

Monitoring Deformations in bridges via InSAR

Status

Title	Monitoring deformations in bridges via InSAR
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1 Executive Summary

This report describes the work we have undertaken for the Proof of Concept (PoC) and how we have met each of the minimum and additional requirements of the PoC. In addition it describes our findings from the analysis of the 20 bridges within the AOI.

As outlined in the Proposed Approach plan, we have completed some additional development work to complete the goals of the PoC, namely automated longitudinal profiles and some incremental improvements to change detection and alerting/reporting. We have many ways to enhance the visualizations of the data to support real users in the next phase of the project.

For the 20 bridges that we have characterized for this project, we have provided all the data in SkyGeo Maps, our web-based GIS portal. We show how this would serve as a catalog of reports for users.

In addition, we have made a summary table (shared separately) that includes all structural and operational information provided by MOW, and environmental information we found elsewhere. In this table we list if a change was automatically detected during the period studied (acceleration or change in amplitude) and if so, at what date. This table is a starting point for tracking possible risk indicators and events, thereby providing a pathway to an alerting system.

Furthermore, we have provided a zip file for each bridge, containing cross sections and a short report about change detection and point density/distribution of points. In a next project phase we will keep providing you the technical InSAR-related expertise. We will support you in the difficult work of helping users look at this large, complex, fuzzy dataset - and in integrating all this dynamic data into the MOW asset management workflow.

Through the PoC we have demonstrated a pathway to do wide area separation of geotechnically irrelevant noise from the type of deformation signal that is of potential concern to the structural integrity of bridges.

We look forward to helping you to take this monitoring approach to its operational phase. We will support the teams at MOW to successfully use the SkyGeo approach for early detection of geotechnical and structural issues with bridge performance.

2 Summary of work

As outlined in the Proposed Approach plan, SkyGeo has processed the TerraSAR-X (TSX) images provided by MOW (2014 - 2016) and Sentinel-1 (S1, A & B) data (2015 - 2021) using a PS/DS approach. We have taken additional steps to tailor the datasets for the goals of the PoC, including:

1. Improved positioning of InSAR points using LiDAR 'snapping' (<https://www.dov.vlaanderen.be/>).
2. Remove the temperature component from the InSAR time series, based on historical weather data from the Ukkel weather station, resulting in duplicate datasets with and without temperature.
3. Horizontal (east-west) and vertical decomposition for Sentinel-1 (for which both ascending and descending orbits are available), on the bridge components (bruggdelen).

A summary of the datasets in SkyGeo Maps are listed in Table 1.

To convert these InSAR datasets into insights into the displacements of bridges, the following steps have been taken:

1. Automation of longitudinal profiles (cross sections) along the length of the bridge. This was already a partial capability of SkyGeo, but some improvements have been made during the PoC, notably automating the cross sections for curved bridges.
2. Change detection, both in terms of identifying a change in displacement rate, but also a change in amplitude which often indicates a change on the surface such as that caused by maintenance.
3. Incorporation of additional external datasets, such as geological maps (Table 2)
4. Alerting system, a concern level defined per bridge shown in SkyGeo maps and a summary table

Table 1: Description of all the InSAR datasets available in SkyGeo Maps.

Dataset name	Time period	Area covered	Description
S1 asc (bridges)	03/05/2015 - 03/11/2021	Bridge and surrounding 10 m	
S1 dsc (bridges)	29/01/2015 - 12/10/2021	Bridge and surrounding 10 m	
TSX (bridges)	24/06/2014 - 23/03/2016	Bridge and surrounding 10 m	
S1 asc (temperature removed)	03/05/2015 - 03/11/2021	Bridge and surrounding 10 m	S1 asc with the seasonal temperature component removed
S1 dsc (temperature removed)	29/01/2015 - 12/10/2021	Bridge and surrounding 10 m	S1 dsc with the seasonal temperature component removed
TSX dsc (temp removed)	24/06/2014 - 23/03/2016	Bridge and surrounding 10 m	TSX dsc with the seasonal temperature component removed
S1 asc (full AOI)	03/05/2015 - 03/11/2021	Full PoC AOI (not including the bridges and surrounding 10 m)	
S1 dsc (full AOI)	29/01/2015 - 12/10/2021	Full PoC AOI (not including the bridges and surrounding 10 m)	
TSX (full AOI)	24/06/2014 - 23/03/2016	Full PoC AOI (not including the bridges and surrounding 10 m)	
Vertical/horizontal	05/2015 to 10/2021	Brugdelen shapes, minus a 10 m buffer around the pijlers	Underlying data: S1 ascending and S1 descending
Vertical/horizontal (temperature removed)	05/2015 to 10/2021	Brugdelen shapes, minus a 10 m buffer around the pijlers	Underlying data: S1 ascending and S1 descending

Table 2: Additional layers in SkyGeo Maps

Layer name	Description
Bridge number	Bridge number, provided by MOW
Maintenance date	Date of maintenance, provided by MOW
Bridge sections	Location of bridge sections, provided by MOW
Pillars	Location of pillars, provided by MOW
Abutments	Location of abutments, provided by MOW
Bridges shapefile	Combined shapefile of all the bridge sections, provided by MOW
Temperature	Time-series of temperature from 2015 to 2021 taken at Ukkel weather station.
Alluvial	Location of alluvial plains. Source, Geological map of Belgium, 1:40 000
Tertiary Geological Map of Flanders	Tertiary geological map of Flanders. Jacobs, P., & De Ceukeiaire, M. (2000). The new geological map of Flanders (Belgium).
Quaternary geological map of Flanders	Quaternary geological map of Flanders. Source: DOV and Bogemans, F. (2005). Technisch verslag bij de opmaak van de quartair geologische overzichtskaart van Vlaanderen.
Peat occurrences	Boreholes locations with peat occurrences from the boreholes DataB of the Geol Survey

2.1 Minimum requirements

Below we discuss how we meet each of the minimum requirements:

Point based deformation map / Platform

SkyGeo maps (<https://maps.skygeo.com>) is a web-based GIS portal which contains the InSAR data map and a number of tools to inspect the results (Figure 1 and 2). A description of all the datasets available can be found in Table 1. As per the requirements, access to SkyGeo Maps will be available for 3 years. Furthermore, each of the InSAR point layers can be downloaded as a .csv from SkyGeo Maps and the additional layers can be downloaded as a geopackage (.gpkg).

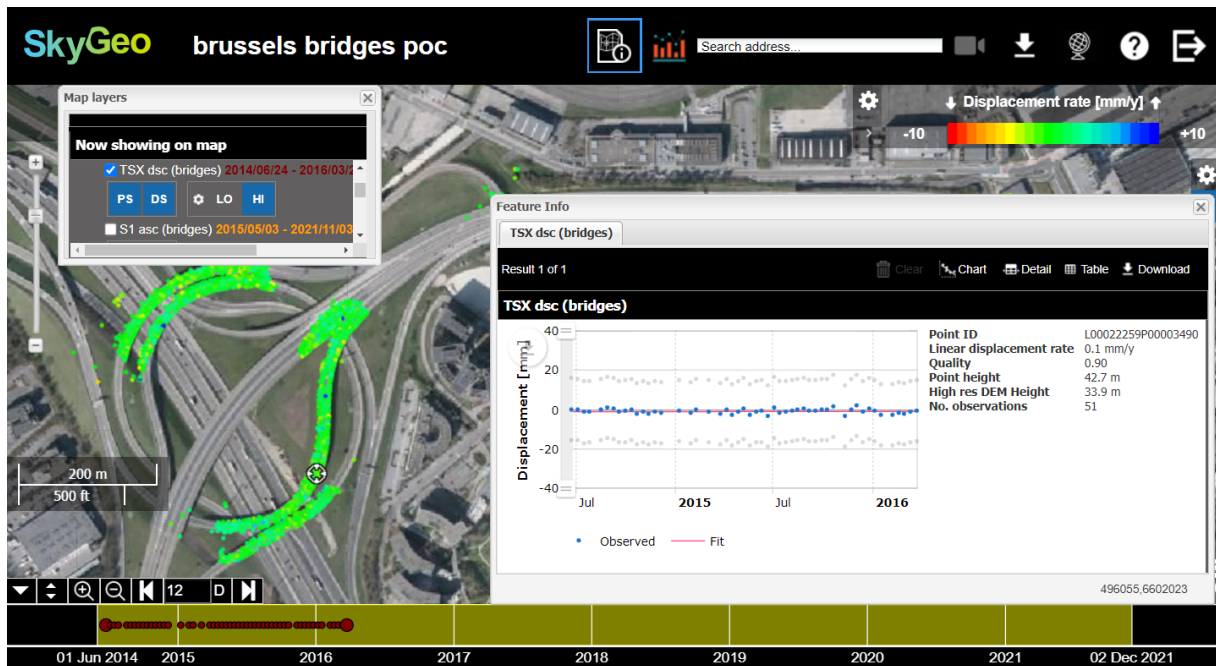


Figure 1. SkyGeo Maps web-based GIS portal containing all the persistent scatterer InSAR points for the given set of bridges. The configurable color bar indicates rate of displacement. For each PS point, the underlying time-series can be inspected. The viewer also contains a number of tools such as area averaging, filtering by displacement rate, profile drawing etc. to help the user inspect that PS data. The yellow time slider at the bottom of the figure indicates the individual TSX acquisition dates underlying the time series shown in the popup.

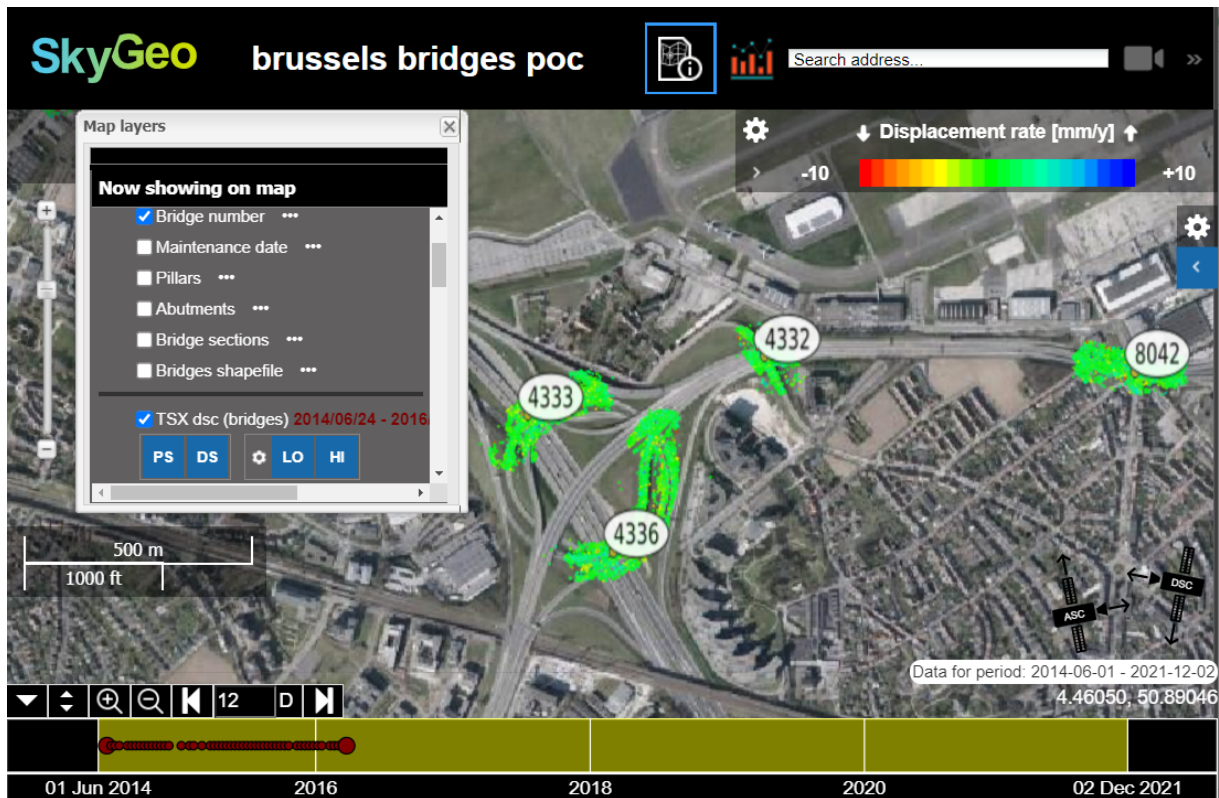
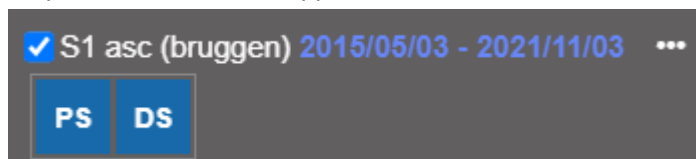


Figure 2. Layer with bridges identified by Bridge number, which can be toggled on and off to see locations and a time series for a point on bridge 9105. The bridge numbers can be made a queryable layer as well for operational use, with each location + ID number pointing to a bridge report in the SkyGeo Report viewer.

PS and DS points

PS and DS (persistent and distributed scatterer, resp.) points can be distinguished with our PS/DS toggle in the data layers panel. For an elaborate discussion on the difference between these two types of scatters, please refer to the Support content under the “?” icon in the top menu of the viewer.



Display of deformation and deformation rate

We have provided two versions of the results in SkyGeo Maps, one where the colour bar is set on displacement rate (mm/yr) and the other on cumulative displacement (mm).

Distinction TerraSAR-X (TSX) and Sentinel-1 (S1) results

These two types of data products can be easily distinguished from the layer names, and inspected and compared using the SkyGeo Maps statistical toolbox (Figure 3).

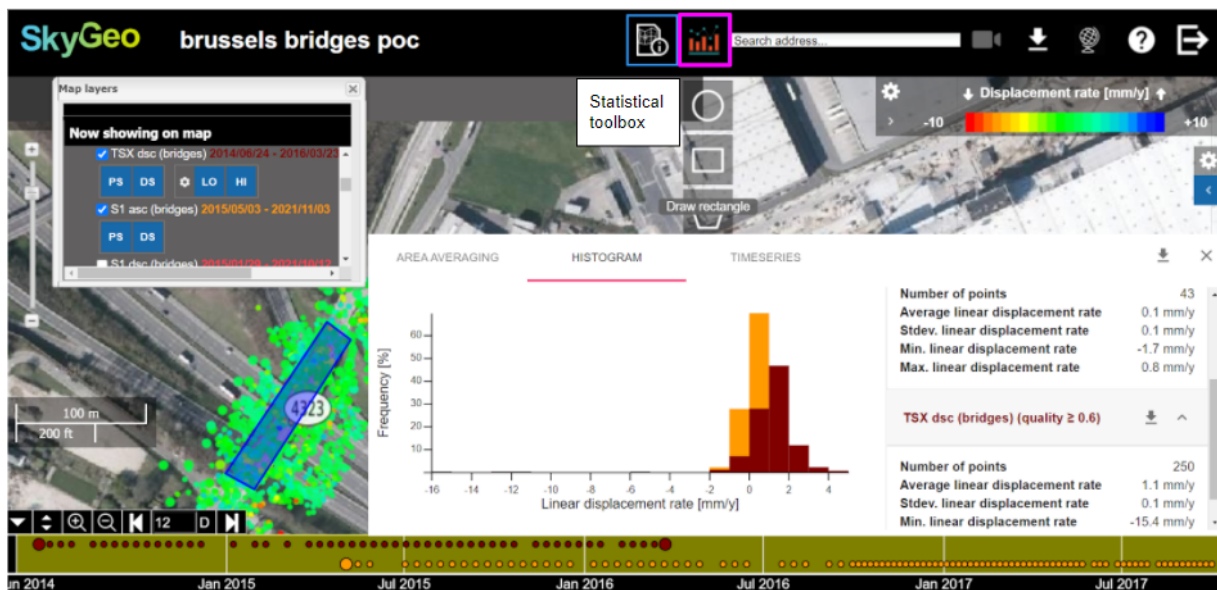


Figure 3. Here we show one way to compare the different data layers in SkyGeo Maps, by using the area averaging tool from the Statistical Toolbox (labelled in pink) and viewing the time series of both datasets, or a histogram (as shown here). The S1 data has a “burnt orange “ color in the viewer - incl. the pop up - and the TSX very high res data has the “dark brick” color in the viewer. This corresponds to the time slider at the bottom where each data set is shown as well (the data sets cover different time periods).

Accuracy

For every point there is a point ‘Quality’, which is a measure of quality of the fit between estimated deformation and observation. The SkyGeo InSAR engineer will choose a suitable minimum point quality dependent on a number of factors including deformation pattern (seasonal, linear, non-linear etc), number of satellite images, terrain etc. There is also the ensemble coherence (Pnt_enscoh) and amplitude consistency (Pnt_ampconsist) which represent the temporal consistency of the phase and amplitude respectively (Figure 4). The standard displacement precisions for the SkyGeo processing chain are outlined in the table below, for S1 it is approximately 2 mm/yr and for TSX < 1 mm/yr (Table 3). Do note that higher quality points have smaller standard deviations.

Name ▲	Value
Point ID	L00004164P00003451
Pnt_flags	0011
Latitude	50.900843 °
Longitude	4.428263 °
Pnt_line	4164
Pnt_pixel	3451
Point height	31.1 m
DEM height	17.2 m
Pnt_geoid	45.48478
Pnt_incidangle	31.61829
Pnt_enscoh	0.66156
Pnt_ampconsist	0.46488
Quality	0.66
Linear displacement rate	0.4 mm/y

Figure 4. Various properties of each PS/DS point can be assessed under metadata. accessed through the PS popup window, at the Detail symbol show in blue.

Table 3. Displacement and geolocation precision of Sentinel-1 and TerraSAR-X PS-InSAR processing.

	Sentinel-1	TerraSAR-X (SM)
Image Frequency nominal	12 days	11 days
Point Density (approx. for Pearl site, after filtering)	~10,000 points per km ²	~100,000 points per km ²
Displacement Precision (Individual Image)	3 to 5 mm	2 to 3 mm
Displacement Velocity Precision (Series of Images)	2 mm per year	<1 mm per year
Geolocation Precision ST DEV	6 to 8 m in x/y-axis (horizontal) 4 m in z-axis (vertical)	2 to 3 m in x/y-axis (horizontal) 1 m in z-axis (vertical)

Georeference

For each point, the DEM height and point height can be inspected, as well as the coordinates of the point in both Lambert and WGS84 coordinate systems (in the detail tab, WGS84 is the 3rd and 4th row, and Lambert coordinates are the last 2 rows of the table, see Figure 5). Reference points can be inspected in SkyGeo maps by right clicking on the layer. More information on referencing and

reference point noise can be found in the separate QC report (section 2.3). The geolocation precision of InSAR points are outlined in the Table 3.

Name ▲	Value
Point ID	L00022526P00003232
Pnt_flags	0011
Latitude	50.884814 °
Longitude	4.464199 °
X_lambert	156716.44877791483
Y_lambert	174943.7914417358

Figure 5. Coordinates in WGS 84 and Lambert can be found under metadata per PS (access through the PS popup window, at the Detail symbol show in blue)

Longitudinal and Width Profiles

The user can manually draw or upload a line to draw a profile in SkyGeo maps. Automation of this process has been completed as part of the PoC and is described in section 2.2.

Reporting

Reporting outcomes are described in 2.3.

2.2 Additional requirements

Maximum availability in case of works

We have not applied any additional processing interventions in the PoC to increase the number of points on bridges where works have been carried out, in other words where persistent scatterers are no longer fully persistent. The projected impact was low for this factor, since only 2 bridges had point loss on small sections in our POC results as due to such maintenance works (see reports per bridge for details). In the next phase, if it is found that temporary works affect point density on a large number of bridges, this work would be expanded. We have designed (and keep building) numerous tools and techniques that we will apply in our processing environment to mitigate here.

In an operational engagement, we will test and validate this per bridge before further automation. The goal is to support operational minimization of effects from works on the ability to do wide area identification of geotechnically relevant deformation signals.

Surroundings

As described in Table 1, there are layers labelled 'bridges' that are the bridges with a 10m buffer applied. There are separate layers labelled 'surroundings' that are the full AOI, minus the area of the bridges. To clearly distinguish between bridges and surroundings. The 10 m buffer allows for inaccuracies in the positioning of S1 points. The TSX layers have a configurable height filter, which can further help distinguish which points belong to which parts of the bridge (Figure 6).

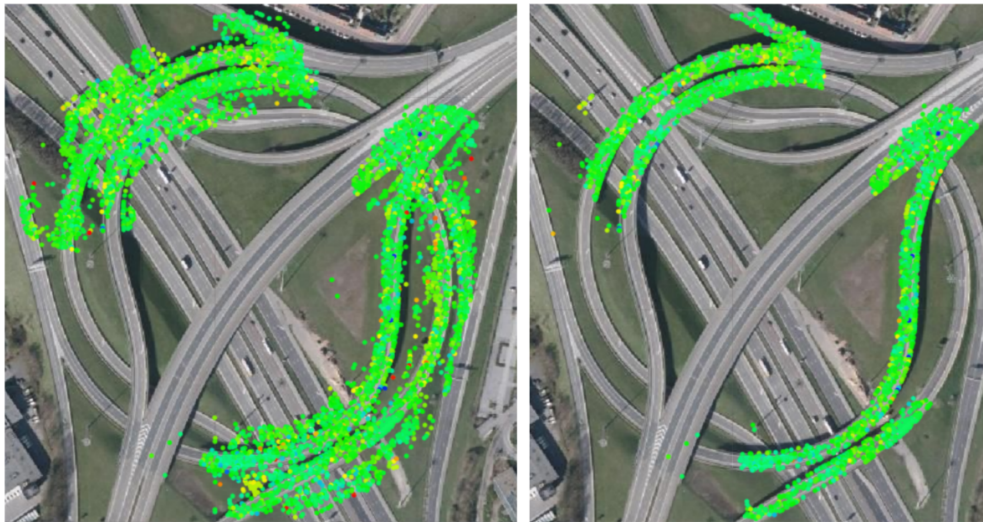


Figure 6. PS-InSAR results over Brug R21, demonstrating the application of the configurable height filter. Left: all points within a 10 m buffer of the bridge. Right: only PS with a georeferenced height > 3 meter. Note that both data sets have been “snapped” to the LiDAR data.

Automation of analysis

Many aspects of the process can be automated, however from experience, even if the whole process can be automated, such an automated solution would still require domain expert input to assess the intelligence and context in order to derive proper conclusions in re. geotechnical and structural stability.

Our processing chain is automated using slurm processing, which allows us to optimally leverage our infrastructure and automatically schedule processing jobs in succession.

For the POC we applied two extra steps from the standard approach, the results with and without temperature correction and snap-to-LiDAR, which refines the point positioning in 3D space. For this we use the uncertainty in the position per point and compare each point to DHMV II LiDAR point-cloud data in order to locate the most likely origin of the scatter. The full processing approach can be automated, however, we have a manual Quality Control procedure before results are released.

The automation of change detection, alerting and longitudinal profiles will be elaborated in the related sections.

Filtering out local disruptions

We have not deemed this necessary to automatically filter out disruptions, because they do not appear to have greatly impacted the point density on the bridges. The point density and distribution of points are discussed further in the individual bridge reports.

Automation of longitudinal profiles

As stated in the tender documents, our automation of length and width profiles has been further developed as part of the POC. We already had the capability in SkyGeo maps for the user to manually select a search radius along a line or upload a shapefile/kml of the specific geometry to plot a profile. We have now automated the process further, so that we use the shapefiles of the bridges provided by MOW and automatically create a line along the centre of the shape along the longest axis and create a cross section collecting all the points within a shape (Figure 7 and 8)). The cross sections have a line of displacement every 6 months (note that we discussed 3 months intervals in a previous meeting with MOW, but for stable bridges, we found the number of lines to reduce the readability of the plots, so have proceeded with 6 month intervals for now).

We recognise there is room for improvement with these cross sections, which can be easily implemented in the next phase of the project. For example:

- The location of pillars are marked on the accompanying image with the cross sections, but not on the cross section itself. Additionally there are a few bridges with missing pillar lines that should be resolved.
- Start and end (0 to X m) and some intervals marked on the basemap.
- The scale on the y-axis should be adjusted in some occasions to increase readability.
- The colours of the lines every 6 months are hard to differentiate and should be changed.

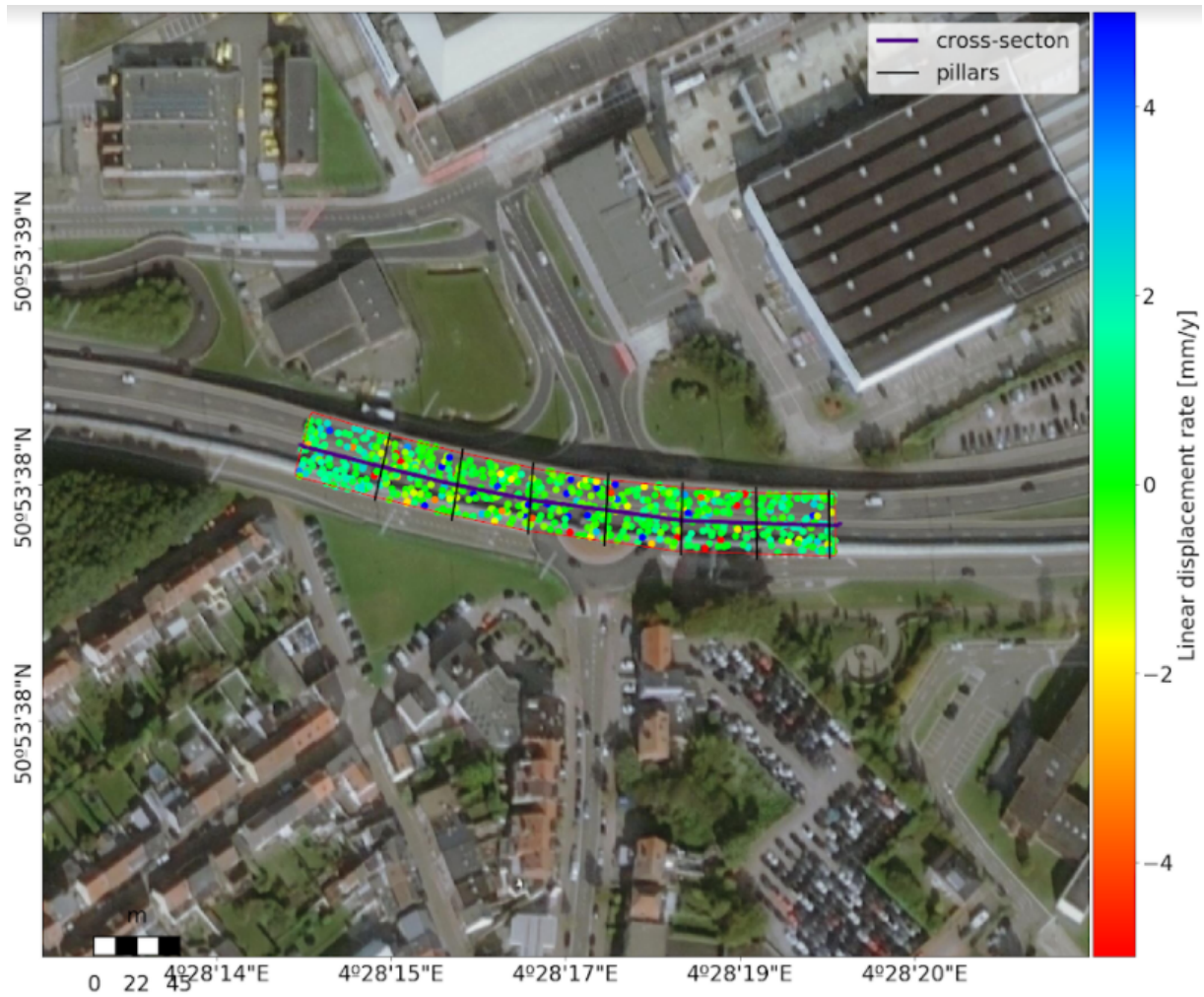


Figure 7. Image per cross section with the cross section line in purple, bridge pillars indicated in black and the area within which points are averaged in red (bridge 8042, TSX).

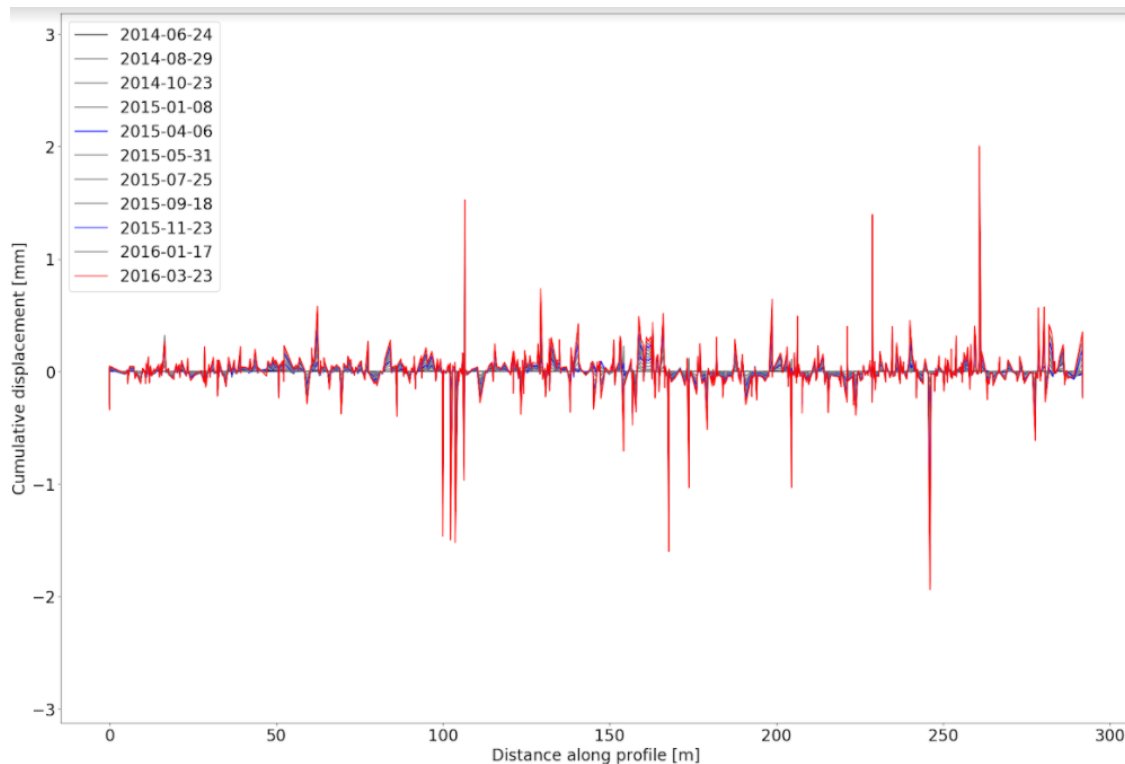


Figure 8. Cross section along the longitudinal profile of a bridge 8042 (TSX) from Fig.7, with a line of cumulative displacement (mm) every 6 months. In spite of a spiked appearance, given the displacement scale of +/- 3mm, these are low noise levels indicating a relatively stable bridge. We can configure additional ways to visualize this stability in the viewer.

Detection of sudden changes in displacements

Our change detection process is semi-automatic. In terms of change in displacement we have an automated tool that enables detection of events based on the computation of the standard deviation for a window (containing a small number of epochs) that slides over the time series. The computation of change is done via the standard deviation (eg. how much a new displacement value deviates from the mean of the preceding displacement values). Therefore the change detection system highlights bridges with a sudden variation in the time series behavior. However, the results for each bridge need to be manually inspected to determine if the detected change is meaningful in terms of displacements/stress for the structure.. This could be expanded in consultation with MOW in future works.

The second part of change detection is a change in amplitude. A change in amplitude means that the reflective characteristics of the reflecting point or surface are changed. This change of reflective characteristics can be best explained by a change of material, indicative of a surface change. This detection of change is fully automated, though manual interpretation is required.

Temperature variations

As described in Table 1, two versions of each dataset have been provided, one with temperature variations included and the other with effects of temperature removed (Figure 9). Daily temperature

readings were extracted from the Ukkel weather station for this correction. The time series of temperature used can be viewed in SkyGeo Maps and compared with the InSAR time series.

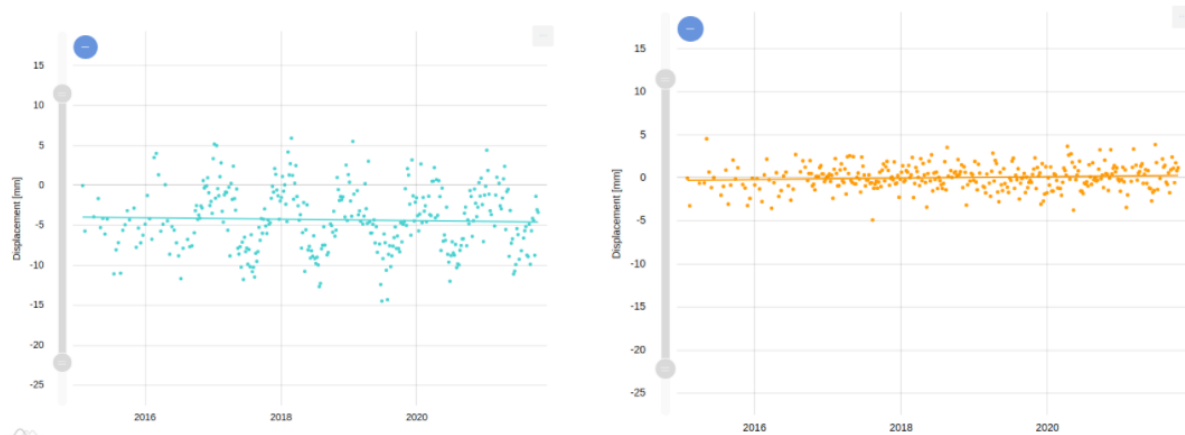


Figure 9. A before (blue) and after (orange) temperature correction time series for part of the Viaduct Zeekanaal Brussel-Schelde.

Alerting system

For the PoC, given that we are looking at historical changes, we have derived an alert system based on whether there has been a change in amplitude (yellow), change in displacement rate (orange), a change in amplitude and displacement rate (red) or no change at all (green). The classification per bridge can be viewed in SkyGeo Maps using the layer 'Bridge Change Detection' (Figure 10). Further information on the change is available in the per bridge report and in the summary table.



Figure 10. Alerting system in SkyGeo Maps, in the same viewer. For the PoC bridges are coloured based on amplitude (yellow), change in displacement rate (orange), a change in amplitude and displacement rate (red) or no change at all (green). This view can also be integrated into the catalog for end-users with access rights to see the report per bridge and or the underlying InSAR data.

Reliability of results per bridge:

In order to assess reliability of the results per bridge we can distinguish different aspects and characteristics of both the bridge and the InSAR result, such as bridge size, spatial resolution of the satellite, bridge material etc. All these factors can be inspected in SkyGeo Maps.

Point density

We find full coverage and maximum point density for most bridges. Outliers are bridges with very long decks (600m+) , where seasonal expansion dominates the signal into speeds that are not measurable without special processing attention. We expect the occurrence of these bridges to be low throughout the whole sample of bridges. The point density per bridge is described in more detail in the per bridge reports.

Horizontal displacement:

We have decomposed the ascending and descending S1 LOS displacements into horizontal and vertical components for each bridge segment. As discussed in consultation with MOW, the areas of the bridge segments in between the pillars are of most importance, because the pillars are expected to be stable. Therefore we have applied a 5 m buffer to either side of the pillar segment and then applied the decomposition on the area between those. Due to the varying size of bridges, and spatial resolution of S1, this has resulted in many blank segments. We would expect this approach to be more successful with TSX, but both ascending and descending orbits would be needed. A comparison of the changes made between the iteration on segment size can be seen in Figure 11.



Figure 11. Decomposition of S1 ascending and descending into horizontal displacements on bridge segments (westward movements in orange and eastwards movements in blue). Left: area in between the pillars with a 5 m buffer on either side. Right: bridge segments with no buffer around the pillars.

In-depth analysis of zones where no InSAR points are available

An interpretation of the lack of points on a particular bridge or bridge segment is provided in the individual report per bridge where necessary.

2.3 Reporting

Report per bridge

Per bridge, a zip folder containing 10 png's and 1 pdf report is provided. The prefix refers to the satellite e.g. TSX, S1_dsc and S1_asc. The cross sections are based on the non temperature removed dataset. For each satellite there are:

basemap	Location of the cross section	Cross section line in purple, location of pillars are black lines and the area within which InSAR points are selected is red. Cross sections are from left to right (west to east).
defo	Cross section of cumulative displacement (mm)	Line every 6 months
_cross_section_linear_rate	Averaged linear displacement rate across the full time period	

In addition for TSX, there is a plot 'TSX_cross_section_seas_amplitude' which is a plot of the seasonal component of the time series along the length of the bridge. A high amplitude (mm) means there is a big thermal expansion/contraction component and is most relevant for the steel bridges.

If this PoC turned into an operational monitoring project, we propose utilising our web-based map reporting for per bridge reports. A demo of this is shown in Figure 12.

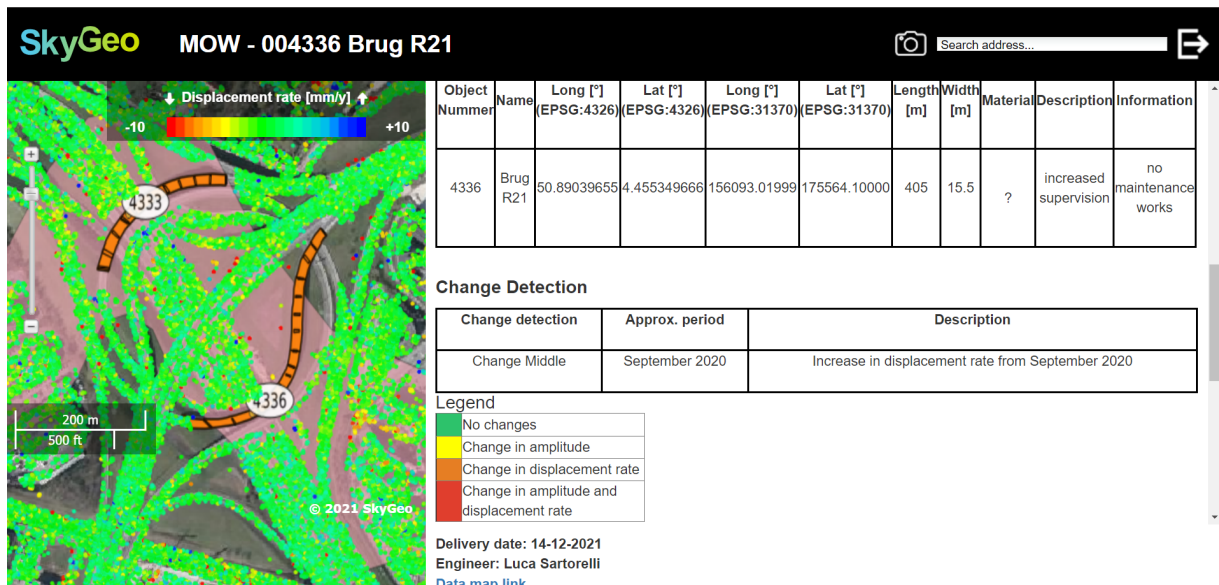


Figure 12. Example of a SkyGeo Maps web-based report for bridge 4336. This report is fully configurable. Text and notes can be added by admins and users (in the viewer and in the report itself). All reports are accessible for users, with configurable access rights, through the map-based / web-based catalog of reports we would provide in an operational monitoring environment.

Quality control report

In addition, we have shared our automated Quality Control (QC) report per dataset (S1 ascending, S1 descending and TSX). These provide detail on the number of images, referencing, atmospheric removal etc. These reports are technical and relate to the InSAR processing and should be interpreted by someone with InSAR experience.

SkyGeo Netherlands B.V		SkyGeo
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Figure 13. Contents page of our Quality Control (QC) Report. A QC report is provided per dataset.

2.4 Result for the bridges in the PoC

The InSAR results for the PoC can be found in SkyGeo Maps, in two viewers named ‘Brussels Bridges PoC’ and ‘Brussels Bridges PoC Cumulative’. The only difference between the two viewers is how the InSAR points are coloured. In the standard viewer points are coloured by displacement rate (mm/yr) and the point colour adjusts on-the-fly with the time slider. In the viewer labelled Cumulative, the point colour is set by the cumulative displacement (total displacement between the first and last date) and the time-slider functionality is turned off. The user can decide which view they prefer.

A table, titled ‘bridge summary table’, is provided which contains a summary of the key information about each bridge, including material, maintenance works, if a change was detected, when the change was detected and if it was a change in amplitude or acceleration. It also contains additional information on the geology, such as if the bridge is within the alluvial plain or has a peat occurrence within 250 m. These factors pave the way for a risk index in future phases of the project.

Of the 24 bridges, 13 had a ‘change detected’. 11 had an acceleration and 8 had a change in amplitude. These changes are recorded over a period of 6-7 years (using both S1 and TSX), hence a

high number. In future project phases, thresholds should be set to determine whether a change is significant enough to report.

3 Conclusion

As we have demonstrated in this report and through regular meetings with MOW throughout the PoC, we have the technical capabilities to meet both the minimum and additional requirements of the PoC. We have completed some additional development work to complete the goals of the PoC, namely automated longitudinal profiles and some incremental improvements to change detection and alerting/reporting.

In order to meet the requirements, the final results contain a lot of data, such as with/without temperature corrections, wide area results, small area contextual processing for the bridges etc. In a next phase of the project, the team at SkyGeo will help to distill the most relevant information for these datasets into a format that is easily digestible for the bridge engineers. This is a core activity of the Technical Services team at SkyGeo, turning millions of coloured InSAR dots into a tailored service that meets the customer requirements and can be integrated into existing workflows.

As a consortium (SkyGeo and RBINS), we can share common knowledge on the relationship between the measured local deformation and possible regional effects due to groundwater extraction, unconsolidated or poorly consolidated soils, and related. The potential scope of other, supporting data sets is likely to expand.

Following the list of 5 requirements in MOW's Scope of Work, we specifically have shown in this PoC that we:

1. Meet the minimum requirements as defined by MOW;
2. Meet all additional requirements within the PoC;
3. Have a team of people with outstanding technical domain expertise in producing and interpreting InSAR estimations and presenting these estimations as a dynamic image, and in scaling this to operational levels (see Appendix A);
4. Can add value by integrating these InSAR results with local expertise and additional local datasets; through extensive experience in similar projects; also by continuously building up a web-based toolset for geotechnical + geostatistical interpretation and reporting;
5. Can add value in aiding interpretation of measured displacements/deformations by providing expert advice, by simplifying and filtering and converting coloured dots into actionable reports; adding automatic detection of signals and events and working together with the MOW team.

In the next phase of the project we can still work out the many technical and operational improvements that have presented themselves in this PoC. We will help make this data accessible and usable for end users; in our experience this is actually the bulk of the operational work for all projects we are engaged in, and will be based on close interactions of the SkyGeo and RBINS engineers with the teams at MOW.

Appendix A - The SkyGeo & Royal Belgian Institute of Natural Sciences team

Name	Years of InSAR Experience	Details
Dr. Jennifer Scoular	8	Jennifer Scoular is an InSAR Application Engineer in the Technical Services Team at SkyGeo. She holds a PhD in applied InSAR for geotechnical hazards from the Civil Engineering department of Imperial College London (UK) and an undergraduate degree in Geology, also from Imperial College London. She has eight years of experience working with radar data and has published multiple papers in peer-reviewed journals applying InSAR methodologies. Technically skilled in both InSAR methodology and geosciences, she supports our customers by developing target-specific solutions for connecting the deformation to the driving geological processes in the subsurface.
Dr. Pierre-Yves Declercq	20	Pierre-Yves is a geologist at the Royal Belgian Institute of Natural Sciences and a leading expert on using InSAR for the Belgian subsoil. He has published multiple papers in peer-reviewed journals applying InSAR methodologies.
Hanno Maljaars	7	Hanno leads the data pipeline team, making sure that all data is made and delivered to customers on time and on spec. This is usually an iterative process so he oversees operational technical customer interactions. He is also in charge of the quality assurance process to meet the high standards that we set as a company. Hanno holds a BSc in Aerospace Engineering and a MSc in Geoscience & Remote Sensing, both from the Technical University of Delft. Since 2015 Hanno has been involved with the InSAR monitoring projects, both onshore and offshore.
Luca Sartorelli	3	Luca Sartorelli is an InSAR Application Engineer in the Data Pipeline Team. He graduated in Environmental Engineering with a master's thesis about Use of SAR satellite data in bridge structural health monitoring. He processes the InSAR data and helps in the displacement interpretation thanks to his expertise in InSAR processing and monitoring skills.
Timo Millenaar	5	Timo Millenaar is a Scientific Software developer at the Platform Team at Skygeo. He holds a MSc and BSc in Geology from Utrecht University with a focus on numerical modelling. By developing new software and maintaining the processing infrastructure he enables data processing and visualisation tailored to the customer's needs.

Question 1:

The points for the analysis with and without temperature correction are not located on the same position, both for TSX and for sentinel. What could be the reason for this?

Answer:

We have used different models for these two datasets, one based on temperature and one without.

By estimating with these different parameters, we affect *all* other estimated parameters, including point positioning and quality parameters.

The difference in unwrapping approach results in a different point position and density.

To elaborate, the temperature dataset is used in the unwrapping step of the processing, so for all subsequent steps, there will be differences in the two datasets. For example, if you have unwrapping errors in the non-temperature corrected dataset you may get incorrect heights which results in incorrect positioning. The difference in unwrapping approach also affects the point quality. So although the point quality is set the same in the viewer (0.6 for both datasets), the final quality attributed to each point, even in the same location, will be different due to the differences in the unwrapping approach.

An alternative approach would have been to apply the temperature correction at the final step, to the non-temperature-corrected PS points. However, for this approach the heights and positions would not *benefit* from using the temperature model. Hence, we show estimates in the viewer derived with the first approach.

Question 2:

In what unit is the point height? This does not seem to match the expectations we have?

Answer:

The height is in metres (orthometric height, height above mean sea level). Can you confirm which layers do not match your expectations? If I set the height slider to 132 - 212m as it is in your screenshot, all the TSX dsc points disappear (because they are below 132m).

We have revisited the results and TSX dsc and S1 asc have logical point heights, within a few metres of the DEM height (per point in the popup). However, in comparing with the S1 dsc results again in light of your question, we notice that there is a systemic error in the viewer configuration for the point height for this layer. The DEM height is off by 45m and point height off by 90m (DEM height plus geoid undulation).

The XY positioning and displacement rates are correct. Nevertheless this could have been picked up during comparison in our Quality Control.

We have updated the viewer with this relative height fix for S1 dsc; the original layers are still there (at the bottom of the layer panel) if you want to compare the heights before/after the change. To emphasise, the XY position and displacement rates have not changed, the only change is the point height displayed.

Question 3:

There seem to be very much DS points (more than PS). If I understood correctly, DS points are based on multiple pixels sending out a low reflection. How is it possible that there are so many DS points? Based on the explanation which is written on the website, we could not deduce this?

Answer:

Persistent scatterers occur where there is a single dominant scatterer within the SAR image resolution cell that yields a consistent reflectivity value in time. Distributed Scatterers are groups of pixels where multiple objects show a weaker reflection, at a relatively similar strength. If a pixel is classified as a Distributed Scatterer, our algorithm will search for neighboring pixels with similar reflection characteristics. If multiple neighbors show comparable reflections, the relatively 'weak' signal is considered persistent.

The DS "patches" can overlap resulting in many DS points which contain overlapping information, hence the high number in certain types of terrain.

The number of PS vs DS depends on the type of terrain. For example, see the figure below: on the airport runway, there are many more DS than PS, which is expected as there are no clear objects that would lend themselves to being a dominant scatterer (PS).

Stretches of road are good candidates for DS, because there is no single dominant scatterer, but a large area with similar reflectivity characteristics.

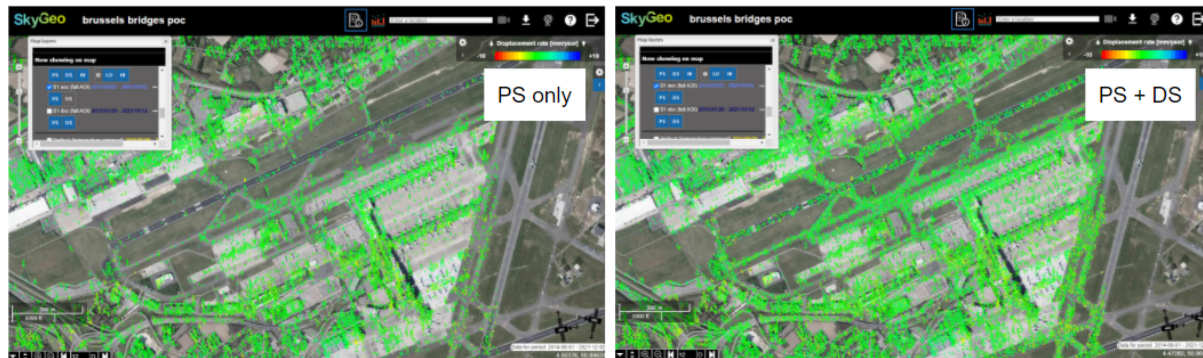


Figure 1. DS vs. PS density over airport .

In an area with houses and buildings, there are more PS than DS, because there are lots of strong reflectors. Houses, streetlamps, sheds etc. can act as natural corner reflectors.



Figure 2. DS vs PS density over a residential area.

On the bridges themselves, the PS are distributed in a non-homogeneous way: PS are mostly concentrated on the edges, where the road meets the safety barriers, or on the central reservation.



Figure 3. PS vs DS density on the road.