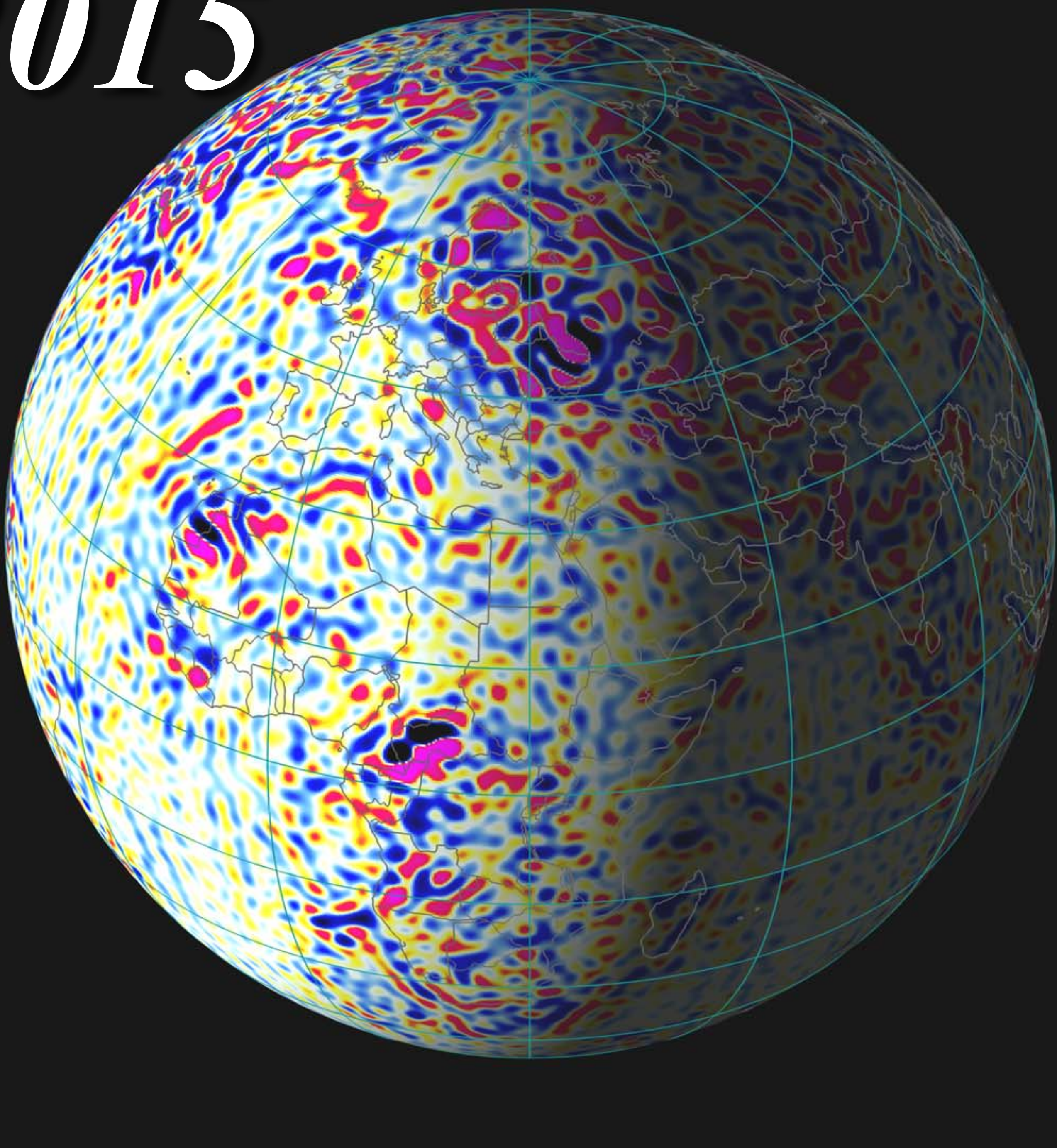
British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

# Geomagnetism *Review* 2015



# Geomagnetism

# Review 2015

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*Front cover*

The vertical component of the BGS model of the global lithospheric magnetic field. Red shows where the magnetic field points inwards and blue shows where the field points outwards. This new model resolves regional features on the scale of 300 km, from a global satellite survey. This is better than half the scale achievable less than ten years ago.

*Bibliographical reference*

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Edinburgh British Geological Survey 2016

# Contents

## Introduction

*An aurora over Iceland – space weather in action (photo by Jez Everest).*

# 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 geomagnetic changes in the solid Earth and in the Earth's atmospheric and space environments, thus helping to develop our understanding of 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 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 and 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 2015 the team numbered 25 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.*

Particular activities of the team are mathematical modelling of the geomagnetic field and its changes, monitoring and modelling of the geomagnetic hazard to technology and the provision of information, data and products for the benefit of society.

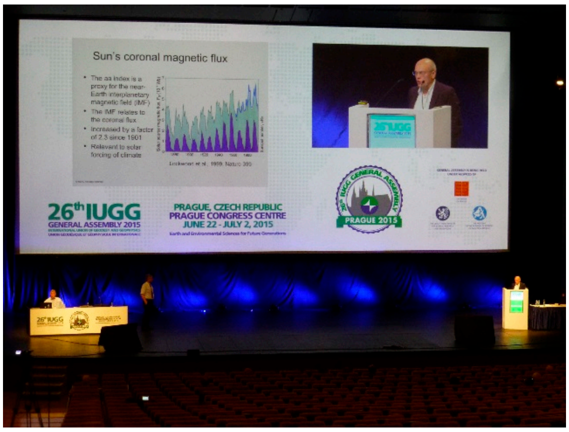
In support of our core function, the team has four primary aims.

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

*Some of the Geomagnetism team staff in December 2015.*

# Introduction




*David Kerridge presenting at IUGG 2015.*

# Looking Ahead to 2016

In 2016 our scientific research will focus on the space weather hazard to technology and infrastructure, as well as 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 program to international standards. We will also continue to produce high quality academic and other geomagnetic models, data products and publications.

## 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 space environment
- Applying our data, models and expertise in services and research for academia, industry and society

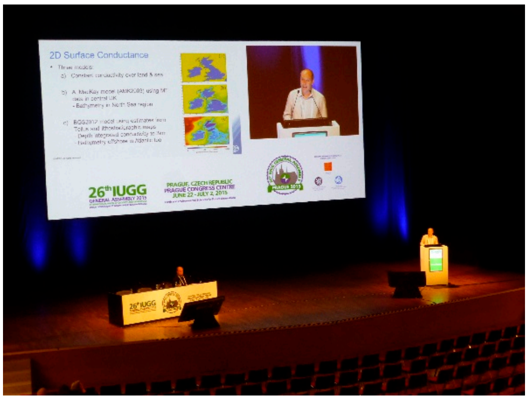
## Main Deliverables

Our specific deliverables for 2016 will be

- An INTERMAGNET-standard ([www.intermagnet.org](http://www.intermagnet.org)) UK and overseas 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 2016 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




*Ciaran Beggan at IUGG 2015.*

sessions) in a number of major international scientific conferences, e.g. the UK National Astronomy Meeting and the 13th European Space Weather Week.

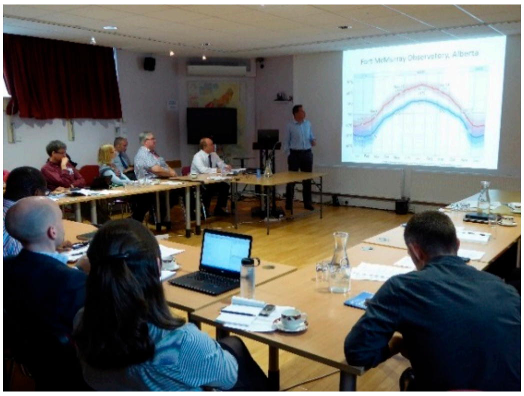

*Alan Thomson chairing IAGA Division V business meeting at IUGG 2015.*

- Publication of a number of papers in scientific and professional journals, and the writing of articles for scientific and other publications
- Provision of data products for the ESA Swarm 'Data, Innovation and Science Cluster (DISC)', the successor to the 'Expert Support Laboratories', set up by ESA in support of the goals of the Swarm satellite mission
- 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
- Production of the 2016 update of the BGS Global Geomagnetic Model (BGGM), using satellite and other geomagnetic data, including data from all BGS operated observatories

- 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


*Sarah Reay at the WDS-SCOSTEP meeting, September 2015.*

- Provision of observatory facilities for calibration and testing of instruments
- Delivery of a lecture course to 4th year undergraduates at Edinburgh University on Geomagnetism and to 3rd year students on Planetary Geophysics, including setting and marking of exam questions, running tutorials; and setting and supervising student projects
- Roll out of the ‘Raspberry Pi’ magnetometer systems as part of 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, for a customer



*Chris Turbitt presenting at the Geomagnetism Advisory Group meeting, September 2015.*

- Development and assessment of near real-time data products from the ESA Swarm satellite mission, as part of the ESA Space Situational Awareness programme, in collaboration with GFZ, DTU and other European institutes
- Collaboration with the University of Otago (Dunedin, New Zealand) on a three-year project to assess and model geomagnetically induced currents in the New Zealand power system
- Relocation of Geomagnetism operations to the new, purpose built, Charles Lyell Building at Heriot-Watt University in February 2016

# Headline Numbers from 2015

Here are some key numbers, which help to put in perspective the team's outputs in 2015

- 100% (>99%) UK (overseas) observatory data coverage
- 292 global oil industry wells supplied with IFR data
- 156 Ordnance Survey map compass references
- 142 global oil industry wells supplied with IIFR data
- 108 magnetic bulletins published
- 31 presentations/posters
- 14 A-to-Z map compass references
- 13 scientific meetings
- 13 Geomagnetic Disturbance Alerts emailed to over 3700 'Aurora Alert' subscribers
- 8 field set-ups for IFR services
- 6 oil industry customer reports
- 6 articles on space weather for RIN 'Navigation News'
- 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 public lectures, presentations and demonstrations
- 6 journal and conference proceedings papers
- 4 PhDs co-supervised
- 3 undergraduate projects supervised
- 3 undergraduate courses taught
- 2 geomagnetic models (UK reference model, BGGM2015)
- 2 observatory tours
- 1 post-doctoral research assistant
- 1 'Hypercube' data set supplied to oil industry

# Technical, Observatory and Field Operations

*View to the azimuth reference mark on Lady Hill, Ascension Island Observatory.*

## UK and Overseas Observatories

BGS operates three absolute geomagnetic observatories in the UK and six observatories overseas to supply high quality, real-time measurements for research and services. We also take a leading role in the expansion of the global observatory network, to improve global magnetic field modelling and for local and global applications. The UK observatories achieved 100% continuous data supply in 2015.

**Technical Developments**

New low-power, solid state data recorders running the updated QNX6.5 operating system have been operating at all observatories for over a year and have proven to be secure and reliable. Recorded data resolution has been modified to 1pT at all observatories in anticipation of the roll out of new magnetometers to meet updated INTERMAGNET data standards.

The Lemi-025 fluxgate magnetometer is the first of these new instruments to undergo long-term testing at a BGS observatory, with initial analysis showing good quality data that meets most aspects of the new INTERMAGNET one-second data standard. However these magnetometers have been susceptible to lightning damage and had to be removed for repair in July 2015. The instruments have now been upgraded to be more resilient and will be re-installed in early 2016.

New scalar Overhauser magnetometers have been purchased to allow a faster sampling of the full field vector. In acquiring data at a rate of 1Hz, these magnetometers will allow greater quality control, particularly so at high geomagnetic latitude observatories.

Electric field monitors have now been running at the three UK observatories since early 2013. In 2015, the signal conditioning hardware was redesigned to include a low-pass filter amplifier. All three observatories are now sampling filtered and amplified data at a rate of 10Hz, improving the quality of recorded measurements.

**Magnetic Observatories**

The new observatory at Fort McMurray, Alberta, came online in early 2015, supplying real-time IIFR data to the local directional drilling industry in partnership with Halliburton-Sperry Drilling.

Service visits were made to remote observatories on Ascension Island, Sable Island and in Northern Alaska. With JCO Observatory (Alaska) being accepted as BGS's eighth INTERMAGNET observatory, these visits are essential for routine calibrations, as well as for infrastructure and instrument improvements in order that data quality continues to meet INTERMAGNET standards. Such visits can also provide collaboration opportunities, an example being the refurbishment in 2015 of the British Antarctic Survey's VLF receiver on Ascension Island, which is part of the World Wide Lightning Location Network.

*Plane landing on South Beach, Sable Island 2015, delivering equipment and personnel for a routine service of the island's observatory hardware.*

In the UK, BGS worked with local planners, developers and power companies to ensure that the pristine measurement environment of Lerwick observatory for magnetic and seismic monitoring was preserved during the development of nearby land for housing.

Hartland Observatory has regularly been used as a calibration facility by third-party magnetometer manufacturers and as a training facility for Royal Navy personnel conducting magnetic surveys in and around the Antarctic Peninsula.

Training was given throughout the year on instrumentation and observing practice to staff from Environment Canada, British Antarctic Survey, Royal Navy and the Met Office.

### The Global Network

BGS continues to be active on INTERMAGNET committees and in the INDIGO project. The objective of INDIGO is to increase the number of INTERMAGNET-quality digital observatories around the world, particularly in developing countries. BGS continues to develop data processing software that is made freely available to overseas observatories. This software is designed to facilitate the production of definitive data meeting the INTERMAGNET standard. BGS staff also visited the INTERMAGNET observatory at Cheongyang, South Korea, to exchange data processing knowledge and further assistance in observatory operation and data publication was provided to institutes in China, Russia and Syria.

### UK Repeat Station Network

The 2015 magnetic repeat station programme covered thirteen measurement sites in the West of Scotland, the Western Isles, South West England and the Midlands. 2015 saw a feasibility study carried out to ensure the future viability of the repeat station network, with one recommendation being the upgrade of the azimuth determining hardware. To this end a tender has been placed for a new differential GPS system, with delivery expected in early 2016.

The UK repeat station network and measurement techniques were presented at the MagnetE 2015 workshop, Budapest, Hungary.

## Technical, Observatory and Field Operations

*Magnetic surveying using a D/I theodolite during installation of the Fort McMurray Observatory.*

# Real-Time Monitoring Established in Alberta, Canada

A new absolute geomagnetic observatory has been installed near the town of Fort McMurray in Northern Alberta to provide real-time magnetic measurements as a navigation reference for the directional drilling industry in the region.

As early as 2009, BGS and Halliburton-Sperry Drilling (HSD) started a dialogue to explore the feasibility of establishing a long-term geomagnetic monitoring station in Northern Alberta. The objective of the station would be to provide navigational reference data to the directional drilling industry, supporting oil production in the Fort McMurray region.

For the reference data to be useful, any monitoring station would need to be able to continuously provide data of high absolute accuracy in real-time. In practice this would necessitate the use of very stable instruments, operated in a controlled environment and backed by routine, calibrating reference measurements. These are the conditions necessary for an absolute magnetic observatory as defined by IAGA (Jankowski & Sucksdorff).

Fort McMurray is located at a high geomagnetic latitude, close to the auroral oval, where the external field contribution is large and can cause significant directional uncertainty if not accounted for by the drilling industry. Since the variability of the external field is not readily predictable, it is necessary to monitor as close as possible to the drill site to minimise navigational uncertainty.

Prior to the installation of the Fort McMurray Observatory (FMC), the nearest absolute observatory to the area was the Natural Resources Canada Meanook Observatory (MEA), some 270km south of Fort McMurray. But by establishing FMC, we are now able to provide a more accurate representation of the natural sources of the local magnetic field (either independently or in conjunction with MEA). FMC will therefore be a valuable long-term local resource when making airborne surveys and taking ground measurements in the region, as well as a source of real-time measurements of the external magnetic field for the drilling industry, through the BGS Interpolation In-Field Reference (IIFR) service.

FMC Observatory has been located on a newly developed HSD site close to the northern Alberta highway 63 at 56° 36' N, and 111° 19' W. Groundwork for the observatory began in late 2014, with the instruments installed in December of that year. Once the absolute levels of the instruments were determined and reliable communications were in place, the observatory came online in early 2015.

One-second tri-axial fluxgate magnetometer and ten-second Overhauser effect proton precession magnetometer measurements, made using a BGS Geomagnetic Data Acquisition System (GDAS), are transferred in real-time to BGS Edinburgh for IIFR processing prior to the data being made available to industry customers via a web interface. The automatic observatory measurements are backed by regular manual D/I theodolite measurements to control the absolute level of the automatic data and FMC has been incorporated into the routine quality control procedures that apply to all BGS IIFR data streams. Typically, FMC IIFR data are available to customers within 3 minutes of recording.

*The new installation at Fort McMurray.*

The large amplitude and rapid time variations of the magnetic field in the Fort McMurray region are only part of the challenge of operating an absolute observatory in Northern Alberta. The outside air temperature can be as low as -30°C during winter and as high as +30°C during summer, freezing and thawing the top layers of the 30m deep muskeg (peat bog). Since the bedrock layer is some 300m below the surface, the instruments have been stabilised using non-magnetic piles, driven four metres into the ground. The temperature sensitive fluxgate magnetometer is housed within an insulated chamber inside an insulated, weatherproof fibre-glass hut. The operating environment of the fluxgate is maintained at a constant temperature using a custom-made, non-magnetic heater, which is accurately controlled using an adaptable proportional controller.

Magnetic measurements are precisely time-stamped against a Network Time Protocol reference clock and are transferred using parallel, independent communications channels (4G cell and satellite ISP) for reliability.

The observatory instruments were calibrated against transferrable standards, traceable to accredited laboratories in the UK (UKAS) during set-up - a process that will be repeated annually.

*Jankowski, J. & Sucksdorff, C., IAGA Guide for Magnetic Measurements and Observatory Practice, 1996, ISBN: 0-9650686-2-5*

## Technical, Observatory and Field Operations

# BGS support for INTERMAGNET: Cheongyang Observatory

*Cheongyang observatory, Daejeon, South Korea.*

Cheongyang Observatory was established by the Korean Meteorological Administration (KMA) in 2008 and is jointly operated by the Korean Research Institute of Standards and Science (KRISS) in Daejeon. Cheongyang Observatory achieved INTERMAGNET status in December 2013. BGS staff were invited to South Korea on a knowledge exchange visit in February 2015, to follow up on a previous visit made in September 2013.

Cheongyang observatory (IAGA code CYG, N 36.4° E 126.9°, 165m altitude) is located approximately 60km west of Daejeon in a remote mountainous area where the level of man-made electromagnetic noise is low. The purpose of the observatory is long-term monitoring of the Earth's magnetic field, space weather monitoring, and to study the possibility of earthquake activity forecasting using geomagnetic data.


*Research supported by activities at Cheongyang observatory.*

Orsi Baillie was invited by Dr Po Gyu Park, Head of Electricity and Geomagnetism, on a knowledge exchange visit to KRISS to:

- provide training in the use of BGS data processing software packages
- assist with deriving quasi-definitive and final baselines and data sets
- advise on observatory data processing and analysis practices

The exchange visit was also intended to support KRISS's determination to continue meeting INTERMAGNET standards.

We can summarise the operational status of CYG and its data, prior to the BGS visit in February 2015, as follows.

- INTERMAGNET membership, obtained in December 2013, was based on quality controlled data from September 2012 through to August 2013
- Vector (X, Y, Z) variation data, and total field (F) data were being

submitted to the Kyoto Geomagnetism Information Node (GIN) of INTERMAGNET on a next day basis (by KMA)
- Preliminary data with fixed baselines were also being submitted to the Kyoto GIN on a next day basis (by KMA).
- However, no quality control procedures were being carried out on these later data sets
- No final data had been submitted for the last 18 months, hence there was a risk of losing INTERMAGNET accreditation

When we visited in February 2015 day-to-day operations were being carried out by a PhD student, Ms Shakirah Binti Mohd Amran under the supervision of Dr Kim and Dr Park.

*At CYG Observatory, Dr Wan-Seop Kim, Shakirah Binti Mohd Amran and Dr Po Gyu Park (left to right).*

During the visit Ms Amran was given broad training in Geomagnetism and specific training on observatory data processing and quality control. In depth demonstration and training was also given in the use of the GDASView and IMCDView custom software packages, to aid the production of definitive magnetic observatory data. Dr Kim and Ms Amran were also interested to learn about the BGS method of baseline fitting using piece-wise polynomials.

By the end of the visit, Ms Amran was able use GDASView to:

- process absolute observations
- identify and remove erroneous variation data
- assess the quality of absolute observations using the collimation errors
- deal with discontinuities, and derive continuous baselines

Since the visit, Orsi Baillie has been in close contact with Ms Amran and as a result the observatory results for 2014 have been submitted to INTERMAGNET for review by the publication deadline.

*Korean hospitality (clockwise from far-left): Dr Wan-Seop Kim, Dr Po Gyu Park, Orsi Baillie and Shakirah Binti Mohd Amran.*

There is a continuing dialogue between BGS and CYG to enable the production of both definitive and quasi-definitive data from the observatory. Ms Amran will complete her PhD in 2017 and plans to return to Malaysia. Therefore it is essential that the necessary observatory data processing and QC practices are in place by that time and both BGS and CYG are working towards that goal.


*Sarah Reay presenting the activities of the World Data Centre for Geomagnetism, Edinburgh, at the WDS-SCOSTEP workshop.*

## Technical, Observatory and Field Operations

# SCOSTEP–WDS Workshop on Global Data Activities for the Research of Solar–Terrestrial Variability

BGS was represented at the SCOSTEP–WDS Workshop on 'Global Data Activities for the Research of Solar–Terrestrial Variability', held at the National Institute of Information and Communications Technology (NICT), Tokyo, Japan, from the 28th to 30th September 2015.

The main purpose of this SCOSTEP-WDS workshop was to encourage interaction between data providers in the World Data System (WDS) and scientific researchers in SCOSTEP (Scientific Committee on Solar Terrestrial Physics). (Both SCOTSTEP and WDS are bodies set up by the International Council for Science, ICSU.) SCOTSTEP's current scientific programme VarSITI (*Vari*ability of the *S*un and *I*ts *T*errestrial *I*mpact) runs from 2014 to 2018 and a major objective of the workshop was therefore to facilitate new interactions between the two bodies, in order to benefit VarSITI and to encourage long-term preservation of its scientific results.

There were 71 participants (53 from Japan and 18 from around the world). Eleven different WDS members were represented and 51 papers were presented over the course of the workshop.

The meeting was split into three main areas:

- Collaboration between SCOTSTEP/VarSITI and the WDS
- Data analysis of a VarSITI 'campaign event'
- Reports from WDS members and other data systems on current and recent activities

Sarah Reay, representing BGS and our World Data Centre for Geomagnetism, Edinburgh, had an active role in each part of the workshop.

On this first day Sarah was a panellist during a discussion on future collaboration between SCOSTEP/ VarSITI and the WDS. This was a wide reaching discussion where we identified many common objectives on data provision and preservation. Following this discussion a Letter of Agreement was signed by SCOTSTEP and WDS representatives, formalising a working relationship between the two bodies.

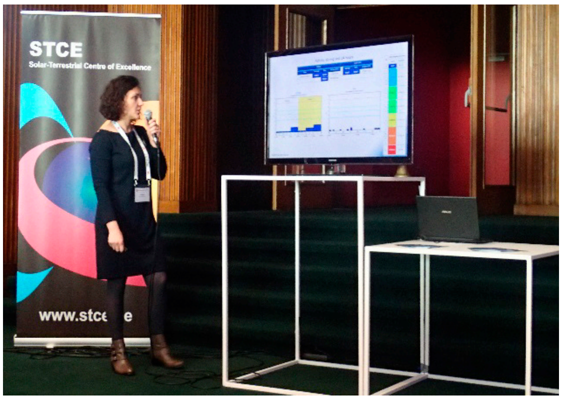
The second day centred on the presentation of work related to VarSITI. Particular focus was given to the 'St. Patrick's Day space weather event' (15-18th March 2015) and the 'Summer Solstice 2015 event' (21-24th June 2015). The 'St. Patrick's Day event' had been identified as an official VarSITI 'campaign interval' and was particularly scrutinised by participants.

During this session Sarah gave a presentation titled "Experiences of Forecasting the Magnetic Storms of March and June 2015 and Analysis of the Resulting Ground Effects in the UK". This detailed her experiences of forecasting geomagnetic activity levels during the St. Patrick's Day storm, as a duty forecaster, and the difficulties that space weather forecasters worldwide experienced in correctly anticipating the observed activity level. Data from the Summer Solstice event were used as a comparison in the presentation and geomagnetic and geo-electric field data from the UK for each event were discussed.

The third and final day of the workshop was devoted to data-related sessions and reports detailing the activities of WDS members whose data are of interest to the SCOSTEP/VarSITI community. Sarah gave a presentation on the current activities of the World Data System for Geomagnetism, Edinburgh. This outlined our current operations and scale of data holdings. Examples were given of how these data are currently used by the scientific community and we also highlighted how our work in digitising historical data could be used for analysing past magnetic storms.


*Participants of the WDS-SCOSTEP workshop hosted at NICT in Tokyo, Japan.*

# Science

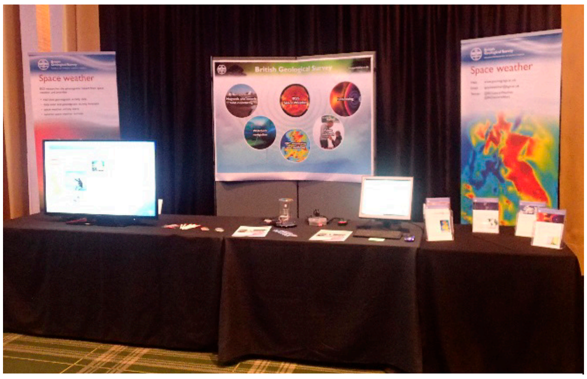



*Orsi Baillie presenting the daily 'Live Space Weather Forecast' at ESWW12.*

## Space Weather and ESWW12

BGS space weather research and applications were strongly represented at the 12th European Space Weather Week (ESWW12) in November 2015, in Oostende, Belgium. This well attended conference and workshop had around 400 participants from 39 countries taking part in 16 sessions, 15 working meetings, a 'trade fair' and several business meetings.

During ESWW12 members of the Geomagnetism team presented a poster (Alan Thomson) and a talk (Gemma Kelly). Ellen Clarke convened a session titled *Geomagnetically induced currents and space weather*, and co-organised with Alan Thomson an 'end-user' lunch event on *Geomagnetically Induced Currents and the Risk to Power Transmission Systems in Europe*. This lunch event promoted lots of discussion between researchers and representatives of industries affected by space weather.



*BGS space weather services trade stand.*

Members of the team also contributed to two further oral presentations and collectively we manned two trade stands during the workshop trade fair. The BGS geomagnetic activity forecasting team were also invited to give another 'Live Space Weather Forecast' during the week, after the success of this initiative last year.

### Science contributions

*Geomagnetically Induced Currents (GIC) at mid-latitudes under extreme Dst scenarios (presentation)*

Extremely large values of the *Dst* magnetic activity index are rare; the largest in recent decades occurred during the March 1989 geomagnetic storm, peaking at -589nT. Estimates of *Dst* for the 'Carrington Event' of September 1859 suggest a peak of at least -850nT, and recent theoretical work has suggested *Dst* could reach -2500nT. From these extreme values of *Dst* we therefore modelled the possible magnitude of magnetic variations that could occur at mid-latitudes during large *Dst* excursions and computed the likely GIC that may follow in mid-latitude

European high-voltage power distribution networks.

*An Assessment of Pc5-Like Pulsations Observed During the Carrington Storm (poster)*

The Greenwich and Kew (both London) observatory magnetograms for 1st-2nd September 1859 show prolonged periods of Pc5-like pulsations (continuous fluctuations with a period of 150-600 seconds), driven by the solar wind during the recovery phase of the storm. Unlike the very high amplitude variations that are off scale during the peak of the magnetic storm, these pulsations have apparently been well preserved in the records. We analysed the measured amplitude and duration of UK Pc5 pulsations in both the Carrington storm and in modern day records. In terms of various measures, the pulsations during the Carrington event are large but not particularly extreme, compared to more recent severe storms. However this conclusion may be a result of limitations in the hardware of the time.

## Fair stands

This year BGS ran two ‘trade stands’ at the ESWW12 Fair to raise the profile of our Space Weather activities and to promote INTERMAGNET.

The *BGS Space Weather Activities* stand showcased many of our services including:

- The ‘Monitoring and Analysis of Geomagnetically Induced Currents’ (MAGIC) service for UK industry
- Real-time geomagnetic activity index production and delivery
- Daily, 3-day space weather forecasts and aurora alert service
- Warning of extreme space weather events for the UK Government and National Grid
- Real-time, 24/7 data supply for the oil and gas industry to aid directional drilling
- Geo-electric field measurements to aid in the evaluation of and development of GIC models
- Public outreach activities - the Raspberry Pi magnetometer and the GeoSocial Aurora map

BGS also organised an *INTERMAGNET stand* at the fair to promote the work of INTERMAGNET to the space weather community. In particular the INTERMAGNET network has evolved to provide one-second data and near real-time data access, specifically in response to monitoring requirements for space weather research and applications.


*The BGS Space Weather Activities flyers and photographs of the BGS stand during the fair.*

## Science


*Ciaran Beggan (left) and Sarah Reay (right) at the 26th Meeting of the IUGG General Assembly Meeting held in Prague, Czech Republic, June 2015.*

# IUGG 2015

The quadrennial meeting of the International Union of Geodesy and Geophysics is an opportunity to present BGS research at the highest scientific level and interact with the global community of geomagnetic and geophysical scientists. Contributions made by BGS at the 2015 meeting are summarised here.

### IUGG and IAGA

Every four years, the General Assembly of the International Union of Geodesy and Geophysics (IUGG) is convened, bringing together the nine scientific associations, of which the International Association of Geomagnetism and Aeronomy (IAGA) is a member. The 2015 Assembly was held in Prague, Czech Republic in June with over four thousand geophysicists attending during the ten day period of the Assembly.

As the conference was in Europe this year (previously Melbourne, Australia), eight BGS staff were able to attend. During the conference BGS contributions included nine talks and five posters across as many sessions at the conference. Other contributions included the co-chairing of three sessions and, as Alan Thomson is currently chair of the division, the running of the IAGA Division V business meeting on observatories, data, indices and modelling. David Kerridge also gave a prestigious invited Union lecture on the role of geomagnetic monitoring in understanding Earth system processes.

The science topics on which we presented included:

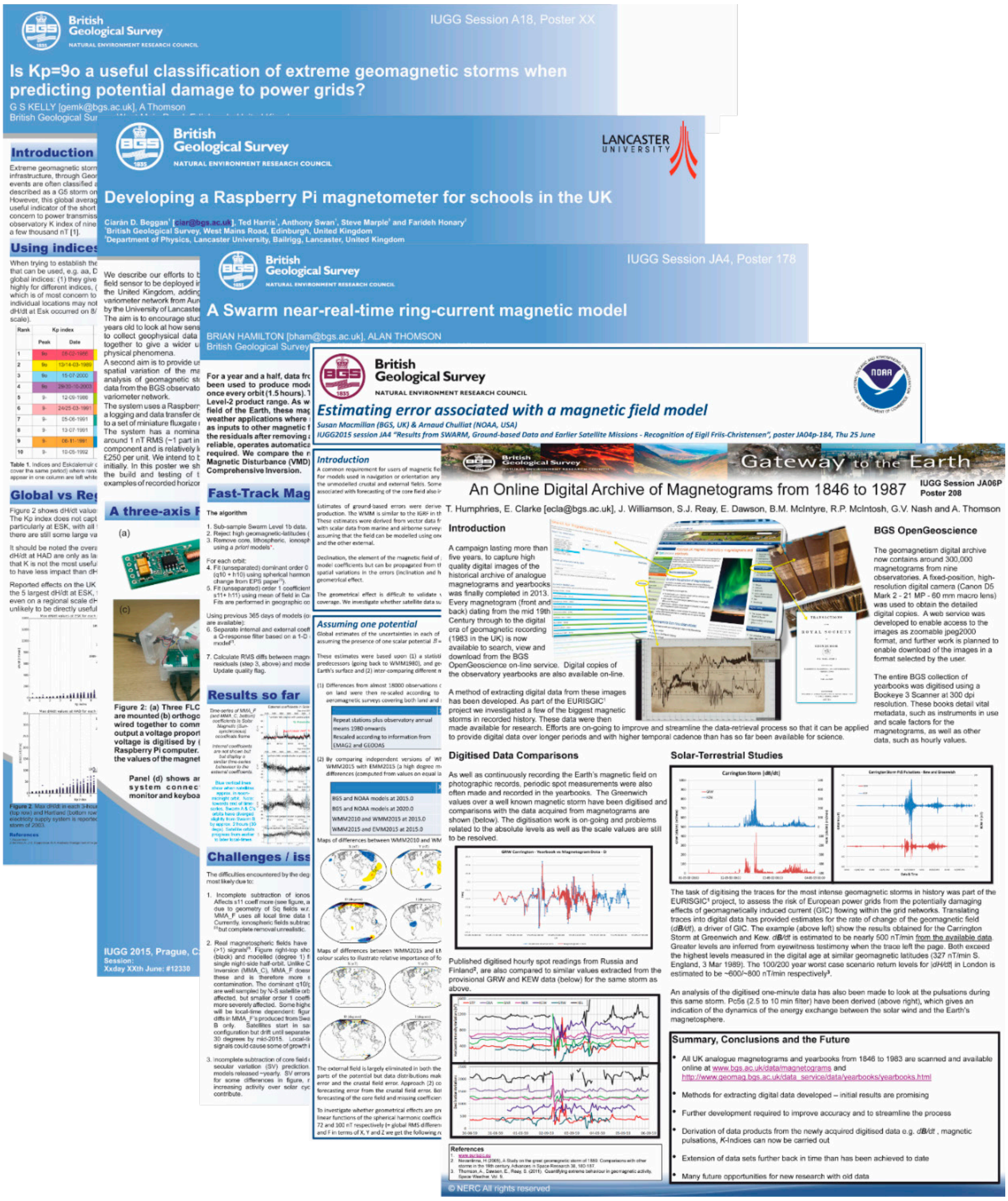
- Magnetic observatory data processing and its real-world application including making surface electric field measurements
- Improved techniques for main field and secular variation modelling using core surface fluid flow models
- Machine learning algorithms applied to forecasting space weather changes in real-time
- Understanding the impact of space weather processes on grounded technology structures (e.g. Geomagnetically Induced Currents)
- Public outreach initiatives such as the BGS Raspberry Pi magnetometer
- Research arising from commercial activities undertaken by BGS such as new observatories and analysis of external errors in magnetic field extrapolation

These oral presentations and posters benefited from collaborations with other

UK institutions, universities and industrial partners, including the Universities of Edinburgh and Lancaster, Halliburton Sperry Drilling, and international partners in NOAA (USA), DTU (Denmark), GFZ (Germany) and IPGP (Paris).

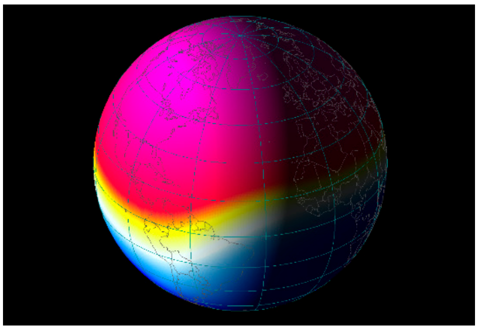
Both David Kerridge and former member of staff John Riddick were presented with certificates and medals for long, outstanding service to the international scientific community.

Finally, Alan Thomson was elected by the IAGA Council of Delegates to the IAGA Executive Committee.




*A selection of BGS scientific posters presented at IUGG, June 2015.*

## Science



*The vertical intensity of the core magnetic field at Earth's surface in 2015. Red shows field pointing inwards, blue shows field pointing outwards.*

# Developments in Global Magnetic Field Modelling

Every year BGS produces global models that describe the magnetic field of the Earth from the surface of the core to the upper reaches of the atmosphere. During 2015 our main model developments concerned improving model resolution both in space and in time. Beyond scientific interests, these models are also used to derive the annual BGS Global Geomagnetic Model (BGGM), for directional drilling purposes, and are also used to monitor accuracy of the World Magnetic Model and the International Geomagnetic Reference Field, which are only updated once every 5 years.

### The models

Our global geomagnetic field models are spherical harmonic (SH) models that represent the major components of the Earth's magnetic field: the main or core-generated field, the crustal field and the external field. BGS models provide a more comprehensive representation of the magnetic field compared to that of the solely main field content of the World Magnetic Model (WMM) or of the International Geomagnetic Reference Field (IGRF).

Time variations in the main and external fields are part of BGS models while the lithospheric field is considered static. Our models are built using iterative least squares inversion and described by SH coefficients that are a fit to observations from the observatory network and from data from satellites orbiting the Earth.

### Continuing advances

For the BGGM several notable features have been added or enhanced this year:

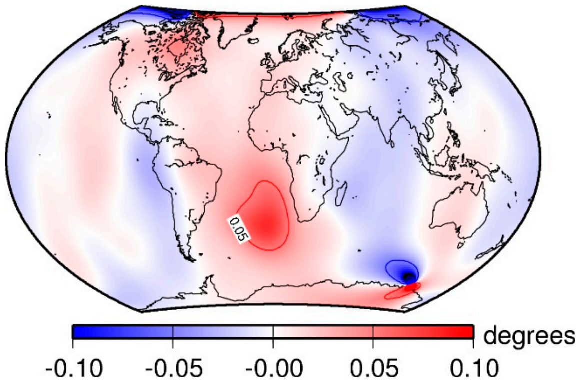
- inclusion of latest data, allowing prediction of the field to 2017
- improved time dependence of main and external fields
- increased resolution of lithospheric field features down to ~300 km (SH degree 133)
- consistent spectral content from 1900–present

These advances have been achieved in a variety of ways. Re-analysis of satellite data from the Danish Ørsted (1999–2014), German CHAMP (2000–2010) and ESA Swarm (2013–present) satellite missions has allowed better representation of the temporal variations from 1999 to the present. Combined with prompt production of observatory data, this improves the ability to make predictions of near-future variations in the field. By also analysing historical observations, the variations of the main and external fields have been modelled back to the year 1900 and integrated with a high-resolution model of the static lithospheric field to give a consistent spectral description throughout this period.

## Lithospheric field

Perhaps the most notable advance is the increased resolution of the lithospheric field to SH degree 133, allowing resolution of features on the scale of ~300 km at the Earth's surface. To achieve this a revamped modelling scheme has been applied, in combination with more extensive use of satellite scalar magnetic intensity data at high latitudes and CHAMP and Swarm gradient data. While field gradients along a satellite's track could already be estimated from CHAMP data, it is the Swarm mission, with its three satellite constellation, that allows the use of gradients between adjacent tracks.

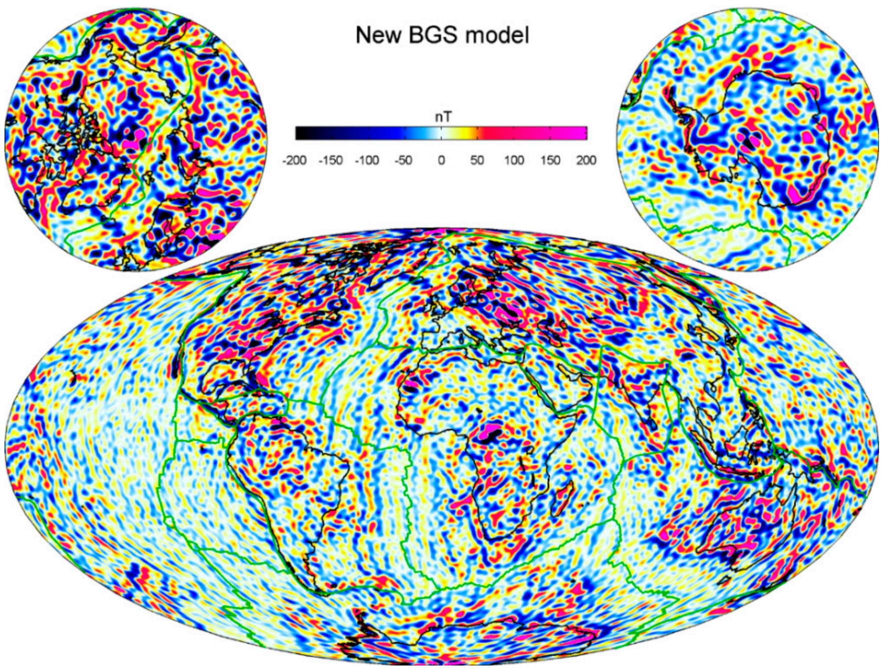
Gradient data, being the difference between measurements at two positions at similar times, are sensitive to small-scale features in the field. Resolution increases are more dramatic in high latitude regions but all regions are improved. It is expected that as the Swarm mission evolves and orbit heights decay, further improvements in resolution down to ~266 km (SH degree 150) may be possible.




*Declination differences at Earth's surface at 2016.0 between a truncated BGS model and WMM2015.*

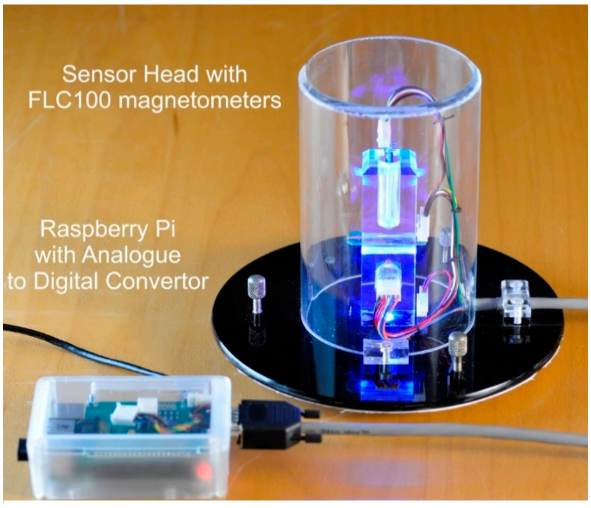
## WMM accuracy

BGS updates the WMM every 5 years in collaboration with US partners. In between each model update we add to datasets, develop modelling capability and monitor the performance of the last update. WMM2015 (produced in late 2014) continues to meet accuracy requirements.




*Vertical component of the BGS lithospheric magnetic field. The model is computed to spherical harmonic degree 133, resolving features down to ~300 km.*

## Science




*Raspberry Pi computer attached to a three-axis magnetometer.*

# Raspberry Pi Magnetometer

The launch of affordable, yet powerful, credit-card sized computers such as the Raspberry Pi, along with the falling cost of sensors and components for collecting geophysical data, has given rise to a new wave of interest in programming and self-built electronic systems. Taking advantage of these developments, we describe our efforts to build a three-axis magnetic field sensor which is primarily designed for use in schools. It is based on high-quality fluxgate magnetic sensors and employs a Raspberry Pi computer to act as the data acquisition and logging system.

In December 2014, the British Geological Survey and Lancaster University won an STFC Public Engagement grant (number ST/M006565/1) to build and deploy ten Raspberry Pi magnetometers to secondary schools across the UK. The primary aim of this project is to encourage students from 14 to 18 years old to look at how sensors can be used to collect geophysical data, in order to promote a wider understanding of physical phenomena, such as space weather.

One of the reasons for doing this now is because, as a society, we are increasingly reliant on space-based technologies such as satellite global navigation systems and communication relays. Although there are visible effects during large geomagnetic storms, e.g. the aurora, these are relatively difficult to observe in the UK due to sub-auroral latitudes, clouds and light pollution. However, the change of the magnetic field associated with auroral displays can be measured at ground level.

A second aim of the project is to provide scientifically useful data on the spatial and temporal variation of the magnetic field across the UK during geomagnetic storms.

### Instrumentation

The new Raspberry Pi magnetometer system consists of three main components: (i) a sensor head, (ii) a data acquisition and logging system and (iii) software required to run, collect and transmit the measured data. The sensor head consists of three FLC100 fluxgate coil magnetometers from Stefan Mayer Instruments in Germany. These miniature magnetometers have an inherent output accuracy of about 0.5 nT at 0.1 – 10 Hz. Thus the sensors can easily measure natural magnetic variations from the effects of the Sun on the ionosphere, such as the daily solar-quiet current, as well as magnetospheric pulsations and geomagnetic storms. The instruments measure short-term *variations* very accurately but the *absolute* level is only approximate.

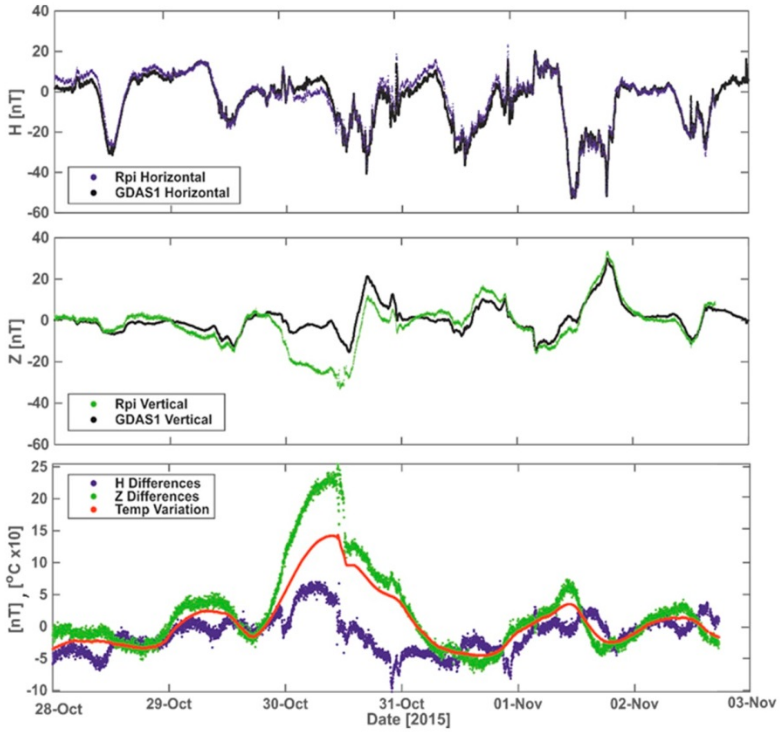
The output connections from each magnetometer are wired back to a 17-bit digitiser directly connected to the Raspberry Pi computer. The digitiser converts the analogue voltage output to a digital value, which the Raspberry Pi computer records along with the time of acquisition. The system also includes an analogue thermocouple on the sensor head to measure ambient temperature and an LED to show the unit is powered on. Software written in the Python language is used to read and record the values of the magnetic field from each component. The data can be recorded to the internal SD card and transferred once per hour across the internet.

## Performance

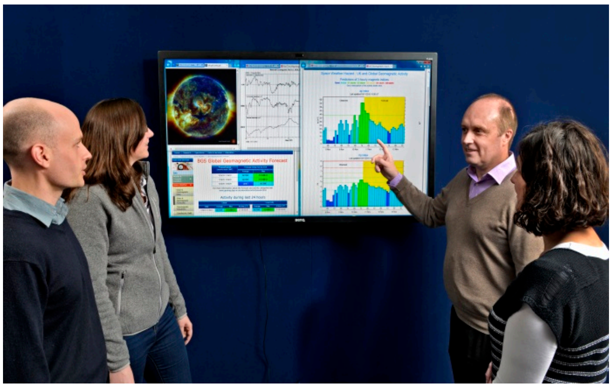
The magnetometers were located about 100m from the Eskdalemuir observatory's GDAS1 scientific instrument to which they were compared. Data were recorded at a cadence of 5 seconds for several weeks. An example of the variation and residuals (i.e. differences) between the data recorded by the Raspberry Pi system and the GDAS1 scientific instrument are shown below.

Note the short period fluctuations between the instruments match very well and these are the signals that we are most interested in. Longer periods correlate with temperature.

The temperature corrected residuals show an approximately Gaussian distribution with a mean of zero and a standard deviation of less than 0.8 nT, meaning the system can perform well within the nominal accuracy requirements we set (i.e. less than 1 nT).




*Variation in the Horizontal (upper panel) and Vertical (middle panel) components of the magnetic field for five days from 28th October to 2nd November 2015. Difference between GDAS1 and Raspberry Pi sensors in the H and Z component and the temperature variation (exaggerated x10) are also shown (lower panel).*



*BGS forecasters discussing a geomagnetic activity forecast.*

# Recent Space Weather Forecaster Training

Over recent years we have invested in training for our space weather forecasting team. In September 2015 Tom Humphries attended an International School of Space Science course in L'Aquila, Italy. Earlier, in September 2014, John Williamson attended the STFC Introductory Summer School in Solar System Plasmas at Imperial College, London.

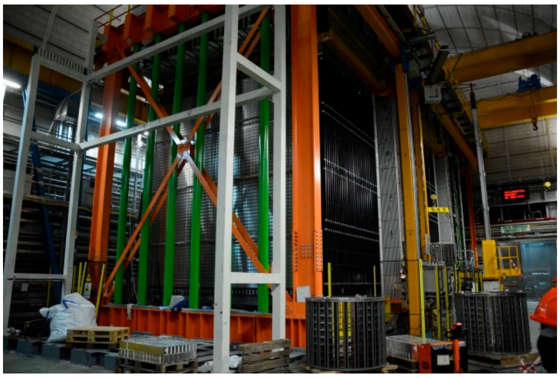
## International School of Space Science, L'Aquila

As part of our continuing aim to better forecast geomagnetic storms, Tom Humphries attended the 2015 International School of Space Science in L'Aquila, Italy. The title of the school was 'Heliospheric physical processes for understanding solar terrestrial relations', with subjects covering all aspects of the Sun-Earth environment from the causes and manifestations of solar variability, through heliospheric particle transport and plasma physics, right to the response of the Earth's environment and climate to solar influences. Also covered were various techniques for data analysis and the modelling of the Sun-Earth environment.

The primary interest of BGS Geomagnetism in this course was in the prediction of solar events (i.e. solar flares and coronal mass ejections, CMEs), better understanding of the propagation of CMEs en route to Earth, and the reaction of the geomagnetic field to CMEs. Better understanding enables better prediction of the path of a CME (to discern whether it is a threat or not) and of propagation time (to improve the prediction of storm onset time, following which geomagnetic activity is at its highest).

*The International School of Space Science students and lecturers arrayed outside the Gran Sasso Science Institute, where the school was held (picture courtesy of Luca Giovanelli).*

In addition to the course of lectures, students were also fortunate to attend a tour of the underground facility at the Laboratori Nazionali del Gran Sasso, which for 10 years has been receiving a beam of muon neutrinos from the CERN accelerator, as part of a study of neutrino oscillations. On the final night of the course, students were also able to participate in the town's celebration of the European Researchers' Night.



*The OPERA detector at Laboratori Nazionali del Gran Sasso, which detects the neutrino beam from CERN (picture courtesy of Luca Giovanelli).*

## STFC Introductory Summer School in Solar System Plasmas

John Williamson attended the STFC (Science and Technology Facilities Council) Introductory Summer School on Solar System Plasmas in September 2014. The School was held at the South Kensington campus of Imperial College, London.

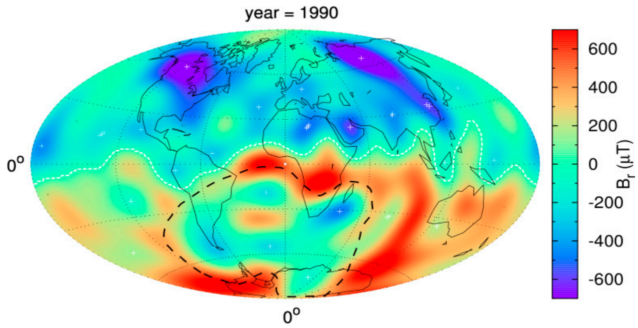
A broad range of subjects were covered, relating to Solar System Plasmas. These included Plasma Kinetics, Fundamentals of magnetohydrodynamics (MHD), MHD Waves and Instabilities, Space Instrumentation, Reconnection and Earth's Magnetosphere, Solar Interior, Solar Atmosphere and Activity, Solar Wind and Heliosphere, Space Weather: Causes and Implications, Shocks, Turbulence and Particle Acceleration, Mesosphere and Thermosphere, Ionospheres, Outer Planets/Moons Magnetospheres, Ionospheres and Atmospheres, Comets and Rosetta, Small bodies and Origins of the Solar System, and finally Exoplanets.

In addition to these lectures, we also had a visit to the Science Museum in London where, in addition to a tour, we participated in exercises in Public Engagement and Understanding of Science, and a presentation on Careers in the Space Industry.

The primary interest on behalf of BGS was in the space weather aspects of the school, which included developing an understanding of the solar processes involved and the causes and effects of space weather. The aim for the BGS forecasting team was to improve knowledge and understanding of space weather phenomena and their interaction with Earth's magnetosphere to aid in the delivery of more accurate forecasts.

*Attendees at the STFC sponsored 'Introductory Summer School on Solar System Plasmas 2014' organised and hosted by Imperial College, London (Photo credit: Matthew Stuttard).*

## Science




*Evolution of the South Atlantic Anomaly (Maurits Metman).*

# Student and Visitor Activities

During 2015, BGS were involved with the supervision and hosting of several undergraduate projects together with the University of Edinburgh. Two PhD students started their geomagnetism projects and several academic visitors were hosted.

### Postgraduate Students

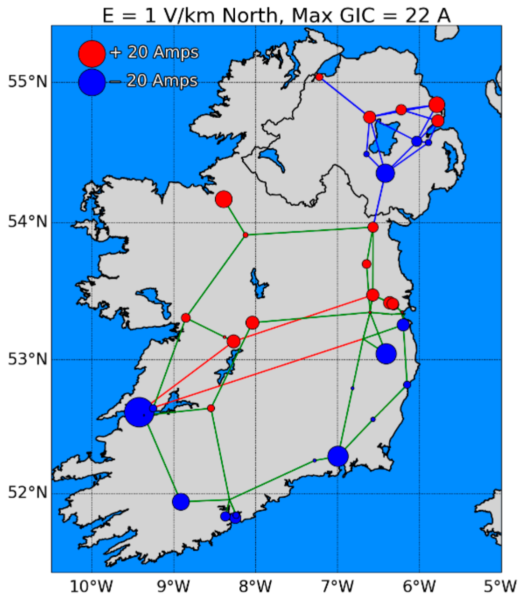
The BGS University Funding Initiative is currently supporting two PhD students in Geomagnetism, both of whom started in September 2015.

**Ashley Smith** at University of Edinburgh is looking into improving the separation of magnetic field sources using Swarm satellite data. In a preliminary study Ashley is detecting the locations and intensities of the auroral electrojets in data from Swarm and earlier satellite missions. The dependency of the variation of the electrojets on solar wind conditions, geomagnetic activity and secular variation of the main field will be investigated with the aim of elucidating the relative importance of these factors.

The other PhD student is **Maurits Metman,** at University of Leeds, who is studying the core geodynamo. He is looking at how magnetic diffusion controls secular variation, as opposed to control by advection of core fluid flow. He is also investigating the evolution of reversed magnetic flux patches, such as the South Atlantic Anomaly, and the control of core-mantle boundary heat flow on the behaviour of the magnetic field and the triggering of dipole reversals.

We currently advise two international PhD students:

**Sean Blake** is a 2nd year PhD student at Trinity College Dublin (TCD). He is supervised by Professor Peter Gallagher of TCD, though advised by staff at BGS on various aspects of Geomagnetically Induced Currents (GIC) and electric and magnetic field modelling.




*Modelling the GIC resulting from a 1 V/km northward electric field within the Irish power network (Sean Blake).*

Sean is researching the effects of GIC in the Irish power grid. He has also helped to set up a chain of variometers across Ireland to help with detailed measurement of the magnetic field variation during storms.

**Rachel Bailey** based at the ZAMG in Austria started in January 2015. She is researching the effects of GIC in the Austrian power grid, with BGS playing a consultancy role.

## Undergraduate students

We had three research projects completed by fourth-year undergraduate students at the School of Geosciences, University of Edinburgh during 2015.

**Nina Kahr** looked at lunar tidal effects in the electric field data from Hartland observatory, identifying the peak periods of variation using Fourier analysis

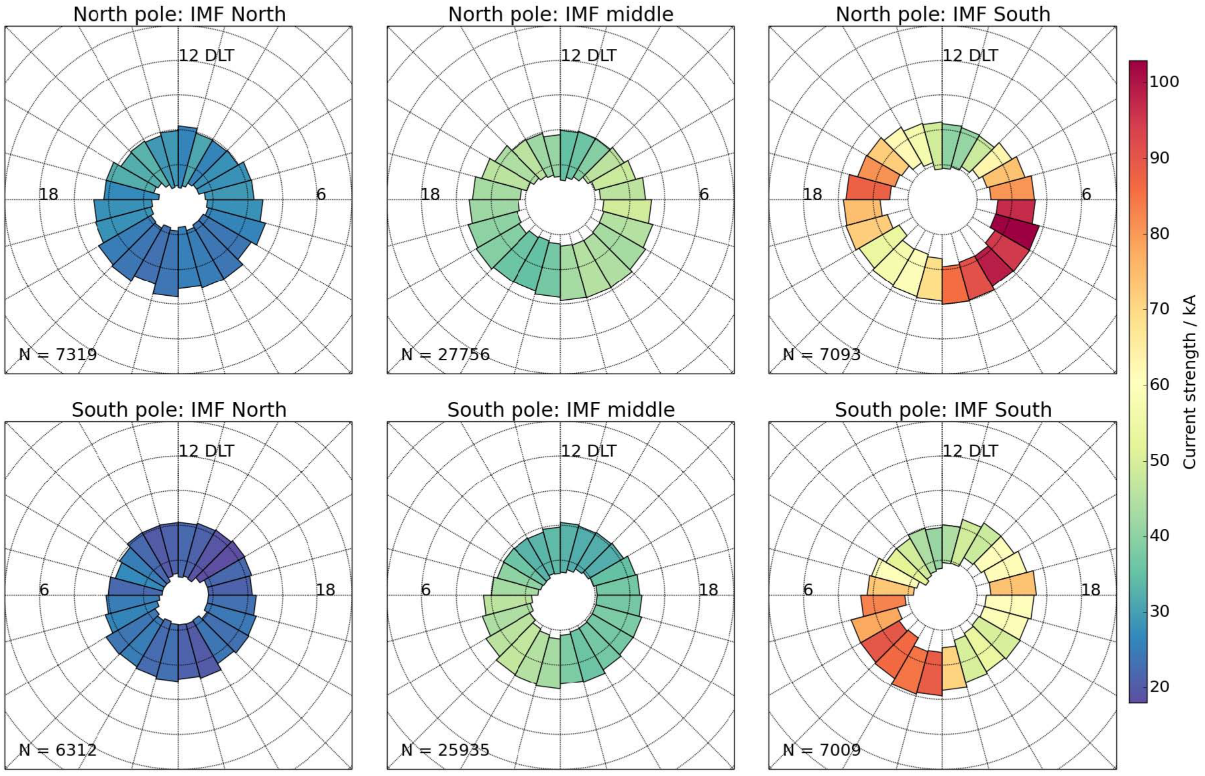
**Ben Cronin** investigated a novel method for reducing the high-frequency noise in magnetometer datasets by jointly inverting the standard one-second data with hundred-hertz induction coil data.

**Marcus Lancaster** undertook a project to estimate the thickness of the ionosphere using Ionospheric Alfvén Resonances and radio frequency data from the Chiltern ionosonde.

## Visitors

**Benoit Heumez** and **Xavier Lalanne** from the Institut de Physique du Globe de Paris (IPGP) visited us in December 2015. We exchanged information about current practices in observatory operations, data processing, real-time data transmission, and INTERMAGNET activities.

**Professor Craig Rodger (University of Otago)** and **Dr Mark Clilverd (BAS)** visited in December 2015 to discuss advanced preparations for a 3-year study, involving BGS staff, into GIC hazard in New Zealand.




*Locations and intensities of the northern and southern auroral electrojets for different orientations of the interplanetary magnetic field as determined from Swarm data. Coordinate system is dipole latitude/magnetic local time (Ashley Smith).*

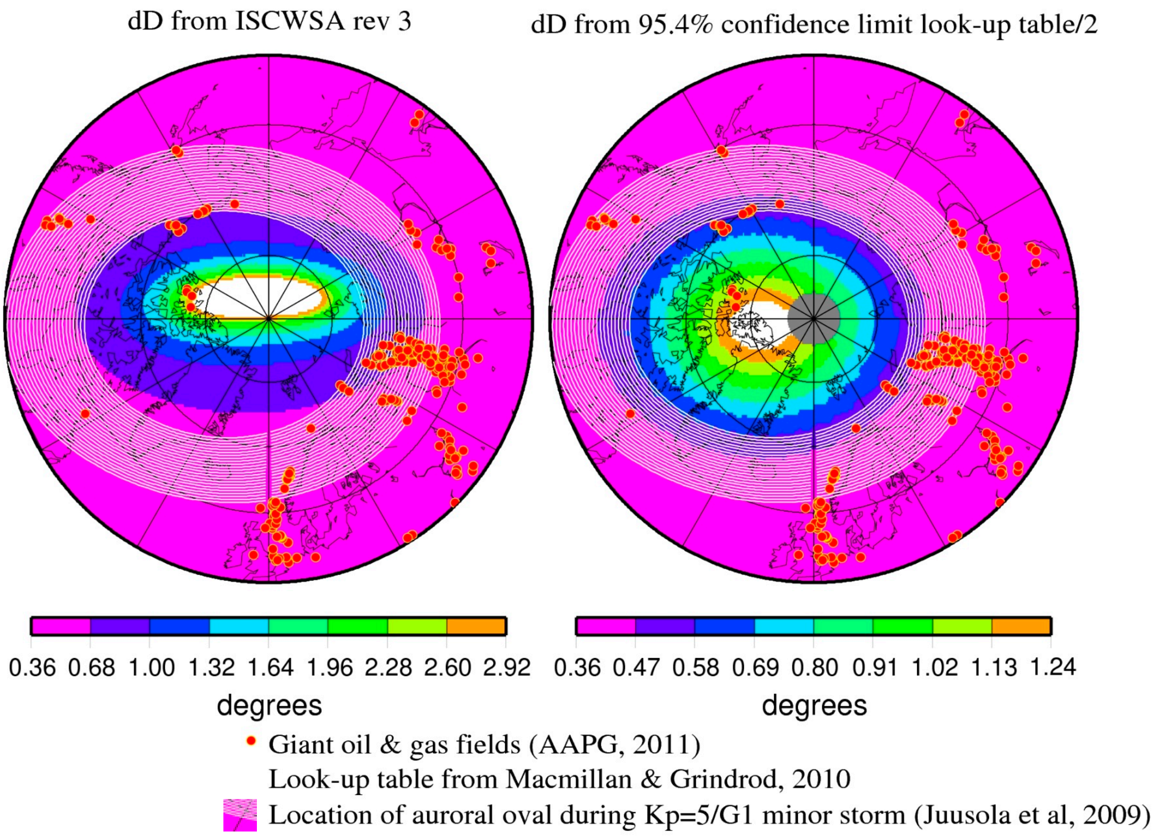
## Applications

*Oil services quality control activities:*
*Brian Hamilton and Orsi Baillie.*

# Oil Industry Developments

Understanding the directional and field strength uncertainties in global models is important in oil industry error modelling. In addition, for navigational referencing, understanding the local geomagnetic latitude is also important, not least when using IIFR services. We therefore discuss some BGS service developments in this area made in 2015.

Accurate knowledge of the navigational error associated with global magnetic field models continues to be important for directional drilling. The industry




*Declination standard errors from the industry error model (left) and from a BGGM look-up table (right). Note that the industry model unnecessarily overestimates errors in the polar region.*

typically uses a simple error model involving, at most, four parameters each of which is assumed constant in value. BGS has long been a proponent of a more comprehensive error model involving three parameters but whose values are drawn from look-up tables arranged by latitude and longitude and which are then usable with high (statistical) confidence levels. Look-up tables would allow errors arising from the auroral electrojets to be better modelled.

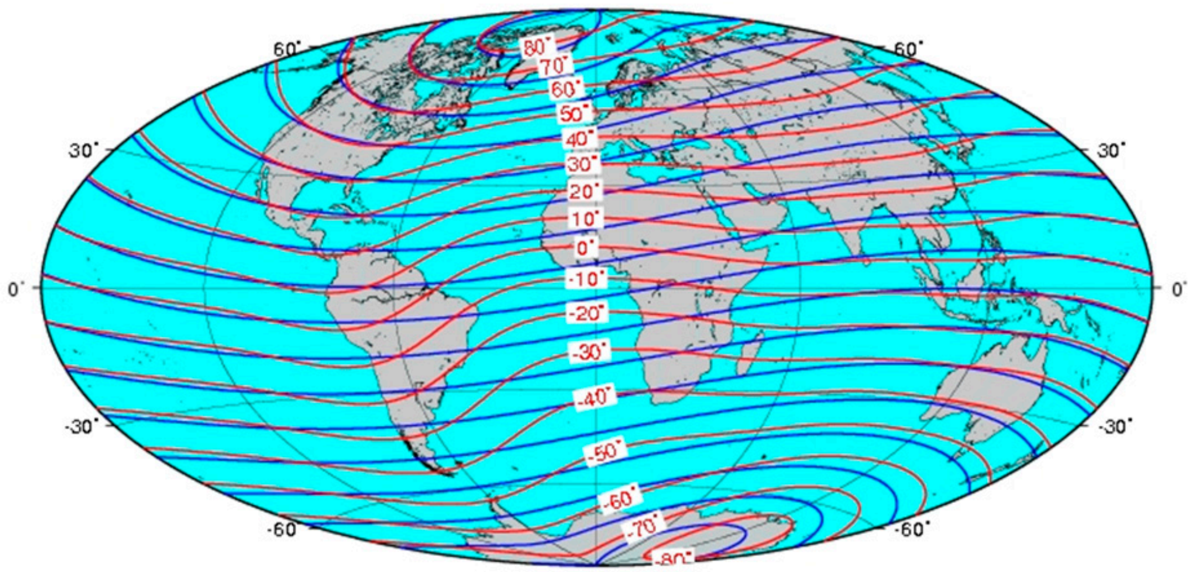
In 2010 BGS published a paper in an industry journal (Macmillan and Grindrod, 2010) detailing the work behind the derivation of look-up tables at different levels of confidence. However the industry needs standard errors so they can be combined with other sources of errors associated with wellbore position, and they are also keen to reduce errors. We will therefore be working on this with industry partners in 2016.

In 2015 a BGS online geomagnetic coordinate calculator was developed and made available. The new calculator uses coefficients for all spherical harmonic degrees (up to 13) of the 12th Generation International Geomagnetic Reference Field and, for comparison, a simple tilted dipole coordinate system is included, where we use only the degree one coefficients of IGRF revision 12. The calculator is available at www.geomag.bgs.ac.uk/data_service/models_compass/coord_calc.html and has proven popular.

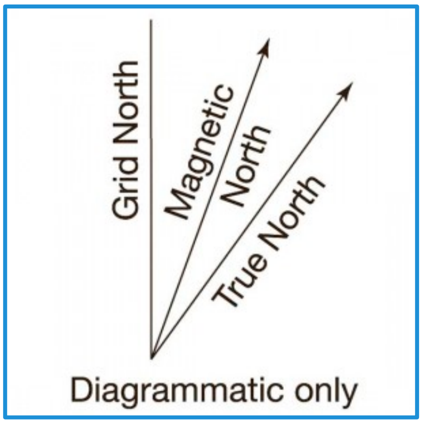
Structural and dynamical features of the ionised and neutral upper atmosphere are strongly organised by the geomagnetic field, and several magnetic coordinate systems have been developed to describe this organisation and the impact it has on defining *geomagnetic latitude*. The significance of this is that locations which have similar geomagnetic latitudes are likely to experience similar levels of magnetic disturbance.

This is useful for directional drilling if sourcing magnetic data when a nearby observatory is not available. However it is acknowledged that the morphology of the internal field, local time and conductivity structures can also influence magnetic disturbance levels and hence also geomagnetic latitude.

*Macmillan, Susan and Steve Grindrod, 2010. Confidence Limits Associated With Values of the Earth's Magnetic Field used for Directional Drilling. SPE Drilling & Completion, 25(2), 230-238. DOI: 10.2118/119851-PA.*




*Different methods of defining geomagnetic latitude: dipole (blue) and quasi-dipolar (red) contours at 2015.0.*



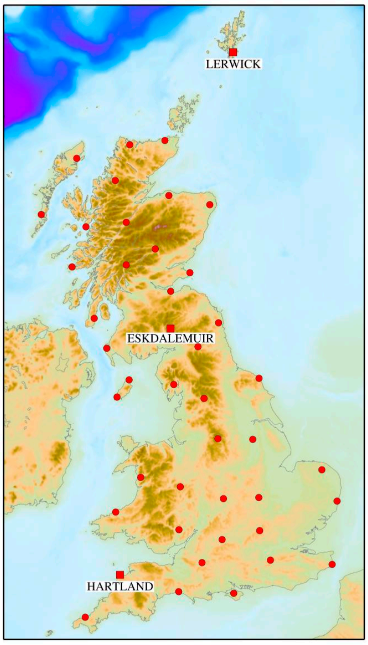

*The new 'norths' icon, produced by the Ordnance Survey.*

# Changes for Compass Users in Great Britain

In 2015 measurements of the Earth's magnetic field were made in Great Britain that indicated the start of a period of easterly Grid Magnetic Angle (GMA) in the country. The last time GMA was easterly was over 350 years ago.

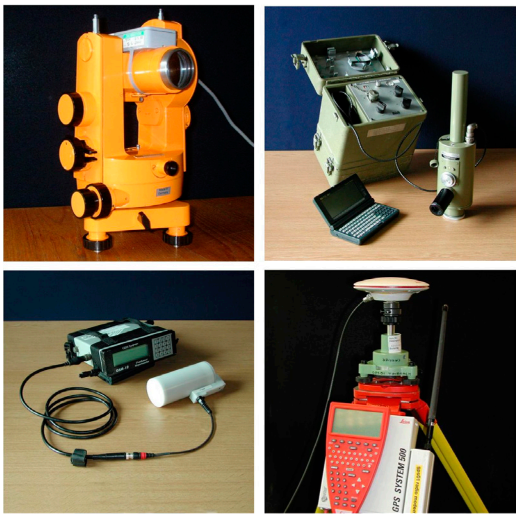
## The measurements

Every year observations of the Earth's magnetic field are made at around ten of the 41 repeat stations spread throughout Great Britain. These data supplement the data from the three magnetic observatories and provide the necessary coverage for production of a regional model of the magnetic field.




*The locations of British repeat stations (spots) and observatories (labelled squares).*

The magnetic measurements are made with similar equipment as used to make absolute observations at an observatory, i.e. a non-magnetic fluxgate theodolite and a proton precession magnetometer (PPM). To obtain true azimuth, use is made of two geodetic-quality GPS receivers. A gyro attachment is used as a back-up and for sites with tree coverage affecting GPS.



*Repeat station instrumentation.*

Each repeat station site was chosen to be free of interference from artificial magnetic field sources such as railway lines, underground utilities and other man-made constructions.

To ensure the permanence of the repeat stations and the network, sites are located in conservation areas and on agricultural land which are unlikely to be developed in the future. Care is taken to make an exact reoccupation of the site so that the slow secular change in the magnetic field can be tracked without any contamination from the local short-wavelength crustal field. Before observations are made the local magnetic field around each site is checked using the PPM. Observations of declination, inclination and total intensity are made. The data are then reduced to quiet night-time values by means of data from the closest observatories.

In 2015 the most south-westerly repeat station was visited again. Once the *D* observations had been processed and corrected for the angle between true and Ordnance Survey grid north, the resulting grid magnetic angle was found to be easterly.

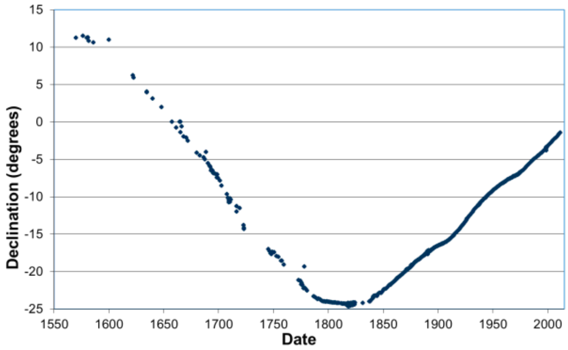
*Magnetic field observations by Tony Swan made at Godrevy Point in Cornwall in 2015.*

## Making history

Before 1660 easterly magnetic angles were recorded by several observers in and around London. But since then we have had varying westerly grid magnetic angles, with the maximum being about 27° west in Shetland in 1818.

## Grid magnetic angle in 2015

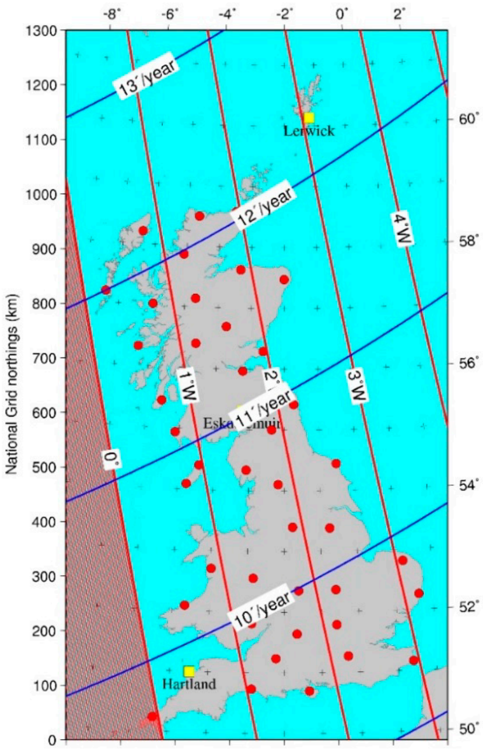
Every year the regional model is updated to include the observations from the




*Declination over 1550-2010 reduced to the location of the Greenwich observatory.*

previous year in order to maintain accuracy**.** This model is used to provide the Ordnance Survey with the corrections necessary for each of their map products for converting between magnetic bearings and grid bearings. It is also used for the BGS online grid magnetic angle calculator.

It will take over 20 years for magnetic north to become east of grid north everywhere. Also, it will not be until about 2018 that we will see magnetic north east of *true north*, starting in Kent, working westward in time.




*Grid magnetic angle and its annual rate of change in 2015. The shaded area shows where magnetic north is east of grid north.*

# Outreach and Knowledge Exchange


*Simon Flower setting up our stand on Geomagnetism at Dunbar's annual Science Festival in East Lothian.*

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

## Scientific Journal Publications

## Published 2015

**Beggan, C.D.** (2015) Sensitivity of Geomagnetically Induced Currents to Varying Auroral Electrojet and Conductivity models. *Earth Planets and Space*, 67 (24)

**Hamilton, B., Ridley, V. A., Beggan, C. D., Macmillan, S.** (2015) The BGS field candidate models for the $12^{th}$ generation IGRF. *Earth Planets and Space*, 67 (69)

Olsen, N., Hulot, G., Lesur, V., Finlay, C.C., **Beggan, C.**, Chulliat, A., Sabaka, T. J., Floberghagen, R., Friis-Christensen, E., Haagmans, R., Kotsiaros, S., Lühr, H., Tøffner-Clausen, L., Vigneron, P. (2015) The Swarm Initial Field Model for the 2014 geomagnetic field. *Geophysical Research Letters*, 42 (4). 1092-1098.

Thébault, E., Finlay, C.C., **Beggan, C.D.**, Alken, P., Aubert, J., Barrois, O., Bertrand, F., Bondar, T., Boness, A., Brocco, L., Canet, E., Chambodut, A., Chulliat, A., Coïsson, P., Civet, F., Du, A., Fournier, A., Fratter, I., Gillet, N., **Hamilton, B.**, Hamoudi, M., Hulot, G., Jager, T., Korte, M., Kuang, W., Lalanne, X., Langlais, B., Léger, J-M., Lesur, V., Lowes, F.J., **Macmillan, S.**, Mandea, M., Manoj, C., Maus, S., Olsen, N., Petrov, V., **Ridley, V.**, Rother, M., Sabaka, T.J., Saturnino, D., Schachtschneider, R.., Sirol, O., Tangborn, A., **Thomson, A.**, Tøffner-Clausen, L., Vigneron, P., Wardinski, I., Zvereva, T. (2015) International Geomagnetic Reference Field: the 12th generation. *Earth, Planets and Space*, 67 (79)

Thébault, E., Finlay, C.C., Alken, P., **Beggan, C.D.**, Canet, E., Chulliat, A., Langlais, B., Lesur, V., Lowes, F.J., Manoj, C., Rother, M., Schachtschneider, R. (2015) Evaluation of candidate geomagnetic field models for IGRF-12. *Earth, Planets and Space*, 67 (1)

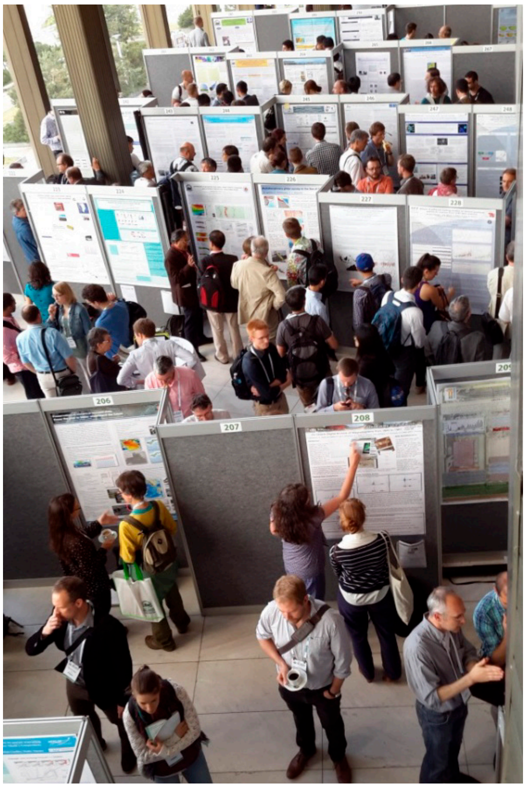
Whaler, K.A.; **Beggan, C.D**. (2015) Derivation and use of core surface flows for forecasting secular variation. *Journal of Geophysical Research: Solid Earth*, 120 (3)

## Submitted, Accepted and to Appear 2016 (at March 2016)

**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.

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

**Beggan, C. D.** and Marple, S. R. (2016). Space weather goes to schools. *Astronomy and Geophysics*.




*Presentations at 26th IUGG held in Prague, June 2015*
***Left****: Ellen Clarke presenting her poster (No.208)* ***Right:*** *Gemma Kelly giving an oral presentation.*

## Other Publications

BGS Reports: ‘2014 Annual Review’

1 joint BGS and NOAA report: ‘The US/UK World Magnetic Model for 2015-2020’

6 Customer Reports (UK survey & OS; oil industry services; Review of European Forecasting Capability)

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 St. Patrick’s Day Geomagnetic Storm... by Sarah Reay:
http://britgeopeople.blogspot.co.uk/2015/03/the-st-patricks-day-geomagnetic-storm.html

* Measuring magnetic history at Godrevy Point ... by Anthony Swan:
http://britgeopeople.blogspot.co.uk/2015/06/measuring-magnetic-history-at-godrevy.html

## Conference Presentations, Posters and Related Activities

Magnetic Interactions, Leeds UK, January

1 poster

SEREN workshop ‘Physical pathways to space weather impacts’, London, UK, February

1 presentation (Thomson)

US-UK workshop on the space weather hazard to power grids, Washington DC, USA, February

1 presentation (Thomson)

ISCWSA (SPE wellbore positioning) meeting, London, UK, March

1 presentation (Macmillan)

Living with a Star workshop on Geomagnetically Induced Currents, Colorado, USA, March

1 presentation (Thomson)

Niemegk Colloqium, Niemegk, Germany, June

2 presentations (Clarke & Turbitt, Thomson & Flower)

IUGG Prague, Czech Republic, June

9 talks (Baillie, Beggan, Billingham, Clarke, Kelly, Kerridge, Reay, Thomson)

5 posters

2 Medals (Kerridge, Riddick)

National Astronomy Meeting, Llandudno, UK, July

1 presentation (Kelly)

1 poster

1 press release

Swarm workshop, Paris, France, September

2 presentations (Brown, Macmillan)

MagNetE Repeat Station Conference, Budapest, Hungary, September

1 presentation (Swan)

ISCWSA (SPE wellbore positioning) meeting, Houston, USA, September

1 presentation (Clarke)

SCOSTEP/WDS Workshop on ‘Global Data Activities for the Study of Solar-Terrestrial Variability’, Tokyo, Japan, September

2 presentations (Reay)

European Space Weather Week 12, Ostend, Belgium, November

1 presentation (Kelly)

1 poster

Two exhibitions stands, Live Forecast (Baillie), End-user meeting & Splinter meetings

Geomagnetism Advisory Group annual meeting, Edinburgh, September

9 presentations (Beggan, Billingham, Clarke, Flower, Kelly, Macmillan, Turbitt, Thomson)

Geomagnetism Team seminars, Edinburgh

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

## Some Other Notable Outputs

Observatory tours

Eskdalemuir Observatory – Edinburgh University School of Geoscience visited in February as part of Innovative Learning Week and a local walking group were also provided with a tour of the observatory.

Hartland Observatory – we hosted visitors from Devon County Council, the observatory was used by a student from Royal College of Art, London as part of a Design Interactions MA project, as well as researchers from Imperial College London measuring microtremors.

Edinburgh University Undergraduate Lecture Series (September 2014 – April 2015)

4th Year Honours Course on ‘Geomagnetism’, by Ciarán Beggan & Gemma Kelly (8 lectures)

3rd year Geophysics course on Earth and Planetary Structure by Ciarán Beggan, & B. Baptie (14 lectures)

3rd year Geophysics course on Geophysical Techniques for Terrestrial Environmental Applications by Ciarán Beggan and Gemma Kelly (10 lectures, 3 labs, fieldwork)

Public Lectures, Presentations and Demonstrations

Educational and training activities, including participation at the Dunbar Science festival (Flower, Beggan, Billingham), March 2015

Presentation at Celebrating Science – Careers Event at Our Dynamic Earth

Involvement in the Space Weather Public dialogue

Institute of Physics ‘Lab in a Lorry’ hands-on experimental outreach event (Billingham)

Falkirk schools S6 Routes into Employment Careers networking event (Billingham)

Invited talk on ground effects and monitoring of space weather, University College London, Mullard Space Science Lab (Billingham)

13 Geomagnetic Disturbance Alerts emailed to over 3700 subscribers.

Mention in The Shetlands Times regarding housing development near Lerwick Observatory.

# Selected Glossary, Acronyms and Links

| | |
|---|---|
| ***Aurora Watch*** | *Aurora alert service run by Lancaster University (aurorawatch.lancs.ac.uk)* |
| ***BAS*** | *British Antarctic Survey (www.bas.ac.uk)* |
| ***BGGM*** | *BGS Global Geomagnetic Model (www.geomag.bgs.ac.uk/bggm.html)* |
| ***BGS*** | *British Geological Survey (www.bgs.ac.uk)* |
| ***CERN*** | *European Council for Nuclear Research (http://home.cern)* |
| ***CHAMP*** | *German magnetic survey satellite (www-app2.gfz-potsdam.de/pb1/op/champ)* |
| ***CME*** | *Coronal Mass Ejection* |
| ***DISC*** | *Data, Innovation and Science Cluster supporting the ESA Swarm mission* |
| ***Dst*** | *A measure of magnetic activity at low geomagnetic latitudes* |
| ***DTU*** | *Danish Technical University, Copenhagen, Denmark (www.dtu.dk/English)* |
| ***EHO*** | *The Earth Hazards and Observatories science directorate of BGS (www.bgs.ac.uk/about/organisation.html?Accordion2=2#eho)* |
| ***ESA*** | *European Space Agency (www.esa.int/esaCP/index.html)* |
| ***ESWW*** | *European Space Weather Week. (sidc.oma.be/esww12)* |
| ***FMC*** | *Fort McMurray Observatory (Alberta, Canada)* |
| ***GeoSocial*** | *BGS social media tool for viewing geoscience data (www.bgs.ac.uk/citizenScience/geosocial/home.html)* |
| ***GDAS*** | *Geomagnetic Data Acquisition System* |
| ***GDASView*** | *GDAS data viewing software* |
| ***GFZ*** | *GeoForschungsZentrum,Postdam, Germany (www.gfz-potsdam.de/en/home)* |
| ***GIC*** | *Geomagnetically Induced Currents (a natural hazard to power systems)* |
| ***GIN*** | *Geomagnetic Information Node (of INTERMAGNET)* |
| ***GMA*** | *Grid Magnetic Angle: the angle between magnetic north and OS grid north* |
| ***GPS*** | *Global Positioning System* |
| ***HSD*** | *Halliburton-Sperry Drilling (http://www.halliburton.com/en-US/ps/sperry/sperry-drilling/default.page?node-id=hfvq7ixm)* |
| ***IAGA*** | *International Association of Geomagnetism and Aeronomy (www.iugg.org/IAGA)* |
| ***ICSU*** | *International Council for Science (previously the International Council of Scientific Unions) (www.icsu.org)* |
| ***IGRF*** | *International Geomagnetic Reference Field (www.ngdc.noaa.gov/IAGA/vmod/igrf.html)* |
| ***IIFR/IFR*** | *Interpolation In-Field Referencing/In-Field Referencing. (www.geomag.bgs.ac.uk/data_service/directionaldrilling/ifr.html)* |
| ***IKE*** | *Information and Knowledge Exchange* |
| ***IMCDView*** | *INTERMAGNET Data Viewing Software* |
| ***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)* |
| ***IPGP*** | *Institut du Physique du Globe de Paris (www.ipgp.fr/en)* |

| | |
|---|---|
| ***ISCWSA*** | *Industry Steering Committee on Wellbore Survey Accuracy. (iscwsa.org)* |
| ***ISGI*** | *International Service for Geomagnetic Indices (isgi.unistra.fr/m)* |
| ***ISP*** | *Internet Service Provider* |
| ***IT*** | *Information Technology* |
| ***IUGG*** | *International Union of Geodesy and Geophysics (www.iugg.org)* |
| ***KMA*** | *Korean Meteorological Administration (www.kma.go.kr/eng/index.jsp)* |
| ***KRISS*** | *Korean Research Institute of Standards and Science (www.kriss.re.kr/eng)* |
| ***LED*** | *Light Emitting Diode* |
| ***MAGIC*** | *Monitoring and Analysis of GIC. A GIC analysis service for the National Grid* |
| ***MagNetE*** | *European magnetic repeat station network (www.gfz-potsdam.de/en/section/earths-magnetic-field/infrastructure/magnete).* |
| ***MEA*** | *Meanook observatory (Alberta, Canada)* |
| ***Met Office*** | *UK Meteorological Office (www.metoffice.gov.uk)* |
| ***MHD*** | *Magnetohydrodynamic* |
| ***MOSWOC*** | *Met Office Space Weather Operations Centre* |
| ***NERC*** | *Natural Environment Research Council (www.nerc.ac.uk)* |
| ***NOAA/NCEI*** | *National Oceanic and Atmospheric Administration/National Centres for Environmental Information (formerly National Geophysical Data Center) (www.ngdc.noaa.gov).* |
| ***Ørsted/Oersted*** | *Danish magnetic survey satellite (www.space.dtu.dk/english/Research/Projects/Oersted)* |
| ***OS*** | *Ordnance Survey (www.ordnancesurvey.co.uk)* |
| ***Pc*** | *Continuous geomagnetic pulsations* |
| ***PPM*** | *Proton Precession Magnetometer* |
| ***QNX*** | *UNIX-like real-time operating system* |
| ***Raspberry Pi*** | *A small, low-cost computer (https://www.raspberrypi.org)* |
| ***RIN*** | *Royal Institute of Navigation. (www.rin.org.uk/general/Navigation-News)* |
| ***SCOSTEP*** | *Scientific Committee on Solar Terrestrial Physics (www.icsu.org/what-we-do/interdisciplinary-bodies/scostep)* |
| ***SEREN*** | *STFC funded series of workshops on themes within space weather science in the UK* |
| ***SH*** | *Spherical Harmonic (Analysis)* |
| ***SPE*** | *Society of Petroleum Engineers (www.spe.org)* |
| ***STFC*** | *Science and Technology Facilities research Council (www.stfc.ac.uk)* |
| ***Swarm*** | *Three-satellite ‘mini-constellation’ for magnetic field surveying. (www.esa.int/esaLP/LPswarm.html)* |
| ***SWENET*** | *Space Weather European Network (ESA) (www.esa-spaceweather.net/swenet/index.html)* |
| ***SWPC*** | *Space Weather Prediction Centre (www.swpc.noaa.gov)* |
| ***TCD*** | *Trinity College Dublin (www.tcd.ie)* |
| ***UKAS*** | *The United Kingdom Accreditation Service (www.ukas.com)* |
| ***VarSITI*** | *Variability of the Sun and Its Terrestrial Impact (a program within SCOSTEP) (www.varsiti.org)* |
| ***VLF*** | *Very Low Frequency* |

| | |
|---|---|
| ***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)* |

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# The Geomagnetism Team in 2015

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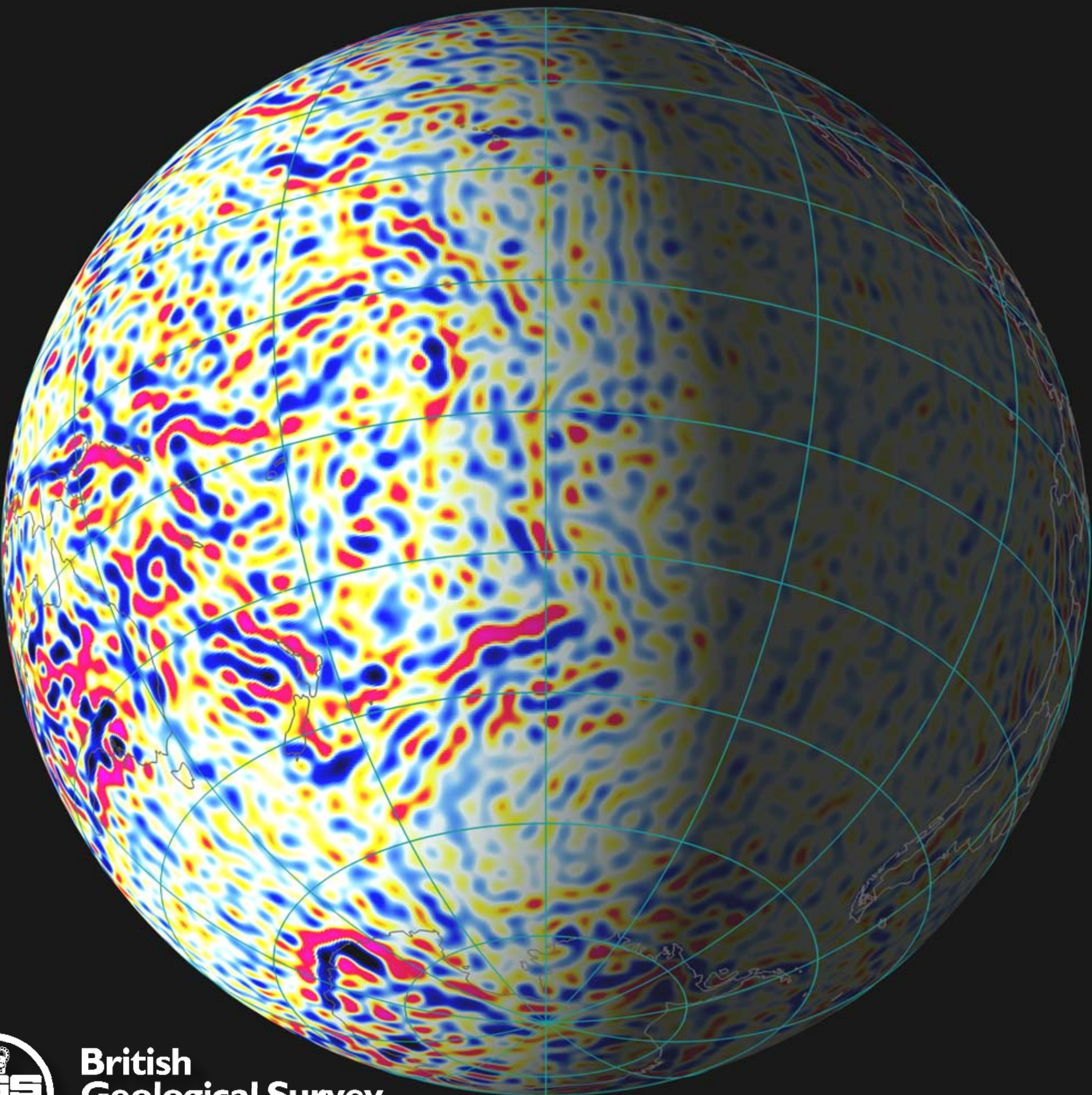
*Cover: The vertical component of the BGS model of the global lithospheric magnetic field. Red shows where the magnetic field points inwards and blue shows where the field points outwards.*
*This new model resolves regional features on the scale of 300 km, from a global satellite survey. This is better than half the scale achievable less than ten years ago.*

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