector for a limited period. This means PS points are born and sometimes die and there is no guarantee to be available all the time for InSAR applications. On the other hand, artificial reflectors (SAR corner reflectors or transponders) can be considered and installed in desired locations. If well maintained, they can survive for a long period at least for several years. There are different goals or applications for the installation of artificial SAR reflectors:

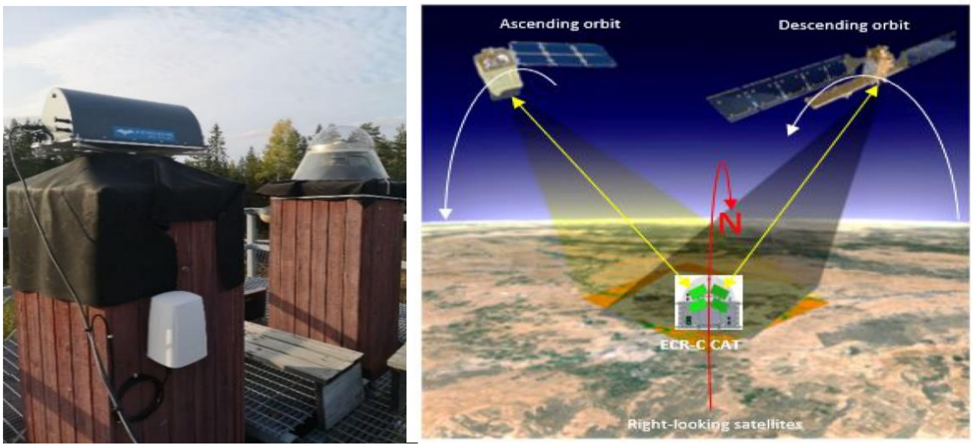
- To make a measurement point at the desired location to monitor the movements with the InSAR technique accurately.
- Improve spatial sampling in areas where there are no natural persistent scatterers (e.g., grass fields).
- Link and comparison between InSAR and other techniques (e.g., co-location of the reflector with GNSS stations, tide gauges and/or absolute gravity points).
- Assign a geodetic reference frame to InSAR results with the relative motion to make them absolute in a well-defined reference frame.
- Accurate georeferencing of the PS measurement points by knowing the corner reflector's location with a few cm of accuracy.

- Link between different tracks (of ascending or descending) of the same InSAR system (e.g., Sentinel-1 or TerraSAR-X) and/or, the connection between different InSAR satellite systems (e.g., Sentinel-1 and TerraSAR-X).
- Calibration of satellite imagery systems (e.g., Sentinel-1, NISAR) which is carried out by system developers (e.g., see Figure 1).

Figure 1, Two of the trihedral triangular corner reflectors installed in Texas for NISAR calibration (Information about Oklahoma and Texas NISAR Calibration Array can be found in the following link: https://uavsar.jpl.nasa.gov/cgi-bin/calibration-nisar.pl).

Artificial corner reflectors have been mostly in a passive form which functions as just signal reflectors without any electricity (see Figure 1) whereas recently the active ones (transponders, see Figure 2) have been developed and used in many experiments.

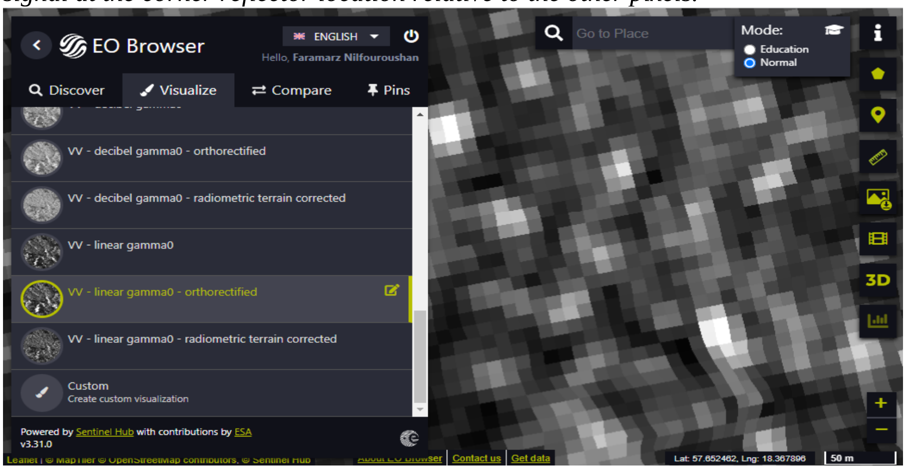
Figure 2, Left, transponder (also called Electronic Corner Reflector (ECR) or Compact Active Transponder, CAT) installed beside the permanent GNSS station MAR6 at Mårtsbo. The white box is the Wi-Fi router for remote access to the transponder for checking the files and possible updates of the satellite configurations. The right image shows the transponder which works for both ascending and descending orbits (the right figure is from @Metasensing ECR manual).

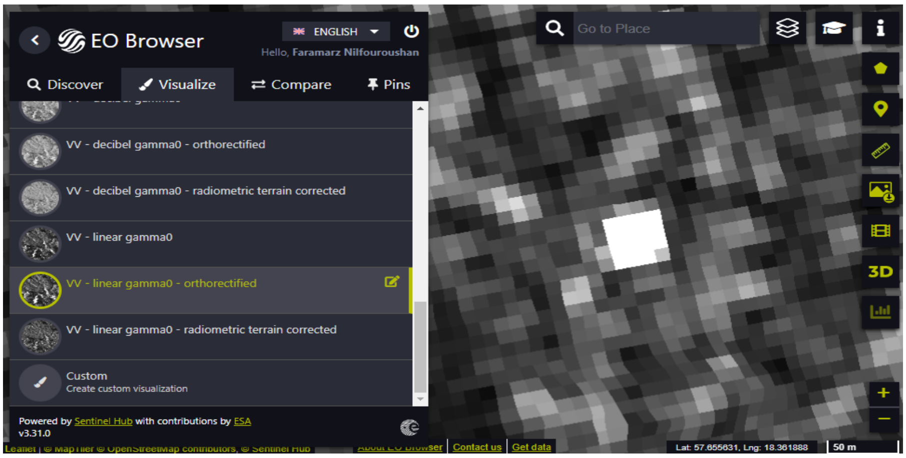


During 2019–2021 Lantmäteriet participated in the ESA-founded project, Geodetic SAR for Baltic Height System Unification, led by the Technical University of Munich (Gruber et al., 2020). The main goal of the project was to investigate the feasibility to connect tide gauges and national height systems around the Baltic Sea using absolute positioning by SAR, via active transponders which in principle act as passive reflectors but have electronics and need configuration. During that project, three active transponders were installed in Sweden at the SWEPOS stations in Mårtsbo, Kobben and Vinberget and they are now still fully operational. The descriptions and the results of the project are available in the final report and two peer-reviewed journal articles (Gruber et al., 2020, 2021 and 2022).

Passive corner reflectors (see Figure 1) have been already installed and tested in many places for different applications, for example, in the Netherlands for geodetic applications (Kamphuis, 2019) and Slovakia or Italy for landslide monitoring (Czikhardt et al., 2021, Darvishi et al. 2018). Corner reflectors have shown their high potential for the detection of mm-level ground displacements using the comparison with GNSS or precise levelling (e.g., Marinkovic et al., 2007). Moreover, co-localizing of the corner reflectors with GNSS stations and tide gauges has been carried out in many places for geodetic applications and geodetic infrastructure development (Garthwaite et al., 2017, Gruber et al., 2022, Kamphuis, 2019).

Figure 3, Intensity images (in GRD format made in EO Browser) before (top) and after (bottom) passive corner reflector installation in Visby on March 2022. Note the whitish pixels in the centre of the bottom image which clearly shows the stronger backscattering signal at the corner reflector location relative to the other pixels.





As mentioned before, radar reflectors are either active (transponders or ECRs) or passive and there are pros and cons for both types as summarized in Table 1.

Table 1, Comparison of the passive and active radar reflectors (modified after Czikhardt 2021).

Reflector	**Passive (corner reflector)**	**Active (transponder)**
Complexity	Simple, easy to manufacture, no electronics, no need for electricity	Relatively complex electronic device, need a power supply (direct or solar panels)
Size	Large/bulky (esp. for C and L bands)	Small/compact
Environmental susceptibility	Conspicuous (vandalism), wind-loading, clogging (debris, precipitation, if no cover to protect)	Temperature, snow/ice cover
Maintenance	Minimal (clogging) if no snow cover	Power supply, GPS clock synchronization, firmware updates, satellite configuration updates
Cost and availability	Size and shape cost dependent, relatively cheap, various shapes	More expensive, limited manufacturers new on the commercial market
Selectiveness	Always on, multiple frequencies/polarizations	Selective (e.g., C/X-band, polarization, on-time)
SAR geometry	Mostly single, but also double geometry (ascending or descending)	Double (both ascending and descending)
RCS	Size, shape, and orientation-dependent, good temporal stability	RF-chain and orientation-dependent, temporal

Reflector	Passive (corner reflector)	Active (transponder)
		stability susceptible to temperature
SAR positioning	Known apex location and easy to measure	Antenna phase centre offsets necessary, antenna-specific internal electronic delays
InSAR	Phase-stable	Phase stability dependent on RF chain, temperature-dependent, possible secular drift
Multi-year reliability	Well-verified (possible damage, vandalism)	Individual calibration recommended (drift, temperature variations, electronics degradation)
GNSS co-location	Can be installed at or near the GNSS stations, robust construction required, it may make multipath depends on the shape, size and orientation of the CR and distance to the GNSS antenna	Smaller size and lightweight and possible to install at existing GNSS masts /pillars, flexible mounting options required for maintenance

2.2. Passive corner reflector design and tests

Manufacturing of the passive corner reflectors relative to transponders is simpler because of no electronic parts. Many factors including the application, weather, materials, background noise at the installation point, and the satellite signal wavelength and orbit geometry, should be considered for the design and installation of such reflectors. Accordingly, the size, shape and materials of the CR are selected. The corner reflector's signal must be visible in the SAR image which means the backscattered signal should be stronger than the background signal level (the 'clutter'). In Figure 3, we notice the brightness of the pixels and we see some locations are more whitish (noisy), which means these are not possibly good candidates for the installation of CRs. The strength of the signal reflected by CR with respect to its surrounding reflections can be measured and is called the Signal-to-

Clutter Ratio (SCR). The random phase variations resulting from nearby scatterers in a pixel (see Figure 4) affect the measured phase of the dominant scatterer and therefore can make errors for point target (e.g., CR) measurements. The LOS measurement accuracy has a direct correlation with the SCR value as shown in Figure 5.

According to Garthwaite et al., (2017), the Radar Cross Section (RCS) of an imaged target is a measure of the size of that target as seen by the imaging radar. The expected RCS value of a reflector depends on the total reflective surface of the CR and the wavelength of the transmitted radar signal (λ in Table 2). For C-band (in the case of Sentinel-1), the wavelength is λ =5.6 cm. The inner leg of the CR is shown by "L" in Figure 6.

Figure 4, All scatterers including the dominant one and the nearby objects in a pixel contribute to the phase measurements (phi) (modified after Garthwaite et al., 2017.

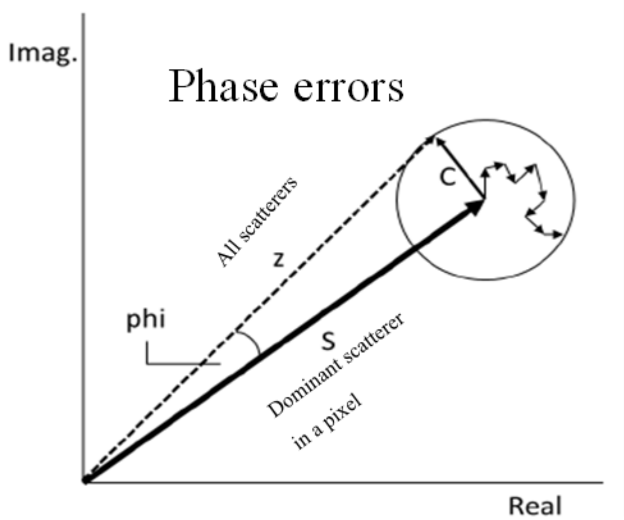


Table 2, Theoretical RCS of some of the common CR types.

Reflector type	**Maximum RCS**
Triangular trihedral	$4\pi L^4/3\lambda^2$
Square trihedral	$12\pi L^4/\lambda^2$

Using the formulas listed in Table 2, we can see for example for a squared trihedral type of corner reflector with an inner leg length of L= 0.7 m, the expected RCS is 34.7 dBm2 (see Figure 6) and for a trihedral triangular shape with the same inner leg, is 25.1 dBm2 which is weaker than the squared shape. In practice, these values cannot be achieved exactly due to various attenuations and possible orientation errors of the CR.

Figure 5, LOS displacement error as a function of estimated signal-to-clutter ratio (SCR) (modified after Garthwaite et al., 2017). For example, the 20 dB SCR, allows reaching about 0.5 mm precision of a single C-band LOS InSAR measurements. However, there are other sources of errors (e.g., orbital errors, etc.) that also contributes to the final precision of the measurements.

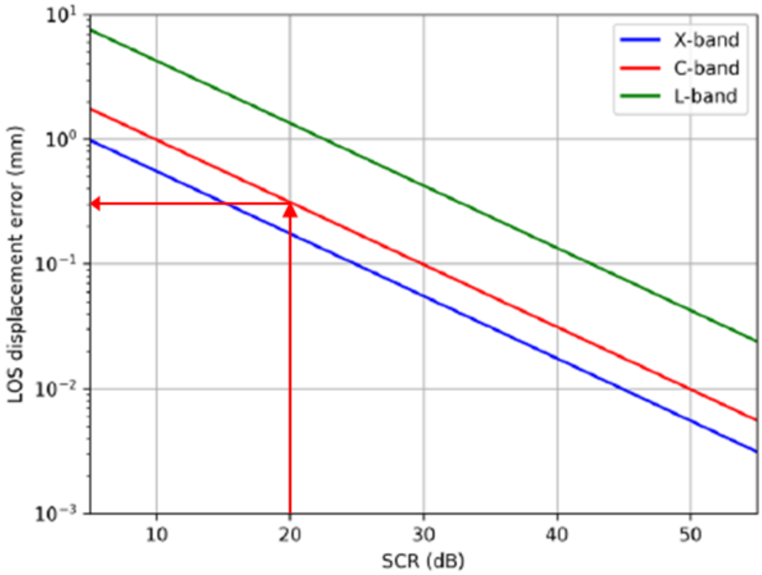
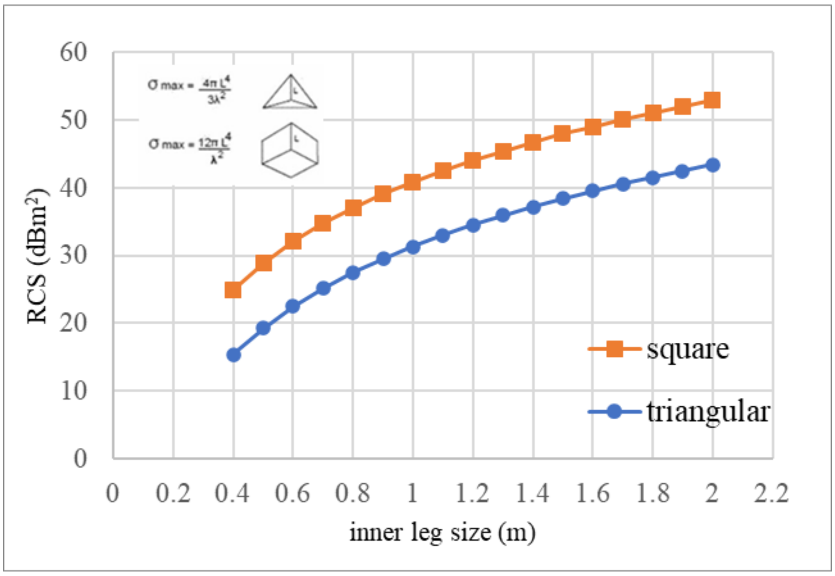


Figure 6, RCS vs inner leg size (L), C-band (Sentinel-1), for trihedral triangular and squared corner reflectors (see their shapes in the inset figure) (modified after Garthwaite et al., 2015).



Since 2018, Lantmäteriet has been considering corner reflectors for geodetic applications and as such has done a literature review and contacted several companies and organizations to find the best design for the CR's and to find the manufacturers. The double-back flipped (squared version) type was suggested by SDFI (Danish Agency for Data Supply and Infrastructure) and the common type of trihedral triangular one was considered to start with for tests and experiments. After several meetings with a Swedish company MK3D (https://www.mk3d.se/), three trihedral triangular CR's with an inner leg of 1 m, 5 mm thick aluminium plates, and snow cover (Plexiglass which is radar transparent) and one double-back flipped squared version with 60 cm inner leg, 5 mm thick aluminium plates was ordered. The expected (theoretical) RCS for these types of CRs is around 31 dBm2 which is sufficient for geodetic applications. The CRs were tested temporarily in the Mårtsbo test field on the wooden pallets (see Figure 7) for some time at the beginning of 2021 and oriented for both ascending and descending orbit geometries. After checking their backscattered images in the Sentinel Hub EO browser (https://www.sentinel-hub.com/explore/eobrowser/) and SNAP software, and knowing they function well, they were transported to the other locations for permanent installations.

Figure 7, Experiments with corner reflectors in Mårtsbo test field. Learning how to orient triangular and double-back flipped squared types for Sentinel-1 ascending and descending tracks.

We sent two of our triangular trihedral CRs to the Chalmers University of Technology (see figures in Appendix) and did some backscattering analysis to suggest the proper location of CR installation at the Onsala space observatory. The double backflipped squared CR was installed in Norrköping airport (see Figure 14). We also designed and tested two trimmed versions of the squared types (1 m inner leg, 3 mm thick aluminium plates, powder coated, with snow protection cover and with expected RCS of 40 dBm2) and installed them in Visby near our twin GNSS stations, see figures in Appendix). After some experiments, and preference for only one CR installation at each site (which is easier, cheaper and has the advantage of monitoring the movements of the same location on the bedrock), we decided to choose the double backflipped squared trihedral types with 72 cm inner leg which is mounted on a single mast and is visible on both ascending and descending tracks. To make it lighter, but still strong enough, we chose a 3 mm thickness of metal plates for the latest CRs. The expected RCS for these types of CRs (for example the one installed in SVEG, see the Appendix) is about 35 dBm^2. We ordered 15 of these types and will continue installing these CR’s this year and next year. The apex (the corner point or intersection point of the three metal plates of the CR) measurement and orientation of the CR’s were carried out using Network RTK GNSS measurements (1-3 cm positioning accuracy).

2.3. Installation of corner reflectors in Sweden

There are different factors which are considered before the installation of InSAR corner reflectors. These factors are, for example, the location of the study area, application (e.g., landslide or geodetic applications), project lifetime (e.g., long-term monitoring for geodetic infrastructure or a short term like landslides) and some general aspects like sky visibility, accessibility and ease of CR transportation, theft and/or vandalism and having landowner’s permission.

For Lantmäteriet, one of the main reasons for installing the corner reflectors is to develop the geodetic infrastructure and co-locate the CR’s with some of the well-established GNSS stations (e.g., Class-A stations which are for geodynamic applications and maintenance of the national reference frames, read more in Alfredsson et al., 2019). Since the Class-A GNSS stations are all installed on the bedrock, therefore the CR should also be installed on the same or close-by bedrock for better comparison of the time series of the station’s movements (CR vs GNSS) with the assumption that they both sense the same bedrock motions. However exposed bedrock (depending on their extent and roughness), sometimes contribute to the large background noise and therefore SCR analysis is needed in advance to find the best possible location for CR installation to reach the mm-level accuracy and to make the CR useful for geodetic applications.

Sky visibility is also important for choosing the location. The CR should be oriented toward the satellite (azimuth and elevation angles are calculated based on the location of the CR and the known orbit geometry of the satellites (e.g., Sentinel-1 in our case). If CR is only oriented for ascending or descending tracks there will be less problem in finding the suitable location, but if the CR is tracking both ascending and descending satellites then both ascending and descending LOS directions (approximately in azimuths of 100° (descending) and 260° (ascending) for Sweden) should be checked and there shouldn’t be any trees/buildings/towers which cause masking the transmitted radar signal. The most common threats are also tree growth and nearby high-rise building constructions. Therefore, a field reconnaissance, checking the aerial photos, maps, etc., in advance and after installations in a regular manner, are important. In case, maybe a routine to clear the obstructing trees after some years is needed.

Most of the suitable locations, close to GNSS stations, to place a CR are not owned by Lantmäteriet and therefore getting permissions from the landowner is required and needs to have cared for well in advance. The properties which have been already rented by Lantmäteriet for GNSS stations are for a certain period from private or state landowners. Before installing a CR, it is essential to check for permission and update the agreements accordingly so that the legal requirements are satisfied. A double backflipped squared trihedral CR approximately requires an $8m^3$ area of space in 3D.

Apart from the physical requirements of the AOI (area of interest) to place a CR in any location, another important factor to be considered is the SCR in the AOI. The signal-to-clutter ratio (SCR) plays a major role in positioning precision and InSAR phase variance. A higher SCR for a fixed detection threshold will increase the detection probability of the desired signal from noise. The areas with lower SCR (~<20 dB) should be avoided if possible. We use GECORIS toolbox (Czikhardt et al., 2021) to carry out such simulations and later in section 1.5, the results of SCR simulations for Norrköping CR are presented.

So far, ten passive corner reflectors have been installed in Sweden by Lantmäteriet except two which were sent to Chalmers University of technology and installed by the staff in the Onsala space observatory (see Table 3 and photos in Appendix). The distribution of these reflectors and transponders is shown in Figure 8.

Figure 8, Distribution of the transponders and newly installed passive corner reflectors in Sweden. As listed in Table 3, there are two corner reflectors at Visby and Onsala. Coordinates are in SWEREF 99 reference frame.

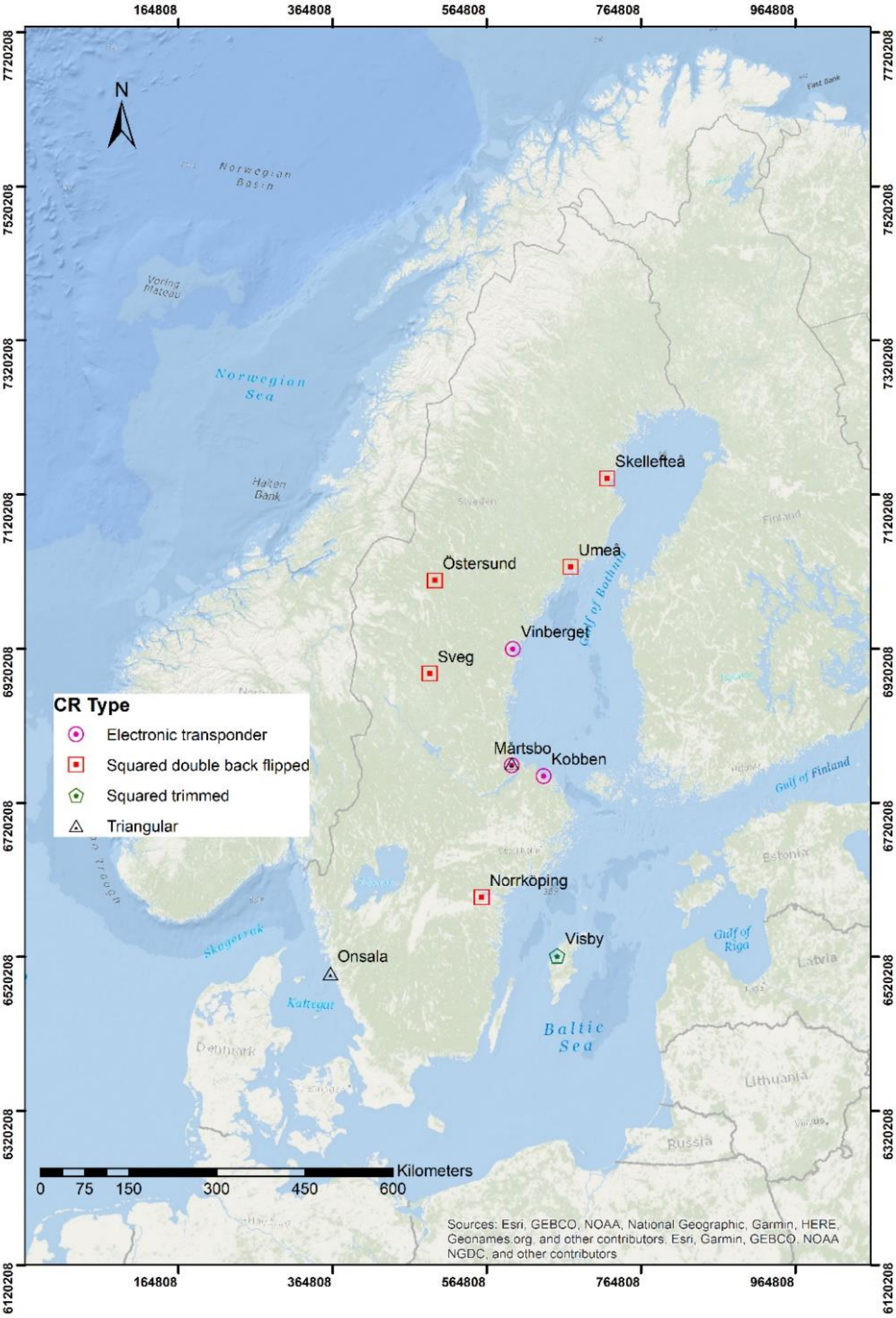


Table 3, Installed corner reflectors and transponders in different locations in Sweden (coordinates are in SWEREF 99 reference frame)

ID	Latitude	Longitude	Location	Passive/Active	Date of Installation	Type	Orientation
ECR01	60.5951	17.2585	Mårtsbo	Active	2020-01-07	Electronic transponder	Asc and Desc
ECR02	60.4099	18.2303	Kobben	Active	2020-06-01	Electronic transponder	Asc and Desc
ECR03	62.3739	17.4279	Vinberget	Active	2020-10-01	Electronic transponder	Asc and Desc
CR01	57.3949	11.9220	Onsala	Passive	2021-06-01	Triangular	Asc
CR02	57.3950	11.9222	Onsala	Passive	2021-09-10	Triangular	Desc
CR03	60.5946	17.2596	Mårtsbo	Passive	2021-09-14	Triangular	Asc
CR04	58.5900	16.2451	Norrköping	Passive	2021-11-04	Double back flipped squared	Asc and Desc
CR05	57.6540	18.3671	Visby	Passive	2022-05-11	Squared trimmed	Desc
CR06	57.6540	18.3671	Visby	Passive	2022-05-11	Squared trimmed	Asc
CR07	62.0173	14.7000	Sveg	Passive	2022-06-14	Double back flipped squared	Asc and Desc
CR08	63.4427	14.8579	Östersund	Passive	2022-09-01	Double back flipped squared	Asc and Desc
CR09	63.5781	19.5096	Umeå	Passive	2022-10-21	Double back flipped squared	Asc and Desc
CR10	64.8792	21.0485	Skellefteå	Passive	2022-10-23	Double back flipped squared	Asc and Desc

2.4. Corner reflectors and multipath effect on nearby GNSS station coordinates

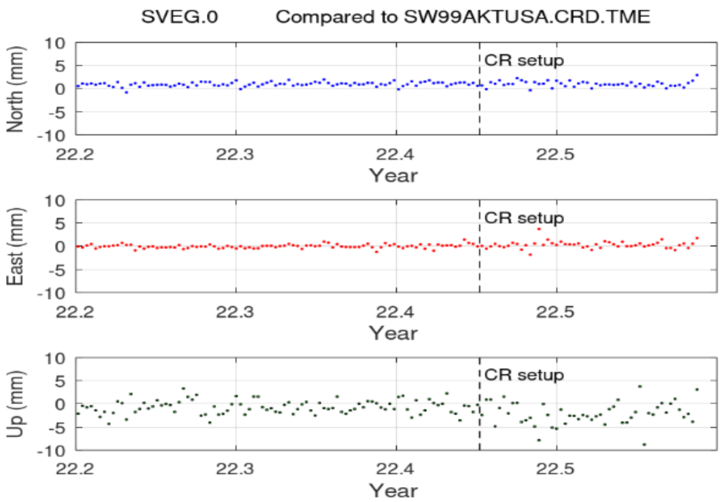
Radar corner reflectors, made of metal plates, may cause multipath if installed at or very close to GNSS stations. Parker et al. (2019) installed several corner reflectors in Australia with a minimum of 30 metres distance from GNSS stations to avoid multipath error on GNSS coordinates. However, later, Fuhrmann et al. (2021), showed that even the CRs co-located directly at the GNSS stations (see Figure 9), don't show a significant multipath effect on the coordinates of the co-located GNSS stations, especially for the ones equipped with choke-ring antenna (just about 0.1 mm). Even they showed the GNSS Signal to Noise Ratio (SNR) was not also significantly affected (just about 1%). However, they argued that their test results can be different if the CR shape and size and its location relative to nearby GNSS are different.

Figure 9, GNSS stations in the Sydney area with CRs attached to the antenna pole used by Fuhrmann et al. (2021).

To investigate if our corner reflectors cause any multipath effect on nearby GNSS stations, we looked at the coordinate time series of the twin GNSS stations in two different locations, Sveg and Visby (see their locations in Figure 8). The installed corner reflector in Sveg is about 6 m away from the GNSS stations (see Figure 10) whereas, in Visby, the twin corner reflectors are about 20 metres away and have a different shape, size and orientation (see Figure 11).

The daily GNSS coordinate time series for three components in SWEREF 99 before and after installation of the corner reflector doesn't show any significant jump in the time series and the coordinate variations are in the range of expected mm-level variations for all stations.

Figure 10, Daily GNSS coordinate time series of twin stations in Sveg (SVEG 0 and SVEG 6) before and after CR installation (the stations each have different choke ring antennas and radomes, double back flipped squared CR is ~6 m away from the mast station).The time series show daily residuals relative to the official SWEREFF 99 coordinates of each station.



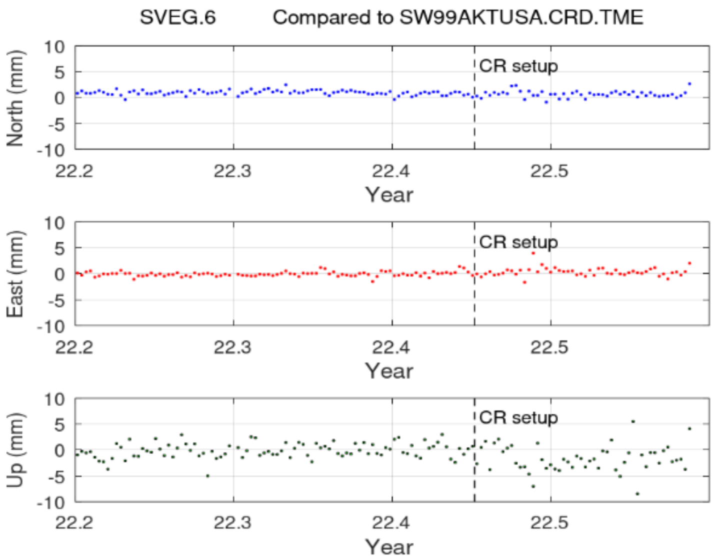
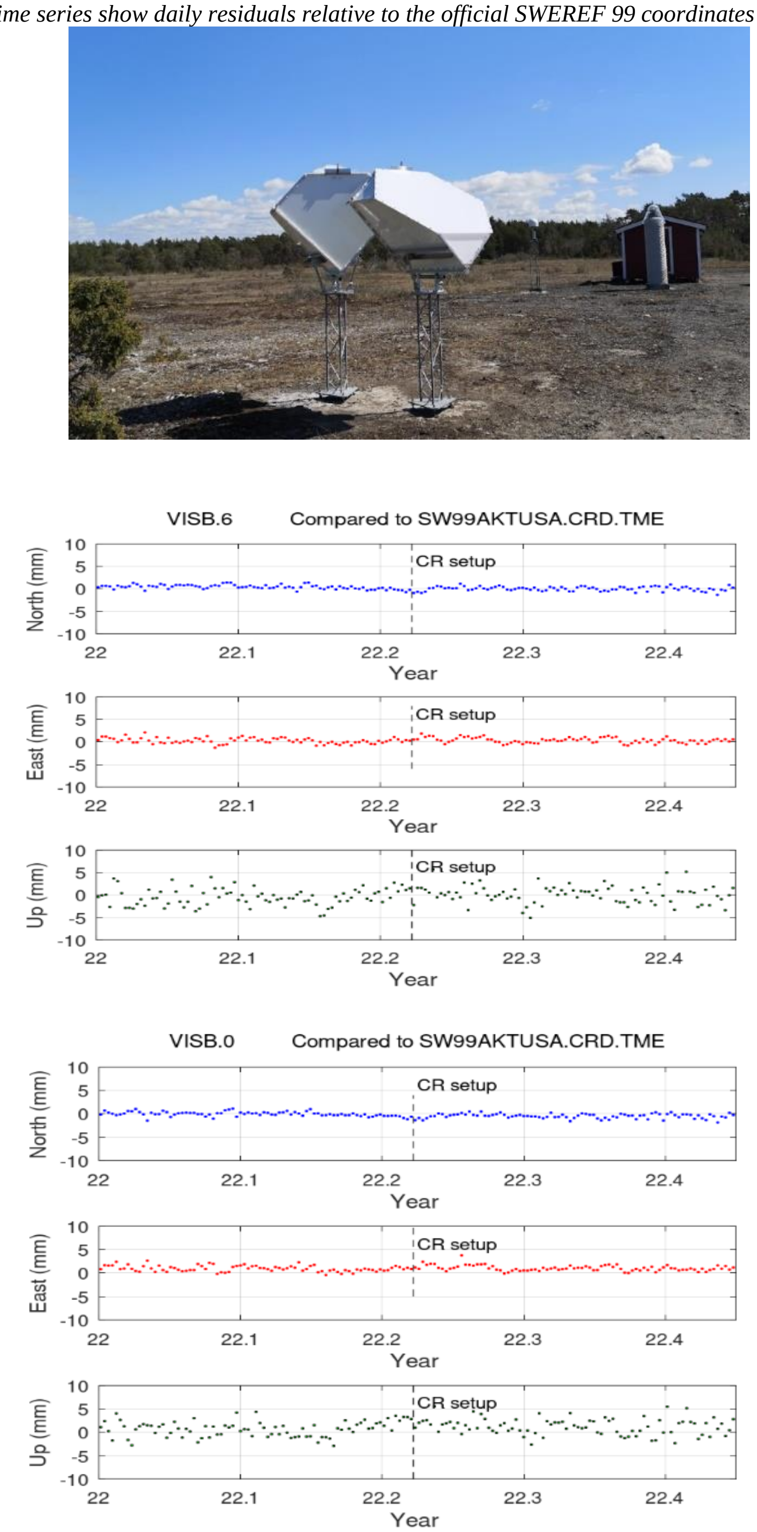


Figure 11, Daily GNSS coordinate time series of twin stations in Visby (VISB.0 and VISB.6) before and after CRs installation (the stations each have different choke ring antennas and radomes, squared trimmed CRs are ~20 m away from GNSS stations). The time series show daily residuals relative to the official SWEREF 99 coordinates of each station.

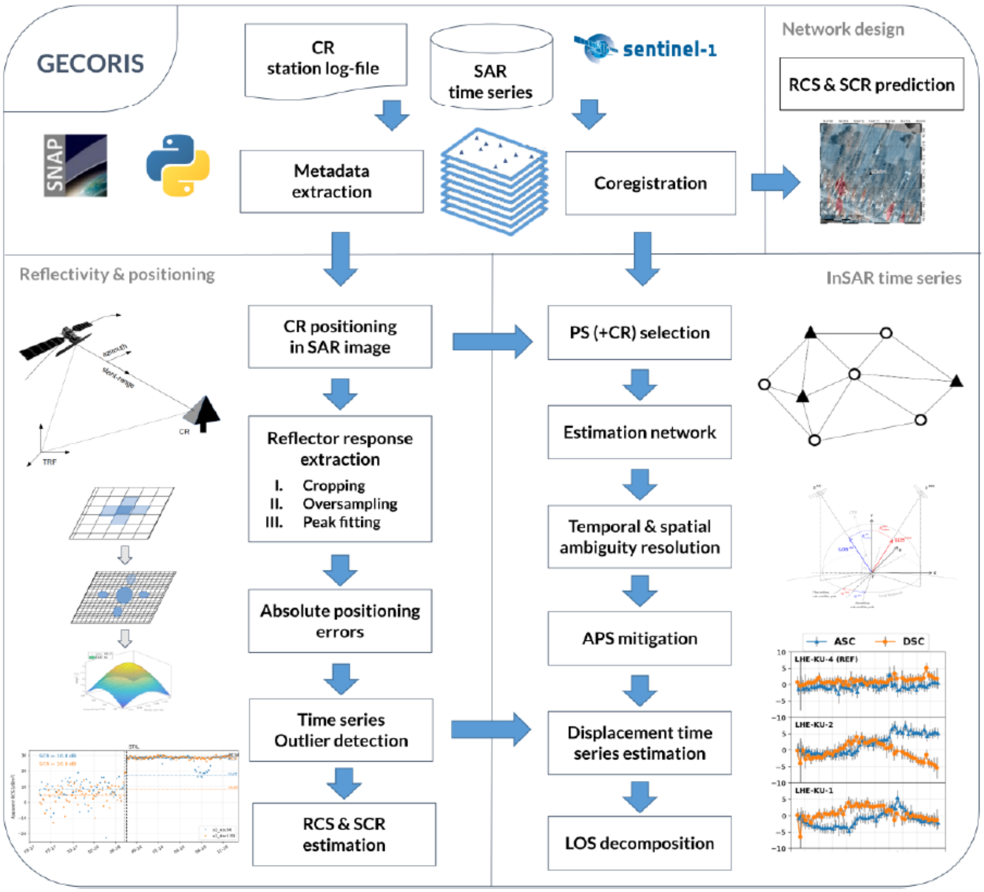


2.5. Data analysis with GECORIS

For data analysis, GECORIS toolbox (Czikhardt et al., 2021) and SANP-ESA Sentinel Application Platform v9.0.0, which are both freely available were used. For installation of GECORIS, firstly Python 3.6 and ESA SNAP 9.0 were installed on Linux and then GECORIS (see Figure 12) was set up.

Figure 12 shows the toolbox capabilities and different steps for data processing (more details in Czikhardt et al., 2021). Here in this report, we show the results for one of the CRs which was installed in Norrköping Airport.

Figure 12, GECORIS toolbox, processing steps and capabilities (Czikhardt et al., 2021).

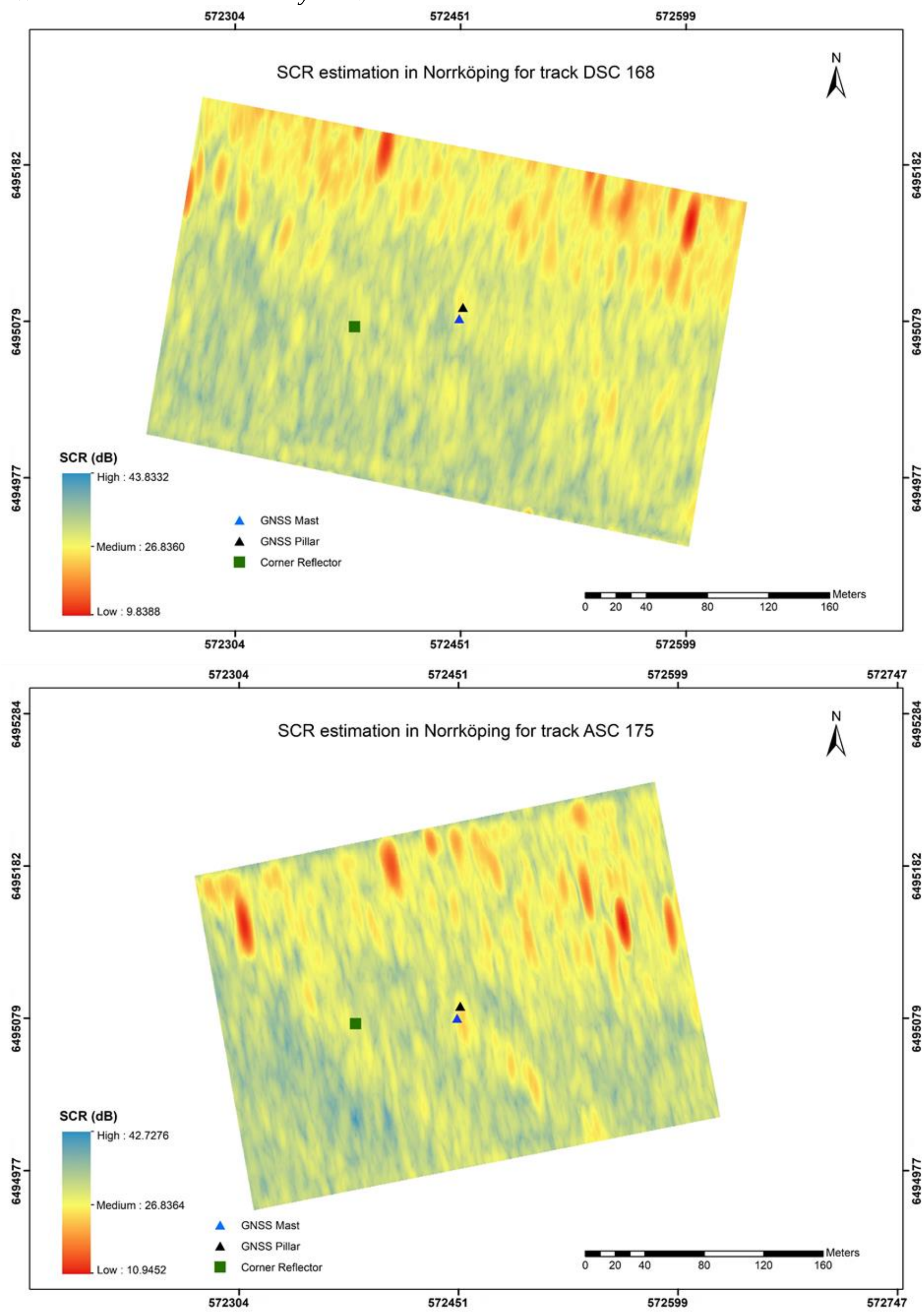


2.5.1. SCR SIMULATION

The GECORIS toolbox computes the ratio between the analytical RCS of the CR and the clutter power, estimated using SAR acquisitions over the AOI. Figure 13 represents the SCR estimation maps over Norrköping for descending track 168 and ascending track 175. The values are calculated for a period of 6 months, using SLC products of Sentinel 1A, from 2020-04-01 to 2020-10-01. As inputs for the RCS estimation 32 dBm^2 is given as the expected RCS from the CR. This value depends on the reflector type and size, and 32 dBm^2 is the approximate theoretical value for a square double backflip type CR with a 60 cm inner leg. Maps are produced for all the tracks which cover the AOI.

These kinds of maps, for example the ones shown for Norrköping in Figure 13, are used to determine which locations are most suitable to permanently install a CR. The lower the value (more reddish pixels) the more unsuitable it becomes and the higher the value (more bluish) the more suitable it becomes to place a CR. According to Figure 5 to maintain the LOS error below 1 mm the CR must be capable of providing an average SCR over 20 dB when other incorporated errors are eliminated. Hence areas with values over 20 dB from Figure 13 are chosen as potential locations to place a CR.

Figure 13, SCR estimation for Norrköping using Sentinel-1 images between 2020-04-01–2020-10-01. Good to mention, here the CR is around 110 m away from the GNSS stations mainly because of the easier bedrock accessibility at the installation point. Maps are in SWEREF99 TM Coordinate system.



2.5.2. SCR AND RCS ESTIMATION

By utilizing GECORIS toolbox, the SCR, and the RCS for the Norrköping corner reflector (see Table 3) have been estimated using the five available tracks of the SAR dataset that covers the period between 2021/08/05 and 2022/07/19 (i.e., before and after the installation date which was on 2021-11-04). Table 4 and Figure14 show the used tracks and the associated data periods, sub-swaths, and incident angles.

Table 4, SAR datasets for Norrköping corner reflector's SCR and RCS estimations.

Used Track	Data Period	Subswath	Incident Angle (deg)
DSC168	2021-08-05 to 2022-07-19	IW1	31.0
DSC22	2021-08-06 to 2022-07-14	IW2	38.6
DSC95	2021-08-07 to 2022-07-09	IW3	42.2
ASC102	2021-08-05 to 2022-07-19	IW2	39.6
ASC175	2021-08-06 to 2022-07-14	IW1	32.2

Figure 14, Double backflipped squared (60 cm inner leg) corner reflector in Norrköping airport, installed November 4th, 2021. The corner reflector's location (marked with a blue triangle) and footprints of ascending (ASC102 and ASC175) and descending (DSC168, DSC22 and DSC95) Sentinel-1 images are shown on the map. The Bottom right shows the incidence angle of different scenes.

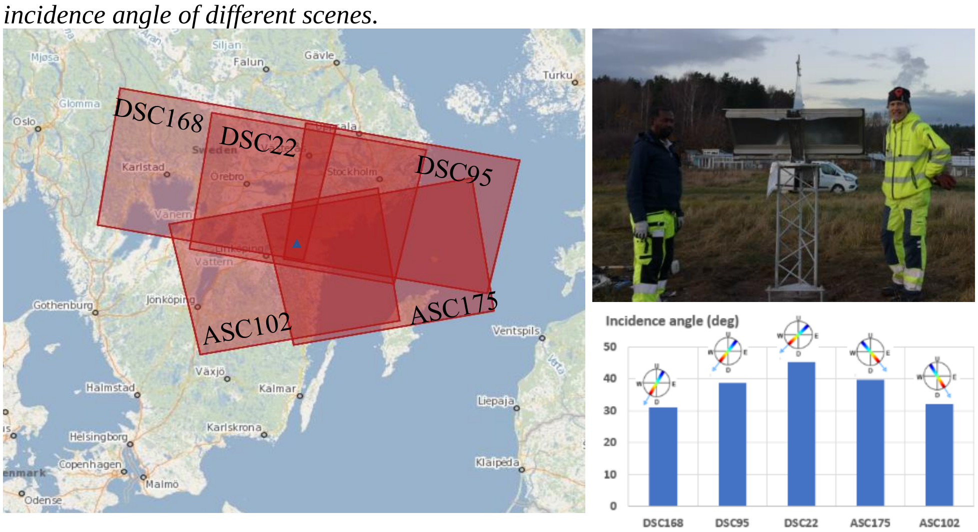


Figure 15 and Figure 16 show the results of SCR and RCS estimations for the CR at Norrköping airport. Because different tracks have different incidence angles (see Figure 14), therefore the apparent RCS will be slightly different. There is a clear jump in RCS values after the installation of the CR. A few days the RCS values are relatively lower (for example for track DSC168) which is due to the snow accumulation in the corner reflector (it is good to mention that the corner reflector in Norrköping is the only CR which has no snow cover). The GECORIS toolbox can also estimate the SCR using the SAR data time series (more details in Czikhardt et al., 2022) and as such we estimated the SCR for this location and Figure 16 shows the results. On average, we see the SCR values are around 20 dB which is good enough for geodetic applications (mm accuracy for LOS measurements).

Figure 15, Apparent RCS estimation for different satellite tracks, sampled between 2021 and 2022. The CR in Norrköping airport was installed on 2021-11-04.

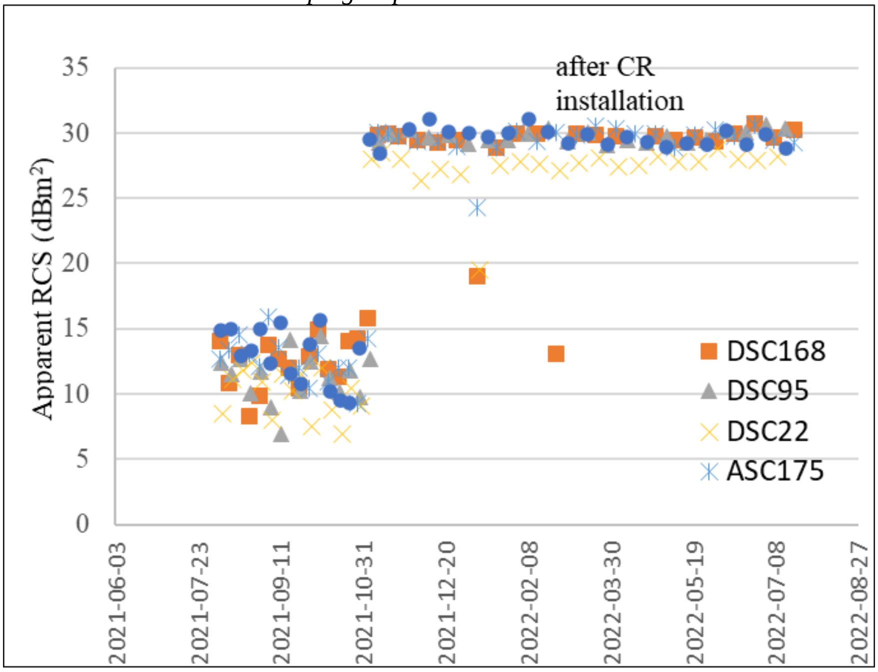
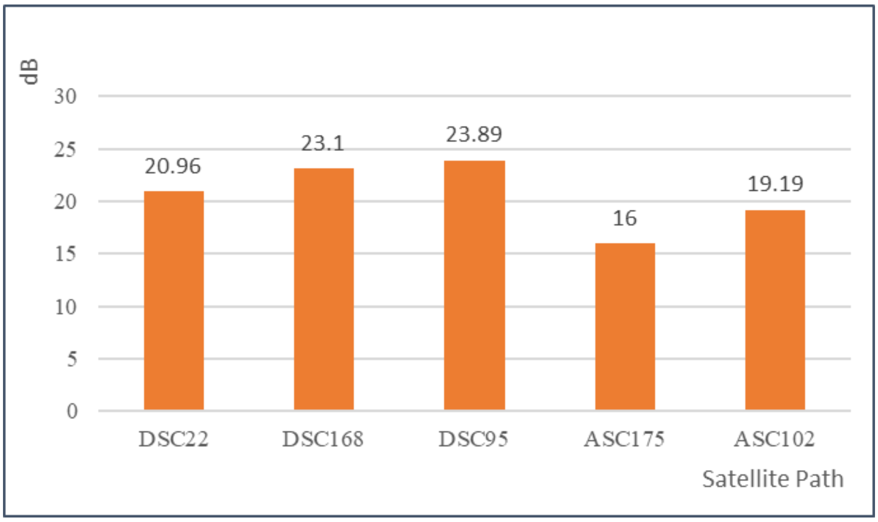


Figure 16, Estimated SCR values(dB) for corner reflector location using data for different Sentinel-1 tracks.



3. Cross-checking of InSAR-Sweden and previous studies

In this section, we use the previous PSI results of land subsidence studies for Uppsala (Fryksten and Nilfouroushan, 2019) and Gävle (Gido et al., 2020) to validate the nationwide ground motion service of Sweden (i.e., InSAR-Sweden). The localization of deformation in these two cities and the Line of Sight (LOS) displacement time series at some locations are compared and cross-checked.

3.1. Nationwide Ground Motion Service (GMS) of Sweden (InSAR-Sweden)

Swedish Ground Motion Service or InSAR-Sweden is based on using both ascending and descending Copernicus Sentinel-1 SAR data and the PSI technique for data processing. This service is a result of a collaboration project between several Swedish organizations and institutes and the Geological Survey of Norway (NGU), the producer of the service. The data used in InSAR-Sweden covers the period between 5 March 2015 to 11 October 2021 (see Table 5).

The PSI results of InSAR-Sweden contain different solutions based on the used geometry and tracks. For the study areas (i.e., Gävle and Uppsala Cities) track numbers 29, 102 and 175 were used for the ascending geometry, while tracks numbers 22, 95 and 168 were used for the descending one.

Table 5, Details of the Sentinel-1 A and B data used for the InSAR-Sweden PSI analysis for Uppsala and Gävle cities.

Data Info	Ascending	Descending
Number of scenes	209	191
Acquisition period	5 March 2015-11 October 2021	9 June 2015- 11 October 2021
Relative orbit	29, 102, 175	22, 95, 168
Acquisition mode	Interferometry Wide swath (IW)	Interferometry Wide swath (IW)
Product type	Single Look Complex (SLC)	Single Look Complex (SLC)
Polarization	VV	VV

3.2. Gävle City ground motion study and comparison with InSAR-Sweden

Gido et al. (2020), studied the ground surface deformation of Gävle city using the PSI technique to map the location of risk zones and their ongoing subsidence rate. Two ascending and descending Sentinel-1 datasets, collected between 16 January 2015 and 19 May 2020 (see Table 6), were processed, and analyzed using SARPROZ software. Furthermore, a relatively long record of levelling dataset, covering the period from 1974 to 2019, was used to validate the PSI InSAR results by detecting the rate of subsidence in some common locations. The PS results were overlaid on the quintenary deposit map of the city for further investigation.

The comparison between the obtained relative vertical rate of the PS results, using the combined ascending and descending datasets, with the computed rate of four different precise levelling datasets connected to four buildings in the city centre, shows close agreement (see Table 7). The PSI results reveal that the centre of the city is relatively stable with minor displacement ranging between -2 mm/year to +2 mm/year in vertical and east-west components. Only localized deformation zones toward the northeast of the city are relatively subsiding with a higher annual rate of up to 6 mm/year in the LOS direction (see Figure 17).

Table 6, Details of the Sentinel-1 A and B data used for the Gävle city ground motion study.

Data Info	Ascending	Descending
Number of scenes	41	50
Acquisition period	16 January 2015–13 May 2020	9 June 2015–19 May 2020
Relative orbit	102	95
Central incident angle	38.77 degree	38.79 degree
Acquisition mode	Interferometry Wide swath (IW)	Interferometry Wide swath (IW)
Product type	Single Look Complex (SLC)	Single Look Complex (SLC)
Polarization	VV	VV

Figure 17, Left side shows the LOS displacement rate of the ascending PS points for Gävle city relative to the reference point (pink colour) reported in Gido et al., (2020). Area 1 shows the maximum displacement zones. The Right side shows the LOS displacement rate of the InSAR-Sweden for the same area and track.

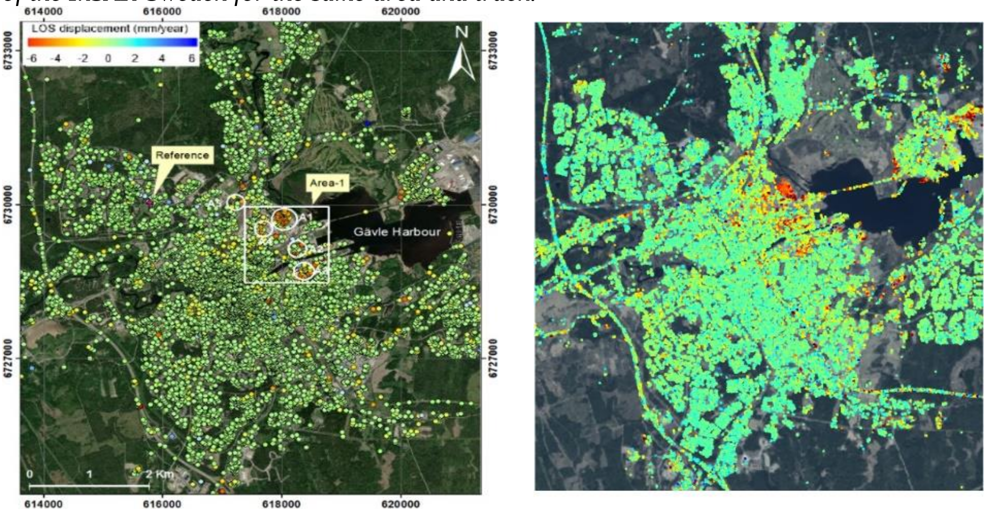


Table 7, Comparison between the relative vertical rate of the PS results in four validated buildings with the computed precise levelling rate.

Validation Site	Method	Track	Point ID	Relative Vertical Displacement Rate (mm/yr)	Relative Vertical Cumulative Displacement (mm)	Coherence
Building-1 (1985-2019)	Pre. Lev	-	Point 7	-1.2	-45.0	-
(2015-2020)	PSI	AD	498	-0.9	-5.0	0.86
Building-2 (2000-2019)	Pre. Lev	-	Point 6	-0.8	-20.0	-
(2015-2020)	PSI	AD	430	-0.7	-5.0	0.88
Building-3 (1976-1982)	Pre. Lev	-	Point 6	-2.0	-10.0	-
(2015-2020)	PSI	AD	396	-0.6	-4.1	0.95

Validation Site	Method	Track	Point ID	Relative Vertical Displacement Rate (mm/yr)	Relative Vertical Cumulative Displacement (mm)	Coherence
Building-4 (1974-1988)	Pre. Lev	-	Point 4	-1.8	-31.0	-
(2015-2020)	PSI	AD	418	0.0	-1.6	0.95

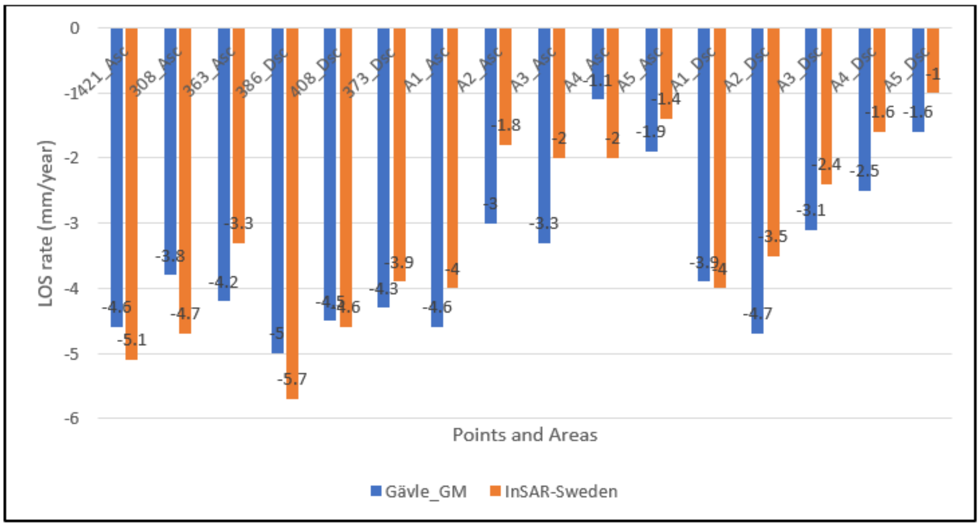
To validate the InSAR-Sweden results using Gävle's study, points, and areas comparison for both the ascending and descending geometries at common locations have been carried out, using the same track. For the study area, the InSAR-Sweden results contain six different solutions based on the used geometry and tracks, three solutions for the ascending tracks with numbers 29, 102, and 175, and three solutions for the descending tracks with numbers 22, 95, and 168, while one track for each geometry has been used (ascending 102 and descending 95) for Gävle study. Therefore, the comparison was held for the common tracks only. The LOS rate in mm/year for six points from the Gävle study (three ascending and three descending) was selected and compared with the LOS rate of the closest six points from the InSAR-Sweden study considering the same geometry and track and based on a minimum coherence of 0.6 as selection criteria. Furthermore, the estimated LOS displacement rate for five selected areas was compared in both studies considering using the same geometries and tracks as well. The PS rates for the areas (A1 to A5) have been estimated by averaging points with minimum coherence of 0.8.

Despite the differences in the period of the data coverage which is about 5.5 years for Gävle and 6.5 years for InSAR-Sweden, the number of used images, the accuracy of georeferencing of the PS points (unknown reference point for InSAR-Sweden), the density of the PS points and the other used characteristics (e.g., coherence, masks) for both studies Gävle and InSAR-Sweden respectively, similar localization of deformation and close rate agreement can be seen in both studies. Table 8 shows the LOS rates and the properties of the selected small areas (i.e., A1, A2, A3, A4 and, A5), and points for ascending and descending geometries for the two studies.

Table 8, Properties of the selected small areas (i.e., A1, A2, A3, A4 and, A5), and points for ascending and descending modes. Gävle ground motion (20150116-20200519) vs InSAR-Sweden (20150305-20212011).

Zone/ID	**Track**	**LOS rate of Gävle ground motion (mm/yr)**	**Coherence of Gävle ground motion**	**St. Dev. Of Gävle ground motion (mm)**	**LOS rate of InSAR-Sweden (mm/yr)**	**Coherence of InSAR-Sweden**	**RMSE of InSAR-Sweden(mm)**
421	Asc_102	-4.6	0.91	2.1	-5.1	0.82	2.2
308	Asc_102	-3.8	0.83	2.8	-4.7	0.82	2.3
363	Asc_102	-4.2	0.92	1.8	-3.3	0.93	1.6
386	Dsc_95	-5.0	0.71	4.0	-5.7	0.59	4.9
408	Dsc_95	-4.5	0.89	2.3	-4.6	0.85	2.5
373	Dsc_95	-4.3	0.82	3.2	-3.9	0.89	3.2
A1	Asc_102	- 4.6	0.89	5.6	-4.0	0.76	3.1
A2	Asc_102	- 3.0	0.90	3.6	-1.8	0.71	3.6
A3	Asc_102	- 3.3	0.90	4.0	-2.0	0.71	3.6
A4	Asc_102	-1.1	0.94	1.5	-2.0	0.70	3.7
A5	Asc_102	-1.9	0.83	2.4	-1.4	0.64	4.2
A1	Dsc_95	-3.9	0.86	4.1	-4.0	0.69	3.8
A2	Dsc_95	-4.7	0.86	5.1	-3.5	0.73	3.4
A3	Dsc_95	-3.1	0.90	3.3	-2.4	0.74	3.3
A4	Dsc_95	-2.5	0.78	3.2	-1.6	0.69	3.9
A5	Dsc_95	-1.6	0.82	2.0	-1.0	0.67	3.9

Figure 18, The LOS rate comparison for Gävle and InSAR-Sweden



3.3. Uppsala City ground motion study and comparison with InSAR-Sweden

The city of Uppsala is undergoing significant subsidence in areas that are located on clay, which acts as a weak layer and causes the sinking of the ground surface and tilting of buildings. Fryksten and Nilfouroushan (2019) carried out an InSAR-based PSI analysis using SARPROZ software to map the ongoing ground deformation and highlight risk zones, using two ascending and descending Sentinel-1 datasets covering the period from 5 March 2015 to 13 April 2019 (see Table 9). The PSI results were validated with the help of relatively long precise levelling records and the available geological data of the study area. The study revealed that the city was undergoing significant subsidence in some areas, with an annual rate of about 6 mm/year along the LOS direction (see Figure 19). Moreover, the areas of notable deformation were exclusively found on postglacial clay.

Table 9, Details of the Sentinel-1 A and B data used for Uppsala city ground motion

Data Info	Ascending	Descending
Number of scenes	42	44
Acquisition period	5 March 2015–1 April 2019	9 June 2015–13 April 2019
Relative orbit	102	95
Central incident angle	38.76 degree	33.32 degree
Acquisition mode	Interferometry Wide swath (IW)	Interferometry Wide swath (IW)
Product type	Single Look Complex (SLC)	Single Look Complex (SLC)
Polarization	VV	VV

Similar to the Gävle study, points comparisons for both ascending and descending geometries at common locations have been carried out between the Uppsala study and InSAR-Sweden using the same track. Six points were selected and compared for each geometry using 0.70 as a minimum coherence. Despite the differences in the period of the data coverage which is about four years for Uppsala and 6.5 years for the InSAR-Sweden, the number of used images, the accuracy of georeferencing of the PS points (unknown reference point for InSAR-Sweden), the density of the PS points and the other used characteristic (e.g., coherence, masks) for both studies Uppsala and InSAR-Sweden respectively, similar localization of deformation and close rate agreement can be seen in both studies (see Figure 19). Table 10 shows the LOS rates and the properties of the selected points for ascending and descending geometries for the two studies.

Table 10, Properties of the selected points, for ascending and descending modes. Uppsala ground motion (20150305–20190413) vs InSAR-Sweden (20150305–20211011).

Zone/ID	Track	LOS rate of Uppsala ground motion (mm/yr)	Coherence of Uppsala ground motion	St. Dev. of Uppsala ground motion (mm)	LOS rate of InSAR-Sweden (mm/yr)	Coherence of InSAR-Sweden	RMSE of InSAR-Sweden (mm)
5504_Asc	102	-5.1	0.94	1.5	-5.1	0.92	1.8
2326_Asc	102	-4.5	0.94	1.6	-4.0	0.85	2.5
472_Asc	102	-3.8	0.85	2.9	-3.8	0.87	2.1
652_Asc	102	-5.1	0.86	2.5	-4.7	0.81	2.7
1169_Asc	102	-5.2	0.89	2.2	-5.1	0.85	1.9
5606_Asc	102	-4.2	0.96	1.3	-3.9	0.93	1.8
1658_Dsc	95	-6.0	0.80	3.0	-6.3	0.88	2.3
3604_Dsc	95	-4.5	0.81	3.3	-4.7	0.70	3.7
6022_Dsc	95	-3.8	0.92	2.1	-3.2	0.94	1.7
5322_Dsc	95	-5.0	0.94	1.6	-5.2	0.91	1.5
5559_Dsc	95	-4.1	0.90	2.2	-3.8	0.95	1.4
1872_Dsc	95	-4.8	0.83	2.8	-4.1	0.96	1.3

Figure 19, Left side shows the LOS displacement rate for the PS points from the ascending data analysis of Uppsala study (Fryksten and Nilfouroushan, 2019). Right side shows the LOS displacement rate of the InSAR-Sweden for the same area using similar geometry and track.

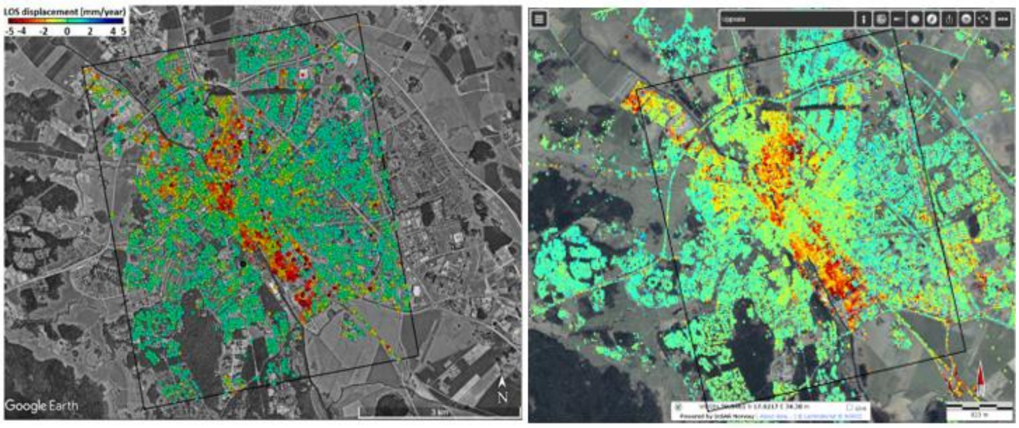
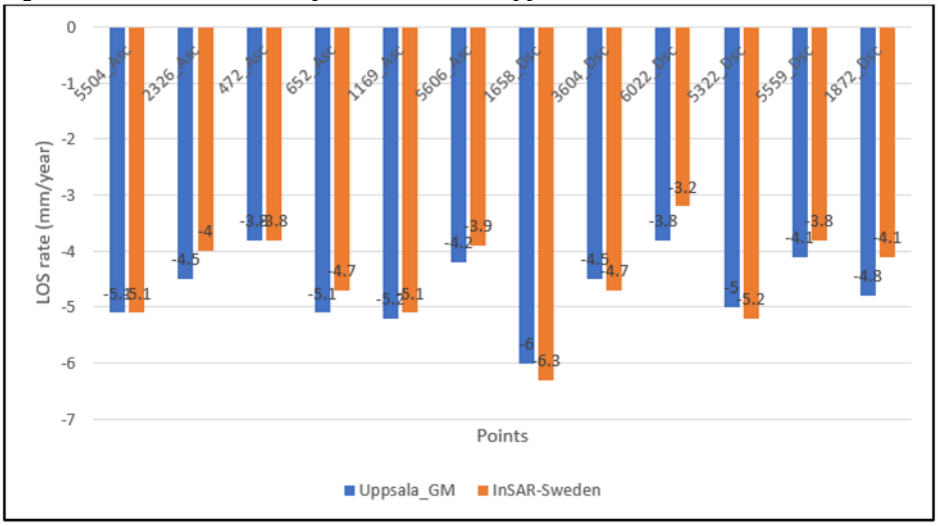


Figure 20, The LOS rate comparison between Uppsala and InSAR-Sweden.



4. Discussion and Conclusion

Our validation analysis in which we compared InSAR-Sweden and previous studies show promising results. Although the number and image acquisition date of Sentinel-1 data and the parameters used for PSI processing are not completely the same, the compared results show a good agreement between corresponding studies on the deformation localization and displacement rate in those two cities in a five-year period. For Gävle and InSAR-Sweden comparison, Figure 17 clearly illustrates the similar localization of the subsidence which concentrates more in the northeast of the city with up to 6 mm/year in the LOS direction. The points and areas comparison shows generally close agreement with minor differences with an estimated RMSE of 0.8 mm/year for the differences and -0.3 mm/year as the mean of the differences (see Figure 18). For Uppsala and the InSAR-Sweden comparison, the similar localization of the subsidence pattern which is up to 6 mm/year, and where it concentrates in the city (see Figure 19). For point comparisons, the estimated RMSE of the differences is 0.4 mm/year with -0.2 mm/year as a mean of the differences (see Figure 20). For both studies (i.e., Gävle and Uppsala) the comparisons were performed for one track for each geometry, 102 and 95 for ascending and descending respectively.

Lantmäteriet has started initiating a new geodetic infrastructure in Sweden using radar reflectors and it is in progress. So far, we have installed three transponders and ten passive CRs in different locations. Different designs and sizes have been tested for passive reflectors and in the end for simplicity, ease of manufacturing and one installation at each location capable of tracking both ascending and descending, we chose the double backflipped squared trihedral type. Initially, this kind of CR with a 60 cm inner leg was installed at Norrköping and tested and the results were promising and showed RCS values of around 30 dBm2 and SCR of about 20 dBM2. To make it even better and secure high accuracy in some locations with higher background noise, we finally decided to increase the size from 60 cm to 72 cm inner leg (CR dimensions: 72x72x150 cm). To keep the CR snow and clogging-free, we equipped the CRs with radar transparent snow cover. The expected RCS values for such reflectors are around 35 dBm2 which is suitable for our mm-accuracy geodetic applications. The geodetic SAR data provided by such installed CRs located close to the permanent GNSS stations provide valuable information for different geodetic and ground motion monitoring applications including the newly launched European Ground Motion Service and its calibration in future updates.

5. Presentations at national and international conferences/meetings

Lantmäteriet independently or together with co-workers of the InSAR-Sweden project has participated and/or presented the project in/at national and international conferences/meetings as follows:

- Darvishi M., Eriksson L., Edman T., Toller E., Nilfouroushan F., Dehls J., (2022), InSAR based Ground Motion Service of Sweden: evaluation and benefit analysis of a nationwide InSAR service, ESA Living Planet Symposium, Bonn, Germany.
- Darvishi, M., Eriksson, L., Edman, T., Toller, E., Nilfouroushan, F., Elgered, G. & Dehls, J., (2022), InSAR-based Ground Motion Service of Sweden: evaluation and benefit analysis of a nationwide InSAR service. Nordic Geodetic commission General assembly, Copenhagen, Denmark.
- Gido N., Nilfouroushan F., Olsson P.A, Puwakpitiya Gedara C., (2022), Svensk markrörelsetjänst (SGMS) – baserad på InSAR-teknik, Geodesidagarna Upplands Väsby, Sweden.
- Nilfouroushan F., Gido N., Olsson P.A, Puwakpitiya Gedara C., (2022), Status report on the installations of geodetic SAR corner reflectors in Sweden, Nordic Geodetic commission General assembly, Copenhagen, Denmark.
- Nilfouroushan F., Gido N., Olsson P.A., (2022), Establishment of a new geodetic infrastructure in Sweden using SAR Corner Reflectors: Progress report, EUREF Symposium, Online.
- Nilfouroushan F., (2022), Lantmäteriets arbete med InSAR och radarreflektorer inom det Nationala geodetiska nätverket, (recorded presentation is available in YouTube https://www.youtube.com/watch?v=hvzsS5isd0M&t=147s).
- Nilfouroushan F., Gido N., Darvishi M., (2022), Cross-checking of the nationwide Ground Motion Service (GMS) of Sweden with the previous InSAR-based results: Case studies of Uppsala and Gävle Cities, EGU General Assembly, Vienna, Austria.
- Nilfouroushan F., (2022), Komplettering av den nationella geodetiska infrastrukturen för InSAR-tillämpningar, Kartdagar, Karlstad, Sweden.

6. Plans and thoughts for the future

We have 11 more corner reflectors in the house which are planned for installation by the end of 2023. To do so, getting permission from landowners, site visits and office works (SCR simulations for the desired locations, etc.) among others, are required before the permanent installation. So far, co-location of the CRs with the GNSS stations has been in focus and will be mostly in focus for future, but we will also see the possibilities if we can have at least one or two of the CRs co-located with tide-gauges. It is good to mention that some of the installed CRs are also co-located with absolute gravity points (see Appendix). Further investigation can be done to possibly install a small network of corner reflectors with shorter distances in an area of interest to learn more about the potentials of such CR networks for example for geodetic applications. The initial plan which is under investigation, is also to buy at least five new CRs every year and to continue with the development of the CR geodetic infrastructure in Sweden. Moreover, it is good to mention, our foucs has been so far on Sentinel-1 (C-band), but we may plan also for installation of the bigger size CRs for L-band future SAR satellite missions (e.g., NISAR).

We will also continue working with CR and ECR data and GECORIS toolbox (or similar toolboxes) to explore more the potentials of such devices, for example, for absolute positioning, time series and displacement analysis, etc., in future.

7. Acknowledgements

We would like to thank our Lantmäteriet colleagues, mainly Martin Lidberg and Eva Uggla, who has been involved in the discussions and initiation of the InSAR-Sweden project. We also appreciate the help of our colleagues, too many to list, for their support and for sharing their experiences. Mehdi Darvishi, a postdoc at Chalmers University is also appreciated for sharing his experience and knowledge on corner reflectors. GECORIS toolbox and SNAP software were used for data processing.

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9. Appendix

Here in this Appendix, some sample photos taken during fieldwork for the installation of corner reflectors at different locations are demonstrated (see Figure 8 for their locations and Table 3 for more details).

Figure 21, Drilling the bedrock to install the metal mast and corner reflector on top of that at Sveg near two permanent GNSS stations (SVEG.0 and SVEG.6). We had bee protection hats at this location because of nearby (~10 m) beehives.

Figure 22, Different types of CRs installed at different locations (see Table 3 and Figure 8). Note the different shapes of the CRs and snow cover. The ones at Mårtsbo and Onsala are trihedral triangular types with inner leg of 1 metre and snow cover. The ones at Visby, are trihedral squared shape (trimmed version) with 1 m inner leg size, and snow cover. The ones at Östersund, Umeå and Skellefteå is double-backflipped squared shape with 72 cm inner leg and snow cover.

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