Using Radar Satellite Data for Ground Deformation Monitoring: ATLAS In SAR

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Abstract

Radar satellite interferometry (InSAR) is a non-invasive surveying technique based on the exploitation of SAR images, able to measure millimetric motion of terrain structures over wide areas in both urban and non-urban environments. Sixense processing chain, ATLAS, has been successfully used to detect and monitor ground motion in many different projects, cities and sectors to follow subsidence, heave, building stability and landslides amongst others. ATLAS reaches high density of measurement points, and covers large areas with high-resolution imagery, and weekly revisits. This presents a huge opportunity for the monitoring and management of infrastructures. However, the unprecedent spatial and temporal volume of InSAR measurements- which are only going to increase with new sensors to come- presents a challenge. Thus, ATLAS is in continuous development to efficiently extract characterized information of maximum benefit to end users by implementing different algorithms and AI methodologies over InSAR Big Data results to provide ready-to-use, actionable information. Different application cases of the ATLAS monitoring in different scenarios will be presented in the field of civil engineering: from ATLAS extended areas results to a local asset focused solution to provide ready-to-use friendly-user information in the ATLAS GIS web platform.

Keywords: Instrumentation & monitoring, InSAR, Ground deformation

1 Introduction

When executing any type of construction work, one of the major challenges is to guarantee that the different infrastructures adjacent to the construction activity are not affected by it, and if they are that it remains within acceptable tolerance. This is exacerbated in heavily urbanised areas, like large cities, due to the high density of population and infrastructures that can be affected by movements related to construction.

The use of traditional monitoring, which entails in-situ instrumentation, requires a good deal of third parties management, installation and preparation, often not allowing much time between the installation of the instrumentation and the start of construction work, which might not provide enough background and historical data to properly understand the behaviour of the terrain. Furthermore, traditional monitoring will be typically focused on an expected "area of influence", few tens of meter around the axis of a tunnel for example, which may limit the understanding of ground movement in case of unexpected movement or overlook potential impact of others construction projects near the "area of influence".

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These limitations can be overcome by using remote sensing techniques such as InSAR, which has been broadly implemented for civil engineering purposes due to its advantages. These advantages include the potential availability of historical data, the removal of any on site access issue, and the large coverage of satellite images that allows detecting measurements over very large areas. Its use also provides a huge cost saving due to no (or very limited) installation costs while maintaining a similar accuracy to more traditional manual monitoring systems.

InSAR, or radar satellite interferometry, is a fully remote sensing technique based on the exploitation of synthetic aperture radar images (SAR), able to measure millimetric motion of terrain and/or structures over wide areas in both urban and non-urban environments.

Atlas, Sixense's InSAR processing chain, has been developed with the aim of monitoring geotechnical and structural deformations linked to urban construction activities and has proven to be a useful and complementary source of information to the traditional monitoring instrumentation.

This paper shows how the Atlas InSAR processing chain has been successfully applied in two different case studies. In the first case study, InSAR has been used for infrastructure monitoring and soil reclamation control in the city of Hong Kong. The city has been monitored with ATLAS using a set of high-resolution TerraSAR-X images acquired over Hong Kong from July 2017 to February 2021. Atlas provided the deformation maps and the displacement time series for a dense network of points over the area during the study period.

The second case study is focused in the use of InSAR in the ground settlement monitoring of a major tunnelling project in the city of London (United Kingdom). This project comprises the construction of a new railway line, which crosses Greater London from east to west and has five tunnelled sections totalling up to 42 km in length. In this case, the area of interest has been monitored with ATLAS using a set of high-resolution TerraSAR-X images acquired over London from August 2013. ATLAS provided accumulated deformation maps and the displacement time series for a dense network of points over the area of interest, during the extended study period.

2 Deformation Monitoring from Space: Atlas Sar Interferometry

2.1 SAR Interferometry

Synthetic Aperture Radar Interferometry (InSAR) is a non-invasive remote sensing technique capable to monitor wide areas of terrain with millimetric precision, making it ideal for the monitoring of infrastructures. InSAR is based on the exploitation of Satellite aperture radar (SAR) images, which are complex radar images containing phase and amplitude information over a very large area, usually few hundreds square km. The InSAR technique consists in analysing the same two SAR images at different date and computing the ground displacement information based on the differences of the phase components (Figure 1).

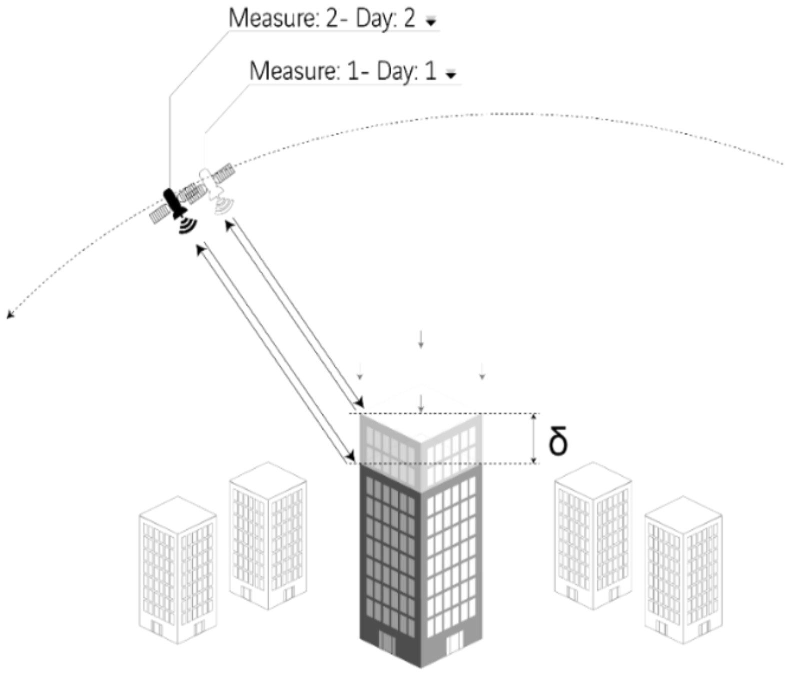

Figure 1: SAR interferometry working principle

To retrieve millimetric measurements, InSAR advanced technique are required. Those techniques produce better precision in the results by correcting atmospheric, orbital, and topographic components of the interferometric phase. Those techniques require at least fifteen SAR images and a robust selection of measurement points reflecting persistently the radar signal back to the sensor. These locations, called persistent scatterers (PS), are permanent highly reflective targets, whose reflections remain constant over the whole image stack during the duration of study. They are generally manmade structures or rocks but can also be arid terrains and other ground features whose orientation and surface characteristics allow a perfect reflection of radar waves.

2.2 Atlas Processing Chain

Sixense has developed its own treatment processing chain, ATLAS, around the core software GAMMA. ATLAS allows for measuring vertical ground and structure movements, with special attention to urban works and critical non-linear movements, on permanent scatterers with millimetric accuracy.

For each measurement point, the ATLAS solution provides maps of accumulated displacement along the study period, time series of deformation for each point monitored mean deformation velocity of deformation, and quality indexes of the measurements.

ATLAS PSI uses more than 15/20 SAR images with atmospheric compensation to derive highly accurate elevation and average displacement rate values for each stable point. The high-level of error compensation allows the generation of time series charts, visualizing the evolution of the displacement of each stable point. Urban, semi-urban or rural areas can be studied in detail (both in terms of high spatial resolution and the historical variation of the displacement) over long time periods.

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The processing steps are summarized as follows:

Image extraction: SAR data is read from the original media and all the auxiliary parameters are retrieved from the product annotations into ASCII auxiliary files.

Image selection: Analyse the set of available images, quality control is done at this stage to detect images with acquisition defects (images altered by satellite manoeuvres, erroneous annotation file parameters and severe weather conditions during the acquisition, etc.).

Image co-registration: A stack of images must be co-registered to a geometry. One image is selected as master and then all the other data is aligned to have a common geometry. Every pixel in all the images must contain the radar response coming from the same ground resolution cell.

Generation of differential interferograms: Selection and generation of interferometric pairs based on the acquisition time, the perpendicular base and the difference in the Doppler centre of each image. The complex interferogram is generated by multiplying the first SAR complex image, named master, with the complex conjugate of the second one, named slave. The DEM in radar geometry is removed from the interferograms to remove the topography component. Note that a component related to height of buildings and DEM errors, called topographic residual error, is still contained in the interferometric phase. The interferograms are also corrected for the so-called flat earth removal and orbital errors.

Selection of measurements points: Selection of the initial measuring points, that is, pixels with low noise level that allow to derive reliable phase measurements, i.e. the so-called Persistent Scatterers (PS). They are points of constant phase quality during the entire study period, whose signal refers to the predominant reflection of the signal in the same object (point-target). They are points that are little affected by the effects of spatial and temporal decorrelation. They are usually found in urban areas, in buildings and infrastructures, and allow to fully exploit the high spatial resolution of high-resolution sensors. The pixels with low temporal variability of the backscattering coefficient during the period of interest are selected.

Ground motion estimation: Obtention of the speed, vertical height and associated quality index for study points referenced to a previously selected reference point. The goal is to estimate and remove the different components of the interferometric phase to reach mm precision on the measurement of the displacement. This is achieved by applying an iterative procedure consisting in a set of spatio-temporal filters to estimate and remove phase component related to atmospheric effects and precise estimation of the residual topographic error (difference between DEM and real height of the measured objects). This is fundamental for a further precise geocoding of the measurements points, as well as to isolate the phase component related to deformation and achieve precise results. The velocity of deformation is derived considering a linear model on the deformation. A quality index of best fit to the model is also derived in this step. Note that thermal effects, i.e. thermal dilation typically over metallic structures, bridges or skyscrapers, can also be modelled and removed.

Precise estimation of deformation time series (linear and no linear) by means of an advanced combination of the so-called spatial phase unwrapping method and a robust least square procedure which makes uses of redundancy to retrieve deformation time series.

Quality control on measurement points. Although each processing step has its own quality indexes, in this step the final quality thresholds are selected depending on the case at hand and the final table of measurement points in LOS is generated. The quality thresholds generally used are the indicator of degree of fit to the phase models used for the estimation of the terrain deformation, and the standard deviation of the motion measure (time series), which is an indicator of the level of noise.

Precise geocoding. This is the last step of ATLAS processing chain. Measurement points needs to be geocoded to obtain map coordinates with an accuracy below 1-2 m. To meet this requirement, both DEM and residual topographic error needs to be used.

3 Atlas Insar Case Studies in Civil Engineering

ATLAS InSAR has proven to be useful for a variety of application in civil engineering, such as linear infrastructure assets, (highways, railways, bridges, pipelines, power-lines and tunnelling), huge surfaces (soil reclamation, offshore oil plants, dams and landfills) and small assets (singe buildings).

In this paper we will present how ATLAS InSAR has been used in two different major cities: Hong Kong & London (United Kingdom). First, we will focus on how InSAR has been used for infrastructure monitoring and soil reclamation control in the city of Hong Kong. After that, an example of the use of InSAR in a major construction tunnelling project in the city of London will be presented.

3.1 ATLAS InSAR Infrastructure Monitoring in Hong Kong

ATLAS was successfully applied to Hong Kong using a set of high-resolution TerraSAR-X images (radar interferometry satellite constellation), acquired from July 2017 to February 2021. 394 km^2 have been monitored with an approximate density of more than 15 000 points/km^2 over urban areas and more than 2 000 000 measurements points. ATLAS InSAR monitoring has allowed the monitoring of extended areas and at the same time to control several infrastructures, such as roads and buildings with high density of points.

The quality assessment on the deformation time series show that 68% of the measurement points presents high quality, 31% medium quality and 1% low quality, being this classification based on the standard deviation of the time series (σ) as follows: High quality $\sigma < 1$ mm, Medium quality $1 \leq \sigma < 1.7$, and Low Quality $1.7 \leq \sigma < 2.5$. Points with higher standard deviation have been discarded.

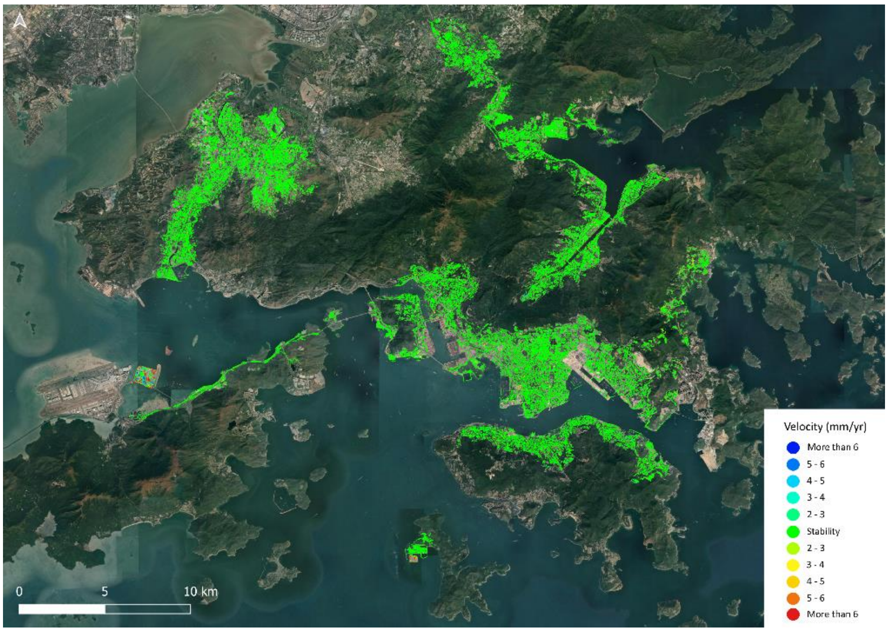

Figure 2: Velocity of deformation map over Hong Kong

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Two examples of road monitoring are shown in this section. The first one is the New Territories Circular Road (9). Figure 3 shows the velocity of displacement map over the road and its surroundings. It shows a general stability (in green) and settlement deformation around points A and B of about 3mm/year and 15mm of accumulated deformation during all the period around.

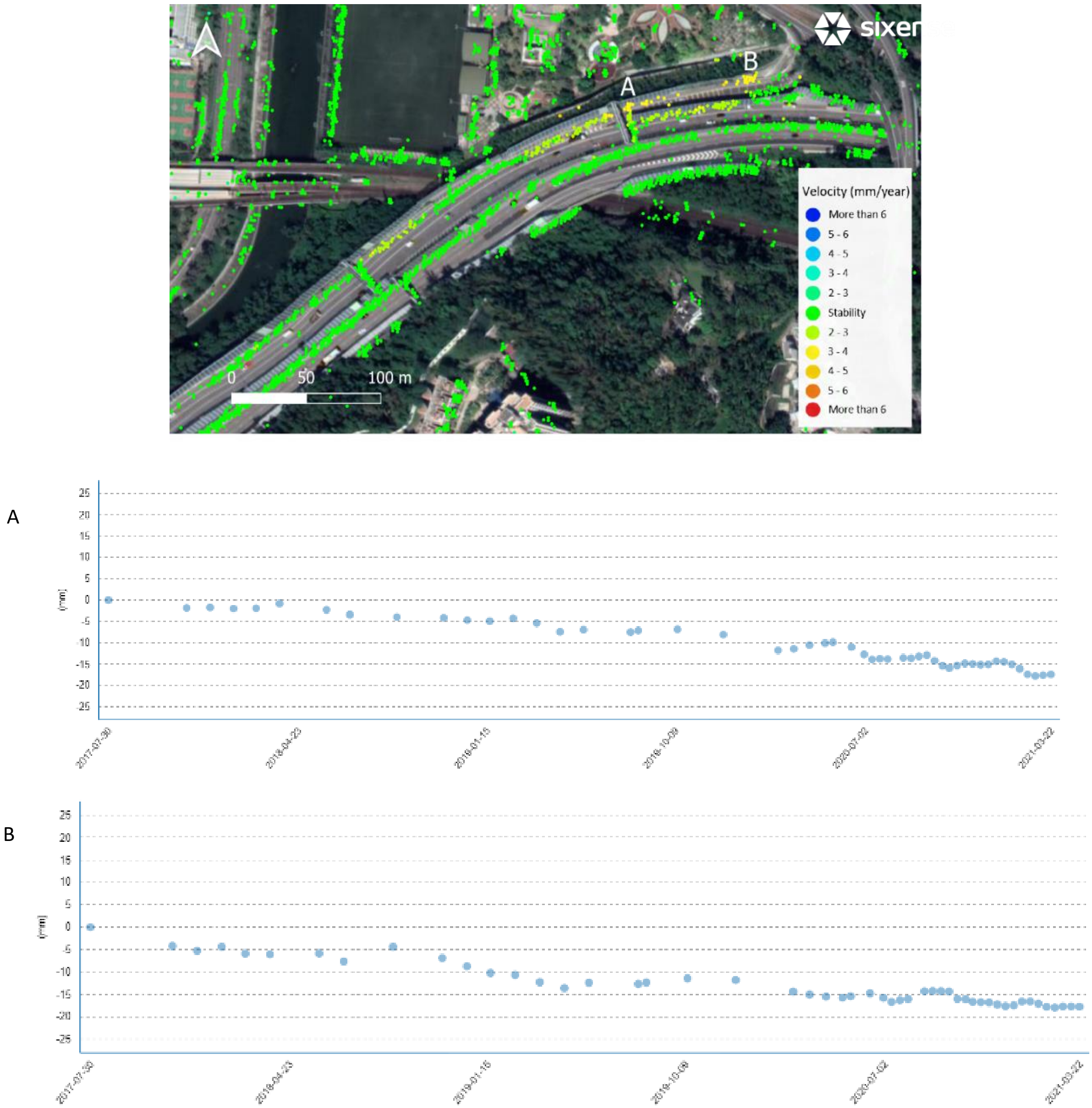

Figure 3: Velocity of deformation map and corresponding time series of a road showing deformation in the north east of Hong Kong

The high density of measurement points obtained and the average sampling rate of 11 days in this project allows to continuously monitor roads and other infrastructures. Figure 4 shows an example of mainly stable road located in the South-West part of Hong Kong during the monitoring period.

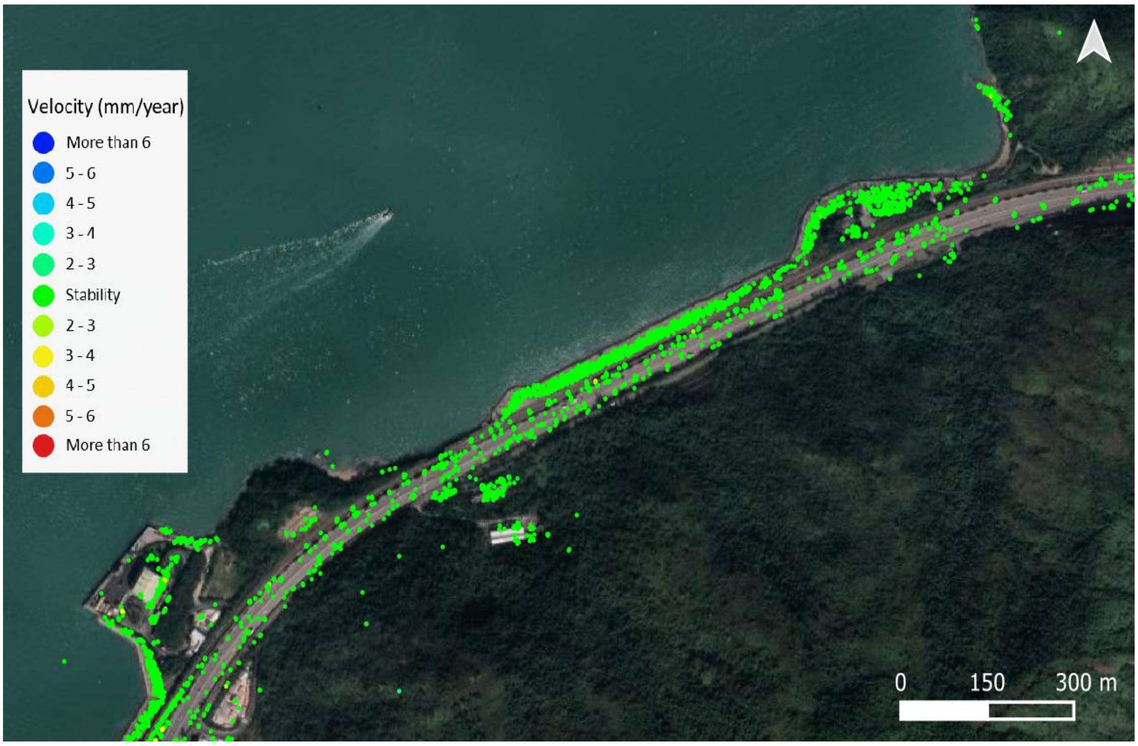

Figure 4: Velocity of deformation map showing stability in a road located at South-West Hong Kong

3.2 ATLAS InSAR Soil reclamation monitoring in Hong Kong

Hong Kong is one of the leading cities in the world and one of the most densely populated places. Hong Kong has a small surface and limited options for expansion, so a way to solve the absence of land and flat territory is soil reclamation. In Hong Kong, between 1877 and 2020, over 70 km^2 of land has been constructed over the sea. This kind of construction needs to be monitored carefully. To this purpose, ATLAS InSAR can monitor the long-term movements, right after the end of the construction activity, and also after many years, in continuous or discontinuous monitoring, if required.

3.2.1 ATLAS InSAR HKBCF Island Monitoring

An example of use InSAR over areas constructed over the sea is the Hong Kong Boundary Crossing Facilities (HKBCF) island, which is part of the Hong Kong-Zhuhai-Macau bridge and serves as a strategic transportation hub on the west of Hong Kong. HKBCF, located east of the Hong Kong International Airport, consists of about 130 hectares of newly reclaimed land. The construction started on January 2016 and ends up on October 2018 with the public opening of the Hong Kong-Zhuhai-Macao Bridge Hong Kong Port.

ATLAS InSAR was successfully applied to Hong Kong Boundary Crossing Facilities (HKBCF) using a set of high-resolution TerraSAR-X images (radar interferometry satellite constellation), acquired over Hong Kong from January 2019 to February 2021. ATLAs results allowed to monitor the long-term movements over the island, after the end of the construction activity. Figure 5 shows the velocity of displacement map over the South-West seawall in HKBCF island. The velocity of displacement map shows differential movements along the coastline (see points A to C in Figure 5).

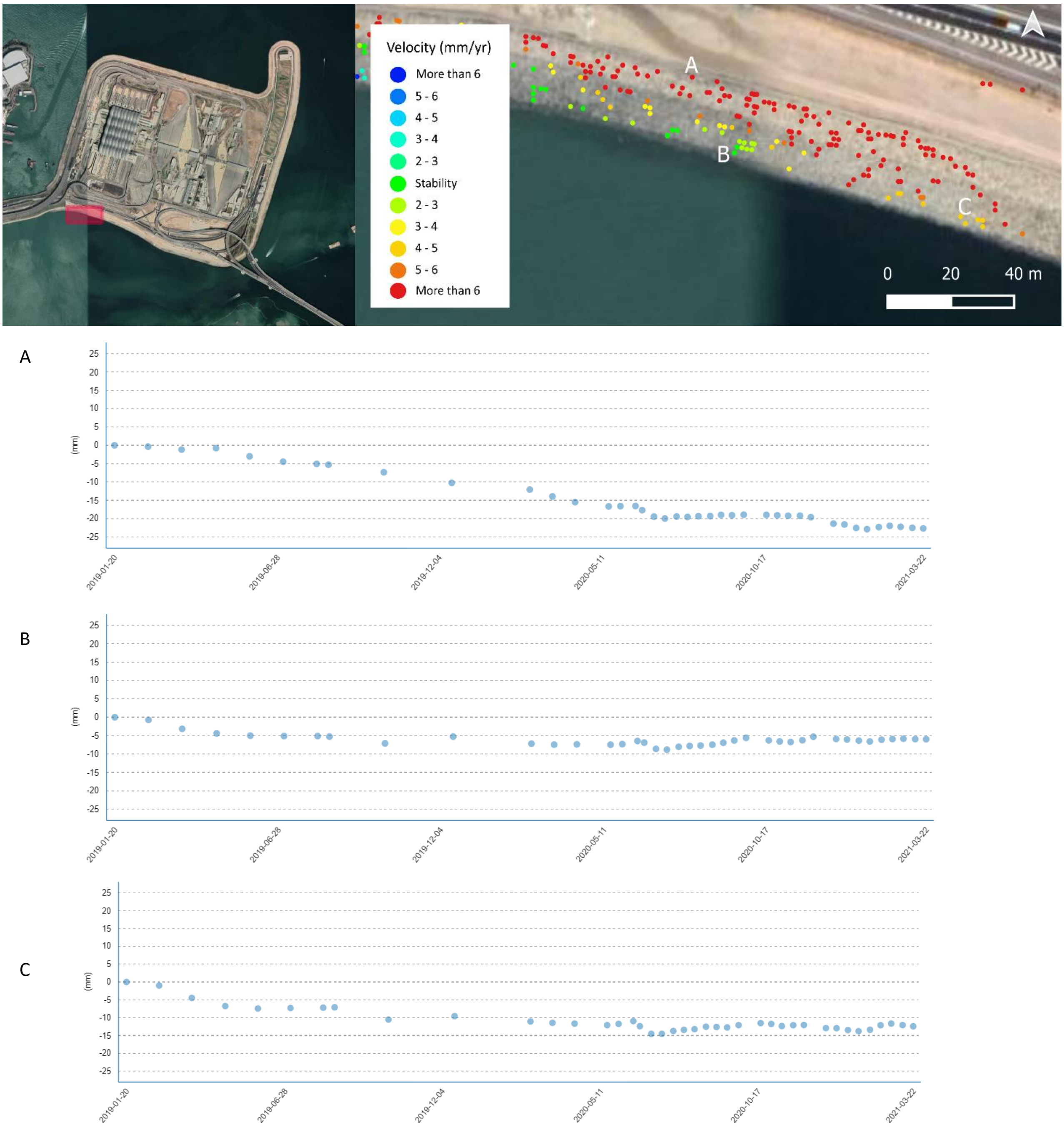

Figure 5: Velocity of deformation map (upper-right) and deformation time series (middle and bottom) over the seawall HKBCF island highlighted in upper-left figure

3.2.2 ATLAS InSAR Power Station Lamma Monitoring

ATLAS InSAR is also useful for continuous monitoring of land reclamation areas. Next example shows the deformation monitoring on the south of Lamma Power Station plant, situated at the Southern edge of Lamma Island (South Hong Kong). The extension was developed on reclaimed land to the south of the power station. The current extension of the reclamation covers about 22 hectares, the first part of which was finished in July 2006.

ATLAS was applied to Lamma island using high-resolution TerraSAR-X imagery (radar interferometry satellite constellation), covering the period from July 2017 to February 2021. Figure 6 shows the velocity of displacement map, which shows a circular settlement deformation in the centre of the island. The maximum subsidence velocity measured is around 12 mm/year with an accumulated deformation reaching 53 mm in settlement during the period of study.

Figure 6: Velocity of deformation map in the South of Lamma Island (Hong Kong).

3.3 ATLAS in Tunnelling Project: Crossrail (London) Case Study

Crossrail is one of the major tunnelling projects done in a heavily urbanised area. It consisted in the construction of a new railway line which crosses Greater London from east to west, with five tunnelled sections totalling up to 42 km in length.

InSAR and the ATLAS processing chain were successfully applied to the project using high-resolution TerraSAR-X imagery, acquired over London from August 2013. The main uses of ATLAS InSAR in Crossrail have been: (a) a source of information for the ground/structure behaviour before the start of the construction activity; (b) a complementary source of settlement data during construction; (c) a check for the long term movements, right after the end of the construction activity, or after many years if claims are raised in a later stage.

ATLAS InSAR measurements allowed to study the effects of dewatering activities, which usually result in settlement of the ground. Satellite measurements cover a very large area, which allowed to study a larger extent than the one initially planned, including zones in which there were no ground instruments results. This advantage of the InSAR technology was crucial to determine the total extension of the settlement due to dewatering activities, which reached a much wider extension than the area estimated at the design phase. This example is shown in Figure 7, which displays the accumulated displacement over the Limmo peninsula and its surroundings from August 2013 to August 2015.

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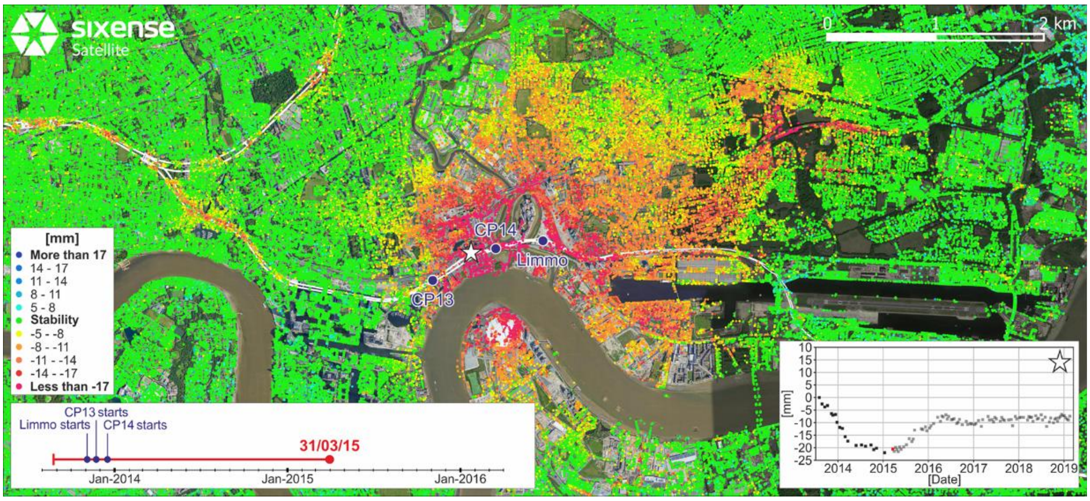

Figure 7: Accumulated deformation map showing the deformation by dewatering in Limmo area (London) derived during the period August 2013 to August 2015. An example of deformation time series of a point located on the area affected by the dewatering is also shown.

Additionally, InSAR results were used to check any widening of the settlement on the planned zone of interest, since tunnelling usually results in settlement movements associated to the loss of volume during the perforation phase. Figure 8 shows the deformation related to the tunnelling activities of the Crossrail project. The image shows deformations of more than 15 mm of subsidence during the period from August 2013 to May 2018.

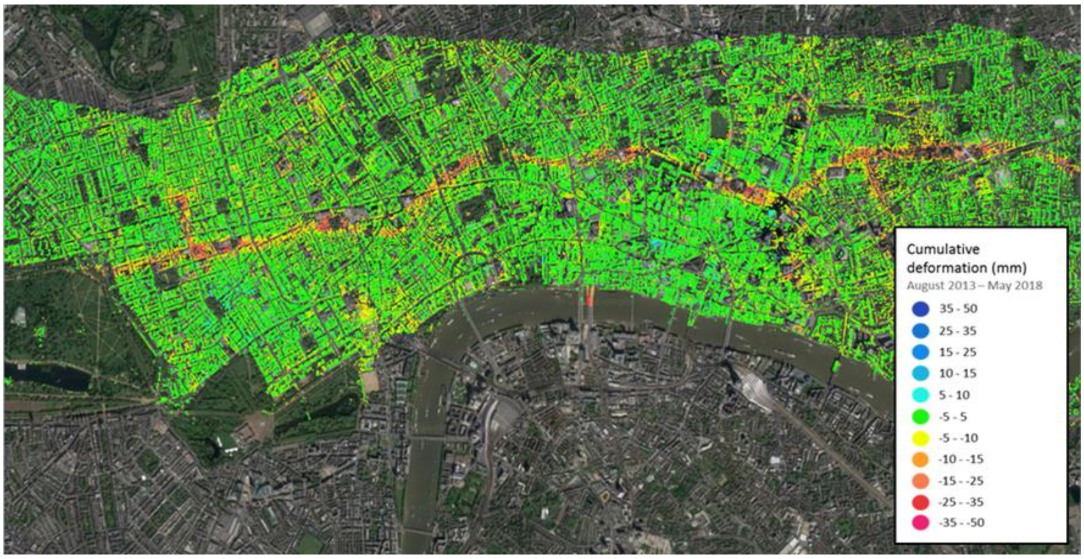

Figure 8: Accumulated deformation map over the tunnel alignment of Crossrail project (London, UK).

4 Conclusions

ATLAS Synthetic Aperture Radar Interferometry (InSAR) is a remote sensing technique, which uses radar satellite-acquired images, which has proven to be a suitable monitoring technique in the field of civil engineering. In this paper, ATLAS processing chain has been presented and three different case applications in two major cities, Hong Kong and London, have been shown.

In Hong Kong city, it has been monitored 394 km^2 with high-resolution TerraSAR-X imagery from July 2017 to February 2021 using ATLAS InSAR. Velocity of deformation maps and deformation time series have been shown for infrastructure monitoring, more precisely road monitoring, and soil reclamation monitoring. The maps exposed above illustrate the advantages provided by the InSAR technique.

In the Crossrail tunnelling activities, in London, 42 km of tunnel alignment have been monitored with ATLAS InSAR using high-resolution TerraSAR-X imagery from August 2013. Velocity of deformation maps and deformation time series showing settlement in the tunnel length and dewatering areas show how the technique was used for monitoring while the construction activities were ongoing and is still used during the post-construction stage.

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