Supporting energy regulation by monitoring land motion on a regional and national scale: A case study of Scotland

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Abstract

The advent of new satellite and data processing techniques have meant that routine, operational and reliable surveys of land motion on a regional and national scale are now possible. In this paper, we apply a novel satellite remote sensing technique, the Intermittent Small Baseline Subset method, to data from a new satellite mission, Sentinel-1, and demonstrate that a wide area map of ground deformation can be generated that supports the regulation of a range of energy- related activities. The area for the demonstration is mainland Scotland (~ 75,000 km^2) and the land motion map required the processing of some 627 images acquired from March 2015 to April 2017. The results show that land motion is encountered almost everywhere across Scotland, dominated by subsidence over peatland areas. However, many other phenomena are also encountered including landslides and deformation associated with mining and civil engineering activities. Considering specifically Petroleum Exploration and Development License areas offered under the 14th Onshore Licensing Round in the UK, examples of the types of land motion are shown, including an example related to soil restoration by a wind farm. It is demonstrated that, in Scotland at least, almost all license areas contain deformation of one form or another and, furthermore, the causes of that subsidence are dynamic and likely to be changing from year-to-year. Therefore, maps like this are likely to be of enormous use in a regulatory framework to scope out pre- existing problems in a license area and to ensure that the correct monitoring framework is put in place once activities begin. They can also provide evidence of good practice and give assurance against litigation by third parties.

Keywords: Earth observation, energy policies, interferometric synthetic aperture radar, power: environmental aspects

Introduction

The extraction of oil and gas resources will result in changes in reservoir pressure which, under certain circumstances, will consequently lead to changes in the surface level.[1,2] The amount of motion depends upon pore pressure changes, the stress response of the reservoir structure to those changes and the mechanics of how the response propagates to the surface.[3] The propagation of the motion depends upon the specific stratigraphy and the presence of faults, which may slip causing tremors.[4] Induced seismicity caused by extraction activities is a well-known phenomenon and areas of intense coal, oil and gas extraction often experience an increase is seismicity because of it.[5–7] Large areas of the UK are currently licensed, or are under review to be licensed, for shale gas exploration using hydraulic fracturing – a stimulation technique commonly referred to as 'fracking'. There has been dismay from the public about fracking over concerns that it will lead to earthquakes and ground deformation, consequently posing a threat to the local economy, the environment and the health of the population.

Oil and gas licensing in Scotland, as well as in England and Wales, is governed by the Petroleum Act 1998. The 1998 Act vests all rights and ownership of petroleum resources (oil and gas) to the government, which then grants a Petroleum Exploration and Development License (PEDL) in competitive licensing rounds for the exclusive exploration, development, production and abandonment of hydrocarbons in the licensed areas. Each area is 10km×10km in extent. Licenses, issued by the Oil and Gas Authority (OGA), apply to both conventional and unconventional exploration and production. This license confers exclusivity in a defined area as against other exploration companies, but does not exempt the company from other legal/regulatory requirements which involve the OGA, the Planning Authority, the Health and Safety Executive (HSE), the Scottish Environmental Protection Agency (SEPA), the Coal Authority and the British Geological Survey (BGS).

The Scottish PEDL areas offered in the 14th Onshore Licensing Round of December 2015 are almost entirely confined to the Midlands of Scotland, as shown in Figure 1.

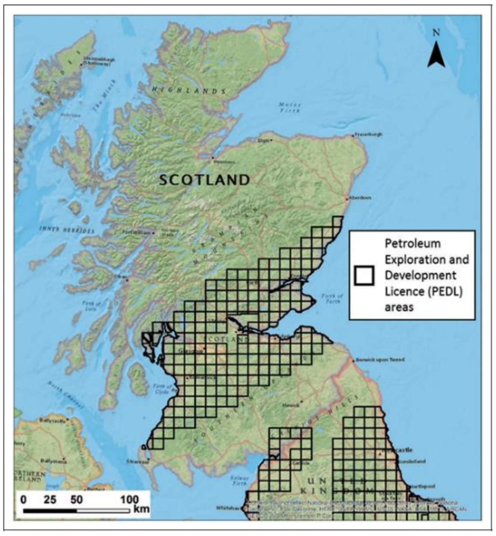

Figure 1*. Fourteenth Onshore Licensing Round Petroleum Exploration and Development Licence block areas offered in Scotland.*

As of August 2016, there are 119 onshore oil and gas sites in Scotland (48 for coal-bed methane and 71 for conventional oil and gas), mostly concentrated in the area between Stirling and Edinburgh. Following debate with prospective licensees, and in accordance with the new devolution settlements set out in the Scotland Bill, the UK Government decided that no new PEDLs will be awarded in Scotland as part of the 14th Licensing Round. However, direct interest in onshore activity has increased due to the presence of a significant volume of potentially productive shale that is associated with the Carboniferous deposits in the Midland Valley sub-basins.

In many regions, the regulation of oil and gas production is complicated by existing natural and anthropogenic conditions, for example, where land motion is influenced by groundwater level fluctuation. Any water abstraction or pumping linked to mining, industrial activity, irrigation or the provision of drinking water may also cause significant subsidence or uplift[8,9]. Under certain circumstances this may also lead to increased seismicity as large-scale extraction and injection changes the load on the underlying geology or groundwater recovery and may re-activate a fault. Induced seismicity is a timely and increasingly relevant topic of interest for scientific community, government agencies and general public,[10] as it results from an anthropogenic disturbance releasing pre- existing natural stresses.[4,11]

The Midland Valley basin is one of the most seismically active areas of onshore Great Britain and has had a long history of coal mining, with three reported cases of mining-induced fault reactivation[12]: Miller Hill in 1980s, Musselburgh in 1996 and Glasgow in 1998. There are many instances where shale gas and oil prospects lie immediately below these historical coal fields[11] and are at risk of subsidence because of the pre-existing unstable ground. Indeed, the central belt of Scotland hosts UK's most productive coalfield and a third of the UK's igneous rock aggregate quarries. Historic mine workings buried deep under- ground have been confirmed as the cause of a collapse in Clydebank's Kilbowie Road in January 2017 and other examples of mine shaft collapses in Scotland (e.g. Ferniehill in 2001) are due to ineffective support pillars left in place, their solubility or the flooding of previous mine chambers. These have been reported by The Coal Authority's public safety team, especially in the areas around Edinburgh and Glasgow.

Natural causes of land motion include compressible ground, landslides, shrink-swell terrain and soluble rocks. Such geohazards are often well-known (in the UK these are identified in the GeoSure dataset of the BGS), but are highly dynamic and represent another source of risk to the energy sector. According to the BGS GeoSure database,[13] potential geohazards threatening terrain stability in Scotland are ascribed to the occurrence of:

1. Compressible ground associated with peatlands covers 27% of Scotland's surface, especially the northern sector of the Isle of Lewis and the River Thurso basin (Figure 2a).
2. Landslides, around 2000 have been identified in Scotland and recorded in the BGS National Landslide Database. More than 75% have been checked for the reported location information. Bedrock-controlled rock slope failures, including falls, toppling/spreading, rock creep and translational landslides occur in hard bedrock with V-shaped valleys across western Scotland.[14] Secondarily, large rock slope failures in eroded, rounded bedrock geomorphology with U-shaped valleys occur. Finally, debris flows are also present in the Scottish Highlands (Figure 2b).
3. Soluble rocks (Figure 2c), like the metacarbonate beds preserved within parts of the Dalradian Supergroup, in the Appin and Schiehallion regions of the Scottish Highlands.[15]

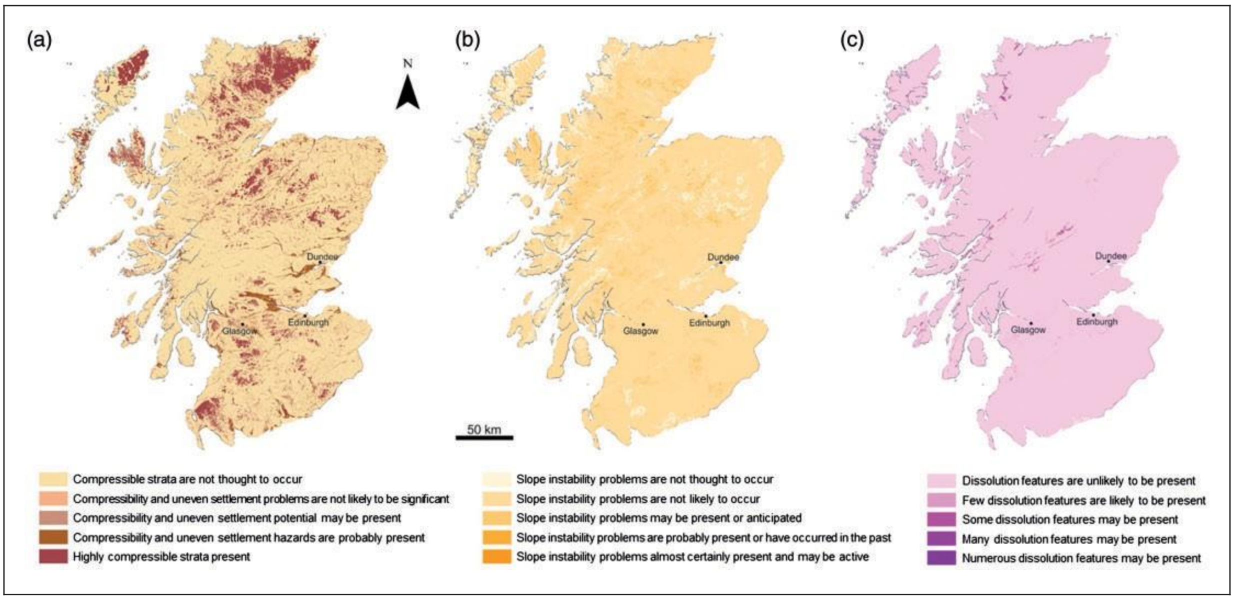

Figure 2. Potential hazards in Scotland associated with (a) compressible ground, (b) slope instability and (c) soluble rocks. Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved.

Although land motion due to oil and gas activities in the UK is not expected to be large nor necessarily result in structural damage, it is recognized that monitoring is necessary to gauge potential damage and to address the concerns of the general public and also governmental bodies regarding environmental protection. Moreover, given the diverse range of natural and anthropogenic sources of land instability affecting Scotland (and the UK as a whole), it is recognized that government regulation should begin with a clear understanding of the dynamics of the land surface across the entire region of concern before PEDL licenses for new activity may be granted. Consequently, there is some current level of discussion within geological surveys across the world that a national land motion product could be an important baseline for the issue and control of licenses for exploration and extraction of oil and gas reserves.

Monitoring may be achieved through a number of techniques, from the installation of seismometers to regular Global Navigation Satellite System (GNSS) and levelling surveys. However, depending on the extent of the reservoir and the geology, production-related land motion is likely to occur over large areas, often kilometers away from the source as the changes in subsurface pressure migrate across the landscape[16,17]. Traditional ground-based surveying is therefore unsuitable because it is impractical for providing detailed coverage over large spatial extents. In any case, measurements of land motion over the entire landscape are needed to establish a baseline, and properly evaluate and predict any hazard caused by extraction and injection activity.

With regards to a national land motion map, an Earth Observation technique called Interferometric Synthetic Aperture Radar (InSAR) represent an ideal time- and cost-effective solution. An InSAR technique can determine changes in surface position between two observations by calculating the phase difference between the two radar signals, enabling sub-centimeter rates of motion to be deduced across large areas.[18] Furthermore, using advanced techniques such as the Intermittent Small Baseline Subset (ISBAS) method, InSAR surveys can be extended to produce results over rural and urban areas alike.[19]

ISBAS is a variant on the well-understood Small Baseline Subset (SBAS) InSAR method.[20] Most implementations of the SBAS method consider only those image pixels that demonstrate consistently high quality (high coherence) over time; the ISBAS method is based upon a relaxation of that constraint, and is inclusive of pixels demonstrating a much wider range of coherence values. To help improve coherence, pixels are averaged to reduce noise, resulting in a lower resolution (90 m for Sentinel-1) in the final product. In this way, the ISBAS method can provide meaningful measurements of land motion over a much wider range of land cover classes than normally possible; which includes most vegetated and forested areas, in addition to urban and rocky terrain. The ISBAS method is currently the subject of a patent application by the University of Nottingham.

The ISBAS technique has played a key role since August 2015 in a research consortium led by the BGS and funded by BEIS for developing methodologies to deliver a baseline environmental monitoring programme in and around Kirby Misperton (North Yorkshire), for which applications for shale gas wells have been made (http://www.bgs.ac.uk/research/groundwater/shaleGas/monitoring/GroundMotionYorkshire.html).

ISBAS has also been recognized as a useful technology by regulators in other countries, such as the Environmental Protection Agency in the Republic of Ireland.[21]

A factor that makes a national land motion map more feasible is the Sentinel-1 satellite mission, which comprises a constellation of two identical satellites with a compatible InSAR capability. It is operated by the European Space Agency on behalf of the European Union and is currently acquiring data of almost the entire land surface of the Earth. The data are free for commercial and institutional use and are available through the Copernicus Open Access Hub[22]. Sentinel-1, then, is clearly an ideal source of from which to drive land motion data on a national-scale. However, as pointed out by Sowter et al.[23] and Novellino et al.,[24] processing the data is challenging and there are inconsistencies in the content of an image frame from acquisition to acquisition. However, if these issues can be overcome, Sentinel-1 has huge potential in this sector.

The aim of this paper is therefore to demonstrate that a national land deformation map is possible using a combination of Sentinel-1 data and the ISBAS method and taking Scotland as the demonstration area. The results reveal that land motion is pervasive throughout Scotland and primarily comprises subsidence over peatland. Deformation observed within PEDL areas was typically associated with landslides, mining and civil engineering activities.

Methodology

To derive the relative average velocity land motion map of the Scottish mainland, Sentinel-1 Interferometric Wide (IW) products were selected and used in conjunction with the ISBAS InSAR technique. The Sentinel-1 tracks that cover the entire area are shown in Figure 3, from which it is clear that three ascending tracks (103, 30 and 132) are sufficient to cover the entire width of the country. Furthermore, three frames from each track were needed to cover the full north-south extent. In addition, we selected images covering the period March 2015 to April 2017 meaning that the number of images in each stack were 207 for track 103, 210 for track 30 and 210 for track 132. In total, 627 Sentinel-1 images were used (Figure 3).

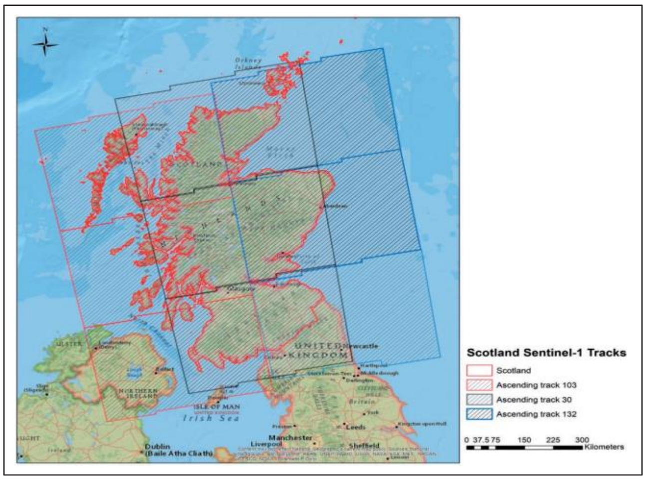

***Figure 3**. Sentinel-1 frames of the Scottish mainland.*

Sentinel-1 data are some 250 km wide and the radar incidence angle, defined by the incident radar beam (the so-called Line of Sight (LOS)) and the vertical (normal) to the intercepting surface, ranges from 29° in near range to 46° in far range. Since InSAR measurement refers to a displacement along the LOS, a variation in the incident geometry also implies a variation in the sensitivity to land motion to the extent that the result at 29° would likely appear different to the result at 46°, causing difficulties when mosaicking in the across-track direction. Therefore, each frame was subset in range by 40% (20% from each side) such that the range of incidence angles was smaller, some 32–42°. This still left a substantial over- lap between tracks to aid in mosaicking.

It has been pointed out in Novellino et al.[24] that, even if the Sentinel-1 frame number is used consistently in the InSAR processing, the extent of each image along-track can vary considerably, meaning that the area of overlap common to all frames can be quite small and hardly ever meets the similar extent of the frame above or below it. Here, this was solved by stitching two adjacent frames from the same time epoch together and using these super- frames as input to the processing. In this way, we could overcome the problem with frame inconsistency and engineer a good overlap between super- frames along track to facilitate the mosaicking process.

The Sentinel-1 ISBAS process, described in Sowter et al.,[24] was implemented here with the following modifications:

1. The stitching of adjacent frames was automated
2. Residual phase slopes in interferograms formed after co-registration were automatically removed using an image processing technique

The thresholds used for the temporal and perpendicular orbital baselines were 365 days and 150 m respectively. Between 850 and 1500 interferograms were generated for each subset. Reference points were arbitrarily chosen to be in highly coherent areas in each subset processed.

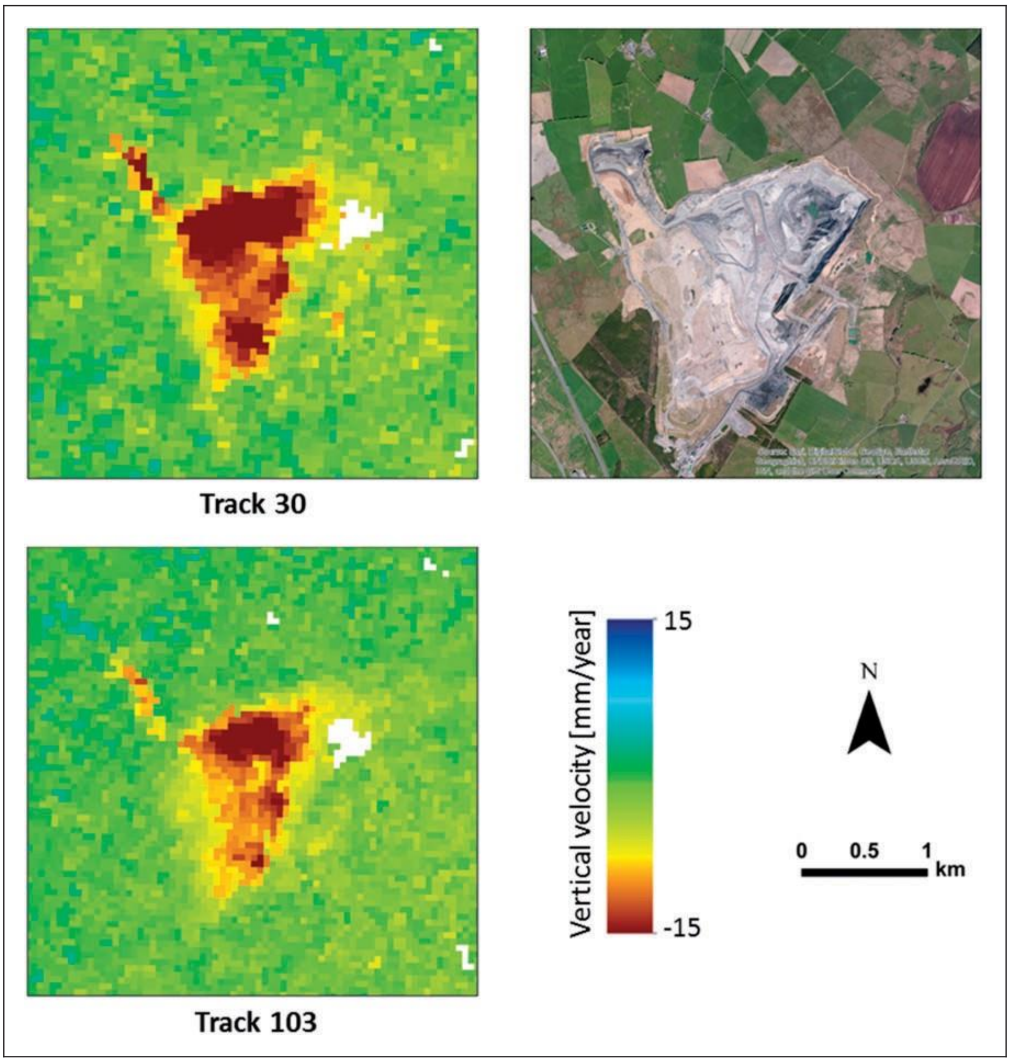

Figure 4. *Land surface reduction rates at the Broken Cross open cast coal mine in South Lanarkshire observed from tracks 30 and 103.*

High relative velocities were occasionally seen in small extremities of the image frame, primarily in corners or in parts of the land jutting out into the sea, especially if these were close to the edge of the image. These were ascribed to phase unwrapping errors and were entirely inconsistent between overlapping tracks. In the mosaicking process, the result most consistent with the local characteristics in the surroundings of the area was used.

All velocities were initially generated as LOS velocities but converted to relative vertical velocities by dividing by the cosine of the incidence angle, primarily to aid the consistency of results in overlapping areas. It is noted that this correction is only warranted if the observed motion is in the vertical direction and may not be appropriate to deformation with a significant horizontal component, such as landslides.

Overlap areas were compared and if any constant offset in velocity values was detected, the frame values were adjusted. This was simply attributed to the arbitrary use of reference points. Near-range to far-range overlaps were compared and were qualitatively in agreement, showing the same areas of uplift and subsidence. However, the far-range results were often smoother and the absolute velocities were slightly smaller. An example of this, showing subsidence of the Broken Cross mine in Lanarkshire, is shown in Figure 4. We assumed that this was due to the reduced sensitivity of the higher incidence angles to vertical deformation. As the results were on-the-whole consistent we chose whichever result gave the better match during mosaicking.

The results for each processed frame were output as an orthorectified image of average velocities. In addition, layover and shadow masks were calculated and velocities from those areas were excluded. Mosaicking of these average velocity images was therefore relatively straightforward, taking place in map coordinates, following the following steps:

1. Any consistent offset in velocity values between overlapping areas was corrected.
2. Anomalous areas in a frame consistent with poor phase unwrapping in overlap areas were replaced with results from another frame.
3. Adjustment and layering was applied based upon visual inspection.
4. A single constant velocity offset was applied to the final mosaicked product by applying the 'Null Hypothesis': maximizing the amount of the image showing least velocity.

Results and discussion

The complete mosaic

The final relative land motion mosaic showing deformation over Scotland is shown in Figure 5. This is the first Scotland-wide ground deformation map. It must be noted that the InSAR technique is primarily limited to very small amplitude changes, and therefore very small rates of change, in the land level due to a short radar wavelength; in this case 5.6 cm. Here, a displacement of only 1.4 cm between any pair of images is potentially ambiguous in the absence of a spatial pattern of well-defined fringes and thus, although the sense of direction of the land motion is maintained in the results, quantitative values may be amiss in some cases.

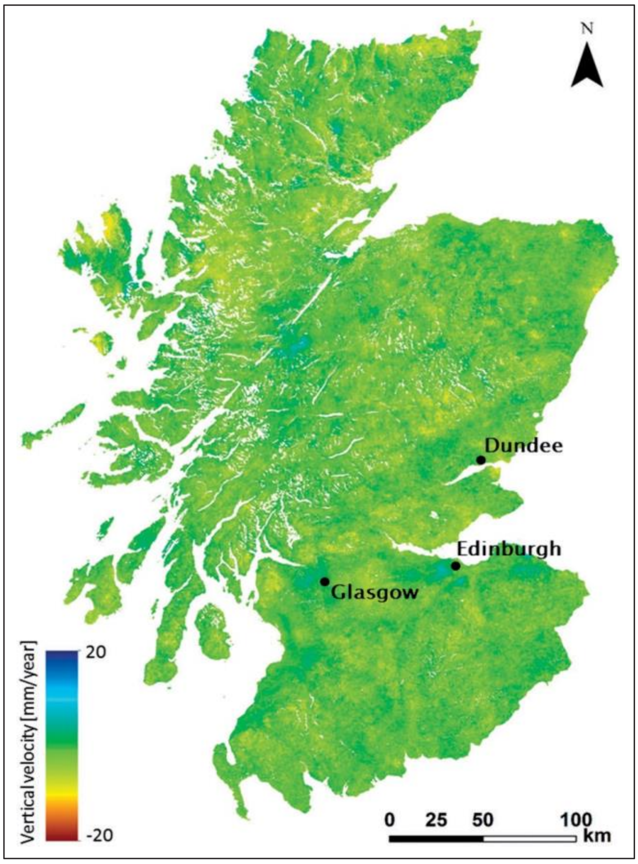

***Figure 5**. The final relative land deformation mosaic of mainland Scotland.*

The pixel size is approximately 90 m both in range and azimuth direction. Excluding water bodies, the survey covered 97% of the available extent of land, the main loss being due to layover and shadow areas. The LOS standard error ranges from 0.4 mm/year to 3.7 mm/year and the overall quality of the mosaic is considered as excellent. At a glance, the main observed deformation patterns in Scotland can be ascribed to highly compressible terrain in the north- east, opencast mines and quarries in the south, and landslide phenomena primarily on the western coast. The ISBAS processing of each frame currently takes two days on a dedicated multi-core PC and the process requires very little user intervention. Mosaicking is also a relatively simple, automated process. Therefore, with a sufficient number of servers, a large mosaic could be produced in days rather than weeks, which could easily support routine, regular
timely monitoring of an active oil and gas site.
However, there were a number of issues that will need to be addressed in future mosaicking activities:

1. The coverage of each image tile may be different due to the different point thresholds used in each case[19]. This results in the edge of a tile often being quite prominent. More consistency in the selection of this parameter is needed from tile-to-tile.
2. Some phase unwrapping errors persist at the extremities of the images. This is particularly prominent on the Isle of Skye where large deformations persist, contrary to expectations. Problems in such case require geological expertise and quantitative comparison to eliminate with confidence.

The deformation map of mainland Scotland derived using the method described above did not use any ground measurements for control of the process. Over such a wide area this is of enormous benefit to the operational application of the technique but may bring questions regarding the validity of the quantitative results, since the vertical velocity measurements are relative to a reference point found within each image frame. For this reason, a qualitative analysis is all that will be attempted here but, in future, it is recognized that the use of large networks of geodetic networks, such as the British Isles GNSS Facility (BIGF) (www.bigf.ac.uk) may be used to adjust the mosaic and result in an increased confidence in the use of the results as a source of absolute measurements. Although the response of the solid earth surface to large-scale glaciation and deglaciation also contributes to the vertical land motion of inland Scotland,[25] these result in very low Vertical Land Motion (VLM) rates of between 0.7 and 1.3 mm/ year across the UK. In essence, the short time-span of the Sentinel-1 acquisition (25 months) in this study would not permit the capture any significant isostatic adjustment in the presented InSAR deformation results as these rates are well below the standard error. In any case, it is also likely that any slow variation in VLM across a Sentinel-1 frame caused by solid Earth motion would be indistinguishable from an orbital baseline error and therefore would be filtered out and not detected in the final ISBAS survey results.

Deformation over the offered PEDL areas

Details from the deformation map over the offered 14th Licensing Round areas are shown in Figure 6. As is clear, there are significant areas of uplift and subsidence within the blocks. The most common causes of land motion relate to motion at the very surface, but there is at least one area that is clearly related to subsurface activity. Specific examples of the causes of land motion are described below.

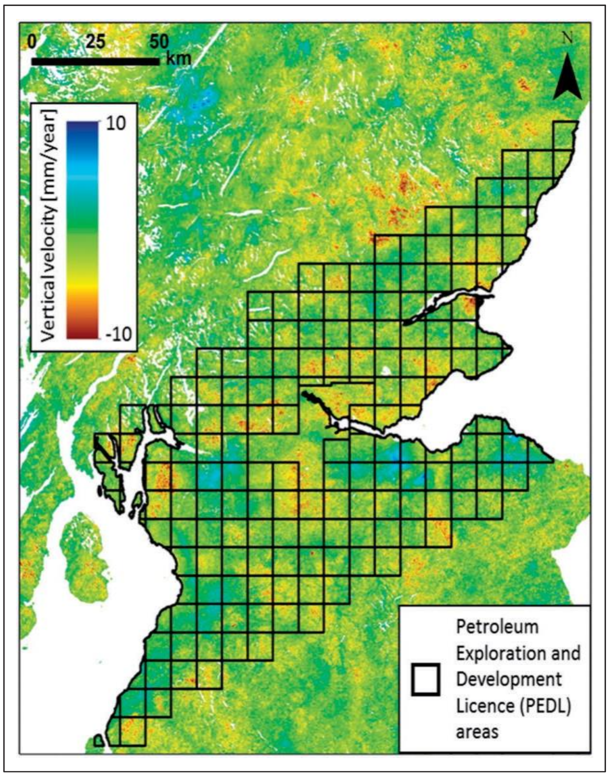

Figure 6. *Relative land motion in the Scottish Midlands overlaid with the 14th Licensing Round PEDL areas.*

Examples of energy-related land motion. Although difficult to ascertain the exact cause, there is a significant area of uplift in the Midlothian coal field that dominates the land motion seen in PEDL block NT26. It is shown in Figure 7 and corresponds very well to other InSAR observations of groundwater recovery over such sites)[26].

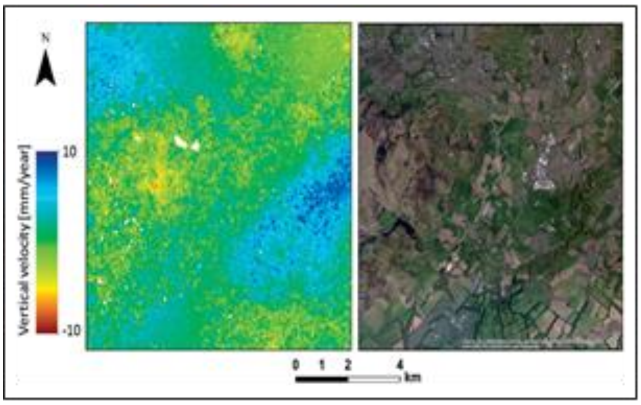

Figure 7. *PEDL Block NT26. Possible effects of the abandonment of a coal mine in East Lothian, where groundwater recovery has caused a large area of uplift (blue) in the east.*

There are also significant areas of surface coal mining, such as affecting PEDL Block NS51 (Figure 8). In these cases, the erosion of the surface level appears as a significant subsidence signature (red).

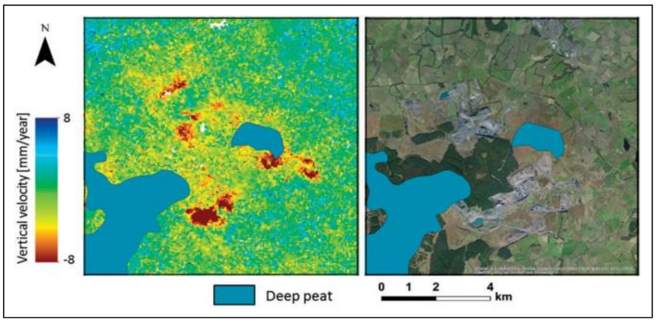

Figure 8. *PEDL Block NS51. Surface mines observed in Lanarkshire, where surface reduction caused by extraction at several clustered sites can be seen as red (subsidence). Subsidence related to the condition of deep peat has been masked out.*

Another significant area of uplift appears coincident with the location of the Crystal Rig onshore wind farm located in the Lammermuir Hills in the Scottish Borders (Figure 9). The third phase of development was commissioned in November 2016 and the uplift is likely due to the re-wetting of the soils following civil engineering works.

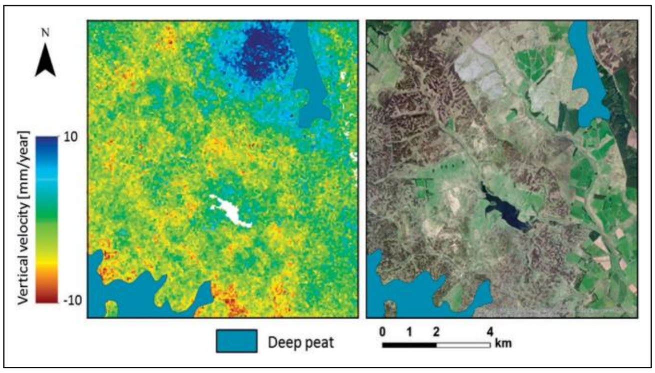

Figure 9. *PEDL Block NT66. Crystal Rig Wind Farm, where soil recovery appears as a large area of uplift (blue). Subsidence related to the condition of deep peat has been masked out.*

Examples of non-energy-related land motion. Deep peat areas appear to be a significant source of land motion, as highlighted in Figure 10. When compared with Figure 5, it is clear that the majority of the land subsidence seen across the PEDL areas is due to peat, when subsiding peatlands are characteristic of drained areas.[27] This also serves to illustrate the capability of the ISBAS technique to monitor peatland surfaces that are a significant source of greenhouse gas when drained.

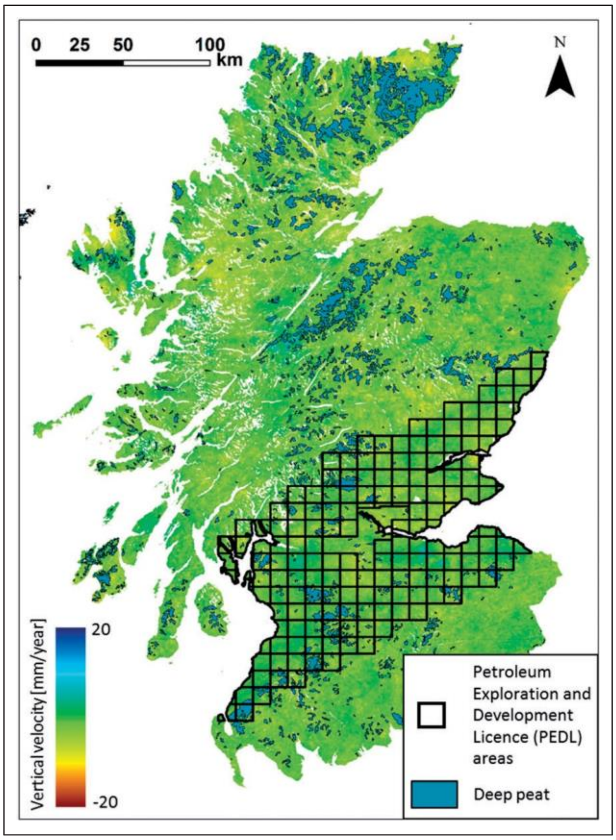

Figure 10. *Relative land motion in the Scottish Midlands overlaid with the 14th Onshore Licensing areas under initial offer and the occurrence of deep peat cover.*

Elsewhere, much of the subsidence may be ascribed to landslides and civil engineering, which includes wind farms. Example of blocks subject to these effects and initially under offer during the 14th Onshore Licensing Round of 2015, are shown in Figures 11 and 12.

Rock falls and landslides may be detected by the ISBAS method[24] and are very common across the highland areas of Scotland. According to the ascending acquisition geometry, the mass movements appear as red areas (subsidence) on the back-slopes (slopes pointing away from the sensor) and blue areas (uplift) on foreslopes (slopes facing the sensor) in the deformation map. An example of an area around Loch Freuchie, Perthshire is shown in Figure 11.

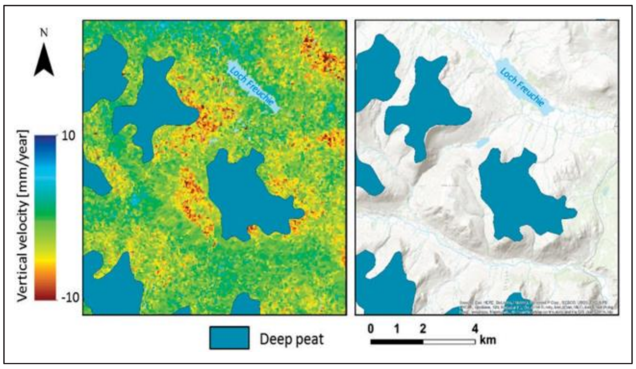

Figure 11. *Offered Block NN83. Landslides and rockfalls, where several observations of motion down a backslope (facing away from the SAR sensor) can be seen as red (subsidence). Subsidence related to the condition of deep peat has been masked out.*

In urban areas there were some specific locations of civil engineering works that appeared as subsidence, most likely due to settlement following construction. An example of settlement at a highway junction is shown in Figure 12.

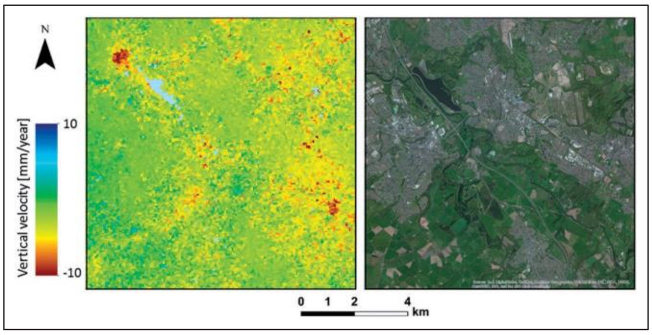

Figure 12. *Offered Block NS75. The M74 Raith Junction Highway Improvement, seen as subsidence (red) in the north-west of this block.*

The need for deformation monitoring. Although no active cases were observed here, oil and gas extraction or storage has the potential to cause subsidence or uplift and, as mentioned previously, therefore requires regulation. What we have indicated here is that land subsidence of one form or another is already a characteristic of many PEDL areas even before operations begin. The consequences of this are that any confusion between pre-existing and new land motion may lead to an oil and gas company being incorrectly blamed for causing subsidence or, in certain circumstances, for causing tremors. For the company, this could be costly in terms of the cessation of operations during investigation or by the installation of further monitoring systems. As noted, there are many other phenomena that cause subsidence or uplift and therefore oil and gas activities cannot be considered in isolation to other factors in the environment.

In order to discriminate the different causes of motion in a PEDL block, a dynamic baseline is required. The specific temporal behavior of each pixel will aid in identifying the response of an under- ground reservoir against pre-existing causes of subsidence. In the UK, the Sentinel-1 repeat cycle is six days, giving plenty of opportunity for a full temporal analysis. Although the ISBAS method is capable of supporting this (Gee et al, 2016)[28], it has not been attempted here as this capability is not yet operational.

Limitations of the technique

The main limitations of the technique relate to resolution, precision and coverage in mountainous areas. The 90 m spatial resolution of the product means that there are likely small-scale deformations that could be easily missed by the deformation map. For example, if there is a very localized collapse in a landscape, such as a sinkhole that only extends over 10 m or so, this is a small fraction of the area of a resolution cell (pixel) and it is unlikely to be detected. Overcoming this would require a greater resolution sensor which would likely be at a premium compared to Sentinel-1 data.

The wavelength of the radar sensor can limit the precision of the measurements, with smaller wavelengths being more suited to the detection of small rates of motion and large wavelengths being more able to detect larger motion.[29] In terms of the observations above, this means that deformation of a rate of more than approximately two centimeters per year is likely to be underestimated. This is illustrated by the results over the surface mining areas in Figure 8, where it is expected that surface erosion is likely to be at rate of many tens of centimeters. Again, this could be overcome by using a sensor with a longer wavelength and also by orders of magnitude improvements to the spatial resolution to assist the phase unwrapping process. Another approach would be to place a very small threshold upon the temporal separation between images pairs such that any changes in phase of more than ±π radians would not occur. This latter solution is limited by the revisit frequency of the satellite and the expected rate of ground motion.

Although the layover and shadow areas have had little impact in the Scottish PEDL blocks, they have severe implications for the monitoring of mountainous areas. Figure 13 shows a mountainous area where much of the land cover falls in a layover or shadow area, for which no measurements of land motion can be made. In such areas, there is very little that can be easily done to overcome this, except the possible integration of a range of surveys that use different imaging geometries (such as ascending and descending orbits, high incidence angles and low incidence angles).

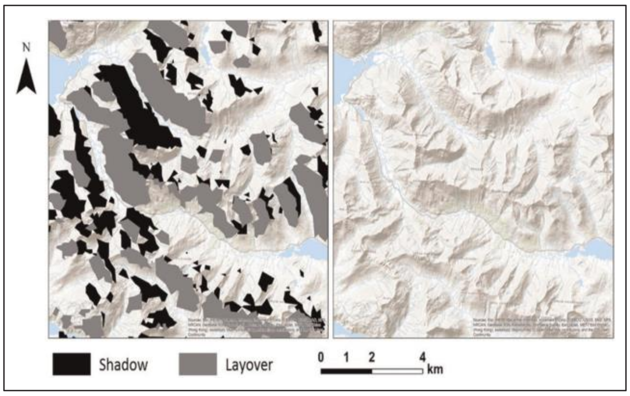

***Figure 13**. An extreme case of mountainous topography with areas masked by layover and shadow.*

Implications for the energy sector

This paper has demonstrated the ubiquitous nature of ground motion across the whole of Scotland, in that there is hardly a single 10 km ×10 km PEDL area that does not contain land motion of some form or another. The vast majority of the deformation is caused by human activity, from active or historical mining and civil engineering, or, as in the case of peat, caused by land management practices. Indeed, it is likely that the land motion observed will change from year-to-year as many of the factors driving the subsidence, such as groundwater levels, are highly dynamic. Deformation maps such as the one presented here will enable regulators and operators alike to more accurately assess the location for any activities and form a framework for their monitoring and adherence to legal requirements regarding environmental protection. For example:

1. Under UK regulations, there are strict requirements regarding the minimization of the environmental impact of exploration and operation. The challenges regard how new deformation will be detected in such a dynamic location as Scotland and ensuring that the activities do not upset the existing causes of land motion. Maps like these will give some clues as to the extent and rate of pre-existing motion but, due to the high dynamics, they will need to be regularly updated if anomalous energy-related activities are to be recognized. They may also be used to help prospect an area for site suitability as a subsidence-prone area may be difficult to operate within, in terms of providing assurance to the regulator that standards are being adhered to.

2. Land motion maps can provide evidence of good practice by the energy industry. For example, we have seen uplift over a wind farm area that is likely related to soil restoration in response to a regulatory requirement, and maps like these could pro- vide further evidence of compliance.

3. Induced seismicity and subsidence are of enormous concern to the general public and often a wind farm or unconventional gas well is not welcomed into an area because of such issues. Even though the new operation is compliant with regulations, it may be blamed and litigated against for motion and tremors that it did not cause, causing costly delays to activities. Land motion maps will certainly help to screen a site beforehand to ascertain if such risks are possible and may help to apportion blame if litigation occurs.

Conclusions

In this paper, we have demonstrated that a mosaicked land motion map of mainland Scotland is possible using C-band Sentinel-1 data. The results reveal that land motion is pervasive throughout mainland Scotland and primarily associated with the condition of peatland. Other observed causes of deformation include landslides, mining and civil engineering activities. The ISBAS algorithm used to generate the tiles for the mosaic is fast and requires very little input in terms of ground knowledge. However, there are some anomalies in the output concerning the phase unwrap- ping process and the density of pixels, but these can be overcome using a more targeted process. We are therefore confident that this algorithm and approach, alongside operational satellite SAR missions like Sentinel-1, are able to support low-cost land motion surveys of entire nations on a regular basis. Furthermore, the addition of a dynamic baseline cap- ability will allow fracking operators, and potentially regulators, to monitor the ground surface effects of their operations as part of mandatory impact assessments and infer whether or not fracking is responsible for localized ground deformations.

The monitoring of ground motion is also import- ant for a wide range of other application areas, too, such as infrastructure monitoring and peatland assessment that would also benefit from regional maps of the surface dynamics for risk assessment and climate change reporting. Maps like this could be therefore be seen as an important national asset to support the design of future policies, the assessment of policy decisions and decision-making across a number of government departments.

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