British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Geomagnetism

Review

2016

Geomagnetism

Review 2016

Alan W P Thomson (editor)
awpt@bgs.ac.uk

Contributors:

Ciarán Beggan, William Brown, Ellen Clarke, Simon Flower, Susan Macmillan, Sarah Reay, Gemma Richardson, Tim Taylor, Alan Thomson, Chris Turbitt

Key words

Geomagnetism annual review.

Front cover

Entrance to the underground vault at Eskdalemuir observatory.

Bibliographical reference

THOMSON, A W P. 2017. Geomagnetism Review 2016. *British Geological Survey Open Report*, OR/17/043 **40** pp.

Edinburgh British Geological Survey 2017

Contents

Introduction.....2
The Geomagnetism team 2
Looking ahead to 2017 4
Headline numbers from 2016 7

Technical, observatory and field operations 8
UK and overseas observatories.....8
XVIIth IAGA workshop on geomagnetic observatory instruments, data acquisition and processing 10
Global data activities: INTERMAGNET and WDC 12
IT developments 14

Science.....16
Space weather developments 16
Global geomagnetic field modelling.....18
Space weather goes to school.....20
UK-Ireland space weather knowledge exchange 22
Student and visitor activities 24
BGS involvement in Swarm 26

Applications.....28
Geomagnetic referencing services for the oil industry.....28

Outreach and knowledge exchange 30

Selected glossary, acronyms and links.....33

The Geomagnetism team in 2016.....35

Introduction

The Geomagnetism display at 'Our Dynamic Earth' public exhibition in Edinburgh, October 2016.

The Geomagnetism team

The Geomagnetism team measures, records, models and interprets variations in the Earth's magnetic field. Our data and research help to develop our scientific understanding of the geomagnetic evolution of the solid Earth and its atmospheric and space environments and help to develop tools for assessing geomagnetic hazards and their impacts. We also provide geomagnetic data, products and services to industry and academia and we use our knowledge to inform the public, government and industry.

The British Geological Survey (BGS) is the main Earth science research institute for the UK and is a research centre of the Natural Environment Research Council (NERC). Geomagnetism research is represented within BGS as a science team in the Earth Hazards and Observatories (EHO) science directorate.

Geomagnetism sits alongside Earthquake Seismology, Volcanology, and Earth and Planetary Observation and Monitoring, as teams within EHO. EHO is part of the Geohazards programme that reports to the Director of Science and Technology and the BGS Executive. The Geomagnetism team receives support from a range of BGS administrative and other teams, including Edinburgh Business Support and IT Systems and Network Support. The Geomagnetism team is primarily based in Edinburgh. In 2016 the team numbered twenty-five staff either fully or partly engaged in Geomagnetism work.

For the purposes of continuous geomagnetic monitoring in the UK, BGS operates three magnetic observatories. These are located in Lerwick (Shetland), Eskdalemuir (Scottish Borders) and Hartland (North Devon). Two of our team members are observatory managers and are 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

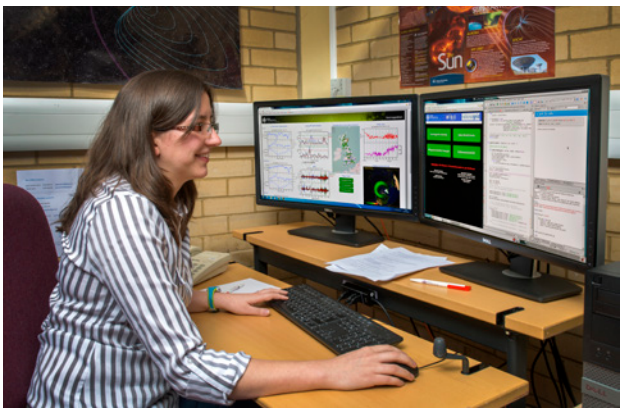
understanding of the Earth and its geomagnetic processes, environments and hazards.

In support of our core function, the team has four primary aims. 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 the 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.

Chris Turbitt presents at the 2016 Geomagnetism Advisory Group meeting in Edinburgh, September 2016.

Introduction



Gemma Richardson assesses the space weather risk to UK infrastructure.

Looking ahead to 2017

In 2017 our scientific research will focus on the space weather hazard to technology and infrastructure and on global and UK magnetic models and the ESA Swarm magnetic survey mission. Major activities to support these activities will include the operation of the BGS magnetic observatories and the UK magnetic survey programme to international standards. We will also continue to produce high quality academic and other geomagnetic models, data products and publications for stakeholders such as the public, government and industry.

Key objectives

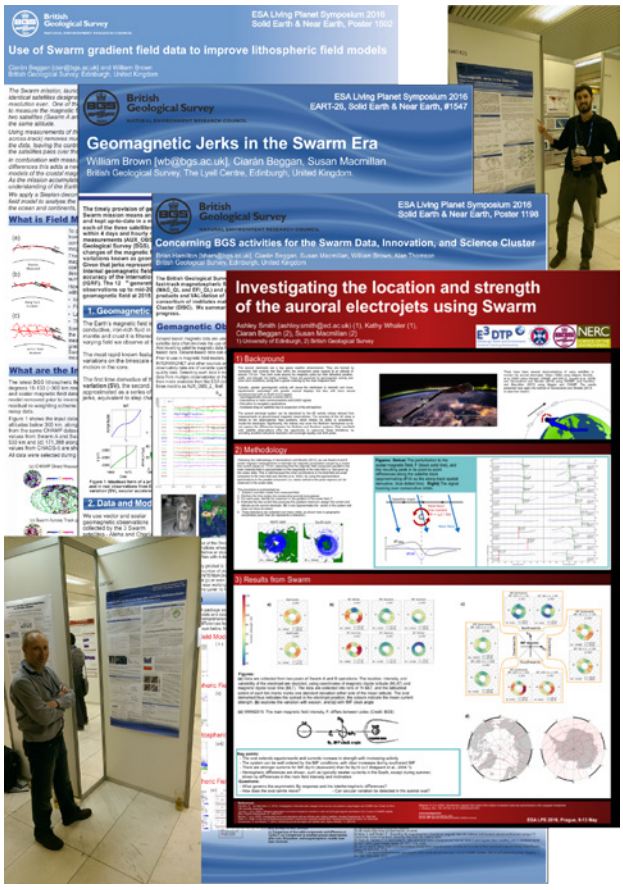
The Geomagnetism team will continue to meet the aims of the current BGS and NERC strategies by means of the following objectives:

- Geomagnetic monitoring and modelling 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

- An INTERMAGNET standard UK and Overseas magnetic observatory network, obtained through regular observatory service visits and high standard quality assurance procedures
- Supply of observatory data and products to INTERMAGNET, according to the timetable set by the INTERMAGNET organisation
- An annual re-survey of sites in the UK magnetic repeat station network, leading to production of the 2017 national magnetic model and delivery of a report to Ordnance Survey
- Publication of our observatory data and data products online and in the 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, e.g. the IAGA Scientific Assemby and the 14th 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 a Geomagnetism team 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 European Space Agency for the Space Weather Network (SWENET); real-time one-minute data from Hartland observatory to the US Geological Survey and the US NOAA Space Weather Prediction Centre (SWPC)
- Support for the UK Met Office Space Weather Operations Centre (MOSWOC) and, as part of the Natural Hazards Partnership project, providing local and planetary magnetic indices, daily forecasts and magnetic data products
- Monitoring and analysis of geo-electric (telluric) measurements at the UK magnetic observatories
- Development of the 'Monitoring and Analysis of GIC' (MAGIC) web tool, in association with National Grid for space weather hazard assessment and monitoring for National Grid
- Production of the 2017 update of the BGS Global Geomagnetic Model (BGGM), using satellite and other geomagnetic data, including data from all BGS operated observatories
- Data collection and QC and model development leading up to revision of the World Magnetic Model 2020
- 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
- The STFC-funded schools' magnetometer project, in association with University of Lancaster's 'Aurora Watch' team
- Study and report on the impact of extreme geomagnetic storms on the UK and French transmission systems, in partnership with the Finnish Meteorological Institute
- Collaboration with the University of Otago (Dunedin, New Zealand) on the final year of a three-year project to assess and model geomagnetically induced currents in the New Zealand power system, leading to developments of UK modelling capability



A selection of scientific posters presented at the ESA Living Planet Symposium, Prague in May 2016, and BGS presenting attendees Drs Beggan (lower left) and Brown (upper right).

- Kick-off and lead Principal Investigator on a NERC Large Grant to study ‘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
- Implementation of web services and metadata standards for 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
- Knowledge exchange activities on space weather and impacts on ground based systems with Trinity College Dublin, supported by the Royal Society and the Royal Irish Academy.

Tim Taylor installing the auroral all-sky camera at Eskdalemuir observatory.

Headline numbers from 2016

Here are some key numbers, which help to put in perspective the team's outputs in 2016.

- >9700 followers @BGSauroraAlert received updates when there was an increased chance of seeing the northern lights from the UK.
- >4700 followers received daily space weather updates on twitter @BGSspaceweather
- 278 global oil industry wells supplied with IFR data
- 115 global oil industry wells supplied with IIFR data
- 108 magnetic bulletins published
- 100% (>99%) UK (overseas) observatory data coverage
- 35 presentations/posters
- 35 Ordnance Survey map compass references
- 13 A-to-Z map compass references
- 13 academic and other meetings
- 12 Customer reports (UK survey & OS; Fort McMurray observatory installation; oil industry services; Space weather impact on UK and French grids)
- 11 field set-ups for IFR services
- 9 oil industry customer reports
- 6 positions on scientific and technical geomagnetism bodies (IAGA Executive Committee, IUGG Georisk Committee, INTERMAGNET Executive Council and Operations Committee x2, IAGA Division V-DAT)
- 6 journal and conference proceedings papers
- 5 articles on space weather for RIN 'Navigation News'
- 4 public lectures, presentations and demonstrations
- 4 Geomagnetic Disturbance Alerts emailed to over 3800 'Aurora Alert' subscribers
- 3 observatory tours, including during the University of Edinburgh 'innovative learning week' and the Met Office open day at Eskdalemuir
- 2 PhDs co-supervised, 1 PhD examined
- 2 geomagnetic models (UK reference model, BGGM2016)
- 1 post-doctoral research assistant
- 1 fellowship from the Software Sustainability Institute

Technical, observatory and field operations

Absolute hut at King Edward Point Observatory, South Georgia (December 16).

UK and overseas observatories

BGS operates three absolute geomagnetic observatories in the UK and six overseas to supply high quality, real-time measurements for research and services. We also take a leading role in expanding the global observatory network, to improve global modelling and for local applications. The move of staff, equipment and stores to the new Lyell Centre took place in early 2016. Whilst planning for and executing the move occupied significant staff time, the move itself was successful and the team ensured that the effect on the continuity and quality of the data supply was minimal. The UK observatories achieved 100% continuous data supply in 2016.

Technical developments

New low-pass filter circuits for observatories with high geomagnetic latitudes have been developed and tested to improve the signal-to-noise in one-second data from DTU FGE fluxgate magnetometers. The filter circuits are adapted versions of those developed for BGS ground electric field systems, but because of the criticality of the observatory data, these new circuits have been extensively tested for long-term stability and reliability at Eskdalemuir Observatory before installation in 2017.

Once returned from repair of lightning damage, further testing of the Lemi-025 fluxgate was carried out at Eskdalemuir to assess the performance of the magnetometer against the INTERMAGNET definitive one-second standard. Testing of new GEM Systems fast-sampling proton magnetometers was also concluded at the magnetically clean laboratory and we are therefore underway with the procurement process for sets of these instruments for each of our nine observatories.

Electric field monitoring has been well established at the three UK observatories for the last four years, but long-term analysis of the data has shown a gradual drift in the measurements at Lerwick and Eskdalemuir. This may be related to the acidic, peaty soils and the resulting degradation of the clay-CuSO4 suspension and/or the telluric probes. A consequence of this has been a saturation of the high gain digitiser, so new electronics have been deployed to allow this quasi-DC signal to be manually offset as part of a service visit.

Magnetic observatories

Regular visits to all observatories are essential for calibrations as well as to complete infrastructure and instrument improvements to maintain data quality and reliability at the level required to meet the standards for membership of the international network, INTERMAGNET.

Visits were made to all observatories in 2016: The three UK observatories, plus Sable Island and Fort McMurray in Canada; Jim Carrigan Observatory in Northern Alaska; and the South Atlantic islands of Ascension, Falklands and South Georgia.

The BGS trip to King Edward Point involved a five-day sailing over rough seas from the Falkland Islands in December 2016. Since the last visit was two years prior, substantial work was undertaken to repair and maintain the observatory infrastructure in this harsh environment. For example, poor seals at the base of the absolute hut had led to water ingress, which routinely freezes, making the process of manual absolute observations treacherous. Hence, the exterior of the hut was sealed and raised floor tiles laid, whilst original wooden props and rope ties securing the door were replaced with non-magnetic latches and brass bolts. Prior to their journey to South Georgia, new observers from the British Antarctic Survey were provided training in manual magnetic measurements at Eskdalemuir and this was followed up with further on-site training during the service visit.

Leaving the Falkland Islands behind on the MPV Pharos, November 2016.

Old cabling removed from Lerwick Observatory, June 2016.

At Lerwick observatory, a maintenance week in June was spent in part replacing old circuits and cabling and this also highlighted that refurbishment of the aging 1920s wooden huts was long overdue. This became more evident following the December storms that damaged the roofing on the absolute observing hut. Structural and asbestos surveys have since been carried out and renovation works are scheduled to be carried out in 2017. Surveying and construction work is often made challenging by the remote location and also by the need to use non-ferrous materials as well as ensuring that the real-time data services are not interrupted.

UK repeat station network

For the 2016 repeat station survey, eleven sites were visited across the UK, from the Isle of Wight to Elgin near Inverness. New Leica GNSS survey hardware has been procured which is able to track three satellite constellations (GPS, Galileo & GLONASS) to reliably locate the repeat station sites in real-time (important at sites with high crustal gradients) and to accurately determine a true north azimuth.

Technical, observatory and field operations

Delegates of the 2016 IAGA Observatories Workshop were accommodated in the town of Dinant on the Meuse River, some 40km from Dourbes Observatory.

XVIIth IAGA workshop on geomagnetic observatory instruments, data acquisition and processing

The 2016 IAGA observatories workshop was hosted by the Royal Meteorological Institute of Belgium at the Centre de Physique du Globe in Dourbes Observatory. These biennial workshops are focussed on exchanging experience in observatory practice.

As well as having representation on the conference organising committee, observers from BGS Edinburgh attended the week-long IAGA workshop on Geomagnetic Observatory Instruments, Data acquisition and Processing in Dinant, southern Belgium in September 2016. Every two years, the international magnetic observatory community meets at an observatory to learn of new instruments and practices, exchange ideas on common observatory issues, standardise observatory measurements and discuss the application of ground-based geomagnetic data in research.

BGS staff took along a Carl-Zeiss/ Bartington THEO010B Fluxgate Theodolite and a Gem Systems GSM-19 Overhauser magnetometer to take part in the instrument inter-comparison sessions. These sessions provide a level of international standardisation for measurements and methods and are important for the quality assurance of observatory data for many institutes.

The conference session on observatory instruments and techniques, which was part chaired by BGS, highlighted advances in fluxgate magnetometers towards meeting the new INTERMAGNET one-second definitive data standard and also presented novel calibration and processing methods for existing data sets, including manual absolute observations.

The session on observatory data acquisition and processing featured many talks on instrument baseline adoption. Baseline adoption is a common problem at observatories. The number of parameters involved and the nature of the signal to be modelled means that it is difficult to solve mathematically but baselines are ultimately responsible for the absolute accuracy of the data published. One of the talks in this session detailed the open

Delegates of the 2016 IAGA Observatories Workshop outside the absolute observing hut of Dourbes Observatory.

source MagPy package, which could potentially become the first common data processing package across the geomagnetic community, while another talk described results of the Cheongyang Observatory, Republic of Korea, with which BGS has worked extensively on baseline adoption and definitive data production.

New observatories and variometer stations in Russia, Greenland, Macedonia, Slovenia, Iran, India, and Antarctica featured in the session on upgraded & new observatories, as did the relocation of the Eyrewell Observatory, New Zealand. Through representation on the INTERMAGNET committee and also through initiatives such as the INDIGO project, BGS provides support for emerging observatories (such as the Mozambique observatory at Nampula, as presented in this session) and also in providing advice and assistance on data processing with the aim of preparing these observatories to meet INTERMAGNET standards.

Although not the primary focus of the workshop, there were further sessions on magnetic repeat stations and applications of observatory data, which highlighted the importance of observatory networks in studies such as geomagnetic jerks, pulsations and magnetotellurics.

The workshop concluded with two open forum sessions. The first, a data processing training session, saw demonstrations of three data processing packages, BGS's GDASView application, ZAMG's MagPy package & IPGP's in-house system, followed by a question and answer session with the presenters. The second session was hosted by a panel of INTERMAGNET committee members, including BGS, and began with presentations on: recent changes in INTERMAGNET; becoming an INTERMAGNET observatory; common causes for observatories losing INTERMAGNET membership; assistance available to new observatories; the future of observatories and data use; and what observatories actually expect from INTERMAGNET. Again, this was followed by an open discussion between the panel and conference on these topics.

Technical, observatory and field operations

Overseas observatory yearbooks – from uncatalogued, to catalogued, labelled and boxed, were transported out of Murchison House to the Keyworth archive.

Global data activities: INTERMAGNET and WDC

The geomagnetism team operate the World Data Centre for Geomagnetism, Edinburgh and make significant contributions to the running of INTERMAGNET—a global network of high-quality magnetic observatories.

World Data Centre activities

The move of operations from Murchison House to the Lyell Centre presented a challenge for the World Data Centre (WDC) for Geomagnetism, Edinburgh. The new site had less archive space available to store physical records so the WDC's collection of UK and overseas yearbooks and magnetograms needed to be considered. Working closely with the BGS Records team a strategy was developed to catalogue, store, transport or dispose of records as required.

Duplicate copies of UK yearbooks were identified and offered to our sister World Data Centres around the world. The World Data Centre for Geomagnetism, Kyoto, was able to accommodate a large number of the duplicates and 235 volumes were shipped to Japan. We also sent a number of volumes to WDCs in Russia and the USA to fill gaps in their analogue holdings.

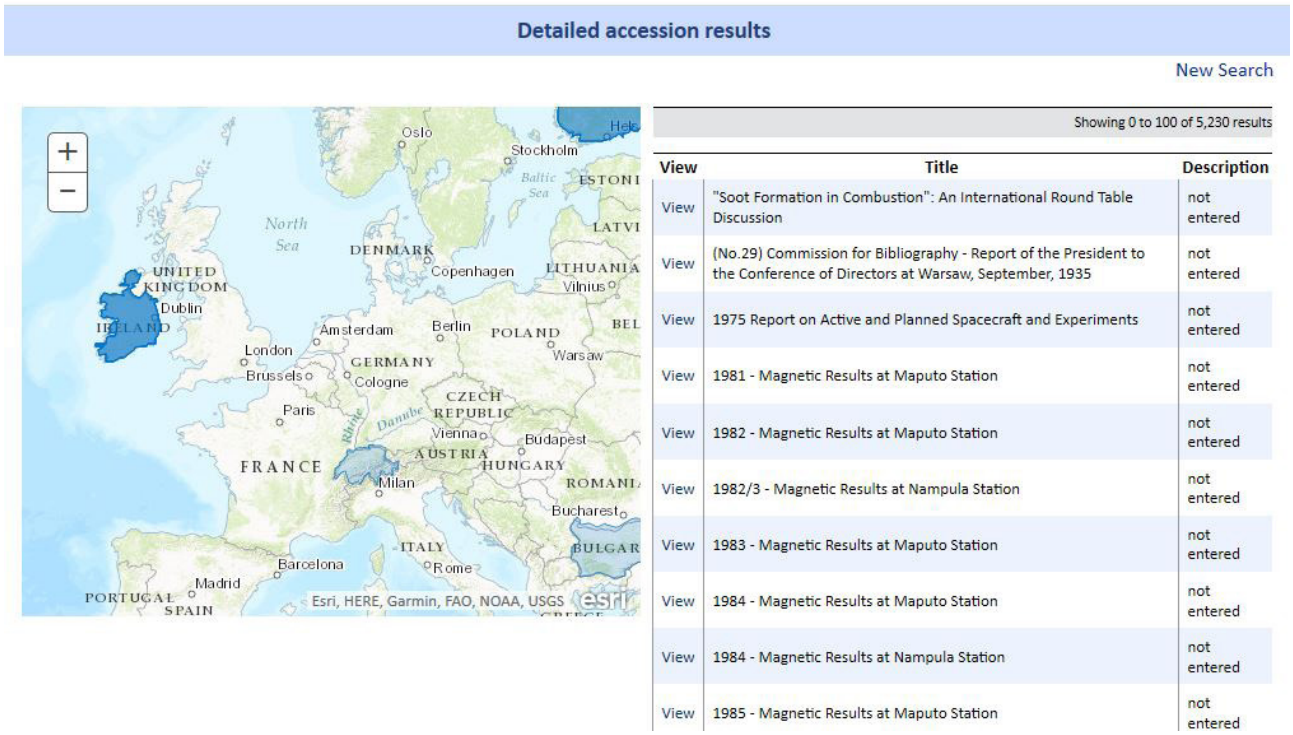
Our collection of over 5000 overseas yearbooks were catalogued by the Records team. Each item was then barcoded and stored in custom-made, archive-quality boxes. These were then transported to BGS headquarters in Keyworth. A request and retrieval system is now in place and the catalogue is available via an online tool.

Our collection of UK yearbooks and magnetograms was transported to the new archive space in the Lyell Centre.

INTERMAGNET

BGS staff have continued to encourage INTERMAGNET observatories to submit 'quasi-definitive' data (data that is correct to within 5nT of the final result). Data that meets this compromise between timeliness and accuracy, but are extremely useful for a number of purposes, particularly in verifying satellite recordings of the Earth's magnetic field. As a result of these efforts over half of the network of around 130 observatories are now producing quasi-definitive data.

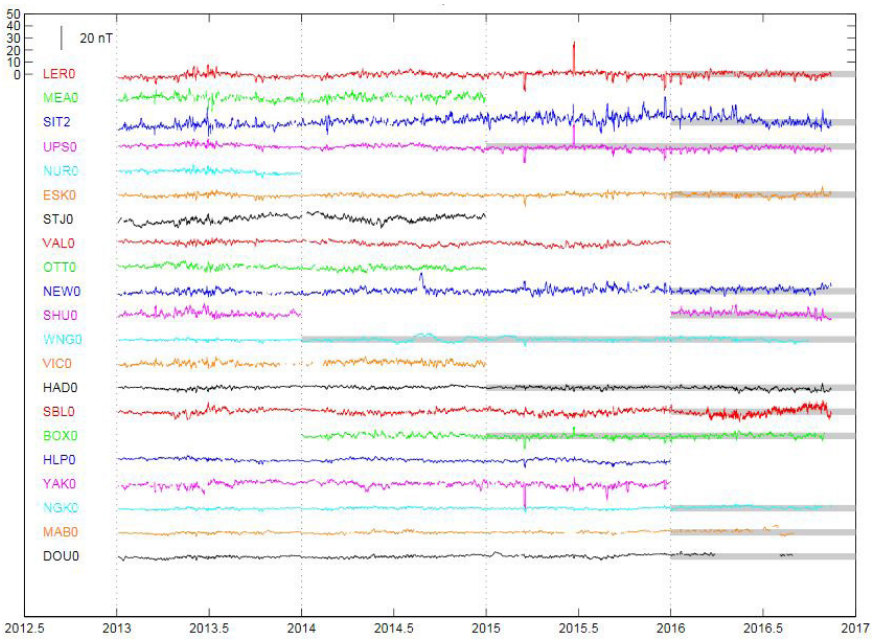
INTERMAGNET made a new 'call for data' to its observatories in 2016, asking for high



Screenshot of BGS Records new accession search online tool containing metadata of our overseas observatory yearbook collection.

resolution '1-second' data. This data will set new standards in resolution and increase the relevance of the observatory network as it opens up parts of the geomagnetic spectrum that have not been so well observed in the past. BGS staff have been critical to the processes that led to the point where INTERMAGNET was able to make this call, leading on the technical description of the standards to which an observatory needs to conform, on the data format used to hold the new data and on the software that will be used to work with and analyse the new data set.

During 2016 three members of the Geomagnetism team held committee posts in INTERMAGNET (out of a total of 18 posts) including the chair of the Executive Council.



Quasi-definitive data completeness from INTERMAGNET observatories. Plot shows residual values after the removal of known signals. Periods of quasi-definitive data are indicated by the thick grey lines.

Technical, observatory and field operations

BGS IT hardware being installed at Heriot Watt.

IT developments

Information technology is at the heart of Geomagnetism science, whether recording data in the field, getting it to customers in real-time or using the latest High Performance Computers to create models. Advanced computer techniques are therefore vital to achieve our goals. Much of the software we need cannot be bought, so the Geomagnetism team includes a number of software engineers. This section describes significant developments that we made during 2016.

The early part of the year saw us completing a major piece of work, to move our computer systems from Murchison House, our old office at Edinburgh University, to the Lyell Centre, our present home in Heriot Watt. The move required work from IT staff in the Geomagnetism Team as well as the staff who manage BGS' IT infrastructure. BGS has significant and complex 'backroom' IT systems which required a specialist firm of movers. The transfer took place over two weekends in January and February and saw the team of 5 IT infrastructure staff in Edinburgh augmented by colleagues from BGS' Keyworth office.

To ensure that our customers saw no loss of real-time data, the Geomagnetism Team set up a new backup data processing and web server system at the Lyell Centre, including new satellite network connections. The system was in place for customers to use before the move of IT equipment started. It eventually replaced the backup system from Murchison House, which was switched off once the building was empty in March.

Moving between the two offices required considerable staff time which slowed progress on a number of our goals during 2015 and 2016. However by March the move was complete and we could progress with other things.

A long-standing requirement was to replace our single web server with a resilient cluster of web servers. We deliver nearly everything that we do through the web. The increasing expectation that our web pages will always be available alongside the need for resilient delivery of real-time data to our customers makes it increasingly important that we have highly reliable web systems. We also need to be able to cope with high levels of demand at times when there is media interest in what we do.

To meet this need we designed a web server cluster consisting of 8 web servers, a parallel file system served by 3 file servers and a

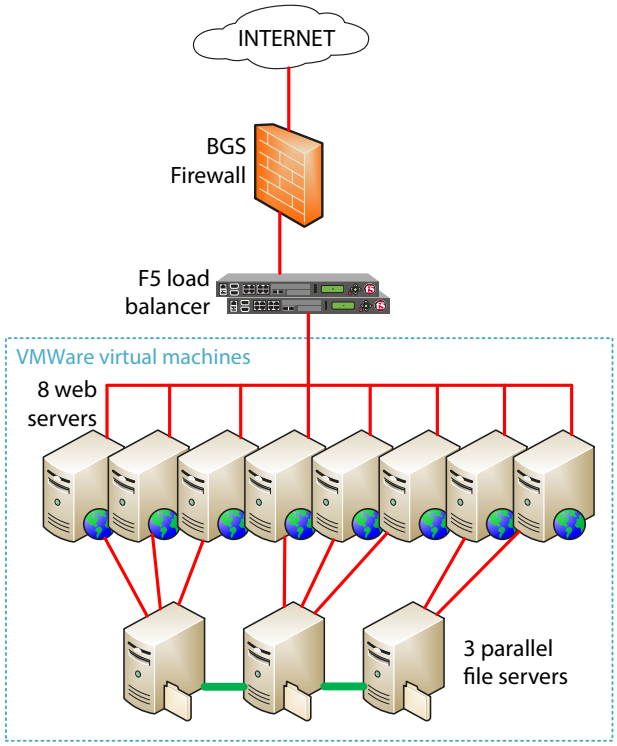
pair of 'F5 Big-IP' load balancers, which are responsible for distributing requests across individual web servers in the cluster. The F5 allows us to quickly vary the number of servers being used, it also allows us to take down individual servers for maintenance. The web and file servers are implemented as virtual machine templates, making it easy to create new servers on demand. The new system came into service in November.

We worked on a number of other IT projects in 2016, including:

A Centos7 virtual machine template for our scientific computing needs. This template is used by all our Linux computers, giving us a homogenous computing platform with a software configuration that is well understood. This is part of our work to move scientific computing from the Solaris to Linux operating system.

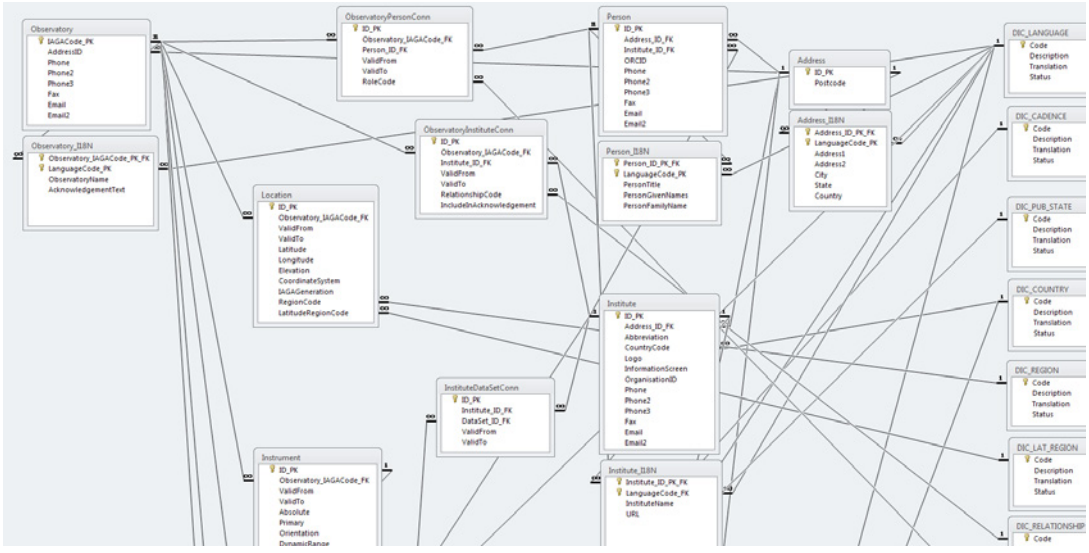
Restful web services were created for the World Magnetic Model, the International Geomagnetic Reference Field and the BGS Global Geomagnetic Model.

BGS staff played key roles in managing the Geomagnetism component of the European Plate Observing System (EPOS), a Horizon 2020 project. EPOS will make a variety of geoscience data sets available to researchers in a way that's easy to combine. The ability to mix data from different scientific disciplines is expected to lead to novel research and discoveries. With EPOS funding BGS are also leading the creation of a metadata system for the global Geomagnetic community.



Simplified schematic diagram of the web server cluster.

The BGS Global Geomagnetic Model user interface was expanded to include the option to work in Universal Transverse Mercator Coordinates (UTM), and to allow the user to convert from Latitude and Longitude coordinates to UTM, and vice versa.



Part of the database schema for the Geomagnetic community metadata system.

Alan Thomson presenting an electronic poster about work on Geomagnetically Induced Currents in the New Zealand power grid.

Space weather developments

The geomagnetism team have had an active year in space weather research, including international collaborations and a strong representation at the European Space Weather Week.

European space weather week

Four BGS staff attended the 13th European Space Weather week in Oostende, Belgium, during November 2016, and presented two talks, a live forecast (Billingham) and contributions to a working meeting on GIC.

Ellen Clarke hosted a Q&A panel on the Socio-economic impacts of Space weather, and Alan Thomson was one of the panellists. This attracted a large crowd during the tutorial session at the start of the week, and prompted some lively debate.

Laurence Billingham presented a talk in the Machine learning and statistical inference techniques session, entitled ‘An application of machine learning to geomagnetic index prediction’. As part of the BGS daily space weather forecast we aim to predict geomagnetic activity for up to three days ahead. To assist in that task we investigated the use of machine learning to aid and improve our forecasts. Laurence presented the latest results, trialling neural networks and ensemble models, and showed that a Random

Laurence Billingham presenting the Live Space Weather Forecast at ESWW13

Forest Classifier model performs best. He also highlighted the importance of having separate training, validation and test sets.

In the Model metrics, verification and validation session Gemma Richardson gave an invited talk: ‘Evaluating the use of geomagnetic indices for identifying potential damage to power grids’. Geomagnetically induced currents (GICs)

are the main space weather hazard to power grids and we would like to be able to better categorise them to identify times when the UK power system is at risk. To do this we are investigating the relationship between GICs and geomagnetic data and indices, with the aim of eventually producing more accurate nowcasts and forecasts of GIC in the UK.

Ellen Clarke and Alan Thomson also convened a working meeting: 'Comparison of ground-level measurements, models and impacts of the St Patrick's day 2015 geomagnetic storm'. This meeting attracted a range of contributions both from across Europe and the rest of the world. It provided an opportunity to highlight both the similarities and marked differences in the response of power grids around the world to the same storm.

Ellen Clarke and Alan Thomson taking part in the Q & A panel on the Socio-economic impacts of Space weather at ESWW13.

New Zealand collaboration

The geomagnetism team are collaborating with the University of Otago on a three-year project to assess and model GICs in the New Zealand power system, funded by the New Zealand Ministry of Business, Innovation & Employment. Transpower (NZ power transmission network operator) has provided more than 14 years GIC data, for up to 17 locations across the South Island; this is thought to be the one of the best archives of such data in the world. This dataset is providing a fantastic opportunity to understand the potential impacts of GIC in New Zealand, and through the collaboration we are able to validate and improve the models we use to calculate GIC in the UK.

Other space weather activities

The geomagnetism team also acted as expert support for the European Space Agency's P2-SWE-II project, which was aimed at updating and improving space weather services to users in the spacecraft operations industry. Gemma Richardson attended a workshop in Harwell in May to provide advice on the use of geomagnetic indices, and helped to facilitate the use of BGS nowcasts and forecasts of the ap index within the project.

The Monitoring and Analysis of GIC (MAGIC) website, which provides National Grid with real-time monitoring of space weather and GICs, has been upgraded.

BGS also completed a study on the impact of extreme geomagnetic storms on the UK and French transmission systems, in partnership with the Finnish Meteorological Institute, for a customer.

Members of the geomagnetism team are also actively involved in a UK-Ireland space weather knowledge exchange (see p22 for more information).

The main magnetic field at the Earth's surface and at the surface of the core, orange indicates field pointing outward, blue inward.

Global geomagnetic field modelling

BGS annually updates its Model of the Earth's Magnetic Environment (MEME), which represents the complex geomagnetic field from the core to the outer magnetosphere. This model is used to update the BGS Global Geomagnetic Model (BGGM) every year. We also monitor the performance of the World Magnetic Model (WMM) and International Geomagnetic Reference Field (IGRF), which are updated on a quinquennial basis.

The MEME is constructed using mathematical functions known as spherical harmonics to distinguish and present the key constituent sources of the geomagnetic field in a compact and efficient manner. These are the internal field, comprised of the time-varying core and static lithospheric or crustal field, and the external field, primarily from the magnetosphere and the secondary field its variations induce. The model is constructed from several million observations taken at ground magnetic observatories and by satellite-based instruments in orbit.

In order to describe the small scale spatial features and constantly time-varying nature of the field we solve this complex problem using inverse modelling for tens of thousands of model coefficients. We describe the internal field to a resolution of spherical harmonic degree 133, equivalent to 300 km wavelength at the Earth's surface. This is in contrast to the quinquennial snapshot models given by the WMM or IGRF where the minimum internal field wavelength is more than 3000 km. The developments made each year with the MEME feed directly into our ability to produce more accurate models for the BGGM, WMM and IGRF. The MEME core field is illustrated above.

Key features

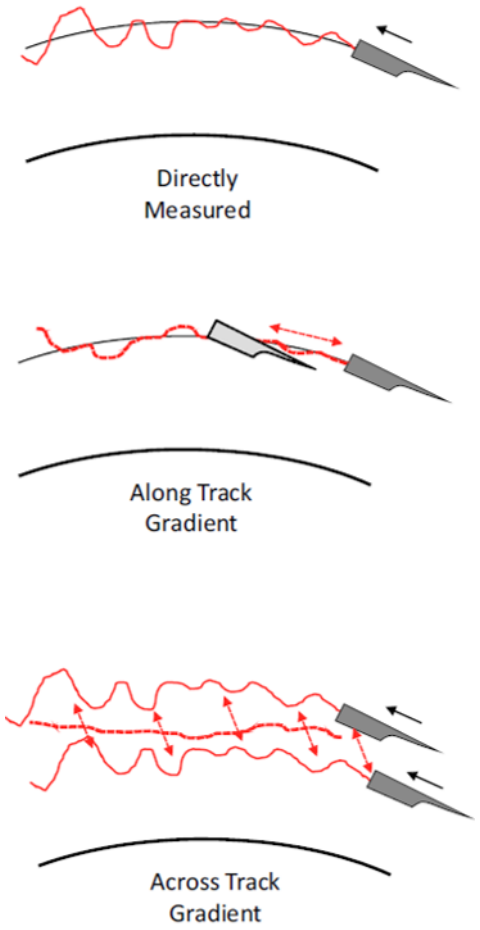
The MEME describes the Earth's magnetic field:

- Arising from time-varying core and external sources

- Arising from static lithospheric sources
- Over the period of 1900–2017 (for the 2017 update) with a prediction to 2019
- To a resolution of spherical harmonic degree 133 or 300 km
- Using historic and the latest ground observatory data worldwide
- Using Ørsted, CHAMP and the current Swarm satellite data
- With vector, scalar and gradient observations

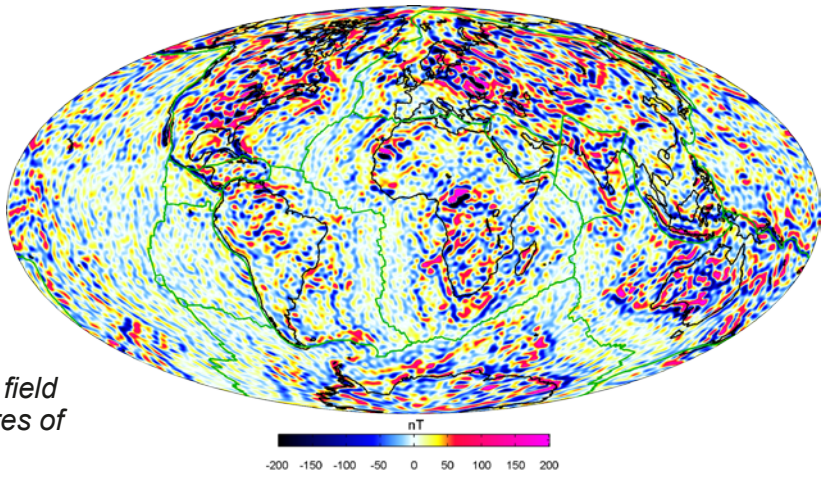
Gradient information and Swarm

Differences between both scalar and vector measurements taken at two points in space, known as gradients, have been possible with single-satellite missions. With a single satellite such as CHAMP, gradients can be calculated along the flight track of the spacecraft, between two measurements taken in sequence, as shown to the right. With the advent of the Swarm constellation however, a new type of information is available for the first time—gradients taken across the track of two satellites orbiting side-by-side, shown to the right.



Gradients can be calculated along the track of a single satellite, or thanks to the ESA Swarm constellation, across the tracks of two parallel orbiting satellites..

The advantage to the gradient technique is that it cancels out the large-scale field which is present in the measurements of both satellites, and picks out the small-scale field which differs between them. After a procedure of corrections for unwanted signals, for example, removing estimates of the time varying magnetospheric, ionospheric and core fields, the sensitivity to small spatial scales can be used to enhance the desirable signal of the lithospheric field. By combining the gradient information with the usual vector and scalar measurements, additional emphasis or resolution of particular signals can be achieved. The crustal component of the MEME model shown to the right is an example of the result of such an approach. Across track gradients also have the added advantage of increasing the region of lateral sensitivity beneath a satellite orbit, helping to model the field at the highest latitudes, including those not directly overflown in the polar gap.



The radial component of the crustal field of the MEME model, showing features of 300 km scale at Earth's surface.

Technical, observatory and field operations

Installing a magnetometer at Vale of Leven Academy, Alexandria (close to Glasgow).

Space weather goes to school

During the year, the first five BGS Raspberry Pi magnetometers were deployed out to schools around the UK, from the Isle of Benbecula to Norwich City, after the final software and hardware design and testing were completed.

In 2015, we reported on a new outreach project at BGS to install magnetometers in schools. A development phase to produce robust hardware and software was undertaken in 2015. At the beginning of 2016, the physical hardware of the three-axis magnetometers had been tested and found to be of suitable quality to measure variations over periods of minutes to hours.

The next step was to complete the software for running, measuring, uploading and displaying the magnetometer data. This task was performed by Dr Steve Marple in Lancaster University who produced an upgraded version of his code for running single-axis magnetometers. He also overhauled the AuroraWatch website to allow data to be displayed from all three channels in real-time and for different time periods. In addition, Steve has also produced a set of Python code to allow any user to directly download data from the internet and display or save it on their computer without the need to visit the AuroraWatch website.

In June, Ciaran Began visited the Institute of Physics (IoP) Physics Teachers conference in Rugby where he made a number of contacts and garnered interest from schools around the UK. Following up on the conference, in August the first two school magnetometers were installed in Oundle School, near Peterborough and Norwich School in the centre of Norwich City. These were given codes: OUN and NOR, respectively. In November, magnetometers were installed in Kirkhill Primary school in Broxburn (near Edinburgh), Vale of Leven Academy in Alexandria (near Glasgow) and Sgoil Lionacleit on the Isle of Benbecula. These are known as BRO, ALE and BEN.

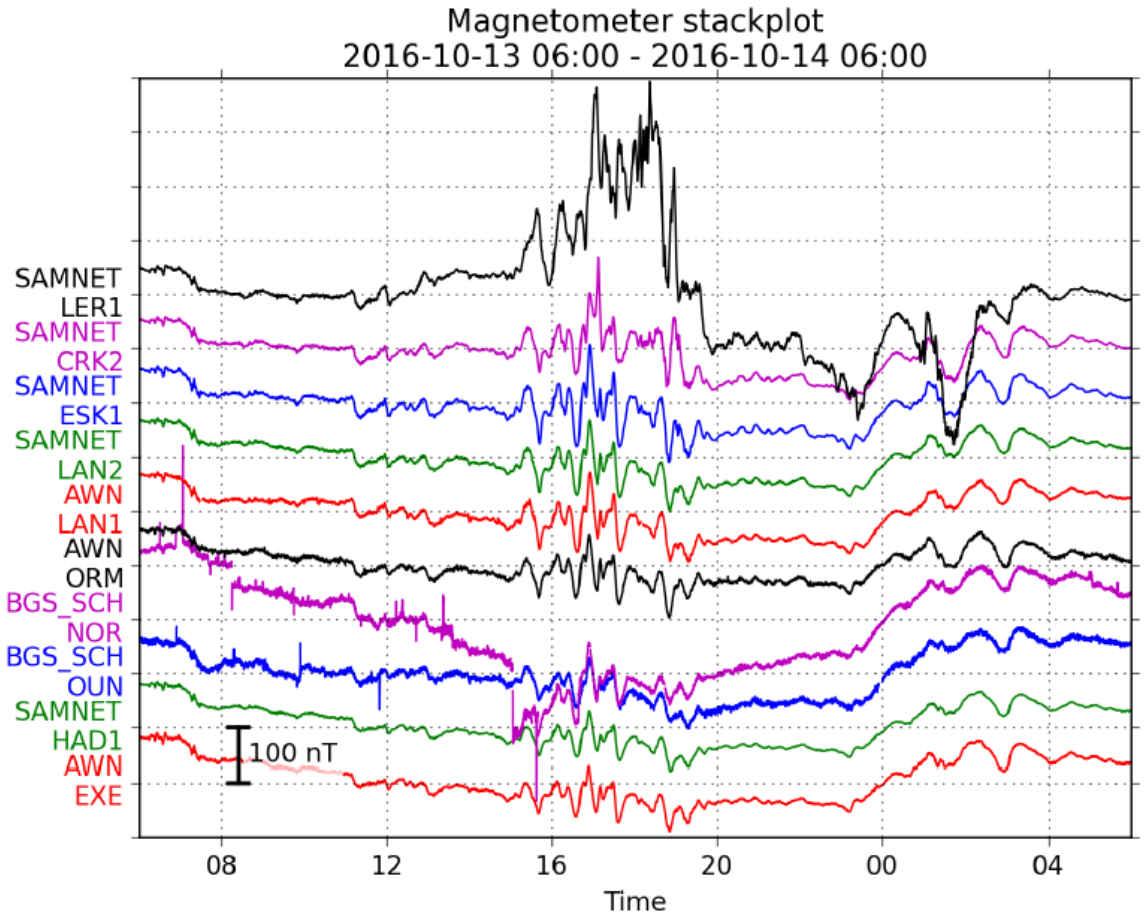
Installation of the magnetometer in Norwich School, Norwich.

In NOR, BRO and ALE, the magnetometers were installed at the back of teaching rooms (pictured left) where the pupils can see the system, while in OUN and BEN they were temporarily placed in a lab or computer room while display positions were being prepared. The network currently covers a geographic range of 52.6° N to 57.4° N and 1.3° E to 7.3° W.

The stackplot (below) shows an example of the variation of the horizontal component of the magnetic field as recorded by the network of school magnetometers including the Lancaster University sub-Auroral Magnetometer network (SAMNET), the AuroraWatch single-axis magnetometer network (AWN) and the BGS School Magnetometer network (BGS_SCH) for a Kp 6 storm of the 13–14th October 2015. The storm is clearly largest over Lerwick, diminishing in strength further south. As the BGS_SCH magnetometers are not temperature-controlled, it can be seen that NOR has a long period drift related to the local environment, but on short periods matches the timing and amplitude of the other magnetometers really well.

In addition to deploying the systems, a set of instructions and notes for teachers were produced along with examples of Python code for reading and processing the data and suggestions for projects. In January, an article was produced for the Royal Astronomical Society's Astronomy and Geophysics journal. We also had around one dozen informal enquiries from members of the public about how to build the system and where to purchase the relevant parts.

All plots and data are available from: http://spp-aurorawatch01.lancs.ac.uk/plots



Horizontal variation of the magnetic field from the Lancaster University Sub-Auroral Magnetometer network (SAMNET including BGS observatories at Lerwick, Eskdalemuir and Harltland), the AuroraWatch network (AWN) and the BGS School Magnetometer network (BGS_SCH) for the Kp=6 magnetic storm of the 13–14th October 2015.

Gemma Richardson, David Kerridge and Alan Thomson outside the Customs House in Dublin after the Irish Space Weather meeting on the 6th October 2016.

UK-Ireland space weather knowledge exchange

In April 2016, BGS and Trinity College, Dublin were awarded a joint Royal Society/Royal Irish Academy International Exchange grant to facilitate knowledge exchange and collaboration on the impacts of space weather in the UK and Ireland. We discuss the highlights of the past year.

In April 2016, Ciaran Beggan at BGS and Peter Gallagher at Trinity College, Dublin were awarded a joint Royal Society/Royal Irish Academy International Exchange Award. This grant is to be used for fostering knowledge exchange through visits by researchers to each other's respective institutes over a two year period. The grant covers the cost of travel, accommodation and subsistence, though not time or related academic costs (e.g. publication fees).

The first visit occurred in June 2016 when Sean Blake came to the BGS office in Edinburgh for three weeks. Sean is a third year PhD student working on the impact of Geomagnetically Induced Currents (GIC) on the Irish high-voltage network. Sean has been advised by BGS since the inception of his project and his visit was an opportunity for some dedicated collaboration time. During his visit we helped him implement a version of the thin-sheet code used by BGS to model the spatial distribution of the electric field due to surface conductance during large geomagnetic storms. This work will inform the next phase of Sean's PhD studies, moving from a simple representation of the conductivity in Ireland to one which can include coastlines and offshore bathymetry.

In October, Gemma Richardson and Ciaran Beggan travelled to Dublin for four days to work in the Physics Department in Trinity College. We spoke extensively with Sean and Peter and met the growing space weather research group at the university. Progress on Sean's first publication and plans for his subsequent papers were made.

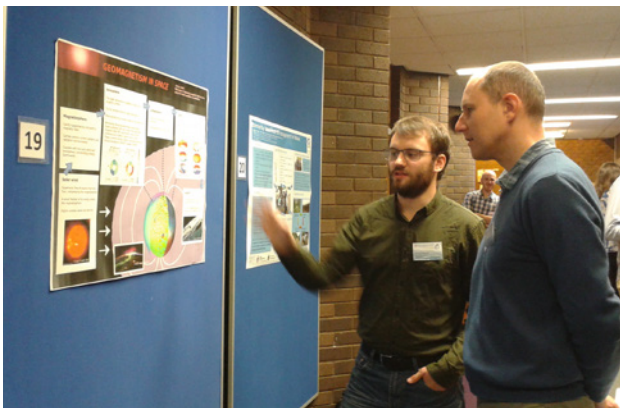
We attended a day-long meeting in the Customs House in Dublin (pictured) organised by Met Eireann with the aim of alerting and informing both government and industry of the potential effects and hazards that a large space weather event might have in Ireland, ranging from GIC through to disruption of GNSS signals.

Alan Thomson and David Kerridge also attended this meeting, which was jointly facilitated by Trinity, Met Office and BGS. The meeting led to a wider appreciation of the possible impacts on a variety of sectors, including electricity distribution and maritime operations (e.g. port authorities). This meeting exposed BGS and its space weather expertise to an international audience.

In December, Joan Campanyà i Llovet (pictured), a post-doctoral researcher at Trinity College visited Edinburgh for a week to learn about the BGS electrical and magnetic observatory datasets. Joan gave a presentation on his work in magneto-telluric (MT) measurement and processing during his previous role at the Dublin Institute of Advanced Studies. He also provided a tutorial on how to perform MT inversions to compute the conductivity of the ground beneath and MT site. This will be useful for us in the future, as we seek to better understand conductivity at depth across the UK.

Further exchange visits are now planned for the 2017/18 financial year.

Ciaran Beggan and Joan Campanya in Edinburgh on the 8th December 2016.



Ashley Smith at a BUFI student meeting at Heriot Watt.

Student and visitor activities

The Geomagnetism team welcome visitors from around the world. We also have a number of PhD and MSc students associated with our researchers, who use BGS data and infrastructure to complete their theses.

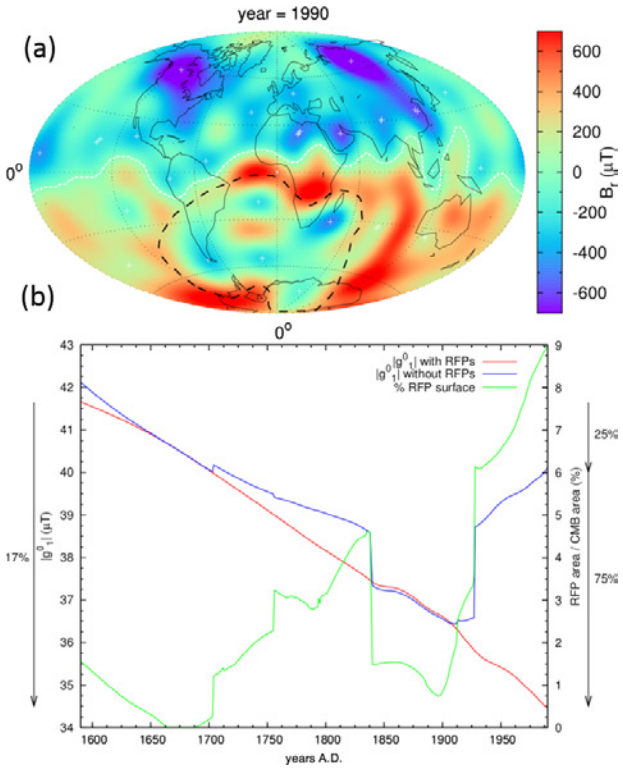
Visitors

As part of an international collaboration with University of Otago in Dunedin, New Zealand, BGS hosted Dr Tim Divett, a post-doctoral researcher working on the modelling of Geomagnetically Induced Currents in the NZ Transpower high-voltage network. New Zealand is unique in having a long-term GIC monitoring programme which started in 2001 (Figure to the right). BGS have been advising the PI Craig Rodgers and his team about how to model the magnetic field, magnetic field variation, electrical conductivity and the high-voltage network. As part of the project two BGS staff visited Dunedin in May 2016 and a reciprocal visit was arranged for Tim Divett to come to Edinburgh. Tim spent three weeks working on a detailed description of transformers, updating the electrical conductivity maps of New Zealand and working on modelling the variation of the magnetic field during large geomagnetic storms.

As part of the Royal Society/Royal Irish Academy Knowledge Exchange Grant BGS hosted two visitors from Trinity College Dublin. Sean Blake spent three weeks in June 2016 and Dr Joan Campanya came for five days in December 2016 (see page 22 for more detail). Finally, we were honoured to have Dr David Boteler from Natural Resources Canada visit for a day to discuss space weather research in Europe and North America.

In May 2016 we hosted Dr Po Gyu Park head of Geomagnetism at the Korean Research Institute of Standards and Science (KRISS). Dr Park's visit was part of the on-going knowledge exchange partnership between BGS and KRISS to support Cheongyang (CYG) geomagnetic observatory operations and data processing. Dr Park and BGS colleagues visited Eskdalemuir Observatory to learn about instrumentation for better temperature control for the fluxgate magnetometer and to see geo-electric field measurement apparatus. Dr Park also gave a seminar talk about his team's research profile focusing on metrology.

In September 2016 we welcomed Vicki Foster and Kieran Love from the British Antarctic survey for training prior to their two-year posting to King Edward Point research station. They had a day's training



(a) Reversed flux patch (RFP) under South Atlantic (dashed black outline); (b) evolution of reversed patches over 400 years in relation to the strength of the dipole coefficient (g01) of the magnetic field. The dipole field has fallen by 17% in strength: around 75% of this fall can be attributed to RFP. (From Maurits Metman)

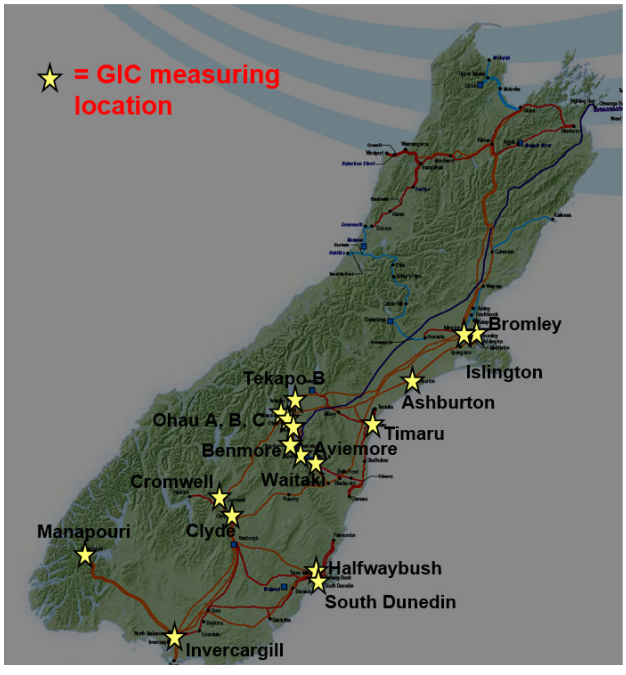
at Eskdalemuir Observatory learning how to do absolute observations. They then spent a day with staff in Edinburgh hearing more about the team's activities and the importance of King Edward Point magnetic observatory, and the observations they would be making on our behalf.

Students

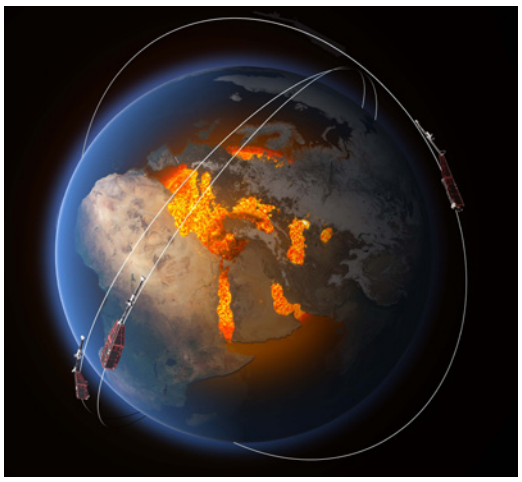
BGS have two PhD students funded with the NERC DTP programmes at Edinburgh and Leeds Universities. The BGS BUFI programme also part-funds their scholarships. Ashley Smith is a second year student at Edinburgh studying the auroral electrojets using Swarm satellite data. His primary supervisor is Prof Kathy Whaler, with Susan Macmillan as his co-supervisor.

Maurits Metman is a second year student examining the large scale change of the magnetic field in the core due to fluid motion and diffusion of the magnetic field. Maurits is supervised by Drs Phil Livermore and Jon Mound, with Ciaran Beggan co-supervising. Maurits visited for two days in January 2016 and discussed his study of how reversed flux patches on the core mantle boundary affect the dipole field as measured at the surface over time (see Figure left).

In addition, we are co-supervising two MSc students at the University of Edinburgh. Hannah Rogers is a one-year MSc by Research student looking at the use of Slepian functions to identify and remove regions of the core-surface boundary where flow models are known to be ambiguous. This is a follow-on from another MSc project in 2011 co-supervised by BGS. Orsi Baillie, a member of the Geomagnetism Team, has also started a two year part-time MSc by Research in which she will investigate the geo-electric field dataset that has been collected by BGS over the past few years at the three UK observatories.



Locations of GIC measurements in the Transpower high voltage grid in South Island, New Zealand. (From Tim Divett).



The three satellites of the ESA Swarm mission.Alpha and Charlie are currently in 450 km altitude near-polar orbits, side-by-side separated by 150 km as they cross the equator, with Bravo currently at 520 km altitude and 6 hours local time separation. Image credit: ESA/ATG Medialab.

BGS involvement in Swarm

Launched in November 2013, the European Space Agency (ESA) Swarm constellation mission represents the cutting edge of developments in geomagnetic observation from space. BGS is involved in both the continuing support and utilisation of the mission and it helps us to develop a new generation of magnetic field models for both academic and applied use.

BGS expertise has been involved from the inception of the Swarm constellation mission (see Figure above) and acts as a support partner in the consortium known as the Data, Innovation and Science Cluster (DISC). BGS also acts as an independent user of the data which Swarm returns.

Support for Swarm

The responsibilities of BGS are broadly split into 3 categories: production of official products; validation of products produced by other institutes; and input of expertise to various committees.

BGS produces the 'fast-track magnetospheric field model', a model of the large-scale external magnetic field about Earth, on a daily basis, for dissemination publicly by ESA. BGS also produces daily 'quick-look' data reports for magnetic and ionospheric plasma observations. On a 3-monthly basis BGS collates and quality controls hourly observations from around 150 INTERMAGNET and other ground observatories worldwide, nine operated by BGS. Since October 2016 this service has also delivered minute and second resolution measurements, within a 4-day lag to match the latency of Swarm data. This facilitates prompt studies of rapid external field features in a manner not previously possible.

Product validation involves the scientific assessment of the quality and reliability of the magnetic field models produced by DISC prior to their public release. For this task the observatory measurements BGS collates are key, providing an independent measure against which to compare the models.

BGS staff are also involved in the assessment of proposed new data

products and models, driven by the desire to fully realise the potential of the mission.

Science from Swarm

Swarm science at BGS involves both academic and applied research, including supervision of PhD students. BGS has recently been represented at 5 major scientific conferences, 4 international and 1 national, giving 4 oral and 9 poster presentations, including at the recent Fourth Swarm Science Meeting, in Banff, Canada. Presentations have covered topics including:

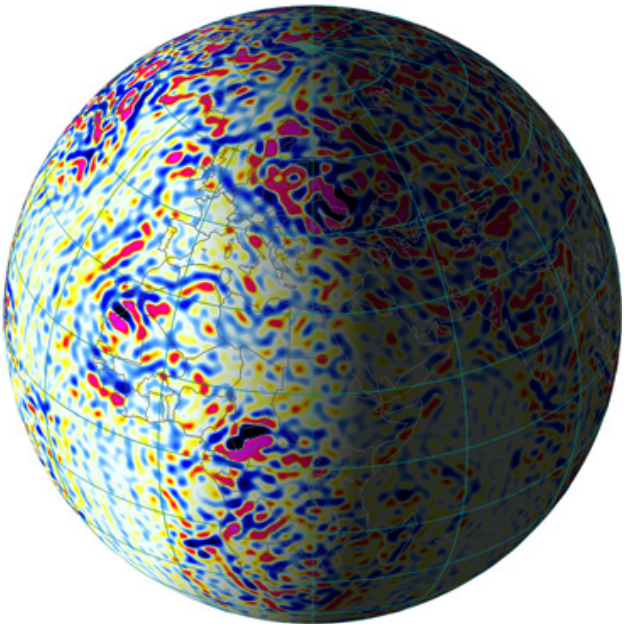
- Using Swarm gradient data to improve lithospheric field models
- Investigating rapid and unpredictable core field changes known as 'geomagnetic jerks'
- Comparing the performance of regularly updated field models to the forecasts of reference models
- Mapping the auroral electrojets in the ionosphere
- The prompt provision and quality control of observatory data
- Use of the experimental high-frequency magnetometers on Swarm to detect lighting in Earth's atmosphere

BGS also benefits from the scientific advances of the whole Swarm community, employing new and innovative field modelling techniques developed to best utilise the unique measurements made possible by the Swarm constellation, such as inter-satellite field gradients.

Future of Swarm

Swarm is approaching a crucial moment in its mission lifetime, a decision on how to advance the orbit evolution, given variables such as the remaining fuel, to further the scientific goals. BGS contributes to the advice delivered to ESA by the scientific community on this complex subject. Options include: forcing the inevitable decay of the orbits to advance the acquisition of low altitude measurements to better capture the lithospheric field; extending the monitoring presence by increasing the orbit altitude; and varying the relative satellite separations to better capture features such as ionospheric variations at different local times simultaneously.

Whatever the decision, Swarm data has already impacted recent updates to the BGS Global Geomagnetic Model (see Figure below), International Geomagnetic Reference Field and World Magnetic Model, and will increasingly do so as science and mission developments progress.



BGS map of the downward component of the Earth's crustal magnetic field, developed with Swarm measurements including new inter-satellite gradient information.

Applications

BGS geomagnetic data support directional drilling for oil and gas.

Geomagnetic referencing services for the oil industry

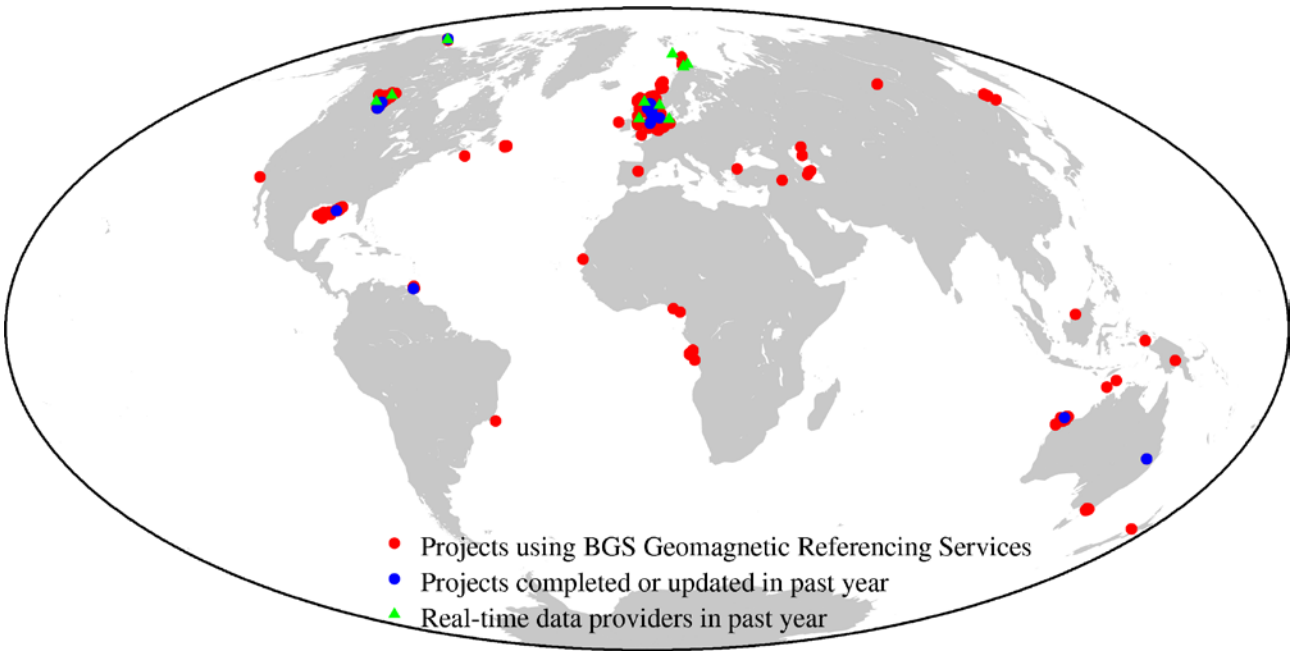
BGS works with drilling companies to provide a three-level geomagnetic referencing service for increasing accuracy of wellbore positioning around the world. The levels are the BGS Global Geomagnetic Model (BGGM), In-Field Referencing (IFR) and Interpolation In-Field Referencing (IIFR).

The BGS Global Geomagnetic Model captures the core field, the steady-state magnetospheric field and long to medium wavelength (to 300 km resolution) crustal field. It is described in more detail under the 'Global Magnetic Field Modelling' section. In-field referencing includes local data, usually, aeromagnetic data, to capture the short wavelength, but sometimes large amplitude, crustal field. Interpolated in-field referencing includes local real-time measurements from nearby INTERMAGNET standard observatories and other calibrated magnetic stations to capture the time-varying field, in particular the daily variation and magnetic storms.

During 2016 eleven new hydrocarbon fields around the world were set up for IFR. This involved locating the aeromagnetic data from the public domain and commercial sources, and searching World Data System data holdings for any other magnetic data in the study areas. The scalar aeromagnetic data were converted to full-field absolute values where possible, and then directional and downward-continuation filters were applied to obtain estimates of the crustal field vector at depth. Local vector observations were used where possible to assess local uncertainties. In total there are currently nearly 500 fields set up for BGS IFR services around the world.

BGS is working with industry on improved methods of delivering the geomagnetic referencing services as well as the associated uncertainties using web services. Web services allow computers to communicate with one another thereby reducing human error and improving efficiency.

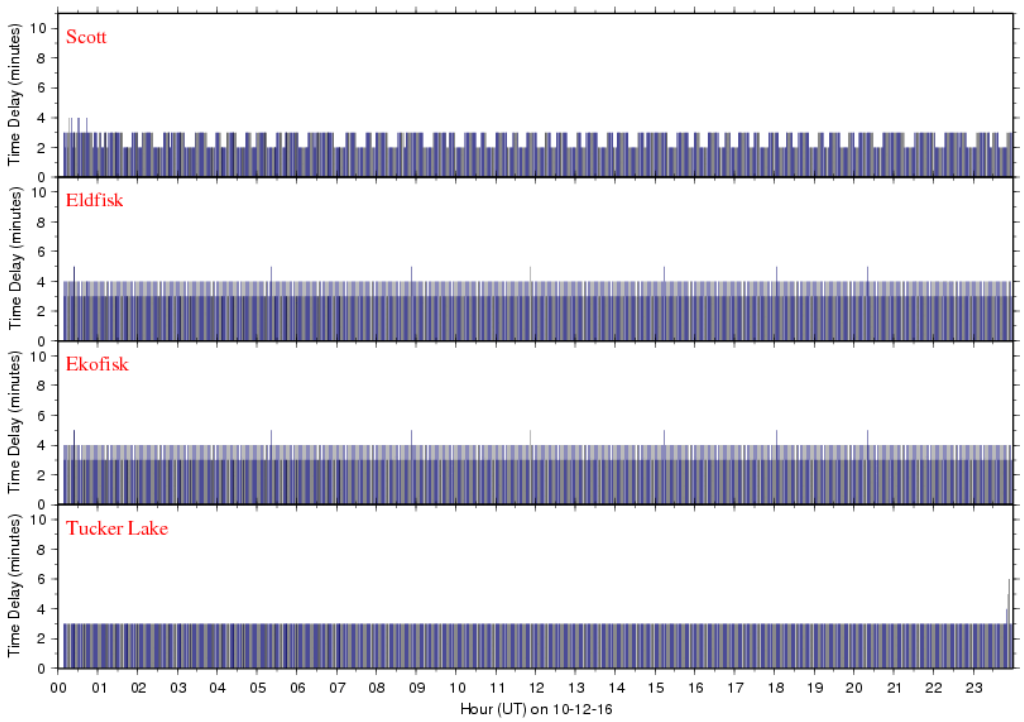
BGS continues to upgrade its real-time data communications and processing mechanisms. Performance is also continuously monitored as in the histogram in the Figure on the next page, which shows the time taken for delivery of one-minute IIFR results at four wells in UK and Norwegian sectors of the North Sea and in Alberta, Canada on an example day. Delivery is made via three separate



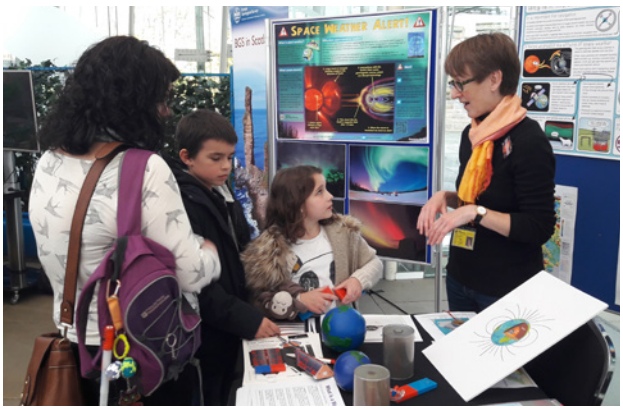
Drilling operations supported by BGS data.

processing pipe-lines, including one off-site. During 2016 over 99% of IIFR data were delivered within 3 minutes from the time the measurements are made.

BGS made a presentation at the Industry Survey Committee on Wellbore Survey Accuracy meeting in Glasgow in 2016 and had various face-to-face and online meetings throughout the year with industry representatives. Susan Macmillan was an external examiner at the University of Tromsø for a PhD entitled 'Effects of Geomagnetic Disturbances on Offshore Magnetic Directional Wellbore Positioning in the Northern Auroral Zone' by Inge Edvardsen of Baker Hughes.



The time taken for delivery of IIFR one-minute data at four wells.



Susan Macmillan at the BGS Science Showcase event at Our Dynamic Earth in October 2016.

Outreach 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.

Published 2016

Beggan, C D, Marple, S R. (2016) Space weather goes to schools. *Astronomy & Geophysics,* 57 (2). 24–26. doi:10.1093/astrogeo/atw072

Blake, S P, Gallagher, P T, McCauley, J, Jones, A G, Hogg, C, Campanya, J, **Beggan, C, Thomson, A W P, Kelly,** G S, Bell, D. (2016), Geomagnetically induced currents in the Irish power network during geomagnetic storms, *Space Weather,* 14, 1136–1154, doi:10.1002/2016SW001534.

Brown, W, Beggan, C, Macmillan, S. (2016) Geomagnetic jerks in the Swarm Era. SP-740 *Proceedings of Living Planet Symposium,* 9–13 May 2016. Spacebooks Online. ISBN: 978-92-9221-305-3

Ridley, V, Holme, R. (2016) Modelling the Jovian magnetic field and its secular variation using all available magnetic field observations. *Journal of Geophysical Research: Planets,* 121

Shore, R M, Whaler, K A, **Macmillan, S, Beggan, C,** Velimsky, J, Olsen, N. (2016) Decadal period external magnetic field variations determined via eigenanalysis. *Journal of Geophysical Research: Space Physics,* 121 (6). 5172-5184. doi:10.1002/2015JA022066

Swan, A, Shanahan, T, Turbitt, C, Rasson, J. (2016) Hardware Developments to Determine the Transfer Function of a 1-second Fluxgate Magnetometer. *JIGU-IAGA Special Volume-2/2016: Geomagnetic Measurements, Observatories and Applications,* ISSN 0971-9709.

Published and to appear 2017 (at April 2017)

Kelly, G S, Viljanen, A, **Beggan, C D, Thomson A W P.** (2017), Understanding GIC in the UK and French high-voltage transmission systems during severe magnetic storms, *Space Weather*, 15, doi:10.1002/2016SW001469.

Oughton, E J, Skelton, A, Horne, R B, **Thomson, A W P,** Gaunt, C T. (2017), Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure, *Space Weather,* 15, doi:10.1002/2016SW001491.

Pulkkinen, A, E, Bernabeu, A, **Thomson, A,** Viljanen, R, Pirjola, D, Boteler, J Eichner, P J, Cilliers, D, Welling, N P, Savani, R S, Weigel, J J, Love, C, Balch, C M, Ngwira, G, Crowley, A, Schultz, R, Kataoka, B, Anderson, D, Fugate, J J, Simpson, M, MacAlester (2017), Geomagnetically induced currents: Science, engineering and applications readiness, *Space Weather,* 15, doi:10.1002/2016SW001501

Other publications

- 1 BGS Report: '2015 Annual Review'
- 12 Customer Reports (UK survey & OS; Fort McMurray observatory installation; oil industry services; Space weather impact on UK and French grids)
- 108 Observatory Monthly Bulletins: http://www.geomag.bgs.ac.uk/data_service/data/bulletins/bulletins.html
- Bi-monthly column on Space Weather for Royal Institute of Navigation's 'Navigation News'
- Contributions to BGS's GeoBlogy:
  * The BGS Aurora Camera (AuroraCam) by Ciaran Beggan: http://britgeopeople.blogspot.co.uk/2016/11/the-bgs-aurora-camera-auroracam.html

Conference presentations, posters and related activities

EGU, Vienna, Austria, April
2 posters

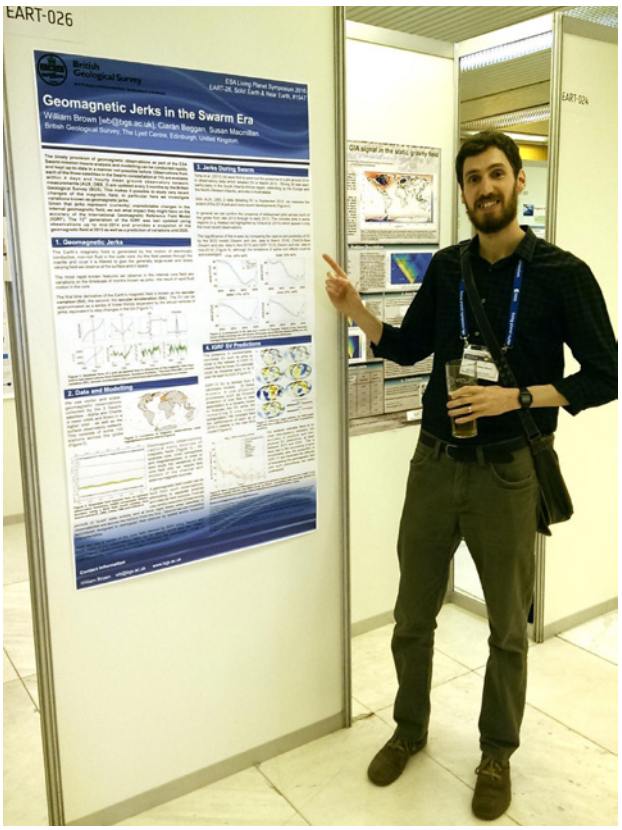
MIST, Lancaster, April
2 posters

ESA Living Planet Symposium 2016, Prague, Czech Republic, May
3 posters

Risks & Hazards Workshop for Emergency Planning Society, Keyworth, June
1 presentation (Beggan)

Swarm 6th Data Quality Workshop, Edinburgh, September
1 presentation (Brown)
2 posters

ISCWSA (SPE wellbore positioning) meeting, Glasgow, September
1 presentation (Beggan)



Will Brown and his poster on display at the ESA Living Planet Symposium in Prague.

World Data System Members Forum, Denver, USA, September
1 poster

IAGA Observatories Workshop, Dourbes, Belgium, September

Geomagnetism Advisory Group annual meeting, Edinburgh, September
5 presentations (Thomson, Turbitt, Macmillan, Brown, Clarke, Flower, Kelly)

Space Weather — Risks and Challenges for Ireland, Dublin, Ireland, October
Co-led a workshop exercise (Thomson)

Lyell Centre official opening, Edinburgh, October
3 posters

European Space Weather Week 13, Ostend, Belgium, November
2 presentations (Billingham, Kelly)
'Live Forecast' and contributions at splinter meetings

Geomagnetism Team seminars, Edinburgh
12 presentations throughout the year by team members, students and visitors

Some other notable outputs

Observatory tours

- Eskdalemuir—Langholm Provost Club (Turbitt)

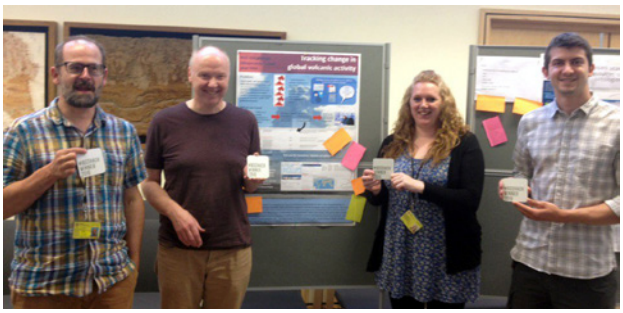
Public lectures, presentations and demonstrations

- FutureFirst workshop—helping school students feel more confident before exams
- Girls into Physics event, Vale of Leven school, workshop on the geomagnetic field (Richardson)
- Invited talk on Space Weather and a Raspberry Pi-magnetometer demonstration at Institute of Physics STEM ambassadors' networking event (Billingham).
- In a 'Better writing for the general public' workshop with the BBC's David Robson, a Navigation News article on space weather was chosen as a the basis for a discussion about the use of visual imagery in language. (Billingham).

Gemma Richardson with pupils from Vale of Leven School at a 'Girls into Physics' event.

Software development

- Laurence Billingham won a fellowship from the Software Sustainability Institute. Through 2017 we will use this fellowship to promote more sustainable research software.
- Participation in a cross NERC workshop on sustainable development of scientific software (Stevenson and Billingham)
- Participation in a Creative Coding Workshop (in Bristol), collaborating with researchers from Imperial, Leeds, and Oxford to produce a useful piece of software in 1 day (Brown, Billingham)
- Software Sustainability Institute Collaborations Workshop (in Edinburgh), collaborative blog on best practice for research software development, team lead for collaborative coding workshop on software credit: forming idea for product, pitching to conference, recruiting team members, managing team from setup through to demonstrating minimal working application (Billingham).
- Winning contributions during a 2-day BGS 'hackathon'. The judges selected 'Global volcanic activity report generation from automated internet searching' team as the winners (Stevenson). A people's choice award went to the 'Stitching core photos—getting the most from the Core Store digital assets' team (Hamilton).



Peter Stevenson (2nd left) part of the winning BGS Hackathon team.

Edinburgh University undergraduate lecture series

- 4th Year Honours Course on 'Geomagnetism', by Ciaran Beggan & Gemma Richardson (8 lectures)

Four Geomagnetic Disturbance Alerts emailed to over 4200 subscribers.

Susan Macmillan and Gemma Richardson were judges at the BUFI Science Festival hosted at Heriot Watt University in June 2016. Current BUFI PhD student Ashley Smith presented his poster 'Geomagnetism in Space' at the event.

Selected glossary, acronyms and links

Aurora Watch	*Aurora alert service run by Lancaster University (aurorawatch.lancs.ac.uk)*
BBC	*British Broadcasting Corporation (www.bbc.co.uk/)*
BGGM	*BGS Global Geomagnetic Model (www.geomag.bgs.ac.uk/bggm.html)*
BGS	*British Geological Survey (www.bgs.ac.uk)*
BUFI	*BGS University Funding Initiative (http://www.bgs.ac.uk/research/bufi)*
CentOS	*Community ENTerprise Operating System (www.centos.org)*
CHAMP	*German magnetic survey satellite (www-app2.gfz-potsdam.de/pb1/op/champ)*
CuSO4	*Copper Sulphate*
DISC	*Data, Innovation and Science Cluster supporting the ESA Swarm mission*
DTP	*Doctoral Training Partnership*
DTU	*Danish Technical University, Copenhagen, Denmark (www.dtu.dk/English)*
EGU	*European Geosciences Union (www.egu.eu)*
EHO	*The Earth Hazards and Observatories science directorate of BGS (http://www.bgs.ac.uk/research/earthHazards/home.html)*
EPOS	*European Plate Observing System (www.epos-ip.org)*
ESA	*European Space Agency (www.esa.int)*
EU	*European Union*
ESWW	*European Space Weather Week. (http://www.stce.be/esww13)*
Galileo	*European GNSS (http://galileognss.eu)*
GDAS	*Geomagnetic Data Acquisition System*
GDASView	*GDAS data viewing software*
GEM Systems	*Geophysical Electromagnetic Systems (http://www.gemsys.ca)*
GIC	*Geomagnetically Induced Currents (a natural hazard to power systems)*
GLONASS	*Globalnaya Navigazionnaya Sputnikovaya Sistema (Russian GNSS) (https://www.glonass-iac.ru/en)*
GNSS	*Global Navigation Satellite System*
GPS	*Global Positioning System*
Horizon 2020	*An EU Research and Innovation programme (https://ec.europa.eu/programmes/horizon2020)*
IAGA	*International Association of Geomagnetism and Aeronomy (www.iugg.org/IAGA)*
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)*
IKE	*Information and Knowledge Exchange*
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)*
IOP	*Institute of Physics (www.iop.org)*
IPGP	*Institut du Physique du Globe de Paris (www.ipgp.fr/en)*
ISCWSA	*Industry Steering Committee on Wellbore Survey Accuracy (iscwsa.net)*
ISGI	*International Service for Geomagnetic Indices (isgi.unistra.fr)*
IT	*Information Technology*
KRISS	*Korean Research Institute of Standards and Science (www.kriss.re.kr/eng)*
LED	*Light Emitting Diode*
LEMI	*Laboratory of Electromagnetic Innovations (www.lemisensors.com)*
MAGIC	*Monitoring and Analysis of GIC. A GIC analysis service for the National Grid*
MEME	*Model of the Earth's Magnetic Environment (http://geomag.bgs.ac.uk/research/modelling/MEME.html)*
Met Office	*UK Meteorological Office (www.metoffice.gov.uk)*
MIST	*Magnetosphere, Ionosphere and Solar-Terrestrial UK scientific community (www.mist.ac.uk/)*
MT	*Magneto-telluric*
NERC	*Natural Environment Research Council (www.nerc.ac.uk)*
Ørsted/Oersted	*Danish magnetic survey satellite (http://www.space.dtu.dk/english/Research/Projects/Project-descriptions/Oersted)*
OS	*Ordnance Survey (www.ordnancesurvey.co.uk)*
PI	*Principal Investigator*
QA	*Quality assurance*
Raspberry Pi	*A small, low-cost computer (https://www.raspberrypi.org)*
RIN	*Royal Institute of Navigation. (www.rin.org.uk/general/Navigation-News)*
SAMNET	*Sub-Auroral Magnetometer network (http://spears.lancs.ac.uk/samnet)*
SPE	*Society of Petroleum Engineers (www.spe.org)*
Swarm	*Three-satellite 'mini-constellation' for magnetic field surveying. (http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm)*
TCD	*Trinity College Dublin (www.tcd.ie)*
UTM	*Universal Transverse Mercator*
WDC	*World Data Centre, part of the World Data System (www.wdc.bgs.ac.uk)*
WDS	*World Data System (www.icsu-wds.org)*
WMM	*World Magnetic Model (www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml)*
ZAMG	*Zentralanstalt für Meteorologie und Geodynamik (www.zamg.ac.at/cms/en/news)*

The Geomagnetism team 2016

Ted Harris retired after 47 years in Geomagnetism at the BGS, including its previous incarnation as the Institute of Geological Sciences. Ted was a mainstay of the Team and will be missed. However in 2016 we were able to welcome Tom Martyn, who joined the Team's field operations section.

Orsolya (Orsi) Baillie	*Geomagnetic Research, Data Processing and QA*
Brian Bainbridge	*IT and Software Development*
Dr Ciarán Beggan	*Geomagnetic Research*
Dr Laurence Billingham	*Geomagnetic Research*
Dr William Brown	*Geomagnetic Research*
Ellen Clarke	*Geomagnetic 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 Brian Hamilton	*Geomagnetic Research*
Theodore (Ted) Harris	*Geomagnetic Data Processing and IKE*
Alexander (Sandy) Henderson	*Geomagnetic Data Processing*
Thomas Humphries	*Data Processing and QA*
Dr David Kerridge	*Geomagnetic Research*
Dr Susan Macmillan	*Geomagnetic Research*
Thomas Martyn	*Technical, Observatory Operations, Field Survey*
Colin Pringle	*Manager, Eskdalemuir Geomagnetic Observatory*
Sarah Reay	*Geomagnetic Research, Data Processing and QA*
Dr Gemma Richardson (nee Kelly)	*Geomagnetic Research*
David Scott	*IT and Software Development*
Anthony Swan	*Technical, Observatory Operations & Field Survey*
Peter Stevenson	*IT and Software Development*
Timothy Taylor	*Technical, Observatory Operations, Field Survey*
Dr Alan Thomson	*Geomagnetic Research and Geomagnetism Team Leader*
Stephen Tredwin	*Manager, Hartland Geomagnetic Observatory*
Christopher Turbitt	*Technical, Observatory Operations, Field Survey*
John Williamson	*Data Processing and QA*

Contact details

Geomagnetism
Earth Hazards and Observatories
British Geological Survey
The Lyell Centre
Research Avenue South Edinburgh
EH14 4AP
UK
www.geomag.bgs.ac.uk

Dr Alan Thomson

Tel: *+44 (0)131 667 1000*
Direct dial: *+44 (0)131 650 0257*
Email: *awpt@bgs.ac.uk*

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL