British Geological Survey

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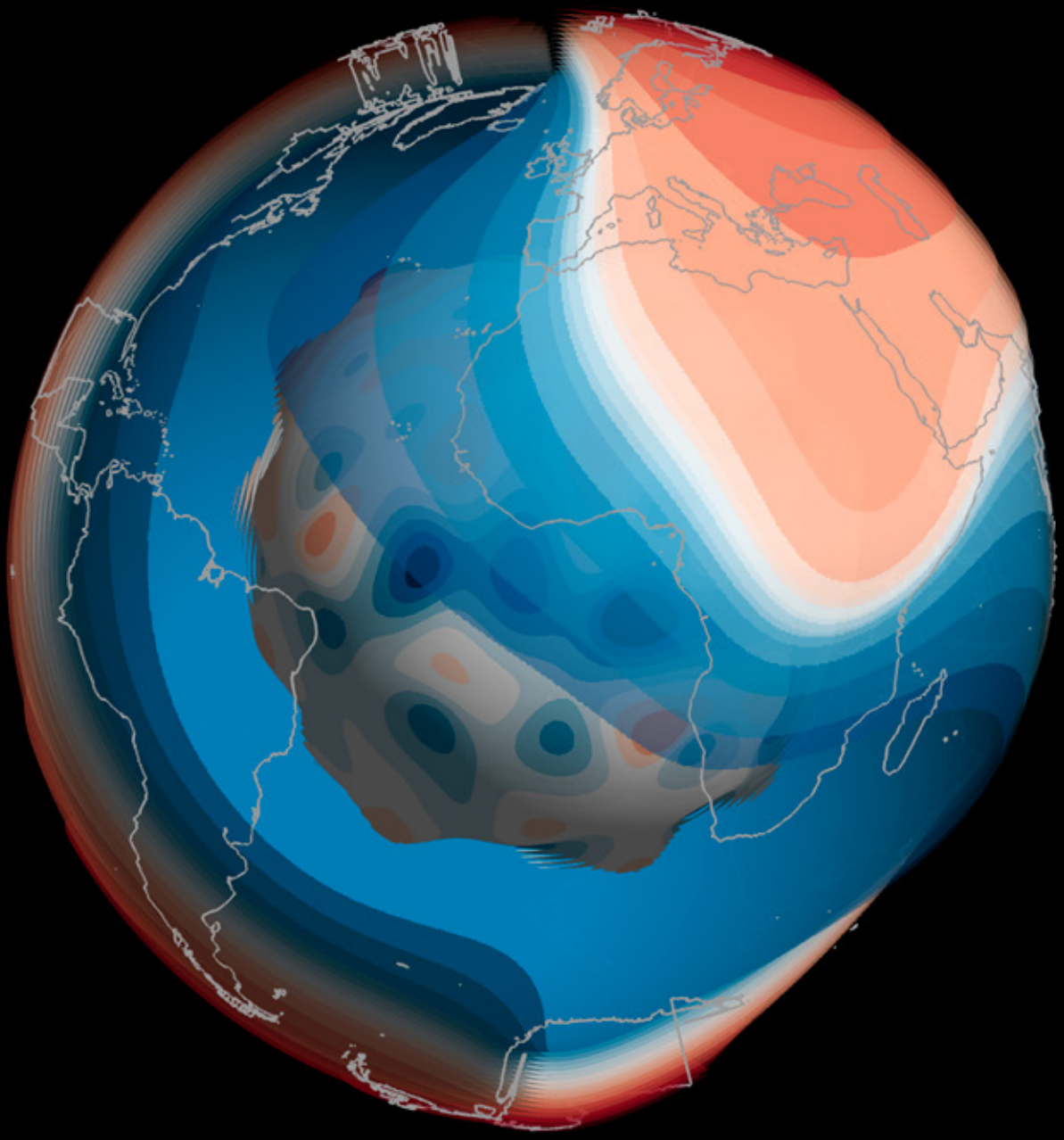
Geomagnetism

Review

2017



Geomagnetism

Review 2017

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Key words

Geomagnetism annual review.

Front cover

The declination of the magnetic field at the Earth's surface and also at the core-mantle boundary in May 2018. The back cover shows the surface magnetic field declination in more detail. Red indicates a direction east of true north and blue indicates a compass direction west of true north.

Bibliographical reference

THOMSON, A W P. 2017. Geomagnetism Review 2017. *British Geological Survey Open Report*, OR/18/036 **44** pp.

Edinburgh British Geological Survey 2018

Contents

Introduction

The seventeen participants at the kick-off meeting for the SWIGS project, June 2017.

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 scientific understanding of the solid Earth and its atmospheric and space environments and help to develop knowledge of geomagnetic hazards and their impacts. We also provide 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 leading 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 within 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 2017, the team numbered twenty-six staff either fully or partly engaged in Geomagnetism research and applications.

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 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 its

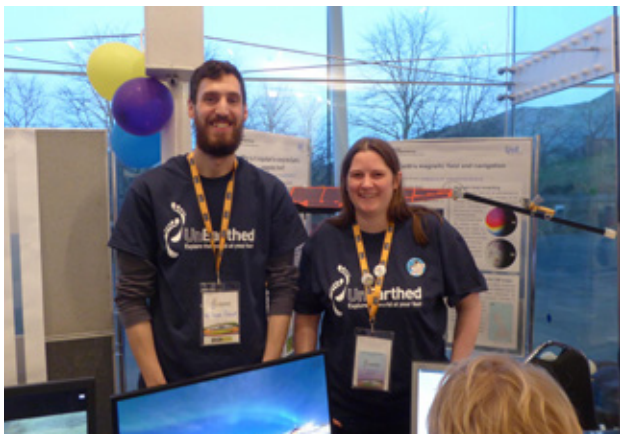
geomagnetic processes, environments and hazards.

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, part 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

Aurora borealis, July 2017, Lerwick, Shetland (image courtesy of Barry Broadbent).

Introduction



Will Brown and Sarah Reay present Geomagnetism science to the public at the NERC Dynamic Earth event in October 2017, Edinburgh.

Looking ahead to 2018

In 2018, we will focus on the space weather and geomagnetic hazard to UK technology and infrastructure, through the NERC-funded 'SWIGS' project. We will also further develop our global and UK geomagnetic models, taking advantage of our involvement in the extended 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 program 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

- 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 (given in no specific order)

- 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 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 2018 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 a Geomagnetism team annual report and hosting of the annual Geomagnetism Advisory Group of Team 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); 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
- Monitoring and analysis of geo-electric (telluric) measurements at the UK magnetic observatories, partly through a University of Edinburgh MSc project
- Development 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 2018 update of the BGS Global Geomagnetic Model (BGGM), using satellite and other geomagnetic data, including data from all BGS operated observatories
- Data collection, 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
- 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

Sunset at Lerwick observatory during a 2017 service visit.

Atmospheric optics: a 22-degree ice halo, sun pillar, parhelic circle and 'sun dogs' behind Jim Carrigan Observatory absolute house, Prudhoe Bay, Alaska, during a 2017 service visit. https://en.wikipedia.org/wiki/Halo_(optical_phenomenon).

capability

- Months 7 to 19 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
- Implementation 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
- 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
- Continuation of our software ‘sprints’ to update Team software packages, in support of scientific and commercial research and services

Geomagnetism and seismology staff at Lerwick museum for the 2017 ‘Open Days’.

Headline numbers from 2017

Here are some key measures of our outputs, which help to put in perspective the Geomagnetism Team's activities in 2017.

- >2.9M web page views on our servers
- >10 300 followers @BGSauroraAlert received updates when there was an increased chance of seeing the northern lights from the UK
- >5200 followers received daily space weather updates on twitter @BGSspaceWeather
- >300 members of the public and 120 school pupils at the Lerwick 'Open Days' event in Shetland
- 225 global oil industry wells supplied with IFR data
- 223 global oil industry wells supplied with IIFR data
- 108 magnetic bulletins published
- 100% (>98%) UK (overseas) observatory data coverage
- 35 presentations/posters
- 79 Ordnance Survey map compass references
- 21 A-to-Z map compass references
- 21 Customer reports (UK survey & OS; JCO observatory service reports; oil industry services;)
- 15 field set-ups for IFR services
- 15 academic and other meetings
- 9 journal and conference proceedings papers
- 6 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)
- 6 articles on space weather for RIN 'Navigation News'
- 6 Geomagnetic Disturbance Alerts emailed to over 3900 'Aurora Alert' subscribers
- 5 public lectures, presentations and demonstrations, including Lerwick Open Days, Dalkeith Science Gala Day, NERC 'Dynamic Earth' Event
- 3 observatory tours, including during the University of Edinburgh 'innovative learning week' and the Met Office open day at Eskdalemuir and Lerwick Open Days
- 3 PhDs co-supervised (Edinburgh x2, Leeds)
- 3 geomagnetic models (the UK reference model, BGGM2017, MEME)
- 1 post-doctoral research assistant
- 1 MSc by Research co-supervised student (Edinburgh)
- 1 MPhil co-supervised student (Edinburgh)
- 1 NERC Highlight Topic grant award (project SWIGS)

Aurora at Lerwick observatory, July 2017 (image courtesy of Barry Broadbent).

Technical, observatory and field operations

Surveying the true north reference at Ascension Island Observatory using differential GNSS.

UK and overseas observatories

BGS operates nine observatories worldwide, as part of the UK contribution to international geomagnetism science. This network provides a continuous monitor of changes in the natural magnetic field and captures the contributions from all spatially and temporally varying magnetic sources from the core to the magnetosphere. As well as continuously undertaking technical developments to take advantage of new instruments and techniques, we take a leading role within the international observatory network to improve the quality and global distribution of measurements of absolute geomagnetic data.

As a core objective, the Geomagnetism Team aims to maintain continuous, real-time geomagnetic monitoring across its network of observatories and to meet the international standards on data quality and delivery laid down by INTERMAGNET. To this end, one of the primary operational functions of the Team is to regularly service and calibrate instruments and observatory infrastructure and to continually improve data quality and delivery.

One such observatory is JCO (Jim Carrigan Observatory), an observatory operated in northern Alaska in partnership with Halliburton Energy Services (HES), to support the local oil production industry. At JCO, the observatory instruments are located in raised sheds above the tundra, supported on piled foundations. The stability of these pillars over time is critical to data quality, so the azimuth bearings between the absolute pillar and fixed true north reference marks, originally determined in 2003, were re-surveyed using a differential Leica GNSS system during an October 2017 visit. We were able to verify (to within 1000th of a degree) that the instrument pillars have not moved or settled over time. The absolute pillar at Ascension Island Observatory was re-surveyed using the same method in April 2017.

Advantage was also taken of the Alaskan visit to complete vector magnetic observations (‘ground shots’) at two remote field sites to further validate IIFR modelling methods over the region. One site was chosen near to Kuparuk, and another approximately 10 miles south of Deadhorse along the Dalton Highway, to coincide with measured crustal anomalies in aeromagnetic survey data.

Using a fluxgate-theodolite to establish the axes of orientation of the Hartland large coil facility.

An early 2018 visit to Port Stanley (PST) is scheduled to put in place measures to mitigate the impact of a new television transmitter installed close to the observatory in March 2017. As BGS has no direct control over the transmitter site, interference from third party equipment has been a regular problem at PST over several years. Along with shortening cabling, a fluxgate magnetometer has been modified with additional analog filtering, which, it is hoped, will result in better signal-to-noise at the site.

Another essential part of these service visits is to provide quality assurance in magnetic measurements, through instrument calibration against national standards. One of the transferable standards that we use is a frequency source that provides a known input for Overhauser magnetometer calibrations. This year we have redesigned our source to provide a 'cleaner' signal (i.e. a reduced error) and a prototype is currently under test, after calibration at a UK NAMAS-accredited calibration facility.

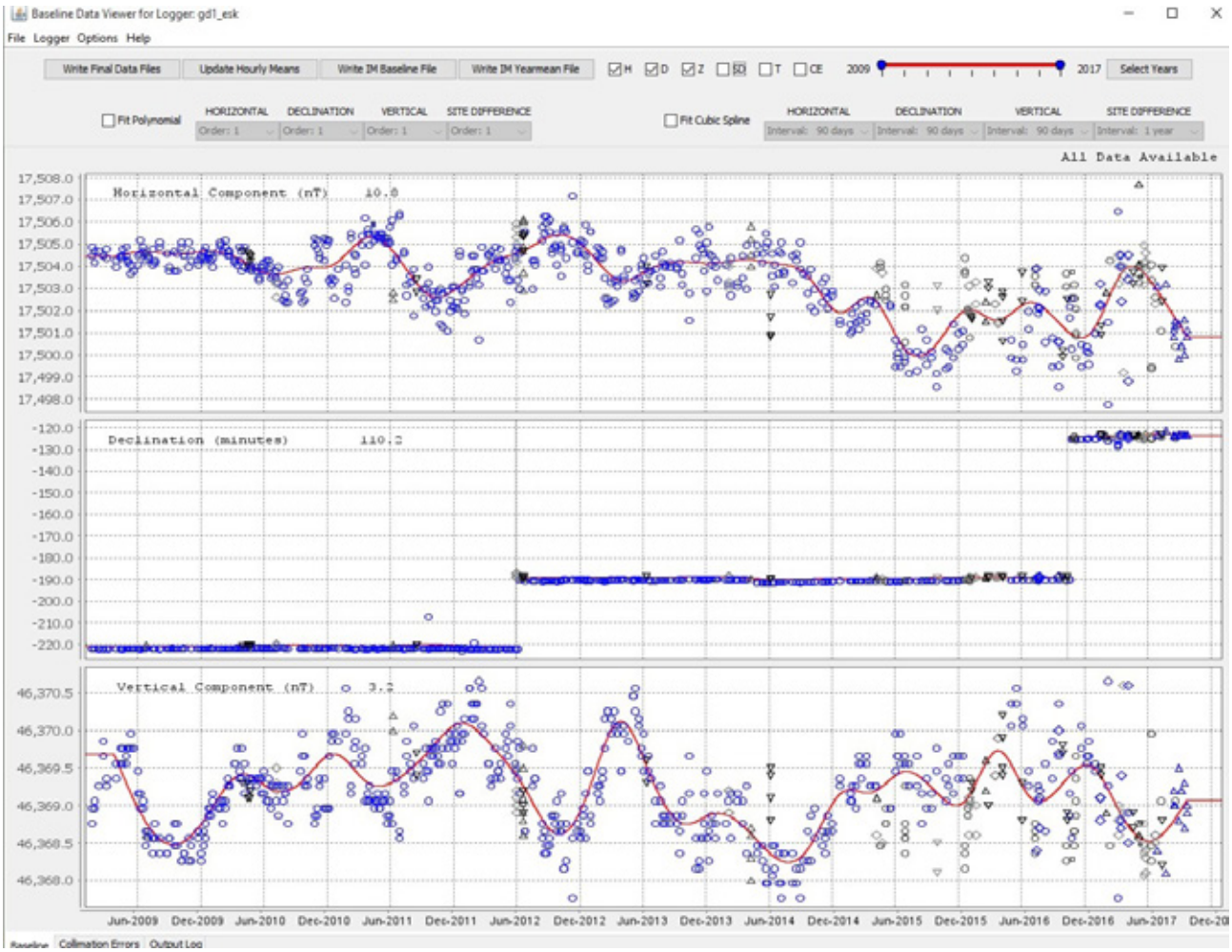
Third party manufacturers use Hartland Observatory as a calibration and test facility and a comprehensive calibration of the observatory's large coil system was completed during the year. The Hartland coil system consists of three orthogonal sets of two-metre Helmholtz coils, capable of generating uniform vector test fields for the evaluation of magnetometers and compasses.

We have continued the rollout of one-second sampling fluxgate and Overhauser instruments at our UK observatories and improvements have also been made to infrastructure. Careful site management in 2017 ensured that magnetic measurements were not affected by large-scale estates works carried out at Eskdalemuir Observatory. Similarly, Lerwick Observatory provided a complete measurement record during extensive refurbishment of the BGS buildings and during the three days of the Lerwick Observatory 'Open Days' in June/July. An all-sky camera, triggered by geomagnetic activity, was installed at Lerwick Observatory to capture images of the Northern Lights. We are currently awaiting a significant magnetic storm on a cloud-free night to verify its capability.

To support the wider international network, the BGS Geomagnetism Team continues to provide chairpersons for three of the INTERMAGNET management committees and we continue to provide practical support for observatories through the INDIGO project. Examples of INDIGO activities include the supply of new instrumentation to the Argentinian Servicio Meteorológico Nacional for its South Orkney Island station and the co-supervision of an MPhil student, who is working on improving the measurement and data processing capability of six Indonesian observatories.

Aligned with this, the Geomagnetism Team has significantly improved a data processing package that it makes available to the international community. This update to the widely used GDASView program allows for multi-year modelling of instrument drift using more advanced mathematical functions. This development is anticipated to yield higher accuracy in the final published data from many observatories.

Looking forward, the Team has been evaluating and procuring instrumentation that will deliver the measurement data required for Work Package 2.2 of the three-year 'SWIGS' project. The monitoring requirements here differ significantly from those of a permanent magnetic observatory and use has been made of the expertise of the BGS Earthquake Seismology Team in operating instruments in isolated locations. As part of the evaluation, a technique was developed to provide the scales, offsets and orthogonality angles of a three-component, full-field magnetometer using free rotations of the instruments in the natural field.



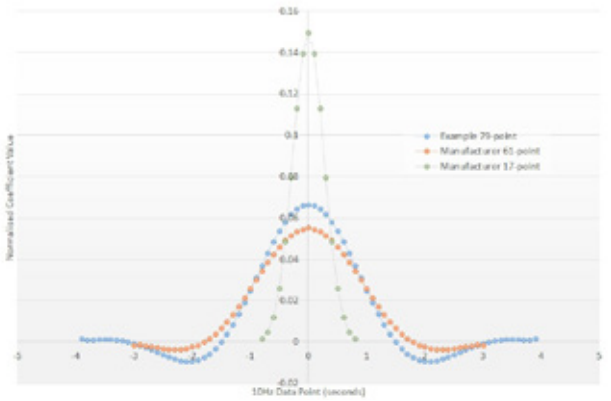
Multi-year baseline variometer fitting using the BGS GDASView application.

UK repeat station measurements 2017 (blue) and planned sites for 2018 (orange) sites. Map shows approximately half of the sites in the UK network.

As well as the continuous measurements at magnetic observatories, the Team conducts a rolling, UK-wide, vector magnetic survey using 40 repeat station sites. During 2017, nine of these sites were occupied in three clusters: northern Scotland, Wales/ Shropshire and the Yorkshire Dales/Peak District. The resulting 2018 magnetic declination model provides present and near-future rates of change of the field over the area of the British National Grid and this will be used to service requests for magnetic north data from the Ordnance Survey in 2018 and early 2019.

UK repeat station measurement tent at Loch Eribol site, near limestone kilns.

Technical, observatory and field operations



10Hz to one-second filter coefficients (17 - green, 61 - orange, and 79 - blue) for a commercially available fluxgate magnetometer.

Progress towards absolute and continuous one-second observatory data

Since digital recording began over thirty years ago, the global observatory community has published one-minute data as its basic data set. With modern instruments and telemetry, this observatory network is now capable of exchanging one-second data in real-time. This provides the scientific community with a new resource for operations and research, particularly in the field of space weather hazard. The Geomagnetism Team is undertaking extensive testing to ensure it meets international quality standards for this new data product.

The Geomagnetism Team has been rolling out next-generation instrumentation to its UK observatories during 2017. Overhauser and fluxgate magnetometers capable of returning one-second data samples are now running on long-term test at the Eskdalemuir and Hartland observatories. Internationally, the observatory network is working to a common data quality standard for one-second data, designed to provide data users with a well-defined, homogeneous data set for applications and research. Instrumentation is now commercially available that, according to manufacturer specifications (LEMI systems), meets the published INTERMAGNET one-second standards. The Geomagnetism Team has been assessing these instruments against the new standards, as well as against stability and reliability benchmarks for current observatory instrumentation.

The INTERMAGNET standard describes a number of criteria that a vector data set must meet, including constraints on the orthogonality of components, instrument noise level and minimum measurement range. Some of these criteria, such as the noise level in the UK instruments, have already been verified. This year, we have focussed on the transfer function of the fluxgate magnetometer and its long-term stability.

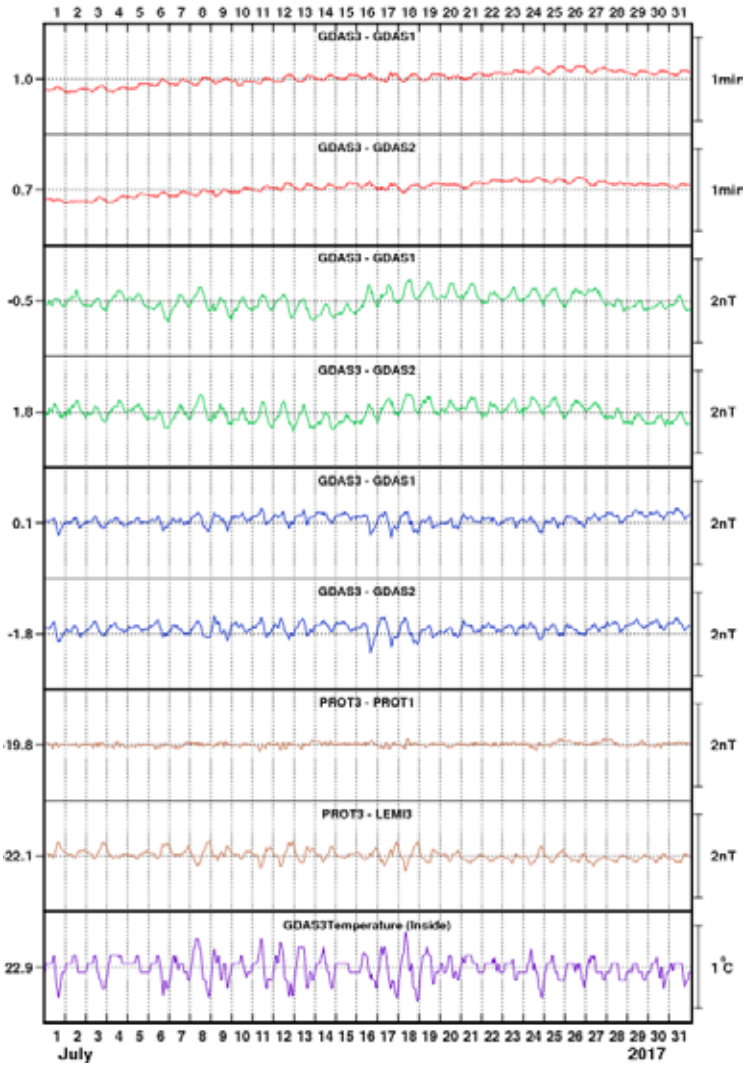
The transfer function defines the instrument amplitude and phase response to a known input. Using an external Helmholtz coil set held within a mu-metal shield, we are able to generate an impulsive magnetic field. We can then analyse the instrument output in the frequency domain, to evaluate the instrument against the published standards.

Much of an instrument's response is determined by the series of digital filters applied to the original analogue signal. The first Figure (left) shows the 17-point and 61-point coefficients of two such final stage filters (10Hz to 1Hz) for a particular instrument, as supplied by the manufacturer, as well as a Team-designed 79-point filter. The results compare the resulting amplitude response, when each filter is applied to the instrument, together with the unfiltered response of the instrument.

We find that both the unfiltered instrument and the 17-point filter do not attenuate sufficiently in the stop band (above 0.5Hz), while the 61-point filter exactly meets both the stop band and pass band (below 0.2Hz) attenuation specifications of the standard. However, the 79-point filter shows that these specifications can also be met without attenuating as severely in the pass band, therefore preserving more signal. All of these filters have also been shown to meet the phase response specifications of the INTERMAGNET standard.

As well as meeting the new standards set for these higher frequencies, the instrument must also fulfil requirements for measurement of the remainder of the spectrum—8mHz (120s) to DC. This simply means that the instrument needs to be capable of tracking true variations from one minute to the next, as well as remaining stable, in absolute terms, over months and even years.

To test this extra requirement we make use of our currently operational fluxgate magnetometers, which have a proven record of being accurate and stable over such periods. By running the two instrument types in parallel at our three UK observatories, we can compare the results, which in theory, should be identical. Plots of differences in the one-minute values, hourly values and daily values show variations that indicate issues and raises some doubt on the capability of the new instrument to meet the standards on longer term stability that we have become accustomed to with the current instruments. The example in the second Figure (below) shows a plot of the differences in hourly mean values measured at Eskdalemuir observatory by both instruments during July 2017. There is an unexplained daily signal in the variation as well as a longer-term drift. Conclusions on this are yet to be made and we will continue to investigate, through further tests carried out in 2018.



Comparison of hourly mean values (top to bottom: X, Y, Z, F and Temperature) measured with new instrument (labelled GDAS3) and those measured with the new LEMI instrument of the current observatory instruments (labelled GDAS1 and GDAS2) at Eskdalemuir observatory during July 2017.

Technical, observatory and field operations

Front page of the INTERMAGNET website: www.intermagnet.org

The World Data Centre for Geomagnetism, INTERMAGNET and the European Plate Observing System (EPOS)

The Geomagnetism Team plays a significant role in a number of international collaborations. We host the World Data Centre for Geomagnetism, a comprehensive digital data set that we actively develop and curate. Staff from the Team hold senior positions in INTERMAGNET, the global network of observatories that monitors the Earth's magnetic field and operates to agreed standards. Geomagnetism is one of ten science areas that will form the European Plate Observing System (EPOS) and the Team is at the forefront of work to integrate geomagnetic data products into EPOS. EPOS will promote cross-disciplinary research and data interoperability. We describe the contributions of Geomagnetism staff to these projects in 2017.

WDC

The Geomagnetism Team hosts the World Data Centre for Geomagnetism, a member of the World Data System (WDS) (https://www.icsu-wds.org/). This involves an active and ongoing program of work soliciting data from institutes around the world, quality checking the data and making it available through the WDC portal (http://www.wdc.bgs.ac.uk/).

Activities during the reporting year included making operational a new website for the World Data Centre, and simplifying access to the large amount of data that we hold on behalf of the community. In December 2017, we submitted an application to renew our WDS membership. A new CoreTrustSeal Trustworthy Data Repository certification scheme has replaced the Data Seal of Approval (DSA) and ICSU World Data System (ICSU-WDS) certifications of Regular Members.

BGS staff at the INTERMAGNET meeting in Hermanus, South Africa.

INTERMAGNET

The Team has major leadership roles within INTERMAGNET, occupying the chairs of the Executive Council, the Operations Committee and the Observatory Applications Subcommittee. In 2017, Team members played a major role in the publication of a new format to be used internationally for the exchange of high resolution one-second sampled geomagnetic data. This follows on from work done by the Team in previous years to create technical standards for the recording of one-second data. These efforts show clearly how BGS is influencing the development of magnetic observatory operations across the world.

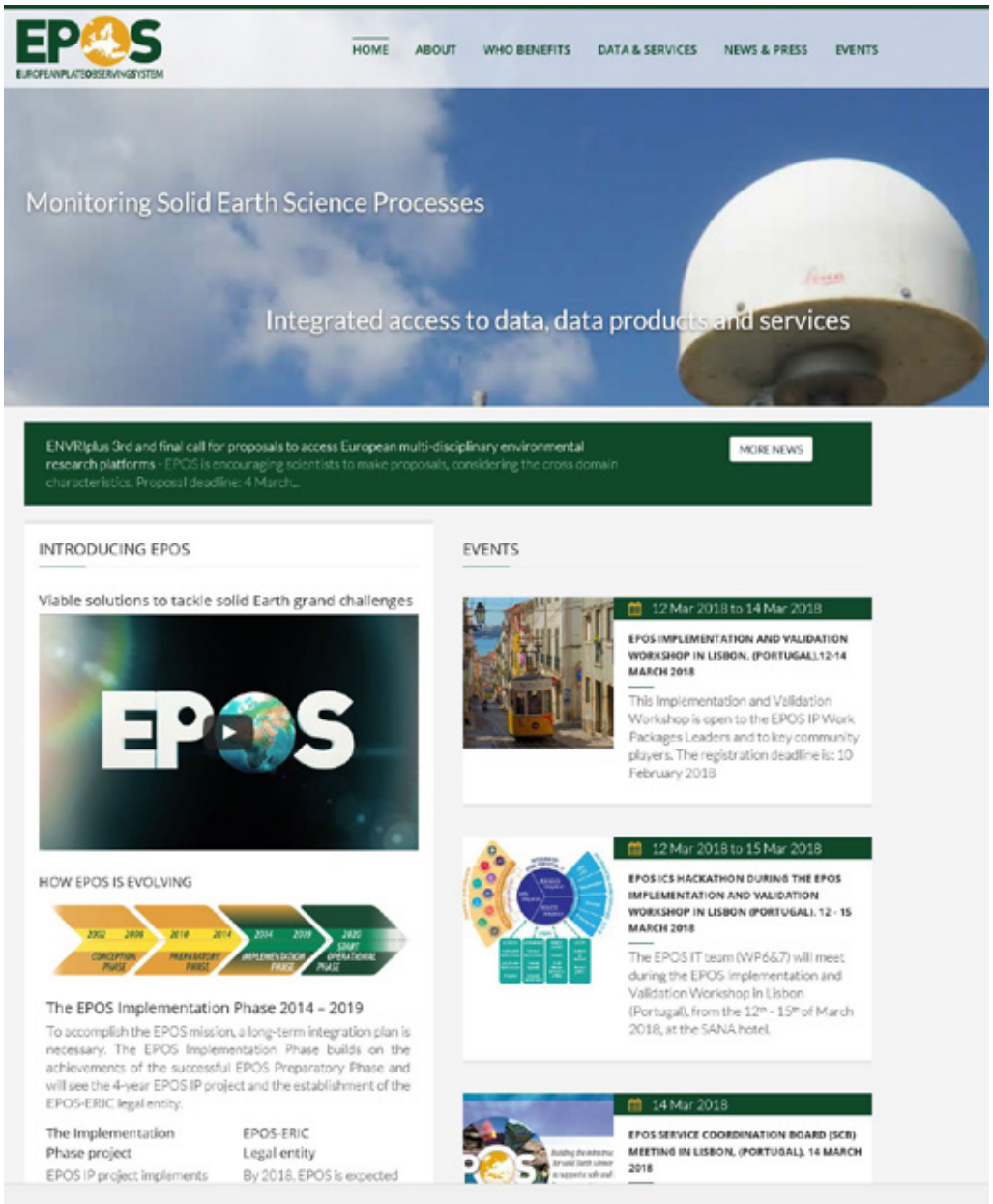
Team members helped organise the most recent INTERMAGNET meeting (Hermanus, South Africa) in 2017. A major discussion point at this meeting, and that the Geomagnetism Team led on, was the means by which INTERMAGNET can better communicate with and represent its stakeholders, both providers and users of geomagnetic data. Other areas that we contributed to included:

- The new software page on the INTERMAGNET web site, which lists useful software for data providers and users (http://intermagnet.org/publication-software/software-eng.php). We helped develop and maintain a significant number of the software projects listed on this page
- Maintenance and operation of the Edinburgh Geomagnetic Information Node, the largest of the five ‘data warehouses’ that INTERMAGNET runs and to which data providers submit their data
- Coordinating work on Digital Object Identifiers (DOI) across INTERMAGNET, with the aim of creating a system that allows data providers to receive credit for the work they do, but which also helps scientists, through making available reproducible data sets that can easily be cited in scientific publications

We have also started an initiative to regularly (four times per year) compile and communicate details on the quasi-definitive data provided to INTERMAGNET. Quasi-definitive data provides a means for observatories to submit absolute geomagnetic data more rapidly than the traditional publication schedule. This can be important, for example, in providing timely data for joint analyses of ground-based and satellite geomagnetic recordings. It is hoped that, by providing regular updates on the quantity and quality of quasi-definitive data provided, we will encourage other institutes to provide more of this type of data.

EPOS

The European Plate Observing System (EPOS) is an EU-funded project to facilitate cross-disciplinary use of data, data products and facilities from distributed research infrastructures in solid Earth science in Europe. Staff from the Team are heavily involved in the project, for example leading the tasks on finance and IT for



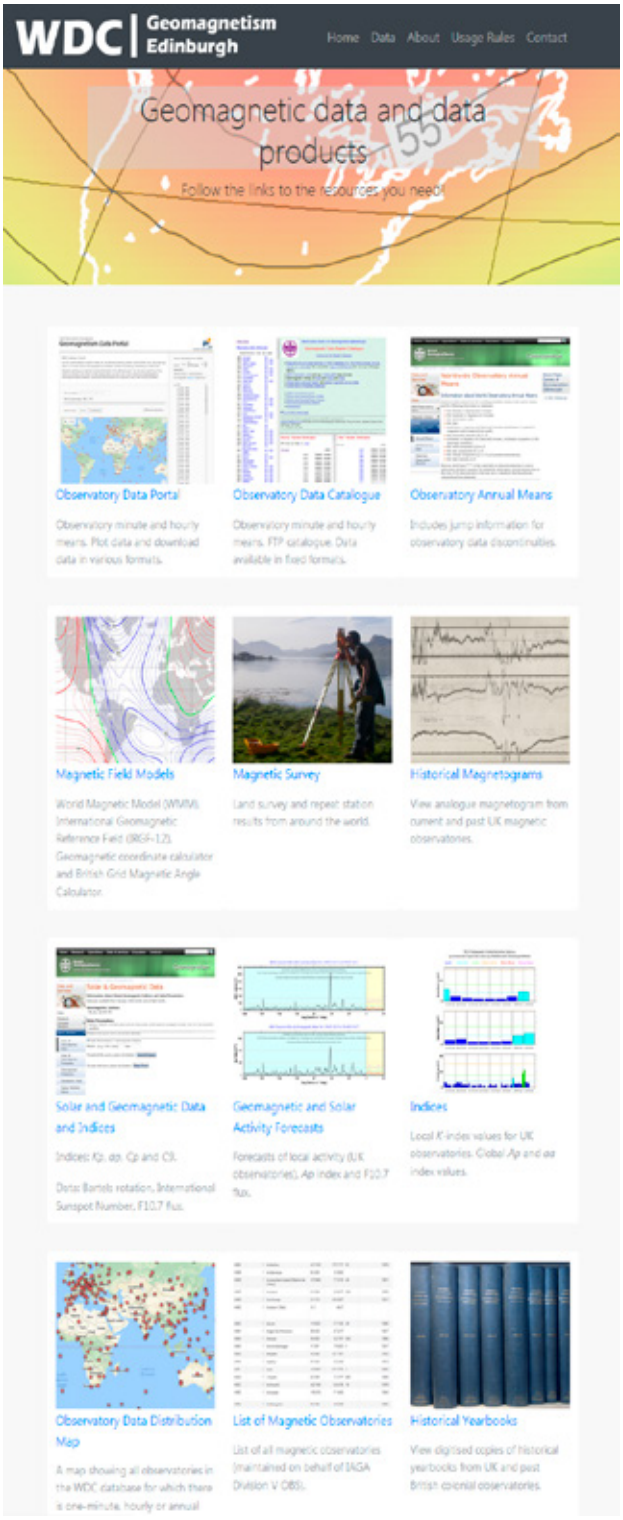
The front page of the EPOS website: www.epos-ip.org.

the ‘Geomagnetism Observations’ work package. The Geomagnetic community is already well organised in terms of collecting and distributing its data to international standards. However, there are some areas where there is room for improvement, such as metadata, and the EPOS project has provided the impetus and the funding to make progress here.

During 2017, we led an initiative to create a central database for geomagnetic metadata. This initiative was first reported last year. Progress this year has included peer review of the database design and publication of the database on BGS database servers. Work has also started to fill the database with metadata from existing sources (such as INTERMAGNET and the World Data Centre).

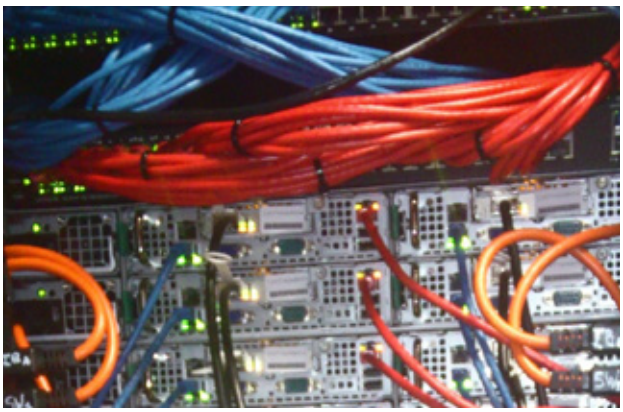
Other

The geomagnetic community needs to update the way it licenses its data. The licenses currently used are not recognised internationally and are not ‘machine readable’. Licensing of data is a sensitive issue for data providers. We have led the discussion within international science communities (such as at the International Association for Geomagnetism and Aeronomy meeting in Cape Town in September 2017) and are starting to formulate recommendations to data providers on how their data can be licensed in a way that makes it more accessible to modern data management systems.



Data products are clearly listed in the new WDC website.

Technical, observatory and field operations



The BGS HPC cluster – rear view.

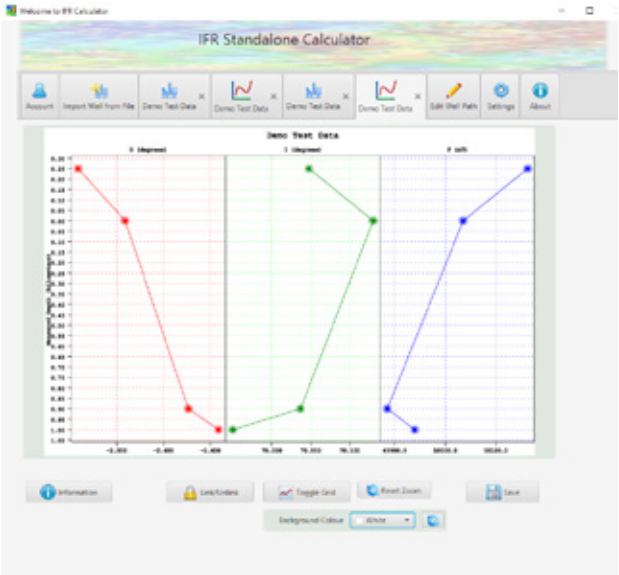
IT developments in Geomagnetism

Robust and resilient IT is essential to much of our work in Geomagnetism: from the software we create to record data at our observatories, through quality control and scientific analysis of the data, to the specialist high performance computer systems used to create geomagnetic field models, and to the web systems we run to make our data available to all users. All this IT must run smoothly, efficiently, and above all reliably. We describe here the developments to our IT systems in 2017.

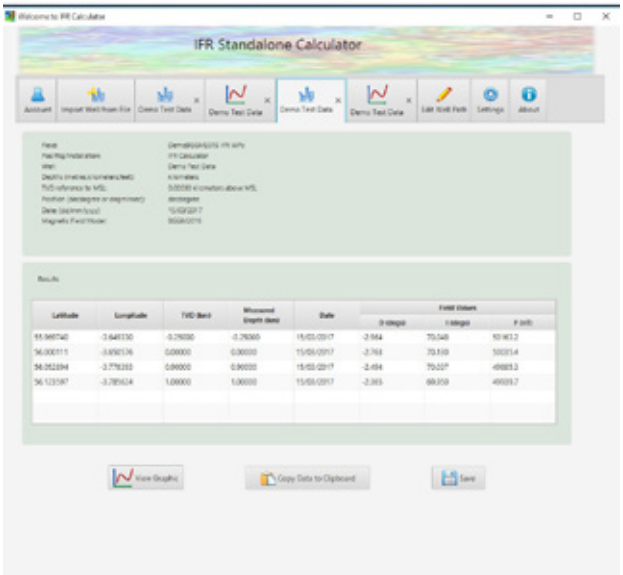
A major IT investment this year has been development of a desktop application for 'In-Field Referencing', tailored to customers' workflows. This software calculates magnetic field values at a set of locations down the borehole in time and space. It reads the well-path information and gives results in a variety of industry-standard formats.

Other significant IT developments we have undertaken this year include:

- Upgrading the operating system on our High Performance Computing (HPC) cluster. This major upgrade to the cluster's software will protect our investment in this hardware for at least another two years
- Starting a collaboration with the Edinburgh Parallel Computing Centre (EPCC) to modernise our software used to calculate magnetic field models on HPC clusters. This new software will be easier to maintain and develop. Additionally, it will give us the option to run the code on commercial HPC clusters, which may be more cost effective in the long run, compared to investing in a BGS replacement cluster. This collaboration with EPCC started in mid-2017 and will finish mid-2018
- Upgrading the software used for BGS and other 'Open Days' to allow members of the public to obtain a magnetogram for any day of interest to them. This software now makes use of the digitised archive of paper magnetograms, going back to the 1850s
- Upgrading the software used to allow customers access to the BGS Global Geomagnetic Model (the high resolution model intended primarily for the oil industry)
- Adding a facility to present a 'slide show' on the magnetic observatory data visualisation software that we maintain on behalf of INTERMAGNET
- Augmenting the significant quantity of software we hold that is dedicated to



Graphical view of the vector magnetic field along a well path, from the IFR Calculator software.



Tabular view of magnetic well-path data.

the real-time collection, quality control and delivery of magnetic observatory data. For a number of years we have been working to migrate this code from Solaris to Linux platforms. We have made significant progress this year, with a complete test system running nearly the full suite of software in parallel with our current production systems

We have worked on a number of initiatives over the year to improve the efficiency and effectiveness of the software development process, including:

- Delivering training in 'Git' version control. We are now standardising Git workflows designed to improve reliability and maintainability of our software. Part of this Git workflow includes peer review of the software that we create and develop
- Starting automated testing of our software, as a regular part of software development. We write the test as another piece of software and this allows others to use the same tests in the future, making software development faster
- Putting in place workflows to ensure that versioning of software code and compiled products is as automated as it can be

This year we ran a number of software 'sprints'—week long (or longer) periods, with dedicated staff—where we made a concerted effort to achieve a number of goals in software development. We held five sprints this year and the sprint methodology is now embedded into our way of working.

Last year we introduced a web cluster to improve the resilience and reliability of our web services. This extra reliability comes at a cost: an increased complexity in managing the cluster. During the year we had a small number of problems with the cluster file system. We are therefore investigating ways in which we can provide a more reliable system.

Science

Space weather impact on ground-based systems

The Geomagnetism Team is leading a high profile NERC-funded project into how space weather affects conducting infrastructures on the ground. To understand this hazard and the risks it poses, the project consortium is researching how the Sun and solar wind interacts with electrical currents in the magnetosphere and ionosphere. Understanding how the solid Earth responds to space weather and these currents, how this induces electrical currents in conducting infrastructures and how we can improve forecasts of space weather and impacts are other major elements of the project.

Project SWIGS (Space Weather Impact on Ground-based Systems) is a four year project funded by NERC, under its 'Highlight Topics' scheme. The SWIGS project team is a consortium of ten UK institutes, twenty-one researchers and six post-doctoral research assistants. This is a major investment by NERC in space weather and the consortium led by BGS comprises many of the major UK players in the subject. SWIGS formally started in May 2017 and held its kick-off meeting in June in Edinburgh.

SWIGS aims for radical improvements in the accuracy of coupled ionosphere-magnetosphere models, and in models of the solid Earth response to these magnetic field sources, that leads to major advances in accurate numerical now-casting and forecasting of Geomagnetically Induced Currents (GIC) in ground-based infrastructures.

Our objectives are to:

- Produce new insights into the structure and dynamics of magnetospheric and ionospheric sources of GIC, including the ring current, field-aligned currents and the auroral electrojets, especially during extreme space weather
- Develop realistic models of the surface electric field, as the source of GIC, from these step-change improvements in our understanding of external geomagnetic fields and from improved knowledge of shallow to deep Earth conductivity in the UK
- Validate models of surface electric fields and of GIC in transformers through field work and measurements
- Develop new UK capabilities in space weather forecasting of geo-electromagnetic variations and GIC
- Produce new insights into extreme events, their cause and impacts, from modelling and statistical analysis, and addressing emerging industry and insurance 'worst case' requirements
- Understand better the role of the Earth's main magnetic field, generated in the liquid core of the planet, as a control on space weather impact location and severity

- Explore and quantify the GIC hazard to the UK electrical transmission, railway and gas transmission pipeline networks

We will therefore develop better physical understanding of electromagnetic fields and currents in near Earth space and in the upper atmosphere, focussing on the couplings between the Solar Wind and geo-electromagnetic processes on the ground and in the ionosphere and magnetosphere (under Work Package 1—see Figure below).

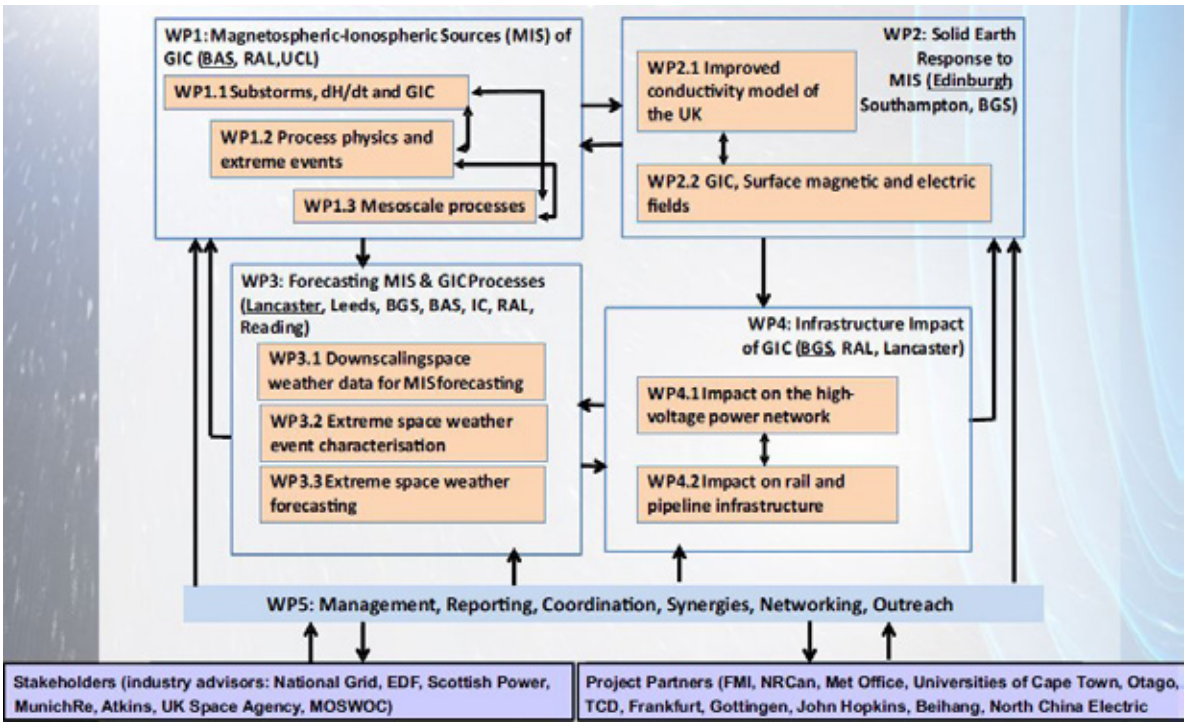
We will also make surface electric field, subsurface conductivity and GIC measurements—creating legacy data sets—to validate existing and new models and to provide estimates of uncertainty in estimated GIC, for example at the transformer level (WP2).

Industry requires better and timely forecasts of GIC and our proposal will seek to improve forecasting of Earth environment and solid Earth processes and extremes (WP3).

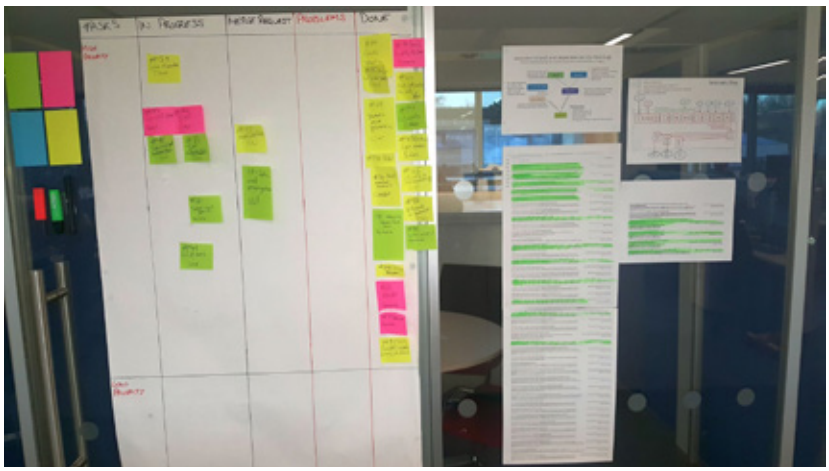
This will all lead to a new generation of solid Earth and space environment models that quantify how space weather, rapid magnetic variations, sub-surface conductivity and surface electric fields impact surface conducting infrastructures such as the National Grid (WP4).

SWIGS is supported by an industry stakeholder group and a group of international project partners from FMI, NRCan, UK Met Office, North China Electric Power University, and the Universities of Cape Town, Otago, Trinity College Dublin, Frankfurt, Gottingen, John Hopkins and Beihang. In addition to our research programme, SWIGS will also promote workshops and other meetings (see Figure).

In this first few months the Geomagnetism Team has concentrated on developing its electrical model of the UK electrical transmission network, undertaken some early research on railway and pipeline systems, made preparations for the upcoming fieldwork campaign and continued our research into a GIC index of activity that is appropriate for quantifying extreme space weather.



Breakdown of SWIGS into work packages, showing links and feedbacks between the activities. Work package leaders are underlined.



'Kanji' board for planning and running a software sprint, showing the progression of each task (left to right across the chart) as it is started, completed, reviewed and then merged into the main code.

Global geomagnetic field modelling

Our global magnetic field modelling code is one of the main assets of the Geomagnetism Team. Over the past year significant effort has been made to modernise the existing code base of our MEME model (Model of the Earth's Magnetic Environment) and in particular its satellite survey data selection component. These improvements will allow the field model to incorporate more geophysical parameters and data, to be run in a highly parallel fashion, and to be easily extendable into the foreseeable future.

The majority of our legacy main field modelling and support code is written in Fortran, a fast and compact computer language. This code base has been constantly developed and maintained over several decades, allowing improvements such as parallelisation and the implementation of spline time-dependence parameterisation. However, as the code grows older, more and more effort is required to maintain and develop it. Hence, we have undertaken several activities to refresh and update the code base, in order to improve its readability and maintainability into the future

EPCC grant

In 2017, the Team began a collaboration with the Edinburgh Parallel Computing Centre (EPCC), at the University of Edinburgh, with Dr Nick Brown. We won a competitive grant from the eCSE (embedded Computational Science and Engineering) programme to fund the update of our Fortran code to modern standards and to implement the capability to compute large-scale matrix inversions using PETSc (Portable, Extensible Toolkit for Scientific computation) and SLEPc (Scalable Library for Eigenvalue Problem computations). These are open-source parallel computing modules, which can scale across thousands of processing cores.

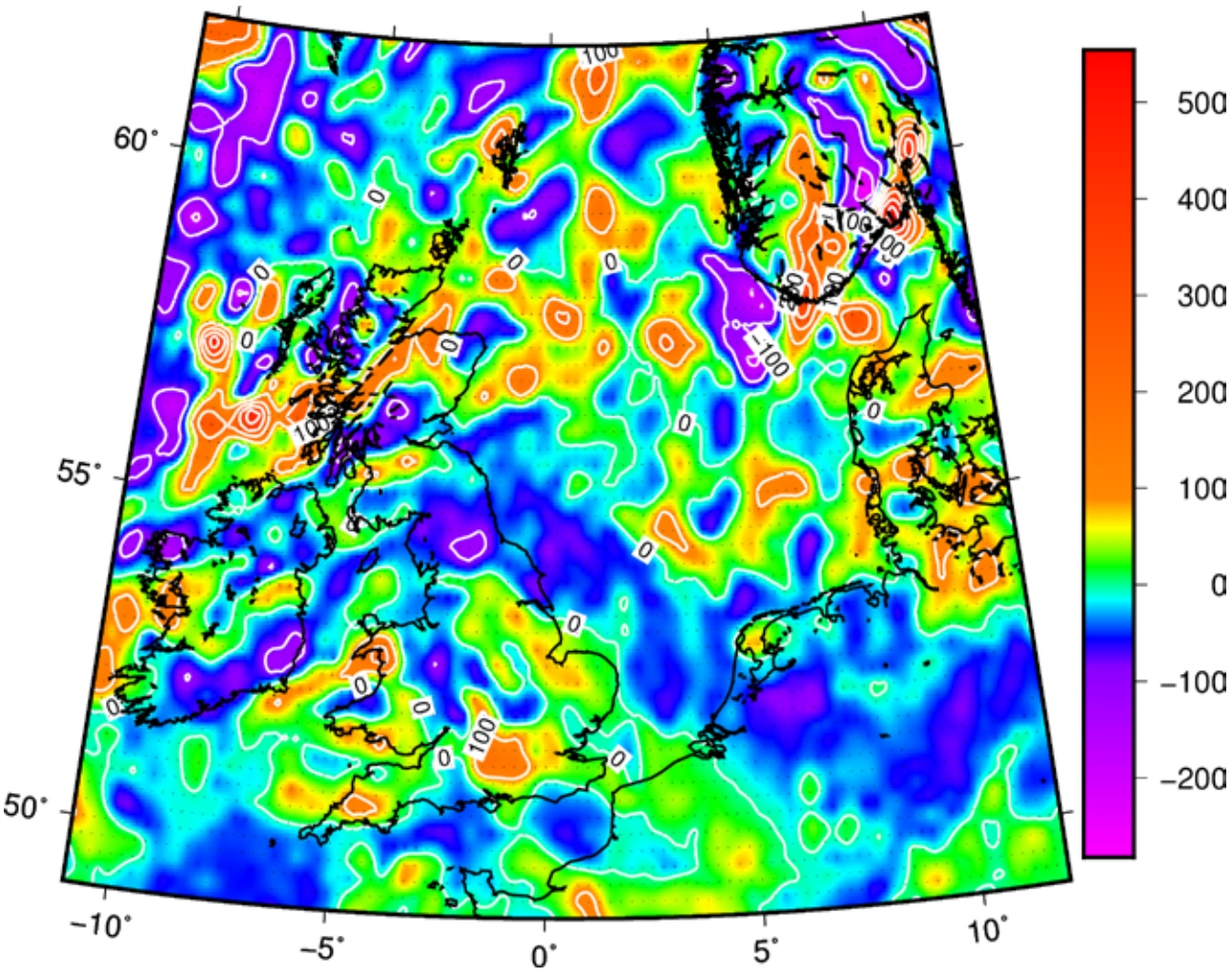
We provided the EPCC with a test version of the MEME 'parent' code, via GitHub, allowing them to re-write and test new code on the Edinburgh ARCHER cluster. The eCSE grant provides around 9

months of Geomagnetism Team staff time, split across the 18 months of the grant. Thus far this effort has allowed the code to be modularised and tested, showing impressive reductions (over ten-fold) in the time taken to invert sets of satellite data to solve for the Gauss spherical harmonic coefficients. Further improvements in modelling capability and processing are expected in 2018.

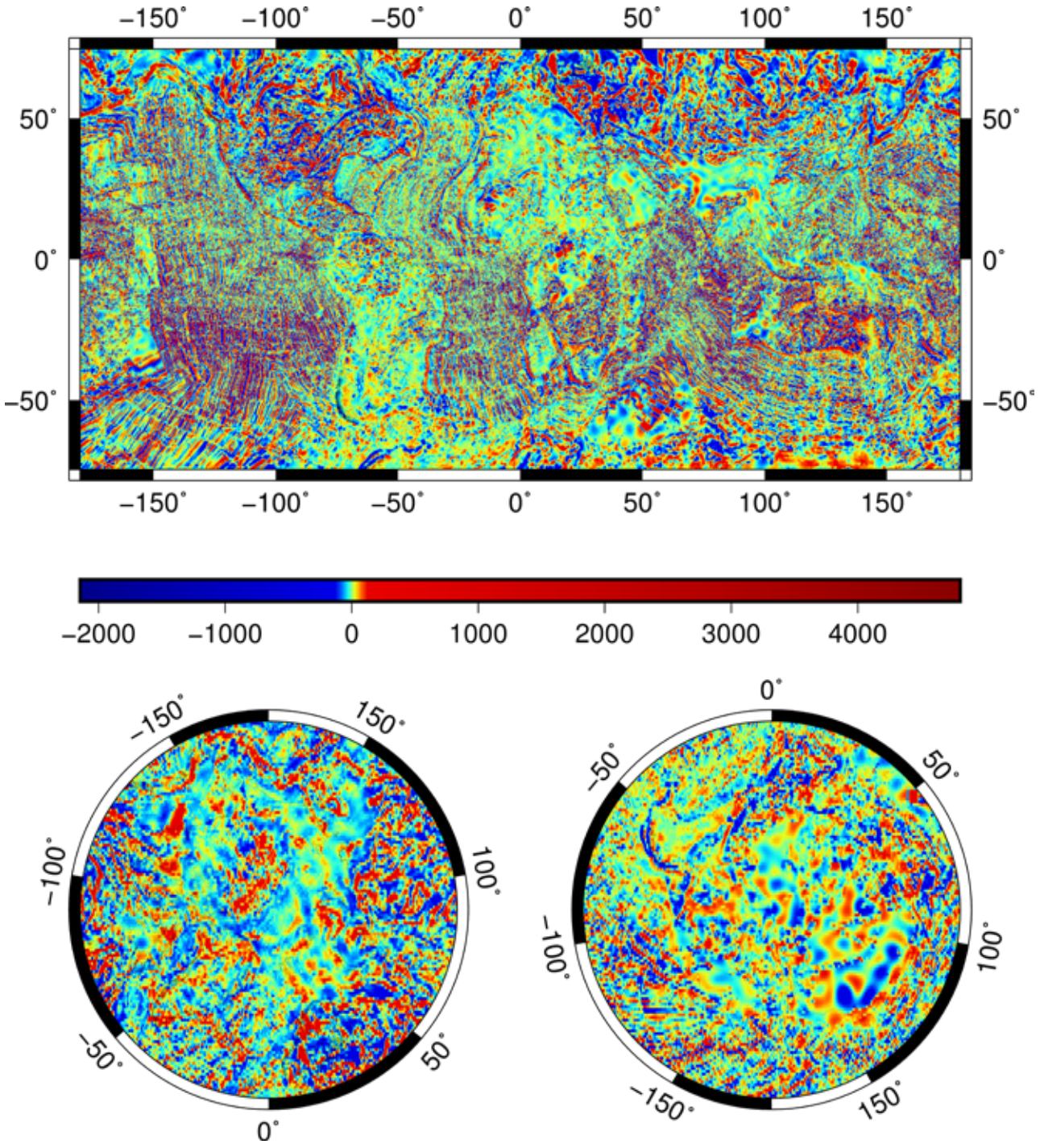
Data selection

In a parallel activity, we decided to refresh our satellite data selection code base. This code was also originally written in Fortran but has become difficult to maintain, update and operate during the Swarm era, partly due to the sheer quantity of data now available from Swarm.

A decision was made to re-write the software in Python, partly to improve its maintainability and performance, and partly as a training exercise allowing development of best-practise software skills amongst the team. This development was 'sprint'-led, with strict control of the development process via version control, continuous integration and code reviews before merging. There were two main sprints in 2017 to complete the work, which involved up to ten of the Team at any one time. Significant progress has now been made in converting the Fortran code to Python and we now have thorough documentation and a fully tested and integrated function code base. The code can now also be parallelised to perform data selection at a highly accelerated rate.



Detail of the vertical component of the BGS crustal magnetic field in the North Sea region, evaluated to degree 800 (50 km scale size). Scale in nT.



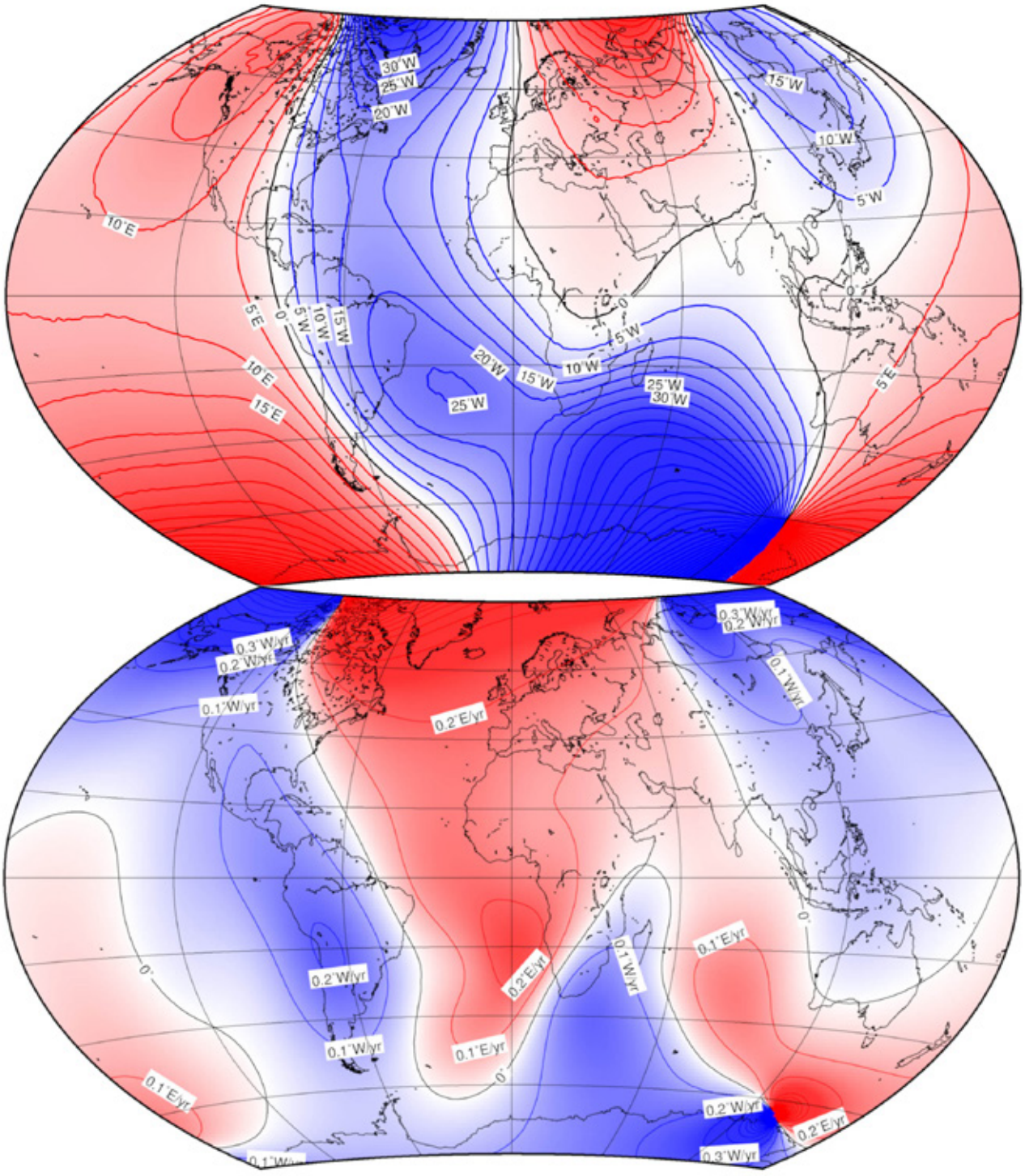
BGS global map of the vertical component of the crustal magnetic field to spherical harmonic degree 800 (a minimum feature size of about 50 km). Scale in nT.

800+ spherical harmonic degree model

Models of the high degree (or short wavelength) crustal magnetic field rely on the collection and integration of data from aeromagnetic and surface marine surveys. There are several publicly available datasets, such as the World Digital Magnetic Anomaly Map (WDMAM), which is an IAGA-led effort to create a grid of scalar magnetic field anomalies with a nominal resolution of 0.2° in latitude and longitude.

We have been working on improving the data that can be processed to create a degree 800 model (resolving magnetic signatures to about 50 km wavelength) and to examine the improvement of the

fit of the magnetic field model to ground-based observations. We have produced a series of inversions from the WDMAM total field anomaly data to create spherical harmonic Gauss coefficients, which can be converted into the three vector components of the field. The Figure (left) shows the vertical field component from this high degree model. This high degree model clearly contains more spatial detail than the current BGGM (for example, the Figure below).



Models of the magnetic declination (in degrees) and how it changes over time (in degrees per year), as estimated from the 2018 revision of the BGGM for 31st December 2018. The colour denotes a magnetic variation or rate-of-change to the west/east of true north in blue/red.

Chris Turbitt shows the mu-metal shielding chamber in the Geomagnetism Lab at Eskdalemuir Observatory to (left-to-right) Dr Joan Campanya, Dr Sean Blake and Prof Peter Gallagher from Trinity College, Dublin.

Student and visitor activities

The Geomagnetism Team welcomes researchers and other visitors from around the world. We also have a number of PhD and MSc students supervised by staff members, who use BGS data and our infrastructure to complete their own research.

Visitors and visits

As part of an international collaboration with the University of Otago, part-funded by the New Zealand Ministry of Business, Innovation and Employment, Gemma Richardson visited Dunedin for three weeks to collaborate with Dr Tim Divett and Professor Craig Rogers on Geomagnetically Induced Current research.

The Royal Society/Royal Irish Academy Knowledge Exchange Grant continued in 2017 and we hosted several visitors from Trinity College Dublin (TCD). Sean Blake and Dr Joan Campanya came for several short visits in 2017, the longest one being in February. Professor Peter Gallagher also visited for a few days and was given a tour of the Eskdalemuir Observatory (see Figure).

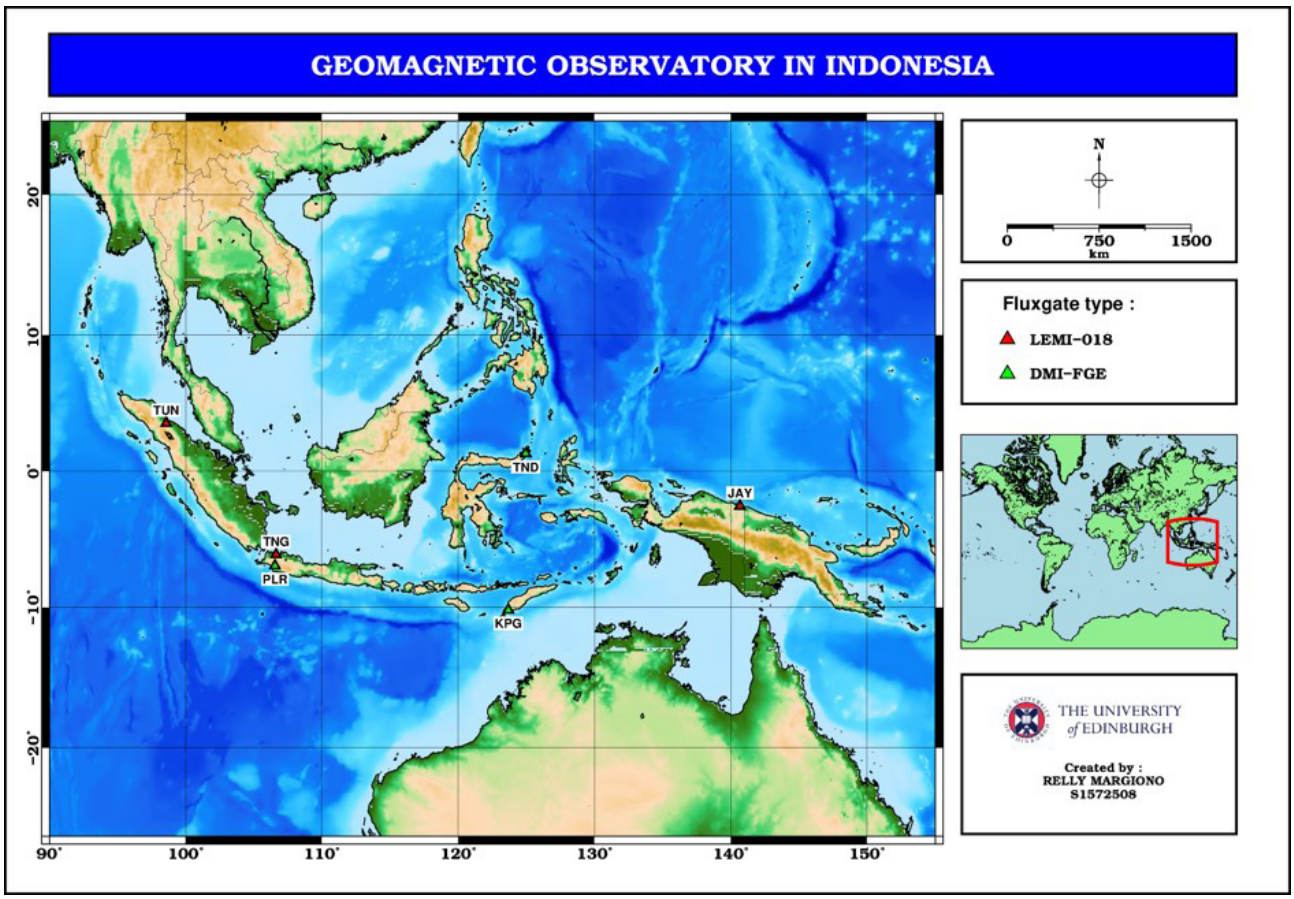
Students

Sean Blake completed his PhD on the space weather hazard to the Irish electrical transmission system and successful passed his TCD viva in December.

Hannah Rogers was awarded her one-year MSc by Research, also in December, and has since moved onto PhD research at Edinburgh University, examining the utility of Slepian functions in modelling the magnetic field using vector data.

The Team currently have three PhD students under the NERC Doctoral Training Programmes of Edinburgh and Leeds Universities. The BGS BUFI programme part-funds these scholarships.

Ashley Smith is in his third year at Edinburgh University studying auroral electrojets in the polar regions using Swarm satellite data. He published his first paper in 2017. Maurits Metman is also in his third year of a PhD at Leeds, researching the large-scale changes of the magnetic field in the Earth's core that are due to diffusion of the magnetic field. Maurits is supervised by Dr Phil Livermore



The location of the six Indonesian observatories studied by Relly Margiono, an MPhil student jointly supervised by BGS and the University of Edinburgh

and Professor Jon Mound, with Ciaran Beggan co-supervising on behalf of BGS. Maurits visited BGS in Edinburgh for one month in March and achieved his first publication later in the year. Our final, first year, PhD student is Hannah Rogers at Edinburgh University (as above).

Orsi Baillie, a member of the Geomagnetism Team, continues her two year part-time MSc by Research, investigating the geo-electric field dataset that has been collected by the Team in the last six years. She presented her work at a number of conferences, such as European Space Weather Week in Belgium.

Relly Margiono, an MPhil student at the University of Edinburgh, started his research in April 2017 into the use and improvement of geomagnetic data from the Indonesian observatory network (see Figure). In the first year of his research, he has focussed on identifying good practise and bringing the entire Indonesian network up to INTERMAGNET data standards. He is working closely with Chris Turbitt and Ciaran Beggan.

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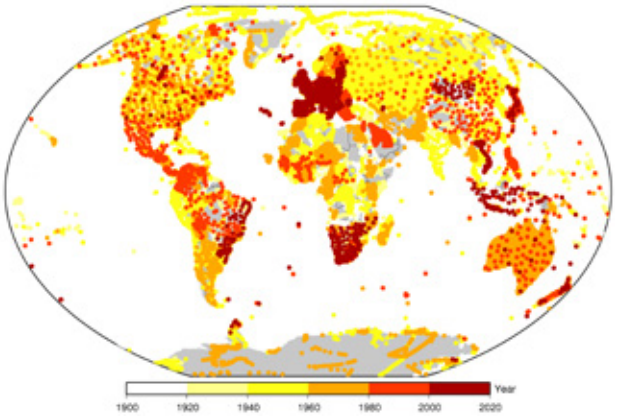
Smith, A R A, Beggan, C D, Macmillan, S, and Whaler, K A. (2017). Climatology of the Auroral Electrojets Derived From the Along-Track Gradient of Magnetic Field Intensity Measured by POGO, Magsat, CHAMP, and Swarm, Space Weather, 15, 1257–1269, 10.1002/2017SW001675



Locations of all vector observations used for assessing one-sigma field uncertainties, colour coded by age of observation. Grey indicates no onshore data and white indicates the absence of data offshore.

Geomagnetic referencing services for the oil industry

The Geomagnetism Team works with oil drilling companies to provide a three-tier geomagnetic referencing service that increases the accuracy of wellbore positioning in major oil and gas fields around the world. These tiers, in increasing order of sophistication, are the BGS Global Geomagnetic Model (BGGM), the In-Field Referencing service (IFR and known as IFR1 or CA within the industry) and the Interpolation In-Field Referencing service (IIFR, or IFR2).

The BGGM2017 was released in April 2017. For the first time, the BGGM produces scalable, one-sigma magnetic field error estimates, for each location and date entered by the model user. By 'scalable one-sigma error estimates' we mean that the code provides a one-standard deviation uncertainty for the magnetic field at the location, which can be mathematically combined with other sources of error/uncertainty from the drill-string by the user. Ultimately, a given user can multiply this one-sigma value by other scale factors of interest, for example to represent one, two, or three standard deviation uncertainties, as if the data were drawn from a Gaussian, or Normal distribution.

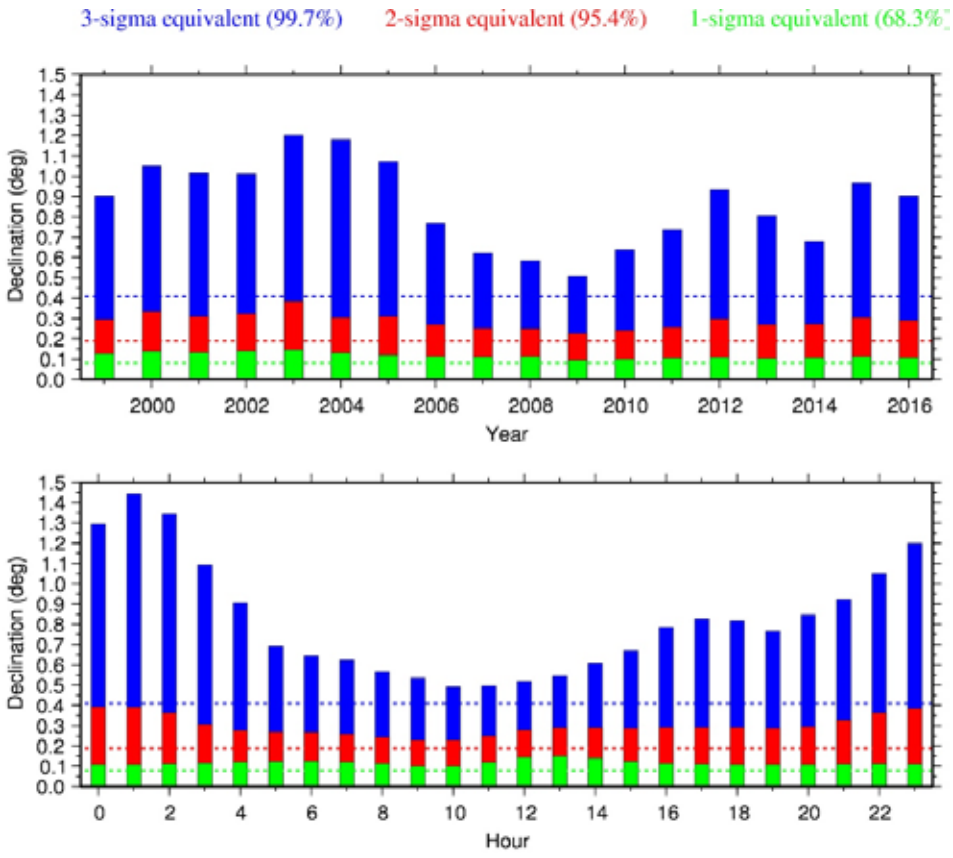
In reality, geomagnetic data and their uncertainties are rarely represented by the Normal distribution. Instead, the data distribution typically has rather long tails, as a consequence of large static crustal magnetic anomalies or from time-varying severe space weather. The industry requires a particularly high confidence level that is often two, three or even four times the equivalent one-sigma error, for collision-avoidance purposes. We therefore calculate such high confidence levels for all locations and dates, which are robust, and then scale these to get the equivalent one-sigma error equivalent (see first Figure above).

We also implemented a BGGM web service in 2017. This web service allows industry software to call the BGGM through a web address. In addition, the BGGM standalone code, BGGMTool, can now read well-plan data in a variety

of formats used by the oil industry. Both these developments are designed to reduce human error and intervention and to improve service efficiency.

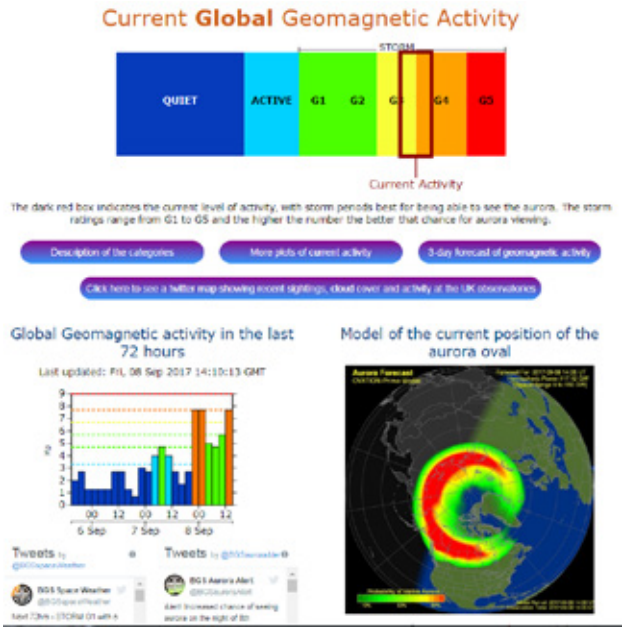
During 2017, we prepared IFR services for nine new hydrocarbon fields around the world. This preparation involved sourcing aeromagnetic data from public domain and commercial databases and searching World Data System data holdings for any other magnetic data over a survey area around each field. For each such 'prepared service', the scalar aeromagnetic data for the area were converted to full-field absolute values where possible, and then directional and downward-continuation filters were applied to obtain estimates of the crustal magnetic field vector at depth, down the well path. Local vector observations were used where available, to assess the local field uncertainties. Several years of one-minute data from the nearest suitable magnetic observatories, available via the WDC, were used to assess the additional contribution to the local field uncertainties caused by the external disturbance field, which varies according to time of day, season and solar cycle.

During 2017, we continued to provide IIFR services for locations in the North Sea (UK and Norway), the Norwegian Sea, Western Canada and Alaska. The most sophisticated service offered with the lowest associated uncertainties, IIFR, makes use of real time magnetic observatory data to combine with IFR. Importantly, the uncertainties can usually be considered fixed with no variation in time (see Figure below) as is the case with IFR and BGGM. The exception to this is high geomagnetic latitude drilling and where the observatory may be located at some distance from the drilling location, in which case geomagnetic activity-related variation in the uncertainties remains. Throughout the year, BGS has continued to assess these uncertainties and provide information to industry.



The 3-sigma, 2-sigma and 1-sigma equivalent confidence limits associated with IFR (histogram bars) and IIFR (dashed horizontal lines) declination values by year (top) and by hour of day (bottom) for a location in the Norwegian Sea.

Applications



A snapshot of the BGS website showing real-time data during the September 2017 storm.

Space weather services and research

Space weather is an important component of the scientific research and operations carried out by the Geomagnetism Team. As a natural hazard, space weather poses risks to technological infrastructures and, at the same time, there is public interest in the beautiful phenomenon of the Aurora Borealis, or Northern Lights. The Team continues to develop our space weather research and to find applications. We also present our work at international conferences, most notably this year at the European Space Weather Week in Belgium.

Upgrading and validating the power network model

A commercial project comparing and contrasting Geomagnetically Induced Currents (GIC) in the UK and French power grids afforded an opportunity to upgrade the way the UK electrical transmission network is modelled. Previously the network had been modelled to a substation level, where each substation is modelled as a single node in the network, connected to other substations/nodes by high voltage transmission lines. Our model now includes a higher level of detail, with characterisation of individual transformers within each substation, and a better representation of any parallel transmission lines between substations.

As part of a collaboration with the University of Otago, Gemma Richardson spent some time at the start of the year in New Zealand. She worked on validating our GIC modelling code for the updated network representation, using a known benchmark test from the scientific literature. This was also an opportunity to work with Dr Tim Divett and colleagues on modelling electric fields and GIC in New Zealand.

An activity index for GIC

Work has continued throughout the year on developing a geomagnetic index that better classifies GIC in the UK power system. The Kp index is often used around the world to identify geomagnetic storms that pose a hazard to power systems. However, as the Kp index is quasi-logarithmic, the top value in the scale (9o) covers a large range of magnetic field

variability. This includes variability during storms that may only pose a moderate risk of interruptions on the power system, up to the most rare and severe storms that could cause widespread and long-term damage.

An investigation into existing indices has shown that there is not currently a suitable index for properly describing the GIC hazard. Therefore, we have sought to develop a completely new index, specifically focused on GIC.

We are exploring two different methods based on geomagnetic data, one in the time domain and the other in the frequency domain. Both methods use a much shorter sampling interval compared to the 3-hour Kp index, which is too long a period to be useful for GIC studies. Both methods are currently being validated against measured and modelled GIC data, with a view to an operational rollout in 2018 in association with Met Office.

European Space Weather week

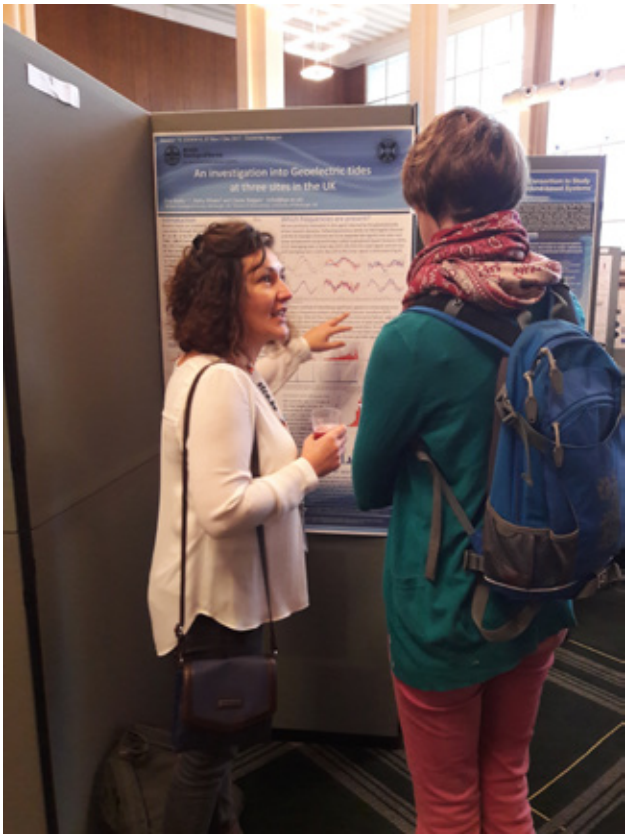
The Team had another strong representation at this year's European Space Weather week in Oostende, Belgium (November 2017). We presented three posters, one talk and a live forecast (by Orsi Baillie). We also convened a dedicated GIC science session and contributed to an invitation-only 'User Lunch' on the subject.

Ellen Clarke presented a poster detailing data available from BGS for space weather applications, whilst Orsi Baillie presented a poster on work from her MSc analysis of the geoelectric data measured at the three UK geomagnetic observatories. Alan Thomson had a poster introducing the SWIGS project, which started this year (see elsewhere under the Science section of this Review).

Ellen Clarke and Gemma Richardson convened a session on 'Ground-Based Operational and Infrastructure Impacts of Space Weather'. In this session Gemma presented a talk titled 'Recent advances and validation of GIC modelling in the UK'. She described the recent work on updating the network and validating the code (as described above). She also compared the Team's electric field and GIC models with UK electric field and GIC measurements, respectively.

The September storm

September 2017 saw one of the largest geomagnetic storms of the current solar cycle. This generated a lot of public interest, with aurora sightings across the UK. The storm was also recorded by the BGS Schools magnetometer network, and for the first time these data have been used for GIC modelling. This was an interesting, if not severe, storm globally with some anecdotal evidence of modest GIC impacts in the power systems of Norway and New Zealand, though not in the UK, the reasons for which will be studied in the coming years.



Orsi Baillie presenting her poster on geoelectric tides observed in the geoelectric data measured at the three UK observatories.

Publications and knowledge exchange

Chris Turbitt leading a tour of Lerwick Observatory.

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 2017

Bailey, R L, Halbedl, T S, Schattauer, I, Römer, A, Achleitner, G, **Beggan, C D**, Wesztergom, V, Egli, R, Leonhardt, R. (2017). Modelling geomagnetically induced currents in midlatitude Central Europe using a thin-sheet approach. Annales Geophysicae, 35 (3). 751–761. 10.5194/angeo-35-751-2017

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Smith, A R A, **Beggan, C D**, **Macmillan, S**, Whaler, K A. (2017) Climatology of the Auroral Electrojets derived from the Along-Track Gradient of Magnetic Field Intensity measured by POGO, Magsat, CHAMP, and Swarm. Space Weather. 10.1002/2017SW001675

Published and to appear 2018 (at March 2018)

Beggan, C D, and Whaler K A. Ensemble Kalman Filter Analysis of Magnetic Field Models During the CHAMP-Swarm gap. Physics of the Earth and Planetary Interiors, accepted

Beggan C D, Billingham, L, and **Clarke, E**. (2017), Estimating external magnetic field differences at high geomagnetic latitudes from a single station, Geophysical Prospecting, accepted

Other Publications

- 1 BGS Open Report: Thomson, A W P, ed. 2017. Geomagnetism review 2017. British Geological Survey, 40pp. (OR/17/043) www.geomag.bgs.ac.uk/documents/reviews/Geomagnetism_Review_2016.pdf
- 10 Customer Reports (UK survey & OS; oil industry services; JCO observatory service reports)
- 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'

Articles in NERC's Planet Earth

- 'Good Pointers' by Ciaran Beggan and Tim Taylor
- 'Revealing the UK's hidden depths' by Ciaran Beggan
- Contribution to BGS's GeoBlogy:
- 'Advance of the Agonic—what does this mean?'...by Susan Macmillan: http://britgeopeople.blogspot.co.uk/2017/10/advance-of-agonic-what-does-this-meanby.html

Conference presentations, posters and related activities

Magnetic Interactions, Edinburgh, UK, January
1 poster

Tectonic Studies Group (TSG), Volcanic and Magmatic Studies Group (VMSG) and British Geophysical Association (BGA) Joint Assembly 2017, Liverpool, UK, 4-6 January
1 poster

RAS Specialist discussion 'Understanding the Space Environment before the Space Age', London, UK, February
1 presentation (Clarke)

4th Swarm Science Meeting, Banff, Canada, March
1 presentation (Brown)
2 posters

Geomagnetism Advisory Group annual meeting, Edinburgh, May
5 presentations (Thomson, Turbitt, Macmillan, Brown, Clarke, Flower, Richardson, Beggan)

IAGA Scientific Assembly, Cape Town, South Africa, August
5 Presentations (Beggan x 2, Thomson, Flower, Cox (on behalf of Brown))
4 Posters
1 Session convened

SWIGS Kick off meeting, Edinburgh, UK, June
2 presentations (Thomson, Beggan)

International Astronomical Union Symposium 335, Exeter, UK, July
1 poster

Swarm 7th Data Quality Workshop, Delft, The Netherlands, October
1 presentation (Brown)

CERN CLIC mini-Workshop on Stray Fields, October
1 presentation (Beggan)

II Pan-American workshop on Geomagnetism, Vassouras, Brazil, November
1 poster

European Space Weather Week 14, Ostend, Belgium, November
1 presentation (Richardson)
3 posters
'Live Forecast'

Session convening and contributions at splinter meetings

BGS Science Festival, Nottingham, UK, December
1 presentation (Reay)
2 posters

AGU Fall Meeting 2017, New Orleans, USA, December
1 presentation (N. Case, Lancaster)
1 poster

Geomagnetism team seminars, Edinburgh

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

Some other notable outputs

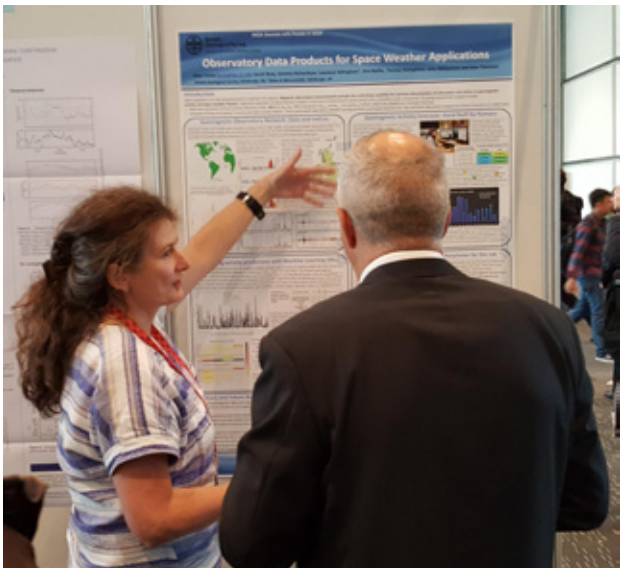
Observatory tours

- Lerwick Open Days, University of Edinburgh 'innovative learning week' and the Met Office open day at Eskdalemuir

Public lectures, presentations and demonstrations

- Lerwick open days in June/July involving a hands-on exhibition, public lectures and observatory tours (see section on 'Lerwick Observatory Open Days' for more details)
- Fun Fairs for member of the public coinciding with the International Astronomical Union symposium in Exeter in July. Ciaran Beggan gave demonstrations on two days covering topics on geomagnetism and space weather monitoring.
- Gemma Richardson participated in the Lyell Centre's doors open day in September. She gave a public talk

Gemma Richardson with BGS Director of Science Mike Stephenson at the Lyell Centre open day.



Ellen Clarke discusses her poster at IAGA Scientific Assembly in Cape Town, South Africa.

on space weather and demonstrated geomagnetism science through the day.
- Simon Flower and Gemma Richardson took a geomagnetism display to the Dalkeith Science Gala Day, which was part of the wider Midlothian Science Festival in October.
- Will Brown, Simon Flower, Susan Macmillan, Gemma Richardson and Sarah Reay participated in NERC's interactive showcase 'UnEarthed' at Dynamic Earth in November. There were over 7000 visitors, including 1300 schoolchildren, over the four days of the event.

Software development
- Data science workshops attended and participated in BGS machine learning discussions
- Six week-long sprints were held throughout 2017 involving 11 staff members working to convert and test all production software to prepare for a transition from Solaris to Linux architecture.
- One week-long sprint was held in November to develop software involved in data selection for BGGM model.

Media
- Filming at Eskdalemuir for a BGS YouTube video in May.
- Alan Thomson and Chris Turbitt interviewed by BBC Radio Scotland in June. Broadcast on 'Newsdrive' and 'Good Evening Shetland'.
- Various mentions in the media in September following one of our space weather alerts including BBC News and Belfast Telegraph.

Education
- Edinburgh University Undergraduate Lecture Series—4th Year Honours Course on 'Geomagnetism', by Ciaran Beggan & William Brown (16 lectures)
- Routes into employment event at Currie High School (Gemma Richardson)
- BGS 'BUFI' Science Festival judges—Gemma Richardson, Will Brown and Susan Macmillan
- Hosted 3 work experience students for a day
- STEM CREST Gold Award of Oscar Chapman, 'Earth's 'Flipping' Poles', mentored by William Brown
- IAU335 Space weather of the heliosphere, Teacher CPD and Public Outreach, July 2017

Other
Six Geomagnetic Disturbance Alerts emailed to over 3900 subscribers.

Orsi Baillie during filming at Eskdalemuir observatory.

Publications and knowledge exchange

Alan Thomson giving a public lecture on the importance of Lerwick Observatory.

Lerwick Observatory Open Days

Shetland is home to one of the longest-running geomagnetic observatories in the world, at 95 years old, on a UK Met Office site just outside Lerwick. The Lerwick Observatory houses a collection of meteorological instruments, as well as BGS geomagnetic and seismic monitoring equipment. Between 29th June and 1st July 2017 the Geomagnetism and Seismology Teams hosted 'Auroras and Earthquakes', a successful series of 'Open Days' for the public, at Lerwick Geomagnetic Observatory and Lerwick Museum.

Established as a meteorological monitoring site in 1919, Lerwick Observatory began making geomagnetic measurements in 1922. Geomagnetic monitoring became a responsibility of BGS, then the Institute of Geological Sciences, in 1965 and monitoring continues, second-by-second, to the present day.

The 2017 'Open Days' for the public covered the themes of Geomagnetism, Space Weather and Earthquake Seismology. We aimed to celebrate the longevity of the observatory and to thank the local community for its support over the years. We also wanted to highlight the significance of the observatory to science and industry around the North Sea basin and beyond.

This near-centennial anniversary provided an opportunity to promote understanding and interest in geoscience in one of the more remote regions of the UK. The logistics of running an event in Lerwick, around 170 km from mainland Scotland and 500 km from Edinburgh, were significant. However, we think, and our audience seemed to agree, that it was worthwhile, even allowing for the 12-hour ferry journey required to bring our science message to this community.

We set up staffed and interactive exhibits at the Shetland Museum and Archives in Lerwick. We also conducted guided tours at the observatory, a few kilometres outside of the town, by busing people to and from the museum. Fourteen BGS staff in attendance were hard at work on both sites, catering for 120 primary and secondary school pupils and 300 members of the public, an impressive turnout of about five per cent of the local population.

Staff guided visitors through a full day's schedule of short talks and an evening public lecture was given by Geomagnetism Team Leader Alan Thomson. Alan talked about Geomagnetism and its usefulness,

as well as Lerwick Observatory's history and its unique contribution to science. Staff informed pupils and public alike of the principles of magnetism, the story of the inner workings of the Earth throughout its history, geomagnetic monitoring from the Earth's core to space, the cutting edge of space weather forecasting, and earthquake hazard and monitoring. All this occurred against the backdrop of a fortuitous magnitude 4.7 earthquake, which occurred just 200 km from Lerwick on 30th June!

The event was made possible by a Royal Astronomical Society small grant award and additional contributions from BP, the BGS Geomagnetism and Seismology Teams, and the support of the Met Office, Shetland Amenity Trust, UNESCO Geopark Shetland, and the Shetland Nature Festival. We must specially thank Met Office staff in Lerwick and numerous BGS colleagues at The Lyell Centre for their organisational help, not least for their significant contributions to the design of our display materials.

The 'Auroras and Earthquakes' event flyer.

Primary school children make their own earthquake during a BGS seismometer demonstration.

Selected glossary, acronyms and links

AGU	*American Geophysical Union (https://sites.agu.org/)*
Aurora Watch	*Aurora alert service run by Lancaster University (aurorawatch.lancs.ac.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/)*
CA	*Crustal Anomaly*
CERN	*The European Organization for Nuclear Research (https://home.cern/)*
CHAMP	*German magnetic survey satellite (www-app2.gfz-potsdam.de/pb1/op/champ)*
CLIC	*Compact Linear Collider*
CPD	*Continuing Professional Development*
CREST	*CREativity in Science and Technology (www.crestawards.org)*
DISC	*Data, Innovation and Science Cluster supporting the ESA Swarm mission*
DOI	*Digital Object Identifier*
eCSE	*embedded Computational Science and Engineering*
EHO	*The Earth Hazards and Observatories science directorate of BGS (http://www.bgs.ac.uk/research/earthHazards/home.html)*
EPCC	*Edinburgh Parallel Computing Centre (https://www.epcc.ed.ac.uk/)*
EPOS	*European Plate Observing System (www.epos-ip.org/)*
ESA	*European Space Agency (www.esa.int)*
EU	*European Union*
ESWW	*European Space Weather Week. (sidc.oma.be/esww13)*
FMI	*Finnish Metrological Institute (http://en.ilmatieteenlaitos.fi/)*
GDAS	*Geomagnetic Data Acquisition System*
GDASView	*GDAS data viewing software*
GIC	*Geomagnetically Induced Currents (a natural hazard to power systems)*
Git	*An open source distributed version control system (https://git-scm.com/)*
GNSS	*Global Navigation Satellite System*
HPC	*High Performance Computing*
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)*
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)*
ISGI	*International Service for Geomagnetic Indices (isgi.unistra.fr)*
IT	*Information Technology*
IUGG	*International Union of Geodesy and Geophysics (www.iugg.org)*
JCO	*Jim Carrigan Observatory (Alaska)*
Kp	*A measure of mid-latitude planetary average geomagnetic activity, on a scale of 0–9.*
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)*
NAMAS	*UK National Measurement Accreditation Service*
NERC	*Natural Environment Research Council (www.nerc.ac.uk)*
NRCan	*Natural Resources Canada (http://www.nrcan.gc.ca/)*
OS	*Ordnance Survey (www.ordnancesurvey.co.uk)*
QA	*Quality Assurance*
QC	*Quality Control*
RIN	*Royal Institute of Navigation. (www.rin.org.uk/general/Navigation-News)*
STEM	*Science, Technology, Engineering and Mathematics*
STFC	*Science and Technology Facilities Council*
Swarm	*Three-satellite 'mini-constellation' for magnetic field surveying. (http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm)*
SWIGS	*Space Weather Impact on Ground-based Systems (www.geomag.bgs.ac.uk/research/SWIGS)*
TCD	*Trinity College Dublin (www.tcd.ie)*
UNESCO	*The United Nations Educational, Scientific and Cultural Organization (en.unesco.org)*
WDC	*World Data Centre, part of the World Data System (www.wdc.bgs.ac.uk)*
WDMAM	*World Digital Magnetic Anomaly Map*
WDS	*World Data System (www.icsu-wds.org)*

The Geomagnetism Team 2017

Staff Changes

Laurence Billingham left the team in March, after five years as a post-doctorate research assistant, working on crustal field modelling, space weather and, latterly, IT-related projects.

Colin Pringle retired from BGS, in October, after more than thirty years' service as an observatory engineer at Eskdalemuir, observatory site manager at Hartland and more recently site manager at the Eskdalemuir observatory.

We would like to thank both Colin and Laurence for their contributions over the years and we wish them both well in the future.

Guanren Wang joined the team in November to support our oil industry services and Claire Brown joined as Eskdalemuir Observatory site manager at the end of the year.

Geomagnetism staff 2017 (full and part-time)

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 (resigned March 2017)*
Claire Brown	*Manager, Eskdalemuir Observatory (December 2017)*
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*
Alexander (Sandy) Henderson	*Geomagnetic Data Processing*
Thomas Humphries	*Geomagnetic 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 (retired October 2017)*
Sarah Reay	*Geomagnetic Research and Data Processing and QA*
Dr Gemma Richardson	*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*
Guanren Wang	*Geomagnetic Data Processing (from November 2017)*
John Williamson	*Geomagnetic Data Processing and QA*

Contact details

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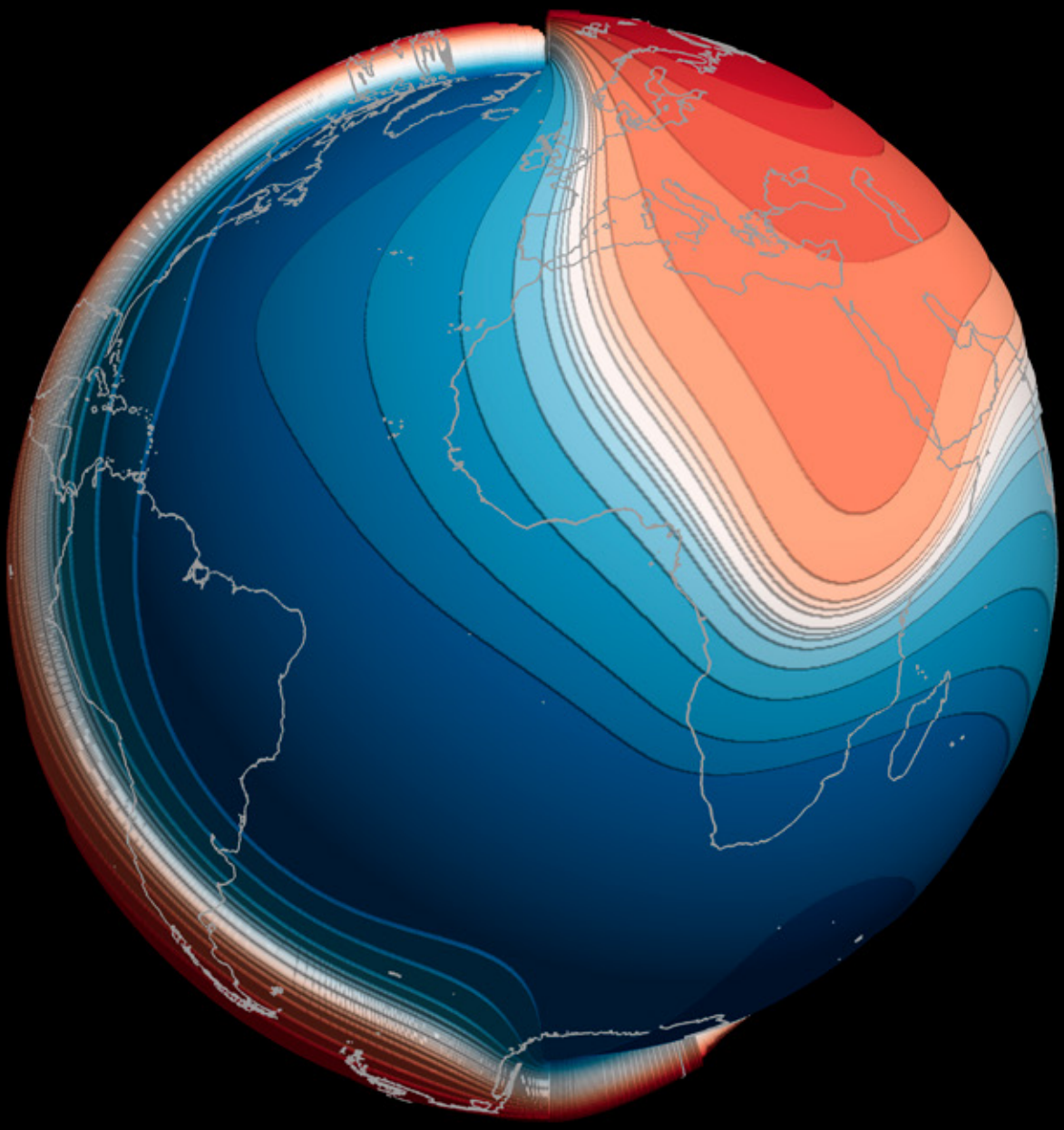

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