Institution: University of Leeds

Unit of Assessment: 7 - Earth Systems and Environmental Sciences

Title of case study: Novel solutions for monitoring and responding to hazardous ground movements using Sentinel-1 satellite radar

Period when the underpinning research was undertaken: 2010 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Tim Wright	Professor	01/05/2006 – present
Andy Hooper	Professor	01/05/2013 – present
Marco Bagnardi	Research Fellow	01/06/2014 – 01/04/2018
Pablo Gonzalez-Mendez	Research Fellow	03/03/2014 – 14/06/2016
John Elliott	Royal Soc. Research Fellow	01/05/2016 – present
Susanna Ebmeier	NERC Research Fellow	01/05/2016 – present
Karsten Spaans	Research Fellow	01/09/2016 – 01/04/2018
Milan Lazecky	Research Fellow	01/09/2018 – present
Yasser Maghsoudi	Research Fellow	01/10/2019 – present

Period when the claimed impact occurred: 2014 - 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

Satellite radar interferometry (InSAR) provides a continuous and reliable data source for monitoring land deformation globally. Leeds researchers pioneered the development and application of InSAR, and informed the European Space Agency data acquisition strategy for the c.EUR1 billion Sentinel-1 satellite programme. Leeds researchers routinely provide and analyse ground movement information used by civil protection authorities worldwide, and have informed decisions in three separate continents, during volcanic unrest or immediately following major earthquakes. This has led to integration into new national monitoring systems. These data are being exploited commercially through tools developed by Leeds spinout SatSense Ltd., across sectors including property and infrastructure.

2. Underpinning research (indicative maximum 500 words)

Ground deformation measurements are made using radar satellite data, through application of a technique called radar interferometry (InSAR). Professor Wright is PI (Co-Is Ebmeier, Elliott, Hooper) of the Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET), a NERC Centre of Excellence, which uses satellite measurements alongside ground-based observations and geophysical models to study earthquakes and volcanoes, and to help understand the hazards they pose. Since 2014, the COMET Directorate has been based at Leeds, and in 2018 was awarded the Royal Astronomical Society Group Achievement Award for: *"its consistently high standard of insight into dangerous movements of the Earth's crust [and exploiting] the revolution in satellite geodesy that allows position and changes in position to be measured accurately and frequently."*

Wright built on his research into tectonic processes [1], which showed that InSAR could be used to map tectonic deformation over wide areas, to lead an analysis of the requirements of the seismic hazard community for Earth Observation Data. The European Space Agency (ESA)/EU Copernicus Sentinel-1 mission, which launched in April 2014, was the first operational satellite radar mission designed for global InSAR. Sentinel-1 data are acquired in a new acquisition mode (TOPS) not previously used for InSAR. Through the ESA-commissioned project "Sentinel-1 InSAR Performance Study with TOPS Data", Professors Hooper and Wright were amongst the first users of this new mode and demonstrated, with a study on the Fogo eruption [2], the potential for providing information on volcanic eruptions and earthquakes within a few days of the event.

Responding to the opportunity offered by the Sentinel-1 constellation, Hooper and Wright co-led development of algorithms and systems to rapidly and automatically process Sentinel-1 data on a large scale, to measure deformation occurring in the seismic and volcanic belts globally, and to make the results easily and widely accessible [3]. This was largely funded by NERC large grant "Looking inside the Continents from Space". Hooper also led development of a new approach to time series InSAR analysis to enable efficient semi-operational monitoring of volcanoes with InSAR [4], as part of the EU FP7 Project "Futurevolc". This approach rapidly assimilates new images and has the advantage of extracting measurements from more points on the ground than previous methods, thus widening the utility of InSAR.

To exploit the InSAR measurements of surface motion, Leeds scientists have also developed tools to model processes occurring beneath the surface, as well as bespoke models produced in the context of individual events [5, 6]. Hooper led the development of generic state-of-the-art Bayesian inversion algorithms (GBIS) that allow users to constrain simple models of volcanic and earthquake processes using InSAR data [7]. These tools have been critical in allowing Leeds researchers to quickly analyse deformation observations in response to hazardous events and to provide information on the earth's behaviour to civil protection authorities.

3. References to the research (indicative maximum of six references)

1. Wang, H., Wright, T.J., 2012. Satellite geodetic imaging reveals internal deformation of western Tibet. *Geophysical Research Letters*, 39(7), L07303. https://doi.org/10.1029/2012GL051222
2. González, P.J., Bagnardi, M., Hooper, A.J., Larsen, Y., Marinkovic, P., Samsonov, S.V., Wright, T.J., 2015. The 2014–2015 eruption of Fogo volcano: Geodetic modelling of Sentinel- 1 TOPS interferometry. *Geophysical Research Letters,* 42(21), pp. 9239-9246. https://doi.org/10.1002/2015GL066003
3. Lazecký, M., Spaans, K., González, P.J., Maghsoudi, Y., Morishita, Y., Albino, F., Elliott, J., Greenall, N., Hatton, E., Hooper, A., Juncu, D., McDougall, A., Walters, R.J., Watson, C.S., Weiss, J.R., Wright, T.J., 2020. LiCSAR: An automatic InSAR tool for measuring and monitoring tectonic and volcanic activity. *Remote Sensing*, 12(15), 2430. https://doi.org/10.3390/rs12152430
4. Spaans, K., Hooper, A., 2016. InSAR processing for volcano monitoring and other near-real time applications. *Journal of Geophysical Research: Solid Earth,* 121(4), pp. 2947-2960. https://doi.org/10.1002/2015JB012752
5. Hamling. I.J., Hreinsdottir, S., Clark, K., Elliott, J., Liang, C., Fielding, E., Litchfield, N., Villamor, P., Wallace, L., Wright, T.J., D'Anastasio, E., Bannister, S., Burbidge, D., Denys, P., Gentle, P., Howarth, J., Mueller, C., Palmer, N., Pearson, C., Power, W., Barnes, P., Barrell, D.J.A., Van Dissen, R., Langridge, R., Little, T., Nicol, A., Pettinga, J., Rowland, J., Stirling, M., 2017. Complex multifault rupture during the 2016 M-w 7.8 Kaikōura earthquake, New Zealand. *Science*, 356, 6334. https://doi.org/10.1126/science.aam7194
6. Sigmundsson, F., Hooper, A., Hreinsdóttir, S., Vogfjörd, K.S., Ófeigsson, B.G., Heimisson, E.R., Dumont, S., Parks, M., Spaans, K., Gudmundsson, G.B., Drouin, V., Árnadóttir, T., Jónsdóttir, K., Gudmundsson, M.T., Högnadóttir, T., Fridriksdóttir, H.M., Hensch, M., Einarsson, P., Magnússon, E., Samsonov, S., Brandsdóttir, B., White, R.S., Ágústsdóttir, T., Greenfield, T., Green, R.G., Hjartardóttir, A.R., Pedersen, R., Bennett, R.A., Geirsson, H., La Femina, P.C., Björnsson, H., Pálsson, F., Sturkell, E., Bean, C.J., Möllhoff, M., Braiden, A.K., Eibl, E.P.S., 2015. Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system, Iceland. *Nature,* 517(7533), pp. 191-195. https://doi.org/10.1038/nature14111

7. Bagnardi, M., Hooper, A., 2018. Inversion of surface deformation data for rapid estimates of source parameters and uncertainties: A Bayesian approach. *Geochemistry, Geophysics, Geosystems,* 19(7), pp. 2194-2211. https://doi.org/10.1029/2018GC007585

2018 Royal Astronomical Society Group Achievement Award (https://ras.ac.uk/sites/default/files/images/stories/awards/winners/2018/Group Achievement Award - COMET.pdf)

Research Funding

- NERC Centre for Observation and Monitoring of Earthquakes, Tectonics and Volcanoes (2014-2021), GBP3.3million (GBP1.5million to Leeds).
- NERC Looking Inside the Continents from Space (2014-2020), GBP2.8million (GBP818K to Leeds).
- European Union FutureVolc (2013-2016), EUR6million (EUR248K to Leeds)

4. Details of the impact (indicative maximum 750 words)

Over the last decade, Leeds researchers have helped develop satellite radar interferometry (InSAR) from a niche research tool to a robust and reliable data stream. This has driven multiple benefits.

Informing European Space Agency acquisition strategy

Having demonstrated the potential for mapping tectonic deformation using InSAR [1], Wright coordinated the recommendations of the international scientific community [A], which guided and informed ESA in setting their specific acquisition strategy over tectonic areas for Sentinel-1 in 2014 [B]. The Sentinel-1 Mission Manager (ESA) states*: "Your research demonstrated the potential of InSAR for assisting in all phases of geohazard management… As a result of your work, we were able to define a tectonic zone mask, and made the decision to acquire both ascending and descending data in tectonic areas...your ongoing guidance has helped us plan extra Sentinel-1 acquisitions to support scientists and civil defence organisations worldwide as they respond to major earthquakes and eruptions."* [B])

Exploiting Sentinel-1 in response to volcanic and seismic events

Leeds researchers routinely provide ground movement information (data and models) to civil protection authorities worldwide during volcanic crises and following major earthquake events. Increasingly, these data are being used worldwide for long-term monitoring. For example, our data [C] contribute to international efforts to integrate InSAR into global volcano monitoring (including the Committee on Earth Observation Satellites Volcano Demonstrator, co-led at Leeds). To demonstrate our global reach, we focus on three examples from Iceland, New Zealand and Ecuador.

Iceland suffers from regular volcanic crises, which have the potential to cause major local and international disruption, as was seen in the Ejyafjalljökull eruption of 2010, when the lengthy closure of trans-Atlantic airspace cost the aviation industry alone more than USD1.7billion (IATA, 2010). Leeds researchers have provided rapid analysis of InSAR results (within a few hours of satellite data acquisition) and software tools to inform the national-level responses of the Icelandic Civil Protection and the update of aviation colour codes, during events at Bárðarbunga (2014/15) and the Reykjanes Peninsula (2020) [D, E]. The Nordic Volcanological Center state: *"Results from University of Leeds were regularly presented at meetings of the science committee of the Icelandic Civil Protection, and as such formed the basis for effective societal response to the events"* [D]. Regarding the 2020 activity, the Iceland Meteorological Office state: *"Professor Andrew Hooper assisted by generating preliminary deformation models to determine the likely cause of the unrest, the geometry and location of the intruded magma body and the rate of magma inflow [...which] supported the initial decision to raise the aviation color code at this volcano to yellow on the 26th January 2020"* [E]. They continue, *"The GBIS software* [4] *has* *proved to be a robust and efficient tool for generating rapid volcanic deformation models in near-real time during volcanic crises, which is essential for facilitating informed decisions regarding the potential threat of volcanic hazards"* [E].

In New Zealand, Leeds researchers supported the response to the 2016 Kaikōura Earthquake, the largest in New Zealand since 1855. The response was coordinated by the national team at GNS Science who state *"The rapid response tools developed by your team enabled the delivery of InSAR data products to GNS within just a few hours of the first satellite overpass, which were vital in supporting the response to the earthquake. These data...helped guide our teams in the field and...supported the national civil defence recovery efforts*." [F]. The new understanding of fault processes from the collaborative research "*has strongly informed our approach to revising the New Zealand National Seismic Hazard Model […and] was also used to update the New Zealand National Coordinate System*." In addition, GNS installed the Leeds LiCSAR system [3] in early 2020 with a c.NZD 60,000 investment "to help monitor deformation across the whole of New Zealand." [F].

In Ecuador, the Instituto Geofísico of the Escuela Politécnica Nacional (IGEPN) is responsible for monitoring geophysical hazards and providing up-to-date information to national civil defence. They have worked closely with COMET scientists at the University of Leeds. In March 2017, Leeds provided rapid data processing and modelling during a major volcanic crisis at Cerro Azul in the Galápagos, within 10 hours of the request. IGEPN state "*Deformation measurements and modelling results provided by […] Leeds contributed to our assessment that unrest was not likely to result in an imminent eruption, and was incorporated into our hazard bulletins."* [G]. IGEPN is now using InSAR tools developed in Leeds to monitor volcanoes across Ecuador, which they state: *"...is a significant help to us for monitoring the 20 of our 40 potentially active volcanoes without any ground-based monitoring,"* and *"At the present time (September – December 2020) we are monitoring a developing situation at Sangay volcano in which the rate of vertical uplift in the summit area is increasing week by week […] automatic processing systems such as LICSBAS, developed in Leeds, have helped us to efficiently monitor the ongoing situation."* [G].

Commercial applications of Sentinel-1

The development of large-scale processing algorithms by Leeds researchers, with improved speed of delivery, accuracy and measurement coverage provided the underpinning technology for Leeds spinout company SatSense Ltd. SatSense produces a high-resolution deformation product for the entire UK from Sentinel-1 data, which is updated within a few hours of each satellite overpass [H]. Data are used by commercial clients in sectors including property conveyancing, geotechnical services, energy, and civil engineering.

SatSense started operating in the first quarter of 2018 when they received investment, including GBP500,000 from Unipart Rail and the Northern Powerhouse Investment Fund (administered by Mercia Fund Managers). The company received an additional external investment of GBP500,000 from Mercia/NPIF in Q1 2020. SatSense has created 4 full-time positions, as well as a part-time chair and financial director. Turnover was [text removed for publication] in 2020, and is growing rapidly [I].

The SatSense CEO states: *"The algorithms developed at the University of Leeds have enabled SatSense to build a unique team and product that is highly valued by our customers in several sectors"* [I]. Customers using SatSense data include Groundsure [J], who are the largest provider of property assessment reports to house buyers; in Q4 2020, SatSense data was used in [text removed for publication] [K]. VP Operations for Groundsure states that: *"SatSense data provide incredibly detailed and reliable satellite-derived deformation analysis in our latest, premium subsidence reports. The data give us a cutting edge over our competitors*" [K]. Network Rail, who operate 32,000 km of rail track in the UK, have used SatSense data to investigate ground stability issues that can impact on their network. [text removed for publication]

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. Wright, T.J., Stramondo, S., Amelung, F., Bawden, G., Norbury, D., Parsons, B., Marsh, S., 2012. Seismic Hazards. In: Ph. Bally ed., *Satellite Earth Observation for Geohazard Risk Management - The Santorini Conference - Santorini, Greece, 21–23 May 2012*. ESA Publication STM-282. Chapter 1 (Lead Author Wright) References [1]
B. Letter from Copernicus Sentinel-1 Mission Manager, ESA, stating that Leeds researchers helped set the acquisition plan for global tectonics and volcanoes and influenced satellite tracking for individual event response
C. Website. COMET-LICSAR data portal (https://comet.nerc.ac.uk/comet-lics-portal/) includes an interactive map for users to access Sentinel-1 InSAR products processed using Leeds automatic processing algorithms LiCSAR and LiCSBAS
D. Letter from Nordic Volcanological Centre
E. Letter from Iceland Met Office
F. Letter from Natural Hazards and Risk Research Leader, GNS Science, New Zealand
G. Letter from Instituto Geofísico of the Escuela Politécnica Nacional, Ecuador
H. Website. SatSense website/data portal (https://satshop.satsense.com/) including a demonstrator data set.
I. Letter from Chief Executive Officer, SatSense Ltd
J. Website. Groundsure website (https://www.groundsure.com/georiskbenefits/) detailing that their Georisk product range uses a “high granularity of recorded satellite movement data, provided by SatSense”
K. Letter from Vice President Operations, Groundsure