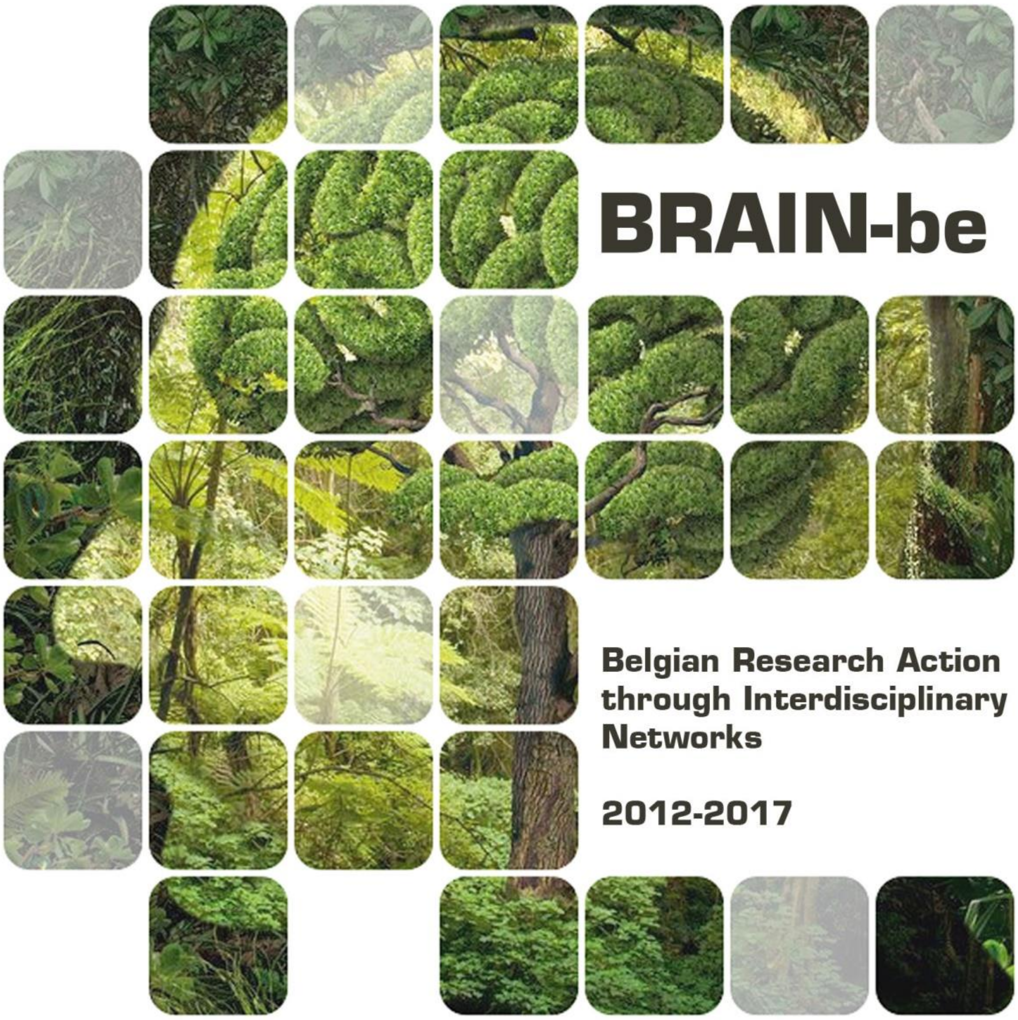

[GEPATAR]

[GEotechnical and Patrimonial Archives Toolbox for ARchitectural conservation in Belgium]

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Axis 6: Management of collections

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Belgian Research Action through Interdisciplinary Networks

2012-2017

NETWORK PROJECT

GEPATAR

GEotechnical and Patrimonial Archives Toolbox for ARchitectural conservation in Belgium

Contract - BR/132/A6/GEPATAR

FINAL REPORT

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ABSTRACT

Context

Built heritage is of exceptional cultural and economic importance for a country and its protection is imperative. In Belgium, thousands of buildings categorized as cultural heritage and more than 300,000 as buildings for preservation. These buildings suffer from physical, mechanical, chemical, and biochemical types of pathologies due to settlement induced damage (Figure 1) caused by heavy industrial and urban development. The measurement of the progression and distribution of ground movement is necessary in order to create reliable forecasting models and to adopt an appropriate structural preservation. However, traditionally it is measured using time consuming and costly in-situ terrestrial methods.

Figure 1: Example of ground settlement damage

Objectives

The GEPATAR project aims creating an online interactive geoinformation tool that allows the user to view and to be informed about the Belgian heritage buildings at risk due to differential ground movements. Specifically, the project built a framework to assess the potential damage caused by ground settlement for masonry, infilled and bare frames structures using Persistent Scatterer Interferometry (PSI). This spaceborne based Synthetic Aperture Radar (SAR) method has been proven as a unique remote-sensing tool for low cost and precise (1 mm) ground surface deformation measurement.

Conclusions

The PS-InSAR processing results permitted to highlight subsidence or uplift that can be interpreted and followed through years with a millimetric precision. The processing realised on different satellites allowed to follow the evolution of the ground movements at different epoch since 1992 up to now. The developed damage model was directly implemented in the GEPATAR toolbox. Overall, it was found that distinguishing between movement due to structural changes, such as alterations in the roof, and movement due to ground settlement and uplift is not straightforward. The GEPATAR toolbox including the integration of the heritage data, the PS-InSAR data, the damage model, is available in three languages under the domain http://gepatar.kikirpa.be/.

Keywords

Structural monitoring, differential settlement, heritage building, InSAR, remote sensing

1. INTRODUCTION

In the current context of global change and general budget restriction an effective protection of cultural heritage in Belgium and across Europe is becoming an important concern for the policy makers and the citizens (http://www.jpi-culturalheritage.eu/). Belgian built heritage is the most diverse and rich patrimony that attracts millions of visitors every year to monuments, historical city centres and archaeological sites. This heritage is an important component of individual and collective identity and plays a fundamental role in the national and regional integration by creating links between citizens. Moreover, the built heritage is of exceptional economic importance for the tourism industry, generating many thousand jobs in the tourism sector, directly or indirectly linked to it.

In Belgium, thousands of buildings are categorized as cultural heritage and more than 300000 as buildings worthy of preservation. Due to climate change, heavy industrial and urban development, cultural heritage buildings suffer from physical, mechanical, chemical, and biochemical pathologies along their history. Several studies have shown that the lowering of the groundwater table due to changes in precipitation patterns and rises in temperature with an increase of pumping has a direct impact on ground movements. An adequate protection and preservation of the built patrimony requires the integration and the analysis of environmental, architectural and historical parameters. The GEPATAR project aims to gather and exploit federal data collections available at RICH and RBINS-GSB for the prediction of structural damage to heritage buildings due to ground movements, based on the fusion of remote sensing and heritage data using innovative processing techniques.

GEPATAR created 2D damage models integrated long time-series radar data with limited information on the structural typology. The GEPATAR toolbox was developed in the form of a WebGIS interface and optimized for the stakeholders and end-users, both for experts as well as the general public. With this toolbox, GEPATAR contribute to the valorisation of the damage models and the data collections regarding built heritage in Belgium at the Federal and Regional levels. The project results also have the potential to radically change the monitoring approaches for structural damage in built heritage and secure the continuity of the Belgian patrimony in the UNESCO's catalogue.

2. STATE OF THE ART AND OBJECTIVES

Cultural heritage buildings suffer from physical, mechanical, chemical, and biochemical types of pathologies during their history, e.g. rock alveolization, efflorescence, biological activity, and capillary ascent of groundwater (Tomás et al., 2012). In addition to alter the appearance of the monument these factors inherent to the building material affect the structural behaviour of the construction and its stability. Moreover, external human factors such as groundwater pumping, underground galleries, excavations contribute to disturb the stability of the buildings. Frequently, collections of archives such as coal mines, galleries maps help to delimit area subject to ground instabilities. On the other hand, underground excavations of phosphate or clays are known but their exact localization is unknown due to their usually artisanal state. For instance, subsidence generates ground settlement due to a growth of soil effective stresses following a reduction in piezometric level. This phenomenon is usually not spatially uniform due to soil properties and spatial variations of deformable soil thickness and piezometric levels, causing differential settlements and distortions that affect the buildings foundations. The measurement of the progression and distribution of these settlements is necessary in order to adopt the appropriate corrective or mitigation measures on the subsidence caused by aquifer or subsoil exploitation. The main assumption of the project is that patrimony buildings are in risk due to the ground deformation hazard around their constructions. State-of-the-art proves that the assessment of ground deformation is done in successful and accurate manner using PS-InSAR method. Therefore, one of the main objectives of GEPATAR is to develop a tool that explores the large SAR image archive available at RBINS for the development of ground deformation mapping. In the last decade, repeat-pass satellite SAR interferometry (InSAR) has proven as a unique tool for low cost and precise ground surface deformation analysis (Ferretti et al., 2001). The use of PS for built-up area deformation has been proven in several research including Le Mouélic et al., 2002, Stramondo et al., 2008; Tomás et al., 2012 and Herrera et al., 2010. In Belgium, Declercq et al., 2012 has shown using PS method that the city of Brussels is on the opposite uplifting due to a historical diminution of the groundwater pumping. Water demanding industries such as breweries have left the city centre for the periphery in relation with economic pressure and land use management. Additionally, Belgium has a long history of coal mining activities which stopped 30 years ago. Calembert, 1955, created a map showing the extension of the influence of the underground activities in the coal basin of Liège. During the exploitation time the ground movement was corresponding to a subsidence but after the closure of the mines in the 1970's the groundwater raised and provoked an uplift (Devleeschouwer et al., 2008). The annual average velocities recorded by Persistent Scatterer analysis was between 1- 2 mm/year over a period of 15 years. Declercq and Devleeschouwer, 2012, Cuenca, 2012 have respectively shown a similar behaviour in the Belgian and Dutch coal area of Limburg.

In short, the GEPATAR project addressed the following objectives:

- Creation of GEPATAR toolbox (http://gepatar.kikirpa.be/). allowed the integration of the PS-InSAR analysis results with the large set of source information regarding the Belgian built patrimony consisting of architectural records, air photos, stability analysis, construction engineering, etc. The toolbox allows the assessment of the ground deformation around cultural heritage buildings and the influence on their construction stability.
- Creation of modules which provide the analysis and the visualization of the ground deformation phenomena and the risk for patrimony in country, regional and local scales.
- The creation of two dedicated tools for the exploitation of RICH and RBINS archives.
- Linking the collections of heritage data stored in RICH and RBINS.
- Update the data and metadata collection of RICH and RBINS in terms of data model. Creation of PS-InSAR processor to allow the exploitation of the large remote sensing archive available at RBINS.
- Enhance the visibility and the usage of the data collection available at RICH and GSB-RBINS.
- The creation of a methodology for assessing the development of damage in building structures, subjected to differential settlement and uplift, using the analysis of PS-InSAR data.
- The creation of 2D damage models using limited information on the structural typology.
- Making progress toward the production of a highly accurate ground stability map

3. METHODOLOGY

WP 1: Management and valorisation

The GEPATAR project structure was subdivided into 4 workpackages of which each partner was involved at different levels (Figure 2). The consortium of the project consists of two federal institutes (RBINS and RICH), federal academy (RMA), research institute (CSL) and university (KULEUVEN).

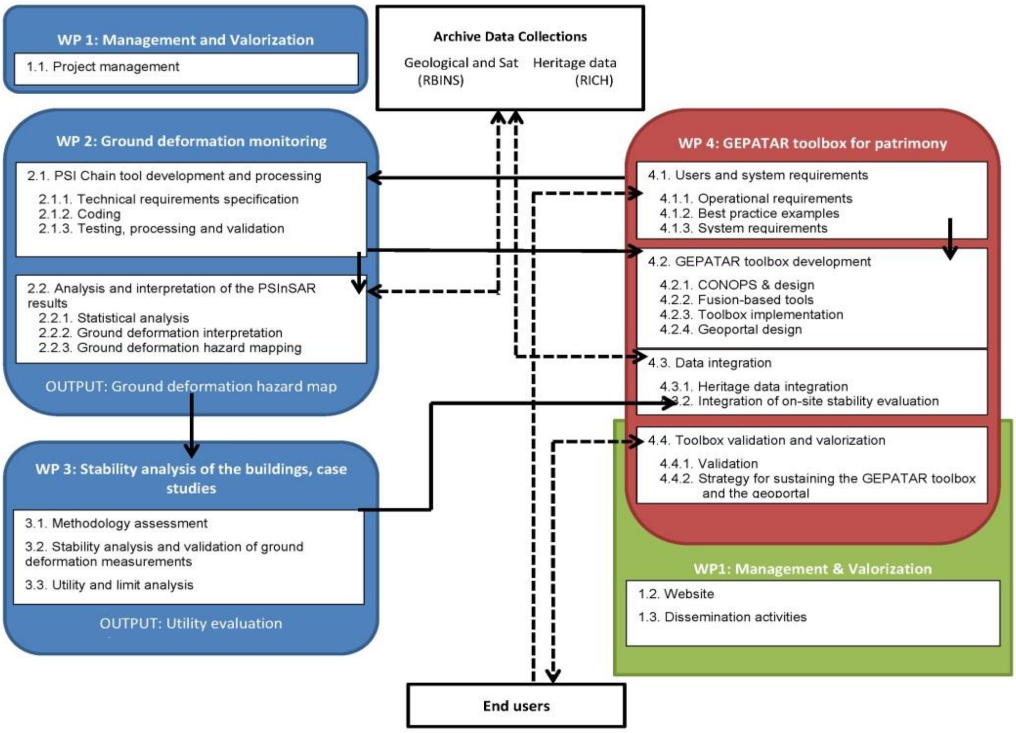


Figure 2 Project structure

The project management (WP1) was coordinated by RBINS as horizontal activities along the project duration. WP1 also integrated the dissemination activities and the valorisation of the project outputs. GEPATAR toolbox was developed also along the project life time, while implementing inputs from the two other thematic work packages WP2 (ground deformation monitoring) and WP3 (stability analysis of the building). In order to ensure proper interaction between the different partners, project meetings were scheduled twice a year including a meeting with the follow up committee. Whenever needed extra meetings were organized as well as bilateral direct exchanges between partners.

WP2: Ground deformation monitoring

Radar interferometry is one of the main tools used in this project to monitor the intensity and the spatio temporal behaviour of the ground deformation in Belgium and its impact on the stability of the patrimonial buildings.

Work package 2 includes

- the PSI chain tool development and processing to extract the ground deformation information from the available PS-InSAR data;
- the development of statistical analysis tools for geographical mapping of the ground deformation;
- the interpretation of the ground deformation based on geophysical data;
- the interpretation of the ground deformation data with relevancy to the vulnerability of the cultural heritage to mechanical damage.

The final outcome is a time-based ground deformation hazard map and a vulnerability assessment of the cultural heritage in relation to the observed ground deformations that is included in the GEPATAR toolbox.

2.1 PS-InSAR chain tool development and processing

As mentioned earlier GEPATAR relies on the PS-InSAR results to measure the ground deformation. The development and the use of a processing chain was necessary for mastering the entire process. Multi-temporal InSAR techniques are extensions of InSAR-DInSAR intended to overcome the issues caused by the spatial and temporal decorrelations and atmospheric delays. The interferogram is at the core of Multi-Temporal-InSAR. These techniques involve the simultaneous processing of a stack of multiple SAR images covering the same Region Of Interest (ROI) allowing the correction of uncorrelated phase noises. PS-InSAR. identifies pixels that have a good correlation and stable phases during a long period of time in the stack of interferograms (Ferretti et al., 2001, 2000). The final results consist of a large set of geo-localised points called Persistent Scatterer (PS) for which the timeseries of deformation based on a reference point is calculated for each satellite images as well as the average rate of deformation. The obtained precision on the velocity reaches $\pm$ 0.5 mm/year.

The PS-InSAR processing chain that was developed by CSL needed to fit the technical requirements of the satellite data hold by RBINS and to handle the new data format of the Sentinel 1 mission. RBINS is using mainly ERS-ENVISAT data that they focus themselves using the ROI-PAC software. As a result, these data are not in the ESA format but in a specific one that had to be handled to allow the CSL InSAR Suite (CIS) to use them. Also, the use of ERS-ENVISAT data in the frame of differential interferometry and PSInSAR require handling precise orbits, which was not the case of CIS. Therefore, this capability has been implemented. Second, being able to use Sentinel-1 data imposes a highly challenging technical requirement. Sentinel-1 uses progressive scan synthesis aperture radar (TOPSAR), which induces fundamental changes in the way to handle data and produce interferograms. Consequently, Sentinel-1 TOPSAR interferometry was developed and implemented. In details, two tasks were performed: implementation of ROI-PAC data format handling, including ERS and ENVISAT Precise orbit handling and development of TOPSAR interferometry to be able to handle Sentinel-1 data. Precise orbit handling implementation was tested also on other test sites in the frame of other projects showing clearly that remaining orbital fringes are correctly removed. The most challenging part of the performed developments were and still are the developments required to implement TOPSAR interferometry. Due to the huge task, it represents, these developments were made in the frame of several projects requesting the use of Sentinel-1 data, including GEPATAR.

In order to increase acquisition coverage at the expense of a loss of azimuthal resolution, TOPSAR systems are using a progressive scanning of adjacent bursts, along and across track. During each burst acquisition, the SAR beam is steered from backward to forward (Figure 3). This steering induces a strong aliasing of the Doppler spectrum and an additional quadratic phase term along the azimuthal direction. This quadratic phase term (or the corresponding linear frequency variation) must first be removed to allow data co-registration and interpolation before being reintroduced within the data. If not removed and handled classically, interpolation of aliased spectrum leads to ripples within the interferogram. In addition, corresponding burst from an interferometric data pair must be co-registered extremely precisely to cancel-out the quadratic phase term through the interferometric process. Required co-registration precision is of the order of 1/1000 of a pixel for proper quadratic phase term cancelation. If not reached, subtraction of both parabolas lead to a remaining linear phase ramp across the interferogram leading to non-continuous phase jumps between bursts.

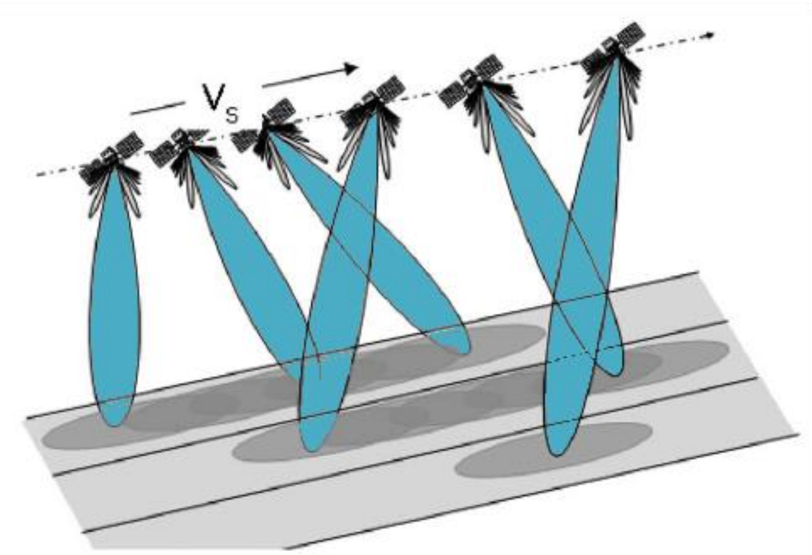


Figure 3 Burst scanning process of TOPSAR acquisition mode.

After several coding progress and attempts it was decided that the PS-InSAR processing will be performed using the Stanford Method for Persistent Scatterers (StaMPS) software which already capable to handle the interferograms of Sentinel 1 SAR images in TOPSAR format issued from Sentinel Application Platform (SNAP). Otherwise, the tasks flow of GEPATAR would have been broken. CSL continued the development of a combination of the CSL InSAR Suite (CIS) and the MSBAS suite developed by (Samsonov et al., 2013). The MSBAS approach is an extension of the SBAS technique allowing to combine different SBAS subsets from different sensors and different azimuth and incidence angles; each subset participating to the global solution through a Tikonov regularization of the under-determinate matrix system of the measured displacements. Resolution of the global system leads to an estimation of both the vertical and East-West displacement rates. The main difference between these techniques is that PS-InSAR analysis is conducted in slant range geometry while MSBAS analysis is directly performed in geoprojected geometries, where all modalities being projected before measurement phase.

After and during the development of the processing chains, SAR data were processed. Three different C-Band ($\lambda = \sim 5.6$ cm) satellites working in covering different periods were used:

ERS 1/2 - 1991-2001 - period 35 days.

ENVISAT - 2003-2010 - period 35 days

SENTINEL 1A (S1A) - 2016-2019 - period 12 days.

The results were compared with previously processed set of images. The comparisons were satisfactory, and the processing chain was thus validated. After the validation process, all the SAR archives (ERS, ENVISAT) and the downloaded Sentinel 1 images were processed. The output of the processing include the localization of the PS, its annual average velocity in the Line Of Sight (LOS) in mm/year, its coherence and finally the displacement in the LOS (mm) for each acquisition with regard to a reference image.

In the case of ERS and ENVISAT, the SAR images are 100 km in the azimuth direction and about 100 km in the range direction while for Sentinel 1A the images are 250 km and 100 km in the range and azimuth respectively. The range is subdivided into 3 swaths. The figure 4 shows the position of the tracks that covers Belgium and the table 1 gives a summary of the characteristics of the different processing realized in the framework of this project. This specific study has been performed using all available data from the European Space Agency (ESA) satellites covering the entire country: ERS1/2 (for the years 1992-2002), Envisat (2003-2010) and Sentinel 1A. For ERS and ENVISAT, 3 tracks were available from East to West corresponding respectively to the 380, 423 and 466 code of identification (figure 4).

The period encompassed by each S1A processing are different. A choice is necessary between keeping the maximum coverage in time vs keeping the maximum coverage in space. S1A was launched in 2014 but ESA changed the acquisition parameters, during 2016-2017, resulting in a major change of the spatial coverage of the images. As the processing results consist of the maximum of the spatial intersection of the stack of the images, the acquisition before 2016 were not used and some shifted images between 2016-2019 were removed from the processing.

T	S	Geom	Sat	Number of Images	Start date	End date	Master	P
380	/	descending	ERS	62	06/08/1992	31/12/2000	06/04/1997	35 days
423	/	descending	ERS	67	26/04/1992	03/01/2001	18/07/1998	35 days
466	/	descending	ERS	77	03/06/1992	07/10/2006	28/03/1998	35 days
380	/	descending	ENVISAT	60	21/12/2003	10/10/2010	12/08/2007	35 days
423	/	descending	ENVISAT	74	12/02/2003	13/10/2010	15/08/2007	35 days
466	/	descending	ENVISAT	48	27/12/2003	16/10/2010	09/05/2009	35 days

166	SW1-SW-2-SW3	ascending	S1A	67	02/06/2017	20/09/2019	09/02/2018	12 days
157	SW2-SW3	ascending	S1A	64	02/06/2016	03/09/2019	16/06/2018	12 days
161	SW1	ascending	S1A	66	14/06/2017	03/08/2019	09/02/2018	12 days
161	SW2	ascending	S1A	94	27/06/16	03/08/2019	09/02/2018	12 days
163	SW1-SW2	ascending	S1A	61	14/06/2017	16/06/2019	08/02/2018	12 days

Table 1: summary of the SAR images characteristics used in the framework of this project. T: Track, S: Swath, Geom: Geometry, Sat: Satellite, P: period

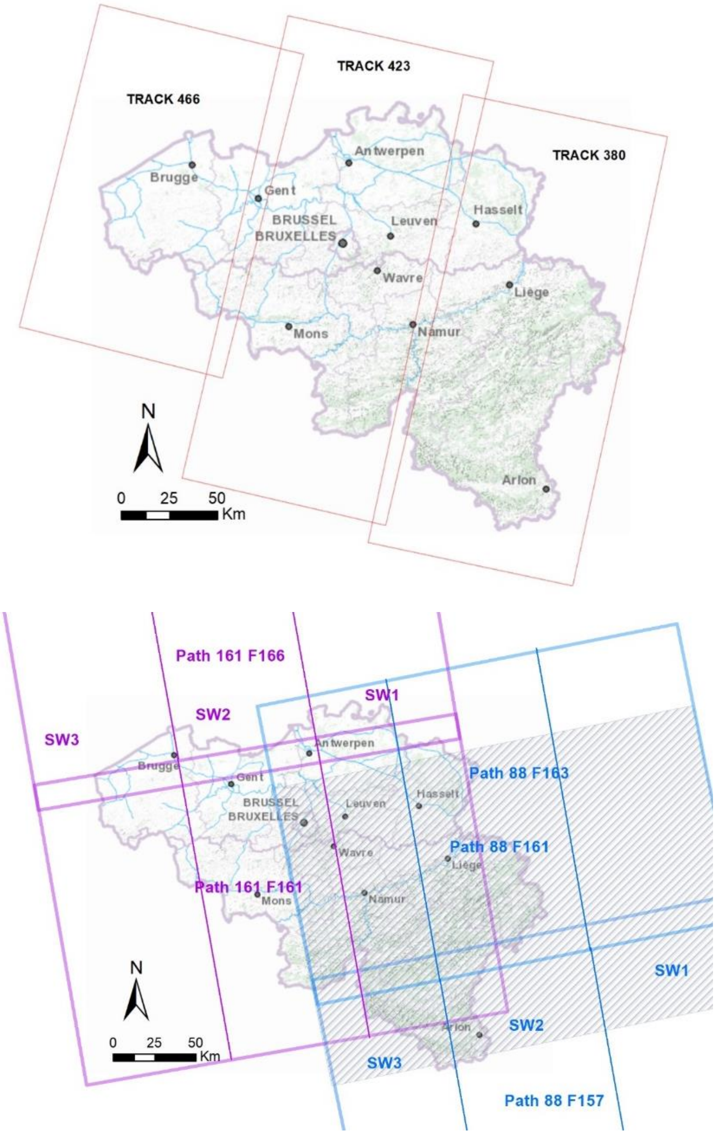


Figure 4 Top image: position of the ERS and ENVISAT descending tracks named 466, 423 and 380 respectively located from West to East. Bottom image: Sentinel 1A ascending tracks (or paths) named 161 and 88 cover the entire country. Each path is subdivided into several frames (F) and each frame is subdivided into three Swaths (SW).

WP 3: Stability analysis of heritage buildings

A methodology for damage assessment was developed, based on the restrictions that the algorithms were to be fully integrated in the GEPATAR Toolbox and analysis could run automatically with inputs provided from queries made by the GEPATAR Toolbox into other data sources, such as patrimonial archives and ground deformation maps.

The developed methodology consisted of following steps:

- defining the inputs: ground deformation data and patrimonial data
- calculation of ground deformation curve
- calculation of related building deformation
- Calculation of potential damage and definition of cumulative damage level

3.1 Procedure for calculation of damage levels

Damage levels for individual buildings are calculated based on information regarding the heritage building (building polygon that represents its contours, building typology, structural typology) and the ground deformation data. The building polygons are constructed based on available patrimonial data on the (x,y) horizontal plane. A buffer of 10m is considered around each building polygon. Ground movement data from InSAR data points within the building polygon and the buffer are used for the calculation of the ground deformation profile.

The ground deformation profile at and around the building polygon is defined as a surface $f(x,y) = a + bx + cy$. The equation constants are calculated from the InSAR data points available on the building and the buffer for a given time period. In the absence of data points, the loading is calculated according to a wide-area surface fit on an interpolated ground movement map.

The vertical movement of each vertex (x_n,y_n) of the building polygon is equal to $f(x\_n,y\_n)$. The slope of each polygon edge is calculated according to the vertical movement of its two vertices. A Gaussian curve is fitted between the vertices of each edge. These calculations allow the determination of the ground deformation parameters of each edge: slope, deflection ratio and angular distortion (Boscardin and Cording, 1989).

Damage is calculated according to the accumulated loading parameter as proposed by different sources in the literature (ASCE (American Society of Civil Engineers, 2006; Burland and Wroth, 1975; Fischer, 2009; Giardina et al., 2015). Three structural typology models are considered: masonry, infilled frame and bare frame. The assignment of the model is done according to the typology, construction year and style of the building.

Four levels of possible damage are specified: a) negligible, b) slight, c) moderate and d) severe. These levels reflect the amount of accumulated settlement damage in the building over the measurement period, as anticipated from the InSAR data. The damage levels are defined according to normalized limits on deformation parameters for each model type.

Additionally, a ground settlement or uplift threshold of 2 mm/year is considered (Peduto et al., 2016). Ground movement above the threshold in either the PS or interpolated grid at the location of each building is indicated in the timeline presented in the GEPATAR Toolbox, highlighting the time periods at which noticeable movement is registered.

3.2 Case studies and field observations

During the development process of the damage calculation procedure, several case studies and field observations were carried out to support and validate subsequent steps of the methodology developments:

Two case studies were monitored on-site (crack monitoring and/or settlement monitoring). In one case, the Saint Jacob Church in Leuven, large-scale structural interventions at the foundations were planned, which might cause settlements. Yet, during the works, no major settlements were observed that allowed comparison with INSAR-data. In the second case, a private residence, settlements were reported by on-site monitoring, yet insufficient PS-points were available for comparison.

To increase the amount of field observations, three site campaigns were organized, of which two in Limburg (former coal mining area and an medium-scale urban area being the city of Hasselt), and one in Brussels (large-scale urban area). During the first two site campaigns, which occurred in the first half of the project, buildings were selected based solely on ground deformation data. For the third site campaign, buildings were selected based on the "Procedure for calculation of damage levels" explained above.

Finally, at the end of the project and upon the GEPATAR Toolbox becoming operational, a fourth site campaign was run, this time in the medium-scale urban area of Leuven city centre. As many sites that were marked by the GEPATAR Toolbox were renovated since the period in which damage was highlighted by the Toolbox, and additional internet search was performed based on publicly available, older Google Streetview data to "look in the past" and confirm the risk levels indicated by the Toolbox.

WP 4: GEPATAR toolbox for Patrimony

The GEPATAR toolbox answered the following list of characteristics that had to be satisfied during the project life time in robust and user friendly manners:

- The GEPATAR is a federal toolbox that gathers and integrates geotechnical and patrimonial information for architectural conservation use in Belgium.
- The targeted users are architects and engineers, local and regional administrative, policy makers and the general public.
- It is an open source toolbox with a user friendly interface that allows visualizing information at different scales from country to single building.
- The toolbox completes the regional and the federal patrimonial archives rather than duplicates their information.
- It integrates heterogeneous source of information from several disciplines including geology, geo-mechanic, risk management, geography, history, architecture, structure engineering and transportation to general information as name, address, coordinates and photos.
- The toolbox is updated periodically by persons in charge at the RBINS and the RICH institutes.

4.1 Users and system requirements

For collecting user's requirements, online questionnaire was created and distributed to administrators and policy makers at communal, regional and federal levels. Forty seven questionnaires were answered by 27 (57%) users from the Flemish speaking community and 20 (43%) from the French speaking community. The questions refer to contain, interface needs, scales and languages. The results are summarised in the table 2 here after:

System requirement	Question	Answer	% answered very important
Contain	Which information related to the cultural built heritage do you want to be able to consult on the web interface?	Name of monument	71.9
		Risk assessment	61.3
Interface	Which cartographic layers do you personally prefer to consult within the web interface?	OpenStreetMap	64.3
Contain/interface	In which way do you want the vertical settlements of a monument to be represented graphically?	A mapping of the average settlements over a period of 20 years	66.7
Interface	How do you want to be able to find a specific monument?	By address	73.3
Language		FR/EN/NL	
Scale		Building scale	

Table 2 : Users and system requirements

4.2 Toolbox development

The GEPATAR toolbox created in cloud computing environment as an open source following the required main characteristics and user's needs are described here above. It main objectives is to evaluate and present the potential damage caused by ground settlement for masonry, infilled and bare frames structures using PSI measurements. The architecture consists of five sections (Figure 5), components that support both real-time and batch processing and uses SQL for optimization and distribution.

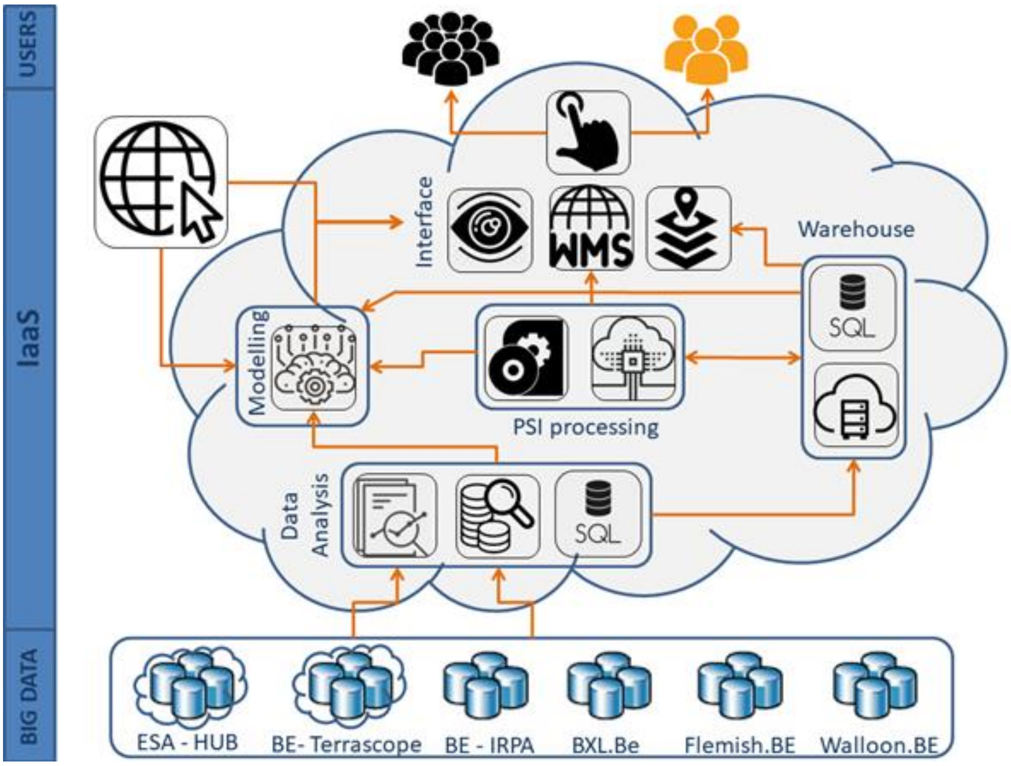


Figure 5 GEPATAR architecture

4.2.1. Ingestion and data analysis

The remotely sensed big data includes historical and recent SAR/SLC imaging collected since 1991 by the ERS-1/2, Envisat and Sentinel missions. The latter are directly obtained from the ESA hub or by opening a gateway to the Belgian Terrascope platform. It also includes very high resolution DEM and other geographical and geophysical data collected and mapped by the three regional administrations of Belgium. The federal and the regional cultural heritage data are migrated for ingestion and analysis. Other complementary data, as OSM layers and GoogleEarth are streamed from the web.

The ingestion and data analysis section includes scripts for data analysis and data mining. The latter, searches within the sources key words and dates for assigning structural style (i.e. masonry, infilled or bare frame) to each polygon. The data analysis includes pre-processing workflow for multi-temporal SAR/SLC acquired over the same region and from the same look angle. The data set is integrated with the orbital information indicating the position of the satellite during the acquisition time, and a DEM of the investigated area for co-registration and geometrical correction.

4.2.2. Warehouse

In the warehouse a Hadoop cluster is used to process and transform the large imaging set into structured data for further processing. It includes all the raster, and the vector layers are required for further processing, modelling or visualization. The warehouse also includes SQL for space allocation, data mining and distribution paths.

4.2.3. PSI processing

The Geology Survey of Belgium externally process the PSI and produce the settlement risk maps as inputs to the system. The survey uses the StaMPS (Stanford Method for Persistent Scatterers) / MTI (Multi-Temporal InSAR) V4.1b, which includes a processing scheme for Sentinel-1 data. The open-source package reads the unwrapped interferograms, references to the same coherent pixel, calculates the phase, inverts the network of the interferograms into time-series, calculates the "temporal coherence", corrects stratified tropospheric delay and DEM error, removes phase ramps and estimates the velocity. The outputs migrate into the damage induced model for further processing and are classified for the creation of settlement risk map at a country scale (1:50,000). This risk map is used as an information layer in the interface.

4.2.4. Modelling

The results of the models described in Section 3 are threshold according to the ASCE7-16 design code (ASCE (American Society of Civil Engineers, 2006) and classified into four damaged levels; negligible (green), light (yellow), moderate (orange) and severe (red) potential damage.

4.2.5. Interface

The interactive interface is designed within the cloud and is supported by image derived visualization tools as Jupiter, Table and D3.js. It integrates web map and GIS formats that allow to sort, visualize and query location in various information layers including OpenStreetMap as required by the user.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

WP1: Management, communication and dissemination activities

WP1 did not strictly speaking produce any results, apart from dissemination activities (Chapter 5), publications (Chapter 6) and the smooth running of the project.

WP 2: Ground deformation monitoring

Measurements of ground movements in Belgium were performed using the radar satellite technique called Persistent Scatterer Interferometry (PSInSAR) (Ferretti et al., 2001, 2000). It permitted to highlight subsidence or uplift that can be deciphered and followed through years with a millimetric precision. The processing realised on different satellites permitted to follow the evolution of the ground movements at different epoch since 1992 up to now. In Belgium, the majority of the natural regional geohazards that can provoke ground movements are of the following types: earthquakes, landslides, karst, subsidence and uplift. On the other hand, human induced geohazards are those related to the overexploitation through drilling activities of underground resources (i.e. groundwater and gas exploitations) and those associated to underground mining or quarrying exploitations (i.e. coal, metallic minerals, stones, ore deposits, etc.). The Figure 6 shows the annual average velocity of the PS during the ENVISAT period (2003-2010) in which some regional movements are highlighted (Table 3) and described below.

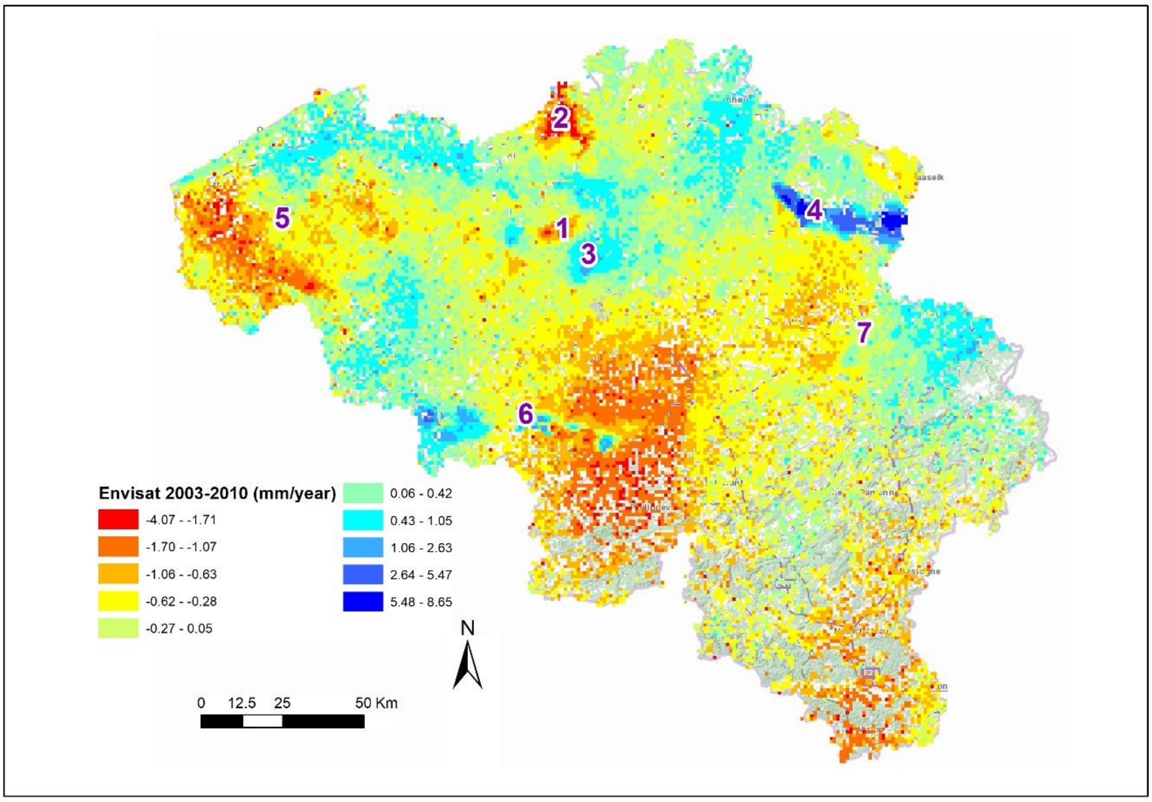


Figure 6 PSI annual average velocity during ENVISAT (2003-2010) in mm/yr. 1. Merchtem, 2. Antwerp, 3. Brussels, 4. Limburg, coal mines, 5. West-Flanders/Kortrijk, 6. Hainaut, coal mines, 7. Liège, coal mines.

ID	Location	ENVISAT (2003-2010) PSInSAR velocity (mm/yr)
1	Merchtem/ Alost	-2.5/3
2	Antwerp	from: -1.5 to -4
3	Brussels	from: +1 to +3
4	Limburg, coal mines	from: +5 to +8
5	West-Flanders, Kortrijk	from: -1.5 to -4
6	Hainaut, coal mines	from: -2 to +3
7	Liège, coal mines	1

Table 3: PSInSAR annual average velocity (mm/yr) of ENVISAT (2003-2010) for a selection of regional ground movements.

1. Merchtem /Alost.

The processing results reveal a previously unknown subsidence/uplift area located in Belgium in the Flemish- Brabant 25 Km NW of Brussels in Belgium (Figure 7). The ROI encompasses the cities of Aalst, Merchtem, Opwijk and Steenhuffel. The land subsidence has an average velocity of 2 mm/years during the time period 1991-2010 and covers an area of 95 Km² Groundwater extractions as process water in the Basement-Cambro Silurian aquifers (HCOV 1300-1340) in Merchtem, Steenhuffel and Londerzeel by breweries maintain a local subsidence around these villages. Thanks to all the different satellites PS measurements it was possible to follow the evolution of the ground deformation (Figure 8). The surface of this subsidence was reduced with the time while the surrounding villages like Aalst and recently in 2011 Opwijk are uplifting. The uplift traduces the global rebound trend of the piezometric levels of the region for which the Flemish Region took measures to reduce the impact of the overexploitation observed in the 1980's (Lebbe et al., 1988). The SENTINEL 1 PS velocity trend (2016-2019) (Figure 9) does not differ much from the last observation period of TerraSAR-X between 2011-2014 exception made of light reduction of the subsidence area in its southern part. The uplifts velocities in the surrounding villages keep the same trend during the SENTINEL 1 period as the previous observation periods. The rise of the water table in the piezometers shows that the phenomenon is still going on.

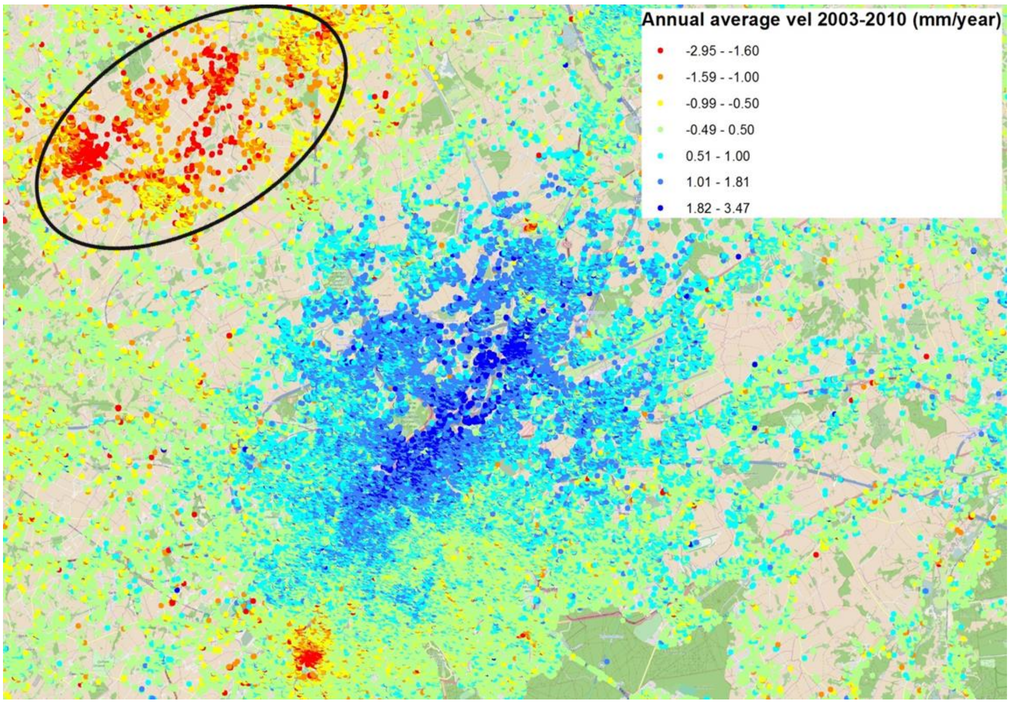


Figure 7 Colour classification based on the annual average velocities of the PS in the LOS direction for ENVISAT 2003-2010.

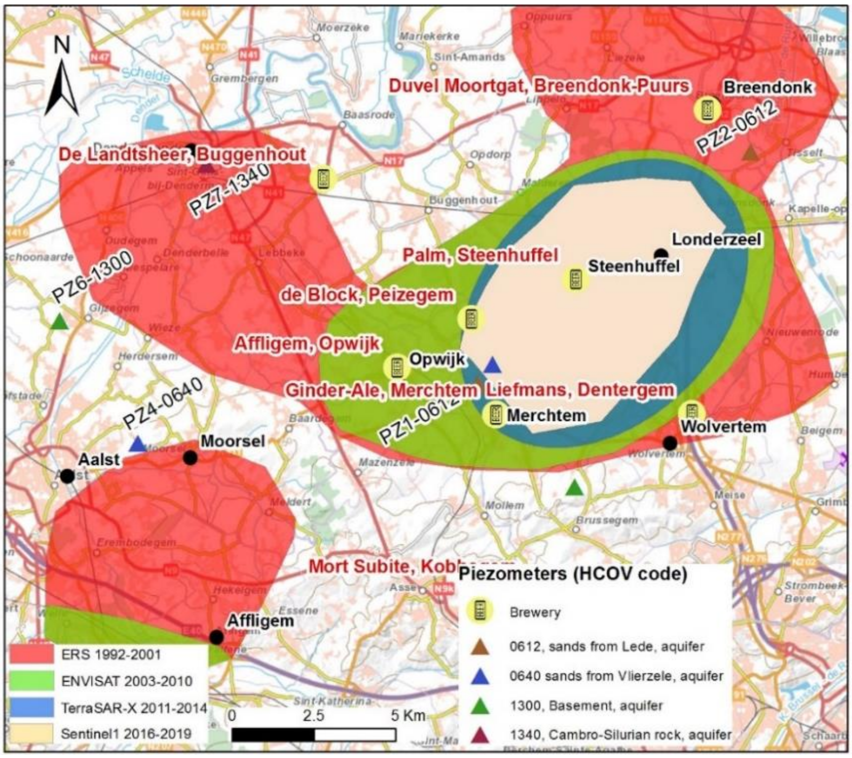


Figure 8 Evolution of the subsidence bowls is summarised through the different processing periods including SENTINEL 1 data, location of breweries and piezometers are indicated.

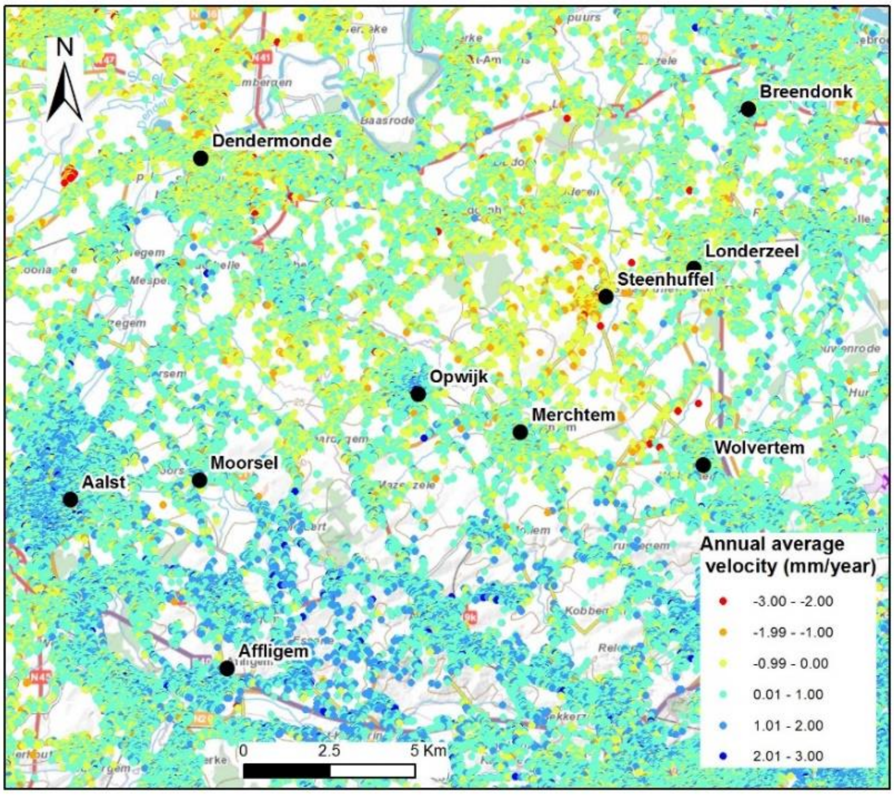


Figure 9 Colour classification based on the annual average velocities of the PS in the LOS direction for SENTINEL 1 2016-2019.

2. Antwerp.

The PS average velocities observed in this zone ranges from -2 mm/year to 3 mm/year on average with a maximum (in absolute value) of 5.8 mm/year. The Figure 10 shows the PS measurement for the S1 period (2016-2019). The harbour (H) situated in estuarine conditions of the Scheldt River characterised by Holocene alluvial sediments is opposed with the city centre of Antwerp (Ant) where Neogene sediments are directly found. The PS velocities measured in the city centre of Antwerp, show that the city is not affected by the subsidence observed in the alluvial plain nearby. In the harbour, the main settlement sems to be due to the consolidation of the Scheldt alluvial deposits in the harbour under the weight of landfills and heavy buildings.

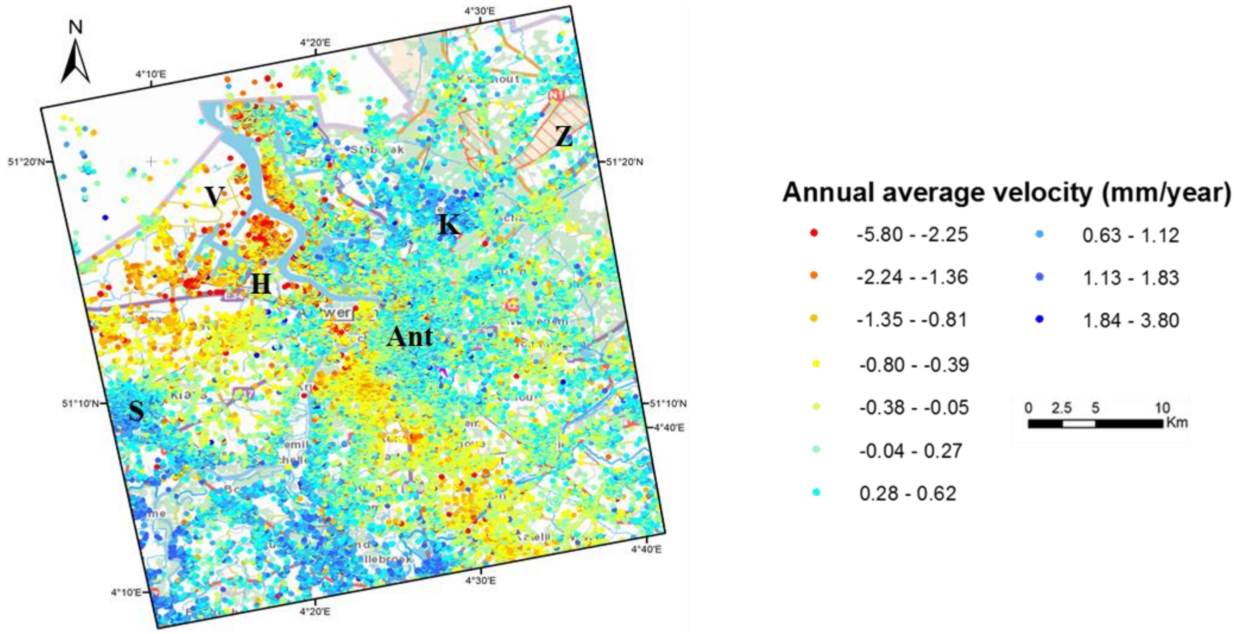


Figure 10 Colour classification based on the average annual velocity of PS points for SENTINEL 1 (2016-2019). (H) for harbour area, (Ant) (S) for Sint-Niklaas (K) for Kapellen, (V) Verdronken Land van Saeftinghe and (Z) De Zoom - Kalmthoutse Heide.

3. Brussels.

In the Brussels region, the general observed trend of the PS positive velocity values or uplift is most pronounced in the city centre, along a SW–NE oriented axis (average velocity of 2.7 mm/year). The affected area roughly corresponds to the Senne river valley inside the historic heart of Brussels (Figure 11).

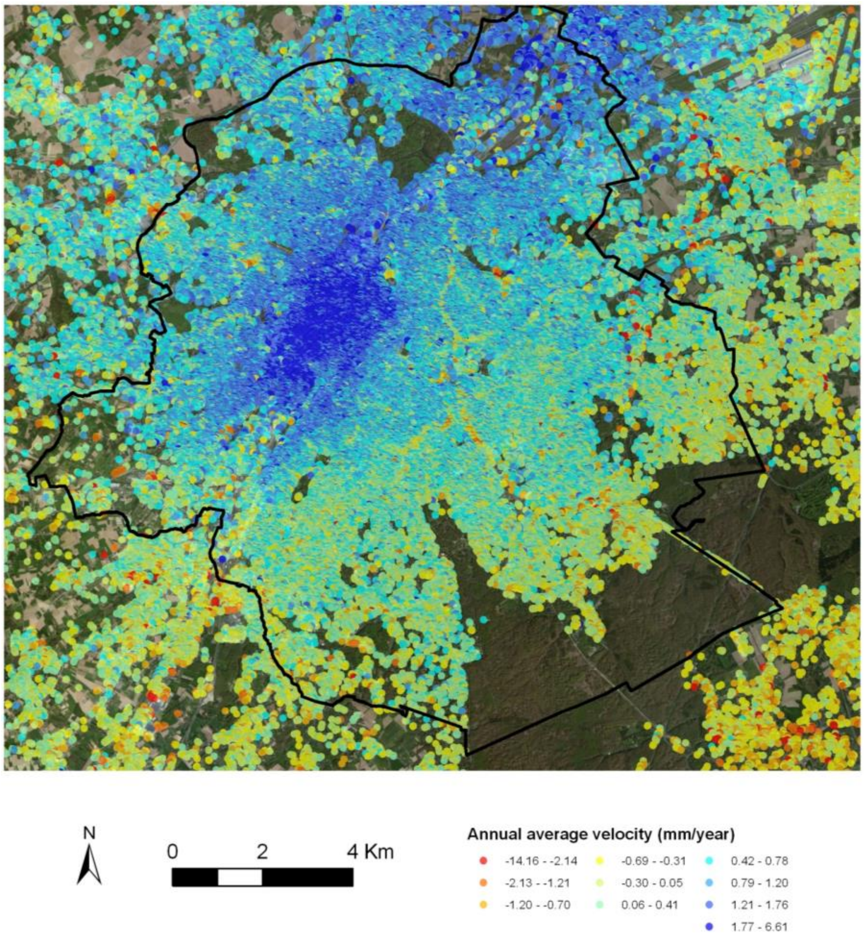


Figure 11 Colour classification based on the average annual velocity of PS points for ENVISAT (2003-2010).

The rebound of the piezometric levels of the deeper aquifers has been the driving force since the 1970s. The end of large-scale groundwater exploitations since the end of the industrialisation of the city is responsible for the groundwater recharge and piezometric level rise. This is attested by several modern (1988–2014) piezometric measurements in these aquifers and by historical piezometric levels in the deep Cretaceous aquifer (Figure 12). From 1880 to 1970, the city centre was probably subsiding due to the drop of the pore water pressures in the Cenozoic and the Palaeozoic aquifers resulting in a compaction of the rocks. The observed uplift rate in the city centre (Tour & Taxis building) is at its maximum during the ERS and ENVISAT periods and tends to reduce during TerraSAR-X and SENTINEL 1 period of time (Figure 13).

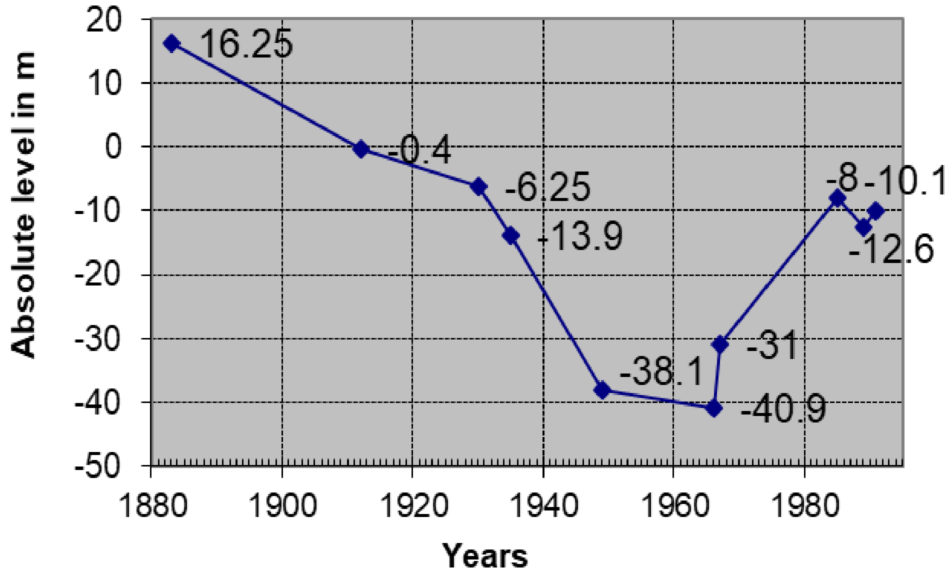


Figure 12Historical compilation of the groundwater levels in the Cretaceous aquifer from 1880 to 1990

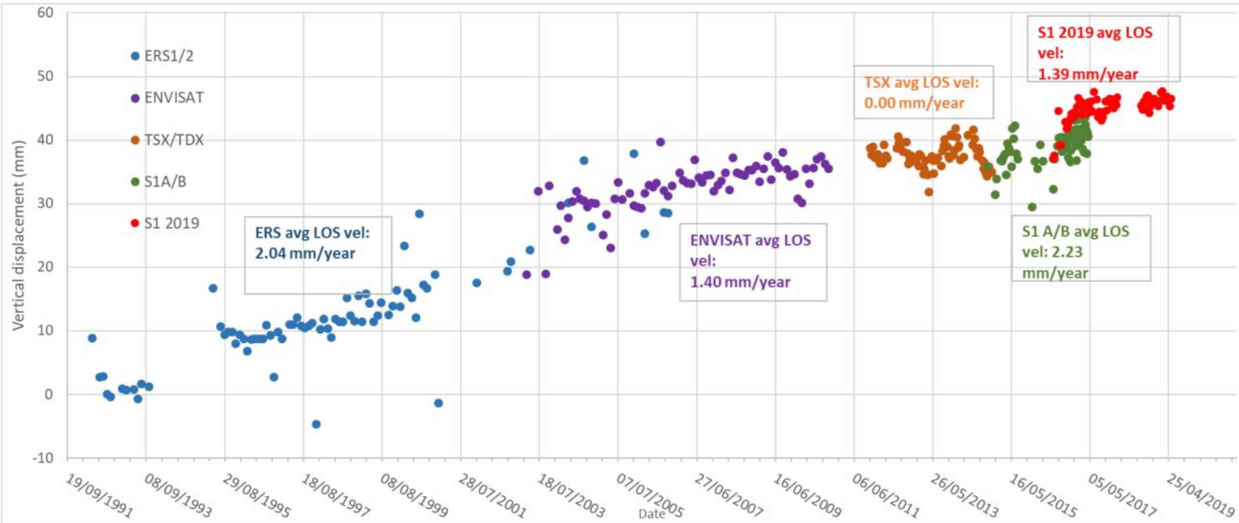


Figure 13 Time series of a PS showing the vertical displacement (in mm) located on the Tour & Taxis building.

4. Limburg coal mines.

During the ERS 1 / 2 period (1992-2001), the annual average LOS velocity map (Figure 14) highlights that the entire area belonging to the coal mine concessions is characterised by two different trends. The western part is showing negative LOS velocities ranging from -12 mm/year to 0.5 mm/year while the eastern part is having positive LOS velocities up to 18.7 mm/year. The spatial extension of the highest LOS velocities in absolute value is mainly limited to the borders of the defined coal concessions. The total area affected by the negative and positive values has more or less an elliptic shape with its main axis oriented east-west. The analysis reveals that a part of the coal basin is affected by a subsidence process related to the long mining activities in the past towards an uplifting. The gradual rise of the water in the former workings is responsible for the observed uplift.

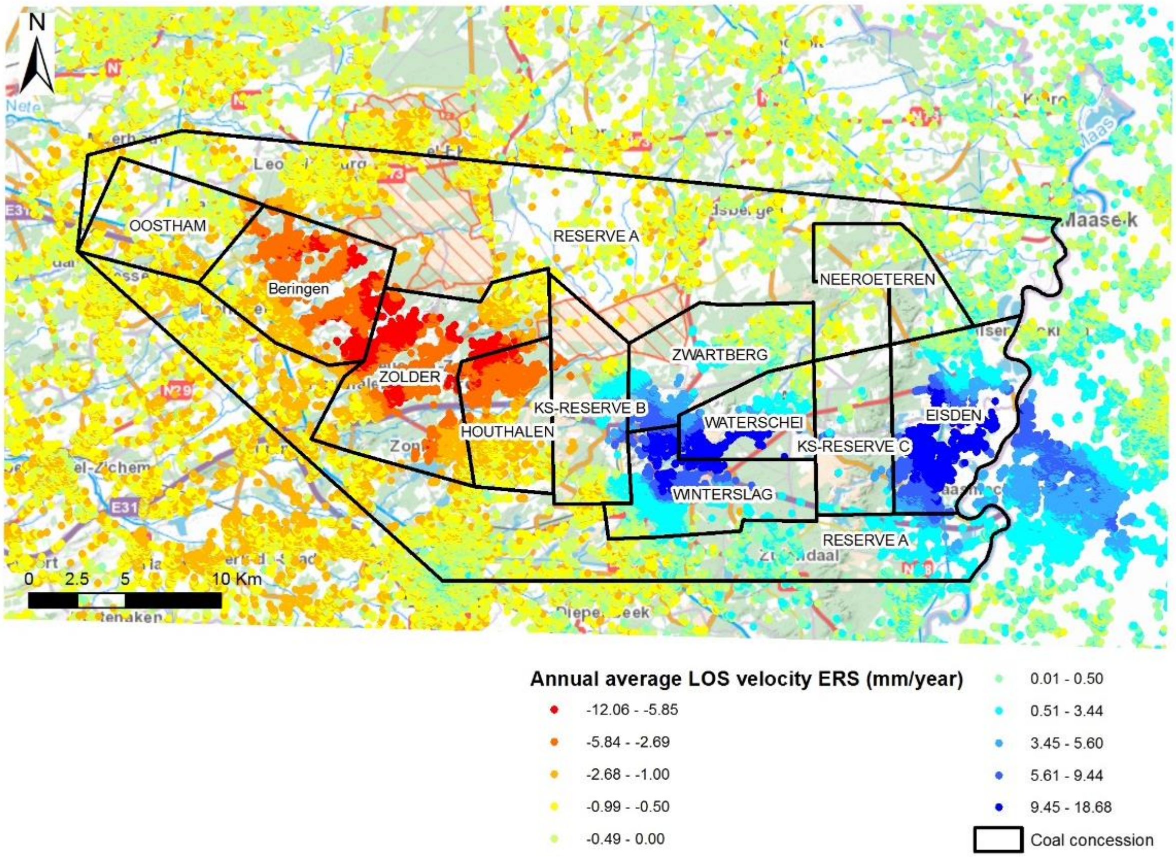


Figure 14 Colour classification based on the average annual velocities of PS points for ERS (1992-2001) and extension of the coal concessions in Limburg

5. West -Flanders Kortrijk.

At the Belgian western coast, a large subsidence bowl is visible since the ERS 1/2 acquisitions in 1992. The Figure 15 shows the situation for the ENVISAT period of time as an example. The negative velocities are forming a subsidence bowl of 45 km long in the NW-SE direction and 25 km wide. The negative velocities are ranging from -1 mm/year to 2.9 mm/year. The isohypses of the Landenian aquifer (Tertiary) is superimposed on the velocities. The isohypses data were produced by the University of Gent (Van Camp and Walraevens, 2009) using MODFLOW. This subsidence was partially mapped by A. Pissart and P. Lambot (Pissart and Lambot, 1989) by comparing two levelling periods realised by the NGI. The subsidence is caused by the overexploitation of the Landenian and Cambrian aquifers (Van Camp and Walraevens, 2009). In addition to the overexploitation the area located between Veurne and Ieper corresponds to the western coast plain characterised by Holocene unconsolidated sediments. Therefore, this zone is prone to settle due to the nature of its sediments (clay, peat).

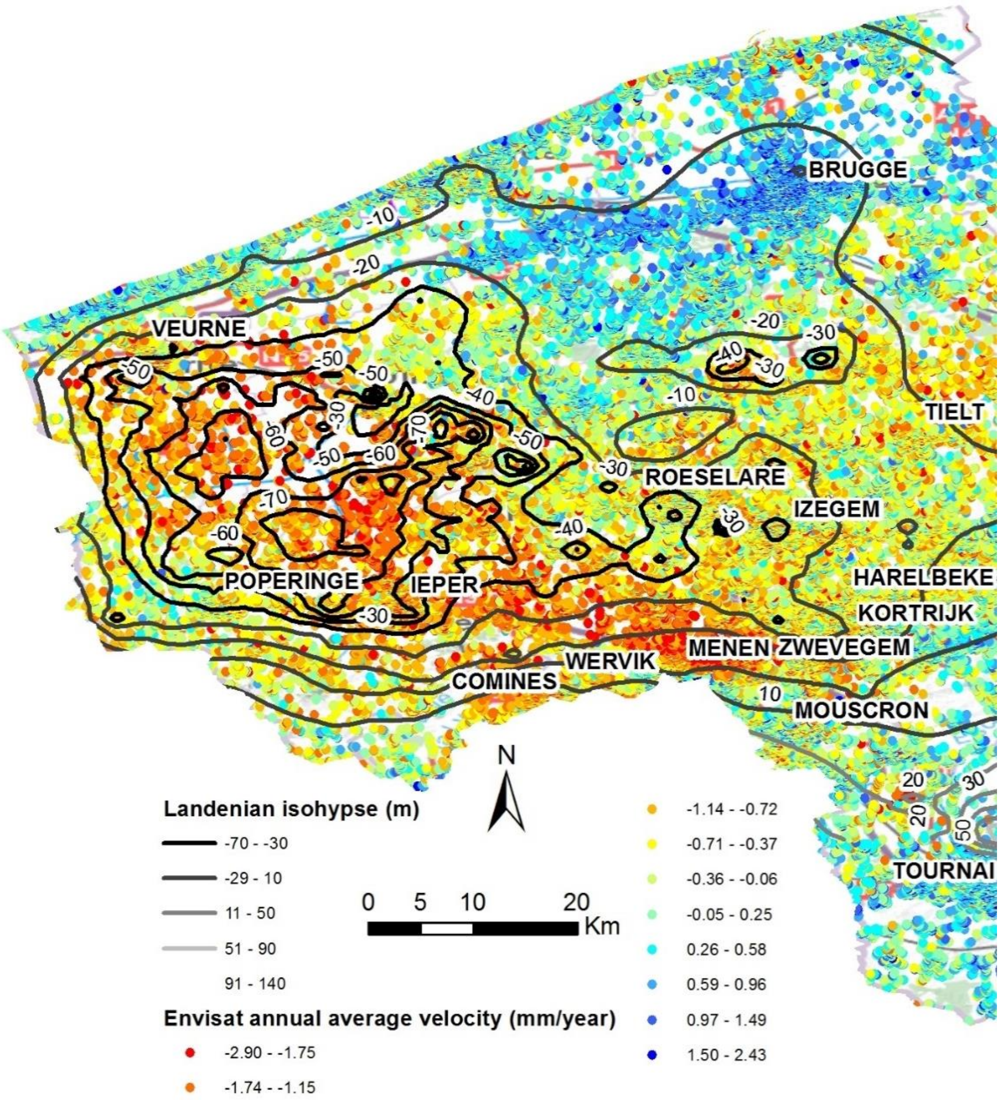


Figure 15 : Isohypse of the Landenian aquifer (m) and ENVISAT (2003-2010) annual average velocity (mm/year) at the Belgian western coast

6. Hainaut coal mines.

The coal extraction in the province of Hainaut seems to exist since the antiquity. Although, the oldest reliable document mentioning coal extraction in Charleroi is a juridical document dated back to the 13th century (Arnould, 1877). The beginning of the industrial development of the collieries started in the 18th century with a net increase of the depth during the second half of the 19th century. The last colliery closed in 1976. The Figure 16 shows the annual average velocity during the ENVISAT period on which the coal concessions are superimposed. From the west (blue) to the east (red) a global trend is still present and needs to be corrected in the future. Nevertheless, for most of the coal concessions, the PS velocities are positive and reached a maximum of 2.9 mm/year. In comparison with the ground movements recorded in Limburg the velocities are almost 10 times lower in this case but the rebound of the piezometric levels of the mining aquifer is responsible for the movements. The differences mainly reside in the time passed since the closure of the mines. In this case the last collieries closed 20 years before Zolder. The available PS measurements are showing the most probable end of the uplift of the mined terrain until reaching the limit of precision of the technique.

Among the coal concessions, Anderlues is still characterised by negative velocities. This coal mine was always considered as "dry" during the exploitation (oral communication M. Dusar) therefore they did not have to lower the water table significantly. This mine is still considered "dry" and having potential for the extraction of natural gas. Since 2018, natural gas is extracted in this mine.

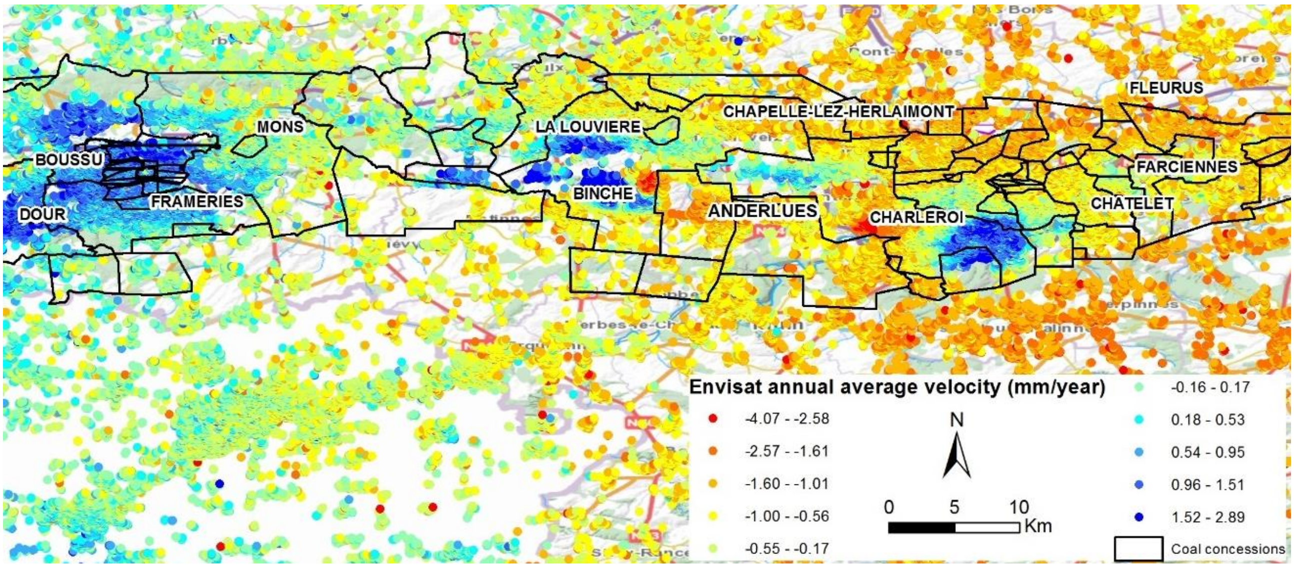


Figure 16 ENVISAT (2003-2010) annual average velocity (mm/year) above the Hainaut coal districts.

7. Liège coal mines.

The city of Liège is the third and last area of the country that is having ground movements related to the coal mining activities. The oldest traces of the use of coal in the Liège district dates back to the Roman period, discovered in 1907 during an investigation on Place Saint Lambert (Gobert, 1910). The strongest exploitation of the Liege mining basin was reached at the beginning of the 20th century (1900-1910) but from the 1920s, the least profitable coal mines started to close and this continued until the closing of the coal mine of Cheratte-chance in 1977 and that of the Blégny-Trembleur coal mine, the last well of which closed in 1980. Analysis by radar interferometry (PSInSAR technique) in the study area generally shows low average annual deformation rates (between -2.7 and 2.6 mm / year) (Figure 17). The Meuse alluvial plain in Liège is characterised by negative PS velocities resulting from the consolidation of the clay and peat content in the sediments of the alluvial plain of the river. The parallelism with the situation observed in the Hainaut coal district is almost perfect. The extraction of coal has played a major role in terms of ground movements, mainly subsidence caused by the mining activities. Readjustment of overburden related to collapses/failures, excessive groundwater pumpings are the key factors causing the subsidence that occurred during the exploitation period. Since the closure of the mines and the concomitant cease of the water pumping activities, it is the rebound of the piezometric levels of the mining aquifers that is the main explanation behind the recorded uplifts

(Devleeschouwer et al., 2008). The recorded PS velocities are in line with the closure of the last mine (Blégny-Trembleur, 1980).

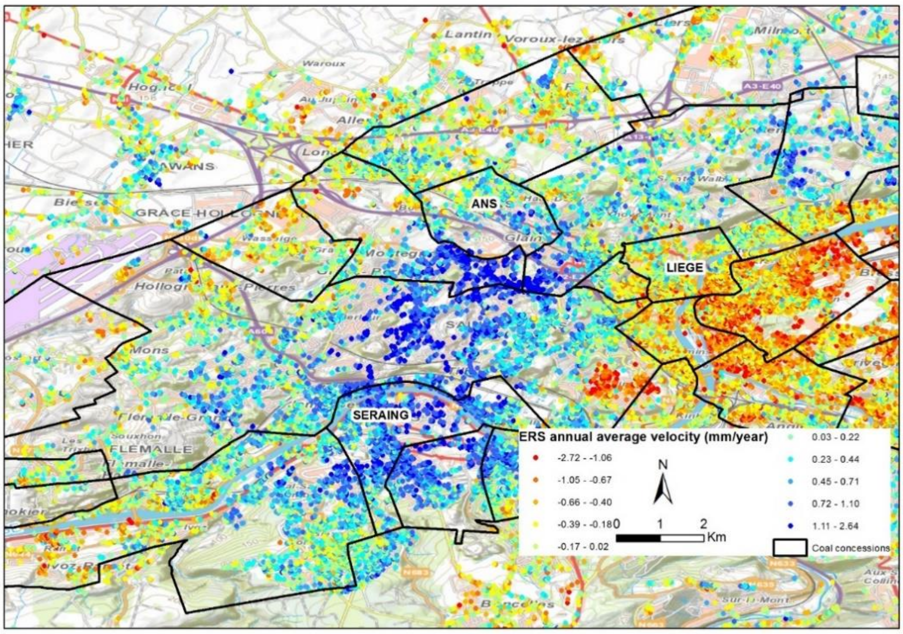


Figure 17 ERS (1992-2001) annual average velocity (mm/year) above the Liège coal districts

Fill the gap between ERS and ENVISAT

The first processing only considered ERS scenes prior to January 2001, when failures of ERS-2 gyroscopes caused instabilities in the orbit and therefore may reduce the performance of InSAR processing. However, in the following years ESA introduced different piloting modes in order to ensure mission continuity and stability of attitude and Doppler Centroid frequency. Quality assessment by ESA found that the nominal data quality progressively improved and the percentage of suitable data for InSAR applications increased. This advanced archive improvement provides an opportunity to extend the existing ERS time series and fill the gap with ENVISAT data (starting in 2003).

It was decided to include the new ERS images in the datasets and to request them via a CAT1 scientific proposal to ESA. In March 2016, the ESA scientific project proposal 32381 was accepted for access the ERS SAR archived products. The acquired scenes are complementary to the datasets already available at RBINS: a complete time series for track 466 (Brugge/coastal plain), additional scenes for tracks 423 (Antwerp/Brussels/Mons) and 380 (Genk/Liège/Arlon) up to 2006. Only a portion of the selected new scenes were successfully processed, however these were already sufficient to fill the gap with ENVISAT (Table 4).

The merged dataset contains a total of 844,921 persistent scatterer points (Figure 18). Time series of displacements can now be combined with the time series from ENVISAT (Figure 19, Figure 20).

Track	Area	Number of scenes	First – last scene
D 466	Brugge, coastal plain	77	03/06/1992 – 07/10/2006
D 423	Antwerp, Brussels, Mons	77	26/04/1992 – 04/10/2006
D 380	Genk, Liège, Arlon	73	23/04/1992 – 03/07/2005

Table 4. Details of the processed ERS time series.

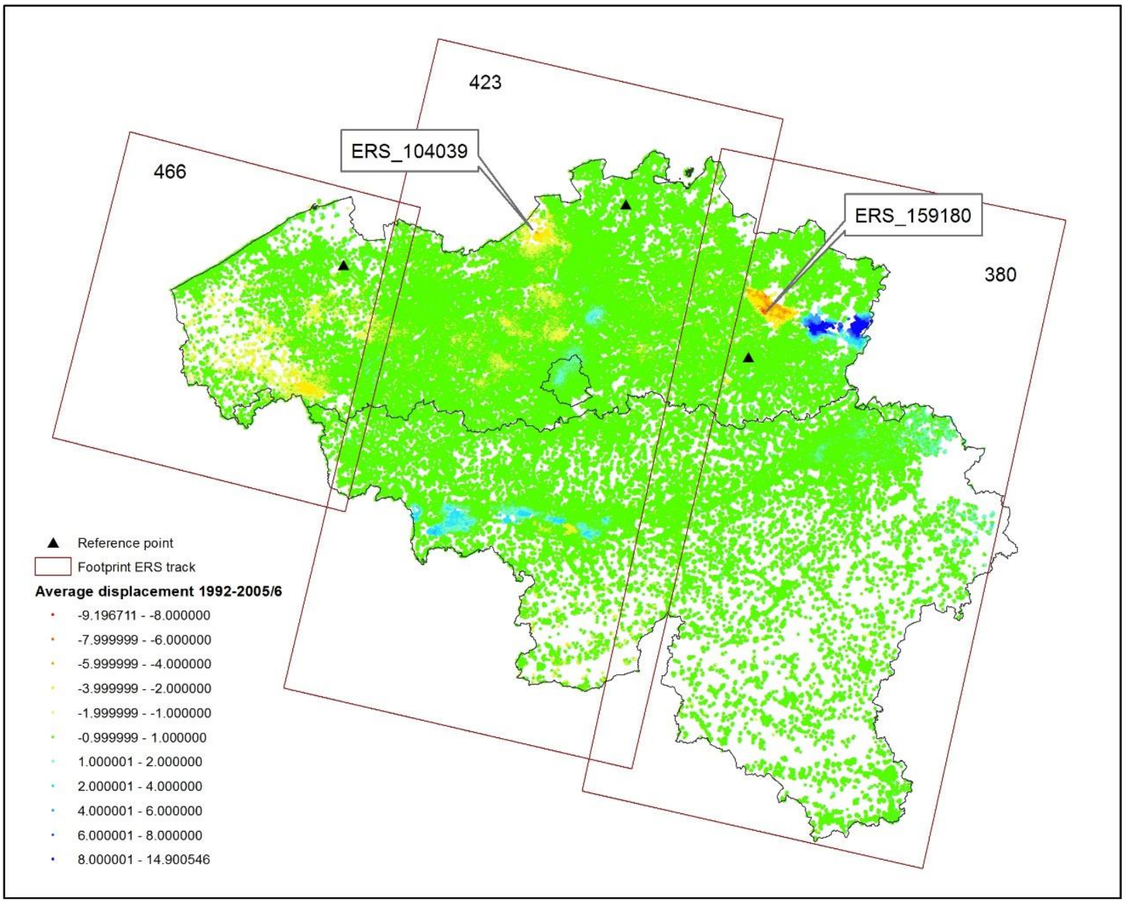


Figure 18 Displacement in line of sight computed from time series of ERS data, 1992-2005/2006; the indicated PS points refer to the next figures

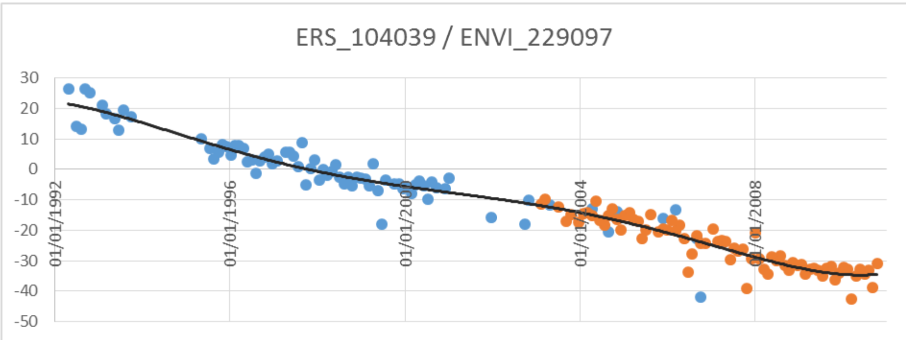


Figure 19 Displacement of a PS point in the Port of Antwerp (in mm, ERS-blue and ENVISAT-orange).

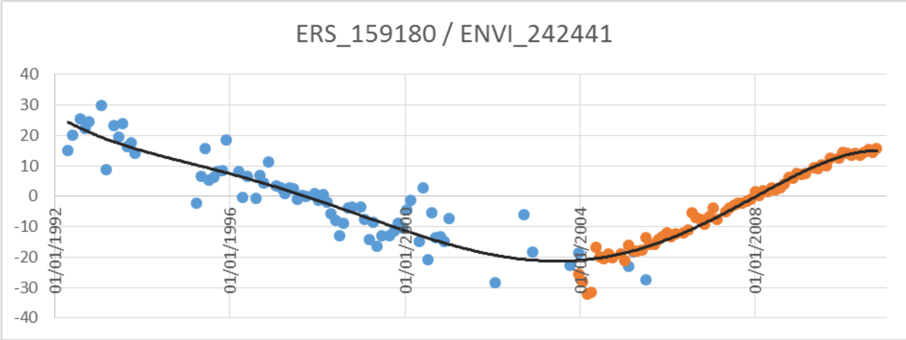


Figure 20 . Displacement of a PS point in Zolder (in mm, ERS-blue and ENVISAT-orange).

The analysis of the PS-InSAR processed results using the C-Band data showed that for many heritage buildings the number of PS/building was limited and sometimes not enough to properly assess the damage risk. It was decided to request high resolution SAR images using scientific proposal of two SAR images providers. The first set of images concerns TerraSAR-X (TSX) that covers the region of Brussels and Como-Skymed (CSK) that includes the Limburg coals mines.

TerraSAR-X data acquisition & processing

In March 2016, the TSX-archive proposal GEO3185 (concerning GEPATAR) was accepted by DLR for the utilization of TerraSAR-X archive data, with a quota of 74 products (Stripmap). The scenes cover the city of Brussels and were acquired between 2011 and 2014 (Table 5). In general, the results demonstrate ground displacements similar to those measured during previous decades with ERS and ENVISAT data, showing a gradual uplift in the city centre (Figure 21, Figure 22). The PS point density is quite high (around 4570 points/km2 in the city centre) enabling the detection of differential settlements at local scale.

Track	Area	Number of scenes	First – last scene
D 48	Brussels	74	30/10/2011 – 14/11/2014

Table 5. Details of the processed TSX time series.

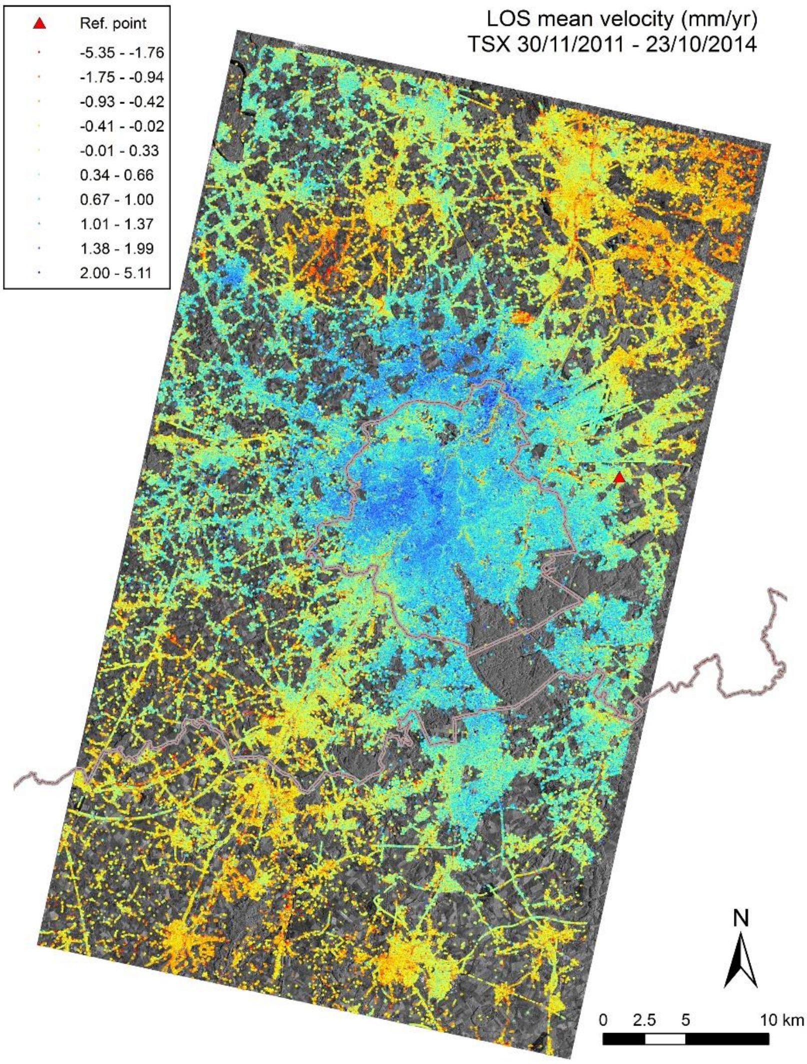


Figure 21 Displacement in line of sight computed from time series of TSX data, 2011-2014.

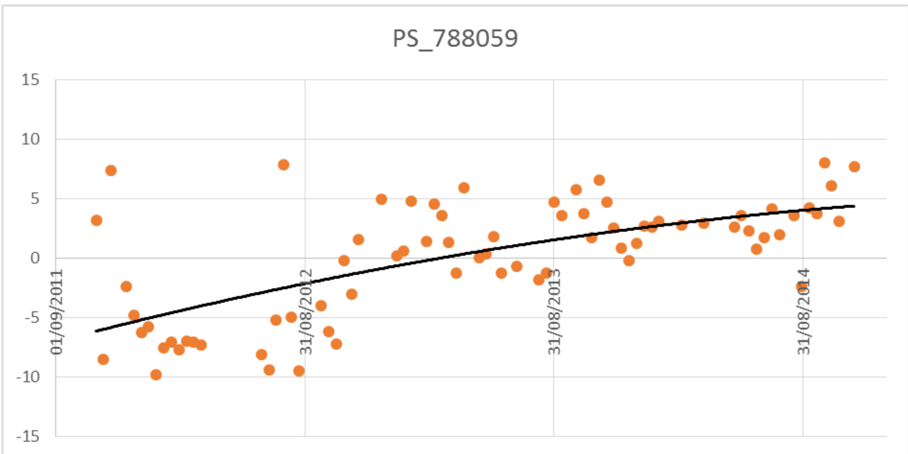


Figure 22 Displacement of a PS point located on the rooftop of Galeries Royals Saint-Hubert, Brussels.

COSMO-SkyMed data acquisition & processing

In September 2016, the COSMO-SkyMed Open Call for Science proposal 445 (concerning GEPATAR) was accepted by ASI, with a quota of 29 archive products (Stripmap/Himage) and 7 new acquisitions (Table 6). The scenes cover the Limburg Coal Basin (Figure 23, Figure 24).

Track	Area	Number of scenes	First – last scene
..	Limburg	29	01/09/2011 – 09/06/2014
		+7	2017-2018 (new)

Table 6. Details of the ordered/acquired CSK time series.

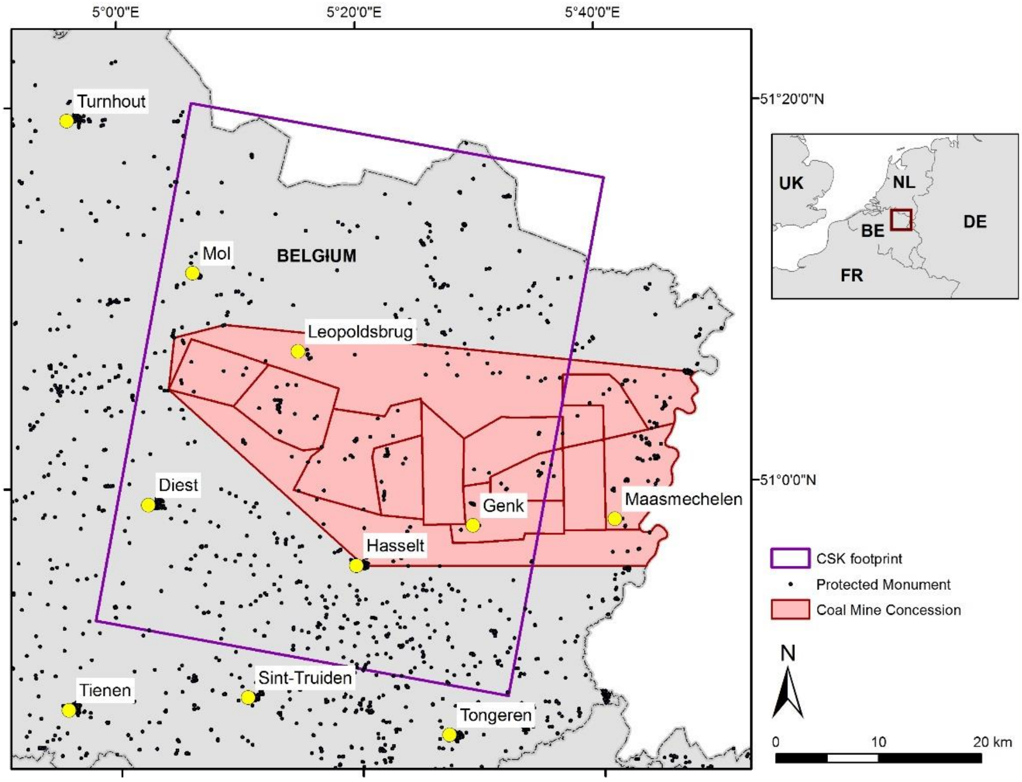


Figure 23 Footprint of the ordered/acquired CSK data in Limburg.

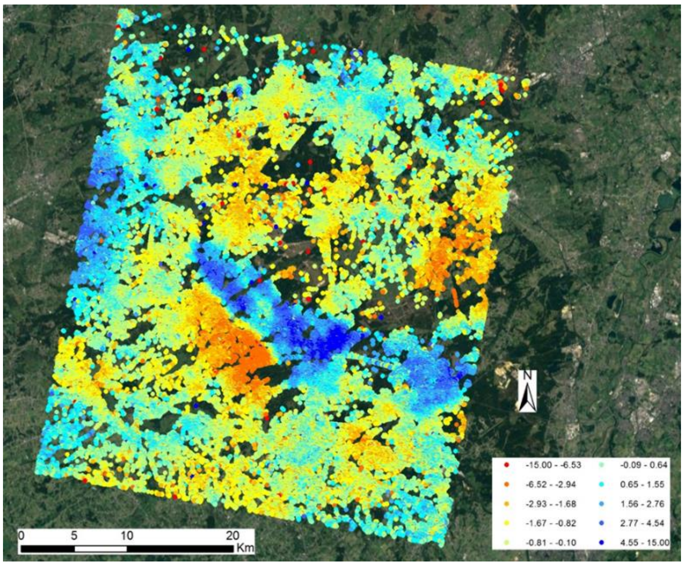


Figure 24 . PSI processing results of the CSK data in Limburg.

The applicability of TerraSAR-X Stripmap data for assessing the stability of individual buildings in urban zones is currently being evaluated. Patterns of differential ground movements derived from PS-InSAR processing are used to identify monuments that are potentially at risk. GIS tools allow the computation of spatial statistics that can be used for characterising local variations in the deformation signal. Summary statistics (Table 7) can be computed for a specified neighbourhood around data points or within indicated polygons (i.e. monuments). Because the "intensity" of differential movement not only depends on absolute differences in velocity but also on the distance over which they occur, a more advanced measure is proposed, which determines the maximum "slope" of differential movement within a predefined radius around each data point (Figure 25). When points (or areas) of large differential movement have been identified, they can be combined with data layers of cultural heritage to identify monuments that are most probably affected or at risk (Figure 26, Figure 27). The output of this analysis helped the final selection of case-studies and the validation requirements on the ground.

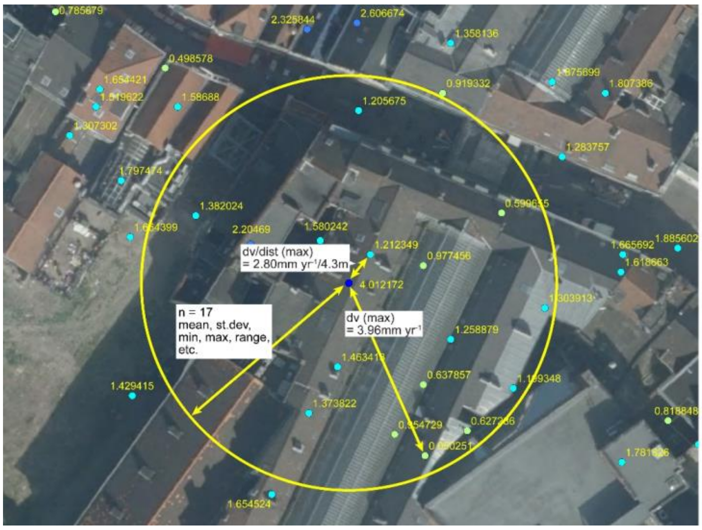
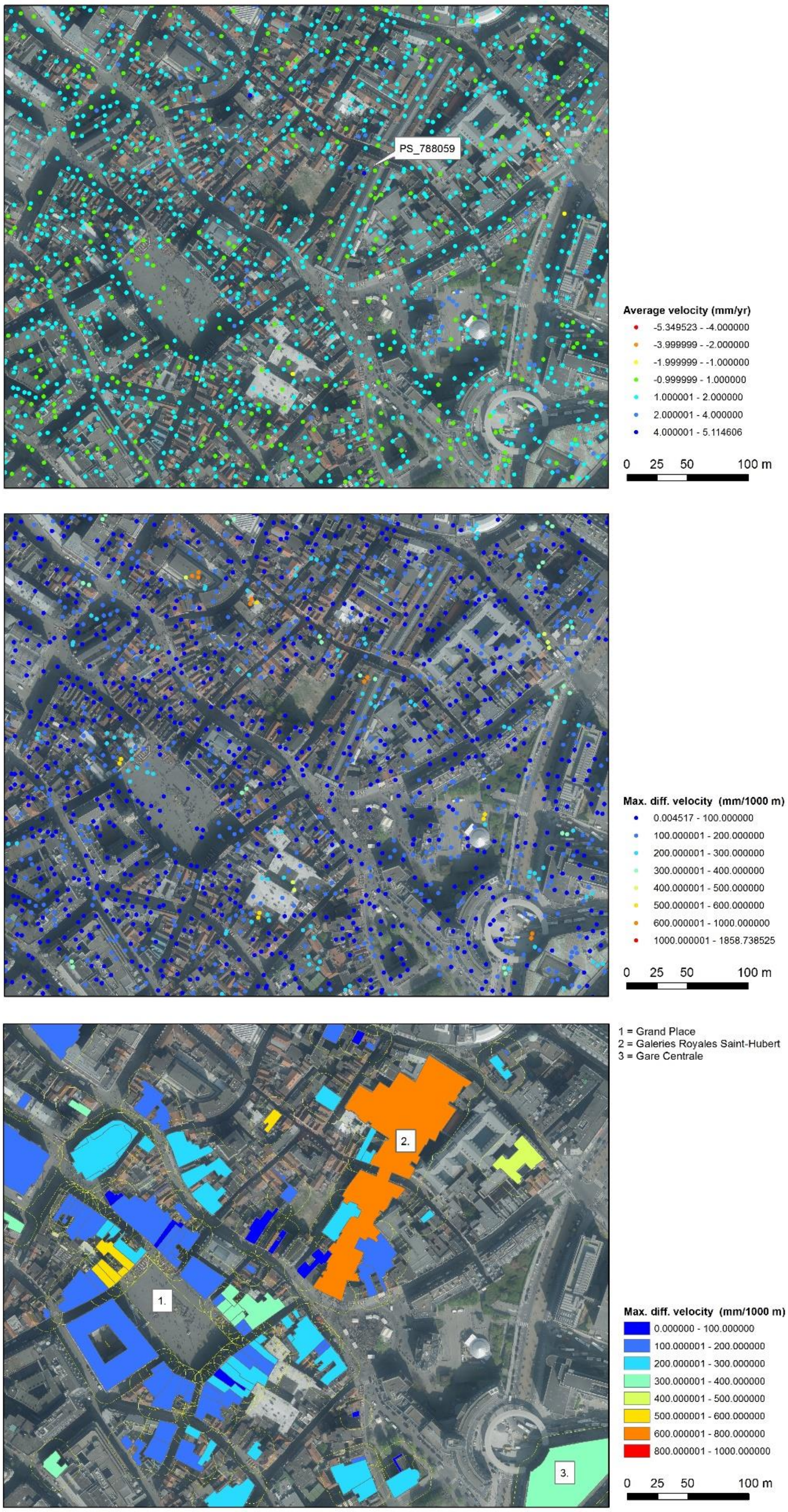


Figure 25 Example of spatial statistics within a predefined radius (here 25 m) around a data point: mean, standard deviation, minimum, maximum, range, difference per unit distance.



a.

b.

c.

Figure 26 Historic centre of Brussels: (a) displacements computed from time series of TSX data; (b) differential movements (maximum dv/dist. within 25m radius, values multiplied by 103); (c) maximum differential movement within the limits of each monument.

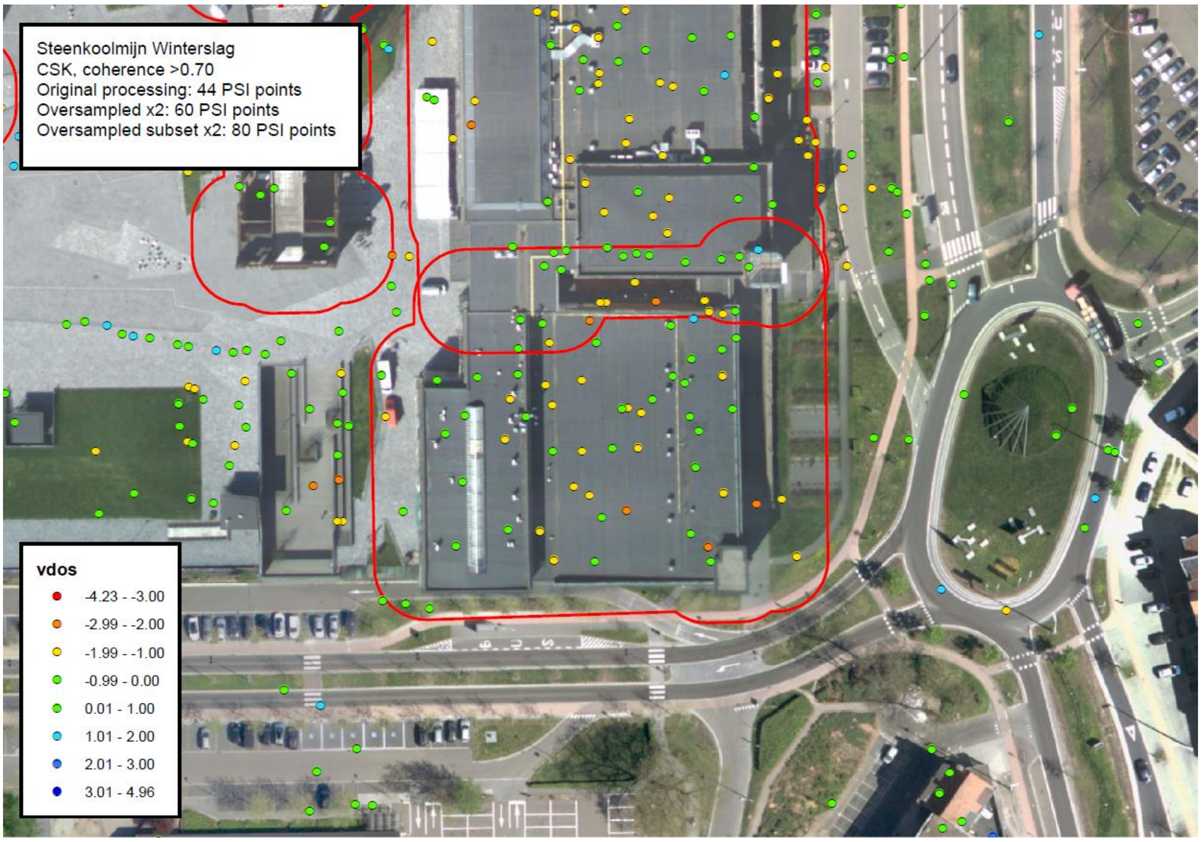


Figure 27 Annual average velocity of the PS in Winterslag (Limburg) using oversampled CSK images.

Summary stats Limburg									
Non-oversampled full image 23/05/2017									
	DOSNR_RO	NAAM	COUNT	MEAN	MIN	MAX	RANGE	STD	
	4.01/71022/134.1	Vml. Provincieraadsgebouw (Hasselt)	27	0.670	-1.212	2.902	4.114	0.970	
	4.01/71016/122.1	vml. burelen technische dienst, balzalen en vml. Paardenstallen (Winterslag)	44	0.398	-1.651	1.798	3.449	0.773	
	4.01/72040/110.1	Sint-Martinuskerk (Meeuwen)	18	-0.743	-3.783	1.215	4.998	1.227	
Oversampled full image 17/10/2017									
	DOSNR_RO	NAAM	COUNT						% Increase no. of PSI
	4.01/71022/134.1	Vml. Provincieraadsgebouw (Hasselt)	38						40.7
	4.01/71016/122.1	vml. burelen technische dienst, balzalen en vml. Paardenstallen (Winterslag)	60						36.4
	4.01/72040/110.1	Sint-Martinuskerk (Meeuwen)	47						161.1
Oversampled subsets 27/04/2018									
	DOSNR_RO	NAAM	COUNT	MEAN	MIN	MAX	RANGE	STD	% Increase no. of PSI
OS1	4.01/71022/134.1	Vml. provincieraadsgebouw	57	0.028	-1.874	2.245	4.120	1.032	111.1
OS8	4.01/71016/122.1	vml. burelen technische dienst, balzalen en vml. paardenstallen	80	-0.601	-2.555	1.260	3.815	0.945	81.8
OS9	4.01/72040/110.1	Sint-Martinuskerk	51	0.087	-2.329	2.633	4.962	0.985	183.3

Table 7. PSI statistics and densification of the PSI using Oversampling on small areas.

WP 3: Stability analysis of heritage buildings

The developed procedure and major results regarding the stability analysis of heritage buildings subjected to ground deformations were presented in the journal paper: “Drougkas, A., Verstrynge, E., Van Balen, K., Shimoni, M., Croonenborghs, T., Hayen, R., Declercq, P-Y. (2020). Country-scale InSAR monitoring for settlement and uplift damage calculation in architectural heritage structures. Structural Health Monitoring – an International Journal, Art.No. 1475921720942120”.

3.1 Procedure for calculation of damage levels

A flow chart of the developed methodology for calculation of the damage levels is presented in Figure 28. The procedure was fully integrated into the GEPATAR Toolbox.

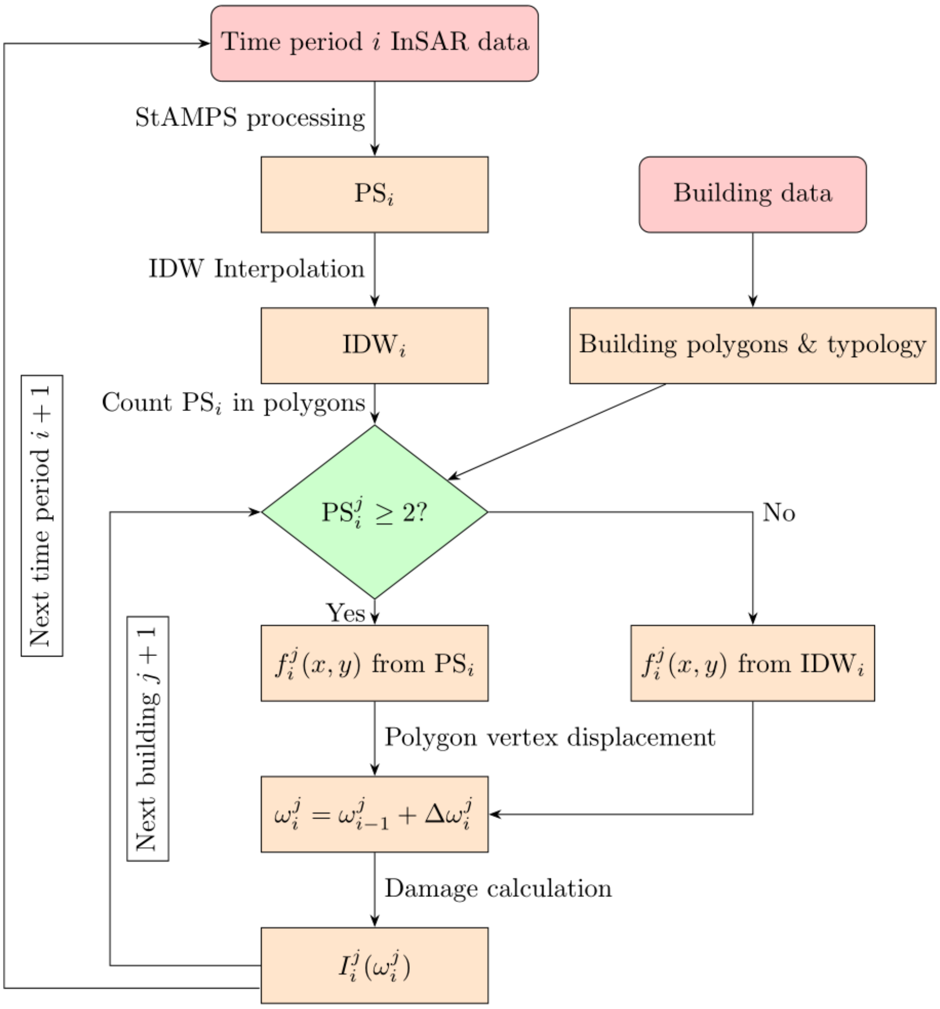


Figure 28 Example of spatial statistics within a predefined radius (here 25 m) around a data point: mean, standard deviation, minimum, maximum, range, difference per unit distance.

Several damage models were implemented and analysed. For masonry, an angular distortion model with damage index (I_a), a strain model with index (I_b), a tilt model with index (I_c), and a deflection ratio model with index (I_d) were implemented (Drougkas et al., 2020). Additionally, damage models for structural typologies with infilled frames (I_e) and bare frames (I_f) were implemented as well. In order to maintain a uniform output, the predicted building damage from all models is expressed on a four-tier damage scale: null/negligible (NN) for $I \in [0,1)$, slight/light (SL) for $I \in [1,2)$, moderate/severe (MS) for $I \in [2,3)$ and very severe (VS) for $I = 3$. Therefore, the damage indices must be normalized to the desired scale.

The results of the damage models were compared to related results from the literature on settlement damage to buildings as assembled and summarized by Namazi & Mohamad (Namazi and Mohamad, 2013). Settlement in these cases was induced by a variety of causes, including tunnelling, self-weight and adjacent excavation. Overall, the numerical damage indices from the de developed approaches showed good agreement with the reported damage for the majority of the cases and for all structural typologies. The masonry models appear to overestimate the damage in two of the cases reported in literature, although the magnitude of the deflection ratio in both cases suggests that the reported damage should normally be higher. The tilt model index (I_c) overestimates the damage for high loads and the deflection ratio model index (I_d) overestimates it for low loads. The angular distortion (I_a) and strain (I_b) model indices produce similar values for most cases, intermediate in magnitude to the other models.

Additionally, the masonry damage models a, b, c and d were submitted to a sensitivity study, the main purpose being to quantify the differences in the predicted damage over a variety of cases. The results of the sensitivity study reflected the importance of considering soil-structure interaction effects in differential settlement analysis for damage prediction in buildings. However, the superstructure characteristics that influence these effects are generally not found in patrimonial building databases and are thus not practical to implement in a country- or region-scale analysis. Therefore, the tilt model (c), which proved to be the most conservative was eventually selected and adopted for the analysis of masonry structures on the country-scale for Belgium.

3.2 Case studies and field observations

Firstly, the potential damage, as a function of the ground movement profile gradient in the area of the building, was analysed for a large number of heritage buildings on a country scale. The analysis highlighted 3715 structures with potential damage ranging from negligible to very severe. The majority of potentially damaged structures are located in the Flanders region, yet the amount of registered heritage buildings is much higher for this region and hence, the percentages for each category are similar for the three regions. This analysis highlighted about 400 specific structures with moderate to very severe potential damage level being in need of further investigation.

In addition to the quantitative damage assessment of the Belgian patrimonial building stock, a further analysis was carried out by identifying heritage buildings in an area subsiding or uplifting at a rate greater than 2 mm/year. While this criterion cannot be used for damage assessment, as it does not take differential settlements within the building into account, it provides an indication of possible regions with risk of settlement damage. The regions exceeding the velocity threshold of 2 mm/year are identified by the velocity values of an interpolation grid (instead of the exact PS points). Building polygons and their offset in contact with interpolation cells having a velocity greater than 2 mm/year are considered to be located on moving soil. The period 1992-1997 indicated a total of 21220 buildings on moving soil, corresponding to 7.9% of the patrimonial building stock. The overall number of heritage buildings on moving soil tends to decrease in later periods, with a small increase noted in Flanders and Wallonia for 2005-2010 and an increase in Brussels during 2016-2018.

The analysis results were compared to site-visit findings from selected case studies. Two methods were employed for the selection of the case studies: (a) selection based on high registered tilt values during the measurement periods, and (b) selection according to the analysis result, i.e. buildings with high potential damage according to the GEPATAR Toolbox. As mentioned before, method (a), which was used for the two first site campaigns was applied in the first half of the project, before the full analysis methodology was available. Buildings selected with method (a) were located in the areas around the closed collieries of Limburg. Buildings selected according to method (b) were located in Brussels and Leuven. In addition, several members of the steering committee indicated interesting case studies, which were analysed on a case-by-case basis.

Twelve buildings were selected according to method (a). According to the analysis results, all the buildings suffered negligible damage during the period 1992-2018. For 50% of the cases, on-site investigation did not reveal any differential movement damage and is thus in agreement with the analysis results. The remaining 50% presented damage, ranging from slight to moderate, but with evidence indicating that this damage was induced and repaired before the beginning of the measurement period.

Three buildings were identified according to method (b) in the city of Leuven, one with moderate and two with severe calculated potential damage. The moderately damaged and one of the severely damaged buildings have undergone renovation interventions. The other severely damaged building indeed presented substantial differential movement damage: wall cracks typical of ground settlement, roof parapet collapse and lintel failure.

Overall, it was found that distinguishing between movement partially registered due to structural changes, such as alterations in the roof, and movement due to ground settlement and uplift is not straightforward. The effects of the former are smeared out in the 10-meter interpolation grid and thus do not affect the velocity threshold criterion. However, they may affect the potential damage calculation in the absence of prominent PS caused by actual ground movement.

3.3 Recommendations with respect to damage assessment

The damage calculation method was tested against a number of case studies from the literature, demonstrating sufficient accuracy in terms of damage classification. The verification against these case studies shows the potential of the calculation method to be in principle applicable at any analysis scale. The different damage indexing methods provide a range of results for common structural typologies.

The analysis results for the entirety of Belgium are presented, in terms of potential damage suffered in the period 1992-2018 and in terms of the amount of buildings on subsiding or uplifting soil. The former criterion, derived from the ground movement gradient in the area of the building, can be used for identifying potential building in need of repairs. The latter criterion, based on the ground movement velocity in the area of the building, can be used for prioritizing large-scale inspection efforts in areas of interest.

While the proposed method shows sufficient flexibility in terms of defining the properties of the building and loading parameters, the matter of soil-structure interaction and 3D stiffness of the buildings during the application of arbitrary soil movement profiles remains open. The next step in the refinement of the methodology developed here would be the incorporation of these aspects in a generalized way.

Practical limitations currently restrict the use of InSAR data to medium-resolution sets. As a subject of future work, a two-step analysis can be designed, in which a wide-area assessment of ground movement is conducted using medium-resolution data, allowing the identification of areas of high interest. These areas can in turn be analysed locally using high-resolution data, such as those provided by the TerraSAR-X or CosmoSkyMed satellites.

Finally, a coupling of damage analysis results with wider site-inspection efforts is necessary and needs to be emphasised in future work. This coupling serves the further validation of this and other similar analysis methods for ground movement damage prediction over large areas and can assist in the establishment of new and the enrichment of existing empirical relations between ground movement measured in the country scale and damage to buildings.

WP4 GEPATAR toolbox for patrimony conservation

4.1 Heritage data Integration

Heritage data integration, illustrating the geographical distribution, typology and relevant historical information and images on the cultural heritage at the different scales and enabling for the end-users to identify the monuments and assess their vulnerability to local ground deformations. Registration and archival of heritage data is a regional matter, as well as providing geographical information. The three regions have their own approach to collect, catalogue and share this information, and the development of both their heritage data archives and GIS-platforms has reached different levels of completion.

Every region maintains two lists: a list of protected heritage and an inventory of valuable heritage. The protected built heritage may contain a variety of objects and classifications, such as monuments, cityscapes, cultural-historical landscapes and archaeological heritage. Hence, the first task was to select the monuments from the protected heritage lists and the inventories of the regions, as the GEPATAR toolbox could only define a risk towards built heritage. Furthermore, for the damage models to operate the following information needed to be extracted from the regional data archives: 1) the building envelopes (polygons) to extract information on the length and orientation of the external walls, and 2) information with regard to the typology and age of the monument to define essential structural characteristics.

Flemish Region

Flanders counted at the end of 2018 11.327 classified monuments, including cityscapes, cultural-historical landscapes and archaeological heritage sites, and more than 90.000 objects in the inventory (which also includes maritime heritage and trees). The information is accessible at http://inventaris.onroerenderfgoed.be. First a selection was made based on the typology "erfgoedtype" (https://thesaurus.onroerenderfgoed.be/conceptschemes/ERFGOEDTYPES). The different categories and subcatogories were evaluated, and an appropriate selection was made to extract the relevant objects within this project.

This information was cross-correlated with the geographical information available at the GIS-platform (geo.onroerenderfgoed.be). Data on the building envelopes is available for download(https://geo.onroerenderfgoed.be/downloads) into two separate shape files for respectively the protected buildings and the inventory. As such a shape file of the monuments and the built heritage in the inventory for the Flanders region was established, with a persistent identifier linking to the heritage data archive of Onroerend Erfgoed. The available shape files were however cross-correlated with the OpenStreetMap data (http://download.geofabrik.de) on the buildings to obtain the actual polygons of the monuments, as the original shape files from Onroerend Erfgoed often included larger areas rather than the individual buildings. Cross-correlation was realised by means of a Python script.

Brussels Capital Region

The Brussels Capital region counts approximately 1,200 classified monuments and more than 40,000 objects in the inventory. The online heritage data archive (http://www.irismonument.be) is however a work in progress. Not the entire Brussels region has yet been covered, and some parts of the region are only partly or even not included for now. Objects already present in the archive are detailly described and categorised. The inventory however doesn't include a geolocalisation of the objects. The Brussels Capital region also maintains a separate GIS platform (http://www.mybrugis.irisnet.be), which includes a layer (shape file) of the inventory, yet without reference to the object in the heritage data archive. The shape file included the actual polygons of the monuments.

Walloon Region

The protected built heritage list of the Walloon region counted almost 4.700 entries at the end of 2018, distinguished between exceptional heritage (274 items) and classified heritage. The inventory counted 52.715 objects at the moment of consultation (http://lampspw.wallonie.be/dgo4/site_ipic/index.php). The heritage data archive of the Walloon region is still under development. An inventory of the entire region has been realised between 1973 and 1997, however this information is not accessible on the online platform. About one third of the communities have meanwhile been updated, but not all to the same level of detail with regard to classification or geolocalisation (Figure 29). About half of the data available online has a geolocalisation registered with it.

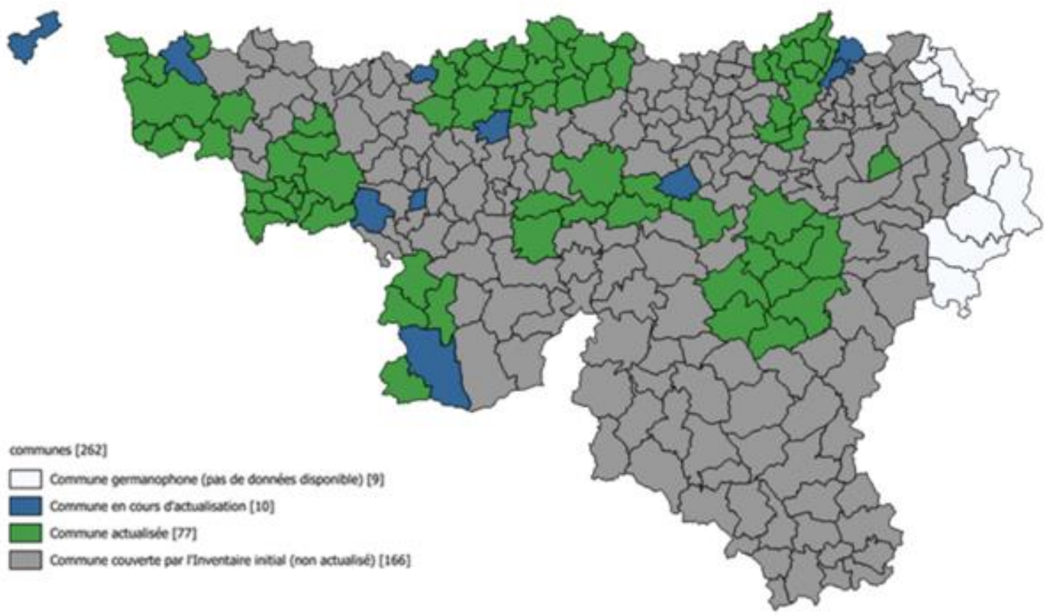


Figure 29 Heritage mapping inventory in Wallonia

Also the GIS-platform (http://geoportail.wallonie.be/home.html) of the Walloon region is still under development. The GIS-platform contains a shape file for the protected buildings, however the geolocalisation is restricted to a single point per monument. A direct cross-correlation with the OpenStreetMap data on the buildings wasn't feasible here, as most of the points in the shape file for the protected buildings were only close to the building envelopes, centred on a complex of buildings or related to an archaeological remnant, statue or font not included in the OpenStreetMap shape file. The cross-correlation was realised by first correlating the data points of the monuments with the cadastral data, and then extracting the building shapes in the OpenStreetMap data for the respective cadastral areas. From the 4.693 data points in the shape file of protected buildings, 2.799 building shapes were extracted. No information could be obtained with regard to the buildings included in the inventory.

To conclude, a shape file containing the building envelopes of the classified monuments and the built heritage objects in the inventory was obtained. The shape file is complete for the Flemish and Brussels Capital region, and only contains information on the classified monuments for the Walloon region. In the case of the Flanders region, a cross-correlation with the heritage data archive could be established.

Although every region categorizes the data in their inventory according to potentially interesting categories such as typology, date and style, their adopted approach for categorization often restricts the usability of the registered data for risk assessment based on the damage models in the GEPATAR toolbox. For instance, the category date generally contains different entries, listing every date or period interventions occurred from the first creation up to the last restauration of the monument. It is even possible that the earliest periods concern constructions which have already long been gone. The categorised information available in the heritage data archives is hence not immediately useful for damage assessment. However, contextual information in the heritage data archives is often very elaborate and could prove to be very useful for automatic damage assessment in the GEPATAR toolbox, provided that artificial intelligence methods are applied for data extraction from the texts and/or images of the monuments.

4.2 GEPATAR toolbox

The GEPATAR toolbox is available under the domain http://gepatar.kikirpa.be/. The visitor requires to accept the following disclaimer before accessing the tools:

This disclaimer was created and reviewed by the legal advisers of BELSPO, KUL, RBINS and RMA.

> Disclaimer
>
> The User acknowledges and accepts that the data and maps displayed are the result of analytical and numerical models and algorithms based on available data, current scientific knowledge, statistical analysis and intrinsic simplifications. They mainly aim at providing initial information on the situation of the studied areas. In situ analysis by experts in geotechnical and structural behavior is required to analyze and validate these initial data. Therefore, the partners of the GEPATAR consortium cannot under any circumstances, be it individually or collectively, guarantee or be held responsible for the accuracy, merchantability or applicability of the data for any particular purpose. The User acknowledges that the data and maps are provided without warranty of any kind.
>
> The displayed information should be interpreted by persons with competence and an appropriate level of skills in the specific areas such as, for example, engineers, architects, geologists, etc. The partners of the GEPATAR consortium cannot be held liable in any way, individually or collectively, for any interpretation of the information such as, by way of example but not limited to, structural, geotechnical, geological interpretations derived in any form or by any means from the data and maps. Nor can they be held liable for any loss or damage incurred by the User or any third party deriving, directly or indirectly, from (i) further processing of the data and maps; or (ii) any interpretation and/or use of it by the User or third parties.

The interface is available in three languages: Dutch (NL), French (FR) and English (EN). The home page (Figure 30) consists of the map of Belgium and the option to see the historical ground displacement per periods.

Figure 30 GEPATAR home page under the domain http://gepatar.kikirpa.be/

The 'Ábout' section provides information about the project, the used damage model and the InSAR processing scheme. The website also provides information about the partners and an option to contact the managers of the domain and the project.

By including the Belgian Patrimony layer the visitor may zoom into area of interest or search for name of monument or address. Figure-31 presents the classification results of hundreds of patrimony buildings in the centre of Brussels and the model analysis for selected building, CIT Emile Blaton. The Figure shows that this building is in light potential damage since 2001 and that the damage was measured by the PS techniques in 4 different periods and in two periods using the interpreted grid. These analysis tools were provided for allowing the users to have an insight on the developed damage during the selected period and the available data. In the case of low data availability, the confidence in the results may be decreased.

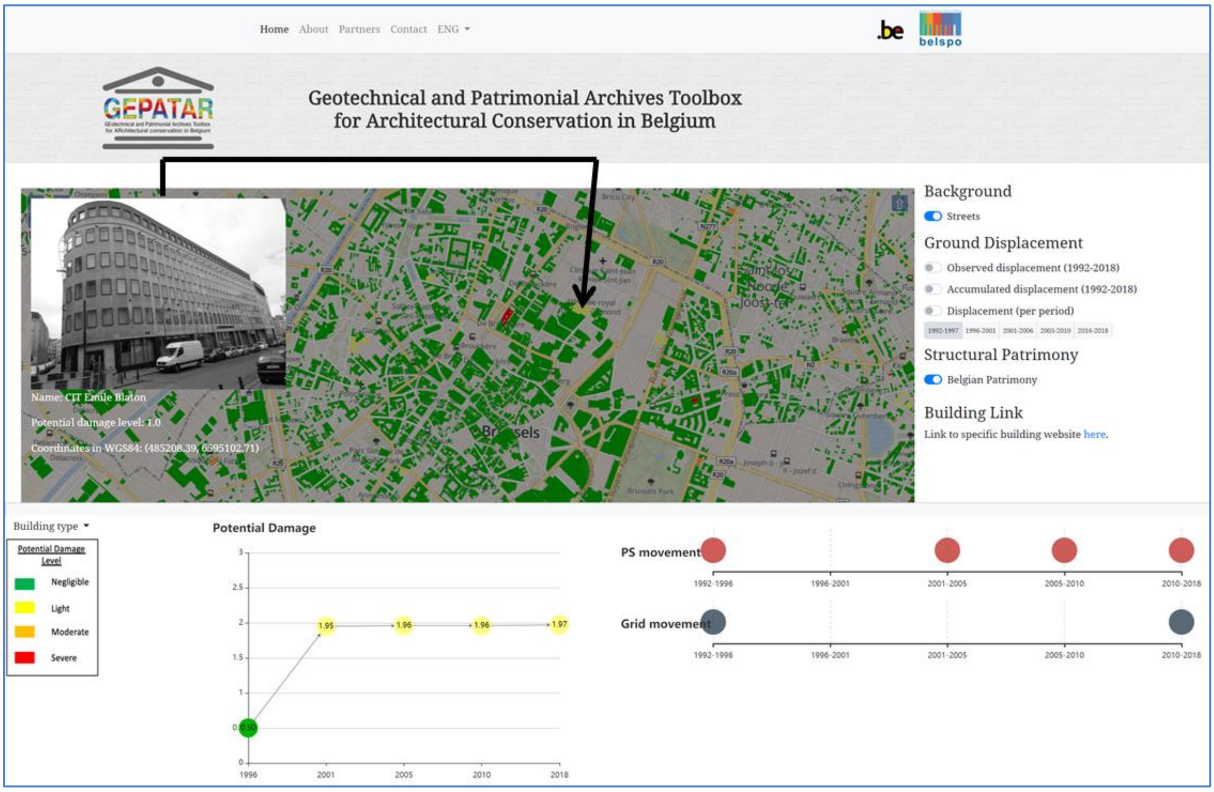


Figure 31 GEPATAR interface – Search results for CIT Emile Blaton, Brussels

Recommendations

The project faced several technical challenges and has demonstrated some limitations in the approach. Specifically,

- A lack of coherence in the patrimony data originate from three different cultural heritage catalogues of the Belgian regions: Flanders, Walloon and Brussels. The GEPATAR toolbox includes scripts for data mining that search keywords and dates for assigning a structural typology for each polygon and applying the relevant damage model. Unfortunately, the quality of the information in these catalogues is largely varied or missing and for many of the buildings it was impossible to obtain information about the history, construction date or materials that may help to define the structural typology.
- Unexplained phase differences between Sentinel-1 and previous spaceborne missions. PSI is calculated using large time series of radar data from historical and current European space programs including ERS-1/2 from 1992-2000, ENVISAT from 2003-2010 and Sentinel-1a/b from 2017 till present. The latter provides an opportunity for obtaining high accuracy (millimetres) in a short periodic monitoring as its revisit cover time is high (6 days in the case of two operating satellites). Nevertheless, during the initial GEPATAR project we obtained large phase differences between Sentinel-1 and previous missions that presented unexpectedly high differential trends. In the future, coupling GNSS stations with PSI data directly on a selection of heritage buildings for which detailed 3D laser scanning could be performed. The time component coming from the time series of PSI and GNSS will become a new input parameter for structural modelling of settlement-induced damage in the heritage buildings.
- The lack of 3D damage models. Accurate damage assessment requires 3D models that integrate large sets of building parameters including the geometry, material, loading, and boundary conditions such as tunnelling-induced strains. These parameters can only be partially obtained from remotely sensed and environmental data sources that are collected on continuous basis. Therefore, it is possible in the future to combine algorithms to realize both data mining in terms of raw text information and image recognition and information extraction
- An evaluation of the toolbox in terms of input/output in relation to its users: the developed GEPATAR toolbox was designed by engineers with focus on efficiently using the available data to deliver the results of a risk analysis in a straightforward manner. Yet, options such as crowd-sourcing (user-based input or feedback) and user-profile-based GUI design were not explored.

5. DISSEMINATION AND VALORISATION

In addition to the publications hereafter in chapter 6, the GEPATAR consortium participated to or organised several events in which the project was presented.

5.1. Organization of workshops

CSL organised the "Dark Side of Remote Sensing" day, December 9, 2015, BelSPo premises. This one-day workshop was dedicated to the presentation of InSAR techniques and existing potentials in Belgium to foster research and activities in this frame and to promote networking.

GEPATAR Infoday that was organised the 12th September 2019 at the Royal Military Academy in Brussels where the partners presented the results of the project with a particular attention to the launch of the GEPATAR toolbox.

5.2. Participation at scientific meetings or conferences

Leidy Bejarano-Urrego has presented: Settlement-induced damage monitoring of a historical building located in a coal mining area using PS-InSAR at the 6th workshop on Civil Structural Health Monitoring (ISHMII), in Belfast in May2016.

Leidy Bejarano-Urrego has presented: Mechanical characterization of masonry on the macro scale from experimental testing and numerical meso scale modelling. at the 10th International Masonry Conference, in Milan, in July 2018.

Els Verstrynge has presented: Advanced techniques for monitoring of settlement-induced deformations and crack growth in historical masonry, at the 10th International Conference on Structural Analysis of Historical Constructions in Leuven, in September 2016.

Jan Walstra has presented: PSI analysis of multi-sensor archive data for urban geohazard risk management: a case-study from Brussels at FRINGE 2017 Workshop in Helsinki, in June 2017.

Jan Walstra has presented: Time-series analysis of SAR images for detecting ground subsidence in the Scheldt estuary at the Geologica Belgica conference, in Mons in January 2016.

Jan Walstra has presented: PSI analysis of TSX archive data for urban geohazard risk management: preliminary results from Brussels at TSX/TDX TerraSAR-X Science Team Meeting, in Oberpfaffenhofen in October 2016.

Jan Walstra has presented: The GEPATAR project: GEotechnical and Patrimonial Archives Toolbox for ARchitectural conservation in Belgium.at the European Geosciences Union General Assembly, in Vienna, in April 2018

Michal Shimoni has presented: GEPATAR: a geotechnical based ps-insar toolbox for architectural conservation in Belgium at the IEEE International Geoscience and Remote Sensing Symposium, in Fort Worth, Texas, in July 2017.

Michal Shimoni has presented: Advances processing of remotely sensed big data for cultural heritage conservation, at the IEEE International Geoscience and Remote Sensing Symposium, in Yokahoma, in July -August 2019.

Pierre-Yves Declercq has presented: Overview of the ground movements highlighted by the Persistent Scatterer Technique (PSI) in Belgium at the Geologica Belgica conference, in Mons in January 2016.

Pierre-Yves Declercq has presented: Cartography of the Belgian monuments at risk via PSI analysis of the ground movements, the GEPATAR project at the Geologica Belgica conference, in Mons in January 2016.

Pierre-Yves Declercq has presented: Subsidence Related To Groundwater Pumping For Breweries in Belgium at FRINGE 2017 Workshop in Helsinki, in June 2017.

6. PUBLICATIONS

Journal Articles:

Drougkas, A., Verstrynge, E., Van Balen, K., Shimoni, M., Croonenborghs, T., Hayen, R., Declercq, P-Y. (2020). Country-scale InSAR monitoring for settlement and uplift damage calculation in architectural heritage structures. Structural Health Monitoring – an International Journal , Art.No. 1475921720942120. doi: 10.1177/1475921720942120

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