Geomagnetism Review

2019

British Geological Survey

Geomagnetism Review 2019

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Colorful Aurora Borealis.
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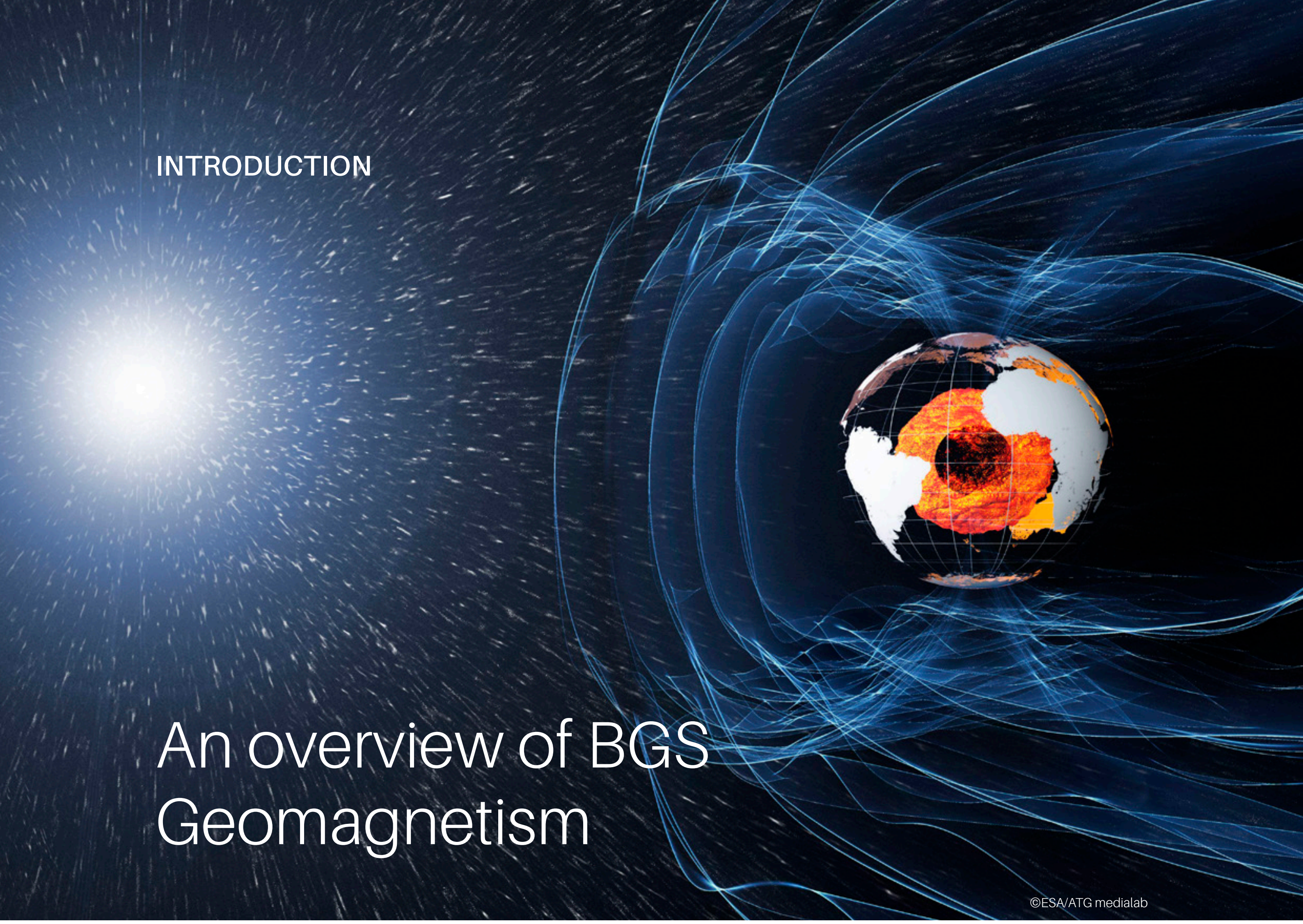
An overview of BGS Geomagnetism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The Geomagnetism Science Capability of BGS measures, records, models and interprets variations in the Earth's magnetic field. Our data and research help to develop scientific understanding of the solid Earth and of its atmospheric and space environments and extend our knowledge of geomagnetic hazards and their impacts. We also provide a range of geomagnetic data, products and services to industry and academia and we use our insights and knowledge to inform the public, government and industry.

The British Geological Survey (BGS) is the UK's leading Earth science research institute. BGS is a research centre of the Natural Environment Research Council (NERC), with parent body United Kingdom Research and Innovation (UKRI).

2019 was a year of transition for BGS. The Research Centre adopted a new Science Strategy and created an associated management structure (Figure 2). The Strategy created three key research 'Challenges' (yellow, orange and blue in the second Figure), providing foci within which BGS will encourage multi-disciplinary science to address emerging topics in these broader 'Challenges'. Within this new structure, the Geomagnetism Team was recast as a 'Science Capability', within the Multihazards and Resilience (MHR) Science Challenge Programme. In 2019, MHR was led by Acting Chief Scientist Dr David Kerridge. In 2020, Dr John Rees will take over as Chief Scientist for MHR. BGS also appointed a new Executive Director Professor Karen Hanghøj in September 2019.

The Geomagnetism Science Capability is primarily based in Edinburgh. At the end of 2019, we numbered twenty-five staff either fully or partly engaged in Geomagnetism work. Geomagnetism receives support from a range of BGS corporate resources, including Business Administration and Systems and Network Support, as well as support from the BGS and NERC Estates teams.

Our remit includes continuous geomagnetic monitoring across the UK. We therefore operate three geomagnetic observatories in the UK, located in Lerwick (Shetland), Eskdalemuir (Scottish Borders) and Hartland (North Devon). Two of our team members are site managers, stationed at the Eskdalemuir and Hartland observatories. We also operate magnetic observatories overseas on Ascension, on Sable Island (Canada), at Port Stanley (Falkland Islands) and at King Edward Point (South Georgia). We oversee and maintain magnetic observatory operations at Prudhoe Bay, Alaska (USA) and Fort McMurray, Alberta (Canada), in association with an industry partner. Our observatory work and the data we collect is one part of our core function:

Long-term geomagnetic monitoring and allied research to improve our understanding of the Earth and of its geomagnetic processes, environments and hazards.

In support of this core function, we aim to be recognised internationally as a world leader in:

- Measuring, recording, modelling and interpreting the Earth's natural magnetic field and its various sources
- Modelling and understanding geomagnetic hazard, a component of the space weather hazard to technology and society
- Delivering tailored geomagnetic data, products and services to academics, business and the public
- Providing knowledge and information for all sectors of society on Geomagnetism science: what it tells us about the Earth and how it can be used in practical ways

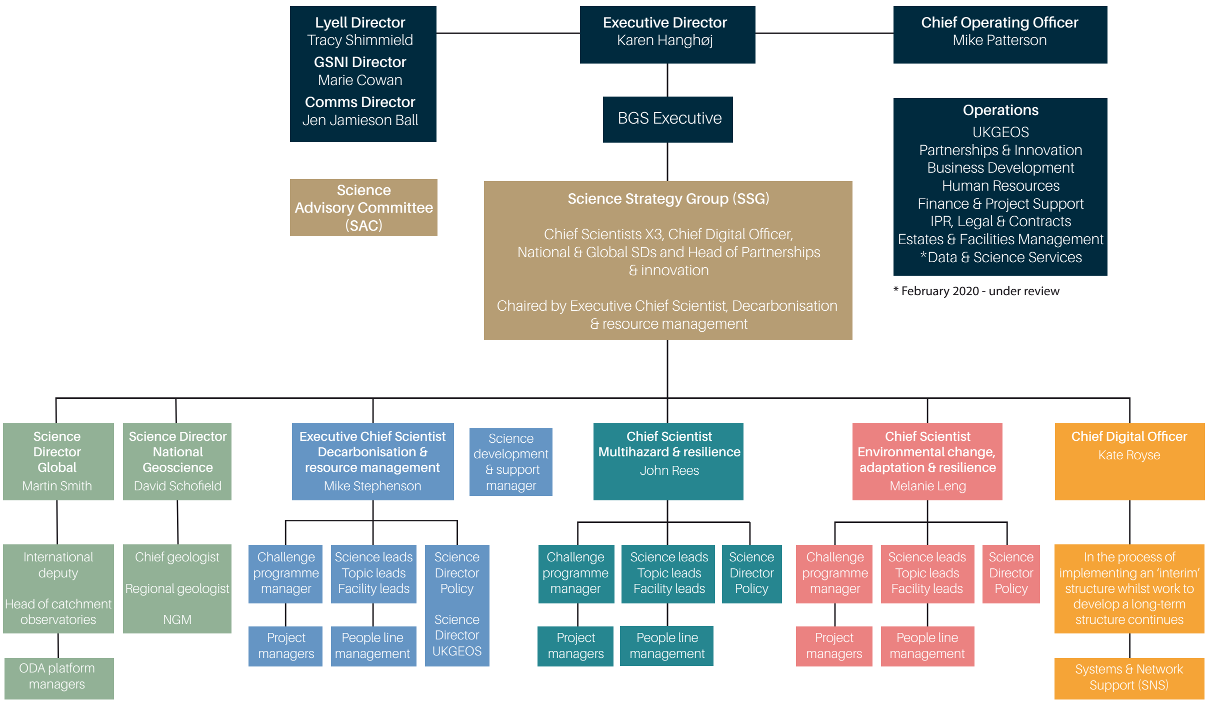

Figure 1 *The BGS Science Structure 2019–2024.*

INTRODUCTION

Objectives and achievements in 2019

Geomagnetism's goals for 2019 included:

- operating INTERMAGNET-standard magnetic observatories
- continuing the UK magnetic survey and producing a 2019 UK magnetic model
- providing finalised magnetic data, products and indices to academics and others
- operating the World Data Centre for Geomagnetism (Edinburgh)
- continuing magnetic data exchanges with INTERMAGNET, SuperMAG, Met Office, NOAA/SWPC and ESA
- producing a 2019 update of the BGS Global Geomagnetic Model (BGGM)
- providing World Magnetic Model and International Geomagnetic Reference Field candidate models
- continuing the NERC 'Space Weather Impacts on Ground-based Systems' project
- carrying on the STFC-funded schools magnetometer project
- completing the EU-funded EPOS implementation phase project

- advancing our geomagnetic research and publishing results
- providing data products and services to a range of businesses around the world

Some key performance indicators for our outputs in 2019 are as follows:

- >2.7M web page views on our servers at an average of 2.2 page views per visitor
- 10 089 followers @BGSauroraAlert received updates when there was an increased chance of seeing the northern lights in the UK
- 5,583 followers received daily space weather forecasts on twitter @BGSspaceWeather
- 214 global oil industry wells supplied with IFR data
- 108 magnetic bulletins published
- 100% data coverage for each of the 3 UK observatories
- 95.53–99.99% data coverage for the 6 overseas observatories
- 66 global oil industry wells supplied with IIFR data
- 23 field set-ups for IFR services
- 24 off-site presentations/posters
- 21 customer reports
- 13 observatory tours and Outreach events
- 11 academic and other science meetings
- 11 'Hypercube' well path navigation solutions for the oil industry
- 10 UK repeat station visits and measurements
- 9 journal and conference proceedings papers
- 7 positions on scientific and technical geomagnetism bodies (IAGA Executive Committee, IUGG Geohazards Risk Commission, INTERMAGNET Executive Council and Operations Committee x2, IAGA Division V-DAT, UK government advisory Space Environment Impacts Expert Group-SEIEG)
- 6 articles on space weather for RIN 'Navigation News'
- 5 public lectures, presentations and demonstrations, including University of Edinburgh, British Science Association (Dundee Science Society), Royal Meteorological Society
- 5 geomagnetic models (UK Ordnance Survey reference model, BGGM2019, MEME, WMM2020, IGRF Candidate Model)
- 4 differential magnetometer systems deployed to measure power line currents induced by space weather
- 3 new grants won (ESAx2, EU H2020)
- 2 co-supervised PhDs completed (Ashley Smith, Edinburgh; Maurits Metman, Leeds)
- 1 PhD co-supervised (Edinburgh)
- 1 MSc co-supervised student (Edinburgh)
- 1 site survey for a magnetometer installation in Northern Ireland

INTRODUCTION

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Geomagnetism's 2020 vision

In 2020, we will focus on the space weather and geomagnetic hazard to technology and infrastructure, mainly through the NERC-funded 'SWIGS' project, the ESA funded 'Geomagnetic Expert Service Centre' project, the EU-funded 'EUHFORIA2.0' project and commercially sponsored studies. We will also focus on developing our global and UK geomagnetic models, taking advantage of our involvement in the extended ESA Swarm magnetic survey mission, including Swarm projects to develop 'virtual magnetic observatory' and higher-resolution magnetospheric model products.

Major activities to support these activities will include the maintenance and operation of the UK magnetic survey program and the operation of the BGS magnetic observatories to INTERMAG-NET standards. We will also continue to produce high quality academic research, leading to better geomagnetic field and hazard models and to data products and publications for stakeholders, such as the public, government and industry.

Key objectives

- Geomagnetic monitoring, modelling and hazard assessment of the shallow and deep Earth and of the Earth's atmosphere and space environments
- Applying our data, models and expertise in services and research for academia, industry and society

Main deliverables (in no particular order)

- An INTERMAGNET-standard UK and Overseas magnetic observatory network, obtained through regular observatory service visits and high standards in instrumentation and data quality assurance procedures
- Supply of observatory data products to INTERMAGNET, according to the timetable set by the INTERMAGNET consortium
- An annual re-survey of sites in the UK magnetic repeat station network, leading to production of the 2021 national magnetic model and delivery of a report to Ordnance Survey
- Publication of our observatory data and data products online and in the BGS Monthly Bulletins series
- Supply of magnetic index products to the International Service for Geomagnetic Indices (ISGI), according to the timetable set by ISGI
- Operation of the World Data Centre for Geomagnetism (Edinburgh), including an annual 'call for data' and associated quality control activities
- Active participation (through presentations and organisation of sessions) at a number of major international scientific conferences, including the annual European Geophysical Union conference and European Space Weather Week
- Publication of a number of papers in scientific and professional journals, and the writing of articles for scientific and other publications
- Publication of the Geomagnetism Capability annual report and hosting of the annual Geomagnetism Advisory Group of stakeholders
- Provision of information and other data through the Geomagnetism web site, the main BGS site and by other electronic means
- The supply of solar and geomagnetic activity index forecasts and now-casts to the European Space Agency for the Space Weather Network (SWENET) and the Geomagnetic Expert Service Centre (G-ESC); real-time one-minute data from Hartland observatory to the US Geological Survey and the US NOAA Space Weather Prediction Centre (NOAA/SWPC)
- Support for the UK Met Office Space Weather Operations Centre (MOSWOC) and, as part of the Natural Hazards Partnership project, provision of local and planetary magnetic indices, daily geomagnetic activity forecasts and magnetic data products
- Research with European colleagues into coupling the EUHFORIA solar wind model to magnetospheric models to study the predictability of induced currents in power systems
- Maintenance of the 'Monitoring and Analysis of GIC' (MAGIC) web tool, in association with National Grid for space weather hazard assessment and monitoring
- Production of the 2020 update of the BGS Global Geomagnetic Model (BGGM), using satellite and other geomagnetic data, including data from BGS operated observatories
- Data collection, QC and magnetic model research leading up to revision of the World Magnetic Model and International Geomagnetic Reference Field in 2024/2025
- Delivery of geomagnetic observatory data and magnetic field products, including daily geomagnetic activity forecasts, to support geophysical survey companies and directional drilling operations, through the 'In-Field Referencing' (IFR) and 'Interpolation IFR' (IIFR) services
- Provision of observatory facilities for calibration and testing of instruments
- Year 3–4 of the NERC 'Highlight Topic' grant studying 'Space Weather Impacts on Ground-based Systems' (SWIGS), in association with nine UK universities and Research Centres and an external stakeholder and partner group of academics and industry representatives
- Provision of web services to, and metadata standards describing, geomagnetic data and models as part of the European Plate Observation System (EPOS) project, funded by the EU under the Horizon 2020 programme
- Provision of data products for the ESA Swarm 'Data, Innovation and Science Cluster (DISC)', set up by ESA in support of the goals of the Swarm satellite magnetometry mission
- Installing a real-time magnetometer system in County Fermanagh, Northern Ireland, in association with GSNI and Marble Arch Park Authority

UK and overseas observatories

To meet the geophysical monitoring deliverables of BGS, the Geomagnetism Capability operates a network of nine absolute magnetic observatories located in the UK and overseas. The observatories meet international standards in quality and data delivery and the real-time measurements of the magnetic field vector they produce underpin critical academic and commercial data products. To enhance our research, BGS also takes a leading role in expanding the global observatory network through collaborations with international institutes and organisations.

Magnetic observatories

A preliminary design and costing was completed in 2019 for new instrument and recording houses at Eskdalemuir Observatory. This new construction project is intended to provide a modern replacement for the 110-year-old facilities currently used to house the observatory magnetic variometers. This will provide the instruments with greater separation from sources of artificial interference such as traffic visiting the site. The rural location of Eskdalemuir has created challenges in this project and it has also been the cause of ongoing communications problems at the observatory. As network access in 2019 has degraded, data transfer has been affected and work is ongoing to provide the site with a new fibre-optic link. This should improve network reliability and bandwidth. Both of these projects are expected to be completed in 2020, provided funding can be secured.

Long-term gravimetric monitoring has been established at Hartland Observatory in a collaboration with the NERC Space Geodesy Facility. The project, including a reference GNSS receiver, is part of a feasibility study into permanent absolute gravity monitoring at the observatory. Hartland was also used as a training facility to provide a course in magnetic surveying to observers from the Royal Navy and staff from the UK Hydrographic Office.

Preparation is underway for a visit to Ascension Island in early 2020, the first since access to the island was restricted in 2017.

Two visits were made to Port Stanley Observatory to install a variometer at a test site some 3.5 km from the existing observatory (Figure 1). The variometer is designed to assess the viability of the new site prior to a permanent move of the observatory; a move that has been made necessary by increasing magnetometer interference from nearby radio transmitters. An opportunity was taken during one of the Falkland Island visits to make a survey meas-

Figure 1 *Installing a non-magnetic housing for the variometer at the Port Stanley test site.*

Figure 2 *Using differential GNSS to establish a true north azimuth at the Mull repeat station.*

urement at Port Louis, where magnetic measurements were first made on the islands in 1842. The 2019 measurements confirmed a 20° westward swing in declination over the intervening 177 years.

Preparation is underway for a visit to King Edward Point (KEP) Observatory, South Georgia in September 2020 and the first since 2016. A new observer from the British Antarctic Survey (BAS) was trained in making absolute magnetic measurements at Eskdalemuir Observatory prior to their year-long detachment at the BAS base at KEP. These observations provide a vital quality reference for the automated measurements, allowing the observatory to retain membership of the international INTERMAGNET network.

An agreement similar to that with BAS has been negotiated with Parks Canada, as they took over operation of the facilities on Sable Island (SBL), Nova Scotia at the end of the year. Environment and Climate Change Canada have supported the SBL Observatory since it was established in 1999. Failure of a PC led to five missing days of SBL data during 2019. However, ECCC staff provided the on-site support required to rectify the fault and resume data recording.

At BGS's second Canadian observatory, Fort McMurray (FMC), Alberta, local staff were also able to diagnose and rectify a cable fault that also led to a short period of missing data. An issue emerged in 2019 with temperature regulation in the variometer house of FMC and this was traced to a gradual deterioration in the hut insulation since the observatory was established in 2015. This problem has a direct effect on data quality during the northern Albertan winter, so a temporary repair has been made, prior to an over-haul of the hut planned for 2020.

A long-standing issue at Jim Carrigan Observatory (JCO), Alaska was addressed in late 2019, with a modification made to the variometer house to decouple the instrument from the building. Prior to this, the magnetic data occasionally contained

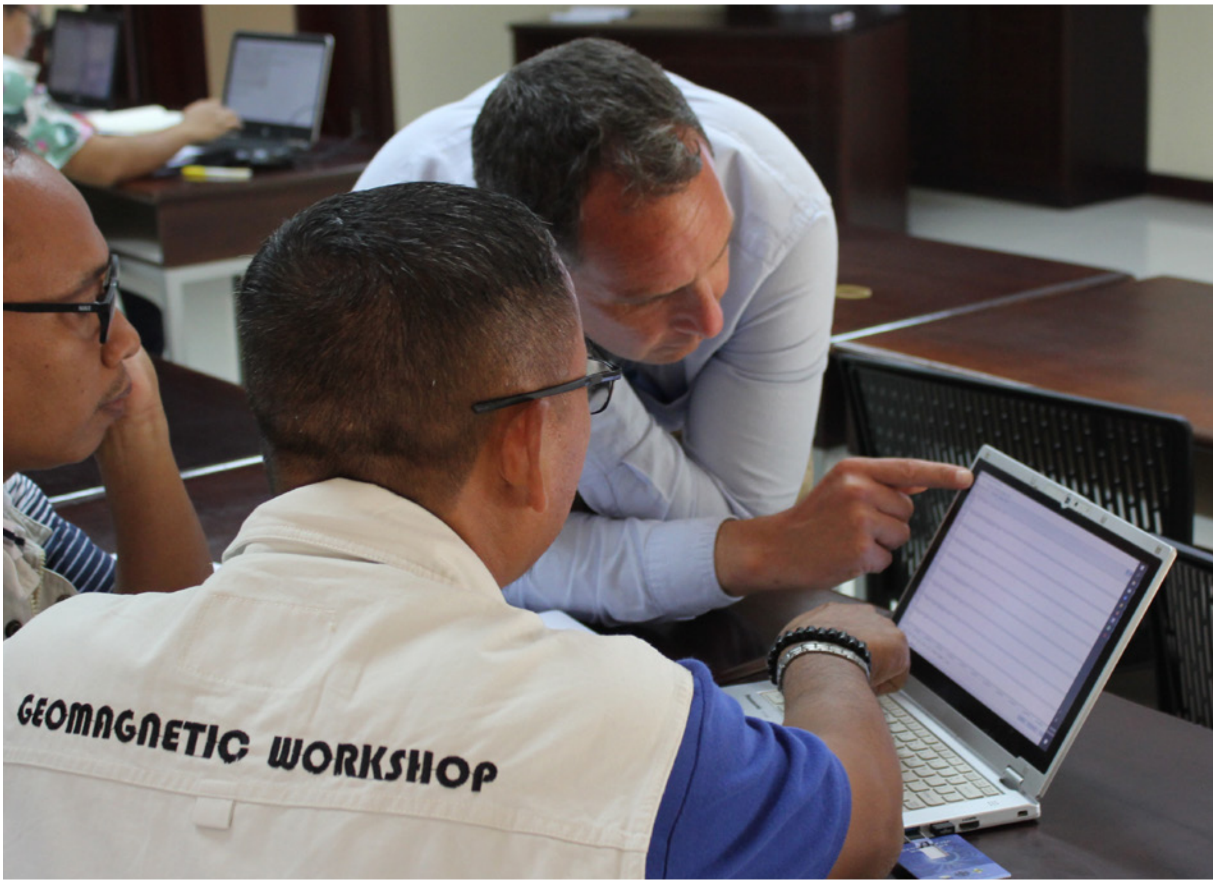


Figure 3 *Data processing training with Chris Turbitt at the 2019 Indonesian Observatories Workshop.*

signal caused by wind-induced vibration of the instrument. The house is raised on four piles above the tundra to prevent snow accumulation, but this means the building is susceptible to vibration in high winds, hence mechanically isolating the instrument should mitigate this problem.

UK repeat station network

Ten magnetic survey measurements were completed at sites in western Scotland and in central southern England, as part of the annual UK repeat station campaign, in support of the annual, regional declination model. (One site visit was postponed to 2020 due to staffing problems). A visit to the Stranraer site provided an opportunity for BGS staff to meet with their Met Éireann counterparts, to compare measurement techniques and exchange ideas on data reduction procedures.

The global network

BGS has continued to provide support to the global geomagnetic data network in the form of instrumentation, processing tools and knowledge exchange through the INDIGO Project and by maintaining a leading role in the INTERMAGNET observatory network. As part of this work, BGS also ran a four-day course in observatory operations, processing and data publication, provided as part of a workshop for observers from the six Indonesian magnetic observatories operated by the national meteorological & geophysical agency, BMKG.

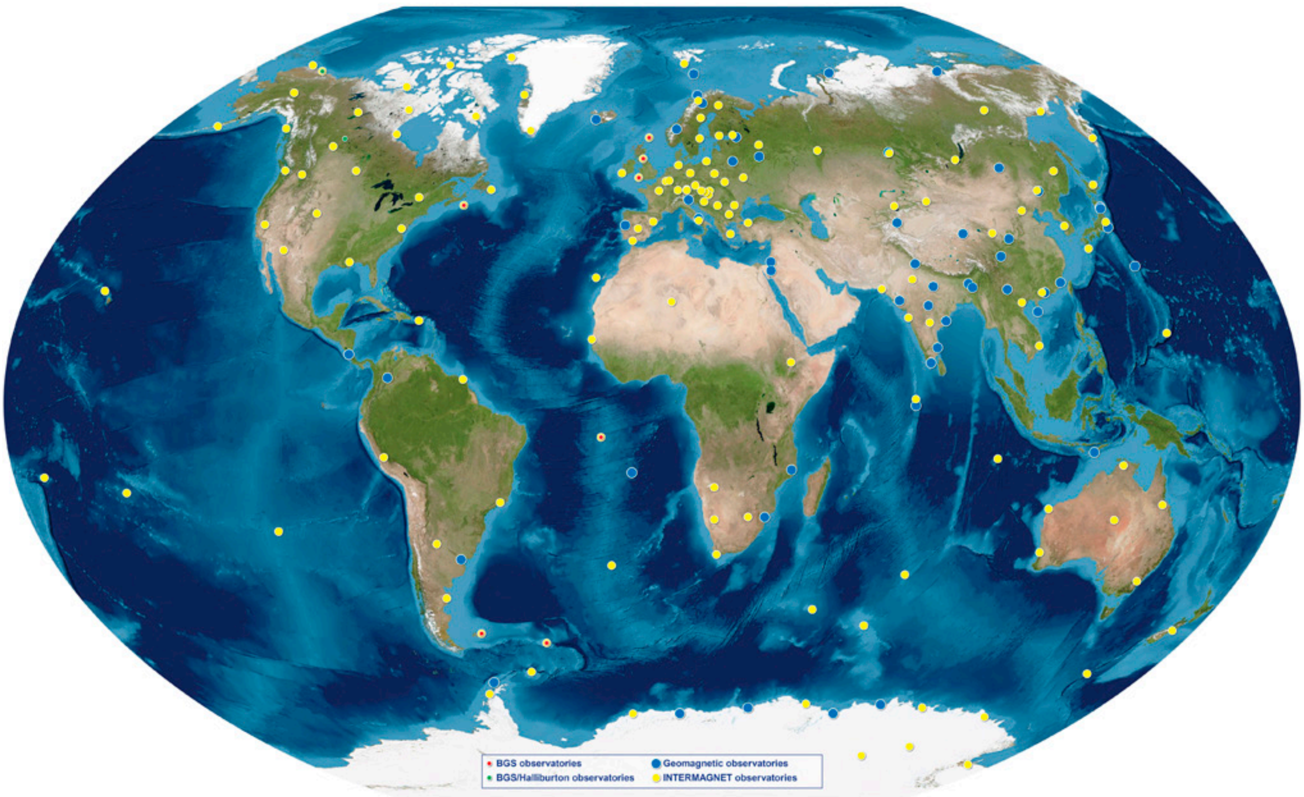


Figure 4 *The distribution of magnetic observatories around the world, identified according to type.*

A geomagnetic observatory in Northern Ireland

Long-term magnetic field monitoring in Northern Ireland would improve our understanding of the space weather hazard across Ireland and the UK. This would be mainly through the reduction in the average inter-observatory distance within these islands, which would allow us to resolve the shorter spatial scale magnetic variations that cause localised space weather impacts on technology. For this reason, in September 2019, Geomagnetism staff visited western Fermanagh to investigate sites suitable for a new magnetic observatory.

At the invitation of the Geological Survey of Northern Ireland (GSNI), in September Geomagnetism staff travelled to the Marble Arch Caves UNESCO Global Geopark (Figure 1). Straddling the border between County Fermanagh in Northern Ireland and County Cavan in the Republic of Ireland, the Marble Arch Caves Geopark was the first area in the UK to be recognised as a Geopark in 2001 and became the first transnational Geopark in the world, in 2008. The park authorities are keen to promote world-leading scientific measurements in the region and to encourage public outreach and understanding, both of science and of the park. GSNI are similarly keen to establish a Northern Ireland based observatory to provide a local geomagnetic capability, as part of monitoring the space weather hazard to critical local infrastructures, such as the power transmission network.

Figure 1 *Right to left: Chris Turbitt, Marie Cowan and Derek Reay outside the Marble Arch Cave visitor centre.*

Chris Turbitt and Ciaran Beggan assessed the suitability of several sites for hosting, initially, a vector magnetometer system and, in the future, a full observatory facility. Four sites around the Enniskillen area were scouted for their potential and a site near to the Gortmaconnell viewpoint (around 2 km from Marble Arch Caves) was selected. This site was chosen because of (a) its proximity to the main site of the Geopark centre at Marble Arch (so that park staff can monitor our equipment), (b) the likelihood of landowner permission for long-term use of the site, and (c) the relatively easy access to power and communications from the local road. The site is around 20 km from Enniskillen on a low hill facing northwards, accessed by a farm track from a B-road (Marlbank Road). The field has very little soil cover, with the bedrock limestone visible in places. Marlbank Road passes around 100 m to the north of the site and there are only a few houses in the area.

A site survey was undertaken to check the magnetic cleanliness of the site. A proton precession magnetometer was then left overnight on the 16th September to record the background scalar magnetic field. In the morning, manual magnetometer measurements were made on a grid of points over the area, to check for obvious anomalies (Figure 2). Any magnetic anomalies found were relatively small (Fig.3), at around 10–12 nT. The site is

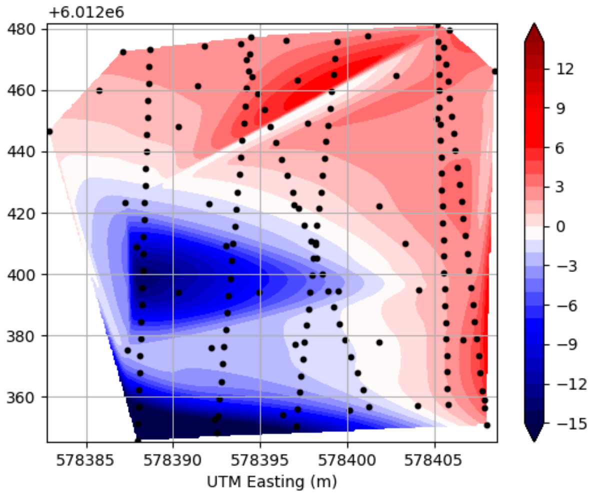
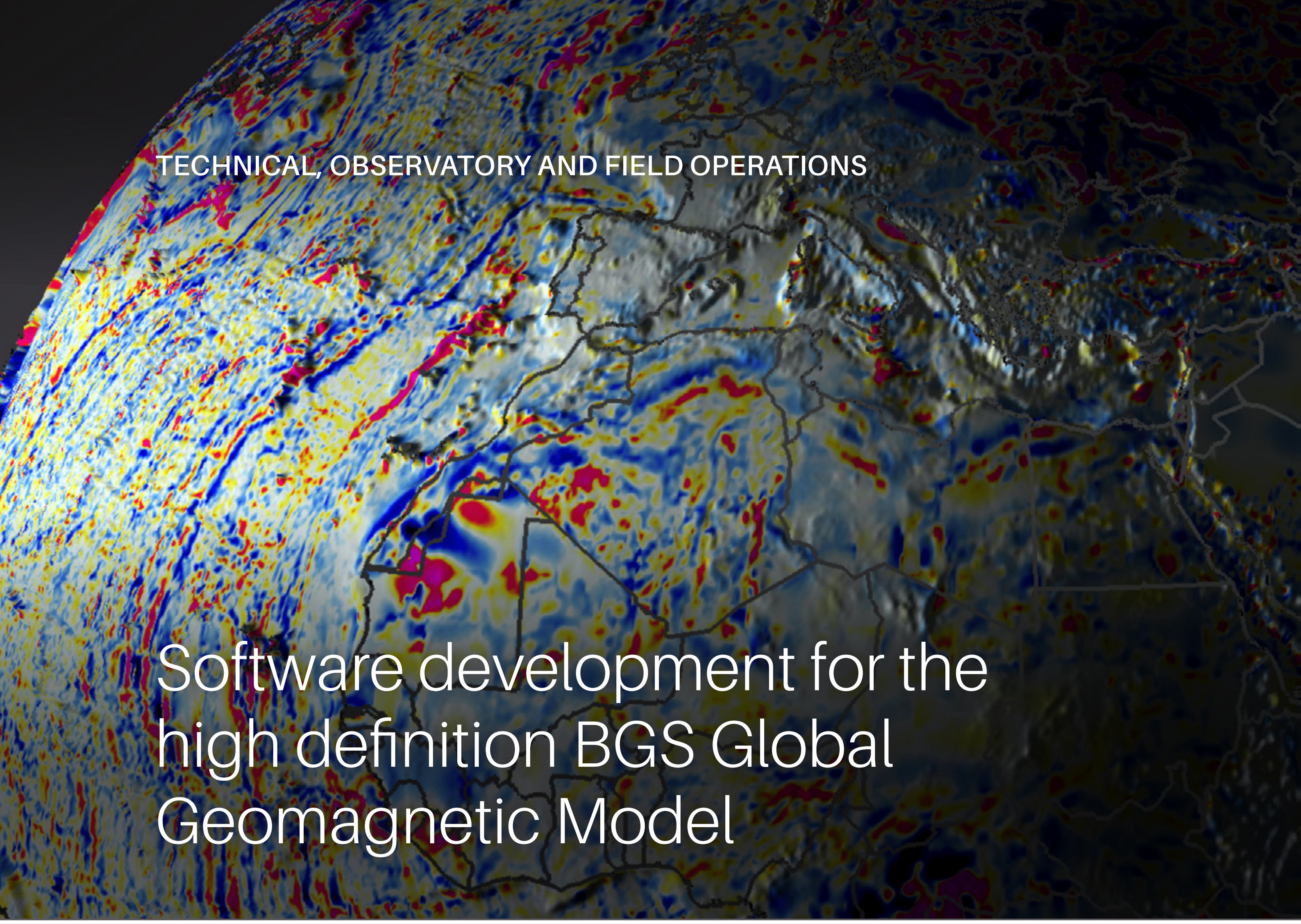


Figure 2 *Map of magnetic anomalies (in nT) at the Gortmaconnell site. Note, as the grid is not sampled uniformly, the contouring is biased by the sampling.*

therefore quite suitable for a variometer station. The next steps in establishing the site will therefore be locating a vector variometer system there in 2020 and thereafter recording magnetic field changes over the long term. This will establish the general behaviour of the magnetic field in the region and therefore the suitability of the site for future upgrade to full observatory quality and status.



Software development for the high definition BGS Global Geomagnetic Model

In April 2019, a new 'high definition' BGS Global Geomagnetic Model (BGGM) was released. The new model is at a much higher spatial resolution than previous models, necessitating a new file format. The new model also carries out significantly more calculations to compute results equivalent to those from older models. For these reasons the software associated with the BGGM needed significant upgrade.

BGGM software remit

The BGGM (Figure 1) is released annually and is widely used within the oil industry. It is also used within Geomagnetism for spot magnetic field calculations. The associated software to support Team and industry use must therefore be available on multiple platforms and is therefore built for a broad user group. Commercial customers are supplied with both the BGGM coefficient file and supporting software. To provide as comprehensive a service as possible, the software is built for Linux, Windows 32 bit and Windows 64 bit, and has support for Fortran, C, Visual Basic and Java.

Software upgrade of the high definition BGGM C library

All the BGGM software is linked to a library of C code. This code was updated for use with the new model format at the beginning of the year. In-house testing of the new libraries followed and the libraries were released commercially in April. The library had to be backwards-compatible with existing products, both in-house and commercially, and had to be compiled on multiple platforms. The release in April of version 3.8 was successful, but after the commercial release and feedback from customers, it became clear that users on Windows would benefit from optimisation of the code run-time and memory allocation. The new model also generated renewed interest in using the code, and customers started making software feature requests. The release of a second version, version 4.0, at the end of the year, used optimised code and had new entry points to support new features on multiple platforms.

New features

The C library underlies a Java menu-driven user application (BGGMTool), a DLL library, a Linux library, an Excel template, and various web-services.

- BGGMTool now has support for UTM grid calculations, new output formats and a progress monitor (Figure 2). It also allows the user to omit the secular variation calculation, which speeds up processing
- The DLL code has been optimised for speed and memory allocation. It now has function calls to verify the model validity without reading in the entire file, and options to omit the secular variation calculation. These entry points are available to VBA (for Excel), and C
- The Excel template provided now supports 64-bit Microsoft Office as well as 32-bit, running seamlessly on both
- A new web service was developed allowing external users to access BGGM error values from the BGS web site using an interactive clickable map, and all existing web-services were upgraded to the new C library

Technical support

Technical support was given to companies incorporating source code into their own applications. More than 45 technical queries were dealt with, all of which needed an individual response for their own unique setup of platform, language, users and expertise. Six different prototype code versions were sent out to license holders who requested them, from which we obtained valuable feedback to help with the development process.

Licensing and distribution

With the heightened digital security surrounding Windows 10, we renewed our efforts to obtain a digital signing certificate. This had been problematic in the past, but this year we were finally successful. The whole package is built into an installer for commercial customers and 2019 saw an unprecedented second software release in November. In-house, software control was improved and all users have now moved to compiling code with the Linux libraries that are centrally stored.

Future plans

It is anticipated that customers will make more feature requests, and there will inevitably be ongoing technical support needed due to the diverse usage of the software. Licensing has changed for Oracle's Java Development Kit (JDK): the software now uses 'OpenJDK' and we will have to ensure that this proves non-problematic in the future.

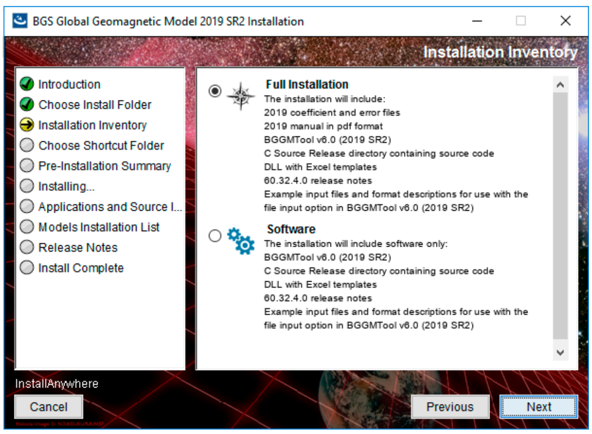


Figure 1 *Installer inventory for software release 2.*

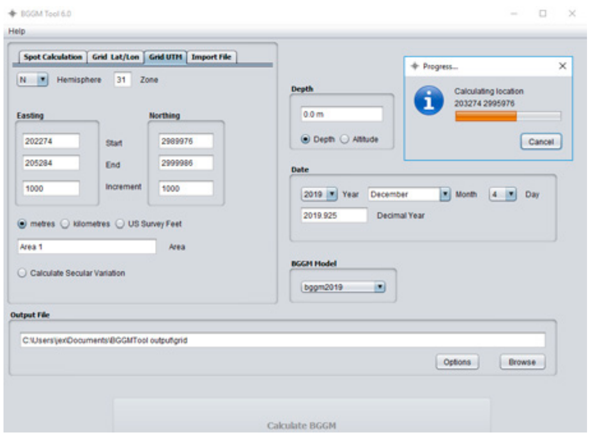
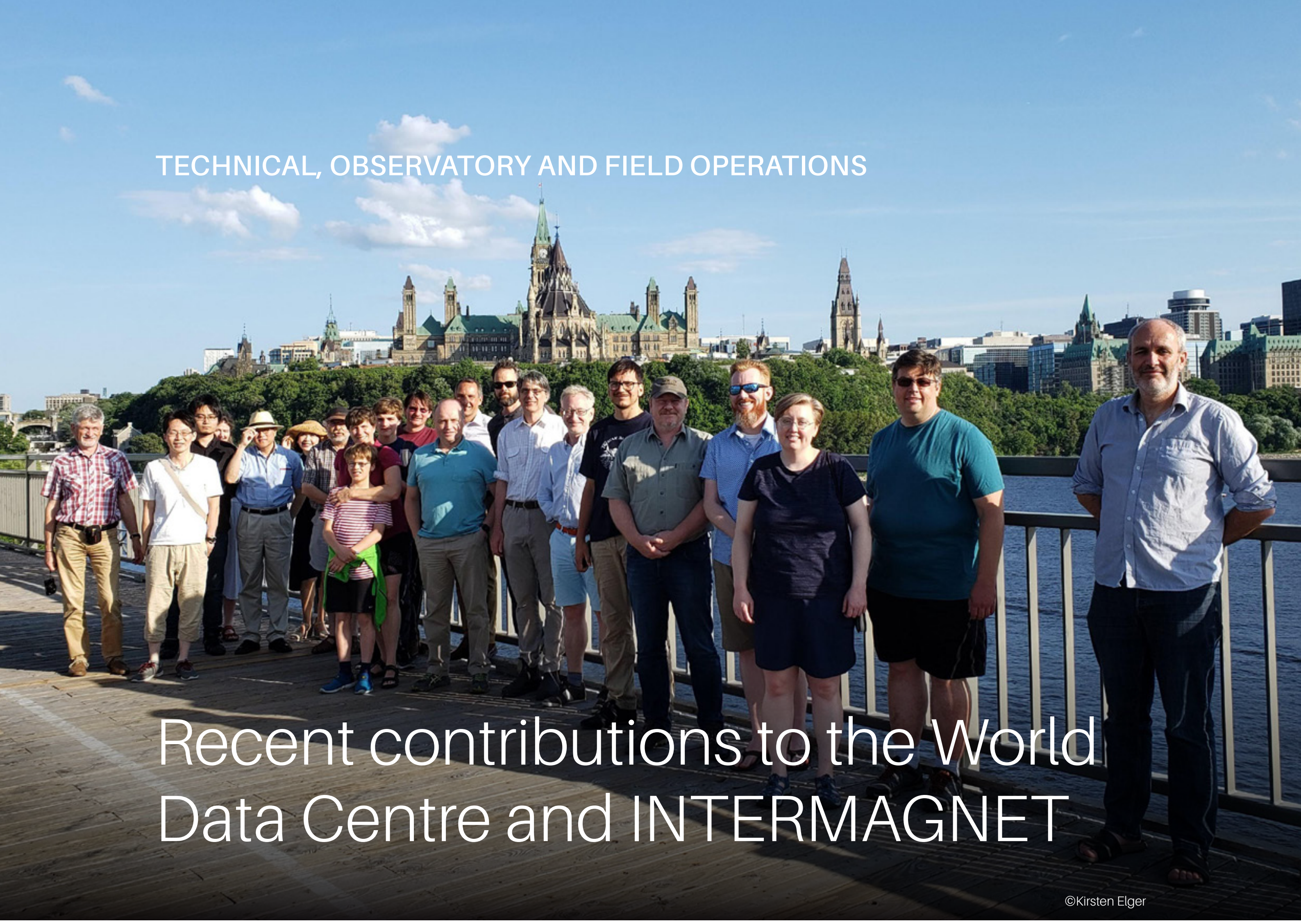


Figure 2 *New User interface and progress monitor for grid UTM option.*



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Recent contributions to the World Data Centre and INTERMAGNET

The Geomagnetism Team operates a World Data Centre (WDC) for Geomagnetism under the auspices of the International Science Council's (ICSU) World Data System. Geomagnetism staff also have leading roles in the INTERMAGNET global network of observatories. We describe updates and events of interest relating to the WDC and INTERMAGNET over the past year.

World Data Centre for Geomagnetism

The global geomagnetic metadata system created under the EPOS project has been enhanced through work by BGS staff to load all metadata from the World Data Centre's metadata database. Work is ongoing to move applications away from accessing the old WDC metadata database to accessing the new global metadata system. This will be a significant step in the take up of the global geomagnetic metadata system.

BGS maintains an active program of data collection on behalf of the WDC. During 2019, we received 185 years of observatory 1-minute data , from around the world (209Mb of compressed data) and 243 years of observatory hourly data, also from observatories around the world (41Mb of uncompressed data).

INTERMAGNET

In 2019, BGS staff were heavily involved, as committee members and as contributing scientists, in driving forward new activities and deliverables from INTERMAGNET. Some of these activities and deliverables are discussed here.

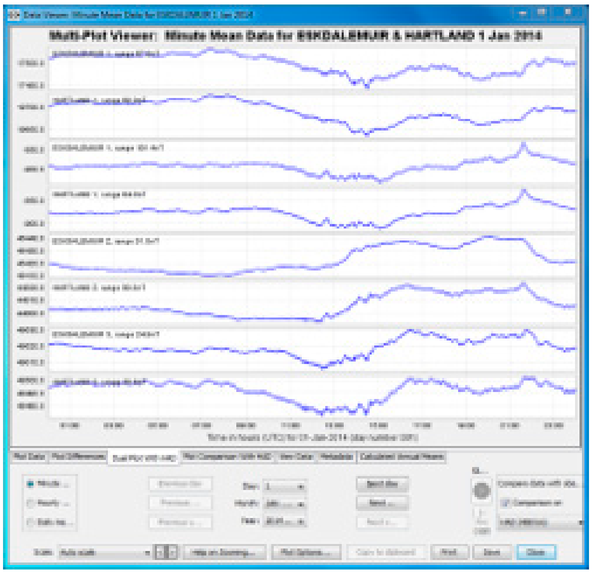

Figure 1 *Screenshot from the Imcdview software, showing 1-minute mean data for Eskdalemuir and Hartland observatories on 1st January 2014.*

During the year, INTERMAGNET released its final data on a physical medium (a USB memory stick), covering definitive data recorded by worldwide magnetic observatories in 2015, at a one-minute sampling rate. As 2015 marked the 25th anniversary of INTERMAGNET data releases, this USB stick contains all the 1-minute observatory definitive data, between 1991 and 2015, which has been submitted to INTERMAGNET.

For data from 2016 onwards (which will be processed in 2020), INTERMAGNET will create a digital 'INTERMAGNET Reference Data Set' (IRDS) annually, essentially continuing the data processing procedures used for each physical medium data release. Each IRDS will be labelled by the year of the latest data, e.g. IRDS-2016. Users and data providers will still be able to request data on a USB stick, funding permitting, but it will no longer be the norm to create a 'physical' record of the data. For data security and preservation, definitive copies of each IRDS will be archived at several INTERMAGNET institutes.

BGS staff worked with colleagues from GeoForschungsZenturm (GFZ), Germany to create Digital Object Identifiers (DOIs) for the INTERMAGNET 2013 (doi.org/10.5880/INTERMAGNET.2013) and 2014 (doi.org/10.5880/INTERMAGNET.2014) data publications. Work is continuing to create DOIs for other years of the INTERMAGNET definitive data set. We also supported INTERMAGNET in developing a web service for INTERMAGNET metadata (partly supported by the European Plate Observing System, EPOS) project. Metadata can be viewed on INTERMAGNET's draft pages, for example the world map of observatories: https://intermagnet.github.io/metadata/map.

Creative Commons 4.0 CC-BY-NC is now the default license for data available from INTERMAGNET, a move that has been led by BGS staff. This allows products to be developed from the data but protects against unauthorised commercial use. The existing data licence (as available for many years from the INTERMAGNET web site) is similar in substance to the CC-BY-NC licence. However, changing to a Creative Commons licence will mean that the new license is widely understood, is machine-readable and is available in multiple languages. Despite adoption of the Creative Commons license as a default, some INTERMAGNET institutes may opt to have less restrictive licenses attached to their data.

We also continued with software development and support for community use. A collection of source code can be found on the INTERMAGNET GitHub. This includes routines and toolboxes in Python, Mathematica, Matlab, IDL and Java for reading and writing the INTERMAGNET CDF format ImagCDF. This repository is open for other source code that would be useful to the wider community and we encourage contributions. Examples of INTERMAGNET software that BGS develops and supports include

- Imcdview, which is an application for manipulating 1-minute definitive data and works with the IAGA-2002 data format (Figure 1)
- Gm_convert, which allows conversion between many magnetic data formats, such as IAGA-2002, WDC format and several INTERMAGNET formats

INTERMAGNET's technical manual describes standards for data measurement, processing, formatting and data submission. The manual also describes how to join INTERMAGNET. Version 5 of the manual is nearing completion and will soon be released to existing and prospective INTERMAGNET members.

Completion of EPOS implementation phase

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The European Plate Observing System (EPOS) is a long-term plan to simplify and unify access to Earth Science data across Europe. EPOS successfully completed its Implementation Phase (IP) in 2019. During the IP, BGS led and made major contributions to the European Geomagnetic Models and Data (EGMODA) service within the wider Geomagnetism 'Thematic Core Service' (TCS) of EPOS. For three years from 2020, EPOS will enter the Pilot Operational Phase (POP). BGS will lead the Geomagnetic TCS during this phase, on behalf of the consortium of institutes within the TCS, maintaining existing EPOS Geomagnetism services and completing several of the remaining tasks from the IP.

In 2019, we enhanced the Geomagnetic EPOS TCS (Figure 1 and 2), which provides the user community with geomagnetic data and products, In summary, we:

- augmented the metadata that describes the data services
- created station metadata for INTERMAGNET, the WDC and IMAGE stations, enabling viewing of the stations on the EPOS GUI
- affixed licenses to the magnetic data and products
- progressed the publishing of DOIs for geomagnetic data
- had BGS service elements validated by the EPOS system and had other services readied for formal validation
- continued to add data to the Geomagnetism community metadata system and continued to create services for the community that provide access to this metadata

GEOMAGNETIC
OBSERVATIONS

Figure 1 *The logo of the Geomagnetic Thematic Core Service (image courtesy of EPOS).*

Figure 2 *The ten Thematic Core Services of EPOS (image courtesy of EPOS).*

We describe some of these activities here in more detail.

There have been advances on data licensing arrangements during 2019. For example, agreement has been reached within INTERMAGNET to use a 'default' license (Creative Commons CC BY:NC 4.0), where individual data providers do not choose an alternative. This work has been documented so that INTERMAGNET's users are aware of the new license terms, and a new data-licensing page has been agreed within INTERMAGNET, though not yet published.

Work is continuing on populating the Geomagnetism community metadata database, including the addition in 2019 of World Data Centre (WDC) metadata (with the inclusion of a small number of additional fields). In the near future, work will commence on services to allow the WDC to query the Geomagnetism community metadata database, removing the need for a separate WDC metadata system. We are also working on tools to allow observatory operators to view and correct the data we hold about their observatories.

We have been developing common web access points to global and regional geomagnetic field models. Web services to global models have already been developed and a web service for World Digital Magnetic Anomaly Map (WDMAM) will be completed after the end of the EPOS IP.

We established links from our Geomagnetic data services, products and models to the EPOS Integrated Core Services (ICS). We:

- successfully updated web service metadata for the ten web services that make up the eight Geomagnetism TCS validated service elements
- made available software to the other nine TCS (Figure 2) to aid with the production of EPOS-DCAT-AP metadata files
- undertook leadership of an EPOS Working Group on time series data pre-visualization within the EPOS GUI. (In the operational phase, the ICS will add pre-visualization software to the EPOS GUI, allowing those TCS who make data available in Coverage JSON format to view their time-series data)

More information on EPOS to date and its plans can be found at www.epos-ip.org and an EPOS newsletter article describing progress on serving Geomagnetic data and products can be found at www.epos-ip.org/epos-and-geomagnetism-together-benefit-community.

An update on the SWIGS project

As the ‘Space Weather Impacts on Ground-based Systems’ (SWIGS) project enters its third year, we provide an overview of SWIGS research work and achievements during 2019.

The SWIGS project is organised into four main packages, led by investigators from British Antarctic Survey (BAS), University of Edinburgh, Lancaster University and BGS (the 2017 Annual Report describes the project structure).

One of the goals of Work Package 1 is better understanding of magnetosphere-ionosphere interactions and how space weather processes drive current systems to extremes. In 2019, Mervyn Freeman (BAS) demonstrated the significance of substorms in driving extreme rates-of-change of the UK magnetic field, particularly at the onset of the rapid expansion of the auroral oval. Andy Smith (MSSL) examined the role of Sudden Storm Commencements in generating the extreme horizontal field changes that can trigger damaging GIC. The link between ionospheric electric field and conductivity was investigated by Andrew Kavanagh (BAS).

Within Work Package 2, Fiona Simpson (Southampton) continued the magnetotelluric survey of northern England and started data processing and 3D modelling of ground conductivity across the northern UK. BGS deployed four more Differential Magnetometer Method (DMM) systems along the east and west coasts of Britain and analysed GIC data for several events (a detailed account of this is contained elsewhere in this report).

An examination of directionality and the global location of extreme events was undertaken by Neil Rogers (Lancaster) under Work Package 3. One consequence of this work is that it will allow calculation of uncertainty envelopes for estimated extreme values. Also in Work Package 3, Jonathan Eastwood (Imperial College London), together with colleagues, continued to develop a magnetospheric-ionospheric coupling model for the Gorgon magnetospheric model. Gorgon offers a UK capability in forecasting of magnetic field changes, driven by solar wind data. Phil Livermore (Leeds) and colleagues continued to research the consequence for space weather impacts arising from long-term change in the strength and orientation of the main magnetic field. Researchers at Reading University continued to produce new insights into historic magnetic field variations over the past 400 years, including the use of 'downscaling' statistical techniques to extract local information from their long-term, large-scale models.

Within Work Package 4, research on the effects on pipelines, rail lines and the high voltage power network continues. Mike Hapgood (Rutherford-Appleton Laboratory) demonstrated a correlation between geomagnetic activity and railway anomaly records in Wales, suggestive of local effects from GIC on rail signalling infrastructure. BGS created a full UK model of the high-pressure gas transmission pipeline network (a model containing over 175 000 pipe sections) and space weather impacts from several large storms have been simulated. Results show large pipe-to-soil potential differences, in excess of normal operating conditions. Initial analysis of dissolved gas data from a UK transformer by Jim Wild (Lancaster) has not indicated a strong direct correlation with geomagnetic activity, at least from a limited study of several recent, but far from extreme, magnetic storms.

Figure 1 *Annual SWIGS meeting at BAS in September 2019.*

The annual SWIGS meeting was held in BAS Cambridge in early September (Figure 1). There were 16 attendees including project partners from South Africa and Ireland. SWIGS partners also hosted science sessions at the National Astronomy Meeting in Lancaster in June and at European Space Weather Week in Belgium in November. There was a strong SWIGS presence at the IUGG conference in Montreal in July. Finally, a public website (http://swigs.bgs.ac.uk/) has been established (Figure 2).

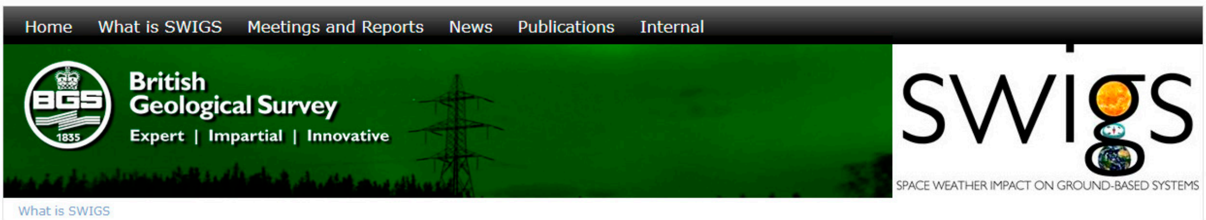


Figure 2 *Project banner from the SWIGS website: http://swigs.bgs.ac.uk.*

Differential magnetometer measurements of induced currents in the UK power grid

One SWIGS research goal is improving the modelling of Geomagnetically Induced Currents (GIC) in the high voltage power transmission system, through increasing the number of direct measurements of GIC, by means of the 'Differential Magnetometer Method'. In 2019, the Geomagnetism Team extended our GIC measurement field campaign further across the UK. Here we give a progress report and present some GIC measurements recorded during a minor geomagnetic storm in August.

The Differential Magnetometer Method (DMM) and GIC model validation

The DMM allows us to indirectly measure GIC in power lines. It was first introduced by Finnish researchers in 2009 and later deployed on a test site by South African researchers in 2015. The DMM hardware includes two fluxgate magnetometers, one directly under a power line carrying GIC, and one at a remote site further away, with each powered by solar panels and batteries. The difference in the magnetic field recorded by both instruments allows us to calculate the GIC in the power line segment via the Biot-Savart law of physics. For SWIGS, we use six bespoke systems, each recording data at one location for around six months before being moved to a new location, thus sampling the area spanned by much of the High Voltage (HV) grid with 12 site occupations. The DMM GIC are then used to verify our model of the HV power grid. We have found that to match our measured DMM line GIC, the model needs a highly detailed network representation and good estimates for all grid parameters, such as line lengths and grounding resistances. Independently measured industry GIC

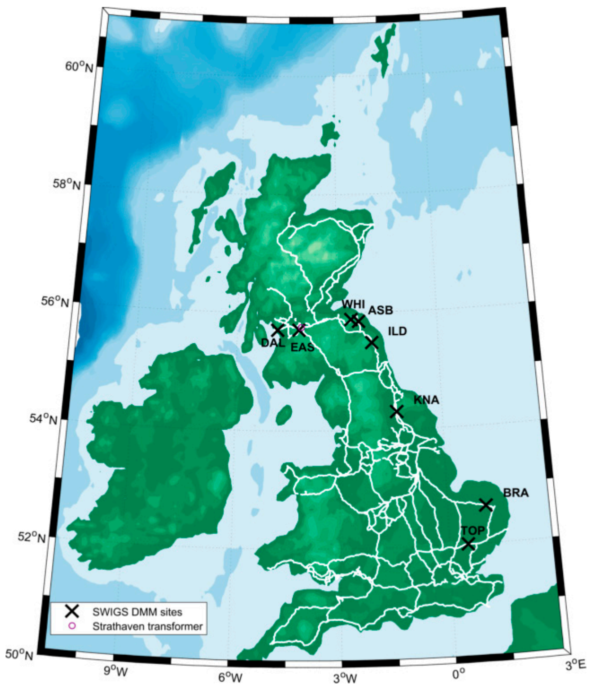


Figure 1 *Map of SWIGS DMM deployments (black crosses) and the HV power grid in the UK (white lines). WHI – Whiteadder, East Lothian; ASB – Abbey St. Bathans, Scottish Borders; ILD - Ilderton, Alnwick; Northumberland, KNA – Knayton; Thirsk, Yorkshire, BRA – Brandon Parva, Norfolk; TOP – Toppesfield, Essex; DAL – Dalry, North Ayrshire; EAS – East Kilbride, South Lanarkshire. EAS is close to the Strathaven substation, where Scottish Power independently measure GIC.*

data are available at a few substations, which also aids the independent verification of the modelled system.

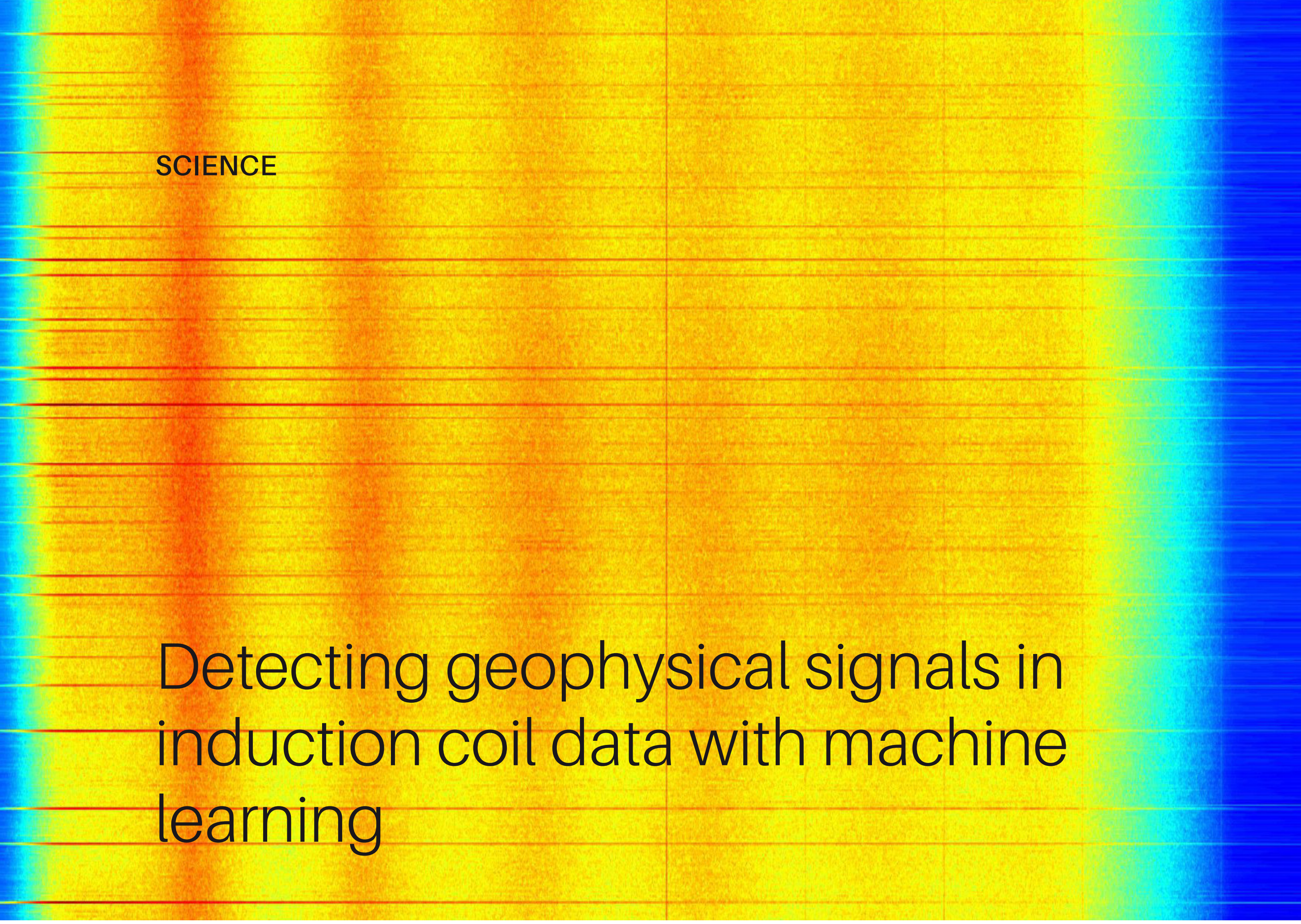
Field work

In year two of our field campaign we installed a further four sites under HV power lines in the UK (Figure 1). Two were deployed in February in East Anglia under lines leading to Sizewell. Unusually warm weather and sunshine (Figure 2) made for an easy installation, after a long drive down the east coast of Britain. Two further sets of instruments were deployed in Western Scotland, one close to Ardrossan and one close to East Kilbride and the substation at Strathaven, where Scottish Power monitors GIC in one transformer. With these four stations operating simultaneously we hope to study the development of the electric field across the UK that drives the GIC during geomagnetic storms.

New GIC data for 2019

2019 occurred during the quiet phase of the solar activity cycle, with only a few G1 and one G2 magnetic storms occurring. Nevertheless, we were able to record GIC in HV lines for significant lengths of time at multiple locations. A period of geomagnetic activity occurred between 31 August and 3 September. Three DMM systems were in operation at the time. Additionally, Scottish Power provided us with data from the Strathaven substation. These recordings are highly correlated with the measured line GIC at the nearby DMM site in East Kilbride (upper two panels). A similar signature was also recorded at sites KNA and TOP further south. Line GIC at TOP (4th panel) has the highest amplitude of all our recordings. This is most likely related to the local line topology and the regional electrical conductivity.

Figure 2 *Good days and bad days in the field (Ciaran Beggan, Adam Collins and Juliane Huebert).*



Detecting geophysical signals in induction coil data with machine learning

In collaboration with the Edinburgh Parallel Computing Centre (EPCC), BGS co-supervised an MSc project to investigate an application of machine learning to identify geophysical signals in Eskdalemuir induction coil data. The aim was to automatically detect 'fringes' caused by magnetic field vibrations at frequencies of 1–10 Hz, observed at local night time in spectrograms of the magnetic data.

The induction coils at Eskdalemuir Geophysical observatory have been collecting data at a rate of 100 Hz since 2012. Within the geophysical signals observed are magnetic field vibrations at frequencies of 1–10 Hz, which are called Ionospheric Alfven Resonances (IAR). The IAR look like a series of thin 'fringes' appearing during quiet local night time (see inset). The properties of these fringes change over the course of a night and are related to upper atmospheric density variations; they are most sensitive to density within the ionosphere (100–1000 km). Previous attempts to automatically extract the frequency and timing of the fringes has had mixed results, meaning manual extraction was still preferred. The aim of this project was therefore to improve and automate the extraction method to allow research to focus on the geophysics involved.

In collaboration with Rosa Filguera at EPCC and Vyron Christodoulou at BGS, an MSc project was developed to try to use machine-learning techniques to recognise and extract IAR fringes automatically. Machine learning is a powerful pattern recognition technique that has become very successful at image processing in the past decade, as new algorithms have been developed and computing power has increased.

Paolo Marangio, an MSc student at EPCC, undertook the project in February. He decided to use the U-net neural network algorithm, which has been shown to have excellent skill at image segmentation. He was supplied with six years' worth of daily spectrograms from the Eskdalemuir Induction coils to process. Of these, around 180 'best' examples of IAR were selected as the training and validation datasets. Once the network had been trained, it was applied to the remaining ~2100 days to produce a dataset of IAR fringes.

Paolo successfully implemented the U-net network and demonstrated its superiority over a previous signal and image processing method (Beggan, 2014). As an example, Figure 1 shows an input test image, with the IAR selected by the Beggan method (the 'ground truth image'). The U-net can be trained over multiple epochs and it outputs a probability map of whether a fringe (essentially a brighter patch) is detected. At each epoch the Training Loss decreases (ideally towards zero) and the Intersection over Union (a measure of fit of the network output to the ground truth increases (ideally reaching one). Once the probability map is thresholded to remove grayscale intensities below a certain value, the IAR fringes become apparent. Even given the relatively poor 'ground truth' data provided, the U-net provides an excellent estimate of the position of the IAR.

The remainder of Paolo's project investigated strategies to implement the U-net on CPU versus GPU clusters and to experiment with improving the performance of the algorithm. The code and Paolo's thesis are available on GitHub and the next steps will be to improve the methodology, using better training data and implementing a robust IAR extraction scheme.

	1 epoch	3 epochs	5 epochs	10 epochs
Training Loss	0.3800	0.2910	0.2862	0.2767
Training IoU	0.7719	0.8193	0.8217	0.8270

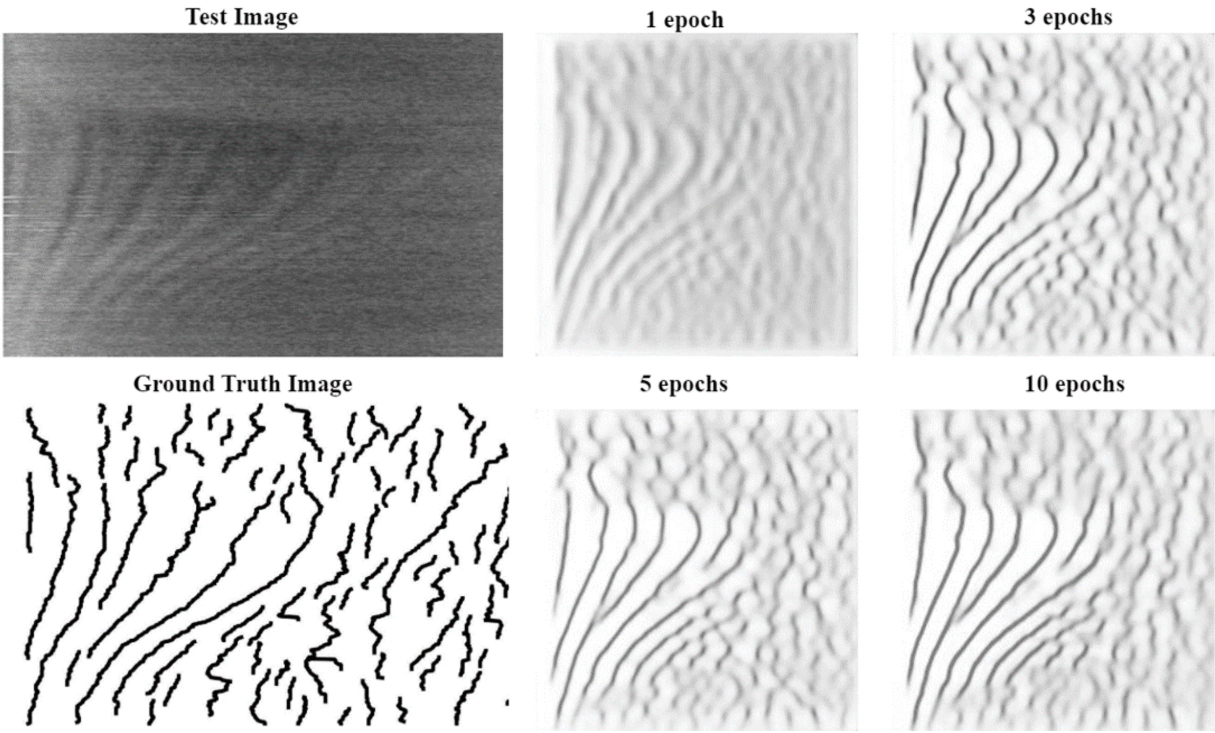
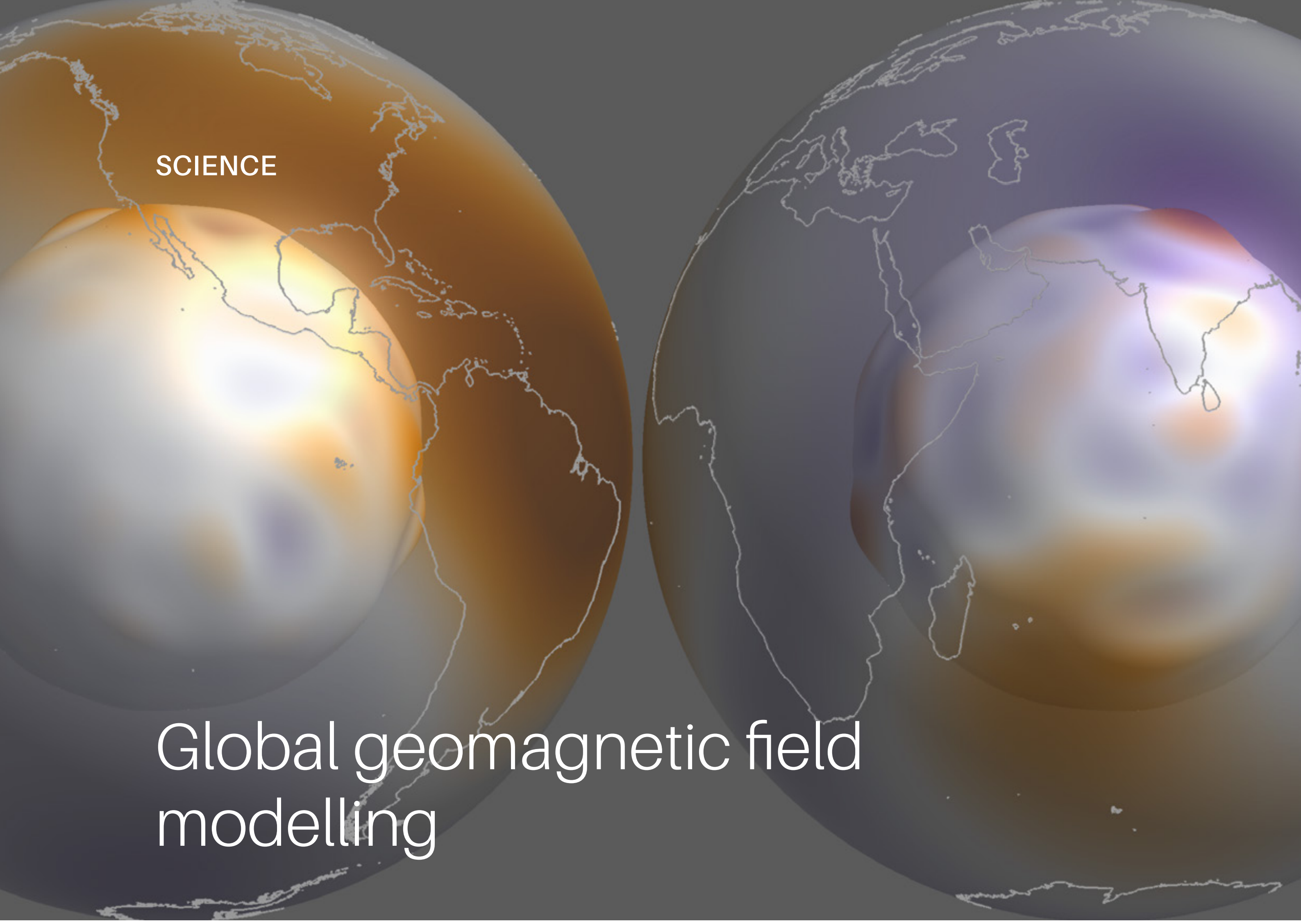


Figure 1 *Grayscale spectrogram (top left) and ground truth (bottom left) and the evolution of the U-net epochs as the network is iteratively trained. After 10 epochs the fringes have been clearly delineated (bottom right).*



Global geomagnetic field modelling

2019 was an eventful year for BGS in global geomagnetic field modelling. We contributed to releases of a new International Geomagnetic Reference Field (IGRF) and World Magnetic Model (WMM), and we provided an annual update of the BGS Global Geomagnetic Field Model (BGGM). We also continued to support magnetic survey satellite missions and the operation of ground observatories worldwide. We also documented an unusual occurrence in the history of geomagnetic observation.

World Magnetic Model 2020

A new generation of the WMM was released in December 2019. This model describes the global magnetic field at the beginning of 2020 and provides a prediction of its evolution for the next five years. (Reference models such as the WMM have to be updated to keep abreast of the constantly, and unpredictably, changing field of Earth's core.) The WMM is a collaboration between BGS and the US National Centers for Environmental Information, and is primarily intended for navigation purposes. The WMM is used by a wide variety of civilian, industrial, governmental, and military organisations to provide magnetic declination corrections, allowing users to orient themselves correctly anywhere from the Earth's surface to in-orbit. The WMM is embedded in many smartphones' map and navigation software, and you may be using it daily without realising. This release sees the introduction of a new model specification, developed with the WMM funding agencies (the UK Defence Geographic Centre and the US National Geospatial-Intelligence Agency). This specification defines how we calculate the model's accuracy and introduces

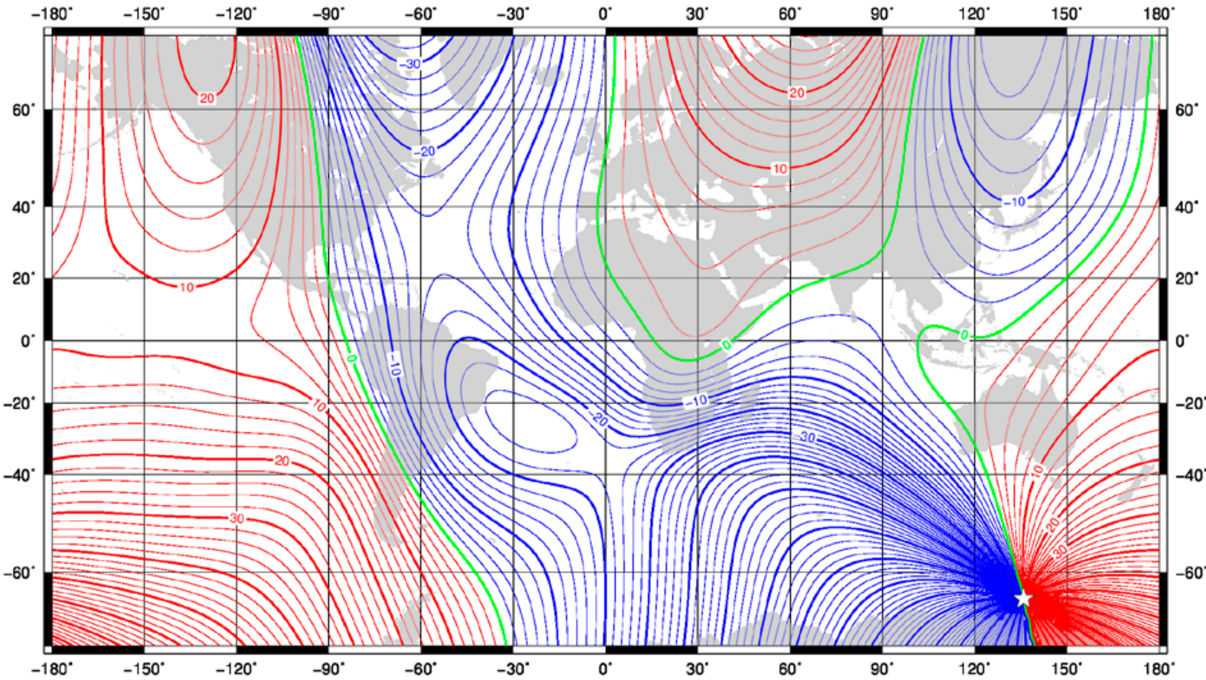


__Figure 1__ Declination given by WMM2020 in 2020, in degrees. Red is eastward (positive) declination, blue is westward (negative), green is the agonic (zero) line.

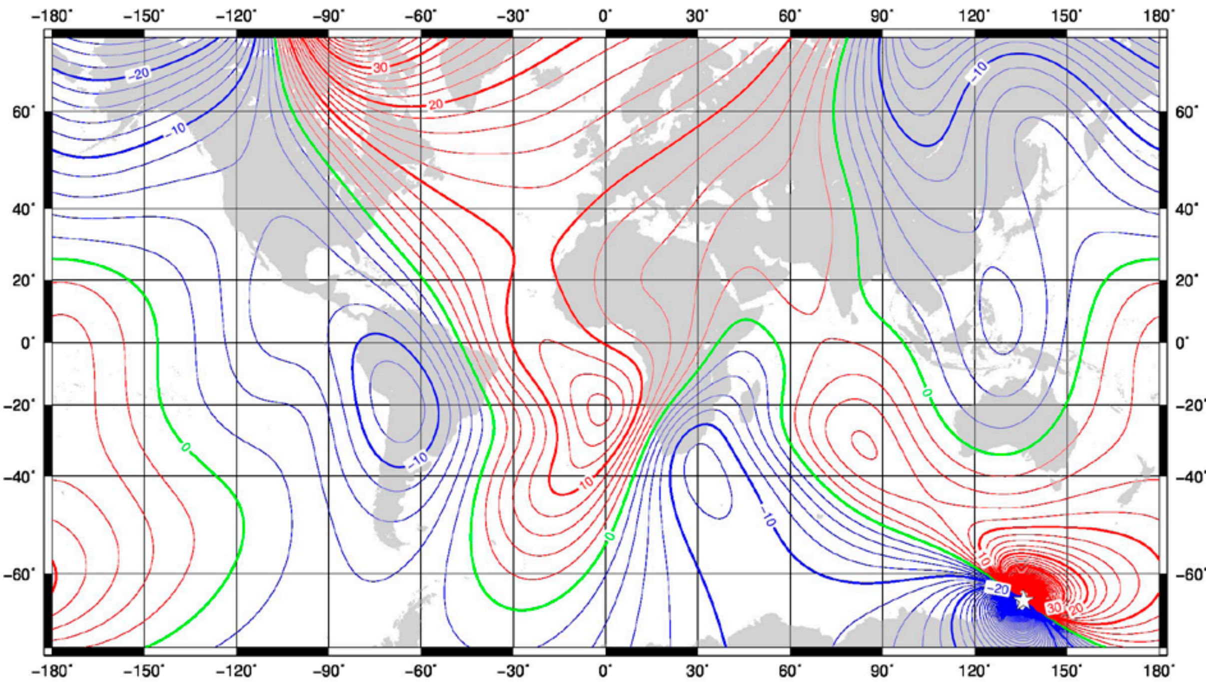


__Figure 2__ Annual rate change of declination for 2020.0 and 2025.0 from the World Magnetic Model (WMM2020). Red — easterly change; blue — westerly change; green — zero change. Contour interval is 2′/year, white star is location of a magnetic pole and projection is Mercator. This is an example of an isoporic chart. Credit: British Geological Survey (UK Research and Innovation).

'Black-Out Zones' near the magnetic poles, where compass navigation becomes unreliable. We will monitor the performance of the WMM for the next five years, in anticipation of the next scheduled update in 2024.

International Geomagnetic Reference Field 13th generation

The IGRF is an international academic collaboration, running since 1965 and endorsed by the International Association of Geomagnetism and Aeronomy. The release of the 13th generation IGRF involved fifteen teams of researchers from nine nations, including BGS. The IGRF is revised every five years, and IGRF-13 describes the large-scale field from Earth's core between 1900 and 2020. It also predicts the change in the field to 2025. The IGRF is the basis for magnetic coordinate systems used, for example by space physicists who wish to study phenomena in near-Earth space that may be better oriented with respect to the Earth's magnetic field, rather than to geographic latitude and longitude. BGS contributed candidate models for all parts of the IGRF-13: a definitive model for 2015; an initial model for 2020; and a prediction of the changes the field will undergo between 2020 and 2025. BGS was involved in analysing all 37 individual candidate models submitted by the teams and in deciding how best to derive the final models from these candidates.

BGS Global Geomagnetic Model 2019 and ongoing research

BGS released an annual update to the BGGM, to provide high accuracy reference magnetic field estimates, in support of directional drilling operations worldwide. The BGGM comes with scalable uncertainties and a high-spatial-definition spherical harmonic degree of 1440, which is equivalent to a spatial scale of approximately 28 km on the ground. The BGGM was updated using the latest data from our magnetic observatories, as well as from global magnetic data gathered through our role as a World Data Centre for Geomagnetism. The model also incorporated data from the Swarm satellite constellation, operated by ESA. This year we have also been involved in novel projects for ESA, using Swarm data, developing 'Geomagnetic Virtual

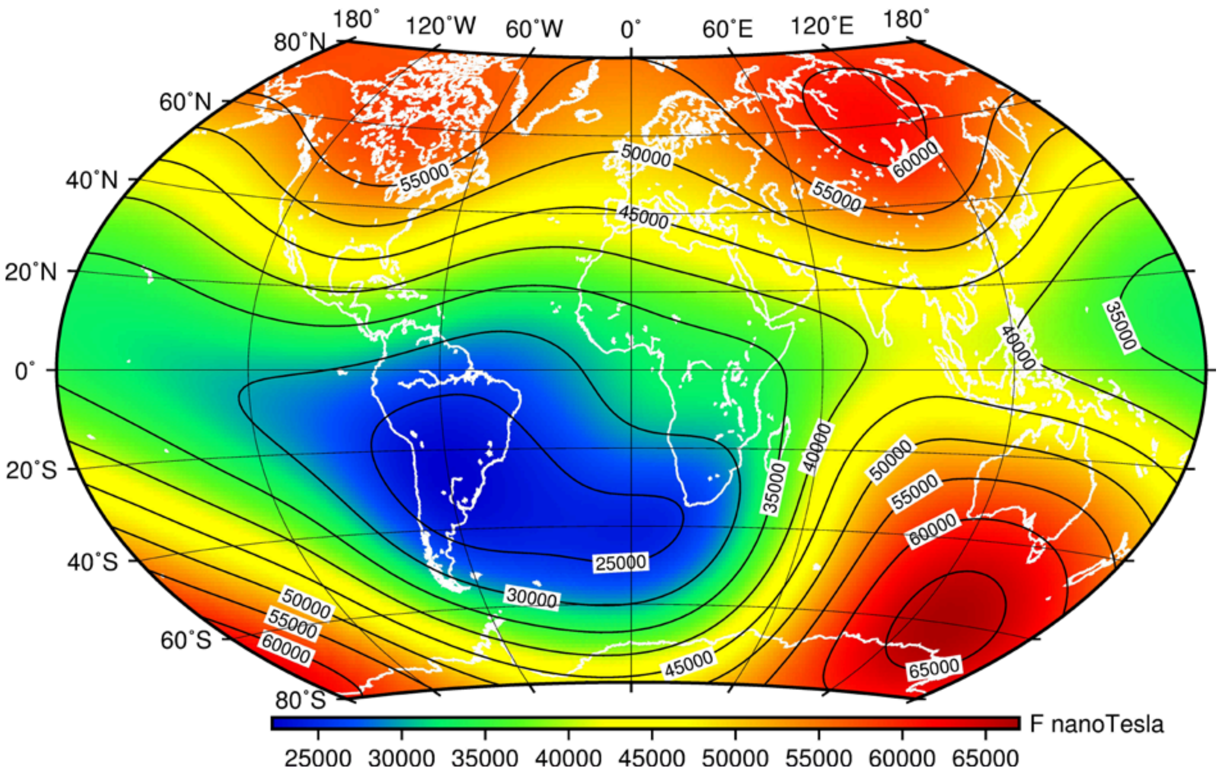


Figure 3 *Field intensity (F) in 2020 according to IGRF-13. Stronger (red) regions host the magnetic poles, the weaker (blue) region is known as the South Atlantic Anomaly.*

Observatories' (discussed elsewhere in this report) and investigating enhancements to our 'fast-track', large-scale magnetospheric magnetic model.

An historic 370 year prediction comes true

Our field modelling activities helped highlight the alignment between the Greenwich meridian, which denotes zero geographic longitude, and the slowly drifting agonic line of zero magnetic declination. This alignment occurred in London in September 2019. This means that, at that time, there was no correction needed between a magnetic and geographic heading at Greenwich: True North and Magnetic North were completely aligned. This is only the second documented occurrence of this phenomenon. The first occurrence was around about 1659, and a few years later Henry Bond made the correct, though unexplained, note that regarding the change of declination that, 'the period of the motion is about 370 years'.

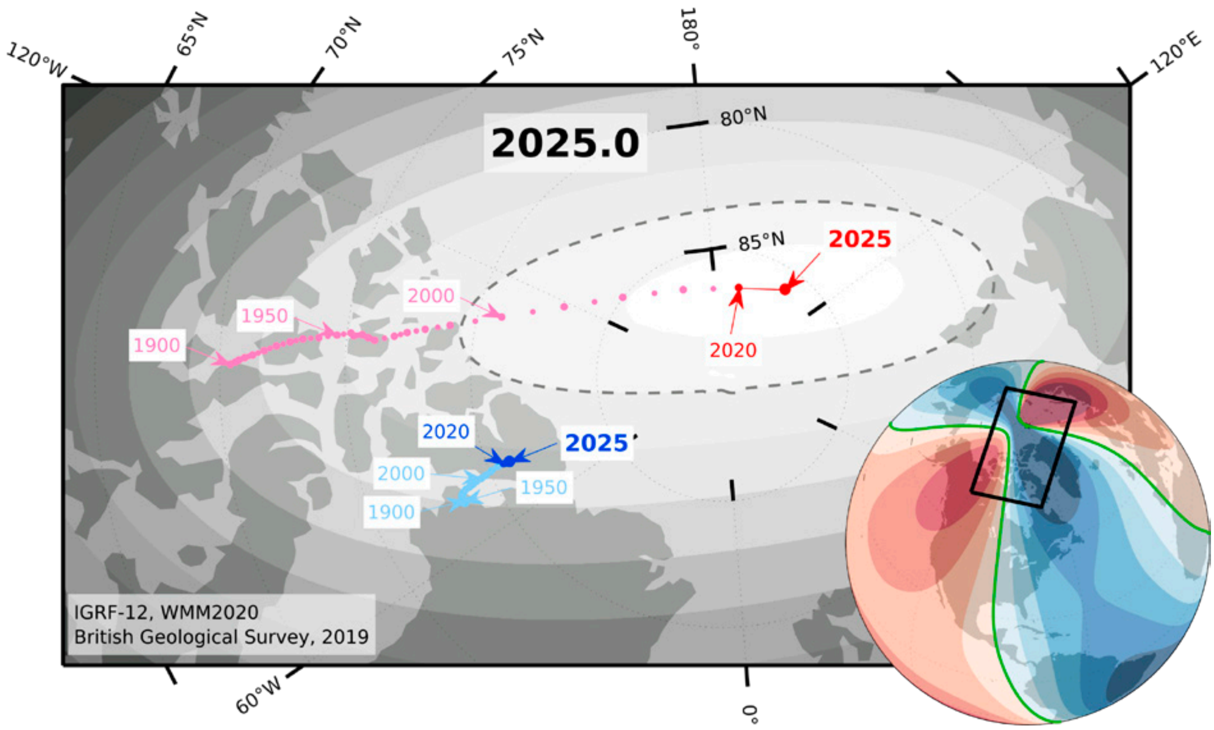


Figure 4 *Locations of the North geomagnetic pole (blue) and dip pole (red) according to IGRF (1900 to 2015) and WMM (2020 to 2025), against 1000 nT contours of the horizontal field strength (grey) predicted in 2025. Inset globe shows 5° contours of declination (eastward, red; westward, blue) and the location of the agonic (zero) line (green), predicted in 2025.*

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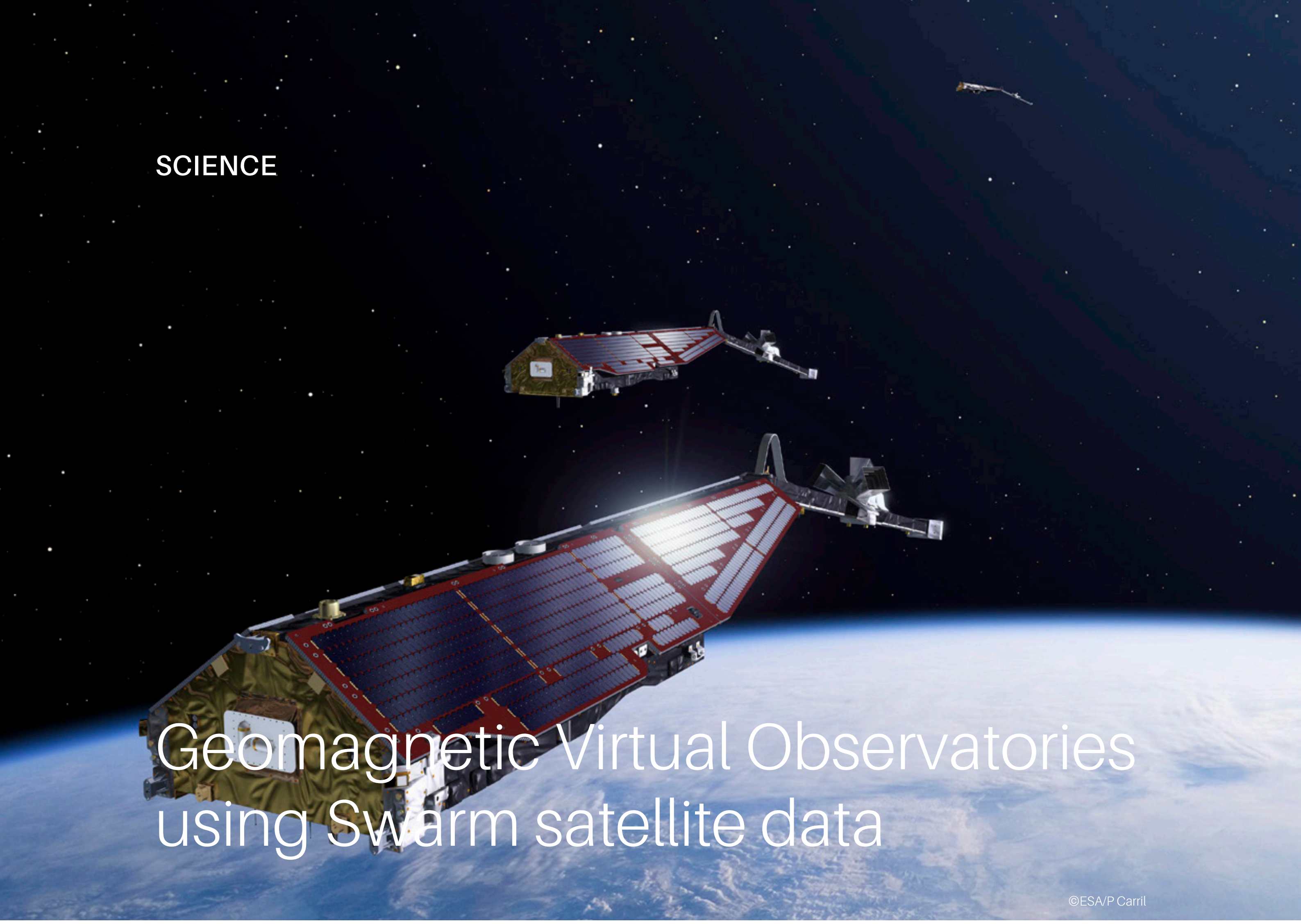

Geomagnetic Virtual Observatories using Swarm satellite data

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The Geomagnetism Team is collaborating with the Technical University of Denmark (DTU) on a project funded by the European Space Agency to use Swarm satellite survey data to produce time series of the geomagnetic field at each point on a fixed global grid. Each grid point is referred to as a Geomagnetic Virtual Observatory (GVO) and the GVO time series will be made available to the wider geomagnetism community as an official Swarm science product.

Measurements of the geomagnetic field across the globe tell us how the field changes in space and time. These variations can provide important insights that can be used in applied geomagnetism, for example through production of reference models that are used for scientific and industrial purposes. Magnetic variations are important also in geomagnetism science, such as helping us reveal the dynamic processes operating inside Earth's fluid outer core. However, a major obstacle to making long term global observations is the highly uneven spatial distribution of ground-based magnetic observatories, which are land-based and mostly in the northern hemisphere.

One solution to this obstacle is to use local modelling techniques and satellite data to create point estimates of the Earth's field at any given location, at satellite altitude. Such locations have become known as Geomagnetic Virtual Observatories (GVOs). The main advantage of GVOs is that time series of the field and its time variation (the secular variation, or SV) can be produced on a denser global grid, allowing better study of regions poorly covered by ground observatories. Figure 1 shows a map of GVOs produced by our partners at DTU, along with monthly SV estimates at those locations.

However, monthly GVOs are contaminated by two main sources: external fields such as the magnetosphere, and a local time sampling bias that arises because the Swarm satellites revisit the same location on Earth roughly every four months. Current methods to remove ('denoise') these signals from GVOs have drawbacks. First, averaging over four months removes the local time sampling bias, but at the cost of reducing the temporal resolution. Second, data selection criteria, such as data only from nightside and magnetically quiet-time conditions, greatly reduces the magnitude of external fields, but results in a small subset (<5%) of the original data being available for subsequent use. Third, removing model predictions of external fields reduces contamination. However, such parameterisations cannot fully describe these physical systems and some signal inevitably remains in the data. The Geomagnetism Team is therefore applying an alternative denoising approach. This is based on Principal Component Analysis (PCA), which does not suffer from the limitations described above. Our denoised GVOs will be passed back to DTU for final processing before being made available to the wider geomagnetism community as an official Swarm product.

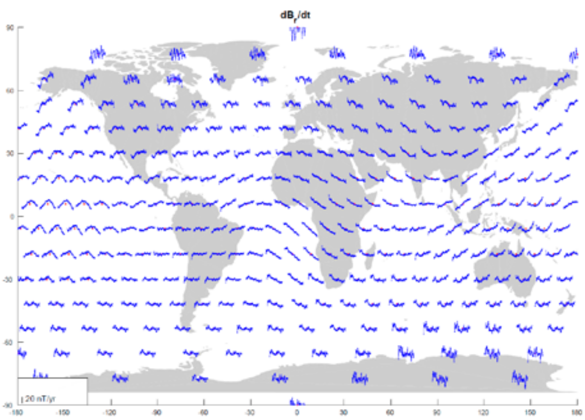

Figure 1 *Map of GVO locations (red dots) and the times series of the radial secular variation (dBr/dt) at that location each month over the Swarm satellite mission (blue lines). Figure courtesy of Magnus Hammer (DTU).*

As an example of the denoising technique (Figure 2) we have selected four GVOs and used PCA on their geomagnetic residuals (the difference between the GVO SV series and that predicted by a core field model). The PCA of these residuals gives information about correlated signals simultaneously present in data at several GVOs but not in the model. Such signals include external fields, sampling biases and unmodelled internal field changes. In this example, the largest principal component (PC) corresponds to correlated signals in the north (X) and vertical (Z) SV components, which is a typical magnetospheric signal at these magnetic latitudes. The second largest PC is in the Y (longitudinal) component and has a peak in its frequency spectrum at the satellite revisit time (~4 months), indicating that this signal arises from satellite orbital dynamics. Removing these two PCs, which are clearly related to identifiable contamination sources, results in much cleaner SV series at all four GVOs.

Figure 2 *Map of the four GVO locations (red dots) used to demonstrate the principal component analysis for low magnetic latitude observatories.*

Conference, student and visitor activities

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The Geomagnetism team welcomes visitors from around the world. We also have a number of PhD and MSc students supervised by our staff and who use BGS data, expertise and infrastructure to complete their research. Team members attended several conferences and international meetings during the year. Here we summarise events at two of the most significant conferences for presenting our work.

Students

BGS co-supervised three PhD students in 2019, funded by the NERC DTP programmes at Edinburgh and Leeds Universities and by the BGS BUFI programme. We also co-supervised an MPhil and an MSc project at the University of Edinburgh (Figure 1).

Ashley Smith completed his final year at Edinburgh investigating how to improve the modelling of crustal magnetic fields in the polar regions using Swarm satellite data. He successfully defended his PhD thesis in September 2019.

Maurits Metman also finished his PhD research on the large-scale changes of the magnetic field in the core that can be ascribed to diffusion of the magnetic field. He undertook his viva in July 2019.

Hannah Rogers completed the second year of her PhD, using Slepian mathematical functions to model the magnetic field using vector data, resulting in a paper in the journal Earth Planets and Space.

Relly Margiono completed his MPhil at the University of Edinburgh, on how to improve the Indonesian observatories network, in order to examine the oc-

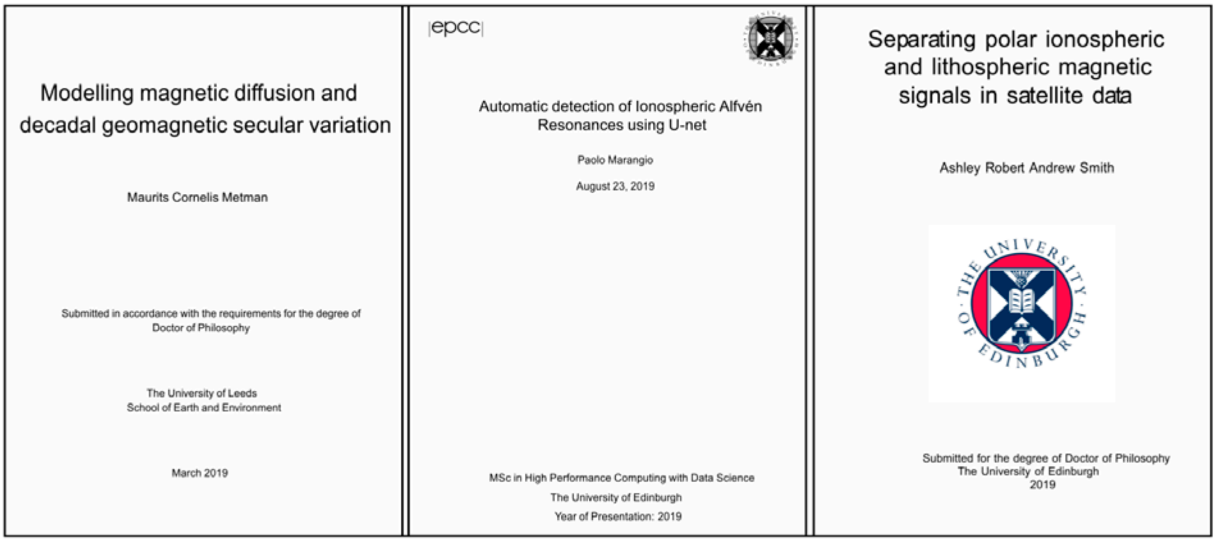


Figure 1 *Front covers of three of the theses submitted by PhD and Msc students in 2019.*

currence of rapid changes in geomagnetic secular variation in that region. He completed his thesis in March and was awarded a degree after successfully defending his work in May 2019.

Paolo Marangio produced an MSc thesis in collaboration with BGS and the Edinburgh Parallel Computing Centre (EPCC). His research focussed on using a machine learning technique (the 'U-net' neural network) to automatically recognise geophysical features in high frequency magnetic data from the Eskdalemuir induction coils (described in more detail elsewhere in this report). Paolo completed his research in August 2019.

Figure 2 *Ciaran Beggan delivering R Margiono's MPhil presentation at IUGG (on his behalf).*

Figure 3 *(Left to right) Guanren Wang, Alan Thomson, Ciaran Beggan, Sarah Reay and Ellen Clarke in the main coffee area at the European Space Weather Week conference in Liege, Belgium, November 2019.*

Visitors

We had a number of distinguished visitors to BGS in 2019. Dr Anca Isac of the Geophysical Institute of Romania (Surlari magnetic observatory) visited in January and we had discussions and presentations on observatory operations. Her time coincided with Scotland's 'Burns Night', so she joined us at our Team's annual haggis lunch. We hosted Dr Maxim Smirnov of Lulea Technical University (Sweden), in June, to develop magnetotelluric services under the EPOS project. Maxim was also helpful in providing advice on improving our magnetotelluric data processing. Dr David Boteler and Prof Trevor Gaunt visited separately in September 2019 to discuss the latest research on geomagnetically induced currents in rail, pipeline and the high voltage power networks. We also hosted Prof Sandra Chapman, Dr Nick Watkins and Lauren Orr in September 2019, to discuss future research and applications for funding, on the use of directed networks in space weather modelling.

Conferences

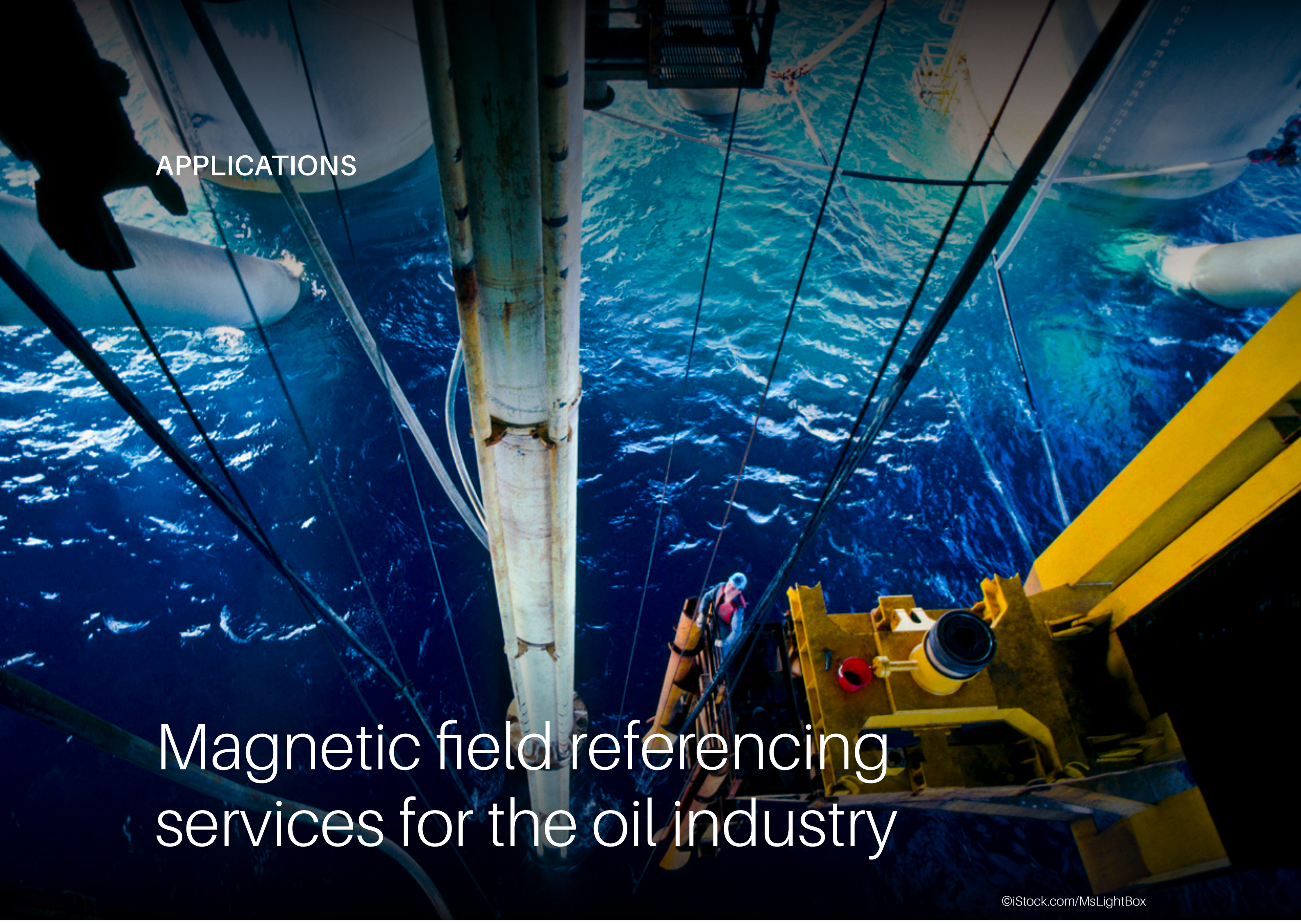
Five members of the Team attended the International Union of Geodesy and Geophysics (IUGG) conference in Montreal, Canada, in July. Ellen Clarke, Ciaran Beggan, Juliane Huebert and Simon Flower made five presentations between them, listing other Team members as collaborators (Figure 2). In addition, we presented four posters on other science achievements of the Team. Ellen, Ciaran and Alan Thomson co-convened various sessions and meetings. Ellen and Ciaran are IAGA working group chairs (on geomagnetic data and modelling, respectively) and Alan is vice-president of IAGA and a member of the IAGA executive committee. Immediately following the IUGG meeting, Alan, Ellen, Simon and Chris Turbitt travelled to Ottawa for the annual three-day INTERMAGNET meeting.

Five members of the Geomagnetism Team attended the 16th European Space Weather Week (ESWW) held between 18th and 22nd November

Figure 4 *Sarah Reay presenting the live Space Weather forecast on Day 1 of ESWW.*

in Liège, Belgium (Figure 3). Ciaran Beggan gave a presentation on 'Building a Raspberry Pi School Magnetometer Network in the UK' where he described the development of low-cost magnetometers systems, controlled by Raspberry Pi computers and operating in several UK schools. In a second presentation, he discussed the latest results from the SWIGS project (titled 'Validating GIC models with line current measurements using the Differential Magnetometer Method'). Sarah Reay delivered to the conference a three-day ahead forecast of geomagnetic activity, as part of the daily 'live space weather forecast' series during ESWW (akin to making a broadcast weather forecast — see Figure 4). Her forecast specifically targeted users interested in geomagnetically induced currents, such as power companies. Alan Thomson led a 'Topical Discussion Meeting' on 'How can we improve modelling of processes driving Geomagnetic Induced Currents and electric field impacts on ground-based systems?' This event attracted around 40 researchers for an hour-long debate on the current state of the art and what future research should address. As this was Guanren Wang's first international science conference, Guan summarised his experiences in a BGS 'GEOBLOGY' blog (https://britgeopeople.blogspot.com/2020/01/geomagnetism-and-european-space-weather.html).

Figure 5 *Ciaran Beggan, Ashley Smith and Susan Macmillan at the Lyell Centre.*



Magnetic field referencing services for the oil industry

Drilling for oil and gas in an efficient and safe manner commonly relies on magnetic survey tools to direct the drill head. These tools require accurate values of the Earth's magnetic field direction and strength along with accompanying verifiable estimates of the associated error. Deriving these values requires a combination of global and local observations of the Earth's magnetic field, as well as of modelling work. It can also require the timely delivery of real-time data from nearby observatories, especially at high latitudes.

The revision of the BGS Global Geomagnetic Model (BGGM) during the 1st quarter of 2019 included new work on modelling the global crustal magnetic field and on estimating error, as well as the usual update of the model of the field arising from the Earth's core. For the first time the BGGM incorporated information on the shorter wavelength crustal field from global compilations of aeromagnetic and marine magnetic total intensity anomaly data. The error arising in the BGGM from un-modelled crustal field was therefore reduced.

Vector magnetic data from both the ESA Swarm satellite mission and the observatory network, up to and including March 2019, were used to reduce the prediction error until the next BGGM revision in 2020.

The work to update the errors takes account of (1) the residual crustal field, including whether covered by near-surface magnetic anomaly data, (2) the residual, rapidly time-varying, field from the ionosphere and beyond (in a statistical sense) and

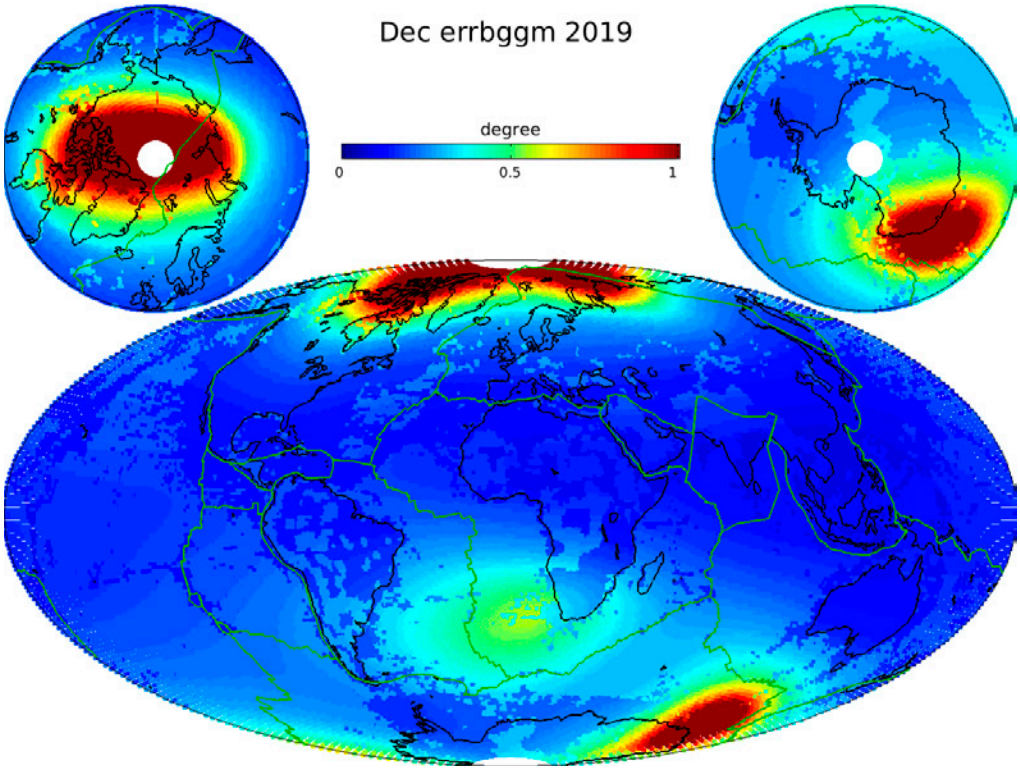


Figure 1 Scalable 1-sigma error in declination at 2019.0 as estimated by BGGM2019.

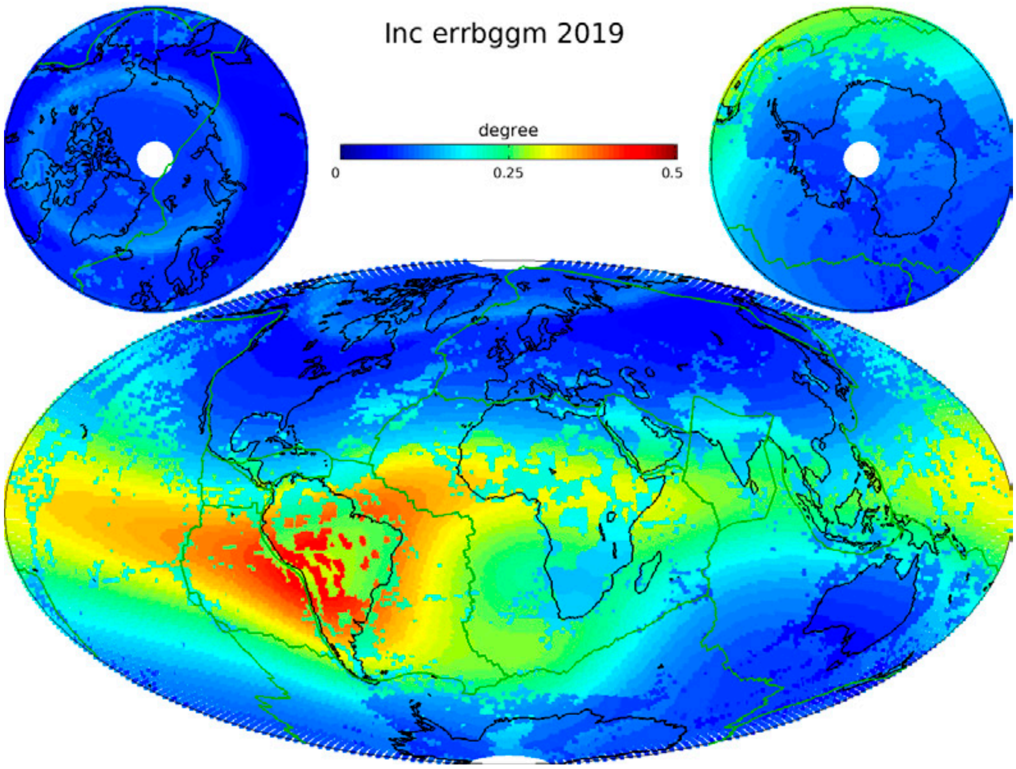


Figure 2 Scalable 1-sigma error for inclination at 2019.0 as estimated by BGGM2019.

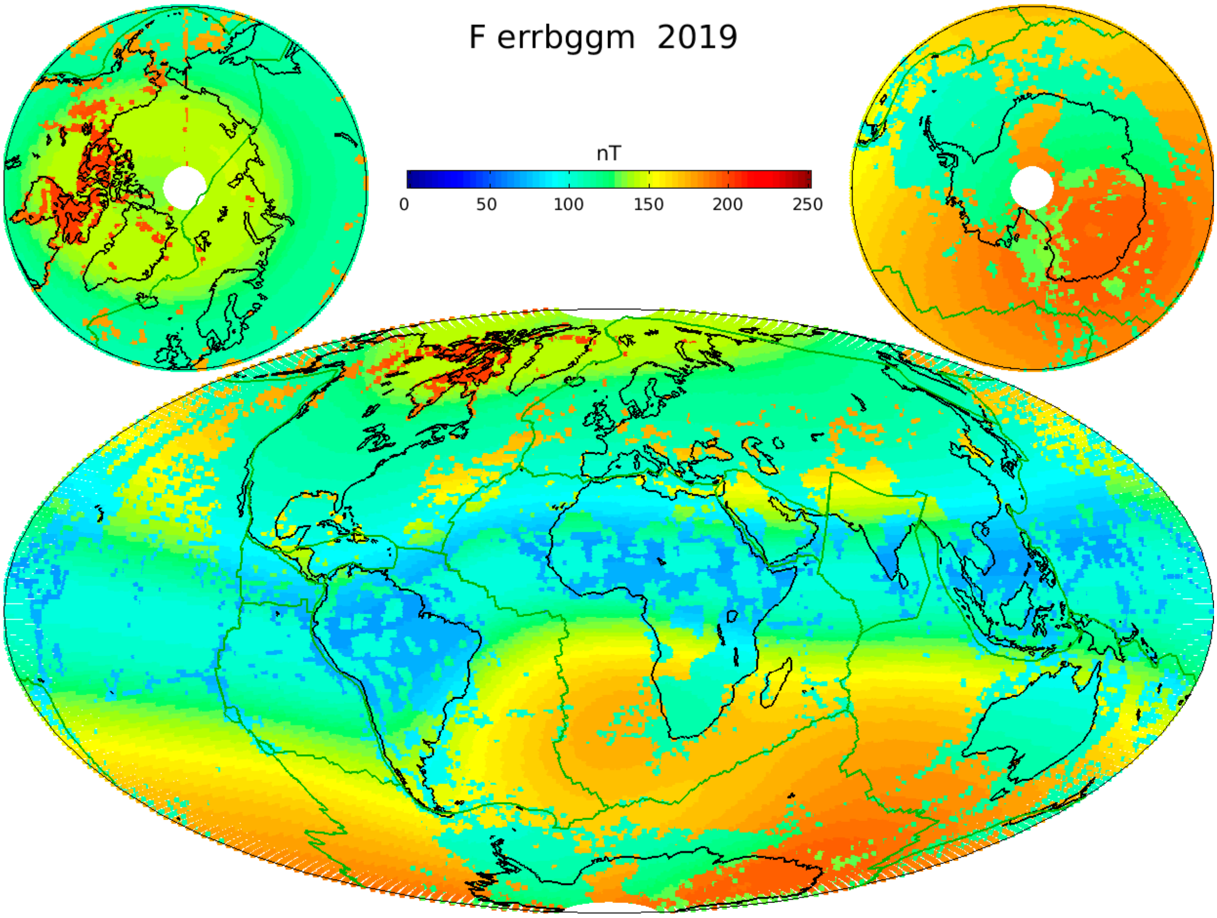


Figure 3 *Scalable 1-sigma error in total intensity at 2019.0 as estimated by BGGM2019.*

(3) core field prediction error. In the final stage the orthogonal (in geographic coordinates) XYZ error estimates in nT are converted to declination, inclination and total intensity estimates taking account of the main-field geometry. The final errors vary both in space and time, and are scalable 1-sigma estimates (Figures 1–3). This is so that they can be easily combined with other wellbore positioning errors and finally scaled up to the high confidence levels the industry uses.

Industry error models separate out the so-called global (bias) terms and random magnetic field error terms and propagate them differently in their final wellbore positioning error estimate software. To facilitate this deconstruction, and to improve how the industry estimates magnetic field errors (they have their own estimates which vary in space only for declination, and not in time), BGS developed a free BGGM error web service.

Although the BGGM now includes more of the crustal field, there is a limit to what can be mapped with a global model. To fill this gap, In-Field Referencing (IFR or IFR1) uses all local magnetic data, usually dominated by data from aeromagnetic or marine magnetic total intensity surveys, and derives vector estimates of the residual crustal field at waypoints along a given planned well-path.

Whilst IFR can account for the finer spatial variation in the magnetic field, a further improvement is also sometimes required by accounting for the finer temporal variations in the magnetic field. This is achieved using real-time estimates of the magnetic field from nearby observatories, which is called IIFR (or within industry IFR2). The reduction in the errors associated with the geomagnetic reference values achieved with IFR over the high definition BGGM varies with location depending on input data quality for the models. Similarly, the error reduc-

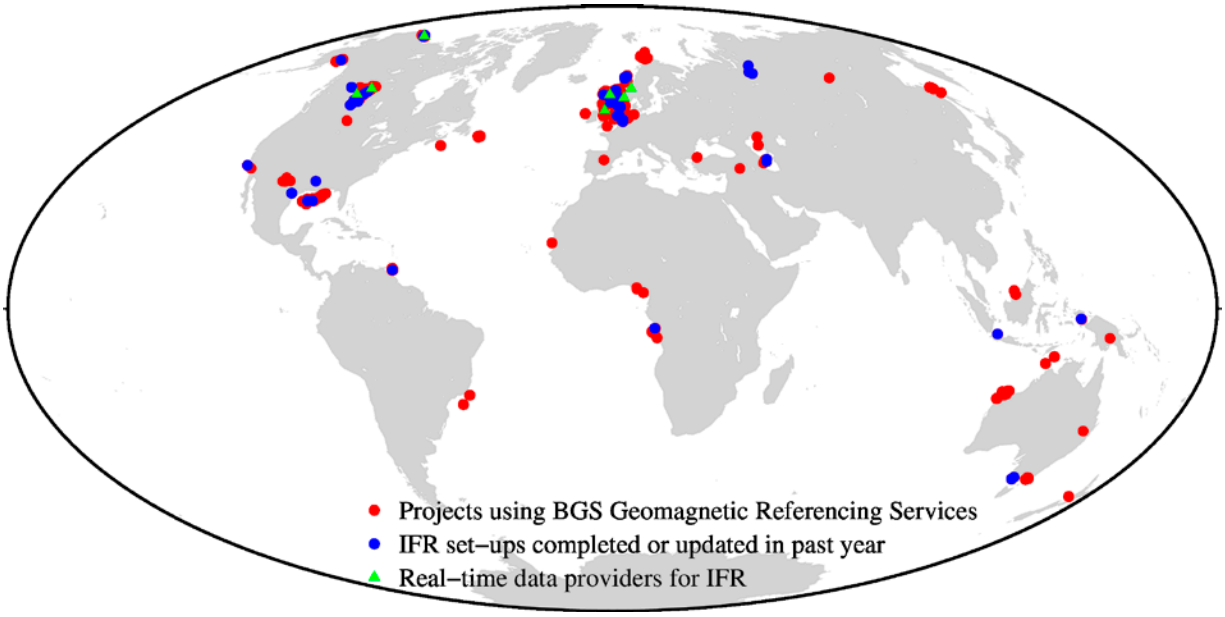


Figure 4 *Locations of In-Field Referencing projects.*

tion achieved with IIFR over IFR varies around the world, although in this case the dependence on geomagnetic latitude is the dominant factor.

The software behind the IFR calculations has been updated to better complement the high resolution BGGM (see elsewhere in this report). BGS IFR and IIFR services continue to be in high demand due to their reliability and high levels of industry confidence. New fields set up for IFR in 2019 were located in Canada, USA, North Sea, Russia, Australia and Indonesia (Figure 4).

Staff from the Geomagnetism Team were present and contributed to both 2019 meetings of the Industry Steering Committee on Wellbore Survey Accuracy. The October meeting, in Calgary, represented the 50th meeting of ISCWSA (Figure 5). BGS has been involved since 1995 with a focus on defining uncertainties associated with magnetic referencing data, an important part of the ISCWSA error model.

Figure 5 *Industry Steering Committee on Wellbore Survey Accuracy: 50th meeting.*

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Space weather and geomagnetic hazard

During 2019, the Geomagnetism Team continued to provide existing services and developed new applications and services, based on our space weather research. These new developments included delivering BGS data products to the re-constituted ESA Geomagnetic Expert Service Centre and the kick-off of an EU funded project, EUHFORIA2.0, studying solar wind prediction and its geomagnetic and radiation impacts. We also continued our space weather research activities under the NERC-funded SWIGS project (described elsewhere in this report) and carried out hazard analysis services and studies for National Grid and EDF Energy.

Met Office

We continue to provide UK Met Office with now-cast and forecast magnetic index data, including a Kp-equivalent index developed to cover Great Britain and Ireland (KGBI) and a new GIC activity index. Our daily, 3-day ahead geomagnetic activity forecast for the public and various industry sectors is also agreed with Met Office during a daily tele-phone call to ensure alignment of the UK forecast message.

National Grid

We operate a real-time service called 'Monitoring and Analysis of GIC' (MAGIC) for National Grid (Fig-ure 1). As part of this service, we model the electric field on the surface of the Earth and the Geomag-netically Induced Currents (GIC) that flow in the UK power transmission network, both of which are caused by space weather. During 2019, MAGIC continued to operate with only minor maintenance. An upgrade of the power grid network model will

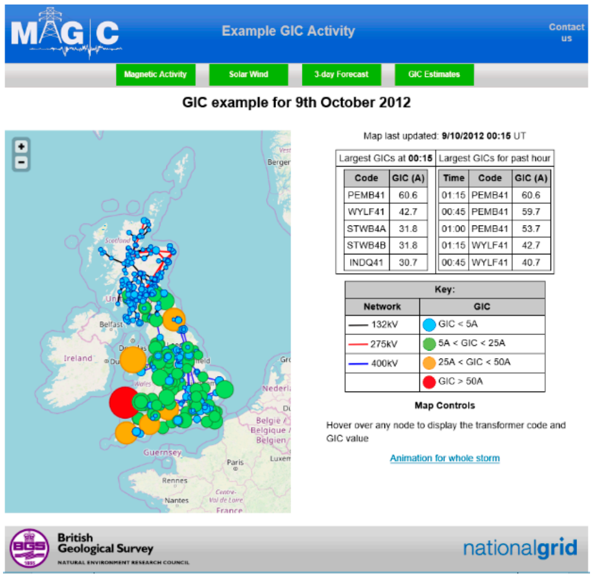


Figure 1 *Screenshot of a MAGIC webpage showing hypothetical GIC for severe geomagnetic activity in the southern half of the UK. Other pages within the MAGIC tool display real-time magnetic activity, alerts, solar wind shock data and the daily BGS 3-day magnetic forecast.*

be due in 2020 and we intend to use our scientific research into the UK geo-electric field, as part of the SWIGS project, to improve the accuracy of our electric field model.

EDF Energy

EDF have commissioned several study contracts, over several years, to explore the impact of severe space weather on the UK and French power transmission networks, with an emphasis on impacts on EDF assets. In 2019, we updated models of the UK and French systems, including for the first time a variety of transformer types and new high-voltage lines. We also examined the impact on these systems of severe hypothetical and historical events, including a sensitivity analysis of GIC, with respect to grid and transformer parameters and ground conductivity.

ESA G-ESC

ESA created Space Weather Expert Service Centres (ESC) several years ago to support its plans for general space situational awareness, in terms of space weather, debris and space object hazards. One of these centres is concerned with 'Geomagnetic Conditions' (the G-ESC). The G-ESC provides geomagnetic data products from institutes across Europe, based on models and real-time data, to a variety of stakeholders concerned with ground-level impacts of geomagnetic storms. BGS became one of the G-ESC expert groups in 2019. We are committed to creating web pages and web services to deliver existing and re-packaged BGS space weather products to G-ESC subscribers. Our G-ESC data products include real-time estimated magnetic indices, products describing power grid and pipeline impacts in the UK, electric field data and auroral images. Forecasts of some of these key data will also be provided. The BGS contribution to the G-ESC will be rolled out in stages until August this year. Thereafter we hope to negotiate a service contract to continue to provide these services and hopefully to bid to introduce more products into the G-ESC product suite.

EUHFORIA2.0

EUHFORIA (EUropean Heliospheric FORecasting Information Asset) is a mathematical model of the solar wind, driven by solar eruptions, constructed by researchers at the Catholic University of Leuven, Belgium. The EUHFORIA2.0 project is funded by the EU under the H2020 programme and the project started in December 2019, to run for four years. One of the science goals of this project is to couple an enhanced version of the EUHFORIA model to models of the magnetosphere, including the electrical currents that link the magnetosphere to the ionosphere. Success in this will provide a new rudimentary capability in forecasting geomagnetic disturbances at the Earth's surface, based on observations of solar activity in the form of coronal mass ejections and coronal holes, one to several days before. The BGS role in the project is to use these forecast magnetic variations to determine the GIC that might flow in examples of power networks in Europe, including the UK and Finland. Our contribution will occur mainly in the second half of the work programme.

Publications and knowledge exchange

A wide variety of outputs are produced by the Geomagnetism Team, including papers in scientific journals, commissioned reports, posters, talks and presentations.

Scientific journal publications

Published 2019

Beggan, C, and Musur, M A. 2019. Is the Madden–Julian Oscillation reliably detectable in Schumann Resonances? *Journal of Atmospheric and Solar-Terrestrial Physics*, 190. 108–116. https://doi.org/10.1016/j.jastp.2019.05.009.

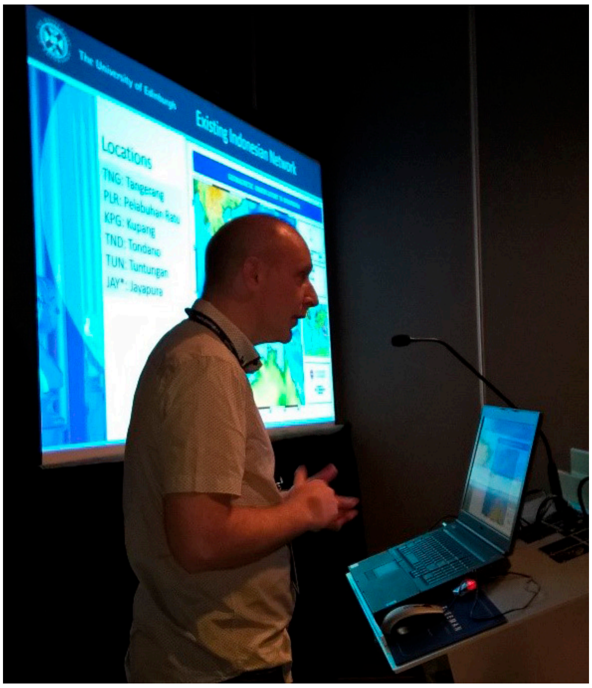
Campanyà, J, Gallagher, P T, Blake, S P, Gibbs, M, Jackson, D, **Beggan, C D**, **Richardson, G S**, Hogg, C. 2019. Modeling geoelectric fields in Ireland and the UK for space weather applications. *Space Weather*, 17 (2). 216–237. https://doi.org/10.1029/2018SW001999.

Macmillan, S, and **Taylor, T**. 2019. A magnetic prediction comes true. *Astronomy & Geophysics*, 60(1), https://doi.org/10.1093/astrogeo/atz041, Feb 2019.

Margiono, R, **Turbitt, C W**, **Beggan, C**, Whaler, K A. 2019. Improvements of geomagnetic data quality at Indonesian observatories. *Conrad Observatory Journal 5 - Special Issue IAGA Workshop 2018*, p.31.

Martyn, T P, Swan, A P, Taylor, T L, Turbitt, C W. 2019. Differential Magnetometer System in Support of Space Weather Impact Modelling. *Conrad Observatory Journal 5 - Special Issue IAGA Workshop 2018*, p.18.

Metman, M C, Livermore, P W, Mound, J E, **Beggan, C D**. 2019. Modelling decadal secular variation with only magnetic diffusion. *Geophysical Journal International*, 219 (Supplement_1). S58–S82. https://doi.org/10.1093/gji/ggz089.



Ciaran Beggan presents results at the IUGG meeting in Montreal, from the Indonesian observatory network, following completion of an MSc project by Relly Margiono of BMKG, Indonesia, together with BGS and University of Edinburgh.

Musur, M A, and **Beggan, C D**. 2019. Seasonal and Solar Cycle Variation of Schumann Resonance Intensity and Frequency at Eskdalemuir Observatory, UK. *Sun and Geosphere,* 14/1, 81–86. https://doi.org/10.31401/SunGeo.2019.01.11.

Oughton, Edward J, Hapgood, Mike, **Richardson, Gemma S, Beggan, Ciaran D, Thomson, Alan W P**, Gibbs, Mark, Burnett, Catherine, Gaunt, C. Trevor, Trichas, Markos, Dada, Rabia, Horne, Richard B. 2019. A risk assessment framework for the socio-economic impacts of electricity transmission infrastructure failure due to space weather: an application to the United Kingdom. *Risk Analysis*, 39 (5). 1022-1043. https://doi.org/10.1111/risa.13229.

Rogers, H F, **Beggan, C D**, Whaler, K A. 2019. Investigation of regional variation in core flow models using spherical Slepian functions. *Earth, Planets and Space*, 71:19. https://doi.org/10.1186/s40623-019-0997-7.

Published and to appear 2020 (as at March 2020)

Brown, N, B**ainbridge, B, Beggan, C, Brown, W, Hamilton, B, Macmillan, S**. 2020. Modelling the Earth's geomagnetic environment on Cray machines using PETSc and SLEPc. *Concurrency and Computation: Practice and Experience*. https://doi.org/10.1002/cpe.5660.

Rogers, N C, Wild, J A, Eastoe, E F, Gjerloev, J W, and **Thomson, A W P**. 2020. A global climatological model of extreme geomagnetic field fluctuations. J. *Space Weather Space Clim*. 10, 5. https://doi.org/10.1051/swsc/2020008.

Other Publications and Reports

Chulliat, Arnaud; **Brown, William**; Alken, Patrick; **Macmillan, Susan**; Nair, Manoj; **Beggan, Ciaran**; Woods, Adam; **Hamilton, Brian**; Meyer, Brian; Redmon, Robert. 2019. Out-of-Cycle Update of the US/UK World Magnetic Model for 2015–2020. National Centers for Environmental Information, NOAA, 16pp. (BGS Open Report OR/19/028)

Reeves, G, **Thomson, A**. 2019. Next Step Space Weather Benchmarks. Report NS GR-10982, IDA Science and Technology Policy Institute. (https://www.ida.org/-/media/feature/publications/n/ne/next-step-space-weather-benchmarks/gr-10982.ashx).

Macmillan, S, and **Taylor, T**. 2019. A 370-year Magnetic Prediction Comes True. Navigation News, January-February, 20–21, Royal Institute of Navigation, London.

Thomson, A. 2019. Space weather: northern lights and technology hazard. The Geographer, pp 27, summer edition, Royal Scottish Geographical Society. (https://www.rsgs.org/Handlers/Download.ashx?IDMF=a7e5473e-b952-4cf0-9b0e-71db-b693a296).

Bi-monthly column on Space Weather review for Royal Institute of Navigation's 'Navigation News' (https://rin.org.uk/page/NavigationNews).

1 BGS Open Report: **Thomson, Alan W P**, ed. Geomagnetism review 2018. British Geological Survey, 48pp. (OR/19/040) https://www.geomag.bgs.ac.uk/documents/reviews/Geomagnetism_Review_2018.pdf

2 BGS Commissioned Reports for 2 non-oil industry customers.

19 BGS Commissioned Reports for oil industry customers.

108 Observatory Monthly Bulletins: http://www.geomag.bgs.ac.uk/data_service/data/bulletins/bulletins.html.

Conference presentations, posters and related activities

Magnetic Interactions 2019 meeting, Liverpool, January

1 presentation (Macmillan, Beggan, Brown, Hamilton)

RAS Ordinary Meeting, London, April

1 presentation (Beggan)

EGU General Assembly, Vienna, Austria, April

1 presentation (Brown, Cox)

ESA Living Planet Symposium, Milan, Italy, May

1 poster (Cox, Brown)

Geomagnetism Advisory Group annual meeting, Edinburgh, June

6 presentations (Thomson, Macmillan, Clarke, Flower, Martyn, Beggan)

National Astronomy Meeting, Lancaster, July

2 posters (Huebert, Beggan, Richardson, Martyn, Thomson)

IUGG General Assembly 2019, Montreal, Canada, July

4 presentations (Clarke, Huebert, Beggan, Thomson)
4 posters (Baillie, Beggan, Brown, Flower, Huebert, Macmillan, Thomson)
3 session co-organisers (Beggan, Clarke, Thomson)
1 vice-president (Thomson)
2 working group chairs (Beggan, Clarke)

BGS Digital Data Workshop, Keyworth, July

1 presentation (Macmillan)

ESA Swarm 9th Data Quality Workshop, Prague, Czech Republic, September

1 presentation (Brown, Cox)

European Space Weather Week 16, Liege, Belgium, November

2 presentations (Beggan, Huebert, Richardson, Thomson)
1 poster (Thomson, Clarke and external collaborators)
'Live Space Weather Forecast' (Reay)
1 Topical Discussion Meeting for 40 organised (Thomson)

Geomagnetism Team seminars, Edinburgh

18 presentations throughout the year by team members, students and visitors

Some other notable outputs

Observatory tours

- Edinburgh University Flexible Learning Week, Eskdalemuir in February (Turbitt)
- Tour of Eskdalemuir for Moffat Probus Club in March (Turbitt)
- University of East Anglia Meteorology Field Course, Eskdalemuir, in April (Turbitt)
- Strathclyde University, Eskdalemuir, in April (Turbitt)
- Royal Navy & UK Hydrographic Office, Hartland, in May (Turbitt)
- Cambridge University, Hartland, in November (Turbitt)

Public Lectures, Presentations and Demonstrations

- Demonstration on Geomagnetism at the 'White House Holiday Club', February (Huebert, Brown)
- Lecture on space weather, University of Edinburgh, in March (Beggan)
- Lecture on Geomagnetism to British Science Association, Dundee branch, in March (Beggan)
- Celebration of Eskdalemuir observatory recognition as a 'centennial observing location' by the World Meteorological Organisation, in July (Turbitt, Macmillan)
- Lyell Centre Doors Open day, demonstrations and talk, September (Reay)
- Lecture on space weather to Royal Meteorological Society, Edinburgh, December (Clarke)
- Lecture course for Indonesian Geomagnetic Observatories Workshop, BMKG Citeko, Indonesia, in September (Turbitt)

Software Development

- Delivery of four geomagnetic index products for the ESA Geomagnetic Expert Centre
- Four 1-week long Sprints to convert the observatory data logging code from QNX to Linux
- Investment in IT best practice by developing our systems to use tools such as GitLab CI, Ansible, Docker, Kubernetes

Media

- Susan Macmillan and Ciaran Beggan responded to numerous digital, print, radio and TV media requests for information on the westward change

of the compass direction in the UK, the first in 370 years, including the moment that true and magnetic north were aligned on the Greenwich Meridian. This included The One Show (Caroline Graham presenting for BGS), Reuters and BBC Radio Scotland (both Ciaran Beggan).
- The release of the updated World Magnetic Model 2015-2020 (version 2 – jointly between BGS and NOAA) generated a lot of media interest. Ciaran Beggan and William Brown gave over 30 interviews to worldwide organisations such as Reuters, BBC, CNN, National Geographic as well as to national press such as the Guardian, Times, Economist, New York Times, Washington Post and websites such as the Atlantic, Vice and Space.com. Podcasts for the Guardian and BBC Focus magazine were also recorded

Education

- Eight University of Edinburgh 3rd year undergraduate Geomagnetism lectures, October to April (Brown and Beggan)
- Geomagnetism student and early career scientist training at IAGA Summer School, Canada, July (Kerridge)
- BAS staff in October, training in magnetic observatory operations for King Edward Point observatory in South Georgia (Turbitt)

Other

- Visit by Chris Turbitt to Citeko, Indonesia in September for keynote address and provision of training in magnetic observatory operations, metadata, INTERMAGNET at the BMKG Geomagnetic Workshop
- Visit by Dr Anca Isac of the Geophysical Institute of Romania (Surlari magnetic observatory) in January including discussions and presentations on observatory operations
- Visit by Dr Maxim Smirnov of Lulea Technical University (Sweden), in June, to develop magnetotelluric services under the EPOS project
- Thomson, Flower, Turbitt, Clarke participated in the annual INTERMAGNET meeting in Ottawa in July
- Ciaran Beggan, Brian Hamilton, Susan Macmillan, Victoria Ridley and Alan Thomson, together with other external co-authors, jointly won the 1st 'Special Paper Award' of the Springer journal 'Earth, Planets and Space' for their paper 'International Geomagnetic Reference Field: the 12th generation' published in 2015. The IGRF paper has been heavily referenced over the years and this free academic model of the geomagnetic field is widely used by scientists and industry around the world.
- Alan Thomson was a section editor for a Cambridge University Press volume on IAGA science achievements to celebrate the organisation's 100 year anniversary. The book is titled 'Geomagnetism, Aeronomy and Space Weather'. David Kerridge was the author of a chapter on the 'Objectives of Geomagnetic and Aeronomy Studies'.
- Alan Thomson was an international panel member of the US Space Weather Benchmarks 'Phase 2' review exercise, held by the US government between March and September
- Alan Thomson was a member of the International Scientific Board reviewing the Large Research Infrastructure CzechGeo/EPOS project for the Institute of Geophysics of the Czech Academy of Sciences (August)
- Susan Macmillan was a judge in a competition called MagQuest run for the US National Geospatial Intelligence Agency to find innovative solutions for long-term provision of data suitable for producing low resolution global magnetic field models
- Site survey by Chris Turbitt and Ciaran Beggan at Marble Arch Caves GeoPark in Fermanagh, Northern Ireland (September) with GSNI (Marie Cowan, Derek Reay, Kirstin Lemon), in preparation for installation of a magnetometer system for long-term space weather monitoring and the building of a wider geomagnetic collaboration across GB and Ireland
- Geomagnetism-sponsored PhD student Ashley Smith, at University of Edinburgh and co-supervised by Susan Macmillan and Ciaran Beggan, successfully defended his thesis on Geomagnetism research with Swarm satellite survey magnetic data
- Maurits Metman (Leeds University) successfully defended his PhD on the use of diffusion in magnetic field modelling in July 2019. He was co-supervised by Ciaran Beggan. His work contributed to a secular variation prediction candidate for the 13th generation of the International Geomagnetic Reference Field.

Glossary, acronyms and links

ap	*The amplitude equivalent of Kp, providing mid-latitude planetary geomagnetic activity levels*
BAS	*British Antarctic Survey (www.bas.ac.uk)*
BGGM	*BGS Global Geomagnetic Model (www.geomag.bgs.ac.uk/bggm.html)*
BGS	*British Geological Survey (www.bgs.ac.uk)*
BMKG	*Indonesian national meteorological and geophysical agency*
BUFI	*BGS University Funding Initiative (www.bgs.ac.uk/research/bufi/)*
CDF	*Computable Document Format*
CI	*Continuous integration*
CPU	*central processing unit*
DCAT-AP	*Data Catalogue Vocabulary Application Profile (for Data Portals in Europe, e.g. EPOS)*
DISC	*Data, Innovation and Science Cluster supporting the ESA Swarm mission*
DLL	*Dynamic Link Library*
DMM	*Differential Magnetometer Method for detecting GIC in power lines*
DOI	*Digital Object Identifier*
DTP	*Doctoral Training Partnership*
DTU	*Danish Technical University, Copenhagen, Denmark (www.dtu.dk/English)*
ECCC	*Environment and Climate Change Canada*

EGMODA	*European Geomagnetic Model and Data service of EPOS*
EGU	*European Geosciences Union (www.egu.eu)*
EPCC	*Edinburgh Parallel Computing Centre (www.epcc.ed.ac.uk/)*
EPOS	*European Plate Observing System (www.epos-ip.org/)*
ESA	*European Space Agency (www.esa.int)*
EU	*European Union*
EUHFORIA	*EUropean Heliospheric FORecasting Information Asset*
ESWW	*European Space Weather Week. (sidc.oma.be/esww16)*
FMC	*3-letter IAGA code for Fort McMurray magnetic observatory (Alberta, Canada)*
GDAS	*Geomagnetic Data Acquisition System*
GDASView	*GDAS data viewing and baseline processing software*
G-ESC	*Geomagnetic Conditions Expert Service Centre (swe.ssa.esa.int/geomagnetic-conditions)*
GFZ	*GeoForschungsZenturm, Germany (www.gfz-potsdam.de/en/home/)*
GIC	*Geomagnetically Induced Currents (a natural hazard to power systems)*
GitHub	*GitHub is a web-based hosting service for software development projects that use the Git revision control system*
GNSS	*Global Navigation Satellite System*
GEOBLOGY	*BGS blog site (www.bgs.ac.uk)*
GPU	*Graphical Processing Units*
GSNI	*Geological Survey of Northern Ireland (www.bgs.ac.uk/gsni/)*
GUI	*Graphical User Interface*
GVO	*Geomagnetic Virtual Observatory*
G1, G2 etc	*Geomagnetic activity index scale (1=low, 5=high), arithmetically equal to Kp-4*
HV	*High Voltage*
H2020	*An EU Research and Innovation programme (ec.europa.eu/programmes/horizon2020/)*
IAGA	*International Association of Geomagnetism and Aeronomy (www.iugg.org/IAGA)*
IAR	*Ionospheric Alfven Resonances*
ICS	*Integrated Core Services*
ICSU	*International Science Council (www.icsu-geounions.org)*
IGRF	*International Geomagnetic Reference Field (www.ngdc.noaa.gov/IAGA/vmod/igrf.html)*
IIFR/IFR	*Interpolation In-Field Referencing/In-Field Referencing (www.geomag.bgs.ac.uk/data_service/directionaldrilling/ifr.html)*
IMAGE	*International Monitor for Auroral Geomagnetic Effects (space.fmi.fi/image/www/index.php)*
INTERMAGNET	*International Magnetometer Network: a global network of magnetic observatories operating to common standards.(www.intermagnet.org)*
INDIGO	*Collaborative effort of BGS and Royal Observatory Belgium, supplying developing nations with magnetometers (described in pubs.usgs.gov/of/2009/1226)*
IP	*Implementation Phase of the EPOS project (2015–2019)*
IRDS	*INTERMAGNET Reference Data Set*
ISGI	*International Service for Geomagnetic Indices (www.isgi.unistra.fr)*
IT	*Information Technology*

IUGG	*International Union of Geodesy and Geophysics (www.iugg.org)*
JCO	*3-letter IAGA code for Jim Carrigan (magnetic) Observatory (Alaska, USA)*
JDK	*Java Development Kit*
KEP	*3-letter IAGA code for King Edward Point magnetic observatory (South Georgia)*
KGBI	*A measure of geomagnetic activity in the region of Great Britain and Ireland on a scale of 0-9*
Kp	*A measure of mid-latitude planetary average geomagnetic activity, on a scale of 0-9*
LTU	*Lulea Technical University (Sweden)*
MAGIC	*Monitoring and Analysis of GIC. A GIC analysis service for the National Grid*
MEME	*Model of the Earth's Magnetic Environment (geomag.bgs.ac.uk/research/modelling/MEME.html)*
Met Office	*UK Meteorological Office (www.metoffice.gov.uk)*
MHR	*Multi-Hazards and Resilience science challenge of the BGS Science Strategy 2019–2024*
MIST	*Magnetosphere, Ionosphere and Solar-Terrestrial UK scientific community (www.mist.ac.uk/)*
MOSWOC	*UK Met Office Space Weather Operations Centre (www.metoffice.gov.uk/weather/specialist-forecasts/space-weather)*
MSSL	*Mullard Space Science Laboratory (University College London) (www.ucl.ac.uk/mssl/)*
MT	*Magneto-telluric*
NERC	*Natural Environment Research Council (www.nerc.ac.uk)*
NOAA	*National Oceanographic and Atmospheric Administration (USA)*
PCA	*Principal Component Analysis*
POP	*Pilot Operational Phase of the EPOS project (2020–2022)*
QA/QC	*Quality Assurance/Quality Control*
Raspberry Pi	*A small, low-cost computer (www.raspberrypi.org)*
RAS	*Royal Astronomical Society (ras.ac.uk/)*
RIN	*Royal Institute of Navigation (www.rin.org.uk/general/Navigation-News)*
SBL	*3-letter IAGA code for Sable Island magnetic observatory (Nova Scotia, Canada)*
SEIEG	*Space Environment Impacts Expert Group (convened by the UK government)*
STFC	*Science and Technology Facilities Council (stfc.ukri.org/)*
SuperMAG	*A US funded project with a database of global magnetic field measurements (http://supermag.jhuapl.edu/)*
SV	*Secular variation (the time-rate-of-change of the magnetic field)*
Swarm	*Three-satellite 'mini-constellation' for magnetic field surveying (www.esa.int/Our_Activities/Observing_the_Earth/Swarm)*
SWENET	*Space Weather Network (ESA) (swe.ssa.esa.int/TECEES/swenet.html)*
SWIGS	*Space Weather Impact on Ground-based Systems (www.geomag.bgs.ac.uk/research/SWIGS)*
SWPC	*Space Weather Prediction Center (USA) (www.swpc.noaa.gov/)*
TCS	*Thematic Core Service (of EPOS)*
UKRI	*United Kingdom Research and Innovation (www.ukri.org)*
UNESCO	*United Nations Educational, Scientific and Cultural Organization*

UTM	*Universal Transverse Mercator (map projection)*
VBA	*Visual Basic*
WDC	*World Data Centre, part of the ICSU World Data System (www.wdc.bgs.ac.uk)*
WDMAM	*World Digital Magnetic Anomaly Map (wdmam.org/)*
WMM	*World Magnetic Model (https://geomag.bgs.ac.uk/research/modelling/WorldMagneticModel.html)*

BGS Geomagnetism in 2019

Staff changes

Brian Hamilton, Tom Humphries, Tony Swan, Tim Taylor and Rob Webster left BGS during the year. Brian researched the global magnetic field and contributed to the BGGM, WMM, IGRF, and ESA Swarm satellite projects. Tom supported our oil industry services, data QA and WDC operations. Tony and Tim carried out fieldwork and observatory operations in the UK and overseas. Rob had joined us just for a short time during 2019 as paternity cover. We thank them all for their greatly valued efforts, some over many years, and wish them well in their future careers.

Adam Collins, Grace Cox, Natalia Gómez-Pérez and Eduardo Toledo joined Geomagnetism during 2019. Adam and Natalia are supporting our oil services and data processing and will take on science research support. Grace will carry out research into and develop models of the geomagnetic field, particularly fields of internal origin. Eduardo will support IT developments, such as web services, within Geomagnetism.

Geomagnetism staff 2019

Orsolya (Orsi) Baillie	Geomagnetism Research, Data Processing and QA
Brian Bainbridge	IT and Software Development
Dr Ciarán Beggan	Geomagnetism Research
Claire Brown	Manager, Eskdalemuir Geomagnetic Observatory
Dr William Brown	Geomagnetism Research
Adam Collins	Geomagnetism Research, Data Processing and QA
Dr Grace Cox	Geomagnetism Research
Ellen Clarke	Geomagnetism Research, Data Processing and QA
Paul Dickson	Geomagnetism Business Account Support
Jane Exton	IT and Software Development
Simon Flower	Technical, IT and Software Development
Dr Natalia Gómez-Pérez	Geomagnetism Research, Data Processing and QA
Dr Brian Hamilton	Geomagnetism Research (to January 2019)
Alexander (Sandy) Henderson	Geomagnetic Data Processing
Dr Juliane Hübert	Technical, Fieldwork and Geomagnetism Research
Thomas Humphries	Geomagnetic Data Processing and QA (to July 2019)
Dr David Kerridge	Geomagnetism Research
Dr Susan Macmillan	Geomagnetism Research
Thomas Martyn	Technical, Observatory Operations, Field Survey
Sarah Reay	Geomagnetism Research, Data Processing and QA
Dr Gemma Richardson	Geomagnetism Research
Anthony Swan	Technical, Observatory Operations, Field Survey (to September 2019)
Peter Stevenson	IT and Software Development
Timothy Taylor	Technical, Observatory Operations, Field Survey (to July 2019)
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Eduardo Toledo	IT and software development
Stephen Tredwin	Manager, Hartland Geomagnetic Observatory
Christopher Turbitt	Technical, Observatory Operations, Field Survey
Guanren Wang	Geomagnetic Data Processing and QA
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