Satellite Radar Interferometry (InSAR) for asset management of railway infrastructure

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Andy is Professor of Geodesy and Geophysics at the University of Leeds. He pioneered the development of new algorithms to accurately extract deformation of the ground from time series of satellite radar images, which are now widely used in the community (StaMPS). He led significant components of major European projects FUTUREVOLC and EUROVOLC, which established integrated volcanological monitoring procedures in Iceland and Europe. Currently he is leading the European DEEPVOLC project which is applying artificial intelligence to forecast activity at volcanoes. In 2016 he was awarded the James B. Macelwane medal by the American Geophysical Union.

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Amy graduated from the University of Exeter in 2017 with a degree in Engineering Geology and Geotechnics and began working in the mining industry as a geological technician. From there she moved onto Asset Management as a graduate geotechnical engineer within Kier identifying and remediating geotechnical defects for the client, Highways England. Amy pursued a masters degree at Imperial College London in Soil Mechanics before working as an Assistant Engineer on HS2, helping to design earthworks, culverts and analyse the ground movement impacts of these structures on neighbouring utilities.

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Matthew is excited by dynamic businesses making their mark on the industry, and joined the SatSense team after being impressed by the potential of the technology and the strength of the technical team. He's held Technical, Commercial and General Management roles which included spending 10 years helping grow a venture capital-backed Cambridge technology spin-out to become a market leader. He holds a degree in mechanical engineering, a masters in engineering management and a PhD in engineering from Cambridge.

INTRODUCTION

Clever processing of signals from the latest generation of orbiting radar satellites are providing innovative new ground movement data that have the potential to help railway asset managers by reducing monitoring costs and identifying areas at risk of failure.

SatSense are working with Network Rail to understand the potential and limitations of their proprietary "InSAR" algorithms and UK-wide data set for monitoring hazardous ground movements that can impact the rail network. In this article, we explain how the technology works, and discuss the potential applications for asset management of railway infrastructure.

THE CHALLENGE

Maintaining railway assets is expensive, from 2019 to 2024 alone the Department of Transport will spend £34.7bn to fund an overhaul of the network[1]. Network Rail manages over 190,000 earthworks, comprising 100,000 embankments, 70,000 soil cuttings and 20,000 rock cuttings with the majority being constructed pre-1880[1]. The majority of earthworks were constructed during the Victorian era when there were no modern-day soil mechanics and/or design standards, which has often led to over-steepened slopes that were poorly compacted being engineered on over-consolidated, high plasticity clay. Subsequently when large rainfalls occur, or the slopes degrade over time, ground movements can arise, and these movements can have a significant impact on the railways. Between 2006 and 2012 it was calculated that to maintain these assets a budget of £90 million was required[2]. Other impacts of ground movement can include derailment, injury, fatalities, performance delay, damage to assets and reputation.

Depending on the earthwork concerned, the type of ground movements can vary, leading to different impacts on the rail infrastructure. In the case of cutting slopes, shallow translational failures and washouts dominate, while in embankments deep rotational slides occur[1]. In cutting slopes where the slopes face the railway line there is a risk of material encroaching on the railway tracks. These can cause train derailments, lead to performance delays or line closures, and in the worst cases to injuries or fatalities. On the other hand, in embankments the risk of debris encroaching on the track is minimal, but sudden deep-seated failures can offset the track. These can also lead to reduced speed limits, increased journey times, line closures and, in the worst cases, to derailments. In February 2020 a landslip occurred north of East Grinstead[3]. This followed a smaller landslip in December 2019, with the line forced to close from 12 February to 30 March 2020.

SatSense InSAR data shows slow movement of the ground began at least three years prior to failure (figure 1).

As well as earthworks, key railway infrastructure assets include bridges, tunnels, and viaducts. Again, in the UK many of these date from the Victorian era and maintenance is a constant challenge, with Network Rail responsible for monitoring and maintaining around 30,000 bridges, tunnels and viaducts[4]. Many of these structures are only monitored with visual inspection and these can fail without apparent warning. In November 2009, a Victorian railway bridge near Feltham in West London failed when one of the abutments was undermined by scour[5]. Small precursory movements that might indicate the onset of failure due to scour are challenging to pick up with infrequent visual inspections, and, even with satellite overpasses every few days, the time between movement and failure might be too short for the movement to be detected by InSAR. However, the detection by InSAR of subsidence prior to the scour-induced collapse of Tadcaster road bridge[6] shows that InSAR has the potential for flagging subsidence caused by scour, prior to collapse. Nevertheless, InSAR is best suited to cases where slower movement occurs over longer time periods.

InSAR – A SOLUTION?

InSAR is a technology that uses satellite-borne radar instruments to measure how the distance to the ground changes with time (figure 2). These measurements can tell us if the ground is subsiding, or moving laterally, with mm/year accuracy. The measurement quality depends on how strong the reflection from the ground cover is and how consistent the reflecting surface is over time – building details typically provide good measurements while trees do not. Sophisticated algorithms are therefore needed to identify the reliable measurements[7].

InSAR has several advantages over measurements made on the ground: firstly, it is inexpensive, as it does not require “boots on the ground”; secondly, the coverage of measurements is typically much denser than that of ground instrumentation; thirdly, the archive of data being continuously acquired by satellites allows us to make measurements backwards in time to investigate the history of ground movement at a site.

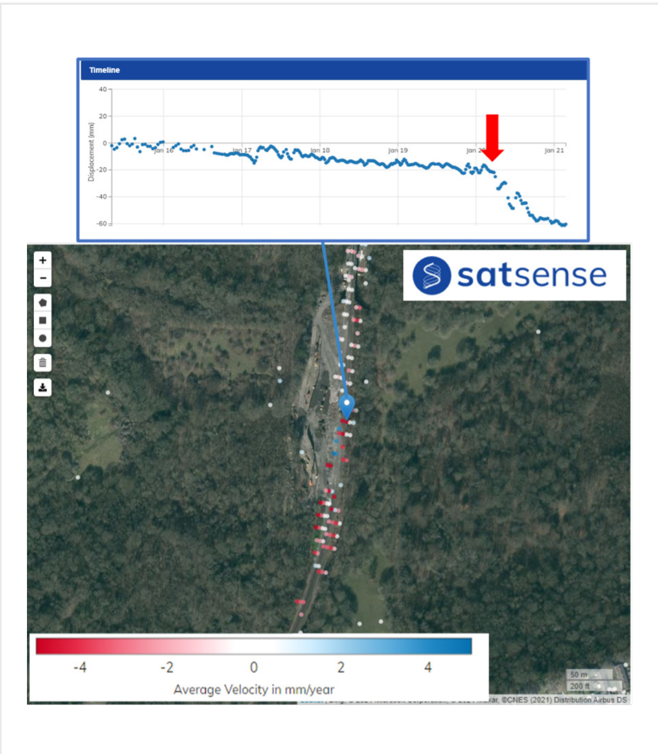

Figure 1: InSAR detection of ground movement at the site of the East Grinsted landslip. The coloured dots show the average velocity, with red meaning movement away from the satellite. The time history of one point is shown, indicating steady movement prior to the large landslip in February 2020 (time marked by red arrow), with larger movements after February 2020 likely associated with remedial work.

Radar satellites have been acquiring ad-hoc measurements since the early 1990s, but the first operational satellite constellation, Sentinel-1, was launched in 2014 and guarantees at least two measurements every six days over the whole of Europe. This freely available data has transformed InSAR into a low-cost, practical tool for routine monitoring of infrastructure[8]. Sentinel-1 data, which provides measurements with medium density (~4 x 14 m spatial resolution), provides the backbone of SatSense products, but when the need arises, we also process commercially available high-resolution data, where spatial resolution is a few meters or higher.

The SatSense solution has three main competitive advantages:

1. It identifies a greater density of point measurements for a given patch of ground;
2. Data is processed for the whole UK continuously, meaning that new measurements are available every few days, and in a timely manner;
3. Outputs are provided more cost-effectively, as the data is pre-processed, without the need for bespoke processing.

As well as the collaboration with Network Rail, SatSense is working with a number of water utilities, through a project sponsored by the European Space Agency, to determine how InSAR can be best used for their asset management. This involves monitoring infrastructure at specific locations and carrying out structured analyses to determine the best way of using InSAR for predictive maintenance around failures, leaks and bursts.

USING INSAR FOR ASSET MANAGEMENT OF RAILWAY INFRASTRUCTURE

InSAR data can be used to address multiple problems that are important for asset management of railway infrastructure, offering a tool that can reduce routine monitoring costs as well as potentially alerting asset managers to unknown ground movements that might impact the railway in the future.

At locations where large-scale movements are constantly monitored, such as the area of the Folkestone Warren landslide[9], InSAR data can be used alongside traditional ground-based monitoring approaches (figure 3). The cost of monitoring unstable ground depends primarily on the number and type of monitoring stations and the frequency of site visits required. The wide spatial coverage offered by InSAR can reduce the number of monitoring stations required and provide reassurance that the full spatial extent of ground movements have been captured by ground surveys.

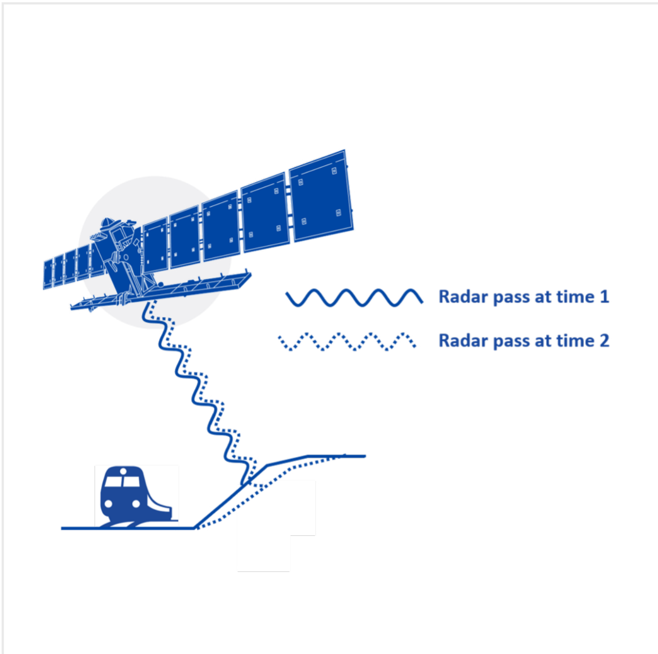

Figure 2: Diagram (not to scale!) showing how InSAR can detect small movements of the ground surface.

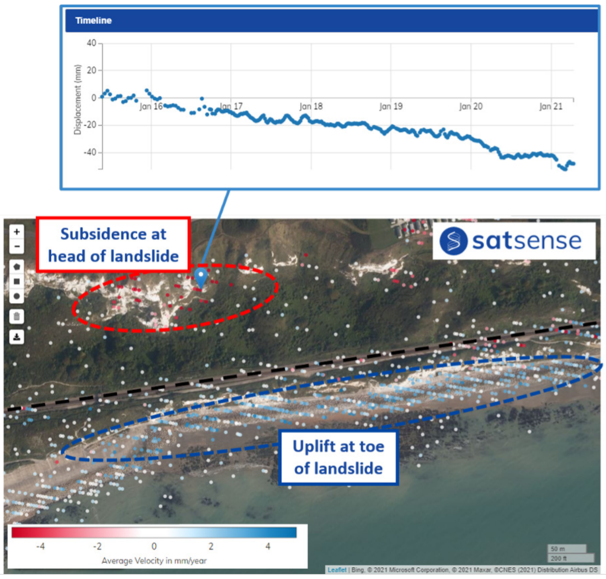

Figure 3: SatSense InSAR data showing continued landslide movement at Folkestone Warren, impacting the South East Main Line (black dashed line). The time history of a selected point shows the movement is not constant in time.

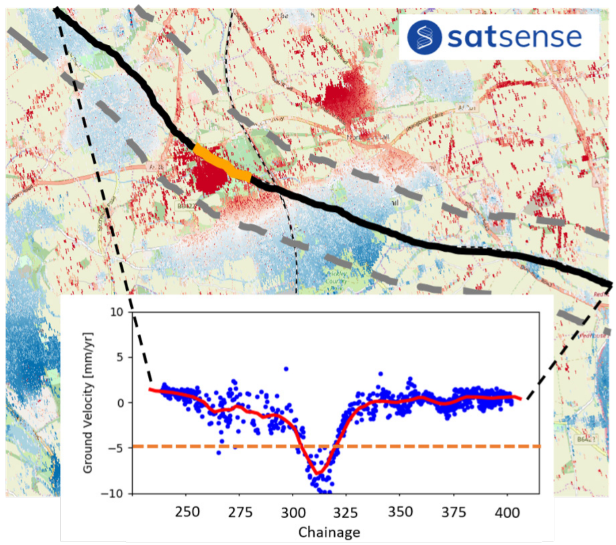

Figure 4: Ground movement due to the legacy of coal mining in South Yorkshire. The highest subsidence rates along the route are flagged.

In addition, the frequent revisit times offered by satellite constellations such as Sentinel-1 can potentially reduce the number of site visits required (most of the UK is imaged 4 times every 6 days by Sentinel-1).

Much of the UK's rail infrastructure, including many bridges and earthworks, is only monitored using periodic visual inspections. Any degradation or movement that occurs between inspections or is small in magnitude might not be picked up. Detecting these movements early can allow remedial work that might prevent future failures. InSAR has the potential for monitoring assets across the entire rail network. Any anomalous ground movement can be flagged, either using simple thresholding algorithms (eg figure 4) or more advanced machine learning approaches[10]. These alerts can be provided to asset managers and be used to trigger or prioritise on-site inspections. Conversely, sites that are shown to be stable using satellite monitoring might require fewer on-site inspections.

A particular issue facing many asset managers is that the rail network can be impacted by processes occurring beyond the boundary fence[1]. Issues can arise due to a variety of processes including the failure of steep-sided natural terrain, instabilities in man-made structures such as mining waste dumps, and construction work (figure 5). The rail network can also be impacted by ground movement associated with legacy mining work, particularly in the UK coalfields where both heave and subsidence can occur, and sudden bursts of movement are possible (figure 4). At present, visual inspection is the only monitoring option for processes beyond the boundary fence. InSAR provides an independent data stream that is capable of monitoring ground movements away from the railway infrastructure that might impact on the safe running of the railway.

At relatively low cost, InSAR data can potentially reduce overall asset monitoring costs for railway infrastructure. Perhaps more valuable, but harder to quantify, is the potential cost savings due prevention of failure – if the data can be used to identify anomalous ground movements prior to failure, with remedial work then able to prevent future unplanned closures or derailments, very large financial and societal costs can be avoided.

LIMITATIONS OF InSAR (AND HOW THEY CAN BE OVERCOME)

To achieve a reliable InSAR measurement, the reflective properties of the ground need to remain approximately constant. Unfortunately, growth of vegetation can lead to changes that cause degradation or even the complete loss of a measurement. InSAR is therefore "opportunistic", in that the choice of where reliable measurements can be made is usually beyond the control of the interested party. However, artificial reflectors can be installed at specific locations, if required. These take the form of either metal corner reflectors, or active transponders, which are smaller but require battery power to function.

Every satellite constellation has a different revisit time, with Sentinel-1 returning at least two times over the whole of Europe every six days. The average return time for commercial satellites is typically longer. This means that if a sudden movement occurs, it may not be measured for a few days. By employing multiple satellites, it is possible to make measurements every day, although the inevitable use of commercial satellites would cause the cost to rise.

Each measurement gives the movement of the ground either towards or away from the satellite. As radar satellites do not point directly downwards, but off to the side, this means the measurements are sensitive to both vertical and horizontal movement. However, as the satellites only travel approximately northwards or southwards, they are only sensitive to horizontal motion in approximately the east-west direction, and any movement in the north-south direction is almost invisible.

Another potential drawback is that measurements depend on the wavelength of the radio waves being transmitted. If the difference between the movement of a point and that of surrounding points is more than a quarter of the wavelength between measurements, then the movement cannot be tracked. For Sentinel-1, this equates to a relative movement of 1.4cm. Total movements greater than this can still be tracked, if there are multiple measurement points in the deforming region, with the difference in movement between each neighbouring measurement being less than 1.4cm.

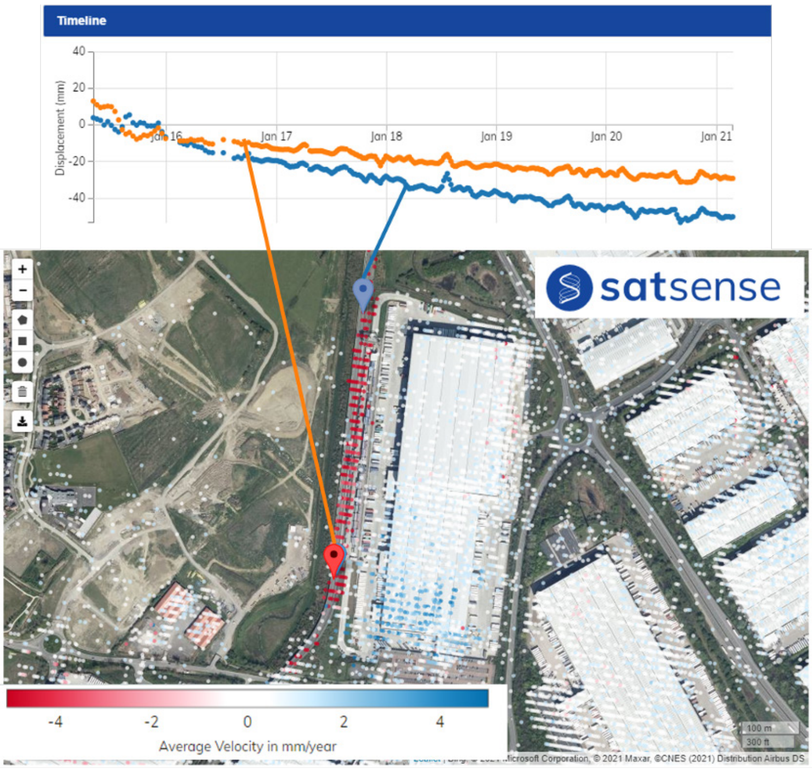

Figure 5: Ground movement due to settlement next to a new distribution centre near Rugby.

There is a maximum density of measurement points that depends on the natural resolution of the radar. For Sentinel-1, this equates to about 4m in one direction (approximately east-west) and 20m in the other (approximately north-south). Commercial satellites typically provide higher resolution, and the minimum spacing between points can be as little as 1m in both directions.

FUTURE WORK PLANNED WITH NETWORK RAIL

SatSense are working with Network Rail over the course of 2021 and 2022 to help better understand the use of InSAR on the UK's rail network. We will be completing a systematic study of locations over the entire rail network where earthworks are positioned, with a wide variety of ground conditions. The level and quality of InSAR coverage from a range of satellite data and processing techniques will be assessed. This will be related to the amount of useful insight that can be gleaned from InSAR at each type of location and asset.

It is planned to undertake a more detailed study of one route. A comprehensive analysis will be performed, comparing data from existing, in-situ monitoring equipment with InSAR data. The degree to which InSAR can replace and/or complement existing monitoring technologies across the rail network will be considered.

A degree of optimisation work will also be undertaken during the project. Metrics that filter noise will be selected for the types of movements of concern, and these metrics will be tested against an independent data set. Artificial reflectors will be installed at locations of interest to Network Rail, with monitoring results being written up and guidance documentation produced.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

It is an exciting time for satellite monitoring of railway infrastructure. The combination of data streams from radar satellites such as Sentinel-1, with new algorithms that are designed to extract the maximum amount of information from the data, mean that we can, for the first time, monitor ground movements across thousands of assets from space, and provide early warnings for failure.

InSAR is not a perfect solution that can replace all existing technologies, but it is a powerful tool that can augment existing techniques, potentially saving monitoring costs and preventing costly and damaging failures.

To view demo data and obtain trial access to SatSense results, asset managers can register at http://satshop.satsense.com

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