A Step Towards Accurate Integrated Monitoring of The Sinking Zones in the Coastal Area of Antwerp Due to Possible Hydrogeological and Geomechanical Processes

A. Choopani[1,2], P. Y. Declercq[1], J. Verbeurgt[3], F. De Doncker[3], P. Orban[2], A. Dassargues[2], X. Devleeschouwer[1]

1 Royal Belgium Institute of Natural Sciences, Department of Geological Survey of Belgium, Rue Jenner 13, 1000 Brussels, Brussels, Belgium
2 Department of Hydrogeology & Environmental Geology, Urban and Environmental Engineering Unit, University of Liège, Liège, Belgium
3 Department of Geodesy, National Geographic Institute, 1000 Brussels, Belgium

atefe.choopani@naturalsciences.be

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Land subsidence, or the sinking of land as a result of compacting compressible layers, is particularly prone to occur in recent loose sediments of estuaries and is generally increased by human activities such as geological unit draining and deep groundwater pumping activities. On the other hand, the compaction of aquitard systems and confining layers in coastal areas due to rising demand for groundwater production added to the global rise of the relative sea level.

The harbor city of Antwerp, whose topography ranges from 0.5 to 5 m TAW, is situated on low-lying polders in the upper portions of the Sea Scheldt estuary. As a result, in the presence of high tides, mudflats and salt marshes were frequently flooded during history before the development of the dikes [1]. After the devastation of the floods of 1953 and 1976, a strategy known as the Sigma plan was adopted with a variation that allowed the water to penetrate regions that were specifically designed to be flooded [2]. This project called for building a 512 km long dike as well as a 5.5 km long and 1.35 m high concrete wall to surround the city. Antwerp's port has also been changed by various human constructions to meet modern industrial demands, including enlarging the land area of the port terminals and deepening the docks so that contemporary standard-sized boats can be moored [2]. The excavated materials were utilized for embankments to expand new industrial or transportation zones, such as harbor roads, as well as new places for the contemporary commodity handling of goods and maintaining dikes as part of the Sigma plan [3].

Although Interferometric Synthetic Aperture Radar (InSAR) measurements are known as very precise data on displacement in the line of sight (LOS) of the satellite (with a precision of ≤ mm/year) for surface monitoring purposes, it comes with its own constraints. InSAR creates measurements across broad regions using transmissions from radar satellites. This technology assesses changes in land-surface elevation with high resolution and spatial precision. Despite being an excellent tool for analyzing deformation, InSAR can only determine displacement relative to a reference date called master acquisition. Furthermore, to minimize InSAR measurement uncertainties, InSAR data also need to be validated using additional observations such as independent GPS campaign data. Moreover, in regions with dense vegetation and inadequate spatial and temporal sampling of the available radar datasets, a loss of correlation will occur. In such areas, Persistent Scatterers InSAR (PS-InSAR) overcomes the limitations of conventional InSAR as an appropriate method for monitoring ground displacements [4]. Even in densely vegetated natural environments, the PS-InSAR time series analysis allows us to investigate the short and long-term behavior of the continually active occurrence of subsidence. Despite all the PS-InSAR capabilities for monitoring surface displacements, it can only produce displacement measurements at Permanent Scatterers (PS) locations where the backscattered signal from the objects changes very little over time. These objects, which are permanent scatterers in ground resolution components, frequently coincide with artificial infrastructures and may be abundantly seen in urban areas as a result. Thus, Ps-InSAR will not be able to calculate displacement values in non-urban areas with limited human infrastructure leading to a sparse number of PSs.

In the literature, the integration of several geodetic approaches in the frame of the Integrated Geodetic Reference Stations (IGRS) is suggested for better monitoring of surface deformation and for overcoming InSAR limitations. A Global Navigation Satellite System GNSS receiver, two InSAR corner reflectors (for ascending and descending satellite tracks), and several leveling benchmarks are all installed upon one firmly anchored concrete landmark to make up the cutting-edge IGRS [5] (Fig. 1).

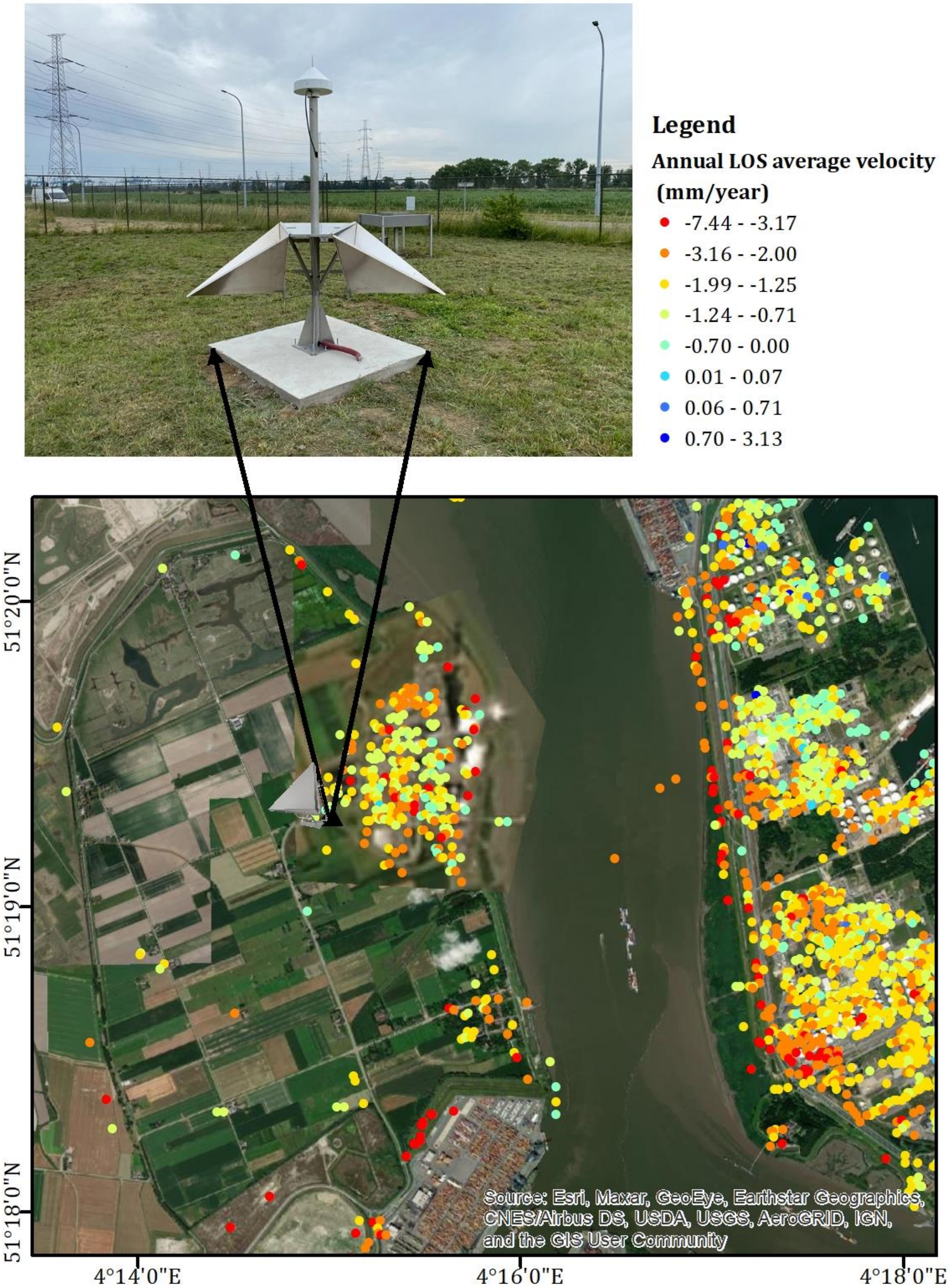

Figure 1 Location of installed IGRS on the average annual velocity map of the PS points calculated from applying PS-InSAR on Sentinel-1 radar data

Using IGRS enables us to (1) combine different geodetic tools or techniques at the same location and (2) increase the confidence and quality of the InSAR measurements through direct cross-validation and calibration of GNSS and leveling [6]. All observations in each consistent temporal sampling are dependent on a certain datum and are of the same type since they are made in relation to the same landmark, which represents the same deformation source. Importantly, IGRS as a corner reflector that is equipped with a GNSS receiver, can function as a single PS in regions devoid of man-made buildings.

As a result, in regions free of InSAR measurement due to a lack of PS points, IGRS offers precise height observations with a high degree of certainty. The IGR station installed in Doel will be the first system installed to monitor the subsidence of the recent sediments along the Scheldt estuary and also in very close proximity to the nuclear installation facilities.

This study is being conducted in the framework of a more comprehensive project called "monitoring LAnd SUbsidence caused by Groundwater exploitation through gEOdetic measurements (LASUGEO)" [7]. There is an objective to install at least 6 to 8 IGRS and deploy them over Belgium to ensure accurate time-series measurement of displacements using InSAR data. Currently, one of the first installations is already being carried out in Antwerp, where displacement time series of plenty of the PS points are being measured using Sentinel-1A radar data. The land subsidence was identified using the more than 300 radar image scenes acquired by European Space Agency (ESA) satellites in the ascending and descending modes using the PS-InSAR technique [8]. The Quaternary sediments of a total thickness of 11.6 meters underneath the specific location of the IGR station are formed by uncompacted sands, clays, peat, and gravel. The most recent ones of the Vlaanderen Formation are associated with the alluvial plain deposits of the Scheldt River and are composed of sands, clays, and peat layers. One cause of the subsidence that PS-InSAR technology has detected in this area should be the geological materials underneath most of the area exemplified in Fig. 1. Those sediments are young and unconsolidated implying that they are easily prone to localized natural consolidation. A study of combined hydrogeological and geotechnical modeling should be investigated to identify any possible additional hydrogeological drivers that may present.

Timeseries of displacement over the past 30 years are assessed and will be calibrated based on the IGRS measurements to be taken in the near future. Time series of GNSS measurements with daily sampling frequency will be simultaneously provided with Sentinel-1A satellite acquisitions that are going to be obtained in the coming months for every revisiting of the Sentinel-1A satellite.

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