INSAR MONITORING OF LANDSLIDES IN BRITAIN: BGS’ FEASIBILITY MAP AND FIRST ISBAS STUDIES OVER THE SOUTH WALES COALFIELD

F. Cigna (1), L. Bateson (1), C. Dashwood (1), C.J. Jordan (1), A. Sowter (2), D. Boon (3)

(1) British Geological Survey, Nicker Hill, Keyworth, NG12 5GG Nottingham, UK, Email: fcigna@bgs.ac.uk
(2) Nottingham Geospatial Institute, Triumph Road, University of Nottingham, NG7 2TU Nottingham, UK
(3) British Geological Survey, Village Way, Greenmeadow Springs, Tongwynlais, CF15 7NE Cardiff, UK

ABSTRACT

InSAR is an accepted method for monitoring ground motion, however its applicability in non-urban areas is generally limited except for rocky terrains. This paper investigates a new method for deriving improved results outside the urban environment. Topographic distortions to the ERS-1/2 and ENVISAT SAR acquisition modes are simulated based on high resolution DTMs of the landmass of Britain. Persistent Scatterers (PS) densities are predicted by calibrating the CORINE Land Cover 2006 dataset using PS data available via the ESA TerraFirma and EC FP7 PanGeo projects. The InSAR feasibility to monitor land motions is discussed for the South Wales Coalfield, and the Intermittent Small Baseline Subset (ISBAS) technique is tested over the Coalfield using 55 ERS-1/2 images (1992-1999). With unprecedented target coverage, ISBAS reveals up to 1cm/yr uplift in areas of former coal mining, likely associated with groundwater rebound following cessation of mine water pumping.

1. INTRODUCTION

Since the beginning of 2012, the British Geological Survey (BGS) has been carrying out a research project aimed at evaluating the feasibility of Synthetic Aperture Radar Interferometry (InSAR) and Persistent Scatterers (PS) techniques to monitor and better understand landslide processes over Britain [1-2]. The project builds upon the successful achievements of recent InSAR and PS applications to landslide hazards in Europe (e.g., [3-6]), and aims to enhance further the research on radar Earth Observation (EO) for mapping landslides, other natural and anthropogenic hazards and land processes in Britain. This research is funded by internal grants of the Natural Environment Research Council (NERC) and also supported by ESA via the Category-1 project id.13543: ‘Enhancing landslide research and monitoring capability in Great Britain using C-band satellite SAR imagery and change detection, InSAR and Persistent Scatterers techniques’, whose results are being used for validation purposes. InSAR feasibility with C-band data has been mapped over the entire landmass of Britain, based on the combined assessment and modelling of topographic and landuse influences on the success of InSAR and non-interferometric (e.g., amplitude change detection) analyses. These effects are simulated using medium to high resolution DTMs, land cover information from the EEA CORINE map, and six PS datasets available over London, Stoke-on-Trent, Bristol and Bath, and the Northumberland region, which were made available to BGS through the ESA GMES TerraFirma and EC FP7 PanGeo projects.

The last two decades of PS (e.g., [7]) and Small Baseline Subset (SBAS; e.g., [8-9]) applications have shown that one of the major drawbacks of these techniques is that generally only urban areas and exposed rocks yield persistent or coherent targets, and this often gives a partial or even incomplete view of the spatial extent of land motions affecting the imaged regions. To address this issue for non-urban and rural areas of Britain, we tested the newly developed SAR data processing technique Intermittent SBAS (ISBAS) [9]. This is a small baseline, multi-looked, coherent target method, which considers the intermittent coherence of rural areas, works over a wide range of land cover classes including agriculture and grassland, and dramatically improves the point density of standard SBAS studies.

Our first test site is the South Wales Coalfield, an area with a long history of coal mining, where expected motions included deformation and subsidence caused by landslide movement, compression and consolidation of normally-consolidated Quaternary deposits and man-made ground, deformation related to the extraction of coal, and abstraction and rebound of groundwater [11]. In this area, the determination of the recent/present state of activity of landslide features is also of critical importance to establish if deep block movements still contribute to landslide activation and reactivation. ISBAS monitoring of the Coalfield in 1992-2008 with ERS-1/2 SAR and ENVISAT ASAR ascending and descending data is supporting geohazard research over this area, which is currently carried out by the Shallow Geohazards and Risks, and the Earth and Planetary Observation and Monitoring Teams of BGS, using both traditional mapping techniques and new technologies, including digital stereoscopic aerial photo interpretation, digital field data capture, terrestrial and airborne LiDAR, and differential GPS [12].
2. THE SOUTH WALES COALFIELD

The South Wales Coalfield is an E-W trending syncline divided by a major NE-SW trending fault system (Neath Valley Disturbance), which effectively forms two sub-basins, the eastern being shallower than the western and containing two subsidiary synclines. The western crop contains high-grade Anthracite coal but is buried to up to 2km, thus limiting development of coal industry to the periphery of the basin. Many NW-SE trending Variscan fault structures cross the basin and E-W trending low-angle thrust faults occur at the northern tip of the Variscan Trust Front in the south east (Fig. 1). The stratigraphy of the coalfield is subdivided into the South Wales Coal Measures Group overlain by the Warwickshire Group (Fig. 1). The South Wales Coal Measures Group comprises the productive Middle and Lower Coal Measures with abundant coal seams interbedded with mudstones, while the Warwickshire Group features predominantly sandstones, subsidiary mudstones and minor coals at the base [13].

Coal mining in South Wales started in Roman times and the industry grew monumentally in the 19th and 20th centuries, with a peak extraction rate of 56M tonnes/yr and 232,800 employees during WWI. The primary coal and iron reserves were around the edge of the coal field (Fig. 1) where resources were mined from shallow workings and horizontal adits driven into the hillsides. Later deep mines were sited on valleys floors enabling access to deeper coal seams, and in the 20th century improvements in mining methods and development of new industries fuelled use of 'steam' and bituminous coal from the central and eastern crops and some Anthracite from the west. Major groundwater pumping schemes were developed to control groundwater inflows into mines, particularly in the east crop where fractured bedrock and deep glacial valleys allow rapid recharge of the coal measures aquifer [15]. The coal industry started to decline through the 1970’s and 1980’s and by the 1990’s most deep mines had closed, with only a few open pits remaining. The last deep mine, Tower Colliery, finally closed in 2008. Most groundwater pumps have now been turned off allowing water levels to rebound to equilibrium levels.

2.1. InSAR feasibility assessment

The use of suitable SAR acquisition modes for the investigated territory is essential for both InSAR and non-interferometric analyses, to ensure that the target areas are visible to the employed sensor mode and acquisition geometry. Visibility of the terrain to the satellite sensor is controlled by the orientation of the land surface with respect to the acquisition geometry (i.e. the orientation of the Line-Of-Sight, LOS), and can vary within different portions of the same scene, depending on local topography (e.g., [5], [2]).

To define the orientation of the ascending and descending acquisition modes of ESA’s ERS-1/2 SAR and ENVISAT Advanced SAR (ASAR) Image Swath 2 (IS2), we employed a 23° look and ±14° track angles to exemplify the LOS orientation over the British landmass. Local terrain orientation was assessed by employing the 5m airborne InSAR NEXTMap Digital Terrain Model (DTM) produced by Intermap Technologies, and its 10m and 50m derivatives. Foreshortening, layover and shadow were identified by combining the approaches described in [16] to identify active and passive layover and shadow, and [17] to map the topographic R-index. The latter coincides with the ratio between the pixel size in ground and slant range, and allows identification of areas of good visibility (+0.3 < R ≤ +1; slopes facing away from the sensor), as well as foreshortening (0 < R ≤ +0.3) and active layover (-1 ≤ R ≤ 0; slopes facing the sensor and steeper than θ, thus producing layover onto other areas) [2].

Fig. 2 shows the resulting SAR topographic visibility map in the ERS-1/2 and ENVISAT IS2 ascending mode for the area of the South Wales Coalfield. Active and passive layover and shadow masks are overlapped onto the R-index map, and identify areas where the above acquisition mode and geometry are not suitable to investigate land motions with SAR imagery acquired with that LOS.

The topographic feasibility maps for the ERS-1/2 and ENVISAT ascending and descending modes show that topography is not the major limitation over most of Britain (see also [1-2]). Generally, the identified areas of layover and shadow for each satellite mode cover only small portions of the imaged areas (e.g., about 1.2% of the land represented in Fig. 2). Evidently, the combined use of both ascending and descending image stacks can compensate and complement the coverage of the terrain visible to the SAR sensor, by guaranteeing good visibility of E-, NE- and SE-facing slopes by using the ascending geometry, and W-, SW- and NW-facing slopes by using the descending mode (e.g., [5]).
The identification of PS targets during the processing depends on the presence of surface objects with a high temporal coherence that can be identified throughout the processed SAR stack. Such objects are associated with land cover and, typically, urban areas result in higher PS density than rural areas.

To provide a quantitative assessment of the likelihood of obtaining PS points for a given area/land use, for our feasibility study it was necessary to first derive the average PS density expected for each land cover category in the UK when using C-band, medium resolution SAR data. To derive expected density for a given land cover class, relationships were sought between the EEA CORINE Land Cover Map 2006 [18] and the following PS datasets (made available via the projects TerraSAR and PanGeo):

- ERS-1/2 ascending mode 1992-2000 and ENVISAT descending mode 2002-2010 PS data for Greater London (processed by NPA);
- ERS-1/2 and ENVISAT descending mode 1992-2005 PS data for Bristol/Bath (processed by NPA);
- ERS-1/2 descending mode 1992-2003 PS data for Stoke-on-Trent (processed by TRE S.r.l.);

For each land cover type the number of PS points was extracted and the corresponding average target densities (PS/km²) were derived for each land cover class. The derived densities were then ranked into nine classes with a rank of 1 corresponding to the highest density and 8 to areas with no PS points. Calibration of the CORINE Land Cover Map by the derived average densities and rankings allowed for quick identification of the expected PS density for any area of Britain [2].

Fig. 3 shows the calibrated CORINE Land Cover 2006 showing predicted PS densities for the different land cover types and classes in South Wales. These predictions refer to the use of a PS approach with C-band medium resolution data. Results from the calibration confirm that the land cover exerts significant control on the potential of PS technologies over this area. Whilst urban areas, industrial/commercial/port units, bare rocks and road/rail networks clearly have high likelihood to result in high PS densities (up to several hundred per km²), densely vegetated areas, marshes and water bodies are characterized by low to null likelihoods. The calibrated CORINE Land Cover Map shows highest predicted densities of radar targets (i.e. 400 to 800 PS/km²) over the dense urban areas (e.g., Cardiff, Swansea, Newport), and minimum densities (i.e. 10-40 PS/km²) over moors, pastures, heathland and woodland over the majority of the area. This PS density prediction may clearly increase by 1 order of magnitude using input SAR data at higher resolutions (e.g., TerraSAR-X) (e.g., [7]), and the spatial coverage of the monitoring results may be improved by using processing approaches such as the ISBAS recently developed at the Nottingham University [10-11], which is capable of providing greater coverage of monitoring targets and therefore a more complete picture of land motions affecting non-urban, rural and semi-vegetated regions.
Similar results from the BGS' InSAR feasibility assessment are discussed in [2] for the area of Manchester and the Peak District in central/northern England. For this region, the visibility of some areas of landslide deposits mapped in the BGS Digital Geological Map of Great Britain (DIGMapGB) at 1:50,000 scale and the National Landslide Database (NLD) in the area of Mam Tor, Derbyshire, is discussed in relation to both local slope orientation and the ascending/descending mode, and land cover distribution for landslide deposits in Britain which often show extremely to very low potential densities of PS targets.

2.2. Intermittent SBAS analysis

We processed 55 SAR images for the seven year period between 25/04/1992 and 14/12/1999, which were acquired by the C-band Active Microwave Instrument (AMI) onboard ESA’s ERS-1/2 satellites along sun-synchronous polar orbits. This stack covers a 100 km by 100 km area, and the slant range and azimuth pixel spacing of the scenes are 8m and 4m respectively which, on the ground, correspond nominally to ~25m pixels. The LOS characterizing the stack has 23.3° look angle referred to the centre of the scene, and is tilted of around 14° with respect to the E-W direction at the latitudes of South Wales. Further details about the input data stack can be found in [11].

Orbit state vectors for the scenes were first improved and orbital errors minimized by employing the recomputed ERS-1/2 orbital data provided by the Delft Institute for Earth-Oriented Space research (DEOS), which were made available via ESA’s project REAPER (REprocessing of Altimeter Products for ERS) in 2011. The image stack was then co-registered to a single master scene acquired on 25/09/1995, thus obtaining co-registration accuracies for the slates as high as 0.05 pixels in range and 0.15 pixels in azimuth. A subset of the full image frame was selected, by clipping the co-registered scenes to a final processing area of ~5,200 km² (~4,300 km² land areas). Multi-looking factors of 4 and 20 were then employed to increase the phase signal quality and reduce radar speckle, and this increased the corresponding size of the image pixels on the ground to ~100m. The average coherence of the processed subset was generally quite low (Fig. 4), with the majority of the area showing very low coherence values (i.e. between 0 and 0.25) and only major built-up areas (e.g., Cardiff and Swansea) and several small villages along the steep sided valleys of the coalfield showing higher coherences (i.e. between 0.25 and 1).

By employing 200m perpendicular baseline and 4year temporal baseline thresholds, a set of 271 small baseline interferograms was generated and, despite the presence of temporal gap in the stack between 1993 and 1995, the network of InSAR pairs showed good density and high level of redundancy (see also [11]).

To select the image pixels suitable for conventional SBAS, the average coherence across all interferograms was cut by using a 0.25 threshold, while for the implementation of ISBAS this value was used to select intermittently coherent pixels within each interferogram, provided that the number of coherent layers for those pixels exceeded 50, which was used as threshold for the selection of intermittently targets (see also [10-11]). Computation of linear velocities was performed by following the methodology described by [10], and based on differential interferograms which were unwrapped by employing the SNAPHU algorithm [19]. Height errors, atmospheric components and time series were also computed using spatio-temporal filters based on the deterministic characterization of the various phase components.

A total of 54,815 coherent pixels were identified with the SBAS approach, showing an average of ~13 points/km² over the entire processing area (Fig. 5). Coherent targets concentrate over the urban areas, where higher values of the average interferometric coherence were observed. Comparison between the results obtained with the conventional SBAS and recently developed ISBAS approach show that the increase in the number and density of identified and monitored targets increased by a factor of ~3.4. Indeed, the ISBAS results provide a total of 190,161 targets (corresponding to ~44 points/km²), which represents a greatly improved spatial coverage when compared to the 13 points/km² obtained via the standard SBAS processing.

Both the SBAS and ISBAS results show that with some notable exceptions South Wales is mostly stable (Fig. 5). The main ground motion feature identified by the results is a large area of uplift in the eastern valleys to the north of Cardiff. Maximum rates are observed in the Bargoed and Bedwas areas on the north-eastern edge of the Llantwit-Caerphilly syncline, where rates as high as 1cm/yr are estimated. It is thought that the observed uplift relates to rebound of mine water levels resulting from the closure of the mines, and cessation of mine
water pumping. Several small areas of ground subsidence are also notable, particularly in Cardiff, along the low-lying coast and estuary, and Port Talbot, where development and modification of drainage has likely led to settlement of normally-consolidated superficial deposits and artificial ground. Further details about the input data, processing methodology and analysis and discussion of the results with respect to the location and number of mining sites across the Coalfield, their years of closure and groundwater data are described in [11].

It is apparent that the increase in spatial coverage afforded by the ISBAS approach offers great advantages for the interpretation of ground motion. The improved density allows for the identification of small areas of motion which fall in the gaps of the SBAS result, but it also allows the edges of displacement areas to be more accurately defined and interpreted. This makes it easier to relate the results to other datasets and hence increases our understanding of the ground motion.

3. CONCLUSIONS

Our feasibility assessment based on ERS-1/2 and ENVISAT data showed that topography is not the major limitation for InSAR and non-interferometric studies of non-urban and rural areas of Britain (geometric distortions for each satellite mode are ~1% of the landmass), while land cover has generally stronger control on the potential of PS technologies over this territory. These feasibility maps are being employed at BGS both to understand – prior to a SAR-based study – if and where geometric distortions and lowest target densities will be, and to select the best data and modes to monitor the various areas and slopes of Britain. Thus, our maps not only show the potential of InSAR monitoring of geohazards in Britain with ERS-1/2 and ENVISAT C-band image archives, but also data from the forthcoming Sentinel-1 constellation that will provide unprecedented and long-term SAR observations of the Earth’s surface starting in 2014.

Improved processing technologies such as ISBAS [10] can provide a more complete picture of land motions due to various processes (e.g., slope deformation, mining, peat motion, and ground water related hazards), by increasing the number of identified targets and providing improved target densities in rural and vegetated areas, exploiting C-band archives and assessing the deformation history of wide territories with enhanced spatial coverage. Our tests in South Wales reveal the potential of this new technique to monitor various non-urban areas of Britain, and provide a complete picture of land motions affecting the Coalfield during the 1990’s, likely associated to groundwater rebound after cessation of mine water pumping, with up to 1cm/yr observed uplift in some areas of former coal mining, and potentially slope deformation linked to large landslide movements.

Figure 5. (a) SBAS and (b) ISBAS results for the South Wales Coalfield, showing average ground motion rates in 1992-1999, overlapped onto hillshade of NEXTMap® Britain DTM (©Intersmap Technologies). Green stars indicate location of the reference point (from [11]).

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5. REFERENCES


