Advancing geohazard mapping and monitoring using Terrestrial LiDAR: Insights from the British Geological Survey

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ABSTRACT

Geomatics is defined in the ISO/TC 211 series of standards as the discipline concerned with the collection, distribution, storage, analysis, processing and presentation of geographic data or geographic information. It is the discipline of electronically gathering, storing, processing and delivering spatially related digital information; it continues to be one of the fastest expanding global markets, driven by technology. The British Geological Survey (BGS) geomatics capabilities have been utilised in a variety of scientific studies such as the monitoring of actively growing volcanic lava domes and rapidly retreating glaciers; coastal erosion and platform evolution; inland and coastal landslide modelling; mapping of geological structures and fault boundaries; rock stability and subsidence feature analysis and geo-conservation. In 2000, the BGS became the first organisation outside the Mining Industry to use Terrestrial LiDAR Scanning (TLS) as a tool for measuring change; paired with a Global Navigation Satellite System (GNSS), BGS were able to measure, monitor and model geomorphological features of landslides in the United Kingdom (UK) digitally. Many technologies are used by the BGS to monitor the earth, employed on satellites, aeroplanes, drones and ground-based equipment, in both research and commercial settings to carry out mapping, monitoring and modelling of earth surfaces and processes. Outside BGS, these technologies are used for close-range, high-accuracy applications such as bridge and dam monitoring, crime and accident scene analysis, forest canopy and biomass measurements and military applications. Key methodologies in TLS are discussed under the headings of Mobile Mapping, Monitoring Change, Virtual Outcrop Modelling and Uncrewed Technologies, featuring examples of work for each. This research underscores TLS's transformative potential in geosciences, particularly for advancing disaster resilience, environmental monitoring, and geological conservation efforts. Terrestrial Laser Scanning (TLS) offers high-resolution, three-dimensional data collection capabilities that can significantly enhance our understanding of geological processes and environmental changes.
The aim of this chapter is to review the types of work that the BGS carries out using terrestrial and aerial LiDAR systems, and to discuss the merits therein.
Keywords: [Terrestrial LiDAR; Geohazards; Mapping; Monitoring; Modelling].

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1. INTRODUCTION

Terrestrial LiDAR has often been used to provide detailed characterization of structural diversity at local scales, but it is largely unknown whether these same structural features are detectable using aerial LiDAR data that are available across larger spatial scales [42, 43]. Geomatics is defined in the ISO/TC 211 series of standards [1] as the discipline concerned with the collection, distribution, storage, analysis, processing and presentation of geographic data or geographic information. It is a relatively new term that has been around in the scientific literature for more than thirty years [44]. This broad term applies to both science and technology, and integrates the more specific disciplines and technologies of geodesy, surveying, mapping, positioning, navigation, cartography, remote sensing, photogrammetry and geographic information systems [41]. The discipline of geomatics continues to be one of the fastest expanding global markets [2]. Ground-based geomatics is driven by technology and, at present, there is a huge demand for land, hydrographic, and engineering surveyors who are able to utilise this technology fully. This is due to a high media profile, the changing nature of mapping and spatial data management worldwide, the need for faster and more accurate data gathering, and the growth in European Union and national governments' spatial data agendas and legislation. As the underpinning information provider of the land and property lifecycle, geomatics is of fundamental importance to society [41].

The most common geomatics applications in the British Geological Survey (BGS) use a Terrestrial Light Detection and Ranging (LiDAR) Scanner (TLS) or the Pegasus Backpack Mobile Mapping Solution (MMS) and a Global Navigation Satellite System (GNSS) in order to obtain a terrestrial equivalent of an airborne LiDAR survey and create a 3D model. Combining a terrestrial LiDAR scanner with a high-resolution digital camera and a high-precision differential GNSS enables coloured point-clouds, textured triangulated surfaces, or orthophotos with depth information to be accurately geo-referenced and captured [41]. The relative distance, elevation angle and azimuthal angle between the laser and the subject are measured in each scan and, once processed; a 3D surface model can be generated. From the 3D models created, a variety of products are derived including Digital Surface Models (DSM), Digital Terrain Models (DTM), Virtual Outcrop Models (VOM), Cross-Sections, Area & Volume Calculations, 3D Photo-realistic Video ‘Fly-throughs’, Discontinuity Maps, Stratigraphic Facies Profiles, Attributed 3D Reservoir Models, Fossil Assemblage Maps, Surface Deformation Feature Recognition Layers, Soil Erosion Maps, Cave Surveys and Change Models [41]. TLS allows geological outcrops to be digitally captured with unprecedented resolution and accuracy [3]. Structure from Motion photogrammetry (SfM) has emerged as an alternative viable technology, whether deployed on an Unmanned Aerial Vehicle (UAV) or otherwise. It is lighter, more compact, cheaper to buy and repair and has lower power requirements than TLS. The BGS has six multi-rotor and two fixed-wing small (<20 kg) UAV’s which it uses to collect data for ground surface and geological investigations [41].

The BGS geomatics capabilities have been utilised in a variety of scientific studies [4] such as the monitoring of actively growing volcanic lava domes and

rapidly retreating glaciers; coastal erosion and platform evolution; inland and coastal landslide modelling; mapping of geological structures and fault boundaries; rock stability and subsidence feature analysis; geo-conservation and public understanding of science [5]. These capabilities can be utilised alongside airborne LiDAR and other Remote Sensing techniques in order to provide a range of complimentary applications, or information [6]. It is clear that LiDAR scanning technology is playing an increasingly important role in the acquisition of 3D spatial environmental data worldwide [41]. This technology and its applications are certain to develop further as the rapidity and accuracy of data acquisition, and associated monitoring and modelling capabilities, become more widely recognised. Outside the BGS, ground-based LiDAR systems are used for close-range, high-accuracy applications such as bridge and dam monitoring [7], architectural restoration, crime and accident scene analysis [8], landslide and erosion mapping, forest canopy and biomass measurements [9, 10], mobile mapping systems, adaptive cruise control systems, manufacturing, and military applications [11, 12] [41].

2. GEODECTIC TECHNOLOGY

In 2000, the BGS became the first organisation outside the Mining Industry to use TLS as a tool for measuring change; paired with a GNSS, BGS were able to measure, monitor and model geomorphological features of landslides in the United Kingdom (UK) digitally. Since acquisition of the first TLS, this technology has proved to be essential for the monitoring of geohazards in both the UK and overseas [41]. The authors have ~20 years of experience in engineering surveying techniques, using TLS, GNSS and MMS. They have carried out terrestrial scanning and terrain modelling of inland and coastal landslides, eroding coastlines, actively growing volcanic lava domes, retreating glaciers, rock stability and subsidence features, soil erosion and geo-conservation. Modern Terrestrial LiDAR Scanners have significantly increased the level of resolution and accuracy achievable, and the speed of data acquisition has dramatically increased, from 4 pts/sec in the early days to around 2M pts/sec latterly [41]. A combination of airborne and terrestrial LiDAR can create high-resolution digital terrain models (DTM) and provide realistic 3D models of built-infrastructure with accurate rooftops and realistic building facades. Combining these factors, with the increase in point density and accuracy achievable means that the ability to capture and measure temporal changes in geological features via repeat surveys has revolutionised ground-based geomatics research [13].

UAV's are becoming increasingly common for civilian use, with the Chinese manufacturer DJI dominating the market [41]. They are used in such fields as surveillance [14], filmmaking [15], scientific research, surveying, disaster relief [16], law enforcement, archaeology [17], forestry and agriculture, as well as recreation. The BGS, like many other organisations, are able to utilise the usability and portability of these aircraft to create photogrammetric images and point clouds using SfM techniques, at a fraction of the cost of using a system mounted on an aeroplane [41]. The resultant data, though not as accurate as that obtained from TLS, should still be considered more than adequate for most uses, and gives the ability to create both 2D and 3D full colour models. In general, UAV

results appear to underestimate the volumes of smaller features, most likely due to the reduced line of sight [18].

Radar Interferometry is another technique used in geodesy and remote sensing to generate maps of surface deformation or digital elevation [41]. The technique can potentially measure millimetre-scale changes in deformation over spans of days to years. It has applications for geophysical monitoring of natural hazards, for example earthquakes, volcanoes and landslides, and in structural engineering, in particular monitoring of subsidence and structural stability. It can be deployed in satellites, as Interferometric Synthetic Aperture Radar (InSAR), such as the European Space Agency (ESA) launched Sentinel-1A and Sentinel 1-B, which provide global scale coverage on a 6-day repeat cycle. Alternatively, it can be ground-based, as Terrestrial Radar Interferometry (TRI), used primarily to remotely measure the stability natural and engineered slopes, in near real-time [41]. It can be used for a wide variety of applications, including surface mining operations, quarrying, landslides, rockfalls, glacial retreat, volcano growth and coastal retreat, but at considerable cost.

Mobile mapping is the process of collecting geospatial data from a mobile vehicle or backpack, typically fitted with a range of GNSS, Photographic, Radar or LiDAR systems. These are combined with time synchronised navigation and imaging sensors. This gives the ability to survey an area as fast as you can drive, or walk. Many publications have been written about these techniques and their relative merits and pitfalls. A comparison of the above techniques is given in Table 1, along with some useful references detailing their typical uses [13 & 18 – 28]. The table presents a synopsis of the pros and cons of each of the techniques, the times taken for data collection in the field and data processing back in the office, and some typical costs of both the hardware (purchase or hire) and software (full price and/or yearly licence) that are required [41].

Table 1. Pros and cons of geodetic techniques

System	Terrestrial LiDAR	Airborne LiDAR	Aerial SfM	UAV SfM
Pros	Long range	Very long range	Good accuracy	Good accuracy
	High accuracy, high precision	Downward scanning	Full colour	Full colour
	High speed data acquisition	Cover large areas	2D & 3D models	2D & 3D models
	Built-in camera	Good accuracy	Downward looking	Down & side looking
Cons	Shadow' areas			Pilot required
	Dense vegetation	Very expensive	Dense vegetation	Dense vegetation
	Severe weather	Lower accuracy	Expensive	Severe weather
	Cloud & fog	Downward scanning	Downward looking	Strong wind
Data Collection	Active Sensing	Active Sensing	Passive Sensing	Passive Sensing
	Survey: 1 hour - 5+ days	Survey: 4 hours - 5+ days	Survey: 4 hours - 5+ days	Survey: 1 hour - 5+ days
	Data: 1 day - 5+ days	Data: 1 day - 5+ days	Data: 1 day - 5+ days	Data: 1 day - 5+ days
Typical Cost	Hardware: £130k	Hardware: £20k (rental)	Hardware: £20k (rental)	Hardware: £5k
	Software: ~£2.5k p.a.	Software: ~£10k p.a.	Software: £3500	Software: ~£3k p.a.
Reference	13	20, 21	22, 23	18, 19
System	Terrestrial Radar	Satellite Radar	Backpack MMS	Vehicle MMS
Pros	Extremely long range	Extremely long range	Scan as fast as can walk	Scan at up to 30mph
	Very high accuracy	High accuracy	High accuracy	High accuracy
	Real time, continuous monitoring	Cover large areas	High speed data acquisition	High speed data acquisition
	Works in cloud & fog	Works in any weather	Works inside & outside	Built-in cameras
Cons	Dense vegetation	Dense vegetation		Heavy
	Severe weather	Expensive	Only scan where walk	Only scan where drive
	Strong wind	Downward looking	Point density	Expensive
	Points must be coincident	Points must be coincident	Bad weather	Severe weather
	Heavy			
Data Collection	Active Sensing	Active Sensing	Active Sensing	Active Sensing
	Survey: 1 hour - 5+ days	Survey: Multiple days	Survey: 1 hour - 5+ days	Survey: 1 hour - 5+ days
	Data: 1 day - 5+ days	Data: 1 day - 5+ days	Data: 1 day - 5+ days	Data: 1 day - 5+ days
Typical Cost	Hardware: £140k	Hardware: Free (data)	Hardware: £230k	Hardware: £350k
	Software: ~£2.5k p.a.	Software: ~£10k p.a.	Software: ~£16k p.a.	Software: ~£16k p.a.
Reference	24, 25	26	27	28

Table 1 shows that LiDAR is the best technique to use in order to generate digital models of the earth's surface and accurate topographic maps for planning, construction, engineering design and environmental management. It is also best suited for measuring distances, heights, areas, volumes and quantities. However, it does have its limitations [29]. LiDAR data is not coloured and relies on RGB overlays from photography. The point clouds it generates are often sparse (dependent on point density) compared to photogrammetry, giving a general shape rather than contextual detail. Terrestrial LiDAR can also suffer from gaps (or voids) in the data, primarily where there are shadow areas caused by sight-line issues or inaccessible sections due to adverse terrain.

3. TLS OUTSIDE BGS

In the UK, the Office of Science and Innovation identified LiDAR technology within one of eight key clusters of emerging science and technology with "the potential to...transform the delivery of public services, challenge society and/or affect wealth creation" [41]. Following this LiDAR:net was set-up to bring together a network of interested parties from academia, industry and NERC. Participants include the Universities of Leicester, Salford, Nottingham Aberystwyth, Glamorgan, Loughborough and Durham, Queen's University Belfast, Infotera, 3D Laser Mapping, Halo-Photonics, Willis Research Network, Halcrow Group Ltd., Ordnance Survey and BGS. Deliverables included the running of dedicated

workshops and a scoping report to input into both the technical Earth Observation development and the NERC Technologies programme.
Other major exponents of terrestrial LiDAR scanning in the UK include Geomatics Group (Environment Agency), Merrett Survey Partnership, Digital Surveys, Bluesky International Ltd., Terrain Surveys, Manchester University and University College London [41].
Outside the UK, the USGS employs terrestrial LiDAR technology for a variety of projects including shoreline mapping, digital elevation and terrain mapping, dam monitoring, soil erosion, snow measurement, ground deformation & landslide mapping, flood hazard mapping & levee failure analysis, habitat mapping and volcano monitoring. It has setup the Center for LiDAR Information Coordination and Knowledge (CLICK) in order to facilitate data access, user coordination and education. UNAVCO maintains a pool of TLS instruments and associated peripherals, digital photography equipment, software and ancillary equipment optimised to support earth science investigators [41]. Projects include landside deformation studies in Puerto Rico, wildfire extent surveys in Colorado, volcano conduit process modelling in Utah and biomass measurements in Florida.
European universities with ground-based geomatics departments include Z-GIS at the University of Salzberg (Austria), Delft University of Technology (Netherlands), University of Bergen (Norway) and Institut Cartografic de Catalunya (Spain). Other organisations working in terrestrial LiDAR include Laserdata (Austria), IMAO (France), SPECIM (Finland), IGI TopScan (Germany), Sineco (Italy), Artescan 3D (Portugal), Dielmo 3D (Spain), Galileo Group Inc. (USA) and Fugro [41].
The BGS uses Riegl and Faro terrestrial LiDAR scanners. Besides these the major manufacturers of terrestrial LiDAR systems are Teledyne Optech (Canada), Z+F (Germany), Topcon (Japan), Leica (Switzerland), MDL (UK) and Trimble (USA). The major software companies with programs able to download and process LiDAR data include Virtalis, Golden Software, Maptek, Applied Imagery, Qcoherent, Pointools, Innovmetric, Blue Marble, Erdas and Esri [41]. Open source and free viewers are available to download, including Cloud Compare, Quick Terrain Reader, Fugro Viewer, Mars Viewer, MeshLab and LASTools.
Over the past two years, the use of TLS has increased dramatically:

- In the gaming industry, it is used to quickly and precisely render whole cities, or to recreate an accurate reproduction of a racetrack, including every undulation etc [41].
- The Police can record the scene a car accident within a few minutes, enabling the emergency services to clear the scene, reducing traffic jams as well as preserving the evidence digitally.
- The automotive industry use TLS as a guidance system for autonomous vehicles. Near real-time processing allows the device controlling the vehicle to detect obstacles and to update its route almost instantly [41].
- TLS gives archaeologists the ability to create high-resolution DEMs of archaeological sites that can reveal micro-topography that may otherwise be hidden by vegetation.

- LiDAR is used in a variety of ways in meteorology including the studies of atmospheric composition, structure, clouds, and aerosols.
- In astronomy, a worldwide network of observatories uses LiDAR to measure the distance to reflectors placed on the moon, allowing the moon's position to be measured with mm precision.
- LiDAR allows conservation research scientists to not only measure the height of previously unmapped trees but to determine the biodiversity of the forest [41].

In geology and seismology a combination of aircraft-based LIDAR and GPS have evolved into an important tool for detecting faults and measuring uplift. This combination was used most famously to find the location of the Seattle Fault in Washington, USA. The USGS is using TLS more and more for land surface analysis, including the monitoring of sand dune movement and soil microtopography and erosion.

4. MOBILE MAPPING

In January 2018, the BGS became one of the first companies in the UK to purchase the Leica Pegasus Backpack, a wearable reality-capture sensor platform, combining five cameras with two LiDAR profilers and a triple band GNSS and Inertial Measurement Unit (IMU), weighing less than 13 kg [41]. It is designed to be deployed quickly and easily and can be used for indoor, outdoor or underground surveys, offering speed and portability advantages over existing terrestrial LIDAR systems, which can weigh in excess of 30 kg and are extremely bulky to carry. This enables the BGS to carry out 3D mapping of long coastal (or inland) sections, landslides and other unstable surfaces, ice sheets and glaciers, railway lines, roads and other linear features [41]. The backpack can also be vehicle mounted, for fast mobile mapping, or pole mounted, for lowering into voids or sinkholes.

Mapping underground structures has always proved to be quite difficult and complex, especially related to the issues of positioning and visibility. The Pegasus Backpack allows the user to move from an area of good GNSS coverage to one with limited or even no coverage. The BGS used this system when mapping the show caverns (old mineshafts) associated with the Heights of Abraham Park (Figure 1), with a 3D section of part of a cavern shown in Figure 2 [41]. Use of the Leica SLAM (Simultaneous Localisation and Mapping) technology and the high precision IMU ensured the achievement of accurate positioning, even during GNSS outages, and with the addition of the external light-source, precise scanning of the caverns was possible [41].

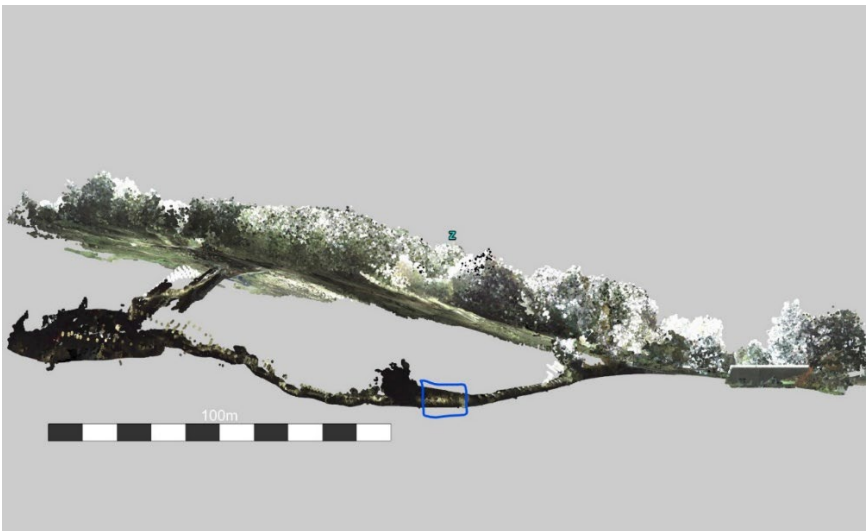

Figure 1. Elevation view of the Masson Cavern at the Heights of Abraham, Derbyshire (BGS, 2018)

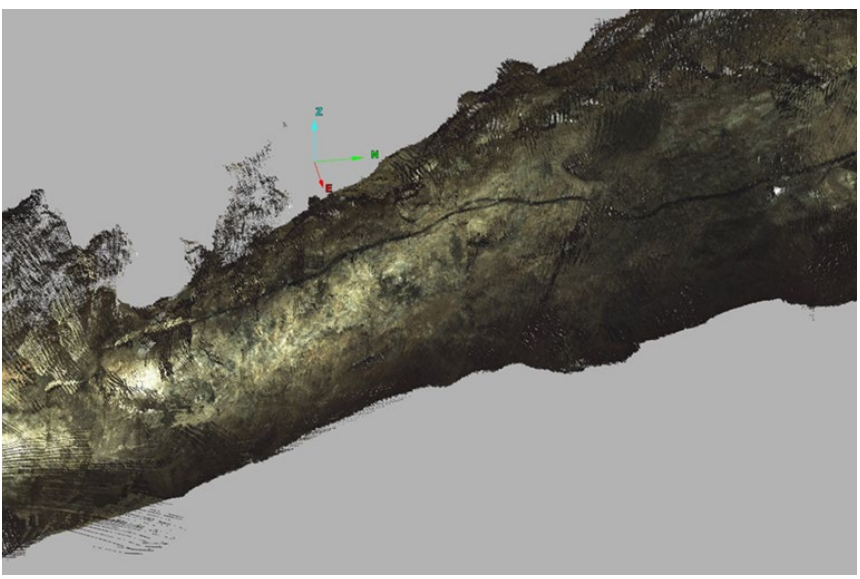

Figure 2. Close-up view of a scanned section of the Heights of Abraham , Derbyshire (BGS, 2018)

The MMS technology has been used by BGS for many current and emerging developments in laser scanning surveys. The Pegasus Backpack has proven invaluable in many projects, some of which are shown in Table 2; where one Pegasus walk can cover the same area as multiple TLS set-ups. The resolution of both surveys will be equivalent, but the point density of the Pegasus will not be as great as that of the TLS survey [41].

Table 2. Pegasus Backpack Surveys

Project	Use	Reason	Figure
Bacton Sandscaping Project	Initial geological modelling	4 km long cliff section	
Hollin Hill Landslide Observatory	Inland landslide monitoring	1 Pegasus walk = 17 TLS setups	
Aldbrough Coastal Observatory	Coastal landslide monitoring	Extend coastal section, beach and foreland	
Incipient Block Failure, Dover	3D survey & change anaylysis	Difficult ground, requiring multiple TLS setups	
Nottingham Castle Pre-design	Internal & external facade scans	Impossible with any other form of laser scanner	3 & 4
BGS Geological Walkway	Incorporation into Minecraft	2 Pegasus walks = 12 TLS setups	
Tenby Beach E-trike Survey	Tidal sand volume calculations	8 km on E-trike only possible with Pegasus	5

Figure 3. Plan view of Nottingham Castle and grounds, Nottingham (BGS, 2018)

Figure 4. Pegasus scan from inside the Long Gallery of Nottingham Castle (BGS, 2018)

Figure 5. Pegasus Backpack mounted on an e-trike at Tenby, Wales (BGS, 2020)

5. MONITORING CHANGE

BGS uses its laser scanning systems to monitor actively eroding sections of coast around the UK. The techniques developed are ideal for this application as TLS is particularly suited to measuring vertical cliff sections [41]. Due to the orientation of these sections, measurements from a plane or satellite may only be able to measure the top edge of the cliff and the platform below, whereas TLS may struggle with data voids on long non-linear sections. These voids are gaps, or holes, in the data usually caused by shadow areas or temporary obstructions. UAV's may offer a compromise solution; they are able to survey both the top and face of the section, albeit at a lower resolution, without any data losses. .
Measuring these features in the field is often very dangerous, due to tidal restrictions and slope access [41]. These techniques enable the measurement of change in the whole cliff section, from a safe distance, and can be used to model how internal processes within the cliff slope affect coastal erosion.
The BGS Coastal Landslide Observatory, at Aldbrough, East Riding of Yorkshire, has been monitored since 2001, using a variety of GNSS, TLS and MMS techniques [30]. The cliff faces northeast, is low (17m) and of regular height. It consists of glacial till and is actively receding, both by toppling and rotational mechanisms (Figure 6) [41]. This work has shown that the cliff is eroding at a rate of up to 3m per year; both landslides and the direct action of the sea crashing against it cause this erosion [31].

Figure 6. Rotational landsliding is the primary mechanism at Aldbrough (BGS, 2017)

Terrestrial LiDAR surveys have been carried out at the Aldbrough site over a 19 year period from 2001 to 2020 (47 surveys in total), centred on the same section of cliff and platform [41]. The scans have varied in the area covered and [this] has necessitated clipping to an arbitrarily defined datum in order for DTM's, change models and volume calculations to be produced from them. Since 2012 the utilisation of the Riegl VZ-1000, with its improved scan range of 1400 m, accuracy of ± 8mm, measurement rate of 62000 points/second and high-resolution digital camera, the quality and resolution of the scans and therefore the surfaces created from them has improved considerably (Figure 7). Added to this is the improvement in the acquisition and pre-processing software (RiSCANPro, Infinity), the post-processing software (I-Site Studio, Cloud Compare) and the visualisation software (QT Modeler, Global Mapper, GeoVisionary) leading to improvements in the ability to visualise and quantify change more accurately and at better scales (Figure 8) [41]. The histogram in Figure 8 shows the colours associated with gain (blue) and loss (red) and also the quantity of each of these values, and where they occur within the model.

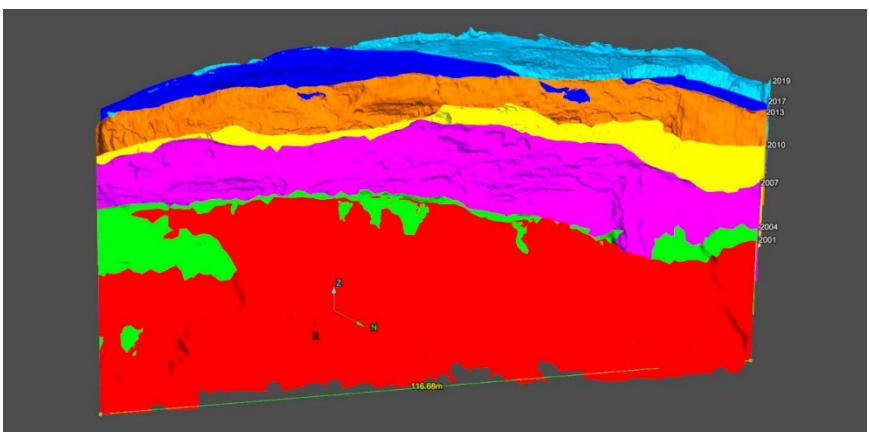

Figure 7. 3D models of the retreating cliff line at Aldbrough, 2001 to 2017 (BGS, 2021 [41])

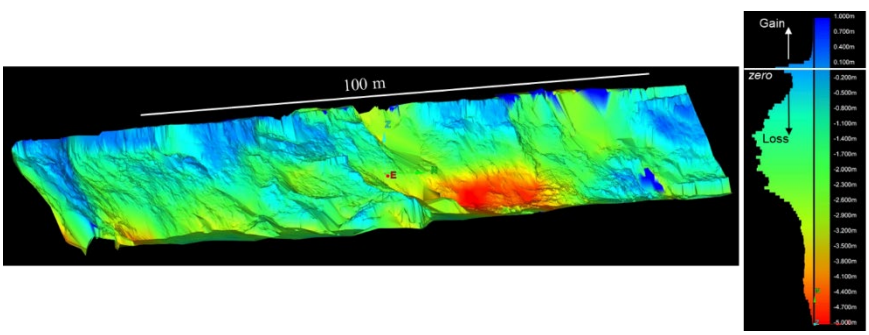

Figure 8. Aldbrough change model, coloured by elevation change, Feb 2016 – Mar 2017 (BGS, 2021[41])

The BGS operate an observatory site at Virkisjökull in southeast Iceland, studying the evolution of the glacier and the surrounding landscape and their responses to regional climate change. Sensors at the site were constantly collecting climate and seismic data, on an hourly basis, over a ten year period, from 2009 to 2018 [41]. Repeated high resolution (25-40 mm accuracy) surveys were carried out annually, over the same time period, and studied how both the glacier and land surface, and the deposits beneath, changed over time. Cutting-edge technologies, not used in such a combination anywhere else in the world, were used to give unique insights into processes of landscape formation and responses of glacial systems to climate forcing. Virkisjökull and its neighbour Falljökull are retreating rapidly, like most glaciers in Iceland [32]. Since 1996, the glacier margin has retreated nearly 500m, and it appears that this rate has accelerated over the last five years (Figure 9) [41].

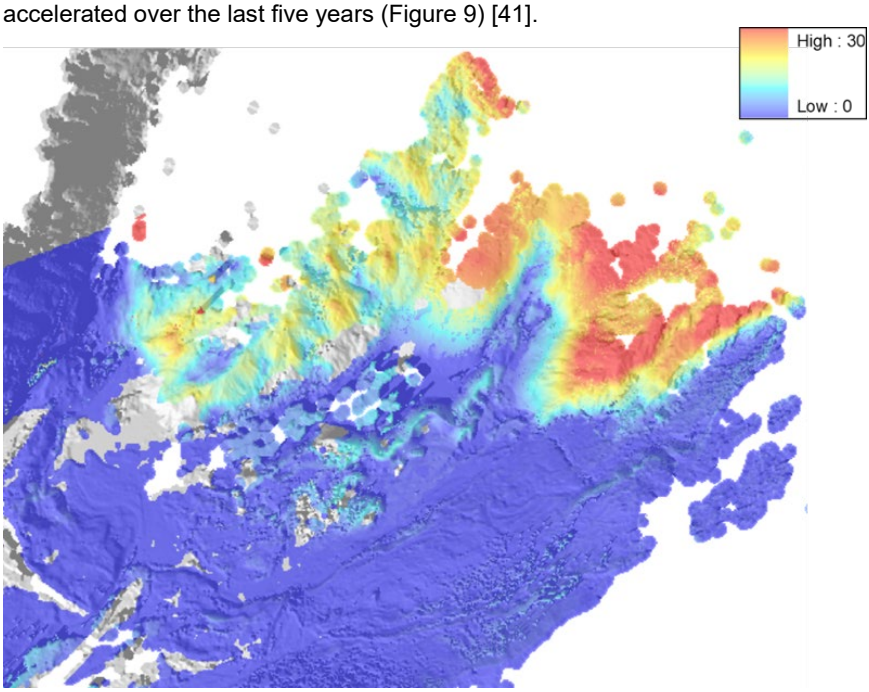

Figure 9. Falljökull glacial margin; change detection model: 2009 to 2012 (BGS, 2021 [41])

By using a combination of repeat TLS surveys, on-ice based GNSS and Ground Penetrating Radar (GPR) the BGS have been able to see the full picture of

glacial retreat for the first time (Figure 10) [41]. This unique approach allowed the TLS surveys to show changes in the glacier, glacial ice margin and glacial foreland, whilst the GNSS stations indicated the speed and direction of glacial flow. This work has shown that the margin of the Falljökull glacier has ceased moving and is now undergoing stagnation [33]. However, field and photographic evidence shows that the icefall remains active, feeding ice from the accumulation zone on Öraefajökull to the lower reaches of the glacier. To accommodate this continued forward motion, the upper section of the glacier below the icefall is undergoing intense deformation (folding and thrusting) and, as a result, is being thrust over the lower, immobile section of Falljökull [34]. This type of behaviour has never been described before and could have implications for how other steep, mountain glaciers around the world are responding to changes in the climate [35] [41]. Because of this Falljökull glacier has been called the 'zombie' glacier [36].

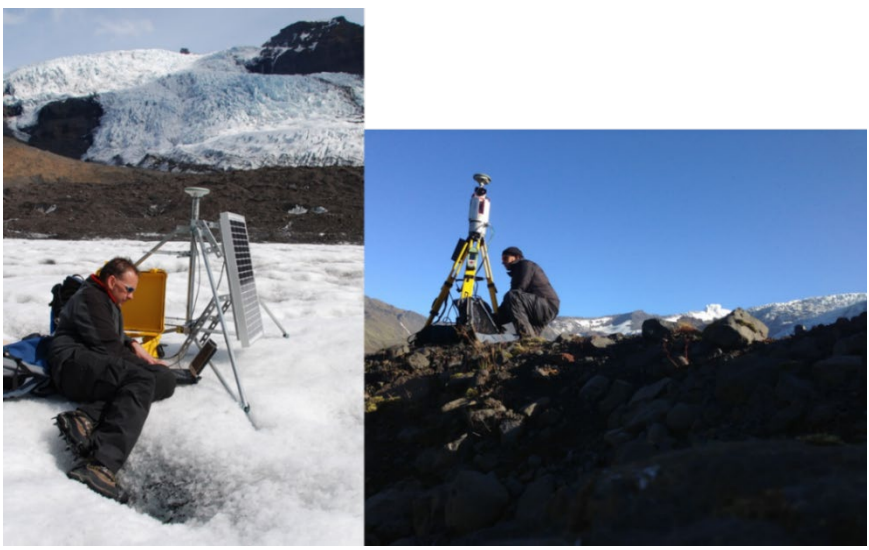

Figure 10. Data download of on-ice GNSS unit. Terrestrial LiDAR Scanning of glacial foreland, Falljökull Glacier, Iceland (BGS, 2014)

There can be few more hazardous situations than that of monitoring a volcanic andesite lava dome for signs of an impending collapse. Partial collapse of a lava dome generates hot, fast-moving pyroclastic density currents [41]. Monitoring in such circumstances requires that measurements be taken from a distance that minimises the threat from eruption and from asphyxiation by volcanic gases. The method also needs to be rapid to minimise the time spent by the monitoring team in the hazardous zone [37]. We have used TLS techniques to monitor the growth of the lava dome of the Soufrière Hills Volcano, on the Caribbean island of Montserrat (Figure 11). In May 2006, our measurements helped to identify the

changes in lava dome growth rate that directly preceded a total lava dome collapse [38]. The technique utilises multiple passes of the scanner, as the presence of volcanic gas and ash (from occasional rock falls) clouds can lead to a reduction of 10-20% in the number of scan points returned [41]. Multiple passes increase the chance of 'seeing' the dome through these drifting clouds.

Figure 11. Scanning the active lava dome of the Soufrière Hills Volcano, Montserrat (BGS, 2014)

6. VIRTUAL OUTCROP MODELLING

A Virtual Outcrop Model (VOM) is a digital 3D representation of the outcrop surface, mostly in the form of a photorealistic textured polygon mesh or a point cloud with associated RGB data.
The BGS has operated a landslide field observatory site at Hollin Hill, in North Yorkshire, since 2004 (Figure 12) [41]. It brings together a combination of field surveying, geomorphological, geophysical, engineering and hydrogeological expertise at BGS. The landslide is several hundred metres wide and extends

some 200 m down slope. It is located on the south facing side of a degraded Devensian ice-margin drainage channel; the slope has an angle of approximately 12° [41].

Figure 12. Aerial photograph of the Hollin Hill landslide (BGS, 2011)

The 'complex' landslide is largely caused by the movement of the Whitby Mudstone Formation, which is highly prone to landsliding [41]. The landslide is characterised by shallow rotational failures at the top of the slope in the Whitby Mudstone, which move through an area of translational landslide movement and "cascade" over the *in situ* Staithes Sandstone Formation feeding into four larger-scale slow-moving (i.e. tens of centimetres per year) lobes of slumped material at the bottom of the slope [39]. Relatively little is known about the hydrogeology of the site. However, a spring line extends across the base of the slope where the Staithes Sandstone overlies the underlying Redcar Mudstone Formation (Figure 13). Figure 14 shows a stylised model (not to scale) of the solid geology and slip surface of the landslide [41].

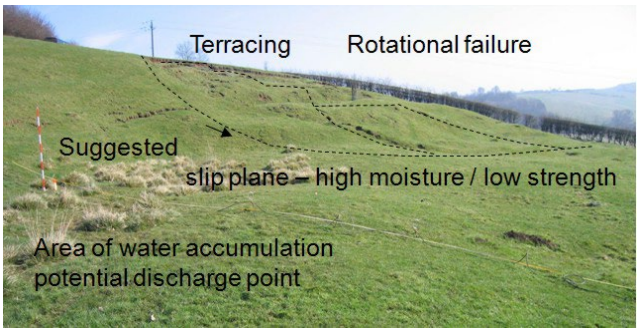

Figure 13. Annotated photograph of the Hollin Hill landslide (BGS, 2011 [39])

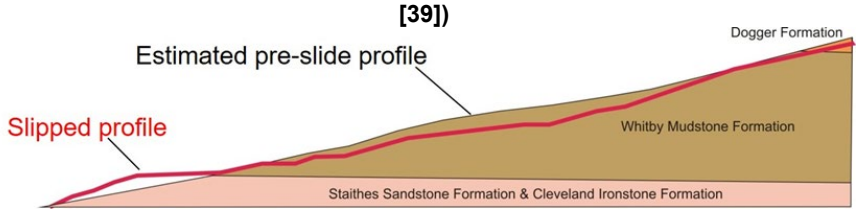

Figure 14. Solid Geology model of the Hollin Hill landslide – not to scale (BGS, 2011 [39])

Both aerial and terrestrial LiDAR surveys have been carried out at this site [40]. These have provided geologists at BGS with the opportunity to study the different technologies for monitoring an active slow-moving landslide site in the UK. The initial method of survey is long-range laser scanning. The first (baseline) survey records the ground surface of the landslide and surrounding area in three-dimensions (Figure 15) [41]. Subsequent surveys of this active landslide record the movement of the slope. Surveys are carried out at six-monthly intervals, the data collected in the field by LiDAR, and GPS are entered into computer-modelling packages. The results are processed to provide data to model the way in which the landslide is moving. Information obtained by the Terrestrial LiDAR survey will allow us to monitor the changing shape of the surface and create change models between visits (Figure 16) [41].

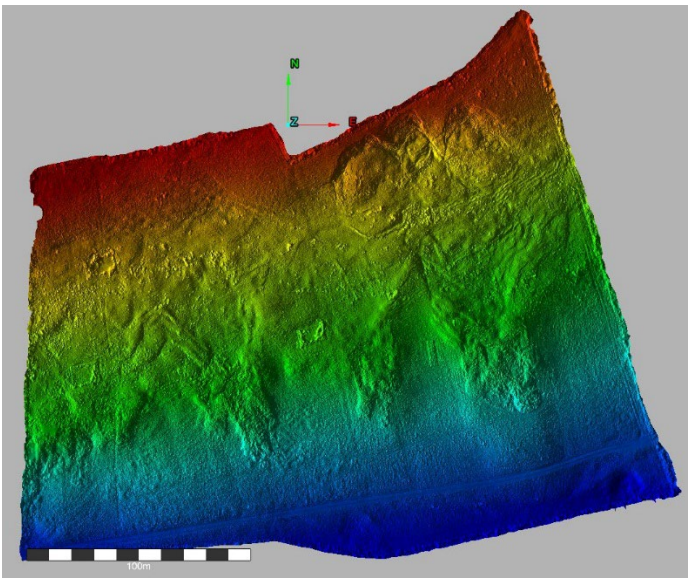

Figure 15. Elevation model of initial TLS survey of the Hollin Hill landslide (BGS, 2021)

Since 2018, the landslide has been monitored using the Leica Pegasus backpack mobile mapping solution, enabling digital terrain and surface models (DTM, DSM) to be created in a shorter time, and changes to be assessed (Figure 17) [41]. The use of MMS on this slope means that the shadow areas that are potentially present when using TLS are eliminated [41]. However, the point density, and therefore the overall resolution, is lower and issues do arise where the vegetation becomes dense.

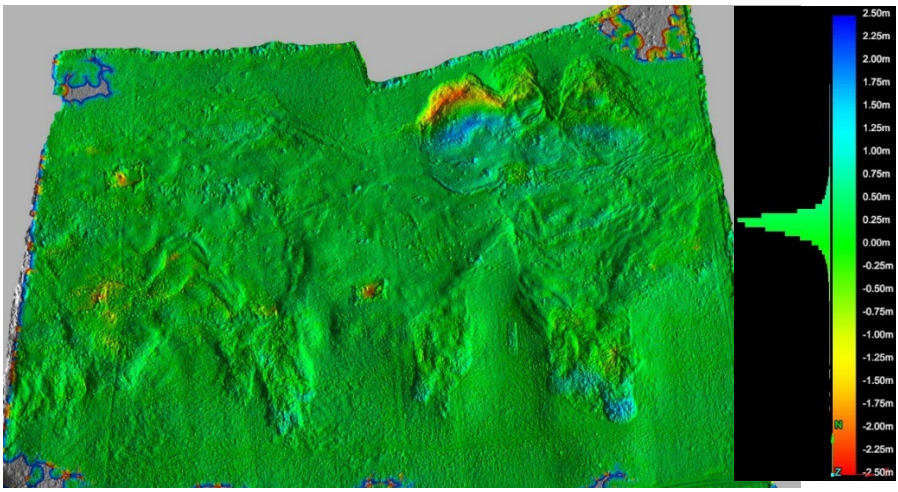

Figure 16. Hollin Hill landslide Change model (2008 – 2018). Red -2.5m, Blue +2.5m (BGS, 2021)

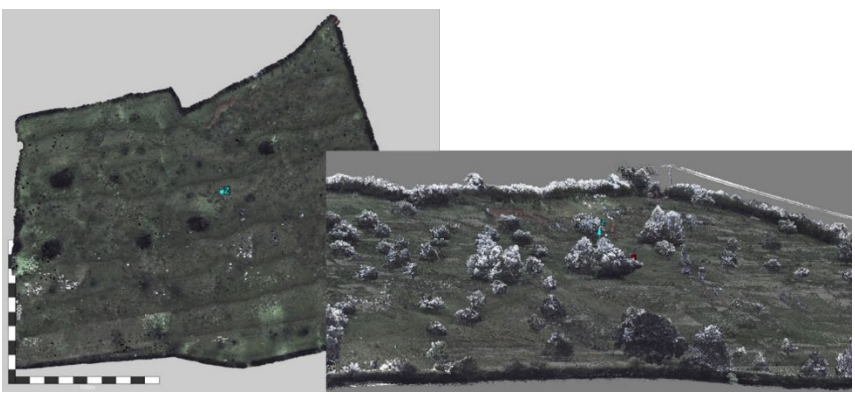

Figure 17. Digital terrain (DTM) and surface (DSM) models of the Hollin Hill landslide (BGS, 2021)

The Seven Sisters, in East Sussex, is a 4 km long and approximately 75 m high series of eight cliffs between Seaford and Eastbourne (Figure 18) [41]. As part of a larger BGS research project into the distribution of flint beds and their relative positions across the Chalk, TLS was carried out along the full length of the Seven Sisters site. TLS provided the optimum solution to the problem of measuring the extent and distance between the Flint bands in such a large cliff, which cannot be reached directly. Due to the tidal range, and the need to work at a safe distance from the cliffs, the Riegl VZ-1000 TLS was used to carry out the survey [41]. The work took 3 days to carry out and was able to provide geologists with extremely

detailed (25 mm accuracy) scans of the full section, in both true RGB colour and intensity (Figure 19), the latter of which provides a more noticeable way to view the much darker flint beds and therefore map them more easily [41].

Figure 18. Seven Sisters cliff, East Sussex – 4 km long x 75 m high (BGS, 2018)

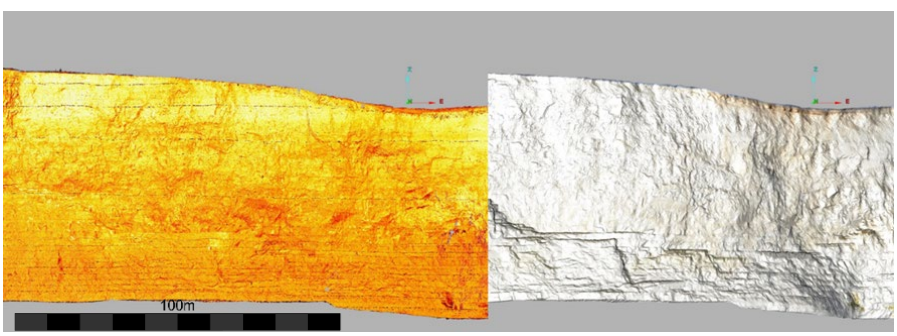

Figure 19. Intensity and RGB colour scans of a section of the Seven Sisters cliff (BGS, 2018)

The main objectives of the BGS Permian Sandstone study, in the Eden Valley, are to undertake discontinuity analysis using LiDAR scans and to provide high-quality 3D images for further stratigraphical study (particularly where outcrops are inaccessible) [41]. The study also links with the Permo-Trias Cross-Cutting Project, to provide detailed geological information to assess the suitability of Permian and Triassic strata for carbon sequestration and to create 3d property models for flow modelling of CO_2. Locations of potentially suitable sandstone outcrops were identified by interrogating several BGS data sets, and following

consultation with hydrogeological and mineralogical colleagues six outcrops were scanned in the Eden Valley [41].
The RGB coloured LiDAR scans were used in order to create DTM's and virtual outcrop models (VOM's) of the outcrops (Figure 20). In turn, these models were used to create 3D S-Grid facies models (in SKUA-GOCAD) to be used for CO_2 flow modelling, as part of research into carbon capture and storage in sandstone reservoirs (Figure 21) [41]. These models provide important sub-seismic scale information about geological heterogeneity for flow simulations.

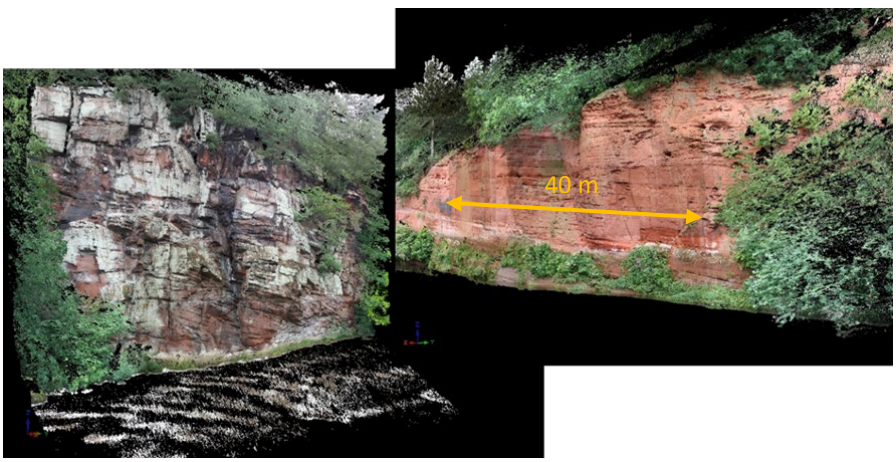

Figure 20. Virtual Outcrop Models of Eden Valley outcrop (BGS, 2010)

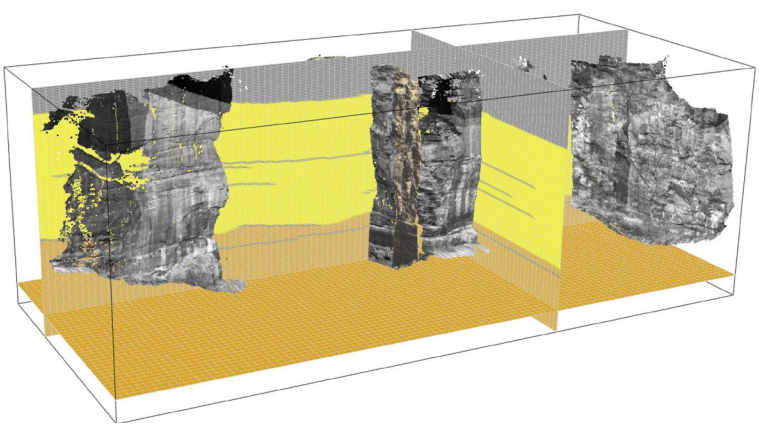

Figure 21. 3D attributed S-Grid generated from VOM (BGS, 2010)

7. UNCREWED TECHOLOGY

The British Geological Survey (BGS) uses Unmanned Aerial Systems (UAS), or drones, primarily to collect data for ground surface and geological investigations, mapping, and surveying [41]. Drones are a fantastic platform for rapidly capturing data which can be used to understand and monitor geological processes. The most common deliverables created from the data collected by UAS include Digital Terrain Model (DTM & Digital Surface Model (DSM) generation using Structure-from-Motion (SfM) or Light Detection and Ranging (LIDAR) technologies. RGB photos & videos, 3D maps, orthomosaics, 2D & 3D meshes & point clouds, and actionable reports. Some of these are shown below. BGS undertake UAS operations under the Civil Aviation Authority approval given in the Uncrewed Aircraft - Operational Authorisation granted by Civil Aviation Authority Permission for Commercial Operations (PfCO) Operator registration number: GBR-OP-NX2PQN84K2VB, CAA reference UAS 2700. All BGS pilots are registered, have a General Visual Line of Sight Certificate (GVC) and are fully insured to fly in accordance with the BGS Flight Operations Manual.
BGS own and operate a suite of sub-25kg rotary UAS for aerial data collection associated with filming, aerial photography, multispectral imaging, thermal imaging, LiDAR and/or gas detecting conducted in surveying, monitoring and/or mapping modes flown under VLOS (Visual Line of Sight) permissible limits for operation. BGS conduct research using:

- DJI Matrice 210-RTK: Red Green Blue (RGB, Zenmuse X5) and Thermal Infrared (TIR, FLIR XT2)
- DJI Inspire-1 RAW: RGB (Zenmuse X5S) and TIR (FLIR XT)
- DJI Inspire-2: RGB (Zenmuse X5), TIR (FLIR XT2) and Rededge Multispectral (Micasense)
- DJI Matrice 300-RTK: RGB (Zenmuse X5), TIR (FLIR XT2) and Light Detection and Ranging (LiDAR, Zenmuse L1) and Carbon Dioxide and Methane gas detection (GasFinder2)
- DJI Phantom-3 Professional: RGB
- DJI Mavic Air (x2): RGB
- DJI Mini 3 Pro: RGB
- DJI Mavic 3: RGB

UAS technology has been used by BGS for many current and emerging developments in laser scanning, photogrammetric, thermal and gas detection surveys. The Matrice UAS have proven invaluable in many projects, some of which are shown in Table 3; where a UAS LiDAR flight can cover the same area as a large Pegasus walk or multiple TLS set-ups, in a much shorter time. The resolution and accuracy of these surveys is similar, although the point density of a TLS survey would be greater.

Table 3. UAS Surveys

Project	Type of Flight	Use	Figure
Kilbourne Hole Volcano	LiDAR & Photogrammetric	3D Model	22 & 23

Croft Quarry	LiDAR	3D Geological Model	24 & 25
Selwick Bay	LiDAR & Photogrammetric	3D Map	26 & 27
Slaithwaite Reservoir	LiDAR	DEM	28 &29
Los Humeros Cladera	Thermal & Photogrammetric	Thermal DEM	30 & 31
Gresham Marshes	LiDAR & Photogrammetric	3D Model	32 & 33

Kilbourne Hole Volcano (KBH) is a maar volcanic crater that is between 24,000 and 100,000 years old and forms part of the Potrillo volcanic field, in New Mexico (Figure 22). This area is part of the Rio Grande Rift, where rising magma interacts with groundwater saturated sediments. The elliptical crater is approximately 3.2 km long x 2.2km wide. BGS were invited by NASA Goddard Instrument flight team to join their field excursion to KBH. The core objectives of this trip were:

- To learn more about the history of phreatomagmatic eruptions at KBH maar volcano.
- To compare terrestrial and aerial LiDAR measurements of surge-bed cross-bedding foresets from within the tuff rings (Figure 23).
- To contribute to the RISE EVA exercises.

Figure 22. Kilbourne Hole volcanic crater (BGS, 2021)

UAS flights were defined in DJI Pilot as pre-programmed surveys. Altitude was set at c.50m, with sensor view angles set at NADIR to collect both RGB and LiDAR surveys with flight paths set to enable front-back and side-side overlap. Output pixel resolution of <1.5 cm. OBLIQUE surveys were flown free hand, capturing multiple RGB images that overlapped, to allow for photogrammetry of the crater walls. Output pixel resolution was <1cm. Flights took approximately 40 minutes each to perform, and there were eight in total.

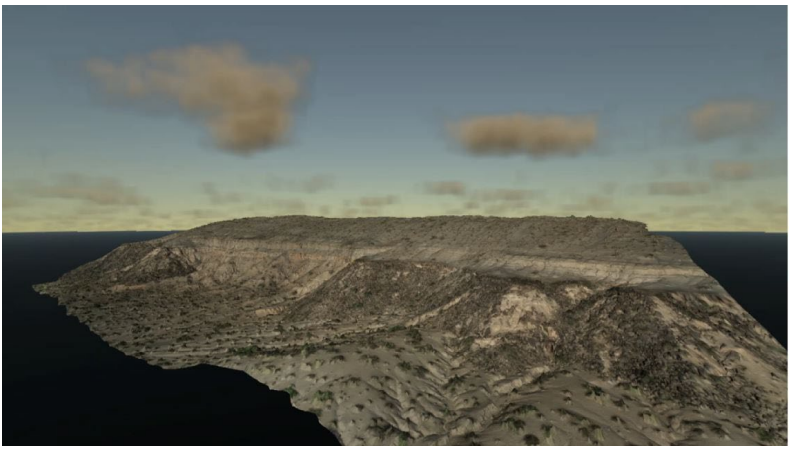

Figure 23. Photogrammetry results from the SE rim of Kilbourne Hole (BGS, 2021)

Croft Quarry SSSI forms part of a group of igneous rock bodies that are exposed at, or near surface, often as upstanding hills in south Leicestershire, known as the South Leicestershire Diorite Suite. Protruding above, and surrounded by, the red Triassic strata, the quartz-diorite and tonalite rocks at Croft have been exploited since Roman times; the current quarry has a depth of -136 m OD, representing one of the deepest quarries in Europe (Figure 24).

Figure 24. Aerial view of Croft Quarry, Leics (BGS, 2022)

The quarry was surveyed using both Terrestrial LiDAR Scanning (TLS) and UAS, from 9 TLS positions including the upper quarry edge and from within the quarry (10 scans in total). UAS flights were defined in Pilot, and manually, as a nadir and at 45° and 90° using the Zenmuse L1 to perform LiDAR and matching RGB imagery. The nadir altitude was set at 50 m to provide a point cloud density of 283 points/m2 and a photo output pixel resolution of ~1.5 cm, with a side overlap of 70%, the scanning mode set to repetitive, a flight speed of 10 m/s, the number of returns set to three, and calibration enabled. The UAS was flown from 5 positions, both on the upper edge and from within the quarry (10 flights in total, 162 minutes flight time); the data was used to create both a 2D and 3D ortho-rectified photogrammetric image (Figure 25a) and a 3D RGB coloured point cloud (Figure 25b).

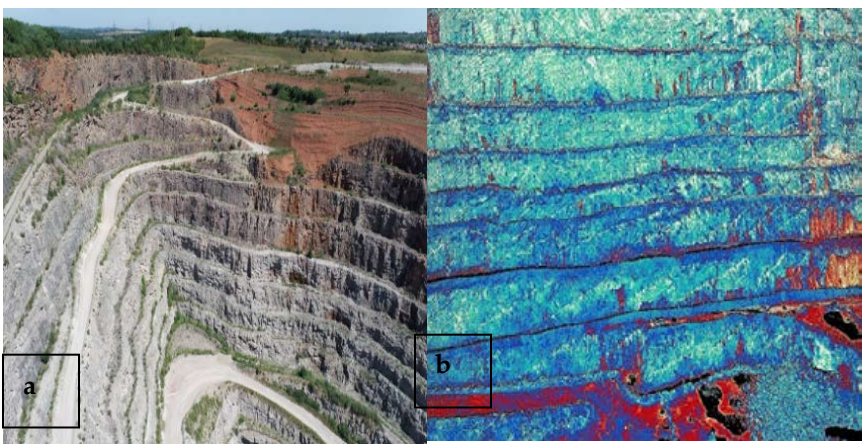

Figure 25. UAS Image looking ENE showing buried topography (a). TLS image enhanced with multi-spectral filters looking East (b) (BGS, 2022)

Selwicks Bay at Flamborough Head on the East Yorkshire coast of England has a well exposed Chalk wave cut platform. Behind the gravel beach are chalk cliffs (Figure 26).

Figure 26. Aerial view of Selwick Bay, Yorkshire. Looking North (BGS, 2022)
Mapping the three-dimensional orientation of geological structures. The structures (faults) are well exposed in the wave cut platform and also the cliff at the back of the beach. Having exposures in two planes (horizontal platform and vertical cliff) allows for the full orientation of the structures to be mapped. The objective was to assess the integration of nadir photography and vertical (cliff) photography into a single model using geolocation through RTK enabled UAS (Figure 27).
The DJI M300 was used due to the high quality RGB imagery acquired by the L1 sensor and the RTK GNSS positioning meaning that no external ground control data was required.
The M300 UAS was carried down to the beach at approximately 4pm, once the beach was empty of the public. Take off was completed from the shingle beach. A nadir survey of the bay was programmed in DJI pilot software with a 50m elevation and 70% forward and 50% side overlap. This survey was flown, once completed the pilot took manual control of the M300 and the camera adjusted to be side looking.
The pilot then flew the UAS at approximately 10m elevation and 30m distance from the cliffs. RGB imagery were manually acquired, the UAS was flown slowly, and frequency of photography was such to ensure sufficient overlap. This required the pilot to keep a careful eye on both the controller screen and UAS, it was therefore essential to have a spotter to ensure safety.

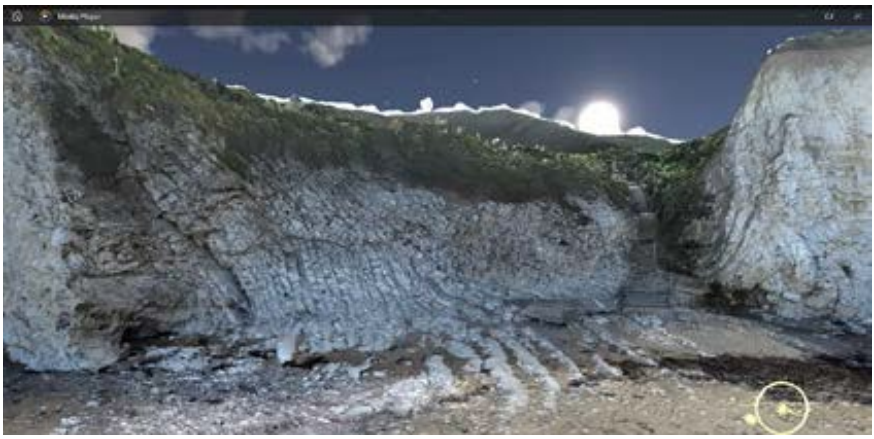

Figure 27. 3D model showing structure in the cliff face at Selwick Bay, Yorkshire (BGS, 2022)

Slaithwaite Reservoir (Figure 28) was constructed in 1797 to supply the Huddersfield Canal and impounds the waters of Merry Dale Clough, a tributary of the River Colne. The reservoir has a surface area of 46,000 m2 and an estimated volume of 175,000 m3. The dam is oriented roughly north south and is built at the east end of the reservoir. It is a 17 m high earth fill dam with a reported puddle clay core. The Canal and River Trust had commissioned SOCOTEC Monitoring LTD to implement geophysical monitoring in collaboration with the BGS to investigate suspected leakage issues of the core, embankment dam, and tunnel using a combination of geophysical monitoring, terrestrial LiDAR, and UAV surveys.

Figure 28. Aerial view of Slaithwaite Reservoir, Yorkshire. Looking North (BGS, 2021)

UAS flights were defined in Pix4D as pre-programmed single-grid surveys. The RGB survey was performed with sensor view angle set at NADIR and flight paths set to enable front-back and side-side overlap of 70 %. Altitude was set at 50 m to provide output pixel resolution of <1.5 cm. Imagery was recorded in JPG format with ground control targets set out across the study site providing accurate geo-positioning using Network RTK GNSS. Flights took approximately 20 minutes each to perform, and there were four in total. Terrestrial LiDAR surveys and geophysical surveys were also carried out during this time to help produce a Digital Elevation Model (DEM) of the site (Figure 29).

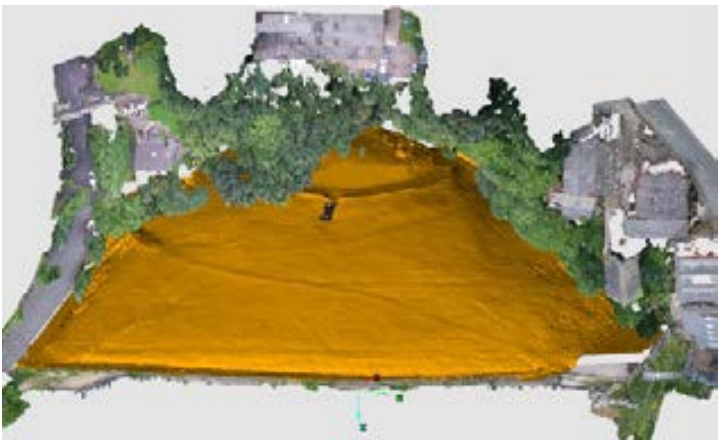

Figure 29. DEM of Slaithwaite Dam and Tunnel (BGS, 2021)

Los Humeros is a 5-8km wide oval caldera situated 200km East of Mexico City (Mexico) at an elevation of approx. 2800±50m (Figure 30). The caldera is bounded by rim faults with steep cliffs and has an active geothermal system that is exploited for energy production. The topography within the caldera is gently sloping, with in-caldera fault escarpments evident in the central and southern areas. The caldera contains evidence of mineral alteration, high temperature anomalies and fault structures indicative of an active geothermal system. Assessing the relationship between thermal UAS data and tectonic structures, surface geothermal manifestations and soil gas monitoring to better understand the tectonic, sedimentary and geochronological evolution of a geothermal system at Los Humeros caldera, Mexico, where geothermal features occur both with and without surface expression.

Figure 30. Los Humeros caldera, Mexico (BGS, 2018)

UAS flights were defined in Pix4D as pre-programmed single-grid surveys. Both RGB and thermal surveys were performed with sensor view angle set at NADIR and flight paths set to enable front-back and side-side overlap of 70% for RGB and 90% for LWIR Thermal. Altitude was set at 80m to provide output pixel resolution of 2cm (RGB) and 15cm (LWIR Thermal). Imagery was recorded in JPG (RGB) and RJPG (LWIR Thermal) formats with ground control targets set out across the study site providing both accurate geopositioning using GPS and temperature calibration using FLIR T650sc. Flights were repeated pre-dawn and post solar heating maximum to enable assessment of temperature amplitude indicative of volumetric variation in ground surface (Figure 31).

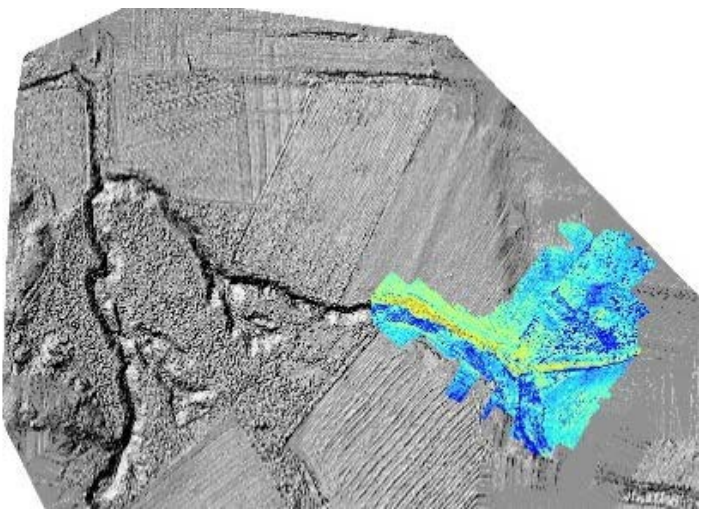

Figure 31. OrthoLWIR on DEM of Los Humeros caldera (BGS, 2018)

Gresham Marshes is an Environment Agency owned small area of land. It is a local wildlife site and wildlife reserve located off Gresham Park Road and Wilford Lane in West Bridgford, Nottingham (Figure 32). The ponds were dug in December 2018 by EMEC. There wasn't a report or official design for the ponds, they were just created by the chaps in the diggers whilst onsite so are no maps showing where they are. The Environment Agency, working closely with the Wildlife Trust, are currently undertaking eco-surveys, footpath clearance and hedge laying activities at Gresham Marshes. The EA contacted the BGS to provide an aerial survey of the pond locations within the site.

Figure 32. Gresham Marshes, Nottinghamshire (BGS, 2021)

UAS flights were defined in DJI Pilot as a series of one nadir and four matching oblique (45°) flights. The LiDAR and the matching RGB imagery was performed using the Zenmuse L1 sensor with a side overlap of 70%, the scanning mode set to repetitive, a flight speed of 10 m/s, the number of returns set to three, and calibration enabled. The altitude was set at 50 m to keep within regulations and to provide a point cloud density of 283 points/m2 and a photo output pixel resolution of ~1.5 cm. Imagery was recorded in JPG format with ground control targets set out across the study site providing accurate geo-positioning using Network RTK GNSS. The five flights took a total of 60 minutes. The outputs were a DEM from LiDAR (Figure 33a) and orthophoto images and models from RGB (Figure 33b).

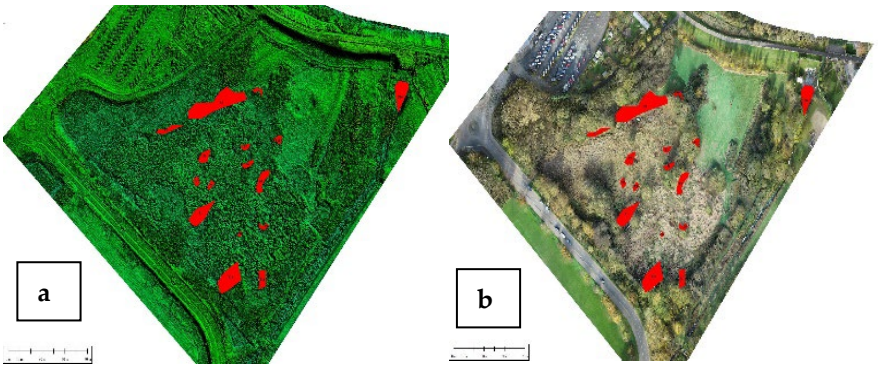

Figure 33. DEM of marsh area with ponds highlighted in red (a). Coloured point cloud of marsh area with ponds highlighted (b) (BGS, 2021)

8. DISCUSSION

The BGS is currently at the forefront of TLS, MMS and UAV based research for geohazard mapping, monitoring and modelling, with over 500 surveys from ~230 sites, both in the UK and overseas, carried out over a 20-year period. During this time, the BGS has utilised these technologies for widespread applications in earth sciences, engineering geology, geohazards and climate change, including terrain modelling of inland and coastal landslides, eroding coastlines, actively growing volcanic lava domes, retreating glaciers, rock stability and subsidence features, soil erosion and geo-conservation. The BGS also has a long history of overseas work in geodetic monitoring, using satellite and airborne Radar and LiDAR and, more recently, using both LIDAR and photogrammetric techniques on UAV's [41].
Examples of these projects can be found at: https://www.bgs.ac.uk/geology-projects/geomatic-surveys/. Besides these, we believe that TLS and other associated techniques can be applied to the following applications:

- Use of TLS to generate digital models of historic buildings, geological outcrops or other structures for geo-conservation, geo-tourism and distance learning.
- Combine TLS with multi-spectral imaging cameras in order to create virtual outcrop models (VOM) of geological structures.
- Use TLS to detect cracks and wet-spots in the clay-lined caps of Landfill sites, particularly with respect to 'closed' landfills.
- Use TLS to monitor long-term ground movement due to shrink–swell clays, compressible soils or Karst as a ground-truthing procedure for InSAR techniques [41].
- Use TLS to 'Join-up' fractures and faults in outcrops. The structures of one side of the outcrop can be measured and then the other side

(inside, if a cave etc.) and a virtual model can be created of the two parts.

- Use TLS to measure the loss of glacial volume. This could be compared to the volume of water flowing out of the glacial lake (during the same time interval). This would give us the total runoff volume that was accounted for by net change in glacier snout storage over time.
- Use of TLS for 3D mapping of temporary exposures, made by excavations, blasting, mass movements (landslides etc.) or even trial pits [41].
- Use of TLS to study coastal evolution, in order to determine the changes in beach thickness over time.
- Use of TLS to monitor pre-cursor displacement failures in cuttings or embankments.
- Use of TLS to complement and calibrate the outputs of digital aerial photogrammetry.
- Use of MMS (Pegasus Backpack) allows Building Information Modelling (BIM) using both imagery and point cloud data to document outdoor, indoor and even underground areas to be carried out [41].
- Use of InSAR to calculate long-term and future effects of coastal retreat in low-lying areas, or glacial retreat, on a local, national or global scale.
- Use of InSAR to calculate potential subsidence rates due to natural subsidence.
- Use of UAV in tandem (or more) to cover medium-large areas of land simultaneously, making surveys quicker.
- Use of UAV incorporating Blue/Green LiDAR to look at near-shore and inland water sources to determine depth and structure of bed.
- Use of UAV as a carrier for geophysical sensors for magnetic and electromagnetic surveys, ground penetrating Radar, seismic surveys and gravity [41].

9. CONCLUSIONS

The developments in, and applications of, terrestrial LiDAR at BGS in the last two decades have demonstrated the wide capability of this, and related techniques, in the field; some examples of which have been described in this paper. Advances in technology have meant that the applications of terrestrial LiDAR in the field of engineering geology have expanded dramatically over this time period. For example, use of the Pegasus Backpack has demonstrated that disaster responders will be able to capture data in 3D, on foot, in danger zone areas; and, in combination with SLAM and IMU, achieves accurate positioning even during GNSS outages [41]. With the addition of the external light-source precise scanning of tunnels and cave systems is also possible. The Pegasus Backpack can also be vehicle mounted, for mobile mapping of large areas, or pole mounted, for lowering into voids or sinkholes. Current GNSS units operate to sub-centimetre accuracy, and can be used to acquire accurate surveys of non-linear features, including watercourses where the depth to the bed cannot be recorded as easily as other features. The ability to combine different technologies

(LiDAR, GNSS, UAV, InSAR) to create a system greater than the sum of its parts has resulted in a powerful tool to research and industry [41]. The BGS is in the process of developing a Low Cost GNSS system as a rugged 'disposable' solution for monitoring the movement of a landslide, the flow velocity of a glacier, volcanic deformation, coastal evolution or differential ground subsidence. Also UAV's can now be fitted with digital cameras, thermal detectors, multispectral cameras LiDAR scanners and geophysics sensors to provide highly accurate data, with full-coverage 2D and 3D models.

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COMPETING INTERESTS

The author has declared that no competing interests exist.

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