Glasgow Geothermal Energy Research Field Site -Ground motion survey report

UK Geoenergy Observatories Programme

Open Report OR/18/054

BRITISH GEOLOGICAL SURVEY

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L Bateson, A Novellino,

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British Geological Survey offices

Environmental Science Centre, Keyworth, Nottingham
NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales
Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh
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Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place, Cardiff
CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford, Wallingford
OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB
Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House, Swindon
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Foreword

This report is the published product of a ground motion study conducted by the Earth and Planetary Observation & Monitoring team of the British Geological Survey (BGS) for the UK Geoenergy Observatories project.

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Summary

The report describes the main findings associated with the baseline monitoring of ground motion for the Glasgow Geothermal Energy Research Field Site (GGERFS) as part of the UK Geoenergy Observatories (UKGEOS) project.

The analysis is based on the interpretation of Interferometric Synthetic Aperture Radar (InSAR) data acquired for the period 1995-2017. Overall, the GGERFS sites are stable, small areas near the 2014 Commonwealth Games athletes' village show a minor subsidence pattern, with rates of ~5mm/yr, observed for the 2015-2017 period between sites GGERFS04 (site currently 'on hold') and GGERFS10. This motion is interpreted to relate to settling of relatively thick superficial and anthropogenic deposits, which have recently been built upon for the development associated with the 2014 Commonwealth Games.

Overall Glasgow and the surrounding area appears relatively stable for the three decades for which InSAR data has been processed. There are notable small areas of ground motion, which appear to relate to both natural (volume change of peat deposits, compressible ground) and anthropogenic (settling of made ground and landfill) factors.

1 Introduction

It remains a research question as to whether changes in underground water levels, pressure and temperature caused by mine water geothermal energy production activities can lead to surface subsidence/uplift. Ground motions have been observed following shallow geothermal drilling through anhydrite-bearing formations at Staufen im Breisgau (Germany; Lubitz et al., 2013) and for the enhanced geothermal field in Pohang (South Korea; Grigoli et al., 2018). However, these examples are for geothermal sites where borehole-related changes in hydrogeological flow led to swelling of anhydrite or are under pressure and hence drilling has disturbed the equilibrium. In mine water geothermal systems the existing anthropogenic hydrogeological pathways are re-used and the mine system is not pressurised, and so whilst ground motion is not anticipated as a result of future geothermal research at the Glasgow site, it is important to establish a pre-drilling baseline.

In order to address this question, monitoring is required to both assess the baseline of naturally occurring ground motion and surface-level impacts of geothermal abstraction and re-injection research activities. Because we cannot assume that the area is stable prior to the GGERFS (Glasgow Geothermal Energy Research Field Site) operations, the baseline survey is conducted in order to determine the pre-existing ground stability conditions due to either natural or induced factors and the occurrence of any displacement at the site.

Once this baseline is established further, ground motion investigations following the onset of GGERFS activities can be compared to understand if there is any impact derived from the geothermal research activities. With this regard, InSAR provides insights into the evolution of the geothermal system by regularly monitoring transient stress related to abstraction and re-injection activities over large areas, and can also be used to assess the stability, and therefore safety, of the above ground infrastructure.

In this study, we present results from geodetic radar surveys using Interferometric Synthetic Aperture Radar (InSAR) technique applied over the city of Glasgow using satellite imagery from June 1995 to December 2017. The investigation is designed to monitor the land stability condition at the GGERFS during phase 1, namely the baseline study before the geothermal infrastructure will be installed to study the low-temperature geothermal energy from the flooded mine workings below eastern Glasgow.

Using InSAR results provides the following benefits:

- Archive radar data acquired since 1990s permitting retrospective investigation.
- Data from currently-orbiting satellites such as Sentinel-1 (S-1) are regularly acquired and available free of charge.
- Time-effective and cost-saving solution compared to traditional techniques such as Global Navigation Satellite System (GNSS) where displacement can be retrieved at regional scale rather than at a point location.
- Non-invasive analysis so no need for permissions is required and remote/difficult to access locations can be investigated.

The investigation is independent of any monitoring carried out by the industry or the regulators, and information collected will be freely available to the public at https://www.bgs.ac.uk/research/energy/esios/glasgow/home.html.

In this report we describe the different satellite imagery (i.e., ERS, ENVISAT and Sentinel-1) and processing methodologies (i.e., ISBAS and SqueeSAR™) adopted for the SAR imagery in section 2. In the Results (section 3), we present the maps of the surface displacement around the planned geothermal field site in Glasgow for the different time spans. We then present geological interpretations for the baseline ground motions observed for the past 3 decades.

2 Dataset and Methodology

The SAR datasets belong to Single Look Complex products of different satellite constellations managed by the European Space Agency and available free of charge: ERS, ENVISAT and Sentinel 1 (S-1) Interferometric Wide swath acquisition mode.

These spacecraft follow near-polar orbits with azimuthal direction approximatively parallel to N-S that defines two acquisition geometries, according to the flying direction of the sensor: ascending (from south to north) and descending (north to south). All the measurements are 1D, detected along the sensor's Line of Sight (LOS) inclined at a θ angle with respect to the vertical direction, known as the incidence angle (Table 1).

	ERS	**ENVISAT**	**S-1**
Pixel size	8m (Rg) × 4m (Az)	8m (Rg) × 4m (Az)	2.3m (Rg) × 14.1m (Az)
ϑ at the scene centre	~23.3°	~23.3°	~37.5°
Minimum revisit time	35 days	35 days	6 days

Table 1 - Properties of ERS, ENVISAT and Sentinel-1A IW SLC products. Rg = range (perpendicular to satellite flight direction) and Az = azimuth (parallel to satellite flight direction).

Three SAR stacks of approximatively 280 satellite images have been considered, covering an area of interest (AoI) of ~1,090 km^2 (Figure 1):

- ERS-1 and ERS-2 descending images from 1995 to 2001.
- ENVISAT descending images from 2002 to 2010.
- S-1 ascending and descending images from 2015 to 2017.

The investigation has been focused on a portion of the whole SAR scenes and centred on the proposed GGERFS borehole locations for phase 1 at Dalmarnock and Cuningar Loop (Figure 1). The area is typical of many towns and cities above abandoned coal mine workings, characterised by a labyrinth of disused mines hewed into the Coal Measures by coal miners in the 19th and 20th century (Monaghan et al., 2017).

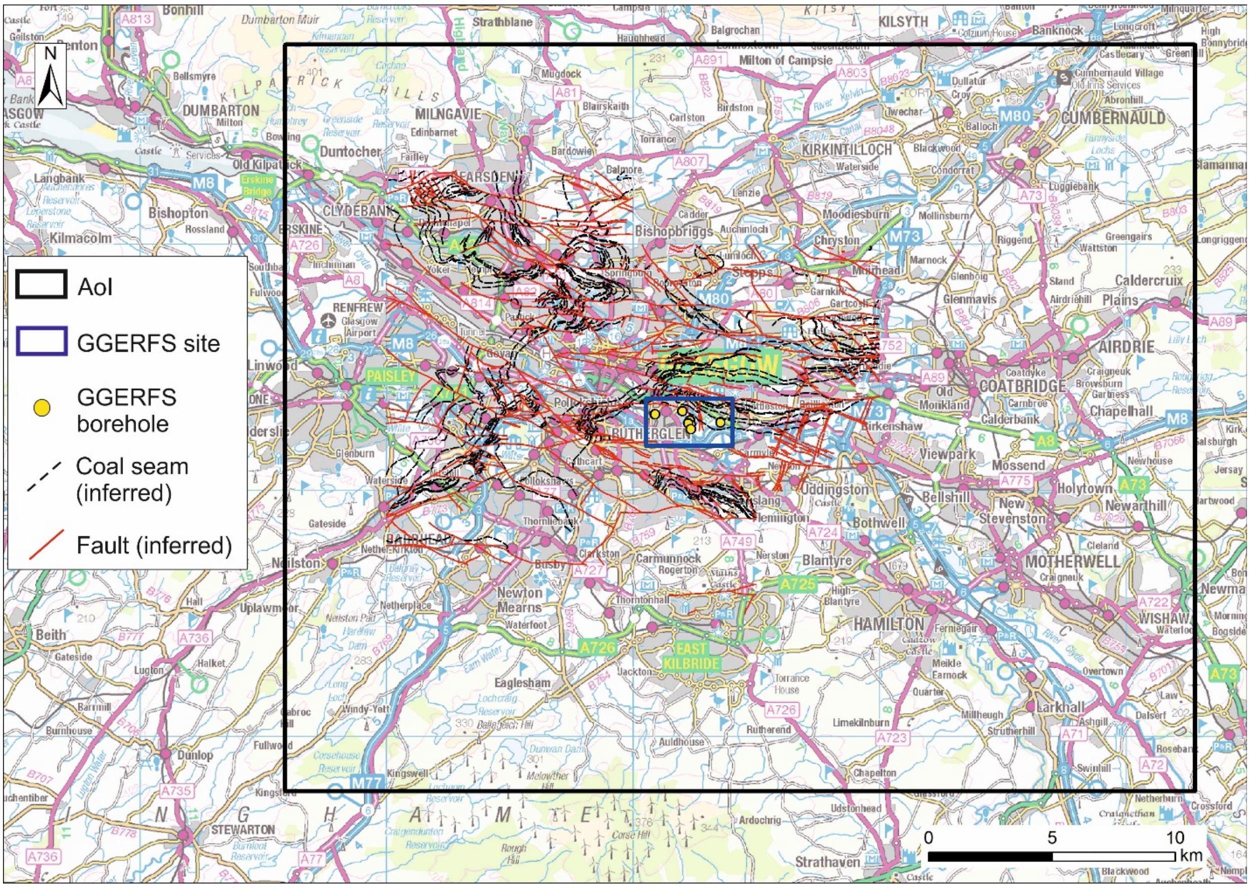


Figure 1 - GGERFS site and the extent of the AoI processed with ERS, ENVISAT and S-1 SAR imagery. Coal seam and fault locations are shown for to the central part of Glasgow only. Contains Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL*. Contains British Geological Survey materials ©UKRI 2019.

The three datasets cover a time span of 23 years with a gap of almost one and a half years between ERS and ENVISAT and ~5 years between ENVISAT and S-1.

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) techniques have been adopted for measuring surface deformation from the three satellite radar datasets. However, temporal changes in the scattering properties of the Earth's surface and changes in scattering properties with different look directions constrain the feasibility of InSAR measurements. Noise is introduced in to the ground displacement signal by both variation in atmospheric properties and inaccuracy in both satellite orbit and surface elevation determination. These sources of error can be addressed via the processing of multiple acquisitions in time, making it possible to obtain high precision measurements of ground displacement (Hooper, 2008) for pixels that show correlation of the radar signal in time or a high radar signal return (e.g. buildings, rocky outcrops and linear structures).

The displacement measurements are relative in both space and time: they are spatially referred to a reference point, and temporally to the date of the first available satellite acquisition in the stack. Therefore all displacement measurements are relative to the reference point, which is assumed to be motionless and selected for its radar properties, with low phase noise in all the scenes of the imagery. For this study the chosen reference point is in the western part of the city.

In order to obtain the most complete investigation in terms of resolution and density of InSAR results, two InSAR methods to process the SAR datasets have been used for this study and, when possible, compared:

- Intermittent Small Baseline and Subset (ISBAS), a patent pending algorithm developed by ©Geomatic Ventures Limited and whose IP belongs to the University of Nottingham - UK (Sowter et al., 2013; Bateson et al. 2015).
- SqueeSAR™, the proprietary multi-interferogram technique patented by TRE ALTAMIRA (Ferretti et al., 2011).

Since all ground motion measurements derived using the InSAR methods are relative to a reference point it is important to understand the stability of this point. In the case of this study two reference points have been used:

- one for the ISBAS processed data (ERS, ENVISAT and Sentinel) at -4.256, 55.861
- one for the SqueeSAR™ processed data (ERS, ENVISAT and Sentinel) at -4.374, 55.858

These reference locations have been assessed against the BGS GeoSure datasets and show a low susceptibility to shrink swell, landslides, compressible ground, running sand, soluble rock and collapsible deposits. Additional confidence is given by the InSAR results themselves, if the reference point was not stable then it would manifest as differences in average velocity between the point and the rest of the measurements points. We do not observe any such differences associated with either of the reference points.

The spatial interpretation of InSAR results consisted of comparison against the following BGS datasets at 1:50,000 scale:

- The Digital Geological Map of Great Britain project (DiGMapGB), namely the geological map data of bedrock and superficial deposits down to 1:10,000 scale (https://www.bgs.ac.uk/products/digitalmaps/digmapgb_10.html).
- The BGS GeoSure dataset, which identifies and classifies the susceptibility connected to areas of potential natural ground movement in Great Britain due to collapsible deposits, compressible ground, debris flow, landslides, running sand, shrink-swell terrains and soluble rocks (Lee and Doce, 2017). The GeoSure datasets are polygon (area) layers, which are described using a simple A to E potential hazard classification (A = Low, E = High).
- Coal Authority data has been accessed via the Coal Authority interactive map viewer

accessible at: http://mapapps2.bgs.ac.uk/coalauthority/home.html. This provides information on the location of potential hazards relating to past coal mining such as old mine entries, areas of surface mining etc.

- The BGS superficial deposits thickness model (https://www.bgs.ac.uk/products/onshore/superficialThicknessModel.html), incorporating the youngest geological formations (less than two million years old).

For the S-1 dataset, the short revisit time allowed us to analyse the temporal evolution of the displacement rates through the classification of time series into distinctive predefined target models (e.g., uncorrelated, linear, discontinuous and seasonal) based on a conditional sequence of statistical test as defined in Berti et al. (2013).

3 Results

Within this section we report the general characteristics for each InSAR dataset as derived from the two different processing techniques. We then present the overall patterns of ground motion within Glasgow for the three time periods covered by the datasets. Following this we examine any ground motions in the GGERFS site and then go on to examine specific ground motions within the wider Glasgow area.

A velocity threshold has been set to ±3 mm/yr considering the standard deviation (σ) of the radar targets in each dataset and the creation of a common arrangement to compare different datasets processed with different techniques (Table 2).

dataset	geometry	technique	Number of targets	Average σ [mm/yr]
ERS	descending	ISBAS	155,614	1.1
Envisat	descending	ISBAS	28,323	1.2
Sentinel-1	descending	ISBAS	201,689	1.7
ERS	descending	SqueeSAR™	191,701	0.3
Envisat	descending	SqueeSAR™	114,989	0.38
Sentinel-1	ascending	SqueeSAR™	247,656	0.69
Sentinel-1	descending	SqueeSAR™	256,914	0.67

Table 2 - Main characteristics of each InSAR dataset used over the AoI.

Finally, the geolocation precision and relative accuracies associated to the radar target location (in a projected coordinate system) are in the order of a few meters.

3.1 ERS

The SqueeSAR™ and ISBAS results from ERS-1/2 data indicates that the majority of the area, including the GGERFS site, was stable in the 1990’s (Figure 2).

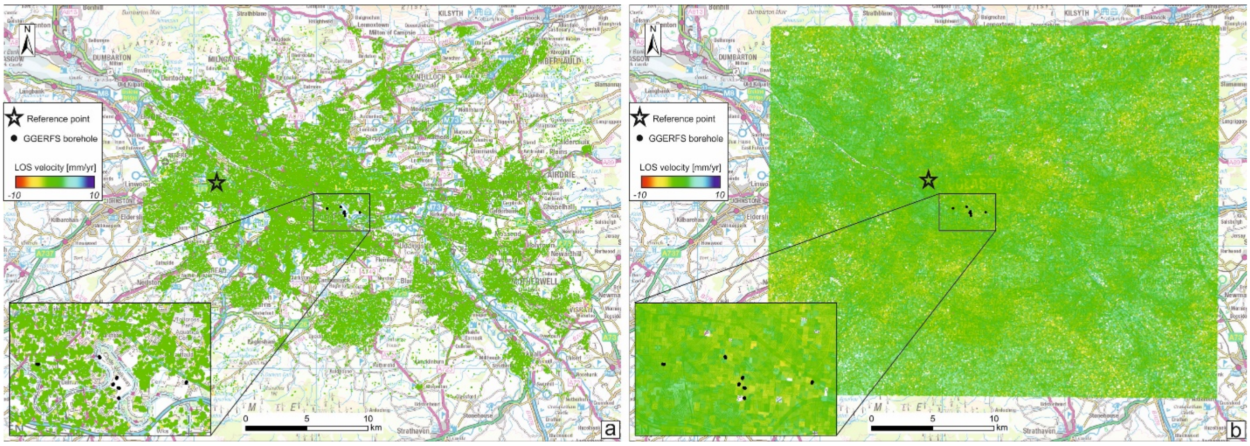


Figure 2 - ERS results from TRE ALTAMIRA's SqueeSAR™ (a) and GVL's ISBAS (b) processing showing average rates of ground motion for the measured points. Location of the reference point is indicated by a star. Contains © Geomatic Ventures Limited 2017 data, © TRE ALTAMIRA 2018 data , Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL*. Contains British Geological Survey materials © UKRI 2019.

Although Glasgow appears stable overall within the ERS time period (1995-2001) there are small areas, limited to spatially isolated radar targets, exhibiting relatively small rates of subsidence which can be either explained by anthropogenic activities or noise in InSAR results.

3.2 ENVISAT

The SqueeSAR™ and ISBAS results from ENVISAT data indicates that the GGERFS site and the majority of the wider area was stable between 2002 and 2010.

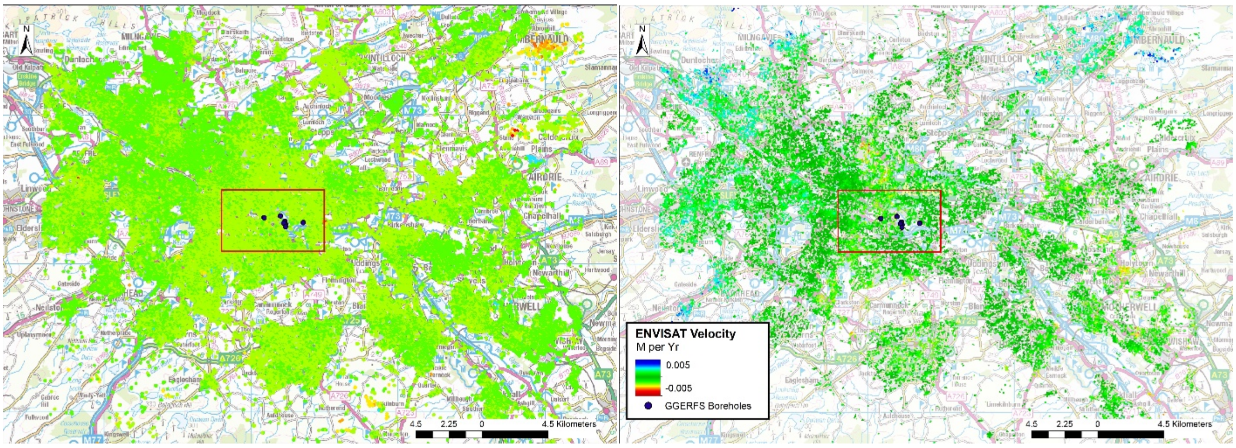


Figure 3 - ENVISAT results from SqueeSAR™ (left) and ISBAS (right) processing showing average rates of ground motion for the measured points. Location of the reference point is indicated by a star. Contains © Geomatic Ventures Limited 2017 data, © TRE ALTAMIRA 2018 data , Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL*. Contains British Geological Survey materials © UKRI 2019.

3.3 SENTINEL-1

TRE ALTAMIRA (Figures 4a-b) and GVL (Figure 4c) results reveal that Glasgow is, overall, relatively stable over the 2015-2017 time period, as processed with Sentinel 1 data. There are notable areas of ground motion, which are addressed in the following sections of this report.

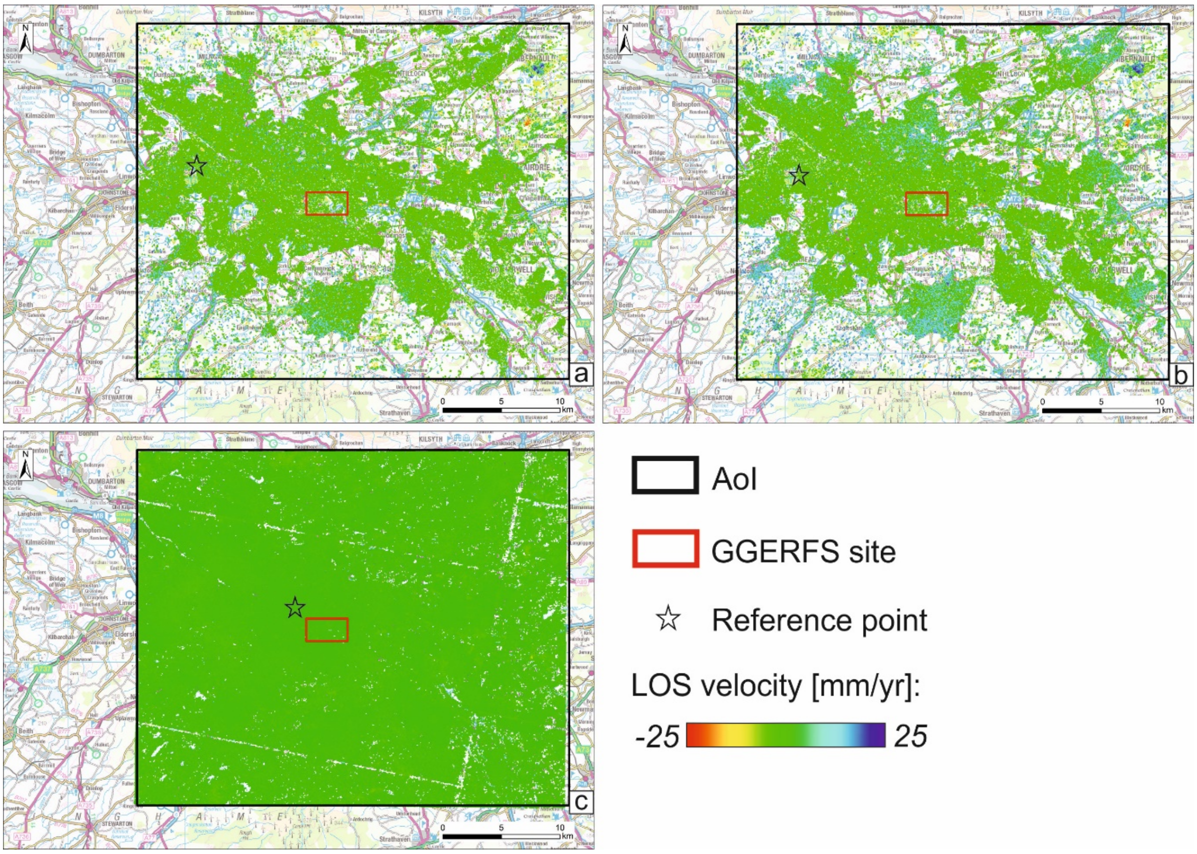


Figure 4 – Sentinel-1 ascending (a) and descending (d) results from SqueeSAR™; Sentinel-1 descending results from ISBAS (c). Location of the reference point is indicated by a star. Contains © Geomatic Ventures Limited 2017 data, © TRE ALTAMIRA 2018 data , Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL*.

Thanks to the availability of both ascending and descending S-1 SqueeSAR™ results over the AOI (see Figures 4a-b), it was possible to combine the single geometry results in order to obtain 2D measurements, along the vertical (Figure 5a) and the horizontal east-west (Figure 5b) directions, given the assumption of negligible motion in the north-south direction.

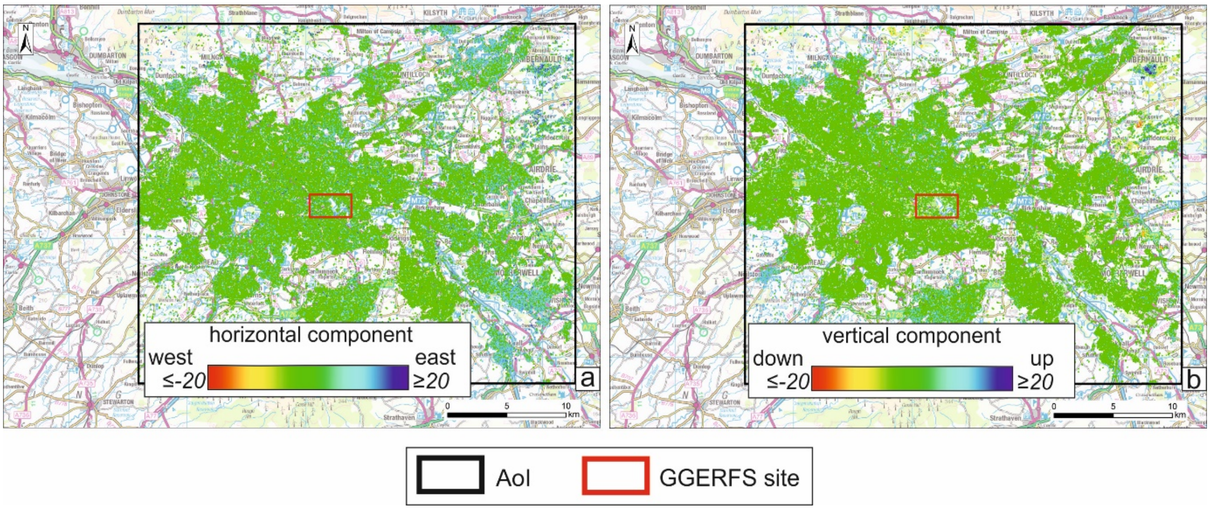


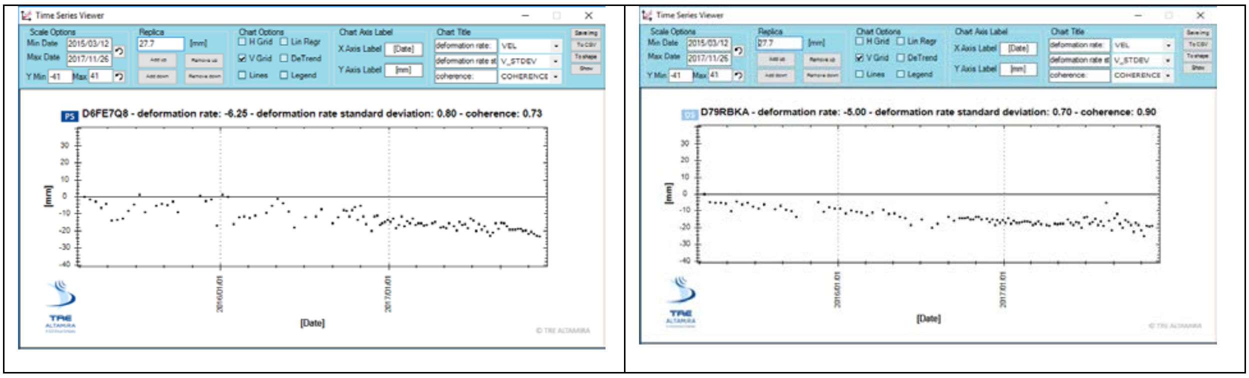
Figure 5 - Sentinel-1 horizontal (a) and vertical (d) components from SqueeSAR™ InSAR results. Contains © TRE ALTAMIRA 2018 data , Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL.*

3.4 MOTION CHARACTERISTICS OF THE GGERFS SITE

Figure 6 - Central portion of the GGERFS site with TRE ALTAMIRA SqueeSAR™ ascending InSAR data. The blue dots are borehole locations, note that the group of three in the north of the Cuningar Loop are no longer being constructed. Contains © TRE ALTAMIRA 2018 data. Contains British Geological Survey materials © UKRI 2019.

The GGERFS site itself is being developed south of a woodland park at Cuningar Loop. The Cuningar Loop and surrounding area were redeveloped for the 2014 Commonwealth Games. In the past the, ~35 hectare area within the loop has been used as a waterworks, and for disposal of building demolition rubble and coal mine waste. The creation of the woodland park, within the Cuningar Loop, including paths and play structures has introduced some objects which act as suitable radar targets and therefore become Persistent Scatterers. Therefore in the TRE ALTAMIRA SqueeSAR™ S-1 results (post 2015) (Figure 6) there are a few measurement points whereas in the ERS and Envisat results (pre-development) there are no InSAR points within the Cuningar Loop (Figure 12).

The TRE ALTAMIRA SqueeSAR™ results provide full time series for persistent scatterers, ascending and descending datasets provide more measurement points than the vertical measurements (which are derived through the integration of ascending and descending observations) and hence give an opportunity to see the detailed 2015-2017 ground motions in this area. Examination of the time series for the S-1 ascending data indicate that the area is subsiding by approximately 30 mm over the 2.5 years processed. Time series for the points highlighted in Figure 6 are shown in Figure 7. These indicate that the motion is largely linear in nature.



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coherence: COHERENCE

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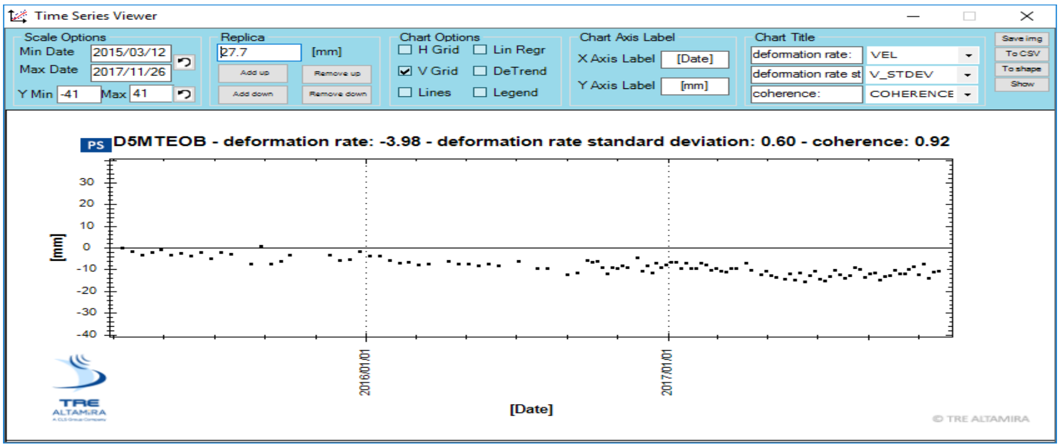
Figure 7 - Time series for the points highlighted in Figure 6. Left is the upper point (number 1) and the right plot is the lower point (number 2).

InSAR time series for the former Athletes Village (the area to the west of the Cuningar Loop) indicate that, although not immediately obvious in the average velocity, this area is also subsiding, although at a lower rate of approximately 15 mm over the 2.5 years processed (Figure 8). This area was developed for the Commonwealth Games Athletes village, development has seen a substantial change in land use. Prior to 2009 two high-rise tower blocks of flats stood in open areas of land (see older aerial photography in Figure 12). These were demolished and smaller accommodation buildings built between 2012 and 2014. We therefore interpret the small rates of linear subsidence seen here relate to settling of the development and loading of the superficial deposits during the widespread development of small buildings.

Figure 8 – Western portion of the GGERFS site with TRE ALTAMIRA SqueeSAR™ ascending InSAR data. The blue dots are borehole locations, note that the group of three in the north of the Cuningar Loop are no longer being constructed. Contains © TRE ALTAMIRA 2018 data. Contains British Geological Survey materials © UKRI 2019.


Time Series Viewer

Scale Options
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Chart Options
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☐ Lines ☐ Legend

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Chart Title
deformation rate: VEL
deformation rate st V_STDEV
coherence: COHERENCE

PS D5MTEOB - deformation rate: -3.98 - deformation rate standard deviation: 0.60 - coherence: 0.92

Figure 9 - Time series for TRE ALTAMIRA InSAR results for the area to the west of the Cuningar Loop (white circle in Figure 8).

Given the past land use, mapped artificial ground and indications of 35-40 m of superficial deposits on and around the site (Figure 10) it is likely that the subsidence observed here is a result of the development activity and subsequent settling of the infilled ground and/or the superficial deposits. The analysis of the vertical time series from SqueeSAR™ confirms that most of the targets in this area have a discontinuous movement with a slight deceleration of the rate located sometime between October 2015 and November 2017.

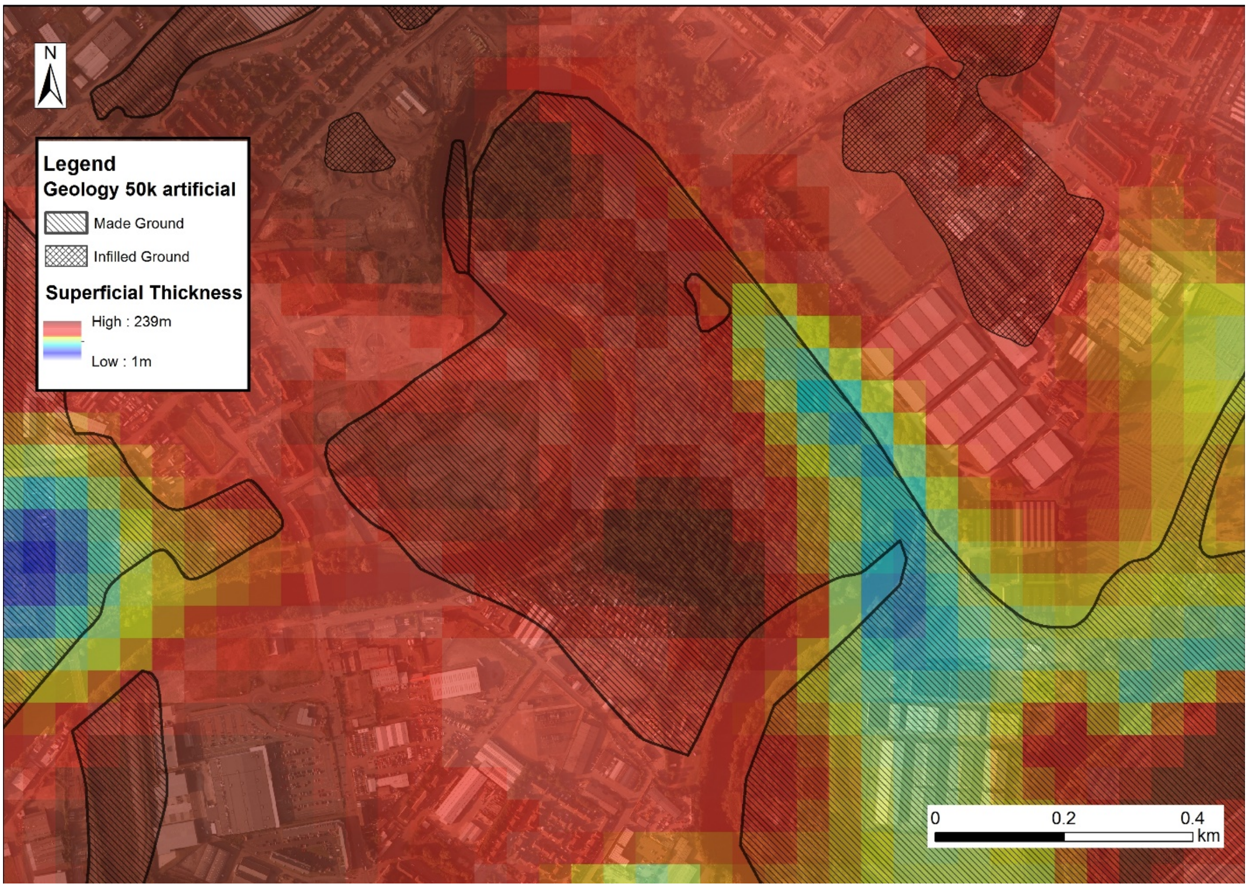


Figure 10 - Superficial deposit thickness and artificial ground in the Cuningar Loop. Contains British Geological Survey materials ©UKRI 2019. Aerial photography © UKP/Getmapping Licence No. UKP2006/01.

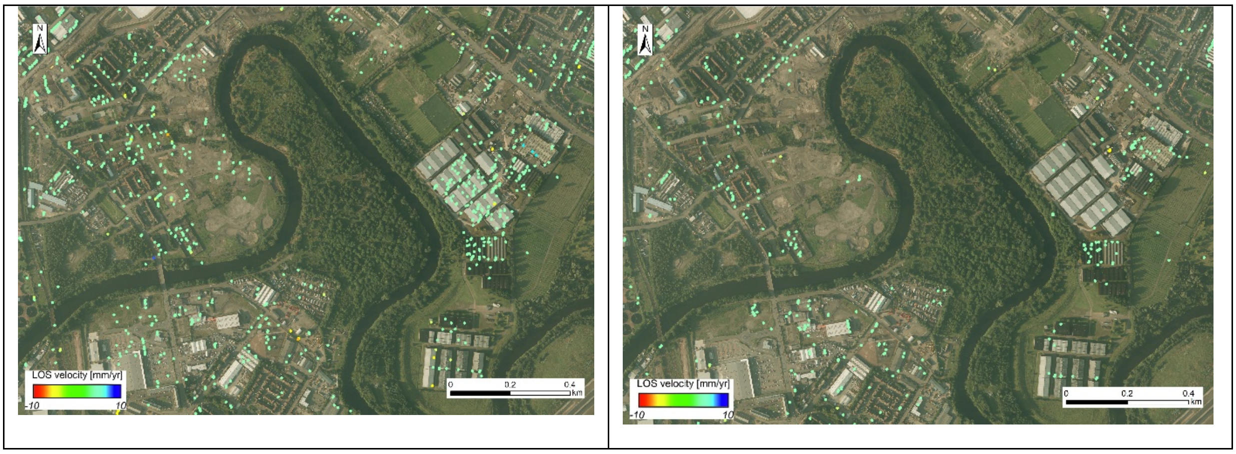
The GVL Sentinel 1 data for the GGERFS site indicates that it is mostly stable; there are two small areas with approximately 2-3mm per year of subsidence within the Cuningar Loop (Figure 11). Although the lack of time series associated with these data makes it difficult to fully understand the indicated motion, they are in the same location as subsiding points in the SqueeSAR™ results and relate to settlement of the built environment.

Figure 11 - GVL ISBAS average motions within the GGERFS site 2015-2017. The blue dots are borehole locations, note that the group of three in the north of the Cuningar Loop and in the far east of this image are no longer being constructed. Contains © Geomatic Ventures Limited 2017 data.

Note the area of subsidence in the lower left corner of Figure 11, motion rates of up to 10 mm per year are observed in both GVL and TRE ALTAMIRA Sentinel 1 results for this area of the M74 motorway. The radar scatterers appear to be related to the motorway gantry but the motion is likely to relate to instability in the embankment supporting the motorway at this location.

ERS and ENVISAT data for the GGERFS site

Although there are no measurement points within the Cuningar Loop, the ERS and ENVISAT InSAR results provided by both TRE ALTAMIRA and GVL indicate the GGERFS and surrounding area to be stable during the 1990's and 2000's.



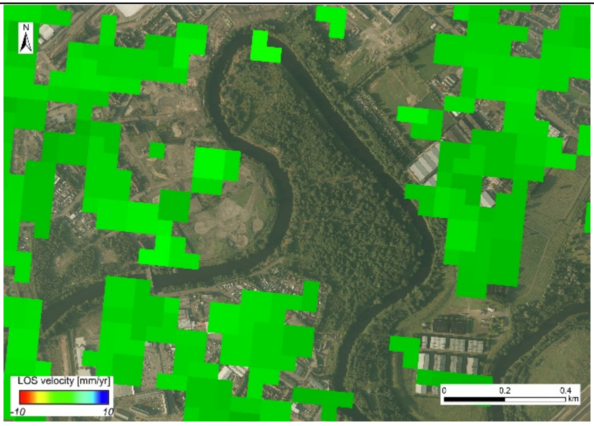
TRE ALTAMIRA ERS	*TRE ALTAMIRA ENVISAT*
	
GVL ERS	*GVL ENVISAT*

Figure 12 - Ground motions for the GGERFS site during the ERS (1990's) and ENVISAT (2000's) as derived by the SqueeSAR™ and ISBAS processing techniques. Contains © Geomatic Ventures Limited 2017 data, © TRE ALTAMIRA 2018 data. Aerial photography © UKP/Getmapping Licence No. UKP2006/01.

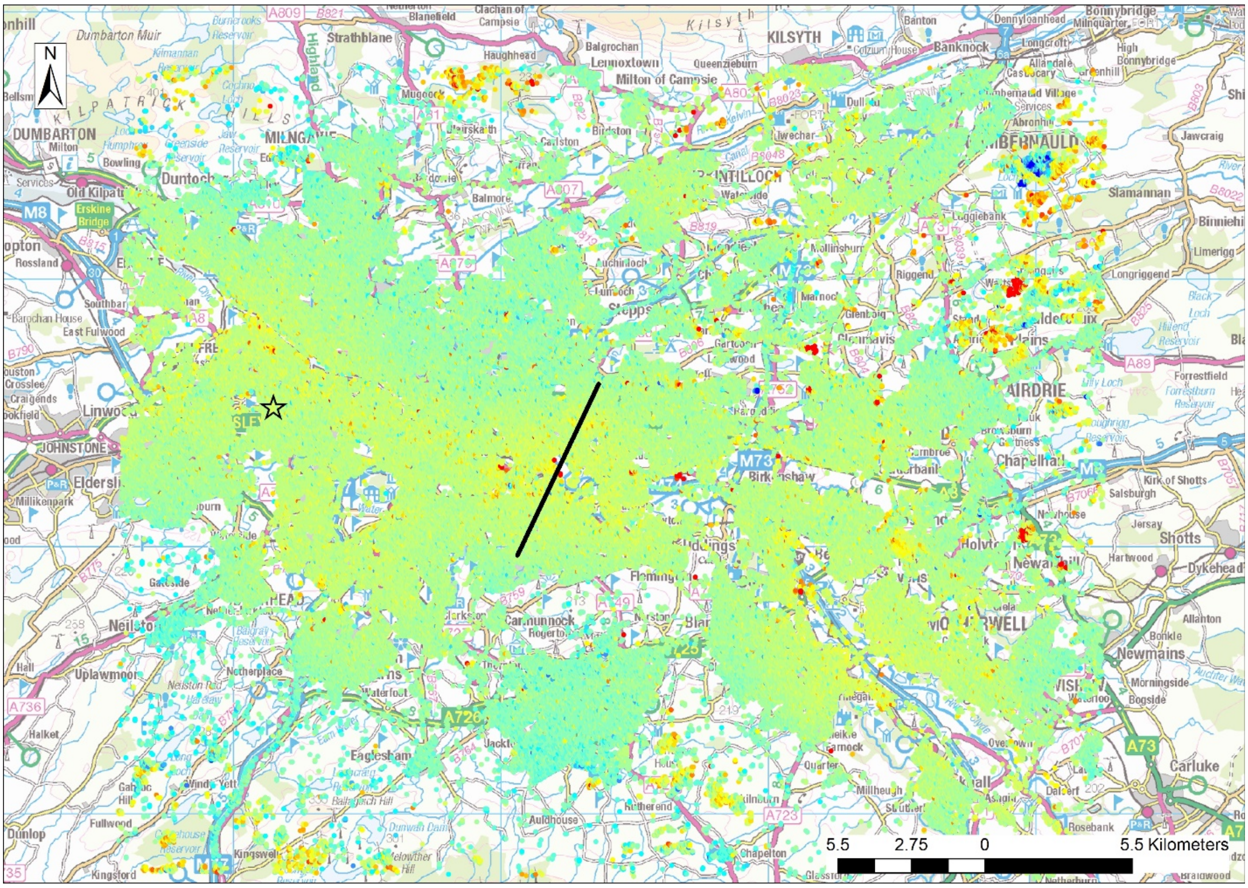
4 Motion Characteristics of the Wider Area

Motions within the Sentinel 1 Glasgow data can be linked to the following processes:

1. Compaction of superficial deposits, in particular alluvium
2. Volume change of superficial peat deposits
3. Anthropogenic activities:
    a. Sand and gravel quarrying
    b. Slope instability of engineered slopes associated with extractive industries

4.1 COMPACTION OF SUPERFICIAL DEPOSITS IN PARTICULAR ALLUVIUM

Vertical motions in Glasgow highlight a small-scale trend for subsidence along the alluvium deposits of the Clyde (Figure 13). These are hard to pick out without the use of a suitable colour scale. The production of a motion cross section (Figure 13) highlights the subsidence seen across the Clyde alluvial deposits.



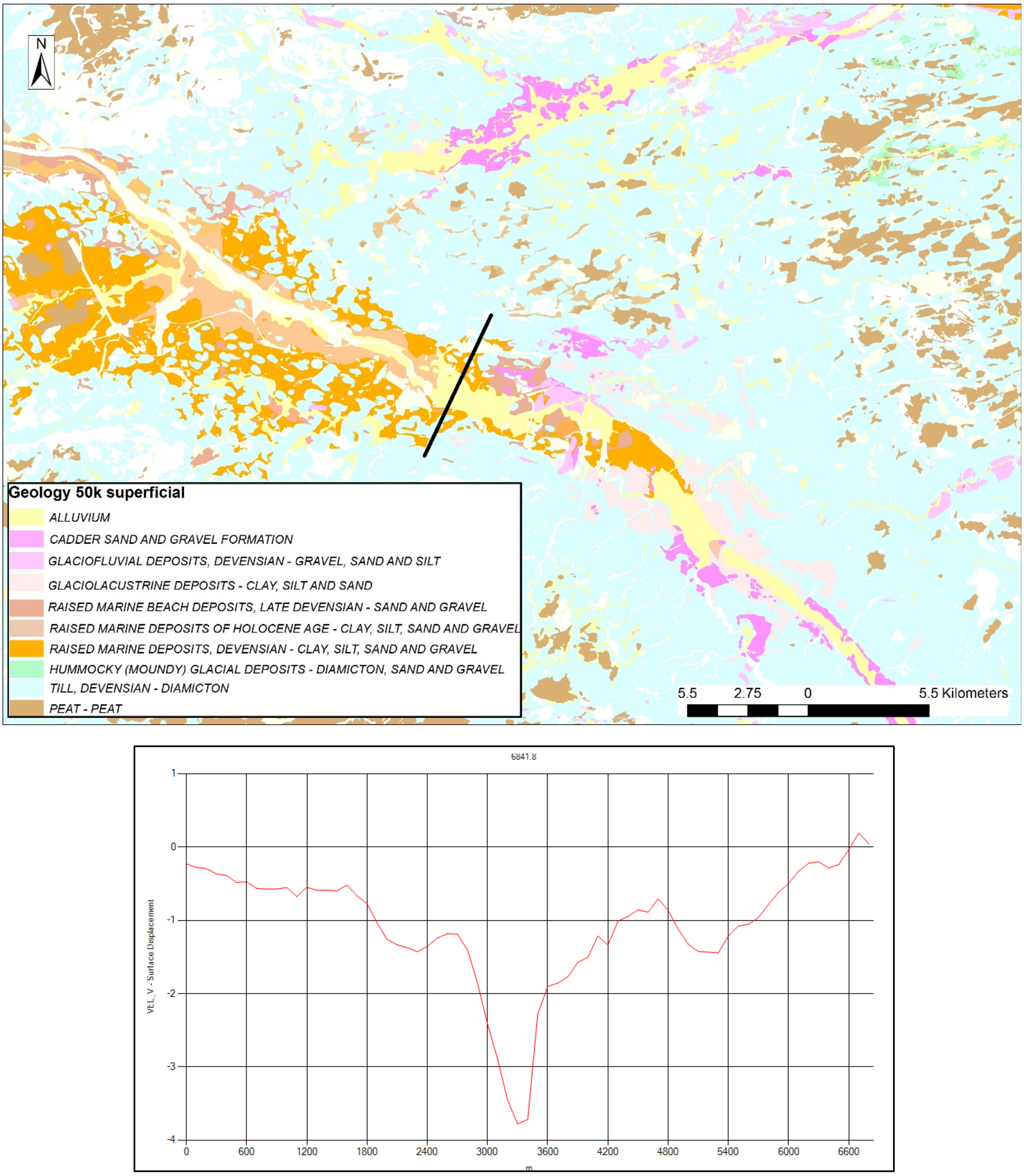


Figure 13 - General patterns of motion in Glasgow as shown by the TRE ALTAMIRA SqueeSAR™ processed S-1 data (top). Note the predominance of pale yellow colour along the Clyde indicating subsidence probably due to the compression of alluvium (middle). A cross section of the linear InSAR velocities (bottom) across the alluvial sediments highlights the increase in average rates of subsidence associated with the river sediments. Contains © TRE ALTAMIRA 2018 data, Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL*. Contains British Geological Survey materials ©UKRI 2019.

4.2 VOLUME CHANGE OF SUPERFICIAL PEAT DEPOSITS

An apparent spatial correlation exists between areas of Peat and areas of ground motion, as shown in the TRE Sentinel 1 vertical dataset. Areas of subsidence seen in the North, South and North East of the area processed all overlie areas of peat as shown in Figure 14. The mechanism for the revealed ground motions is likely to be volume changes within the peat in response to changes in its water content and/or loading.

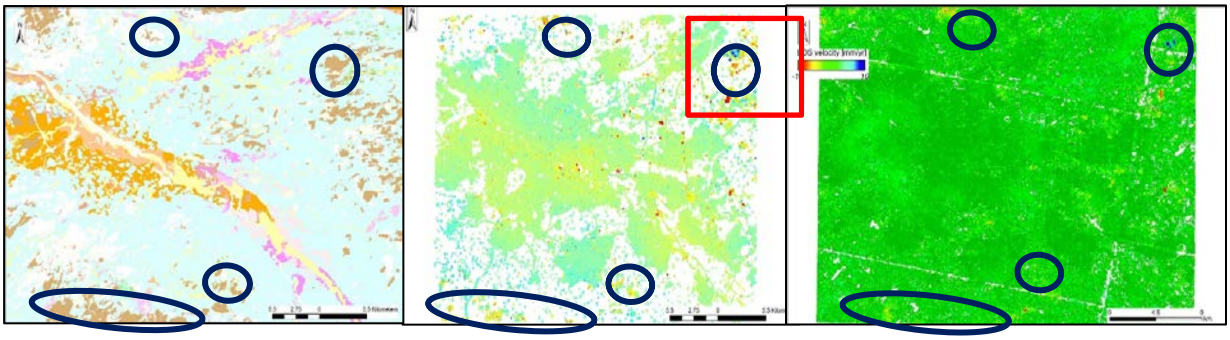
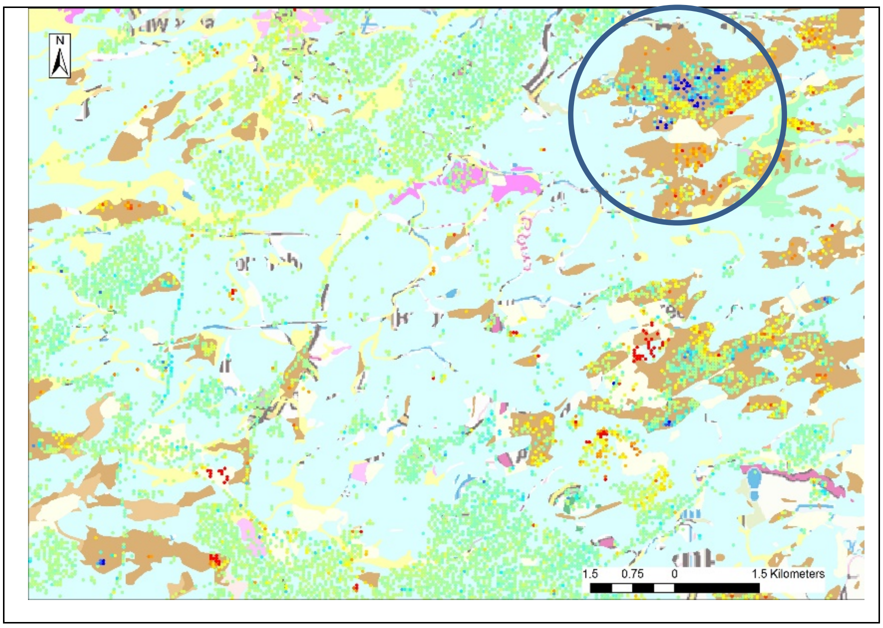


Figure 14 - Centre – TRE ALTAMIRA SqueeSAR™ Sentinel 1 average vertical motions for (2015-2017) and right – GVL Sentinel 1 LOS motions compared to the superficial geology (left). Black circles indicate where motion overlies areas of superficial peat. Red box shows area of detail in Figure 15. Contains © TRE ALTAMIRA 2018 data. Contains © Geomatic Ventures Limited 2017 data. Contains British Geological Survey materials ©UKRI 2019.

The relationships to the superficial peat are clear when the area is examined in more detail (Figure 15). For example to the east of Cumbernauld there is a clear spatial relationship between the peat and the area of vertical motion. Note the similarities between the TRE and GVL InSAR results. Comparison with Coal Authority mining data (http://mapapps2.bgs.ac.uk/coalauthority/home.html) shows that there was no coal mining activity in this area.



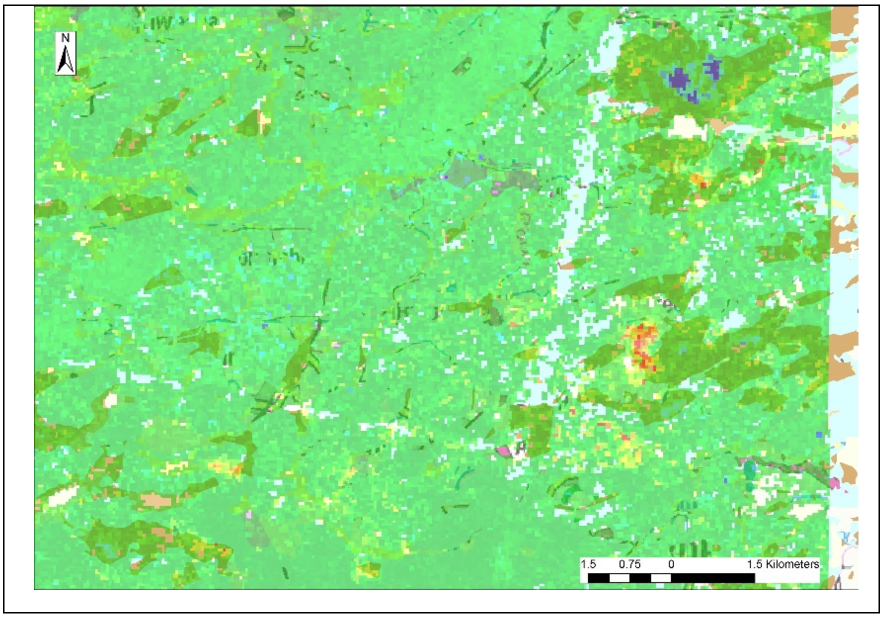
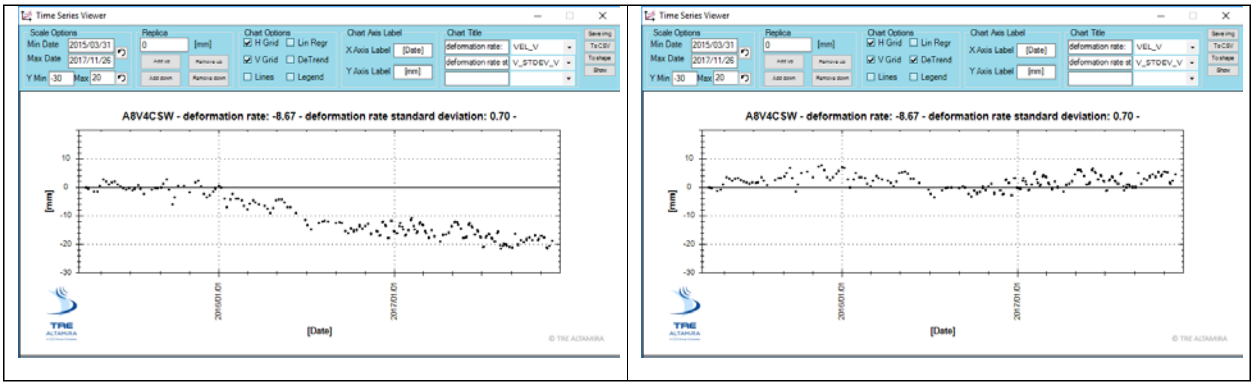


Figure 15 - TRE ALTAMIRA SqueeSAR^{TM} (top) and GVL (bottom) S-1 average motions for (2015-2017) overlain on the superficial geology for the Cumbernauld area. Contains © TRE ALTAMIRA 2018 data. Contains © Geomatic Ventures Limited 2017 data. Contains British Geological Survey materials ©UKRI 2019.

These areas of peat-related ground motion typically have average linear rates of subsidence of 10/15 mm per year. The trend of this subsidence is linear (Figure 16) and may be either negative or positive depending on the moisture change. Removing the linear trend reveals a variation of approximately 5-6 mm over a 2 month period, this roughly bi-monthly cyclicity may be related to moisture changes within the peat.


Min Date 2015/03/31
Max Date 2017/11/26
Y Min -30 Max 20
Replica 0 [mm]
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X Axis Label [Date]
Y Axis Label [mm]
Chart Title: deformation rate: VEL_V; deformation rate st V_STDEV_V

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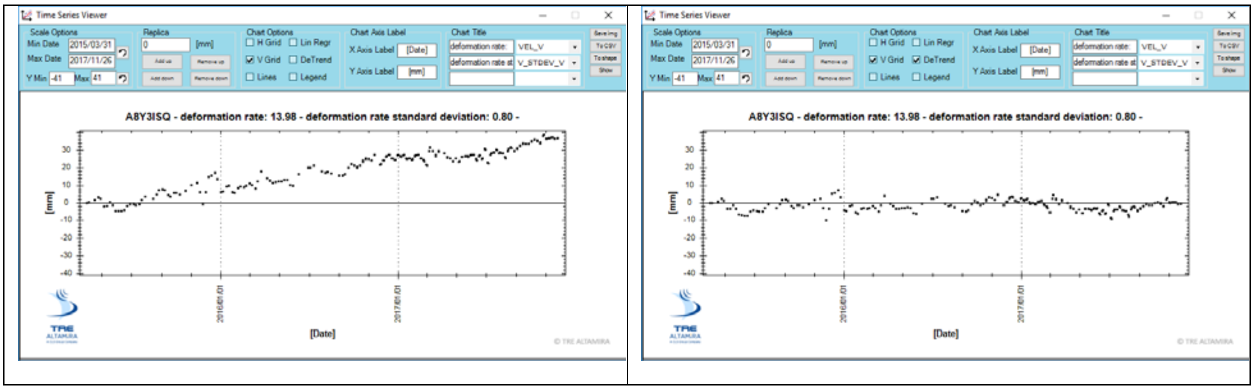
Chart Title: deformation rate: VEL_V; deformation rate st V_STDEV_V

Figure 16 - left: Time series for a single point within the subsiding peat area (see Figure 15) showing an overall linear pattern of subsidence. Right: De-trended plot of the same time series showing the roughly bi-monthly variability in the ground motion.

The area to the east of Cumbernauld undergoing uplift has average linear rates of uplift of 10-15 mm per year and the time series shows that the character of the motion is largely linear over the time period March 2015 to November 2017. The overall pattern of uplift is linear (Figure 17), however de-trending the time series shows there is some variability as the peat contracts and responds to water inputs.



Time Series Viewer

Scale Options: Min Date 2015/03/31; Max Date 2017/11/26; Y Min -41; Max 41

Replica: 0 [mm]

Chart Options: ☐ H Grid ☐ Lin Regr ☑ V Grid ☐ DeTrend ☐ Lines ☐ Legend

Chart Axis Label: X Axis Label [Date]; Y Axis Label [mm]

Chart Title: deformation rate: VEL_V; deformation rate st V_STDEV_V

A8Y3ISQ - deformation rate: 13.98 - deformation rate standard deviation: 0.80 -

Time Series Viewer

Scale Options: Min Date 2015/03/31; Max Date 2017/11/26; Y Min -41; Max 41

Replica: 0 [mm]

Chart Options: ☐ H Grid ☐ Lin Regr ☑ V Grid ☑ DeTrend ☐ Lines ☐ Legend

Chart Axis Label: X Axis Label [Date]; Y Axis Label [mm]

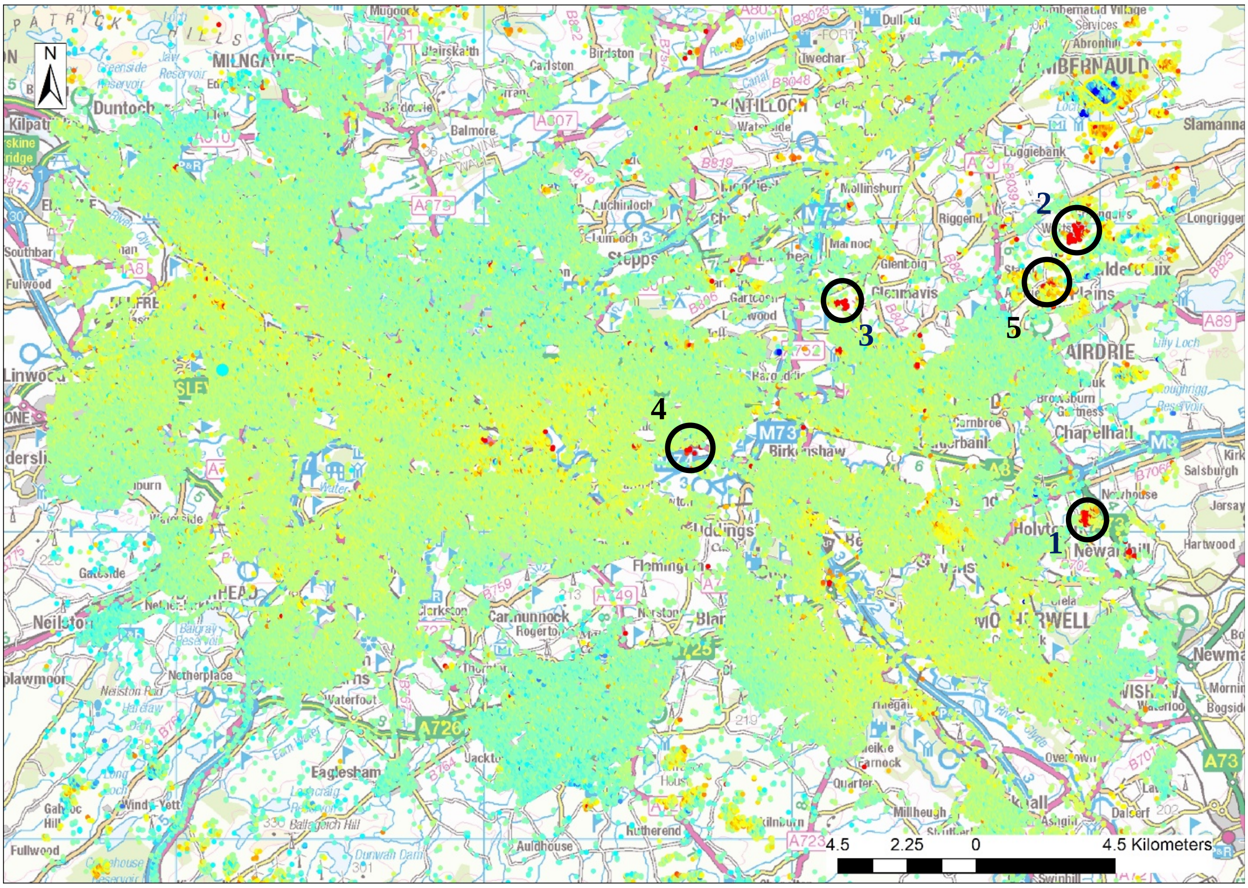
Chart Title: deformation rate: VEL_V; deformation rate st V_STDEV_V

A8Y3ISQ - deformation rate: 13.98 - deformation rate standard deviation: 0.80 -

Figure 17 - left: Time series for a single point within the uplifting area (blue points in Figure 15) showing an overall linear pattern of uplift. Right: De-trended plot of the same time series showing the roughly bi-monthly variability in the ground motion.

4.3 ANTHROPOGENIC ACTIVITIES: SAND AND GRAVEL QUARRYING

There are several prominent areas of subsidence shown in the Sentinel 1 InSAR results from both TRE Altamira SqueeSAR™ results and GVLs ISBAS results. Many of these relate to active and/or former sand and gravel extraction sites, subsidence associated with these is likely to be caused by settlement of infilled ground or motion of slopes produced by the quarrying process.



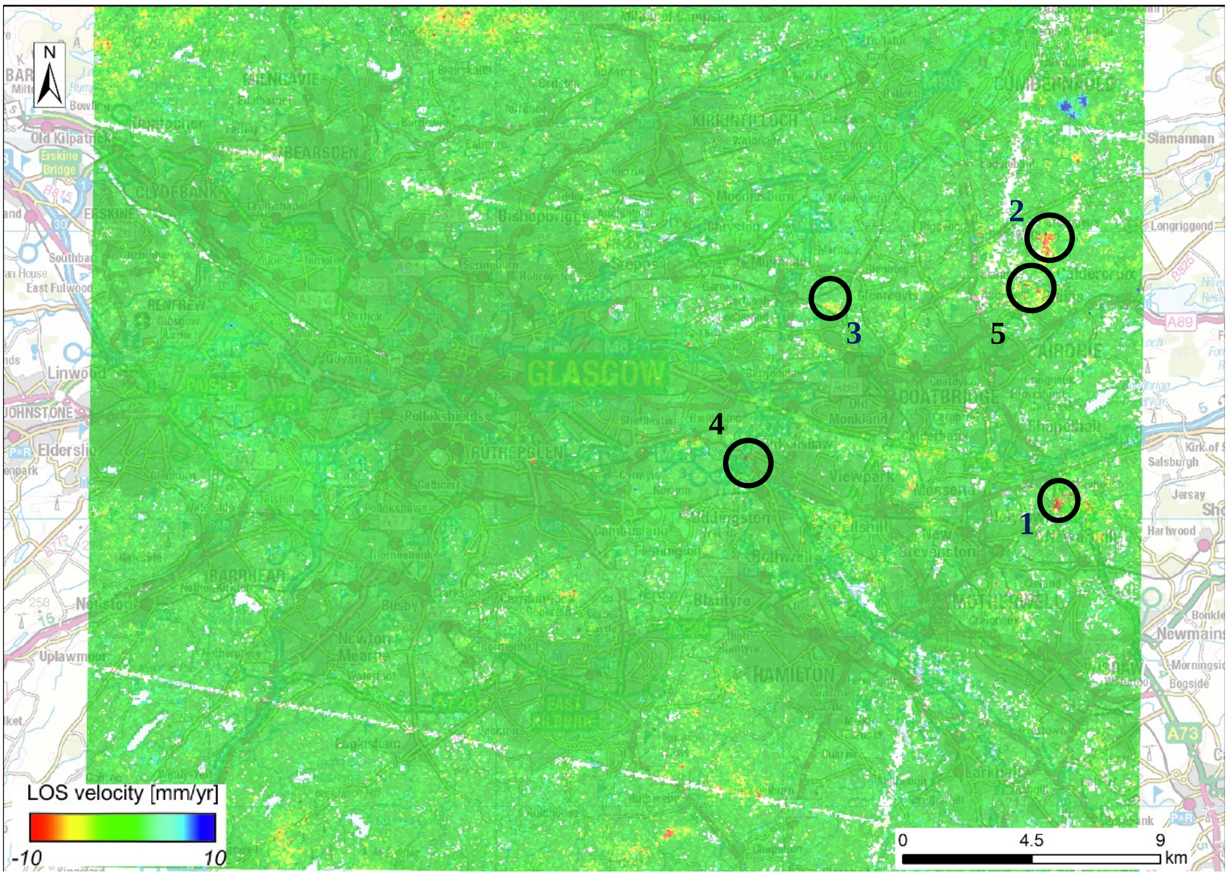


Figure 18 - Top: TRE ALTAMIRA SqueeSAR™ Sentinel 1 average vertical motions for (2015-2017) with areas of anthropogenic induced motions highlighted by black circles. Bottom: GVL Sentinel 1 average LOS motions for (2015-2017) with areas of anthropogenic induced motions highlighted by black circles. Contains © TRE ALTAMIRA 2018 data. Contains © Geomatic Ventures Limited 2017 data. Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL*

The following figures highlight the detail of motion features highlighted in Figure 18:

Figure 19 - TRE ALTAMIRA SqueeSAR™ S-1 average vertical motions for (2015-2017) for the Pickerstonhill area (area 1 on Figure 18). The OS map and aerial photography shows that the subsidence is associated with quarrying sites and remediated quarrying sites. Contains © TRE ALTAMIRA 2018 data. Contains © Geomatic Ventures Limited 2017 data. Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL.* Aerial photography © UKP/Getmapping Licence No. UKP2006/01.

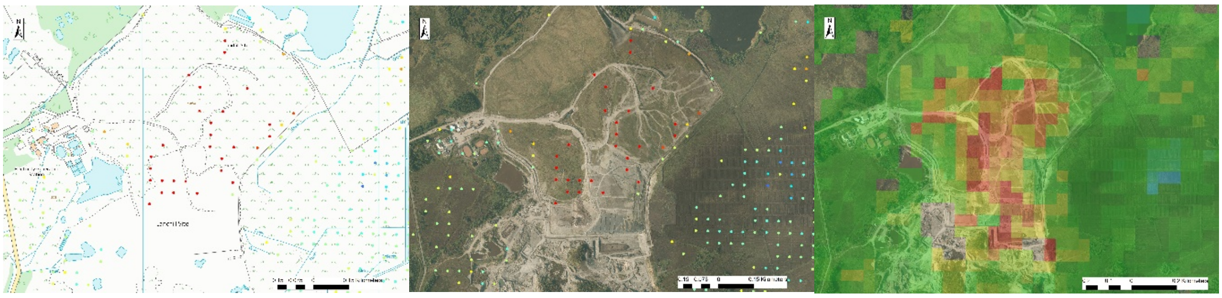


Figure 20 - Left and centre - TRE ALTAMIRA SqueeSAR™ S-1 average vertical motions for (2015-2017) for the Airdrie area (area 2 on Figure 18). The OS map and aerial photography shows that the subsidence is associated with settlement of infilled ground following landfill of former quarry sites. Right; GVL Sentinel 1 average LOS motions for the same time and location. Contains © TRE ALTAMIRA 2018 data. Contains © Geomatic Ventures Limited 2017 data. Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL.* Aerial photography © UKP/Getmapping Licence No. UKP2006/01.

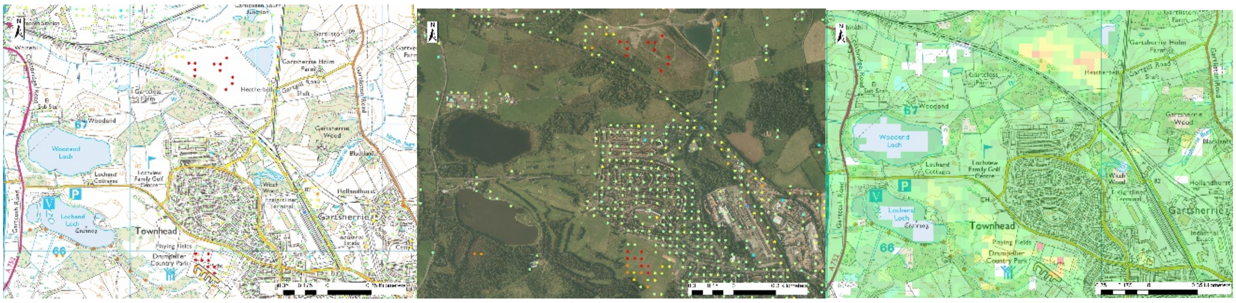


Figure 21 - Left and centre: TRE Altamira SqueeSAR™ Sentinel 1 average vertical motions for (2015-2017) for the Townhead area (area 3 on Figure 18. The OS map and aerial photography shows that the subsidence is associated with settlement of infilled ground in a former extraction site, subsidence to the south relates to development of a former extraction site and subsequent settling of in-filled ground. Right: GVL Sentinel 1 average LOS motions for the same period and area. Contains © TRE ALTAMIRA 2018 data. Contains © Geomatic Ventures Limited 2017 data. Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL.* Aerial photography © UKP/Getmapping Licence No. UKP2006/01.

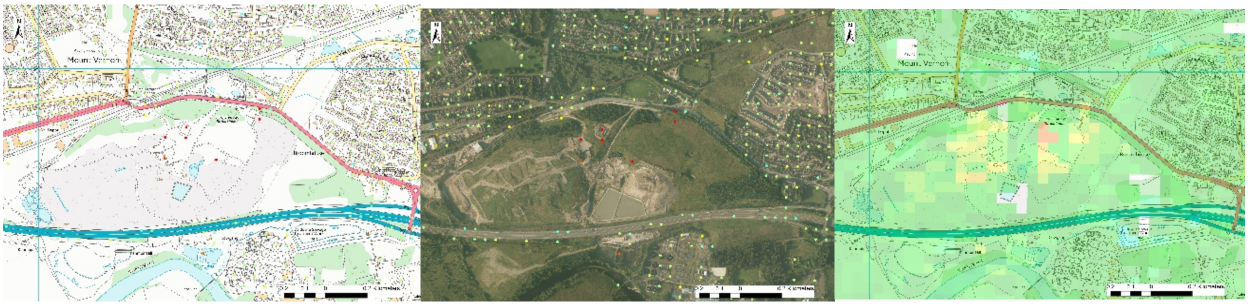


Figure 22 - Left and centre: TRE Altamira SqueeSAR™ Sentinel 1 average vertical motions for (2015-2017) for the Broomhouse area (area 4 on Figure 18). The OS map and aerial photography shows that the subsidence is associated with settlement of infilled ground in a former extraction site. Right: GVL Sentinel 1 average LOS motions for the same period and area. Contains © TRE ALTAMIRA 2018 data. Contains © Geomatic Ventures Limited 2017 data. Ordnance Survey data © Crown copyright and database

right 2018, license number *100021290 EUL.* Aerial photography © UKP/Getmapping Licence No. UKP2006/01.

4.4 ANTHROPOGENIC ACTIVITIES: SLOPE INSTABILITY OF ENGINEERED SLOPES ASSOCIATED WITH EXTRACTIVE INDUSTRIES

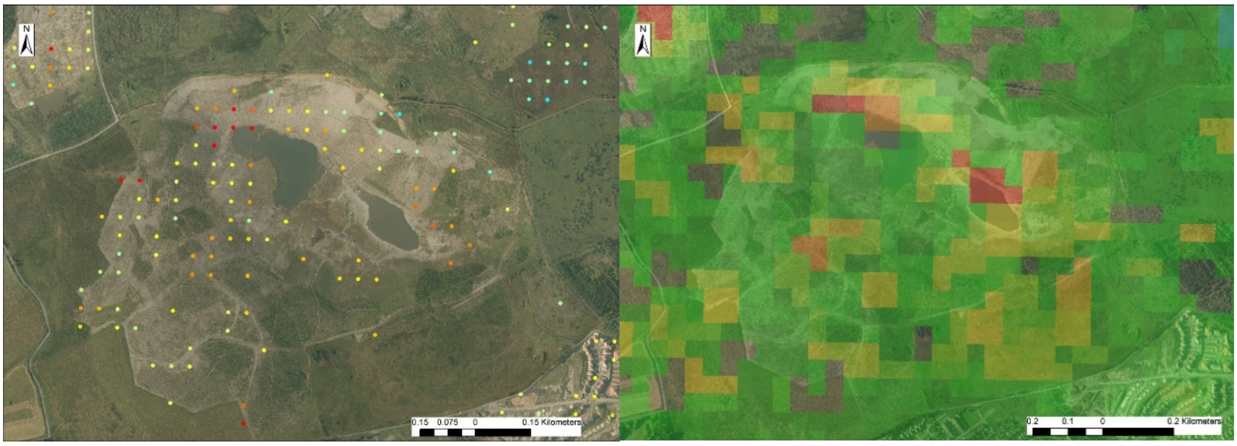


Figure 23 - Left: TRE Altamira SqueeSAR™ Sentinel 1 average vertical motions for (2015-2017) for the Airdrie area (area 5 on Figure 18). The aerial photography shows the motion is associated with engineered slopes. Right: GVL average LOS motions for the Sentinel 1 (2015-2017) for the Airdrie area (area 5 on Figure 18). Contains © TRE ALTAMIRA 2018 data. Contains © Geomatic Ventures Limited 2017 data. Aerial photography © UKP/Getmapping Licence No. UKP2006/01.

5 Known subsidence in Glasgow and InSAR data

Due to a substantial industrial past, including underground mining, the Glasgow area is an obvious suspect for subsidence. In 2001 BGS and the British Space Agency commissioned an InSAR study for Glasgow and Newcastle using ERS data to reveal ground motion for the 1990's. At the time InSAR was an immature Earth observation technique and this was one of the first studies of its type in the UK. Glasgow and Newcastle were chosen due to their coal mining history and the knowledge of BGS engineering geologists of subsidence problems in these areas. The results of the study indicated that Glasgow was largely stable from the InSAR point of view in the 1990's (as does this current study). The Newcastle data obtained at the same time revealed interesting patters of motion associated with active coal mining amongst other processes (Gee et al, 2017).

Subsequent InSAR studies on UK coalfield areas (Sowter et al, 2013; Bateson et al, 2015) have shown distinctive patterns of ground motion related to coal mining, and it has been possible to identify areas of active and abandoned mining activity via their ground motion signature. These motions cover a relatively large spatial area and usually relate to changes in the groundwater level, which are caused by the different phases of mining. During active mining the ground water level is depressed by pumping to allow for underground working, this causes a lowering of the ground surface. Once the mining has finished and the pumps are switched off, ground water levels recover and uplift is observed. Such patterns are observed in South Wales, Northumberland, South Yorkshire, Stoke on Trent and North Derbyshire. However, there is no evidence in any of the InSAR results of these characteristic ground motions in the Glasgow area. This is likely because mining under many areas of Glasgow is significantly older than the satellite data (for example in the vicinity of the GGERFS site, recorded mining ended in 1934) and therefore water levels have recovered prior to the 1990's.

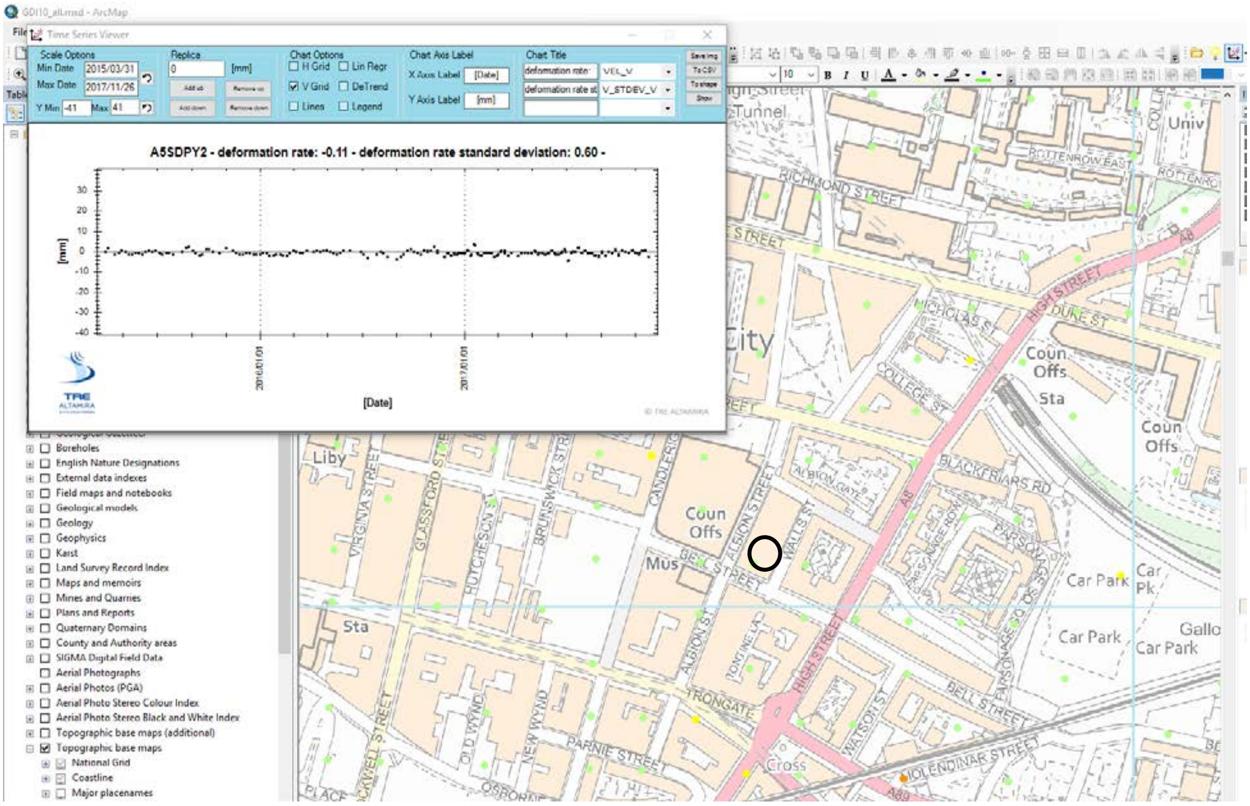
A web search for 'Glasgow Subsidence' returns several stories in the local press of subsidence events in Glasgow in the recent past. So, the question remains as to why we do not see these reported areas of subsidence within the InSAR data? The following reasons may account for this:

1. **Default display**: The default way to view an InSAR data set is as coloured points on a map. The points are colour coded by the linear average velocity; this means motions which occur over a short time period can be masked out when the average for the longer processed time period is used to display the point.
2. **Small spatial scale of subsidence**: The majority of subsidence events reported in Glasgow are associated with phenomena occurring over a short spatial scale. InSAR points are acquired via opportunistic measurements of persistent radar targets; it is not possible to choose which points will be measured. Therefore, an InSAR point is often too far from the event in question.
3. **Fast rates of subsidence**: InSAR techniques are only able to resolve ground motions of less than half a wavelength between processed radar images. In the case of C-band radar (as used here) this is 2.3cm (5.6cm radar wavelength) and the revisit times are every 6 days for Sentinel 1 and 31 days for ERS and ENVISAT. Therefore if an area is moving faster than 2.3cm between the image acquisitions then these areas are effectively moving too fast to be accurately represented.

With these limitations in mind we tested some of the subsidence events found in the media.

15th June 2018: Subsidence on High Street / Bell Street Junction

https://www.glasgowlive.co.uk/news/glasgow-news/glasgows-high-street-down-one-14789230


GDI10_all.mxd - ArcMap

Time Series Viewer

Scale Options
Min Date 2015/03/31
Max Date 2017/11/26
Y Min -41 Max 41

Replica
0 [mm]

Chart Options
☐ H Grid ☐ Lin Regr
☑ V Grid ☐ DeTrend
☐ Lines ☐ Legend

Chart Axis Label
X Axis Label [Date]
Y Axis Label [mm]

Chart Title
deformation rate: VEL_V
deformation rate st V_STDEV_V

A5SDPY2 - deformation rate: -0.11 - deformation rate standard deviation: 0.60 -

Figure 24: TRE ALTAMIRA SqueeSAR™ Vertical InSAR data for High Street / Bell Street junction. Contains © TRE ALTAMIRA 2018 data. Ordnance Survey data © Crown copyright and database right 2018, license number *100021290 EUL.*

In Figure 24 the average velocity of the point nearest the junction shows that the area is stable (points appear green), time series plot also shows that the area is stable; there are no sudden changes within the time series. Note the report of subsidence is June 2018 and the time series only extend to November 2017. In this case the time series does not extend across the date of the subsidence, however the authors have access to demonstration InSAR data from a different processing company which does extend to June 2018 and we do not see significant motion in this area at the time in question.

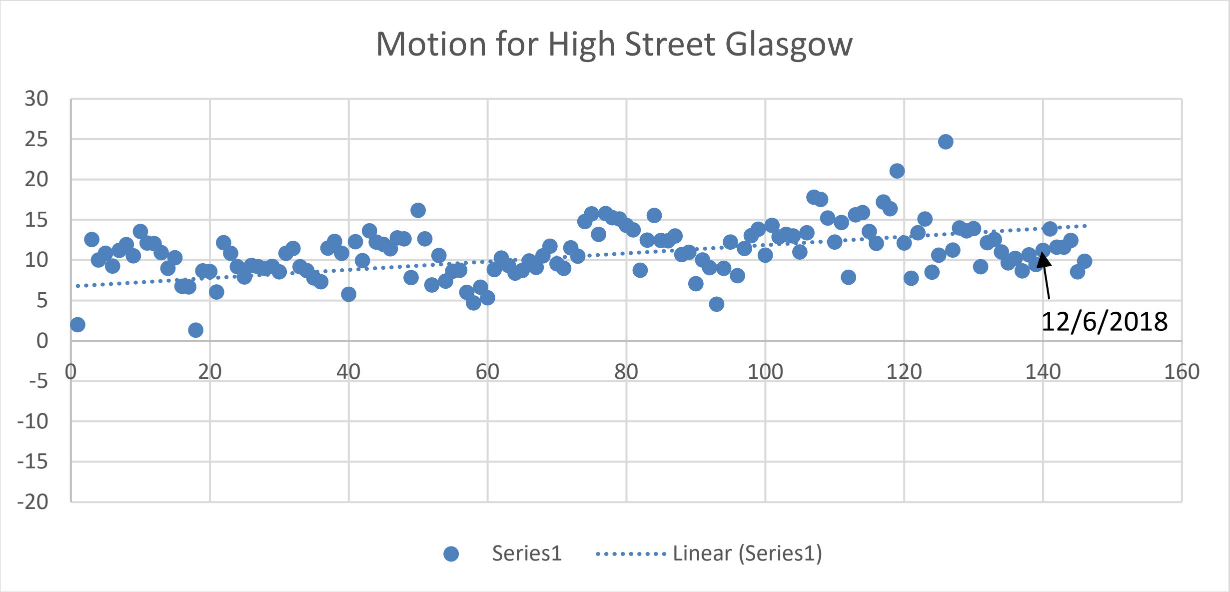


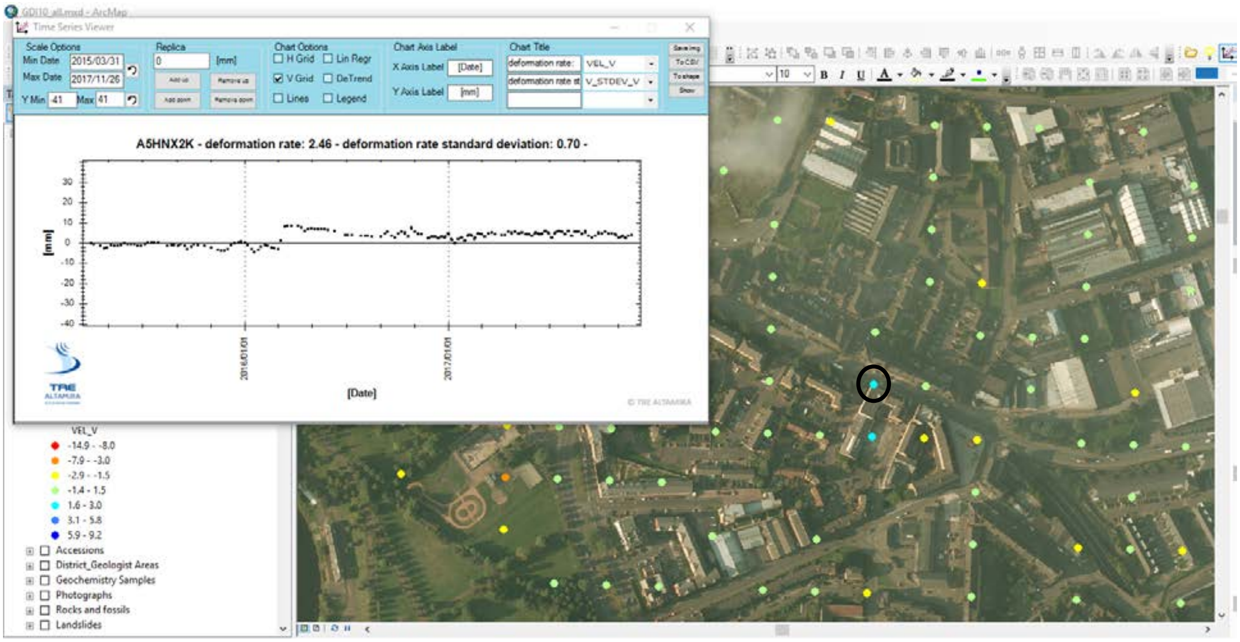
Figure 25: Time series for an InSAR measurement point from a demonstration dataset that BGS have access to for the area in question in Figure 24, note the linear motion and lack of significant variations in June 2018.

594 London Road, Glasgow

http://www.bbc.co.uk/news/mobile/uk-scotland-glasgow-west-16547142

13 January 2012

In 2012 extensive cracks appeared in the facade and internal structures of a London Road block (north of GGERFS) that was deemed unsafe and then demolished (https://www.eveningtimes.co.uk/news/13241269.Road_closed_after_sewer_collapses/). Unfortunately this ground motion occurred during a period when there was no operational European Space Agency radar satellite, therefore we are not able to provide InSAR analysis using this free data source.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X Axis Label [Date]
Y Axis Label [mm]
deformation rate: VEL_V
deformation rate st V_STDEV_V

A5HNX2K - deformation rate: 2.46 - deformation rate standard deviation: 0.70 -

Figure 26: TRE ALTAMIRA SqueeSAR™ vertical InSAR data for London road, note time series step in March 2016. Contains © TRE ALTAMIRA 2018 data. Aerial photography © UKP/Getmapping Licence No. UKP2006/01.

Although this report was from 2012 (when we do not have suitable satellite imagery coverage) the time series for 2015-2017 shows an interesting 10mm step in the motion history in March 2016. It is possible that this motion relates to remedial work carried out on the property in the years following the damage.

The two cases above represent motions that are challenging for medium resolution C-band InSAR to address; they both concern rapid motions over a small spatial scale and in each case the InSAR data does not cover the event itself. The first example highlights that it is not possible to guarantee a measurement point over the area of interest and the nearest point may not pick up such a localised motion. Data from higher resolution X-Band radar satellites, such as TerraSAR-X or COSMO-SkyMed, offer a better chance to detect such changes but at a financial cost. The second example highlights a data gap within the freely available ESA datasets; with the launch of Sentinel-1A in 2014 and Sentinel-1B in 2016 and the European Space Agency’s plan for a 12-year operational lifespan of systematic data acquisition the chance of such gaps is reduced. Later data over this site does show some motion which may relate to the original reported motions.

6 Conclusions

Collection, interpretation and processing of geo-thematic data were fundamental to characterise the spatial and temporal evolution of ground stability conditions from 1995 to 2017 in and around the GGERFS site. For the GGERFS site and wider Glasgow area ground motion data has been examined for three periods using three processing techniques. The following is evident from the data:

1. Glasgow and the surrounding area is largely stable for the time periods 1995-2001, 2002-2010 and 2015-2017
2. We found no evidence for ground motions relating to the coal mining history of this area. We do not see the regional patterns of uplift that has been observed in InSAR results for other UK former coal mining areas likely due to the age of mining, which stopped in the late 19th and early 20th century in urban parts of Glasgow. Investigation of the InSAR time

series for media reported subsidence events in Glasgow show that fast motions involving a small spatial area are difficult to detect with InSAR.
3. Small areas of ground motion are observed; these are interpreted to be caused by the compression of natural superficial deposits and man-made ground. This is especially true where there has been recent anthropogenic activity such as building or quarrying. Subsidence and uplift relating to volume change within superficial peat deposits are also observed and some cyclicity is evident within the motion time series for these points, which may relate to changes in water content.
4. A constant, yet small, pattern of subsidence is observed along the Clyde in the TRE ALTAMIRA data, this corresponds to compression of the alluvial deposits.
5. The GGERFS site has a lack of radar reflectors in the 1990’s and 2000’s due to the lack of buildings / radar reflectors at that time. In 2015-2017 radar targets are introduced by the development which has taken place. Although not a dense network of points they do reveal small rates of subsidence which appears to have started in early 2016. This subsidence likely relates to settling of the relatively thick superficial and man-made deposits within the area.
6. Similarly, settlement of the Commonwealth Games Athletes village housing area to the west of Cuningar Loop is observed in the 2015-2017 data.
7. The three types of InSAR processing applied to the site provide comparable results; we see the same features in the average velocity plots for SqueeSAR™ and ISBAS.
8. As expected the ISBAS Sentinel-1 processing provides almost complete coverage for the average linear velocity results, however, due to the lower spatial resolution and lack of time series it is harder to use this data to fully understand the motion characteristics

Now that we have characterised the ground motions in the Glasgow area for the last three decades we have a good baseline on which to monitor any potential effects of the planned geothermal research activities. Further InSAR investigations with the Sentinel-1 constellation are planned to be conducted once the abstraction and re-injection of mine water activities start in order to analyse any disturbance derived by human activities to the preceding natural condition described in this report.

The next investigation of ground motion conditions for GGERFS will account for additional information coming from both passive and active radar reflectors planned to be installed at Cuningar Loop in late 2019. These will be used to calibrate SAR imagery and will guarantee reliable InSAR measuring targets.

7 Acknowledgments

The authors would like to acknowledge ©Geomatic Ventures Ltd and TRE ALTAMIRA who processed the ISBAS and SqueeSAR^{TM} data respectively. Sentinel-1 data have been obtained via the Copernicus Program of ESA.

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