British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

Geomagnetism *Review 2014*

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Geomagnetism

Review 2014

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Introduction

Geomagnetism team display at the official opening of the UK Met Office Space Weather Operations Centre

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 evolution of the solid Earth and its atmospheric, ocean and space environments, and help develop our understanding of the geomagnetic hazard and its impact. We also provide geomagnetic products and services to industry and academics and we use our knowledge to inform the public, government and industry.

The British Geological Survey (BGS) is the main Earth science research facility for the UK and is a research centre of the Natural Environment Research Council (NERC).

Geomagnetism research is represented in BGS as a science team within the Earth Hazards and Observatories (EHO) science theme. The Geomagnetism, Earthquake Seismology, Earth and Planetary Observation and Monitoring and Volcanology teams join the Space Geodesy, British Isles Continuous GNSS and Geophysical Equipment Facilities, as parts of EHO.

EHO, in turn, is one of twelve BGS science themes that deliver the BGS science strategy. EHO is within 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 Systems and Network Support.

The Geomagnetism team is primarily based in Edinburgh. In 2014 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), at Eskdalemuir (Scottish Borders) and in Hartland (North Devon).

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We also operate magnetic observatories overseas on Ascension Island, 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 are in the process of commissioning a new observatory at Fort McMurray in 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 (space weather) 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 a world leader in

- Measuring, recording, modelling and interpreting the Earth's natural magnetic field and its sources
- Modelling and understanding the geomagnetic hazard, a component of the space weather hazard to society's technologies
- Delivering tailored geomagnetic data, products and services to academics, business and the public
- 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

Tony Swan talks at the 2014 Geomagnetism Advisory Group meeting in Edinburgh

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Introduction

The observatory grounds at Ascension Island observatory

Looking Ahead to 2015

In 2015 our research will focus on the space weather hazard to technology and infrastructure and the ESA Swarm magnetic survey mission. Our major activities to support this will include the operation of the BGS magnetic observatories and the UK magnetic survey to international standards. We will also produce academic and other geomagnetic models and data products.

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 2015 will be

- An INTERMAGNET-standard (www.intermagnet.org) UK and overseas observatory network, obtained through regular observatory service visits and high-standard quality assurance procedures
- Full commissioning of the new Fort McMurray magnetic observatory in Alberta, Canada
- 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 2015 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

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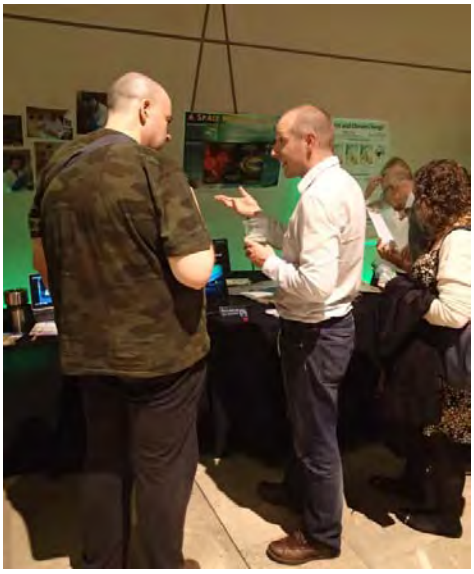
Service for Geomagnetic Indices (ISGI), according to the timetable set by ISGI

- Operation of the World Data Centre for Geomagnetism (Edinburgh), including an annual 'call for data' and associated quality control activities
- Collaboration on existing international geomagnetic observatory (INDIGO) and survey programmes (MagNetE)
- Active participation (through presentations and organisation of sessions) in a number of major international scientific conferences, e.g. the UK National Astronomy Meeting, the 12th European Space Weather Week and the IUGG congress, Prague.

Observatory site preparations at Fort McMurray, Alberta, December 2014

- Publication of a number of papers in scientific and professional journals, and the writing of articles for scientific and other publications
- Operating the BGS 'Expert Support Laboratory' providing data products for the ESA Swarm Satellite Constellation Applications and Research Facility, in support 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 to USGS and NOAA Space Weather Prediction Centre (SWPC); and real-time magnetograms



Ciaran Beggan demonstrates the Schools Magnetometer project at the Natural History Museum's 'Science Uncovered' event

- Working with the UK Met Office Space Weather Operations Centre (MOSWOC) and as part of the Natural Hazards Partnership project, to provide local and planetary magnetic indices and daily forecasts and magnetic data products

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- Monitoring and analysis of the geo-electric (telluric) measurements at the UK magnetic observatories
- Maintaining the Monitoring and Analysis of GIC (MAGIC) web tool, in association with National Grid
- Producing the 2015 update of the BGS Global Geomagnetic Model (BGGM), using satellite and other geomagnetic data, including data from all BGS operated observatories
- Delivering geomagnetic observatory data and magnetic field products including daily geomagnetic activity forecasts, to support geophysical survey companies and directional drilling operations, as part of In-Field Referencing (IFR) and Interpolation IFR (IIFR) services
- Providing observatory facilities for calibration and testing of instruments
- Delivering 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
- Building 'Raspberry Pi' magnetometers and rolling out the STFC-funded schools' magnetometer project, in association with University of Lancaster's 'Aurora Watch' team
- Studying and reporting on the impact of extreme geomagnetic storms on the UK and French transmission systems, in partnership with the Finnish Meteorological Institute, for a customer
- Carrying out a review of the current state of geomagnetic activity forecasting across Europe for ESA, as part of the ongoing ESA Space Situational Awareness (SSA) programme, leading to recommendations on future developments of the SSA Service Coordination Centre
- Preparing for the move of BGS Scotland to the new, purpose built, Charles Lyell Building at Heriot-Watt University in early 2016

Discussions at the 2014 Geomagnetism Advisory Group meeting

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Headline Numbers from 2014

Here are some key numbers, which help to put in perspective the team's outputs as a whole for 2014.

- 598 global oil industry wells supplied with IFR data
- 276 Ordnance Survey map compass references
- 100% (>99%) UK (overseas) observatory data coverage
- 96 magnetic bulletins published
- 75 global oil industry wells supplied with IIFR data
- 42 presentations/posters
- 21 oil industry customer reports
- 20 field set-ups for IFR services
- 12 scientific meetings
- 10 A-to-Z map compass references
- 6 articles on space weather for RIN 'Navigation News'
- 5 positions on scientific and technical geomagnetism bodies
- 5 public lectures, presentations and demonstrations
- 4 geomagnetic models (WMM2015, 12th generation IGRF candidates, UK reference model, BGGM2014)
- 4 undergraduate projects supervised
- 3 journal and conference proceedings papers
- 3 undergraduate courses taught
- 3 post-doctoral research assistants
- 1 'Hypercube' data set supplied to oil industry
- 1 STFC Public Engagement grant for Raspberry Pi magnetometer
- #1 most-read blog on the BGS 'GeoBlogy' site at britgeopeople.blogspot.co.uk/
- 1 observatory tour
- 1 podcast, 1 YouTube video and a number of newspaper and web articles and quotes

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Technical, Observatory and Field Operations

Fluxgate-theodolite sitting on the absolute pillar at Ascension Island Observatory

UK and Overseas Observatories 2014

BGS operates three absolute geomagnetic observatories in the UK and six overseas to supply high quality, real-time measurements for research and services. We also take a leading role in expanding the global observatory network, to improve global modelling and for local applications. The UK observatories achieved 100% continuous data supply in 2014.

Technical Developments

The data recorders at all of the observatories were upgraded during 2014 to low-power, solid state PCs to improve battery-backed operation at locations where power cuts are common. These new recording platforms have been specified to support an upgrade to our proprietary recording & communication software that has been in development for the past two years. Our software is now running under the QNX6 real-time operating system, one of the benefits of which has been to allow us to improve internet security in response to increasing cyber threat at remote sites.

Coupled with the roll-out of new recorders and software, we have improved the resolution of the recorded data to 1pT in anticipation of the installation of higher sensitivity magnetometers at the observatories. The first of these instruments, a LEMI-025 fluxgate magnetometer, is now installed on one of the main systems at Eskdalemuir Observatory for long-term performance evaluation.

Magnetic Observatories

December 2014 saw the second service visit to the King Edward Point (KEP) Observatory, located in the south Atlantic island of South Georgia. The remoteness of this observatory makes it unique amongst BGS Observatories in its requirements for travel to site, a journey that involves several days at sea. As a consequence of this, observatory visits can only be carried out every two years, creating a special need to ensure that the observatory infrastructure has not degraded in the extreme weather conditions found on the island and that the logging system is robust and operating soundly.

In addition to instrument maintenance and calibrations, special care was given to refurbish the interior of the Absolute Hut to make it weather tight and an environment better suited to manual observations in the depths of winter – aiding the production of better quality results. New members of staff from the British Antarctic Survey base in

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South Georgia were trained in the making of observations and were given familiarisation briefings on our sensors & logging equipment.

Further visits were made to the remote observatories on Ascension Island, Sable

The view towards King Edward Point Observatory, South Georgia, at the base of Mount Duse

Island, at Port Stanley and in Northern Alaska. With Sable & KEP Observatories now accepted into the INTERMAGNET network, these visits are essential in maintaining the level of data quality and data continuity set by this international data distribution and standards body. The visits also provide opportunity to improve the infrastructure and instrumentation on site.

At Ascension, a new observing pillar was constructed to replace a wooden tripod, making the observing process easier and more accurate, which should lead to an improvement in observation quality. Due to the high gradients in the magnetic field at the site, it was critical that the concrete pillar was precisely positioned at the same location and height as the original tripod.

One of the additions to JCO in Alaska was an electrical power monitor that relays the status of the site electrical supply to an alert system Edinburgh in order that failures are quickly detected and rectified.

A significant improvement to the UK network was the replacement of the on-site generator at Hartland Observatory. Generator-backed electrical supply is one of the measures taken to ensure reliability at observatories that are critical to space-weather or oil industry data supply. The Hartland replacement was carefully co-ordinated to ensure that neither recordings nor communications were disturbed during the work.

At Eskdalemuir, final testing has been completed on a recording system to be installed at a newly established Canadian observatory in support of local oil and gas production. This observatory is expected to be on-stream early in 2015.

The Global Network and the 2014 IAGA Observatories Workshop

Some of the performance testing techniques developed by BGS to evaluate new magnetometers were presented at the biennial IAGA Workshop in India. BGS was also represented on the panel during a workshop discussion on the future of magnetic observatory networks and IAGA's supporting role.

Workshops such as these also provide an opportunity to meet and train observers from international observatories that make use of instrumentation or applications supplied by BGS. One such observatory is the Syrian Observatory, which has operated with a BGS FLARE Plus system since 1998.

UK Repeat Station Network

The 2014 magnetic repeat station programme covered eight measurement locations in east & central Scotland and the east of England. A plan will be implemented in the coming year to upgrade the post-processing software currently used.

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Participants of the INTERMAGNET EXCON/OPSCOM Meeting at the National Geophysical Research Institute, Hyderabad,India. October 2014

Technical, Observatory and Field Operations

The BGS Contribution to INTERMAGNET

BGS continues to make a significant contribution to the INTERMAGNET programme (www.intermagnet.org). INTERMAGNET is a consortium of institutes and observatories around the world that make measurements of the Earth's magnetic field and meet agreed quality standards. BGS leads the work on development of and compliance with INTERMAGNET standards and INTERMAGNET's IT infrastructure. In October 2014 the regular INTERMAGNET meeting was held in Hyderabad, India, after the IAGA magnetic observatories workshop. Both meetings were hosted by the National Geophysical Research Institute.

All Change at the Top

Three out of the four members of the INTERMAGNET Executive Council, including the chairperson, moved on in 2014, including David Kerridge of BGS who had served since 1992. Alan Thomson from BGS has now been appointed to INTERMAGNET's Executive Council and is the new INTERMAGNET chairperson. We also have two representatives on the operations committee: Chris Turbitt and Simon Flower.

The World Data System

INTERMAGNET has been awarded 'network' membership of the World Data System (https://www.icsu-wds.org/). The World Data System is an interdisciplinary body of the International Council for Science and exists to enable universal and equitable access to quality-assured scientific data and information and to ensure long term data stewardship.

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First Evaluation of QD data

INTERMAGNET has been collecting quasi-definitive (QD) data since 2012. One of the features of this data product is that it is not possible to evaluate the quality of the data until the corresponding definitive data has been created. The INTERMAGNET meeting in Hyderabad provided the first opportunity to evaluate the quality of QD data that has been provided to INTERMAGNET.

40 of the 140 INTERMAGNET observatories provided QD data in 2012. Out of these 38 observatories produced data that is compliant with the QD standard (which states that quasi-definitive data should be within 5nT of the definitive data).

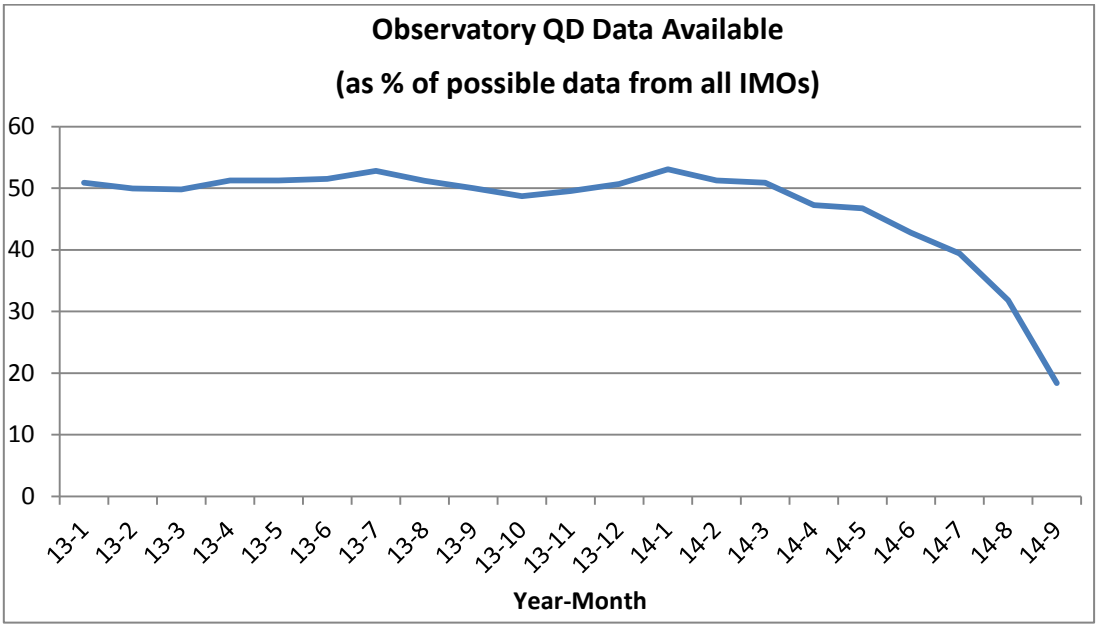
These results, for the first year of a new data product, show that the production of quasi-definitive data is realistic proposition. There is room for improvement in the number of observatories who contribute this data and INTERMAGNET has been working to convince the operators of the benefits of producing this data product. The Figure below shows statistics on the amount of QD data received in 2013/14 (the drop off at the end is due to data not yet received at the time of preparing the Figure).

One Second Data Product

INTERMAGNET is about to start producing a major new data product: one-second data. Although INTERMAGNET currently collects one-second data, this is provided by observatories on a 'best endeavours' basis and does not conform to any particular standard.

INTERMAGNET has agreed a challenging but realistic standard for one-second data that observatories will, in most cases, need to work towards. A new data format has been agreed for this data.

BGS staff have led the work to create these new standards. Work is ongoing to create tools for data quality control and, ultimately, for users to be able to work with the data. It is hoped to make a first call for one-second definitive data in 2015 (for data recorded in 2014).



The number of magnetic observatories contributing quasi-definitive data to INTERMAGNET (as a percentage of the total number of observatories participating in INTERMAGNET) between January 2013 and September 2014

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Gemma Kelly presenting the daily live Space Weather forecast at ESWW11

Science

Space Weather and ESWW11

There were several advances in space weather research and applications at BGS in 2014 and the results were presented at the 11th European Space Weather Week (ESWW11), held in Liège, Belgium in November. ESWW11 was well attended with over 400 participants taking part in 14 scientific sessions and 20 splinter meetings.

The Geomagnetism team had a strong presence at the 11th European Space Weather Week (ESWW11), with two electronic-posters, one paper poster and an invited talk (Ellen Clarke). Members of the team also contributed to two further posters and presented in the 'Ground Effects Topical Group' splinter session.

The forecasting team were also invited to take part in a significant new ESWW initiative this year and present our 'Live Space Weather Forecast' during the week. The live forecast was presented by a different forecasting agency each day, reviewing space weather conditions for the previous 24 hours, and forecasting activity levels for the next 24 hours.

In the next four sub-sections we summarise the space weather research and other activities that we presented at ESWW11.

Extremes in Worldwide Geomagnetic Activity Geomagnetic storms pose a hazard to many modern technologies. Therefore understanding how severe such storms can be is important to a wide range of space weather data and forecast end-users. Extreme value statistical (EVS) methods were applied to a global set of geomagnetic observatory data to determine the one in 100 and one in 200 year extreme values in the North, East and horizontal magnetic field strengths and their time rates-of-change.

Data from 22 worldwide observatories were analysed, carefully chosen to provide a good geographical spread and long duration time series. The data were carefully quality controlled to produce a time series of residuals, with respect to quiet-time levels. The EVS technique was then applied to each observatory data set.

We found that the estimated largest return values were found for observatories between approximately 55° and 70° geomagnetic latitude, supporting an earlier study of European data only. And, as a particular example, the largest 100

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year return level in the East component of the field was found at Fort Churchill observatory (Canada), at 5400nT.

Improving Operational Geomagnetic Index Forecasting

Geomagnetic indices provide a useful parameterisation of storm-time magnetic conditions. Indices are also required by a variety of space weather models and end-users. Currently we produce forecasts of the 3-hourly ap index, estimated using linear regression techniques. However machine learning algorithms are now being investigated, to improve the way we forecast geomagnetic activity, for example by allowing us to include as many input data types as possible.

Many of the machine learning models we have tested so far show an improvement compared to our existing forecast algorithm. In particular machine learning models appear to be better at forecasting, i.e. anticipating, magnetic storms, which is of most importance for evaluating the risk to technology.

The Accuracy of Extrapolated Magnetic Observatory Measurements for MWD in the Arctic

The drilling of many extended-reach oil wells is helped by using the geomagnetic field as a reference. External field disturbances, caused by space weather, can reduce the accuracy of this reference and render it less helpful for drill guidance. External field activity can perturb the overall measured magnetic field direction by several degrees during periods of disturbed space weather. At high latitudes such perturbations can occur even during periods of relatively quiet space weather.

At BGS we use real-time data from a nearby magnetic observatory to correct for any influence of the external field and bring the accuracy of the reference field to within industry acceptable limits.

However the ‘corrective power’ of the real-time data depends on many factors including: distance to the drill site, latitude and the dynamics of the external field. For instance, as drill site-observatory distance increases, a point will be reached where the error in mapping between the two locations will become equal to the effect of the external field.

We are therefore currently studying pairs of high-latitude magnetometer stations; comparing their data streams to quantify each observatory’s corrective power (see page 24).

Mapping the Aurora Using Social Media

The BGS GeoSocial Aurora application for mapping the aurora http://www.bgs.ac.uk/ geosocial

The BGS has developed a new application to display the locations of aurora sightings across the UK and beyond, using data obtained from social media.

The BGS GeoSocial web site (www.bgs.ac.uk/geosocial) shows a map that displays data from the UK geomagnetic observatories, as well as cloud cover information (using data provided by the Met Office). Twitter users can submit sightings that are then displayed on the map using the **#BGSaurora** hashtag. Indirect tweets related to the topic (e.g. **#aurora**) are also shown.

The motivation for this development has been twofold: 1) to engage the public, and help inform them where and when the aurora is visible, and 2) to gather new data potentially useful for scientific analysis.

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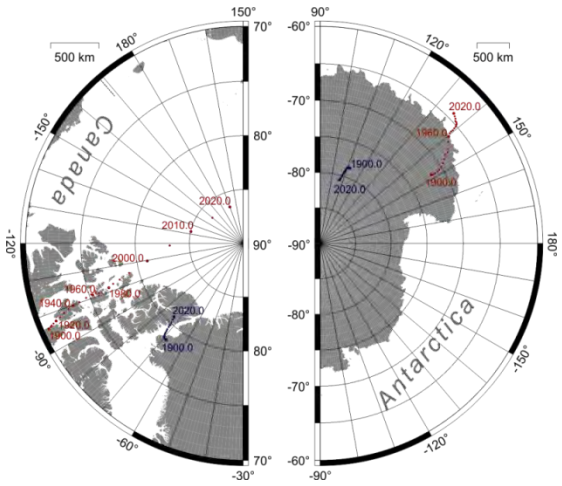

Geomagnetic (blue) and dip (red) poles from the IGRF-12 field model

Science

Global Modelling: WMM2015 and IGRF-12

Every five years the BGS, in conjunction with the National Oceanic and Atmospheric Administration in the United States, issues an update of the World Magnetic Model (WMM). The WMM was revised in 2014 to provide a model of the Earth's main magnetic field at 2015.0 and a prediction of the change of the field over the five years to 2020.0. BGS also contributed to the International Geomagnetic Reference Field (IGRF) model, which was also revised this year. The IGRF is a similar reference magnetic field model that can also be used up to 2020. The IGRF is developed collaboratively by various research institutes around the world.

World Magnetic Model

The World Magnetic Model (WMM) is a mathematical model of the Earth's main (i.e. core-generated) magnetic field, updated every five years. It is developed together with the National Oceanic and Atmospheric Administration (NOAA) in the USA and is intended primarily for use in navigation systems for the UK and US military.

The WMM2015 model describes the main field of the Earth at 2015.0 up to degree and order 12, which approximates to a length scale of around 3300 km at the Earth's surface. As the main magnetic field changes continuously, a prediction of the change over the subsequent five years to 2020.0 is also included.

Data for the WMM comes from both the global ground-based magnetic observatory network and satellite surveys such as the current ESA Swarm mission. The WMM consists of a set of coefficients describing the spatial features of the magnetic field and how they change with time, coded in software and used to compute the value of the magnetic field at any position on or above the Earth's surface. In addition, BGS offers a free online calculator for use by the general public.

In the past decade, the WMM has become popular in smartphone mapping and

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navigation applications as a means of making declination corrections. The declination angle at the phone's location is used to convert the digital compass measurements of magnetic north (made by the phone) into true north. While the correction is currently small in the UK (less than 2°), it can be quite large in some parts of the world, for example in California the declination angle is over 12°.

For the WMM2015 release, a significant amount of research was carried out to understand the average uncertainty or error associated with values produced by the model. As well as the main field, there are other sources such as the external field and the crustal field. As these other sources are not captured by WMM2015, we conducted a study to describe the uncertainty arising from not including them in the model. Our conclusion was that the average global uncertainties were smaller than the accuracy required by the US and UK military.

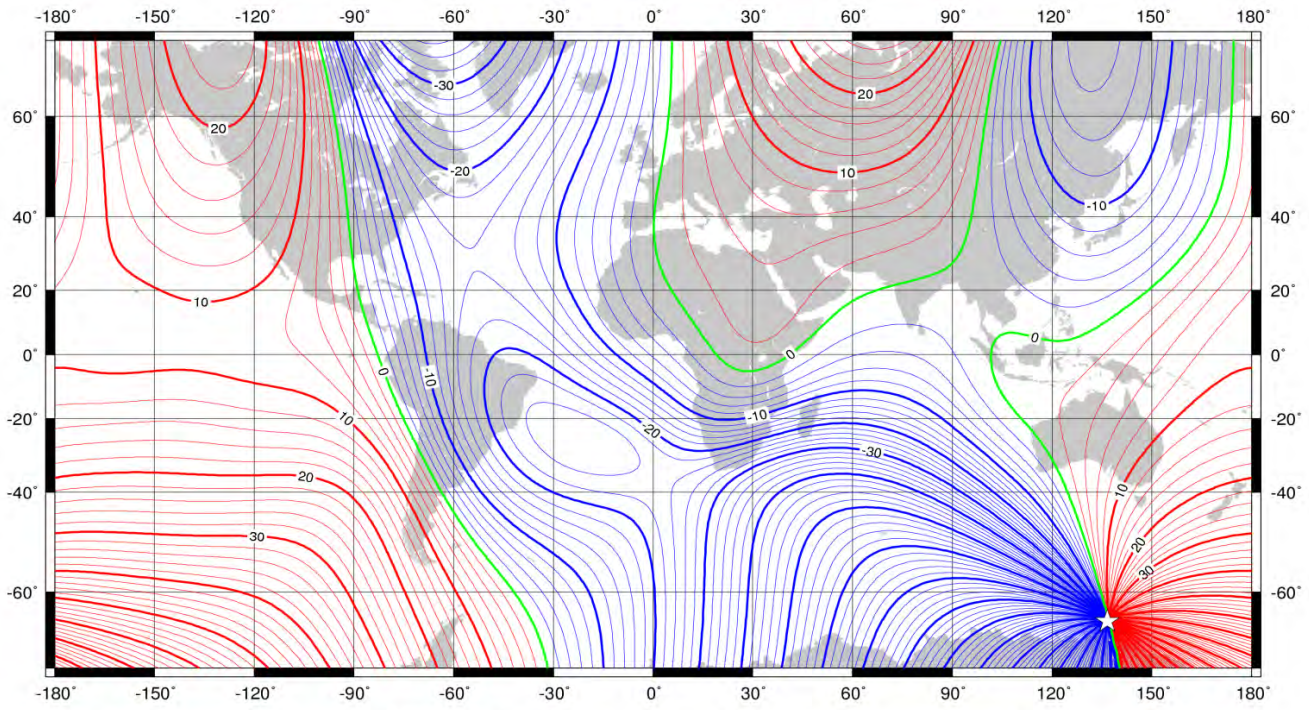
IGRF-12

The International Geomagnetic Reference Field (IGRF) model, generation 12, is a collaborative main field model also released and updated on a quinquennial basis.

It consists of what is known as a 'definitive model' up to 2010.0, a model for 2015.0 and prediction of field change for the five years to 2020.0. The IGRF-12 model describes the magnetic field up to degree and order 13, different to the WMM, with the predictive part covering variations only up to degree and order eight.

Nine research institutes submitted candidate models to the IAGA IGRF-12 task force for consideration, including the BGS. Most models were similar, mainly due to the use of similar satellite and observatory data sets and data preparation techniques. The final IGRF-12 models were then generated from these candidates using 'Huber weighting' in space to combine the models in an optimal manner.

The IGRF-12 is approved by IAGA as an official standard model for scientific applications. A special issue of *Earth Planets and Space* will be published in 2015 describing the derivation of each candidate and the comparisons made between models.



Declination (magnetic variation) at 2015.0 from the World Magnetic Model (WMM2015). Red - positive (east), blue - negative (west), green - zero (agonic line). Contour interval is 2°, white star is location of a magnetic pole and projection is Mercator. This is an example of an isogonic chart. Credit: British Geological Survey (Natural Environment Research Council).

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Science

Night-time launch of the Swarm satellites from the Plesetsk Cosmodrome aboard a Rockot rocket on 22 November 2013

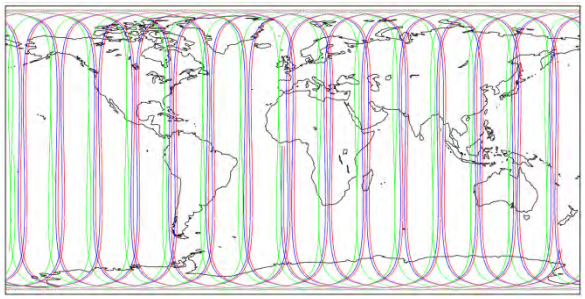
ESA Swarm Mission

ESA's Swarm mission was launched in November 2013. Since then, this three satellite constellation has been sending back an abundance of high quality vector measurements of the Earth's magnetic field over all parts of the globe. Here we take a look at the Swarm data and present two projects that have benefited greatly from this mission.

Swarm Data

Since its launch Swarm has already accumulated 10s of millions of measurements. The mission is expected to last a minimum of five years and therefore promises much more data. The Swarm magnetic field data intended for most scientific applications is the 'Level 1b' (low rate) product, which provides vector and scalar samples of the magnetic field every second for each of the three satellites.

Two of the satellites fly in close proximity in near identical orbits at ~470 km altitude to allow measurements of the field gradient, whilst the third flies at ~520 km altitude and in an orbit that changes over time at a different rate to the other two. The map (right) shows all satellite tracks for a single day. Sixteen orbits per day give near global geographic coverage, with the gaps between tracks being filled in on subsequent days, through satellite drift. In local-time (i.e. relative to direction of Sun) coverage is slower to accumulate, completing full global coverage about three times per year for each satellite.



Orbit tracks of Swarm A (red), B (green), and C (blue) over one day (21 September, 2014)

The orbits are almost exactly North-South but a slight inclination means data within 2° of the North- and South-Poles are not sampled.

With three satellites flying simultaneously at different altitudes and local times, the Swarm mission provides the most comprehensive satellite data coverage ever achieved. Such an abundance of high quality data is a boon for science and field modelling. BGS was one of the first institutions to make use of these data and

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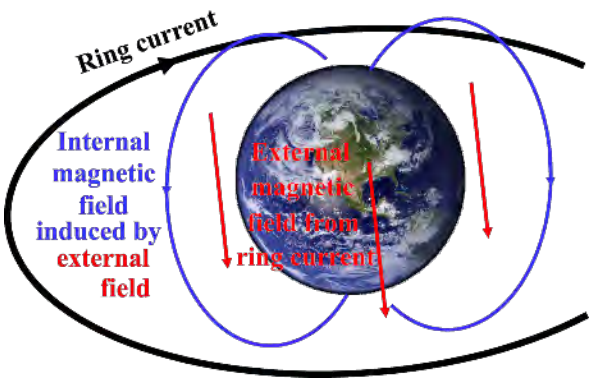
our science has already benefited from them. Two examples are given below.

Rapid Magnetospheric Model

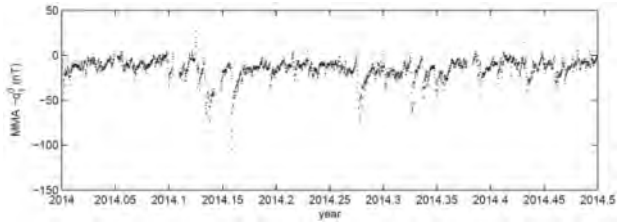
ESA commissioned BGS to develop a rapidly-delivered, per-orbit, magnetospheric model based on Swarm data. This model describes the large-scale magnetospheric field, primarily from the ring current, orbit by orbit.



Simplified diagram of the Earth's ring current (black) and the magnetic fields it produces: external (red) and induced internal (blue)

This model became operational in September 2014 and has been producing daily updates ever since. The processor generates the new day's model coefficients within one hour of receiving the Swarm data and is capable of near real-time delivery, if required by ESA in the future.

The Figure below shows the magnetic field at the Earth's surface from the dominant part of the external component at the Earth's surface. Large deviations indicate disturbed field / enhanced ring current.



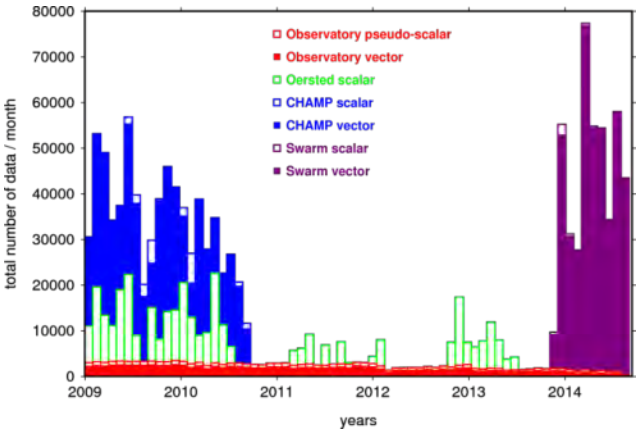
North-South component of the magnetospheric field derived from Swarm data over the first six months of 2014

We find the Swarm magnetospheric model is less susceptible to baseline jumps than the real-time Dst, an equivalent widely-used index based on low-latitude magnetic observatory data.

Global Field-Modelling

Global geomagnetic field models require global data coverage. Observatories provide excellent time resolution, which is very useful for estimating the time variation of the field, but their spatial density is low in remote and ocean areas. Satellite data therefore provides the required high spatial-resolution coverage.

Since the end of the CHAMP satellite mission in 2010, there have been relatively few data satellite available for global modelling: intermittent scalar data from the venerable Ørsted satellite have been necessarily supplemented by the reliable observatories' time-series.



Total number of selected (geomagnetically quiet) data per month for IGRF-12 candidate models from each measurement platform

This relative dearth of data makes the job of estimating the field in that period, and into the future, more difficult. However from November 2013, there has been a huge surge in available vector satellite data (see Figure above). The data rate now available exceeds anything previously. This has allowed BGS to generate high quality main field and secular variation models for the BGGM2014, IGRF-12 and WMM2015.

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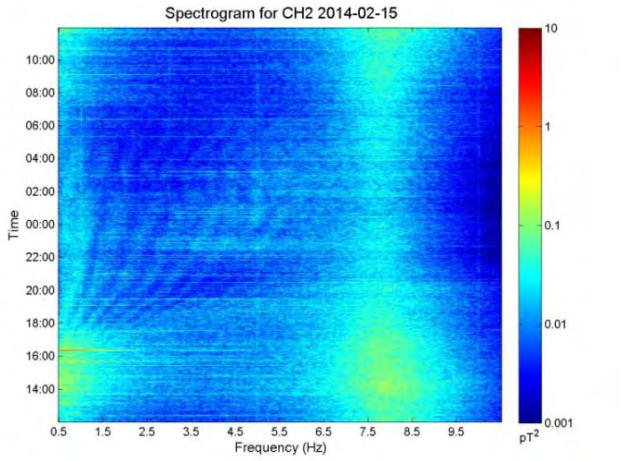

Spectrogram for 15/16th March 2014. The wispy fringes between 18:00-04:00 and 1-5 Hz are the Ionospheric Alfvén Resonances. The first Schumann resonance is the diffuse region visible around 8 Hz

Automatic Detection of Ionospheric Alfvén Resonances

BGS operates two high frequency induction coil magnetometers at the Eskdalemuir observatory. These coils record magnetic field variations at higher frequencies than our standard observatory instruments. We have used the induction coils to study a particular physical phenomenon called ionospheric Alfvén resonances (IAR). A new method has been developed to automatically find and classify certain patterns in the IAR data and we have examined some of the seasonal and cyclical trends in the data.

Induction coils measure small and very rapid changes of the magnetic field. A set of induction coils at the Eskdalemuir observatory record magnetic field changes over a frequency range of 0.1—50 Hz, which typically encompasses geophysical wave phenomena related to the conductive parts of the upper atmosphere (generally referred to as the ionosphere).

The ionosphere acts as a partial 'barrier' which electromagnetic (EM) waves can bounce off, become trapped in and resonate back and forwards for short periods. Schumann resonances (EM waves trapped between the Earth's surface and the bottom of the ionosphere) and Ionospheric Alfvén Resonances (EM waves travelling along magnetic field lines trapped between the bottom and the top of the ionosphere) are two such examples. However, to properly observe these phenomena, we have to look in the frequency domain of the measured magnetic time-series.

The IAR are known as spectral resonance structures (SRS) and are visible as a series of fringes in spectrograms of the magnetic field rate of change (see Figure above). There are several parameters that can be computed from the SRS to give information about the ionosphere itself. For example, the frequency interval (Δf) between spectral lines can be used to determine the length interval of the ionospheric cavity and the density of the electrically charged particles in the ionosphere. To compute this manually is onerous, so a method to automatically

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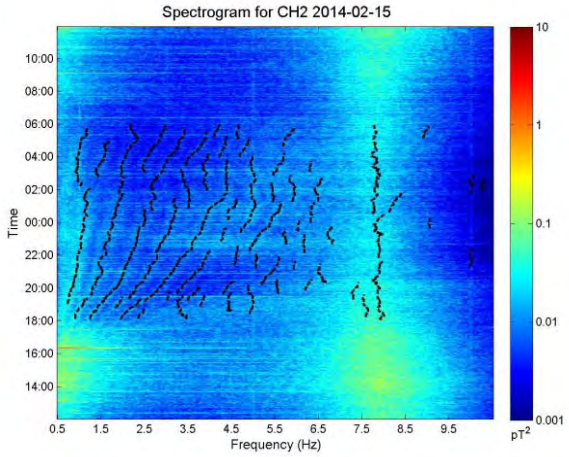
detect the SRS fringes and the relevant parameters has been developed.

The method can be divided into two parts. The first part uses *signal processing* techniques to identify the SRS peaks within each line of the spectrogram while the second part involves the use of *image processing* to link the individual peaks together and discern the continuous fringe patterns. The method is fully automatic once some thresholds have been set by manual inspection. As with any method, there is a trade-off to be made between detection of signal and sensitivity to noise. The Figure below shows results for the 15/16th March 2014. The black lines denote the detected SRS.



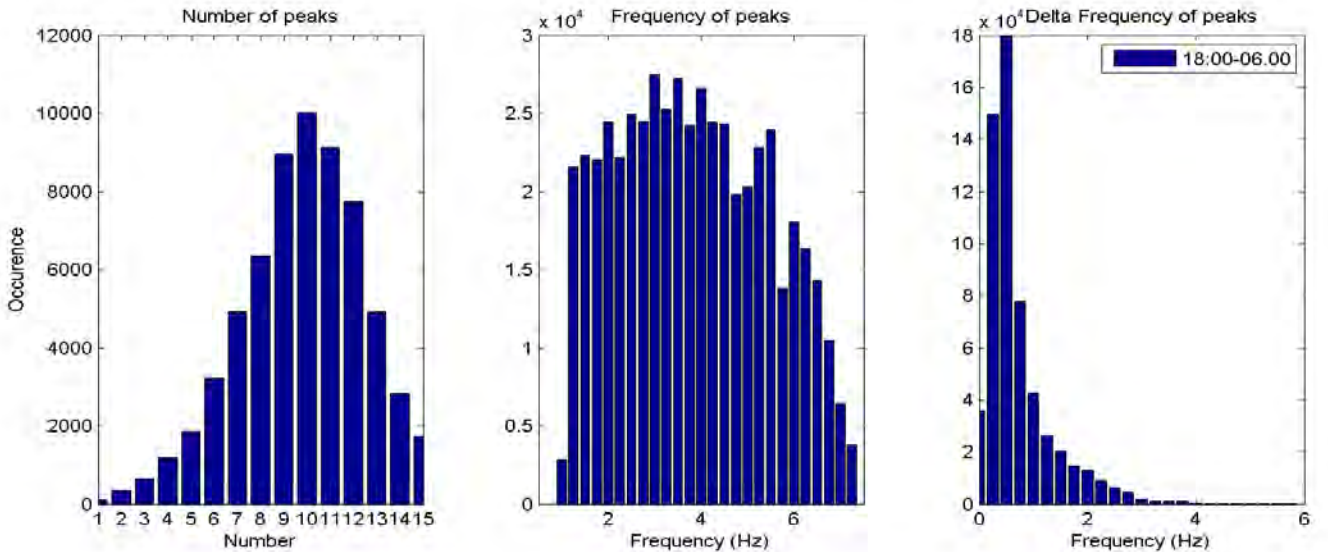
Results from the automatic detection of SRS

Once the algorithm has automatically detected the SRS, we are interested in extracting useful parameters such as the number of fringes, the frequencies they occur at and the width between the peaks (Δf).

The histogram (Figure below) shows the results from processing approximately eighteen months of induction coil data (Sep 2012-Feb 2014). The most common number of fringes is 10, which occur across the frequency range 1-6 Hz with an average Δf of 0.5 Hz.

In addition to these average trends, there are also clear seasonal trends in the data when examined month by month. For example, the average value of Δf is largest in Northern Hemisphere winter and smallest around the equinoxes. There are also longer trends in the data related to the solar cycle and the influence of the Sun's magnetic field on the ionosphere. In future, with a longer dataset, we will be able to extract all of these effects.

The parameters derived from this study match the findings from other published research, giving us confidence that the data from the induction coils are of suitable scientific quality. The detection method can also be applied to other phenomena of interest in the induction coil data such as automated detection of Schumann resonance properties or of magnetospheric pulsations.



Histogram of selected SRS parameters for 18 months of induction coil data (Sep 2012-Feb 2014)

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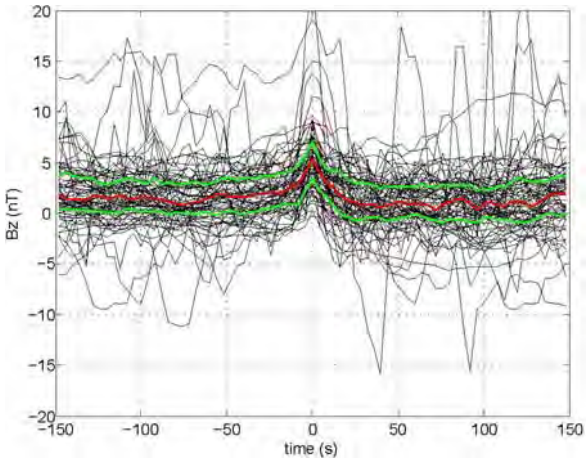
Student and Visitor Activities

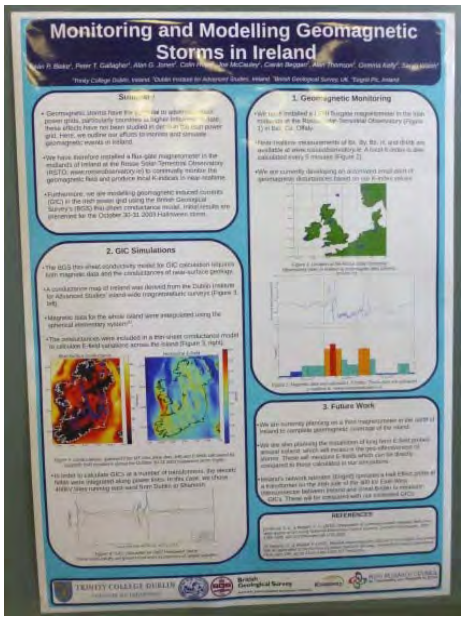


Signature of tail-ward-propagating dipolarisation fronts in the Z-component of the magnetic field in Cluster spacecraft data. Red (green) is the mean (mean +/- 1 standard deviation) level from a number of superposed events.(Nina Kahr)

During 2014 BGS were involved, with the University of Edinburgh in conceiving and supervising several undergraduate projects concerning geomagnetism. BGS Geomagnetism also undertook PhD supervision and hosted a number of visitors from the UK and abroad.

Postgraduate Students

In March 2014, BGS agreed to advise Sean Blake, a new PhD student at Trinity College, Dublin, supervised by Prof. Peter Gallagher in the Astrophysics Research Group. Sean is investigating the effects of Geomagnetically Induced Currents in the Eirgrid transmission network in Ireland, as well as other space weather effects. He produced posters for the European Space Weather Week and American Geophysical Union conferences in 2014.



Sean Blake's poster at European Space Weather Week in November 2014

Undergraduate Students

We helped devise and supervise five research projects by 4th year undergraduate students at the University of Edinburgh School of Geosciences during 2014.

Jenny Johnson investigated the properties of polarisation of electromagnetic (EM) waves from lightning strikes around the world, as recorded in the Eskdalemuir induction coil magnetometers. The project focused on diurnal and seasonal variations in the splitting modes of EM waves as they resonate around the globe. The research was very thorough and received a high mark from the examiners.

Nina Kahr undertook a three month research project to study data from the ESA Cluster satellite mission. Nina made a survey of tail-ward propagating dipolarisation fronts, events occurring in the Earth's magnetotail and related to the magnetic reconnection that drives geomagnetic storms. She surveyed eight years of Cluster magnetometer and ion-detector data for events propagating away from Earth (see Figure above). These are

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thought to be ‘mirror events’ to the storm-triggering flows. She performed the first multi-spacecraft analysis of tail-ward propagating dipolarisation fronts and tested two hypotheses: (1) that the occurrence of tail-ward dipolarisation fronts does indeed mirror that of Earthward propagating ones, and (2) that the tail-ward flows are larger in scale than the Earthward events observed in the same region.

Aidan Hunter studied the relationship between coronal mass ejections (CMEs) and geomagnetic storms. Aidan calculated the Direction Parameter (DP) – a measure of how symmetrical a halo CME is around the Sun – for 53 full halo CMEs which were associated with X-class flares. He then assessed how effective the Direction Parameter is as a predictor of geomagnetic activity, and found a high correlation between DP and the Kp index. This work will feed into space weather forecast operations at BGS.

Moses Mwakyanjala (below) spent six weeks as a summer project student developing code and software for a Raspberry Pi based magnetometer system. Moses developed the outline for a website implementation of a network of magnetometers and showed how to deliver data in real-time in a web-service accessible to the public.

Kittiphon Boonma examined the occurrences of magnetospheric and ionospheric pulsations in Eskdalemuir induction coil data, showing that the occurrence of such features compares well with those found by other researchers.

Visitors

Adhytia Putra is a photojournalist who spent some time at the BGS in May and June. He produced an experimental documentary work called ‘Natural Surveillance’ documenting the magnetic observatories at Eskdalemuir and Hartland and our work back at the office in Edinburgh. You can see Adhytia’s finished work at: http://naturalsurveillance.weebly.com/

Photographer Adhytia Putra’s Natural Surveillance project. Image is copyright Adhytia Putra.

Rachel Bailey from ZAMG (Austria) visited BGS in June. She gave a presentation on Conrad Observatory at a team seminar and provided insight into the Austrian Schools magnetometer project she manages. Rachel is now leading a PhD project to study GIC in Austria, on which BGS are advising.

Visitors from GIMS Lab, Russia, together with BGS staff: Vorobev, Kelly, Turbitt, Shakirova, Macmillan, Kerridge, Sep 2014

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Gemma Kelly talks about BGS Space Weather Applications at the launch of the Met Office Space Weather Operations Centre (October 2014)

Applications

Space Weather Applications and Services

Research into space weather and the related geomagnetic hazard finds application in a number of data products and services to academic and commercial users. In 2014 BGS was involved in a number of projects that highlighted the importance of our space weather research and services in hazard assessment for technological infrastructure.

The Geomagnetism team continues to work closely with a number of partners with an interest in Space Weather.

In March the Geomagnetism team hosted the first Space Weather Research Network (SEREN) workshop on geomagnetically induced currents. The aim of the STFC-funded SEREN project is to develop research partnerships, particularly on space weather impacts on ground-based technologies. The event was well attended, with representatives from the Cabinet Office, National Grid, Scottish Power, Atkins, Met Office, Natural Resources Canada, UK space agency and several UK universities all in attendance.

The workshop provided a forum for discussions about how best to move forward in improving our ability to assess and mitigate geomagnetically induced currents in power grids, and in providing nowcasting and forecasting tools to support this. It was also a good opportunity to gather perspectives from both users of space weather services and the research community.

In October, representatives from BGS attended the launch of the new Met Office Space Weather Operations Centre (MOSWOC). This marked the official start of their 24/7 space weather operations.

Collaboration with the Met Office continues to grow stronger. Daily teleconferences to discuss the space weather forecast help improve geomagnetic activity forecasts by making use of joint expertise. Continued maintenance and development of the data BGS provides to the Met Office also helps to ensure alerts and warnings are timely and correct.

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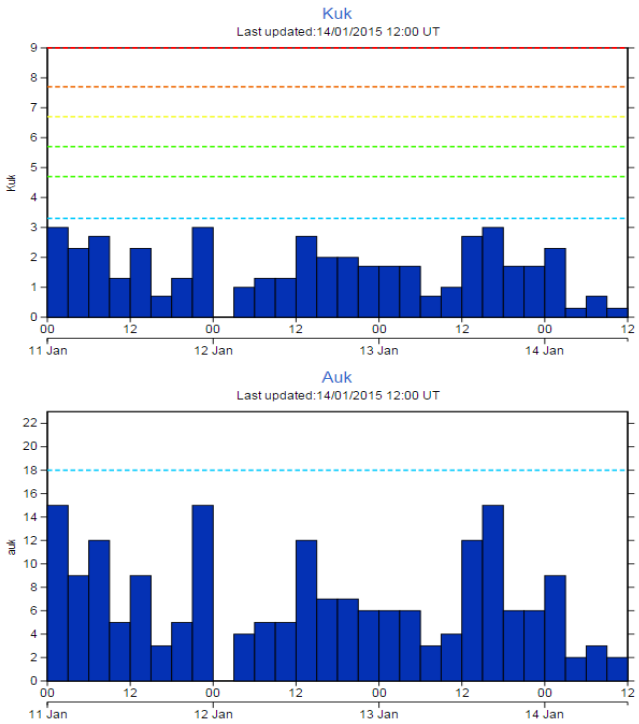
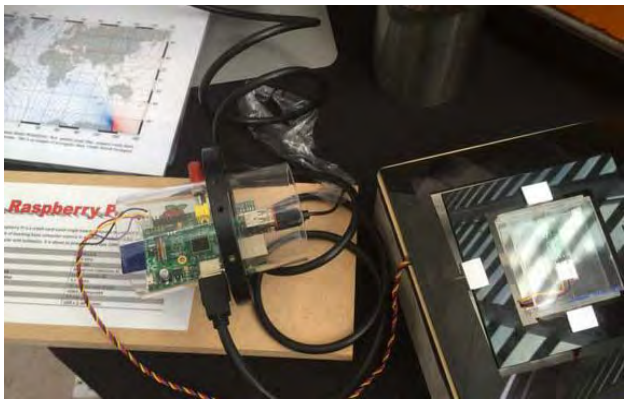
Members of the Geomagnetism team also participated in the UK 'Space Weather Public Dialogue'. This is a project aimed at building a better understanding of how members of the public understand the risk of space weather. The findings are being used to guide future government policy and communications on space weather. Find more information about the project at talkspaceweather.com



Local geomagnetic indices Kuk and Auk are provided to Met Office in near real-time

Highlights of Other Activities

- Continued maintenance and development of the MAGIC ('Monitoring and Analysis of GIC') web tool for National Grid.
- 3 posters, an invited talk and a live space weather forecast presented by BGS staff at the 11th European Space Weather Week in Liege, Belgium.
- Three posters on recent BGS space weather research at the 'Hot Spring MIST' meeting in Bath.
- Sensitivity analysis of our UK GIC model with respect to changes in both the external magnetic field strength and direction and the Earth conductivity model. The location and magnitude of the geomagnetic electrojet is found to be the primary control on the size of GIC, although conductivity can be locally important.
- Analysis of coronal mass ejection parameters available in near real-time, in relation to geomagnetic storm magnitude, to produce 'look-up' tables for use in our operational space weather forecasting.
- A successful application for funding to STFC to measure the effects of space weather in the UK by building and using a network of 'school magnetometers'.
- Launch of a new aurora mapping tool (www.bgs.ac.uk/geosocial) using social media to record sightings of the northern lights in the UK.
- Manning a space weather stand at the 'Science Uncovered' event at the Natural History Museum.
- An Earth System science spring school talk about space weather.
- Continued data exchange with the US National Oceanic and Atmospheric Administration's Space Weather Prediction Centre (SWPC), in Colorado.
- Attendance and presentation at the final meeting of the EURISGIC ('European Risk from Geomagnetically Induced Currents') FP7 project in Helsinki, January.



The Raspberry Pi magnetometer from the schools magnetometer project on display at the Natural History Museum as part of 'Science Uncovered' 2014

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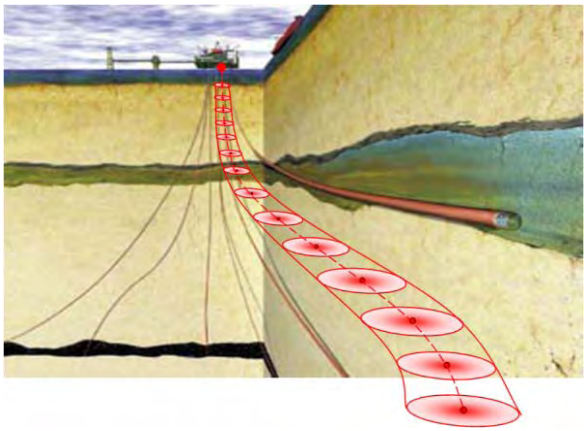
Applications

Directional Drilling at High Geomagnetic Latitudes



Drilling a deviated well to an oil or gas target. The ellipses indicate the drillers estimated uncertainty in the well bore position.

The IIFR service uses geomagnetic observatories to improve the accuracy of geomagnetic referencing in measurement while drilling surveys. Indeed, as drilling gradually creeps northwards and typical time variations in the magnetic field caused by solar activity become greater, the need for IIFR and suitably located high-standard observatories is likely to rise. Attaining the desired accuracy for extended-reach drilling is a far greater challenge at high geomagnetic latitudes than elsewhere in the world. The use of observatories will certainly help but the question is: what is the critical distance from the drill site within which an observatory's data still reduces uncertainty.

The Earth's magnetic field is a vital directional reference when drilling for oil and gas around the world. Using a combination of magnetic sensors and accelerometers in the bottom hole assembly, together with accurate estimates of the geomagnetic field, directional drillers are able to safely direct wells towards intended geological targets.

In 1994 BGS along with industry partners developed a method for improving the accuracy of geomagnetic referencing for directional drilling operations by including both the local spatial and time varying components of the Earth's magnetic field. This technique, known as Interpolation In-Field Referencing, or IIFR, has been used extensively ever since. With increased drilling activity at higher geomagnetic latitudes – in locations such as Alaska, Canada and the Barents Sea – IIFR is now more important than ever.

At such locations maintaining the desired accuracies in extended-reach drilling can be a much greater challenge than elsewhere in the world and for MWD operations, where gyroscopic methods may not be an option, the use of geomagnetic referencing is essential. In order to reach challenging oil and gas targets and to avoid well collisions it is important to estimate the uncertainties as accurately as possible, as well as to reduce these uncertainties where feasible.

Disturbances in the Earth's magnetic field caused by electrical currents flowing in the ionosphere and magnetosphere can significantly perturb the strength and direction of the magnetic field measured down hole. During storms, variations in declination of several degrees over a short period of time can occur and it is well established that these effects are on average greater at higher magnetic

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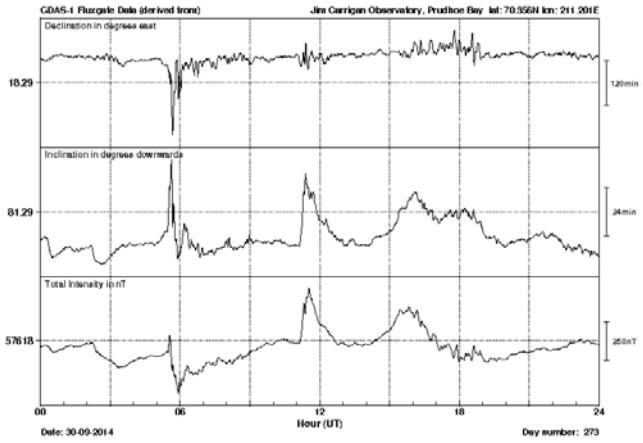
Map showing oil fields in the Northern regions where IFR has been set up. IIFR has also been used operationally at most of these locations

latitudes such as those nearer the auroral zone. Even during magnetically quiet times, variations can exceed desired thresholds for MWD at these locations.

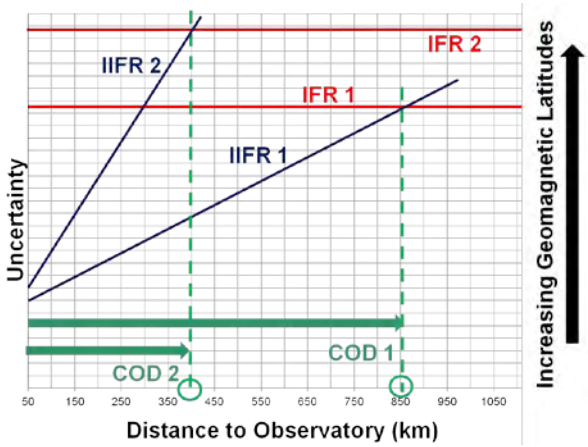


Magnetogram showing typical variations in declination (top), inclination or dip (middle) and total field intensity (bottom) at JCO, Alaska. This day is not classed as an 'International Disturbed Day' yet declination changes by >4º

The IIFR solution has been successfully employed at a few high latitude locations with the disturbance field variations accounted for at the drill site by applying real-time magnetic field measurements made at a nearby magnetic observatory. However many drilling campaigns are further off-shore or in remote locations where it is not possible (or certainly not straight forward) to measure the strength and direction of the Earth's magnetic field near the drilling location, to the required accuracy and time resolution.

In order to quantify how the uncertainties change with distance between observatory and drill site a comprehensive study using observatories at high geomagnetic latitude locations (60-75°) is on-going and this will be completed in 2015.

Pairs of sites are used to extrapolate the disturbance field and determine the critical observatory distance (COD), beyond which the accuracy is no longer improved by adding the time-varying values to models. The COD depends on the geomagnetic latitude of and the direction to the observatory(s).



Schematic to demonstrate the improvement in uncertainty using IIFR over IFR and how this drops off with distance from the drilling location. Two example geomagnetic latitudes (1=lower and 2=higher latitude) are show. The COD is reached when IIFR (blue) no longer reduces the uncertainty compared to IFR (red).

With >3000 years of station pairs, a robust statistical analysis is possible. The inclusion of data over periods of more than 11 years, will also provide the seasonal and solar cycle variations in the COD.

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Over 1000 people visited Murchison House during the annual BGS Edinburgh Open Day in September 2014

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.

Scientific Journal Publications

Published 2014

Thomson, A. W. P., 2014. Geomagnetic Observatories: Monitoring the Earth's Magnetic and Space Weather Environment. *Weather* 69 (9), pp 234-237

Beggan, C., **Hamilton, B**., **Macmillan, S.** and **E. Clarke**, 2014. Improving models of the Earth's magnetic field for directional drilling applications. *EAGE First Break*, 32 (3), pp 53-60

Beggan, C.D., 2014. Automatic detection of ionospheric Alfvén resonances using signal and image processing techniques. *Ann.Geophys*, 32, pp 951-958

Submitted, Accepted and to Appear 2015 (at March 2015)

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

Whaler, K., and **C. Beggan**, 2015. Derivation and use of core surface flows for forecasting secular variation, *Journal of Geophysical Researc*h

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

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Other Publications

1 Open BGS Report: “2013 Annual Review”, BGS CR/14/16.

25 Commissioned Customer Reports (UK survey & OS; oil industry services)

96 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’

Geomagnetism Geohazard Briefing note http://www.bgs.ac.uk/downloads/start.cfm?id=2893

Contributions to BGS’s ‘GeoBlogy’ site:

*‘Something’s happening to Magnetic North in Great Britain’, by Susan Macmillan: http://britgeopeople.blogspot.co.uk/2014/01/somethings-happening-to-magnetic-north.html

* “The geomagnetic storm that wasn’t....” by Gemma Kelly: http://britgeopeople.blogspot.co.uk/2014/01/the-geomagnetic-storm-that-wasnt-by-dr.html

* Aurora Borealis goes (Geo) Social... by Emma Bee http://britgeopeople.blogspot.co.uk/2014/10/aurora-borealis-goes-geo-social-by-emma.html

The Geomagnetism team taking part in meetings, events and presentations at the 11th European Space Weather Week in Belgium

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Conference Presentations, Posters and Related Activities

RAS Specialist Discussion Meeting: ‘Geomagnetic field dynamics and structure on timescales from minutes to decades’, London, UK, January

3 posters

The STFC supported ‘SEREN’ Workshop on Geomagnetically Induced Currents, Edinburgh, UK, March

4 Presentations (Thomson, Beggan, Kelly, Clarke)

RAS Specialist Discussion Meeting: ‘UK-SEDI: The frontiers of deep Earth research’, London, UK, March

1 poster

EGU, Vienna, Austria, April

2 Presentations (Beggan, Ridley)

1 Poster

Hot Spring MIST, Bath, UK, April

3 posters

Geomagnetism Advisory Group annual meeting, Edinburgh, May

6 presentations (Macmillan & Billingham, Dawson, Kelly, Swan, Ridley, Thomson)

Swarm CAL/VAL workshop & ESA Swarm Science meeting, Copenhagen, Denmark, June

2 presentations (Macmillan, Ridley)

4 posters

IAGA Observatories Workshop, Hyderabad, India, October

2 talks (Swan, Thomson)

2 posters

The Geological Society of America meeting, Vancouver, Canada, October

1 presentation (Bee)

1 poster

ISCWSA (SPE wellbore positioning) meeting, Amsterdam, The Netherlands, October

1 presentation (Macmillan & Billingham)

European Space Weather Week 11, Liege, Belgium, November

1 presentation (Clarke)

5 posters

Presentation of ‘Live Forecast’ & Attendance at various ‘splinter meetings’

4th Swarm Data Quality Workshop, Potsdam, December

1 presentation (Thomson)

AGU, San Francisco, USA, December

3 posters

Geomagnetism Team seminars, Edinburgh

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

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Some Other Notable Outputs

Outreach Events Linked with the Observatories

In conjunction with the Met Office, BGS Geomagnetism Team participated in the Dumfries & Galloway Day of the Region 2014 and the opening of the Eskdalemuir Community Hub by providing guided tours of Eskdalemuir Observatory.

Several other observatory tours at Eskdalemuir & Hartland were also given to members of the public, such as those for the University of Edinburgh Innovative Learning week.

A one day seminar on global geomagnetic modelling was held at Hartland Observatory for staff from the UK Hydrographic Office.

The UK observatories were also used as resources in collaborative art & science projects with students from University of the Arts London and the Royal College of Art.

Edinburgh University Undergraduate Lecture Series (September 2013 – April 2014)

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

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

3rd year Geophysics course on Geophysical Techniques for Terrestrial Environmental Applications by Ciaran Beggan and Victoria Ridley (10 lectures, 3 labs, fieldwork)

Public Lectures, Presentations and Demonstrations

BGS Edinburgh Open Day (Geomagnetism Team), the 'Bang Goes the Borders' public science event (Kelly and Ridley), 'Science Uncovered' event at the Natural History Museum, London, Physics 'Lab in a Lorry' (Billingham: http://www.labinalorry.org.uk/)

Gemma Kelly gave a talk at the Earth System science spring school in Lancaster in April about geomagnetism and Space weather ,

Ciaran Beggan gave a talk titled "Solar storms and the Earth's magnetic field" on10 Sep 2014 to Falkirk Astronomical Association

Ted Harris participated at British Science Week & Rockwatch Family Fun Day at Keyworth

Work Experience Placements

Over the course of the year Ted Harris organised and coordinated 21 School Work Experience Placements within BGS Edinburgh. Students came from schools in Scotland, England and as far as Paris each spending a week in Murchison House

Geomagnetic Disturbance Alerts

7 Geomagnetic Disturbance Alerts emailed to over 3000 subscribers. 50% growth in subscriber numbers.

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World Model & Reference Field

World Geomagnetic Model 2015 produced & distributed to User Group

Collaborator on the 12th Generation of the International Geomagnetic Reference Field

Press & Media

Mentions in the press (quoting from our aurora alerts or twitter forecasts) during space weather events in January, February, December

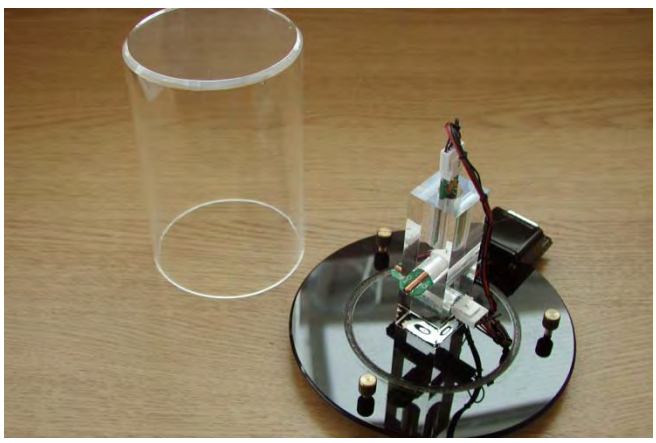
Space Weather YouTube video https://youtu.be/Go4x6QWLdRw

Beggan, C. and Shanahan, T., Planet Earth Online podcast “Unravelling the intricacies of Earth's magnetic field”, http://planetearth.nerc.ac.uk/multimedia/audio/warm.mp3, 7 January 2014

BGS School Magnetometer

Raspberry Pi Magnetometer: STFC Public Engagement Grant awarded to produce 10 three-component magnetometers for schools

Sarah Reay’s YouTube presentation “Space Weather”



Prototype 3-Component Fluxgate sensor for the School Magnetometer

Geomagnetism on Social Media

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Selected Glossary, Acronyms and Links

AGU	*American Geophysical Union (www.agu.org)*
Aurora Watch	*Aurora alert service run by Lancaster University (http://aurorawatch.lancs.ac.uk/)*
BGGM	*BGS Global Geomagnetic Model (www.geomag.bgs.ac.uk/bggm.html)*
BGS	*British Geological Survey (www.bgs.ac.uk/)*
Cabinet Office	*(www.cabinetoffice.gov.uk/)*
CHAMP	*German magnetic survey satellite (www-app2.gfz-potsdam.de/pb1/op/champ/)*
Cluster	***Multi-satellite ESA mission studying the solar wind (http://sci.esa.int/cluster/)***
CME	*Coronal mass ejection*
EGU	*European Geophysical Union. (www.egu.eu/)*
EHO	*The Earth Hazards and Observatories science theme of BGS (www.bgs.ac.uk/about/organisation.html?Accordion2=2#eho)*
EM	*Electromagnetic*
ESA	*European Space Agency (www.esa.int/esaCP/index.html)*
ESWW	*European Space Weather Week. (sidc.oma.be/esww6/)*
EURISGIC	*European Risk from Geomagnetically Induced Currents (www.eurisgic.eu/)*
EXCON	*Executive council of INTERMAGNET*
EVS	*Extreme value statistics*
GIC	*Geomagnetically Induced Currents (a natural hazard to power systems).*
GNSS	***Global navigation satellite system***
IAGA	*International Association of Geomagnetism and Aeronomy (www.iugg.org/IAGA/iaga_pages/index.html)*
IAR	*Ionospheric Alfven resonance*
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. (http://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/)*

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ISCWSA	*Industry Steering Committee on Wellbore Survey Accuracy. (iscwsa.org/)*
ISGI	*International Service for Geomagnetic Indices (www.icsu-fags.org/ps06isgi.htm)*
IT	*Information technology*
IUGG	*International Union of Geodesy and Geophysics (www.iugg.org)*
MAGIC	***"M**onitoring and **A**nalysis of **GIC**". A service for the National Grid.*
MagNetE	*European magnetic repeat station network (http://www.gfz-potsdam.de/en/section/earths-magnetic-field/infrastructure/magnete/).*
Met Office	*UK meteorological office. (www.metoffice.gov.uk/)*
MIST	*Magnetosphere, Ionosphere, Solar-Terrestrial (Physics). (www.mist.ac.uk/)*
MOSWOC	*Met Office Space Weather Operations Centre*
MWD	*Measurement While Drilling – a technique used in the oil and gas industry.*
NAM	*National Astronomy Meeting (www.ras.org.uk/)*
NERC	*Natural Environment Research Council (www.nerc.ac.uk/)*
NOAA/NGDC	*National Oceanic and Atmospheric Administration/National Geophysical Data Center (www.ngdc.noaa.gov/).*
OPSCOM	*Operations committee of INTERMAGNET*
Ørsted/Oersted	*Danish magnetic survey satellite. (web.dmi.dk/projects/oersted/)*
OS	*Ordnance Survey. (www.ordnancesurvey.co.uk/oswebsite/)*
QD/QDD	*Quasi-definitive (magnetic observatory) data*
QNX	*UNIX-like real-time operating system*
Raspberry Pi	***Small, low-cost computer (https://www.raspberrypi.org/)***
RIN	*Royal Institute of Navigation. (www.rin.org.uk/)*
RAS	*Royal Astronomical Society. (www.ras.org.uk/)*
SCARF	*Swarm Satellite Constellation Applications and Research Facility*
SEREN	*STFC funded series of workshops on themes within UK space weather science.*
SPE	*Society of Petroleum Engineers (www.spe.org/spe-app/spe/index.jsp)*
SRS	*Spectral resonance structure*
SSA	***Space Situational Awareness***
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/)*
USGS	*United States Geological Survey (www.usgs.gov/)*
WDC	World Data Centre, part of the World Data System (www.wdc.geomag.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 (Austria) (http://www.zamg.ac.at/cms/de/aktuell)*

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Cover: Sable Island Observatory, Nova Scotia, Canada.
Foreground is the Proton Magnetometer in its housing, the Variometer Hut is on the extreme left.
Photo: Chris Turbitt