



British
Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

Geomagnetism *Review* *2012*



Geomagnetism

Review 2012

Alan W P Thomson (editor)

awpt@bgs.ac.uk

Contributors:

Orsi Baillie, Ciarán Beggan, Ellen Clarke, Ewan Dawson, Simon Flower, Brian Hamilton, Ted Harris, Gemma Kelly, Susan Macmillan, Sarah Reay, Tom Shanahan, Alan Thomson, Christopher Turbitt

The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office.
Ordnance Survey licence number 100017897/2012

Key words

Geomagnetism.

Front cover

A snapshot of the electric field strength across the UK during the geomagnetic storm of 17 March 2013.

Bibliographical reference

THOMSON, A.W.P. ET AL 2013.
Geomagnetism Review 2012.
*British Geological Survey
Open Report OR/13/030*

44pp.

© NERC 2013

Edinburgh British Geological Survey 2013

Contents

Contents	1
Introduction	2
Technical, Observatory and Field Operations	8
UK and Overseas Observatories	8
Geoelectric Field Monitoring	10
High Frequency Magnetometers	12
The BGS contribution to INTERMAGNET	14
Science	18
Magnetic Field Reversals	18
A global analysis of observatory data for an archaeological geophysics meeting	20
The ESA Swarm Level 2 Processing Facility – Operational Phase	22
Student and Research Associate Activities	24
Applications	26
Directional Drilling.....	26
Space Weather Applications and Services	28
Outreach and Knowledge Exchange	30
Other Publications	32
Geomagnetism at the British Science Festival 2012	34
Acknowledgements	36
Selected Glossary, Acronyms and Links	37
The Geomagnetism Team in 2012	40

Introduction



*Visualisation of the Earth's magnetosphere.
Image courtesy of the NASA Goddard Space Flight Center*

The Geomagnetism Team

The Geomagnetism team measures, records, models and interprets variations across the world in the Earth's natural magnetic field and how these variations change in time. Our data and expertise help to develop scientific understanding of the evolution of the solid Earth and its atmospheric, ocean and space environments. We also provide geomagnetic products and services to industry and academics and we use our knowledge to inform and educate 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 is represented in BGS as a science team within the Earth Hazards and Systems (EHS) theme, alongside Earthquake Seismology and Volcanology. EHS is, in turn, part of the Geoscience Survey and Monitoring Directorate. (Note that a reorganisation of BGS is planned for 2013).

EHS is one of twelve BGS science themes that deliver the BGS science strategy. Science strategy in BGS is supported by the Geoscience Information and Knowledge Exchange and Resources and Operations programmes. We also receive additional support locally from BGS Edinburgh Business Support and Business Administration and, on IT, from System and Network Services.

The Geomagnetism team is primarily based in Edinburgh. In 2012 the team numbered twenty-six staff either fully or partly engaged in Geomagnetism work. In addition in 2012 we had one external PhD student, co-supervised with the University of Edinburgh, and one external post-doctoral research assistant, at the University of Liverpool, as well as one visiting scientist at our Edinburgh office.

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).

We also operate magnetic observatories overseas on Ascension Island, at Port Stanley (Falkland Islands), King Edward Point (South Georgia) and on Sable Island (Canada). We oversee and maintain magnetic observatory operations at Prudhoe Bay, Alaska (USA).

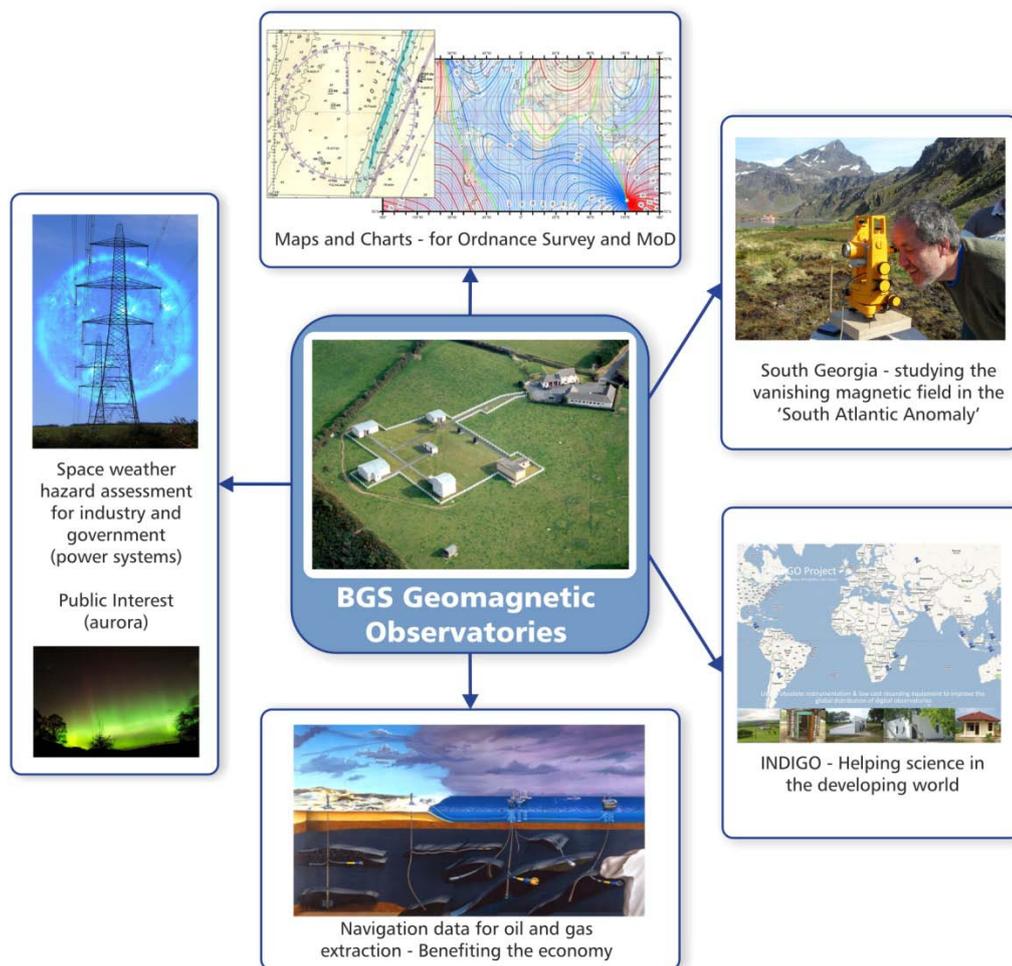
Our observatory work and the data we collect is one part of our core function:

Long-term geomagnetic monitoring and allied research to improve our understanding of the Earth and its natural environment.

Other 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 three primary aims.

We aim to be a world leader in

- Measuring, recording, modelling and interpreting the Earth's natural magnetic field and its sources.
- 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.



Introduction:

The Year in Perspective



Absolute observations being taken on Ascension Island during an annual service visit.

Looking Ahead to 2013

The Geomagnetism team's activities in 2013 will centre on scientific opportunities arising from the ESA Swarm magnetic survey mission and the current high profile of the space weather hazard to technology. Continuing activities will include operating the BGS magnetic observatories and the UK magnetic survey to international standards. We will also continue to produce industry standard and academic geomagnetic models and publish new scientific research in Geomagnetism

Key Objectives

The Geomagnetism team will operate and maintain magnetic observatories and the UK magnetic survey to internationally recognised standards.



We will put in place measures to ensure continuous high-quality data delivery from Lerwick Observatory during major building works.

We will also produce mathematical models of the Earth's magnetic fields and publish results where appropriate.

The team will undertake new scientific research to improve understanding of magnetic processes and hazards from the Earth's core out to space; research that will underpin a range of applied science activities.

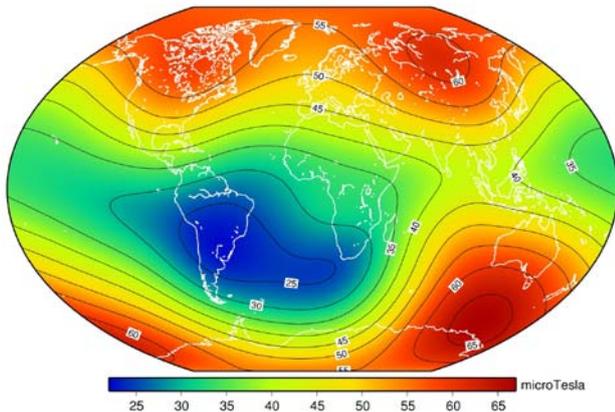
We will develop the Edinburgh World Data Centre for Geomagnetism and develop novel Information and Knowledge Exchange solutions for the delivery of data and products to academic and business customers.

We will represent BGS externally, including on scientific bodies such as INTERMAGNET and IAGA, and exert influence through leadership roles in UK and international scientific projects and professional bodies.

We will contribute to BGS and NERC goals, e.g. on geo-science knowledge, resources,

whole-Earth processes, and Earth hazards and provide National Capability in environmental geomagnetic monitoring.

Team outputs, including global and national geomagnetic field models and space weather hazard products, will be supported by Government and the private sector (e.g. MOD, NATO, the hydrocarbons sector, National Grid, Met Office, ESA and EU).



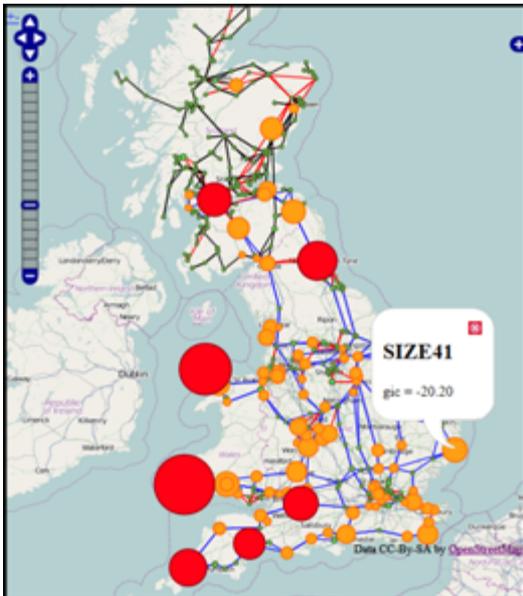
Total magnetic strength (in μT) in 2012, highlighting the weakening field over the South Atlantic.

Main Deliverables

Our specific deliverables for 2013 will be

- Operation of an INTERMAGNET-standard UK and overseas observatory network
- Provision of real-time and other observatory data products through the BGS Geomagnetism website
- Supply of observatory data to INTERMAGNET, according to the timetables set for each data type
- Production of the series of Monthly Bulletins and Observatory Yearbooks and publication on-line
- Magnetic index products supplied to the International Service for Geomagnetic Indices (ISGI), according to the timetable set
- Production of the 2013 BGGM
- Geomagnetic observatory data products to support MWD directional drilling operations, as part of IFR and IIFR services, and other geophysical survey companies
- Operation of the World Data Centre for Geomagnetism (Edinburgh)
- Re-survey of 8 sites in the UK magnetic repeat station network
- Production of the 2013 UK national magnetic model and delivery of customer report to Ordnance Survey
- Pursuing new scientific collaborations that address BGS challenges and NERC themes, particularly through any NERC 2013 theme action plan on space weather, or through the UK Space Agency involvement in the ESA 'space situational awareness' program
- Collaboration on existing international geomagnetic observatory (INDIGO) and survey programmes (MagNetE)
- Participation (through presentations and organisation of sessions) in at least one major international scientific conference, e.g. the 2013 IAGA congress
- Publication of two or more first-author papers in scientific and professional journals, and the writing of articles
- Provision of geomagnetic information and space weather forecasts including: solar and geomagnetic activity index forecasts and nowcasts to the European Space Agency (ESA) for the Space Weather Network (SWENET); real-time one-minute data from Hartland to NOAA Space Weather Prediction Centre (SWPC); daily one-second data to SAMNET; and real-time magnetograms, local and planetary magnetic indices and daily geomagnetic forecasts to UK Met Office as part of the Natural Hazards Partnership project

- Publication of a Geomagnetism team annual report
- Monitoring and analysis of the geo-electric (telluric) measurements now made at the UK magnetic observatories (in association with the EURISGIC FP7 project)
- Upgrading of models of the UK power grid and electrical conductivity (in association with the EURISGIC FP7 project and National Grid)
- Upgrading the Monitoring and Analysis of GIC (MAGIC) web tool, as per future agreements with National Grid



An example of the current 'MAGIC' web tool used by National Grid for analysis of GIC

- Collection and processing of geomagnetic data ahead of World Magnetic Model revision in 2014-2015
- Provision of observatory facilities for calibration and testing of instruments
- Hartland observatory one-minute mean data supply to USGS, as per agreed schedule
- Provision of lectures and tutorials to 4th year undergraduates at Edinburgh University on 'Geomagnetism'; set and mark exam questions; set and supervise student projects
- Provision of lectures and tutorials to 3rd year undergraduates at Edinburgh University on 'Planetary Geophysics'; set and mark exam questions; set and supervise student projects
- Extraction of digital data from 15 of the most extreme historical geomagnetic storms from the images of analogue magnetograms
- Continuation of the programme to digitise UK observatory magnetograms and yearbooks, overseas yearbooks and other BGS and WDC analogue holdings

- Participating in UK space weather workshops, under the STFC 'SEREN' project, to develop research partnerships, particularly on space weather impacts on ground based technologies
- Operation and maintenance of the BGS Swarm satellite 'Level 2' models and data processing system for ESA, to support the Swarm mission

Some Notable Results from 2012

Elsewhere in this report we provide further detail on some of our major outputs and activities in 2012.

Here though are some key numbers, which help to put in perspective the team's outputs as a whole for 2012.

>300,000 analogue magnetograms available on-line as digital images

100% (>99%) UK (overseas) observatory data coverage

96 magnetic bulletins published

65 Ordnance Survey Explorer map compass references

40 Ordnance Survey Landranger map compass references

30 field set-ups for IIFR/IFR services and 28 customer reports

3 journal papers, 14 scientific meetings, 20 presentations/posters

6 articles on space weather for RIN 'Navigation News'

6 positions on scientific and technical geomagnetism bodies

4 post-doctorate research assistants (one with University of Liverpool)

3 observatory tours

2 undergraduate courses taught

2 geomagnetic models (UK reference model and BGGM)

2 undergraduate students

1 television and 1 radio interview and >13 newspaper and web articles

1 accepted regular membership of the ISCU World Data System

1 YouTube video, 1 podcast

1 PhD student

1 overseas visitor

1 event at the British Science Festival



The extraction of digital data from the scanned historical magnetograms will begin in 2013

Technical, Observatory and Field Operations

UK and Overseas Observatories



*Air approach to Sable Island Observatory,
Sable Island, Nova Scotia*

BGS operates three absolute magnetic observatories in the UK and five 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 2012.

Technical Developments

Through a consultation exercise with the scientific data user community and instrument manufacturers, a BGS-chaired discussion for INTERMAGNET published a standards document for one-second definitive observatory data. This will provide a framework for manufacturers and observatory operators (including BGS) to prepare for the production, dissemination and publication of one-second data.

BGS is now working towards achieving these broadband, low-noise data quality standards. Although broadband instruments are not expected to be installed at the BGS observatories until 2013, initial long-term stability tests on seismic digitisers have been carried out at Eskdalemuir Observatory in preparation. In addition, installation of a mu-metal shield at Eskdalemuir will allow new instrument noise characteristics to be directly evaluated.

UK Magnetic Observatories

Further effort has been made at Eskdalemuir to decrease the likelihood of data loss from man-made noise by improving the instrument distribution around the site with the commissioning of a third, temperature-

controlled variometer site. In addition, a low-gain magnetometer (which reduces the risk of saturation during a large magnetic storm) has been set-up at the observatory to capture any extreme geomagnetic activity during the peak in solar activity.

Although the induction coils at Eskdalemuir have been installed for a number of years, these instruments (which operate in a higher frequency band than conventional observatory magnetometers) have been renovated to reduce noise.

Initial tests and the first deployment of a long-term geo-electric field monitoring system have also been completed at Eskdalemuir. This will provide real measurements for verification and development of GIC models in the National Grid.

The Met Office project to replace the office building at Lerwick Observatory (which houses BGS communications infrastructure and recorders) is now not likely to begin until early 2013. However, BGS have worked extensively with Met Office to ensure that the magnetic recordings at Lerwick will neither be delayed nor disturbed during the construction works. This has also provided an opportunity for dialogue on more general agreements on operations at Lerwick and Eskdalemuir.

Due to its location in the south of the UK, Hartland Observatory continues to be used as a calibration facility for magnetometer manufacturers and as a training facility for Royal Navy personnel embarking on surveying deployments in the South Atlantic.

Overseas Magnetic Observatories

Work was completed on the BGS observatory on South Georgia with a site visit to King Edward Point in November 2012. This brief visit provided time to verify instrument calibrations, to check the integrity of the instrument enclosures and to provide observation training for newly arrived British Antarctic Survey staff.

Because of the high dependency on real time IIFR data from Jim Carrigan Observatory, Alaska, a second data recording system was installed to increase the redundancy in equipment and increase the reliability of the station. This visit also provided an opportunity to train new local observers and to discuss BGS IIFR services with local operators. We also presented a preliminary study into the relationship between external field uncertainties and distance between monitoring and drilling sites.

Radio interference from high power transmitters is an increasing problem at Port Stanley Observatory, Falkland Islands. A decision was made to move the absolute measurement location and during this year's visit a new site was identified and surveyed. A new hut will be erected here in early 2013.

After a period of funding uncertainty, the first visit to Sable Island Observatory for three years was completed in April 2012. With BGS now operating the contract with Environment Canada, more frequent absolute observations are being made and yearly service and calibration will be resumed. During the 2012 visit an improved temperature controller was installed. Temperature control has also been added to the Ascension Island Observatory fluxgate magnetometer to improve data quality.

UK Repeat Station Network

The 2012 magnetic repeat station programme covered 11 UK measurement locations in the North of Scotland; Isle of Man; Lake District & North of England; and the South-East of England. 2012 was the second year when a differential GPS system was used in preference to a north-seeking gyroscope to determine the azimuth of true north whilst making declination (compass variation) measurements.

Global Network

BGS continues to support the INDIGO Project, which aims to increase the global distribution of digital magnetic observatories. Developments in the BGS data handling package have simplified the process of publishing final, definitive data from raw instrument data. This year saw the successful application of Pilar Observatory, Argentina to INTERMAGNET, data publication being a pre-requisite of membership.

Technical, Observatory and Field Operations

Geoelectric Field Monitoring



Installation of the measurement electrodes at Lerwick observatory in the Shetland Islands.

BGS is currently installing surface electric field monitoring systems at the UK observatories (Eskdalemuir, Lerwick & Hartland) to measure the changing electric field generated near the Earth's surface. Monitoring the electric field will allow validation of models derived by the team and help improve predictions of potentially damaging geomagnetically induced currents in the power grid. Data are recorded at 1 Hz along East-West and North-South electrode lines and automatically transmitted back to Edinburgh for analysis and near real-time display.

Background

To understand how space weather impacts the grid, BGS has a model of the surface electric field, induced by rapid geomagnetic variations, coupled to a DC model of the UK's power transmission system. The electric field is the source of electrical currents flowing in the Earth's crust (Telluric currents) and these can damage transformers in the power grid.

However, the electric field is not routinely measured anywhere in the UK. BGS is now installing electric field monitoring equipment for long-term measurements at the three UK observatories. These data will be used to help constrain electric field models and, as a result, improve the prediction of induced currents in the UK power system.

Measurements of the electric field are made by recording the voltage difference between two points in the ground, separated by a known distance in a given orientation.

Hardware

Two electrode pairs are used in a North-South and East-West configuration to capture the strength and direction of the surface electric field vector. The electrodes are spaced approximately 100m apart and are located as far as possible from sources of cultural noise and non-natural conductive structures (e.g. buried pipes and cables).

Non-polarising electrodes (LEMI-701, CuSO₄ Chemistry) are used to make the voltage measurement as they prevent any self-potential effects caused by the interaction of the electrode conductor with the surrounding soil and offer very good stability for long term measurements. They are buried at a depth of at least 70 cm to reduce temperature fluctuations and transient soil-conductivity changes due to heavy rainfall.

Voltage measurements are made via a 24-bit analog to digital convertor (Earthdata, PS-2400) that has an output rate of 50 Hz and data resolution of 1 μ V. These data are

then digitally filtered (using a Windowed-Sinc kernel) to produce 1 Hz samples that are collated in hourly files and automatically transmitted, every 10 minutes, back to a BGS data server in Edinburgh.



Signal termination and digitiser enclosure
(Lerwick observatory)

Plots of the electric field data are generated alongside magnetic data from the UK observatories for comparison and analysis.

These data can be viewed via the BGS Geomagnetism website:
www.geomag.bgs.ac.uk/data_service/space_weather/geoelectric.html

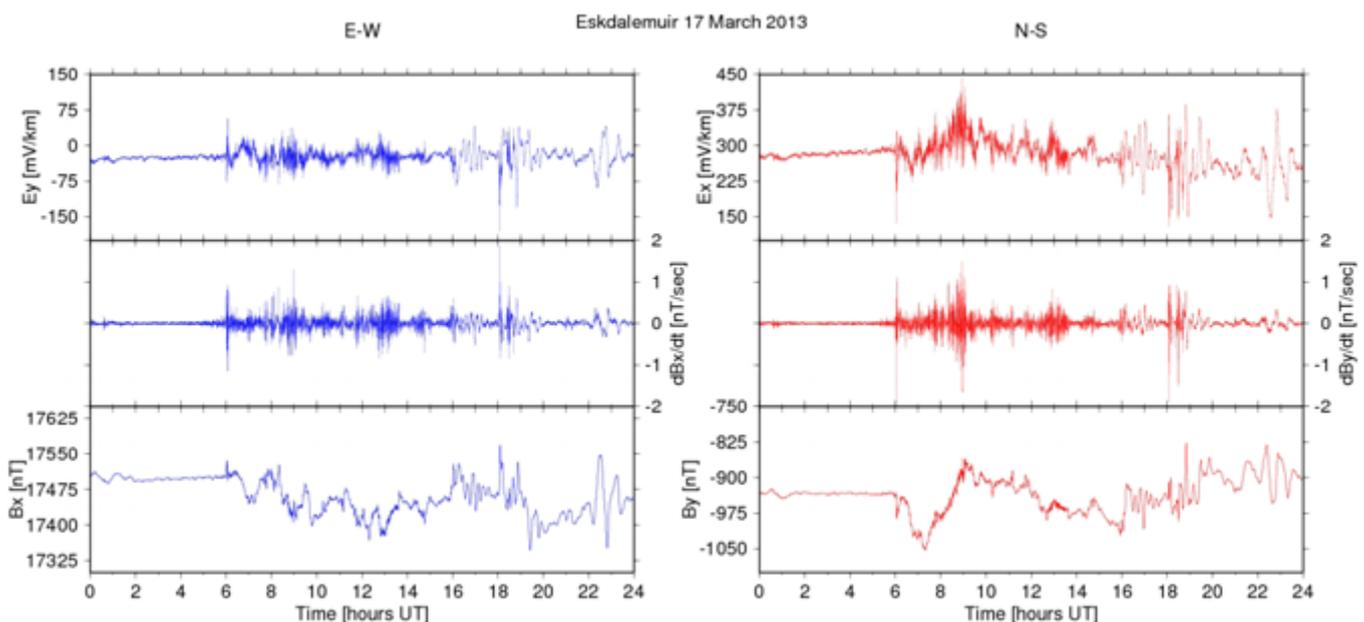
Deployment Status

Installation at Eskdalemuir observatory was completed in November 2012 and Lerwick observatory in March 2013. Deployment at the Hartland site is planned for late April 2013.

The two completed systems have run reliably since installation with 100% data availability. The signal to noise ratio at Eskdalemuir is not as good as the Lerwick site, likely due to nearby equipment producing contaminating currents in the measurement system and a naturally weaker signal due to the lower latitude of the site. A new location for the electrodes, further away from existing equipment has been identified to reduce this.

The Eskdalemuir system has only been recording data for a short amount of time, but indications are that the data are of sufficient quality to reliably capture the predicted changes in the electric field during periods of increased magnetic activity.

Figure 1 shows a comparison of the electric and magnetic field components as measured at Eskdalemuir observatory on 17th March 2013 during magnetic storm conditions.



Comparison of orthogonal magnetic (B) and electric (E) field components at Eskdalemuir observatory. The E-W direction is denoted 'y' and the N-S direction 'x'. dB/dt is the time rate of change of the magnetic field.

Technical, Observatory and Field Operations



Installation of the North induction coil (white tube, foreground) at Eskdalemuir in the Scottish Borders. The induction coils are protected from wind, rain and snow under a non-magnetic wooden cover (standing upright, background, prior to installation).

High Frequency Magnetometers

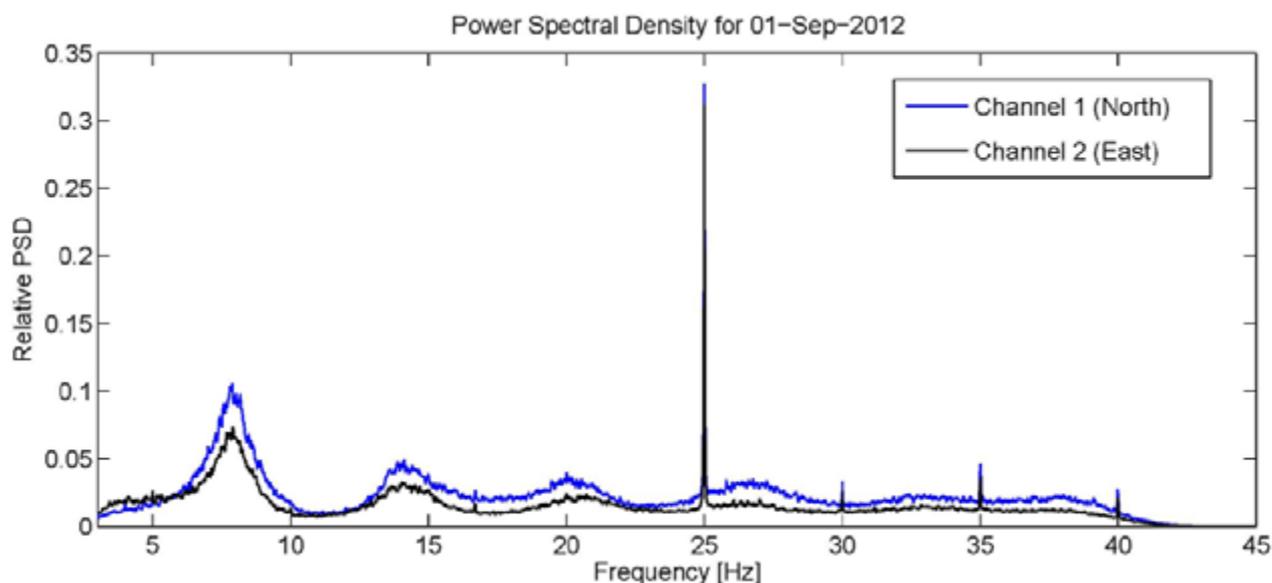
In June 2012, BGS installed two high frequency (100 Hz) induction coil magnetometers at the Eskdalemuir Observatory, in the Scottish Borders of the United Kingdom, a rural valley with a quiet magnetic environment. These induction coils permit us to measure very rapid changes of the magnetic field in the Extremely Low Frequency (ELF) range, in a pass-band from around 0.1 Hz to 100 Hz. We intend the coils to become part of our long term scientific monitoring of the magnetic field, in this case for ionospheric and magnetospheric research.

The instrumentation consists of two induction coil magnetometers manufactured in France by Elan around 1990. The coils were previously part of the Natural Environment Research Council's (NERC) national geophysical equipment pool and were available for loan to UK universities and research institutes for magnetotelluric induction studies. In 2008, they were decommissioned by NERC and passed to BGS. The instruments were refurbished by the Geomagnetism engineering team, fitted with new connectors, tested and installed at the Eskdalemuir observatory.

The current system consists of two coils (oriented North-South and East-West) connected to a signal digitiser located a

few meters away from each coil. The digitiser is linked to a 'breakout box', which provides power and converts the output signal from the digitiser for wired transmission to a computer logger located in a vault approximately 150m away. The data from the induction coils are recorded at 100Hz by the onsite computer where it is collated into hourly files. The data is automatically collected once per hour by the main Edinburgh office.

The induction coil data are processed once per day for quick look purposes and the spectrogram images are uploaded to the BGS Geomagnetism public website at: www.geomag.bgs.ac.uk/research/inductioncoils.html



Power Spectral Density plot for two hours of data (00-02 UT 01-Sep-2012) recorded for the North and East channels. The signal has been pass-band filtered between 3-40 Hz. Six Schumann resonances can be detected as well as cultural noise from the UK electrical system at 25 Hz. The smaller sharp 16.66, 30, 35 and 40 Hz peaks are also harmonics induced by the UK electrical system.

The system has been in full-time operation in a commissioning phase since July 2012 and has achieved about 90% data availability. Further hardware improvements are planned to ensure near full-time data recording.

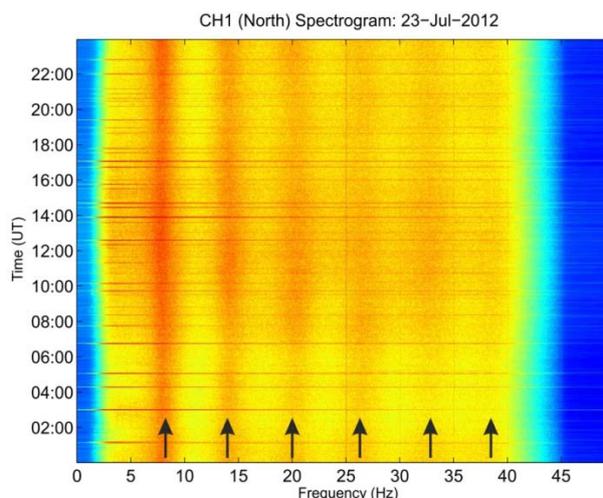
There are currently two main science objectives for the coils: 1) monitoring of the ionosphere and related phenomena via Schumann resonances; and 2) monitoring of the magnetosphere via low frequency pulsations.

In the Figure above - a power spectral density plot containing two hours of data - Schumann resonances are seen as a set of spectral peaks in the ELF portion of the Earth's electromagnetic field spectrum. These are caused by lightning discharges from within the cavity formed by the Earth's surface and the ionosphere. The resonances should appear as distinct peaks around 7.86 Hz, 14.3 Hz, 20.8 Hz, 27 Hz, 34 Hz and 39 Hz. However, in reality the peaks tend to be diffuse due to the cavity being 'leaky', as well as being due to ground roughness and absorption.

The Figure to the right shows a spectrogram (power at each frequency versus time) for one

whole day, illustrating the diffuse nature of the resonances and local lightning effects (mid-late afternoon). We also detect a strong narrow peak at 25 Hz, which is a harmonic of the UK electrical power system.

This is intended to be a long-term monitoring project. There are a number of features in the data that BGS wish to investigate, including the diurnal and seasonal variation of the Schumann resonances. We will also look for solar cycle and climate variations in both the ionospheric and magnetospheric signals.



Spectrogram of 100Hz data from Channel 1. Arrows indicate the locations of the diffuse Schumann resonances. Local lightning storms are evident throughout the day, as broadband (horizontal) lines.

Technical, Observatory and Field Operations



The BGS contribution to INTERMAGNET

BGS makes a significant contribution to the INTERMAGNET programme (www.intermagnet.org), a consortium of institutes and observatories around the world who make measurements of the Earth's magnetic field and meet agreed quality standards. In addition to operating a Geomagnetic Information Node (GIN), three BGS staff are currently members of INTERMAGNET committees and BGS leads the work on development of and compliance with INTERMAGNET standards and INTERMAGNET's IT/IS infrastructure. Data are provided from five BGS observatories.

Quasi –Definitive Data

Geomagnetic observatories have typically created their definitive data sets annually. The process of finalising data from an observatory can involve a lot of labour intensive work and this, together with a lack of pressure on observatories to complete this work to any set timescale, has resulted in considerable delay in publication of definitive observatory data across the observing community. In comparison, geomagnetic satellite measurements are made available more rapidly, partly because of differences in the processing methods needed for satellite as opposed to ground-based data.

Definitive data from observatories is important in the production of models of the magnetic field. These models are becoming increasingly accurate and since they are modelling a phenomenon that is changing with time, their accuracy is to some extent dependent on the age of the data on which they are based. These models of the Earth's magnetic field can be used to verify the accuracy of data from satellites, but such

comparisons are only useful if they are made shortly after measurement.

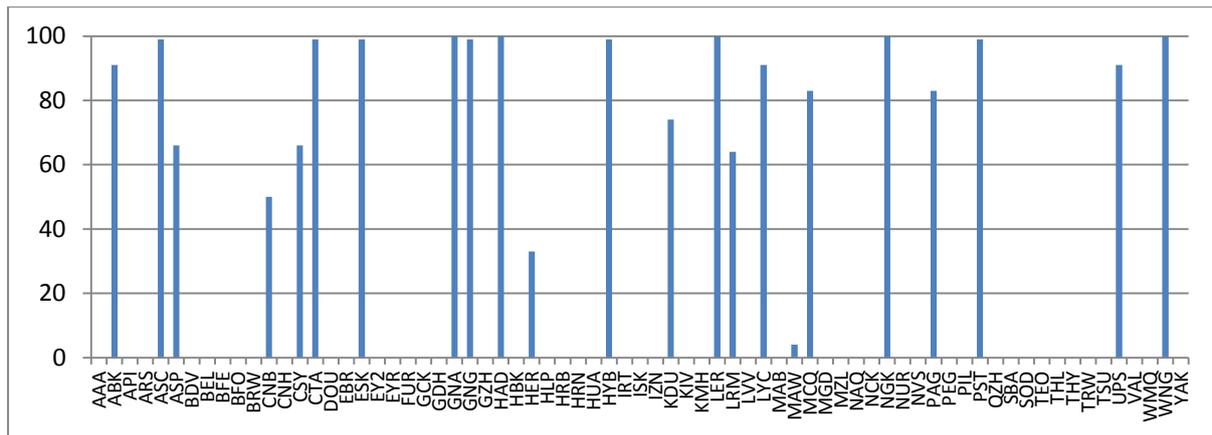
To address the need to produce usable data for models and comparisons with satellite measurements, INTERMAGNET has defined a standard for quasi-definitive (QD) data from observatories and is encouraging observatories to produce QD data within three months of measurement. The definition used by INTERMAGNET is

“Quasi-definitive data are (H, D, Z) or (X, Y, Z) 1-minute data:

- Corrected using temporary baselines*
- Made available less than 3 months after their acquisition*
- Such that the difference between the quasi-definitive and definitive (X, Y, Z) monthly means is less than 5 nT for every month of the year*

Point c is checked a posteriori by comparing quasi-definitive and definitive data from the previous year.”

(from www.intermagnet.org/faq_e.php)



Percentages of quasi-definitive data from various observatories collected at the Edinburgh INTERMAGNET geomagnetic information node for 2012

Provision of Quasi-Definitive Data

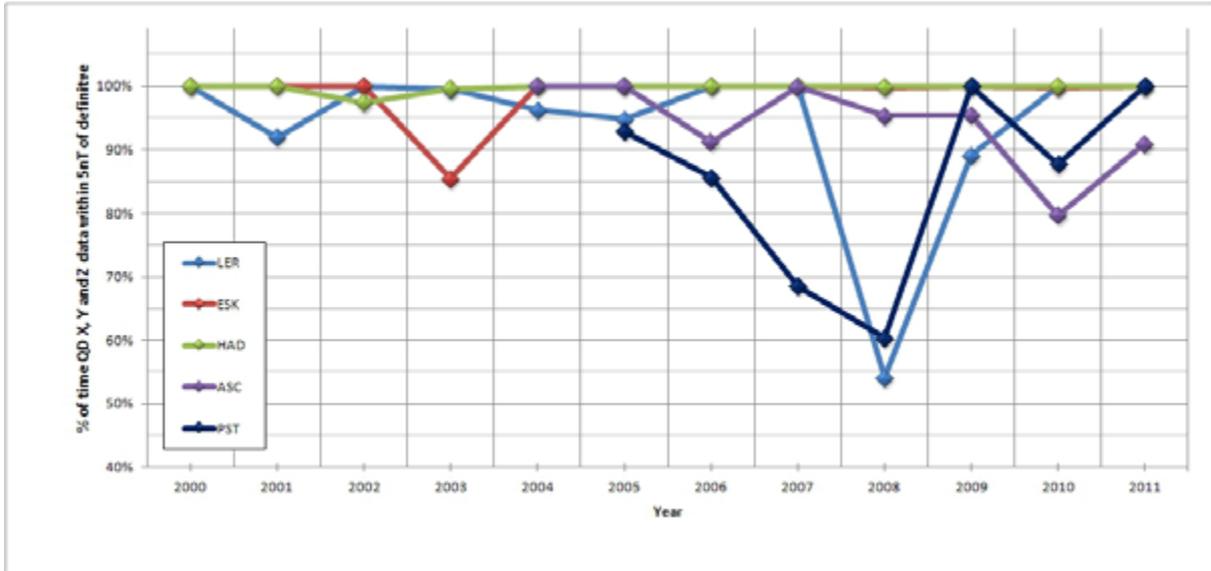
BGS has been delivering quasi-definitive one-minute data to the Edinburgh INTERMAGNET GIN on a next day basis since August 2012. The automated data processing software combines the daily extrapolated baseline values of H , D and Z , derived from baseline functions computed using absolute observations, with the corresponding variometer data. Details of how QD data are produced can be found in Thomson *et al.* (2009) and Clarke *et al.* (2013).

Before the term ‘quasi-definitive’ was adopted and before August 2012, BGS had been submitting data of this type to the Edinburgh GIN but labelled as type provisional (INTERMAGNET type “R” for “reported” or “A” for “adjusted”), which had baselines applied but not necessarily fully quality controlled. This was done on a next-day basis, shortly after UT midnight.

BGS data are now delivered on three different time scales:

1. Shortly after UT midnight by automated processing software (provisional type data)
2. Once the full quality control procedures have been completed, the QD data are prepared and also delivered by running the data processing software in manual mode, on a next (working) day basis.
3. At a later stage, when baselines are revised, QD data may be resubmitted to the GIN within the 3-month window. The time stamp of the data is indicated in the header line “Data file created on” to keep a record of when the QD data was produced.

The accuracy of the BGS’s data is assessed following the publication of definitive data for the previous year using INTERMAGNET guidelines.



Evaluation of the accuracy of BGS QD data over the past decade, showing the annual percentages of hourly-mean QD values which fall within 5 nT of the final definitive values (for five selected BGS observatories).

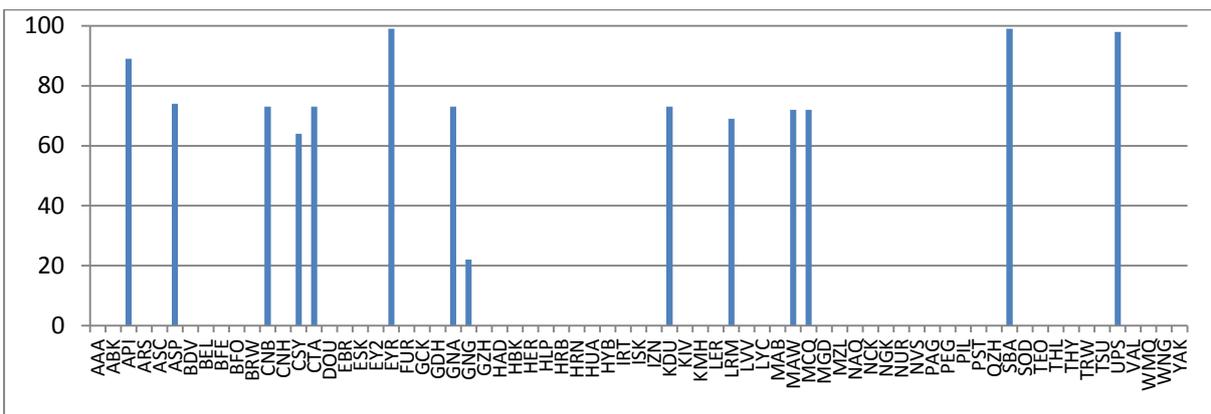
One Second Data

For many years the basic product that geomagnetic observatories have created is a minute-mean time-series recording of the Earth’s magnetic field.

In recent years advances in technology have enabled higher sampling frequencies and a number of observatories have started to record second-mean values (i.e. data are sampled at a higher frequency than 1Hz, then filtered and averaged to

produce a single mean value for each second of the day).

INTERMAGNET has now published standards that observatories must meet in order to submit one-second data. Details of this standard are available from INTERMAGNET and were presented at a recent IAGA workshop (*Turbitt et. al 2012*)



Percentages of one-second data collected for various observatories in the Edinburgh INTERMAGNET geomagnetic information node in 2012

Improving Real-Time Performance

Real-time performance suggests a minimal delay between making a measured, quality-controlled, data sample and having it available to end-users. When INTERMAGNET was created in the 1980s it was a challenging target to make data available within 72 hours. In the era of nearly universal Internet it is becoming possible to reduce this to minutes. This opens up the INTERMAGNET data sets to a new community of space weather scientists, for whom the value of data is (partly) associated with how recently it has been recorded.

The current INTERMAGNET infrastructure, which BGS staff have been at the forefront of creating, allows data to be available to users within twenty minutes of recording. To do this requires the support of staff at the institutes who run the observatories. BGS staff, through INTERMAGNET, have been encouraging observatory operators to meet these new and challenging targets.

INTERMAGNET has ambitions for even faster exchange of data. BGS staff are contributing their experience of this type of work in the commercial sector to this project.

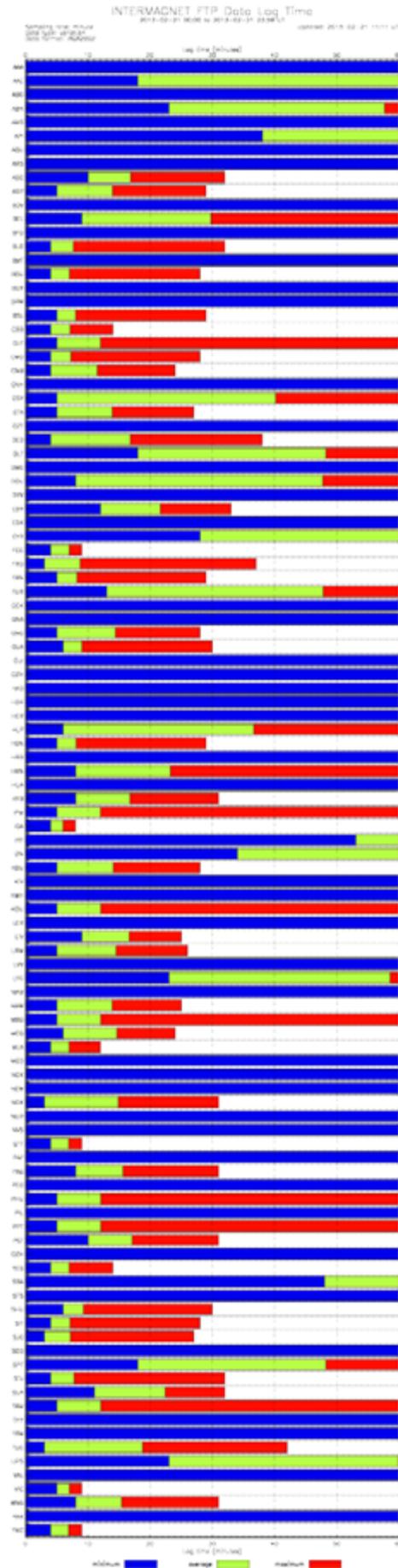
Right: Delay time between measurement and availability on the INTERMAGNET Edinburgh GIN, classified as minimum, average and maximum, for all observatories.

References:

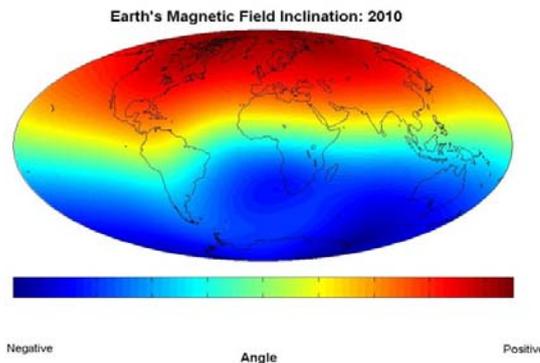
Thomson, A.W.P, Baillie, O., Beggan, C., Clarke, E., Hamilton, B., Reay, S.J., Turbitt, C.W. 2009 Geomagnetism Annual Report

Clarke, E., Baillie, O., Reay, S.J., Turbitt, C.W. 2013 A method for the real-time production of quasi-definitive magnetic observatory data.

Turbitt, C.; Matzka, J.; Rasson, J.; St-Louis, B.; Stewart, D. 2012 An instrument performance and data quality standard for INTERMAGNET one-second data exchange. In: XVth IAGA Workshop on Geomagnetic Observatory Instruments and Data Processing, Cadiz, Spain, 4-14 June 2012.



Magnetic Field Reversals



Inclination angle ($\pm 90^\circ$) of the Earth's magnetic field in 2010 based on the IGRF-11 model. The large 'kink' along the equator is due to the South Atlantic Anomaly; a region of weakening magnetic field strength.

The geomagnetic field is generated by dynamo action in the outer core. The energy comes from a number of sources, including the freezing of the inner core and the subsequent release of lighter elements. These drive fluid flow which in turn powers the geo-dynamo. The whole system is chaotic but exhibits two stable configurations, namely a strong north and south-oriented dipole field. However, the field has been weakening over the past 175 years. Thus, common questions asked by members of the public are: (a) what happens when a reversal occurs and (b) are we due a reversal soon?

It has been well established, from research over the past fifty years, that the Earth's magnetic field orientation can reverse over time [e.g. reference 1]. Maps of the magnetic field orientation on the oceanic floor reveal patterns of reversal (and in doing so provide insights into other processes such as plate tectonics). However, the magnetic field reversal rate is not constant and neither is the time interval fixed between reversals.

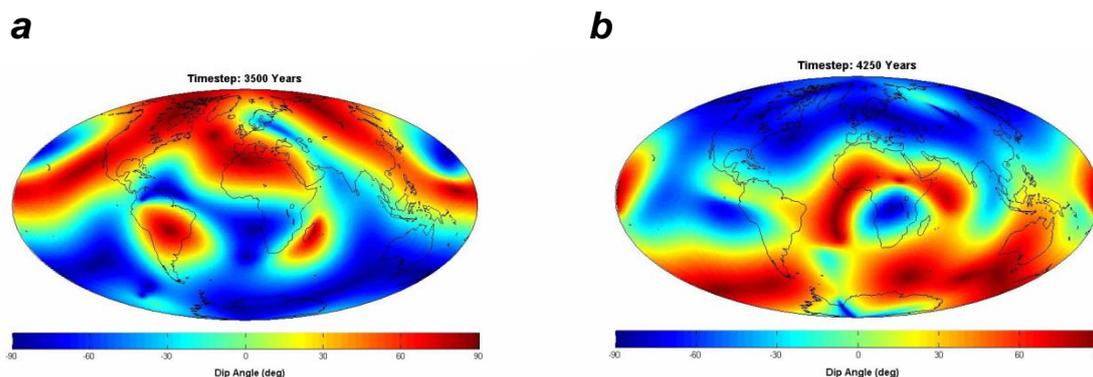
Work in 1980s [e.g. 2] showed that during a reversal the field decreases in strength, while the inclination (or dip) and declination of the field vary wildly over the course of approximately 5,000-10,000 years. It is difficult to determine an exact length of a reversal due to the limited time resolution of radiometric dating techniques. However it is clear, from where magnetic field reversals are recorded in erupted lavas, that these observations are typical of a reversal.

More recent results from computer simulations of the geo-dynamo [3] confirm the observation that the main field dipole weakens, forming multiple local magnetic poles for many hundreds of years before reforming back to a south-north or north-south configuration.

A simulation of the magnetic field at the Earth's surface during a reversal can be run using a simple reversal model. The Figure below shows two snapshots of the inclination from the middle period of a modelled reversal scenario. Note that the inclination angle is spatially extremely variable during the reversal (as is declination, which is not shown here).

In this reversal scenario there would be major consequences for the use of the magnetic field for navigation. Other possible side effects from a weaker field include the need for satellites and high flying aircraft to have additional shielding against high energy particles e.g. from the Sun. However, as reversals are slow processes we would have plenty of time to adapt our technology to the changing conditions.

Forecasting the short term change of the main magnetic field is currently an active area of research at BGS. However, in a manner similar to weather forecasting, there is a time limit beyond which it is impossible to predict how the field will change



Snapshots of the inclination angle from a 7,500 year simulation of a reversal during which the total field strength falls to 10% of current levels. Panel (a) shows the field before it is about to reverse and (b) shows the field as it has transitioned through to a reversed configuration.

Various researchers have suggested that the short term limit for detailed predicted is on the order of ten years [4], while prediction of the large scale variation is unattainable beyond a century [5], due to the chaotic nature of the field.

Much concern has been raised about the rapid decrease in the strength of the magnetic field since the 1840s (approximately 15% decrease in 175 years). Extrapolation of this trend would herald to a fall to zero in just over a millennium.

However, investigation of the strength of the magnetic field recorded archaeological artefacts (bricks, pots, fire-baked rocks) allows us to infer the global change of the field over the past 10,000 years. These archeomagnetic models [6] show that the magnetic field has been much stronger over the past two millennia, was much weaker between five and nine thousand years ago and is, in fact, merely returning to its average strength as determined over a ten thousand year period.

This does not imply that a reversal cannot occur in the near future; but it will certainly be difficult to tell if we are in a reversal until it occurs.

So, most geophysical evidence suggests the process is relatively slow on human and technological timescales. Given that there have been hundreds of known reversals in the geological record, there is little to no

evidence of major biological or environmental damage during such events. This suggests that it will primarily be technology that is most at risk from any major changes in the Earth's magnetic field.

This article was prepared in response to a number of enquiries received in 2012.

[1] Sarson, G.R. in 'Encyclopedia of Geomagnetism and Paleomagnetism' (eds.: D Gubbins and E Herrero-Bervera), 2007.

[2] Mankinen, E.A.M. Prévot, C. S. Grommé, and R. S. Coe, *Journal of Geophysical Research*, **90**, 1985.

[3] Glatzmeier G. and Roberts, P.H., *Nature*, **377**, 1995.

[4] De Santis, A., E. Qamili, and G. Cianchini., *Physics of the Earth and Planetary Interiors*, **186**, 2011.

[5] Hulot, G., F. Lhuillier, and J. Aubert , *Geophysical. Research Letters*, **37**, 2010

[6] Korte, M.; Constable, C.; Donadini, F.; Holme, R, *Earth and Planetary Science Letters*, **312**, 2011

Science

A global analysis of observatory data for an archaeological geophysics meeting

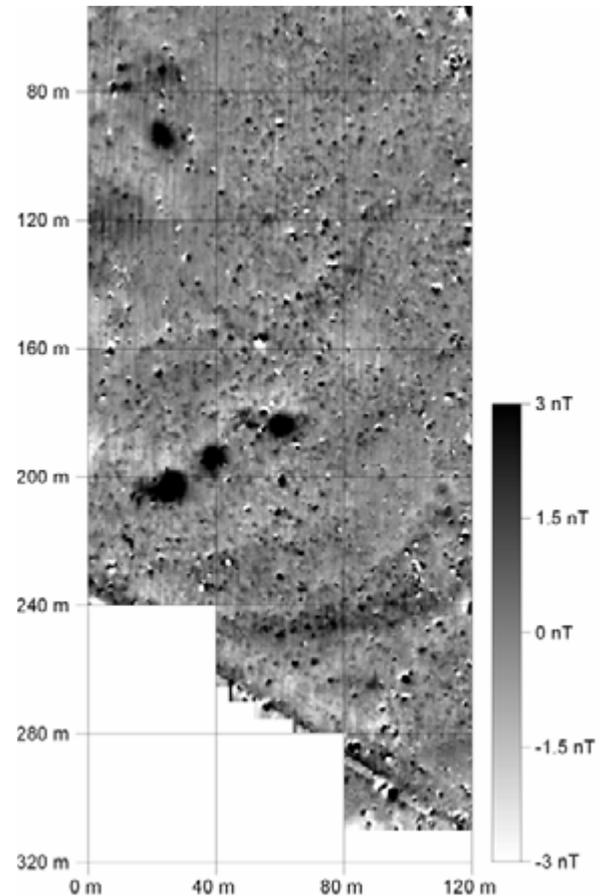
The majority of surveys by archaeological geophysicists are magnetic but how aware is this community of the naturally varying magnetic fields and what impact might these have on their results? This is a question we set out to address by participating in an archaeological geophysics meeting organised by the Near Surface Geophysics Group in London in December 2012.

Archaeological magnetic surveys often seek to detect very small signals, sometimes sub-nT. Many surveys are done using gradiometers, where two or more sensors are mounted on a frame, which is then man-handled, wheeled or driven around a site. With this approach the time-varying fields are effectively removed and do not contaminate the final results. However single sensor surveys are potentially more sensitive to buried artefacts and these also get carried out. In these cases on-site reference base stations should be in operation, in a similar manner to the way a repeat station site is checked for magnetic contamination. But contamination or failure of the base station is not unknown and it is therefore useful to know the likelihood and magnitude of the time-varying field at a given site.

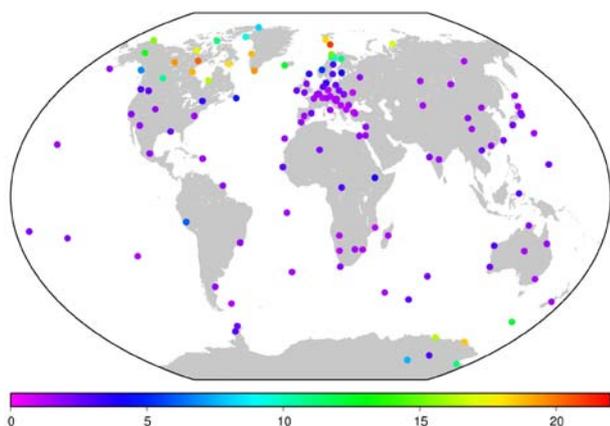
Two metrics were considered relevant for this community: the hourly standard deviation and the maximum rate of change in total intensity per minute.

Using data from 150 observatories spanning 21 years we were able to derive maps showing the spatial variation in the hourly standard deviation and to further analyse its temporal variation, e.g. by local time, month and year.

From the global map of data from 1991-2010 (*Figure below*) it can be seen that locations underneath the auroral electrojets experience the highest variability in time-varying magnetic fields, with the mean hourly standard deviation over 21 years reaching 23 nT. The maximum hourly standard deviation observed is over 800 nT and the maximum rate of change is close to 1400 nT/minute, both occurring during the October 2003 storm, but at different observatories. Locations underneath the equatorial electrojet, an ionospheric current system associated with the dip equator, experience higher levels of variability than those at mid-latitudes.



A magnetometer survey of a neolithic flint mine (Koch *et al*, 2012).
Note scale of ± 3 nT.



Mean hourly standard deviation in total intensity (nT), 1991-2010

Looking at temporal variations at Tromsø observatory in northern Norway (*Figure right*), it can be seen that the night time is on average more disturbed than the day. This is due to reconnection processes in the magnetotail and subsequent release of energy back to the night-side of the Earth. The equinoctial months are also more disturbed as a result of the more favourable geometry for energetic charged particles from the solar wind to enter the magnetosphere at these times. Solar cycle effects are also evident in the third panel. These plots were produced for all observatories and some interesting variations were noted.

Another aspect we considered was the effect of induced currents during a magnetic storm over distances similar to those between a base station sensor and a survey sensor. For example, total intensity data during the October 2003 storm from two sensors at Eskdalemuir were compared and differences of up to 3 nT were observed.

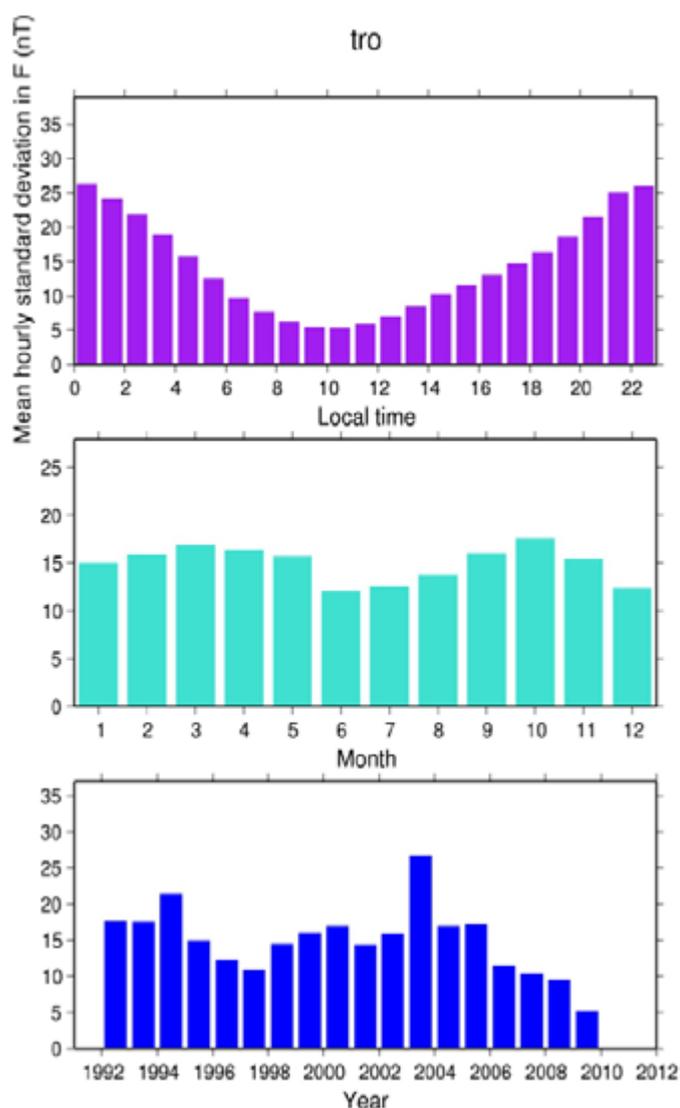
Another naturally varying field that can be problematic for archaeological surveys is the crustal field. Most countries now have a complete aeromagnetic survey and although these will be of variable resolution, depending on flight line separation and altitude above the ground, they are certainly useful for indicating sites which might suffer from short wavelength crustal field contamination.

This study used data from the World Data Centre for Geomagnetism run by BGS and in our research we identified some large spikes

in the data holdings. Finding these spikes is like looking for a needle in a haystack but 100 spikes were identified out of a total of 10^9 values. These will be flagged as erroneous thus, as a by-product, improving the quality of the WDC database.

Our work is likely to be of interest to companies who conduct aeromagnetic surveys, especially as the use of gradiometry is less common here than in the archaeological magnetic survey community. For example, a threshold of 10 nT/10 minutes is frequently used in aeromagnetic surveys to determine whether re-flights are necessary.

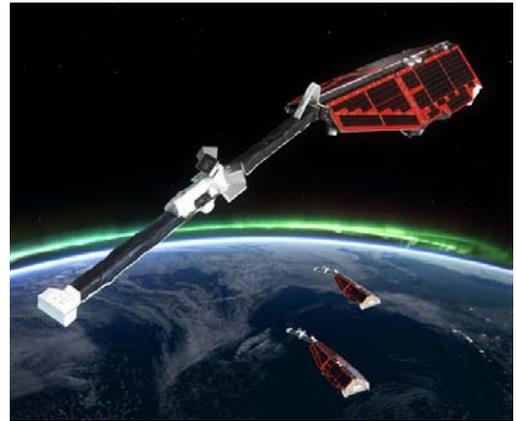
Future work will include extending the study back in time to use all of the WDC holdings, and adapting it to be more relevant for the aeromagnetic survey community.



Variation of mean hourly standard deviation in total intensity (nT) with local time, month and year

Science

The ESA Swarm Level 2 Processing Facility – Operational Phase



The Swarm satellite 'constellation' in orbit (artist's illustration, courtesy of ESA)

The European Space Agency's Swarm mission is due for launch in 2013. Data from the Swarm mission will be processed by BGS, as part of a multinational consortium, to provide scientific quality models of the Earth's magnetic fields and of other environmental variables. These will be known as 'Level 2' products and are intended for wide scientific and other use. The BGS contribution to the Level 2 processing facility will operate for around five years, during the mission lifetime, and be fully integrated with the daily processing activities that serve our users.

For two years BGS has been developing a software package to support a distributed ESA 'Level Two' (L2) processing system, as part of a consortium that includes DTU Space (Denmark), GFZ Potsdam (Germany), IPGP (France), ETH Zurich (Switzerland), Charles University of Prague (Czech Republic) and DEOS (Holland). Additional support has been provided to the consortium by NOAA/NGDC and NASA-Goddard (USA).

Known collectively as the Swarm Magnetic and Atmospheric Research Team (SMART), the consortium has completed the Swarm Constellation Analysis and Research Facility (SCARF). This is the means by which the L2 products will be delivered to the academic and applications communities. ESA will provide the SCARF output through a Payload Data Ground Segment (PDGS) facility for the mission that will operate at ESRIN in Frascati, Italy and Farnborough, England.

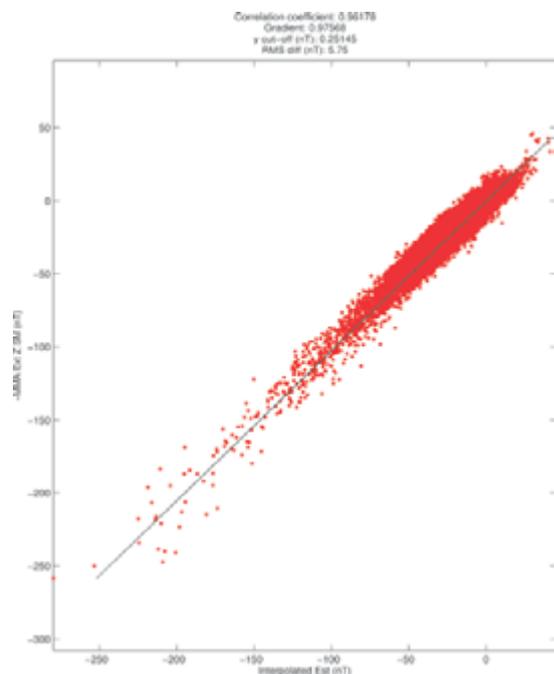
The BGS sub-system comprises four 'processing chains'. These chains produce the

L2 products 'fast track magnetospheric model' (known as MMA), the 'Quick-Look model (QL)', the 'L2 products validation model' (VAL) and the magnetic observatory database (AUX_OBS).

The MMA is an analogue of the ring-current magnetic index Dst , but is an analogue solely derived from magnetic data measured by the three satellite 'constellation'. Dst is a standard index calculated from the horizontal magnetic field measured at four low-latitude magnetic observatories. Its importance lies in the fact that it measures (primarily) the strength of the magnetospheric ring current that circles the Earth at a few Earth radii. This current is modulated by the strength of the solar wind and the energy input from solar storms.

The MMA is a vector version of Dst and will therefore improve on Dst by capturing any asymmetry in the ring current. The MMA will also be computed once per orbit and separate the internal and external field contributions within the product. Further, given the expected

level of Swarm instrument stability, the MMA should prove to be of particular, and immediate, use in magnetic field modelling activities and in monitoring ring current changes. Its rapid production may also lead to wider 'space weather' applications for the Swarm mission data.



The MMA fast-track magnetospheric model, in nT (y-axis), compared with the external field component of Dst (x-axis, also in nT) for a synthetic data set during system testing. High correlation, as here, implies high confidence in the MMA product

The QL product is intended to provide a 'health check', on a daily basis, for the basic Swarm calibrated data (known as L1b) returned from the satellites and provided to users by the PDGS. Through visualisation of L1b data differences between satellites, power spectra, spikes and data 'jumps', users will be able to rapidly determine the quality of data for personal use and analysis. QL will also help inform satellite operators of problems with the Swarm instrument packages.

Validation (the VAL product) is essential to the successful operation of the SCARF. The range of L2 magnetic products, produced by our colleagues, will be compared by BGS against existing models and independent (e.g. magnetic observatory) data. Some of the processing chains operated by our consortium colleagues produce similar products, but with

subtle differences depending on product end-user. Validation will therefore include cross-comparisons between the SCARF chains.

A key concept in the validation scheme is the 'scientist in the loop' (SIL). Though many of the validation activities are automated, an assessment by a scientifically trained researcher (the SIL) will provide qualitative comments to back the quantitative automated measures. Finally the quality of the L2 products will be assessed by an ESA 'Quality Working Group'. The validation products produced by BGS will be a major component of that assessment and feedback to ESA.

Magnetic observatory data, through the AUX_OBS product, will be of benefit to magnetic field models derived from Swarm data, primarily by providing an independent control for secular variation. The AUX_OBS product will be developed through BGS WDC and INTERMAGNET activities, with the product updated every three months during the mission.

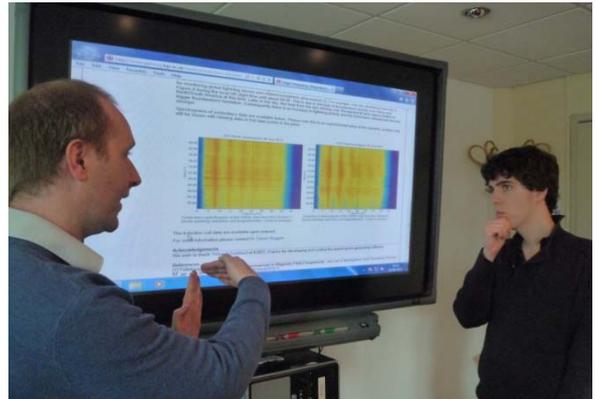


Locations of magnetic observatories that contribute quasi-definitive data (Dec 2012) to be incorporated into the AUX_OBS product

By collaborating with European and international colleagues, through the SCARF and during the Swarm mission, BGS will benefit from and contribute to scientific advances in understanding the Earth's natural environment.

Science

Student and Research Associate Activities



Thibaud Gabillard (right) and Ciaran Beggan examine spectrograms from induction coil data

Rob Shore and Virginie Penquerc'h made significant contributions to the scientific developments of the Geomagnetism team through ongoing PhD, PDRA and other research projects. We also had extended visits from Thibaud Gabillard (France), Tamás Nagy (Hungary) and Esteban Cabrera (Argentina), as well as help from retired staff member John Riddick and Edinburgh university student Jenny Jones.

Rob Shore is based at the University of Edinburgh and is writing up his PhD thesis in the first quarter of 2013. He has been investigating the “virtual-observatory” approach to working with satellite data and the application of Ampère’s integral to data from near-simultaneous over-flights of the Ørsted and CHAMP satellites, to resolve the ionospheric currents passing between the two satellites’ orbits.

He has also studied the use of Empirical Orthogonal Functions to test for differences in quiet-time magnetic field structures between solar maximum and solar minimum. The main motivation for this part of the project was mantle induction, as for this it is often assumed that the inducing field is symmetrical.

Using observatory hourly mean data spanning 1997 to 2010 Rob has found that the balance of partial to symmetric ring current signal changes with solar activity. This is important in utilising satellite data where the mission lasts a significant part of a solar cycle. Rob summarised this work at the British Geophysical Association’s 2012

post-graduate conference in Leeds, winning a prize for an oral presentation.

Thibaud Gabillard is an undergraduate studying engineering at the ESEO Grande Ecole d’ingénieurs in Angers, France. Although not a geophysicist he was keen to expand his knowledge in Earth science and volunteered for a summer placement and secured ERASMUS funding for his visit.

Thibaud visited BGS from June to September 2012, working on signal processing of the data from the high frequency induction coils installed at Eskdalemuir. He developed code for visualising the data from the magnetometers in terms of spectral content and power. In addition, he analysed data from the standard BGS magnetometers, looking at the spectral power during large geomagnetic storms (which is typically broadband, except for pulsations). His outputs included a written report for his university tutor, a presentation to the team and code to process the induction coil data which is now used to create the daily ‘quick look’ images on the Geomagnetism website.

Virginie Penquerc'h is a Post Doctorate Research Assistant at the University of Liverpool, shared with BGS and funded through a NERC National Centre for Earth Observation grant (2010-2012).

Virginie continued to develop and apply new methodologies for the modelling of the internal geomagnetic field, in association with Prof. Richard Holme of Liverpool University, particularly to account for errors arising from external (magnetospheric and ionospheric) field contributions.

She also wrote a program to select magnetic measurements made by satellite according to user-selectable criteria. This is intended for use during the ESA Swarm mission. Virginie ended her PDRA at the end of 2012 and has moved into teaching.



Virginie Penquerc'h with Brian Hamilton

Esteban Cabrera / John Riddick

BGS funded Esteban Cabrera, an observer from the Geophysics Department of the National Meteorological Service of Argentina, to attend the IAGA Observatories Workshop in San Fernando, Spain. There, he presented the results of a co-operative project to reinstate absolute magnetic measurements at the Argentinean Antarctic base of Orcadas del Sur. The observatory uses equipment developed by ex-BGS's John Riddick and donated by the BGS-backed INDIGO Project. He also attended a training course at BGS Edinburgh which aimed at improving the data quality at the Argentinian observatories, prior to their application for membership of the global INTERMAGNET network.



John Riddick (left) with Esteban Cabrera (centre) and Chris Turbitt (right)

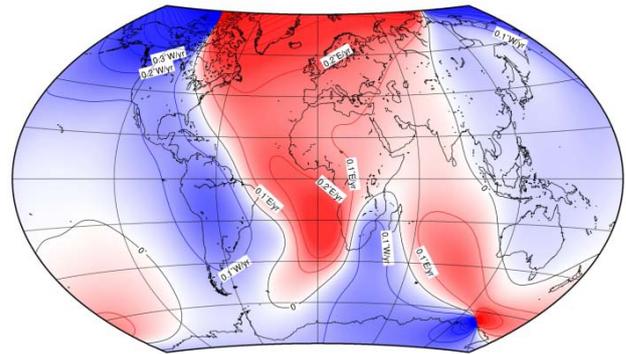
Tamás Nagy of the Geodetic and Geophysical Institute of Hungary (GRI) visited BGS to help us make progress in digitising historical magnetograms. In particular, he assessed the suitability of two different digitising software packages (GraphDigitise – developed in house by BGS, and Engauge Digitizer, a free open source software used by GRI to digitise analogue electric field records). It was recommended that the Engauge software was better for the digitisation of the BGS historical magnetograms. Tamás also trained BGS staff to use the software, wrote workflow instructions and *R* language code to post process the digitised data. He also made recommendations on how to develop the Engauge software further.



Tamás Nagy presenting his work at a Geomagnetism Team seminar

Jenny Johnson is a third year undergraduate at the University of Edinburgh. She volunteered her time to spend a week in the Geomagnetism team in early January. She investigated the online archive magnetograms to identify the scaling parameters in the yearbooks that corresponded to the traces for some of the largest recorded geomagnetic storms, writing a short report on her findings.

Directional Drilling



Rate of change of declination from BGGM2012

The geomagnetic field is a vital directional reference when drilling for oil and gas at many locations around the world. Using a combination of magnetic sensors and accelerometers in the bottom-hole assembly and accurate estimates of the local geomagnetic field, the drilling surveyor is able to safely direct the well towards its intended geological target. Wells are often drilled over considerable distances and in deposits already congested with existing wells. The BGS has been providing a variety of services based on the geomagnetic field for underground navigation for a number of years and here we describe activities undertaken in 2012.

The BGS Global Geomagnetic Model (BGGM) is updated yearly and provides an estimate of the magnitude and direction of the large-scale magnetic field. The sources modelled by the BGGM include those arising from time-varying dynamo action in the liquid outer core, the relatively static crustal field and the quiet, night-time magnetospheric field. In 2012 new data, mostly collected in 2011 from the global network of observatories and from the Ørsted magnetic survey satellite, were added, thereby ensuring that the BGGM continues to accurately track field changes over time.

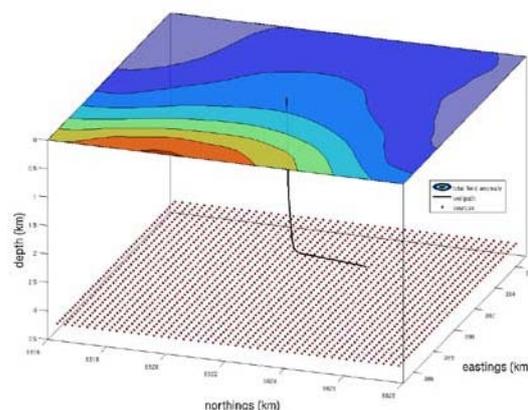
Complementing the new data, research has focused on new methods to improve the way in which the BGGM models field variations over time, as well as their spatial resolution. In 2012, forecasts of the field were provided for the first time from a physics-based model of the fluid flow at the surface of the core. Research has also been carried out on the use of higher order B-splines that can create a smoother and more realistic representation of how the core field has changed in the past. The large scale crustal field has been better constrained by employing an alternative scheme for weighting the contribution of observatory relative to satellite data. An

investigation into the effect of incorporating into the BGGM an existing grid of measurements derived from a variety of magnetic surveys is also ongoing.

The smaller scale crustal field is best captured by local, extensive magnetic surveys, usually made by aircraft but sometimes by ship or by a ground survey. These surveys generally comprise measurements of the strength of the field only, and the directional information at drilling depths has to be derived. In 2012 the BGS completed several projects around the world where magnetic data in the vicinity of a field were acquired and processed, and site-specific uncertainties computed. Twenty eight reports were delivered to customers and geomagnetic referencing data for waypoints along over 900 wells were provided. One such project was for a field offshore New Zealand where there was particular concern about magnetic effects from nearby volcanic rocks. An aeromagnetic survey was specifically commissioned to aid directional drilling in this area. Another area offshore NW Australia also required an aeromagnetic survey to be commissioned, this time by BGS.



Aeromagnetic surveying for directional drilling (image credit: Fugro)



Total field anomaly at surface, a well path along which magnetic field vectors are to be supplied, and array of equivalent sources constructed at depth

Research into different approaches for determining the full crustal field vector at depth is underway. By applying inverse modelling techniques, we can construct a set of magnetisations which give rise to field anomalies equal to those measured during aeromagnetic or marine surveys. The magnetic field along the well path can then be found via simple forward modelling. This method makes different assumptions about the nature of the anomalies than the existing spectral method. The two techniques are complimentary but the 'equivalent source' method may be able to provide more accurate crustal field vectors at depth in situations where the spectral technique is less appropriate.

An important contribution to the estimate of uncertainties, especially at high latitudes, is from the time-varying external field. This cannot be modelled accurately and is best monitored in real-time using nearby observatories.

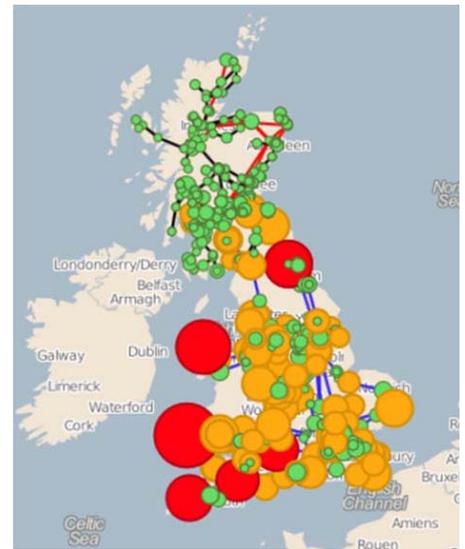
For this reason the BGS operates the Jim Carrigan Observatory on the North Slope of Alaska in collaboration with Halliburton. During the site visit in September 2012 preliminary assessments of uncertainties associated with data from this observatory and from other high latitude observatories, when applied to directional drilling some distance from them, were presented to parties from the oil industry. The uncertainties were found to increase with distance from each observatory but less severely than initially expected.

The speedy delivery of appropriate data products to customers is vitally important as it means downhole magnetic measurements can be processed quickly and any critical steering decisions can be made in near real time. In 2012 the BGS delivered nearly 100% of processed data products within 5 minutes of measuring the raw data at its remote observatories.

In May 2012 the Industry Steering Committee on Wellbore Survey Accuracy had its meeting in Edinburgh. Around 80 drilling surveyors from around the world attended and 20 of them elected to take a day trip to Eskdalemuir observatory organised by BGS. An enjoyable day was had by all.

Applications

Space Weather Applications and Services



BGS provides estimates of GICs in the mainland UK power grid for monitoring the geomagnetic hazard to technology

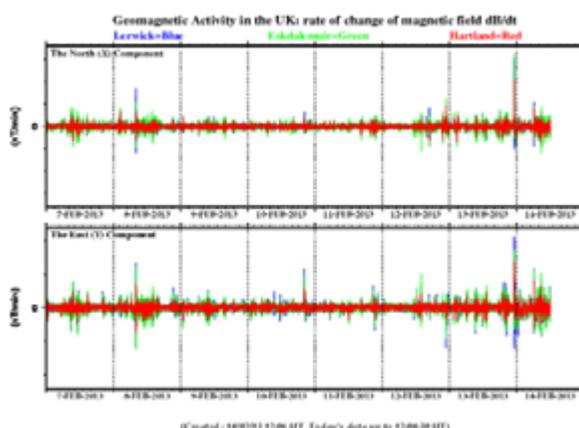
Research into space weather and the geomagnetic hazard finds application in a number of data products and services to academic and commercial users. Developments in 2012 have included an update to our model of Geomagnetically Induced Current (GIC) flow in the UK power transmission system, along with a revision of how these data are presented to National Grid, and provision of magnetic index data products to the Met Office.

In partnership with National Grid, there have been several improvements made to the MAGIC ('Monitoring and Analysis of GIC') web pages. The model of GIC flow in the grid has seen a major revision, including an updated version of the transmission system for the whole of GB, regular updates on the largest estimated GIC and a new map for displaying this information. The MAGIC pages also now include real time plots of the rate of change of the magnetic field at the three UK observatories.

BGS also extended its research into GICs in the Irish power grid. This led to a visit to EirGrid (the electrical transmission operator for Republic of Ireland) in Dublin to discuss monitoring and analysing space weather impacts on the Irish power system.

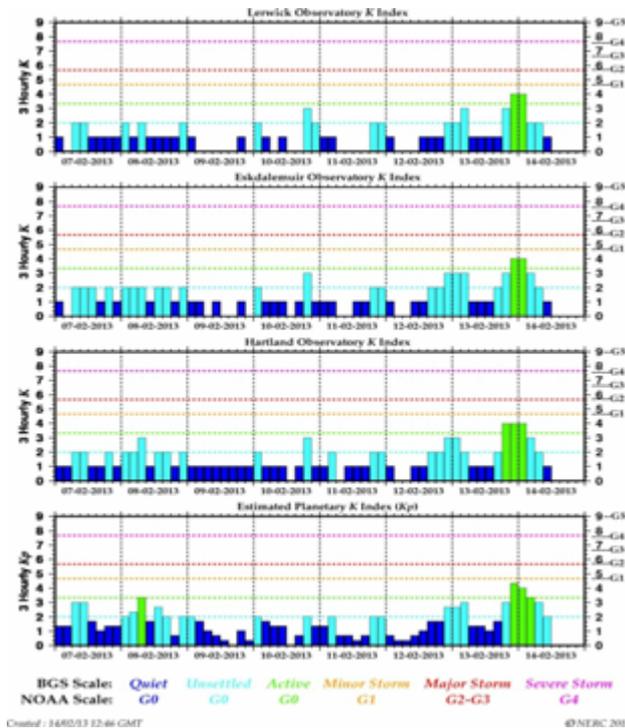
In September the EURISGIC ('European Risk from Geomagnetically Induced Currents') progress meeting was hosted by BGS in Edinburgh. At this meeting we presented progress on our most detailed model yet of the GB transmission system and its response to space weather, and on a new conductivity model for the UK based on the 1:625k geological map.

Web pages delivering real time data to the Met Office have now been updated to include observatory K indices. Work is also underway to provide the Met Office with further Space Weather products from UK geomagnetic observatory data in an updated secure web page. This will include a new automated prediction of three-hour ap and Kp magnetic indices, which has been developed at BGS. This work is part of the Natural Hazards Partnership (NHP), which brings together expertise from across the UK's leading public sector agencies to deliver better coordinated



Near real time geomagnetic monitoring data available on the MAGIC website

and coherent advice on natural hazards to the government, civil contingencies and the resilience community.

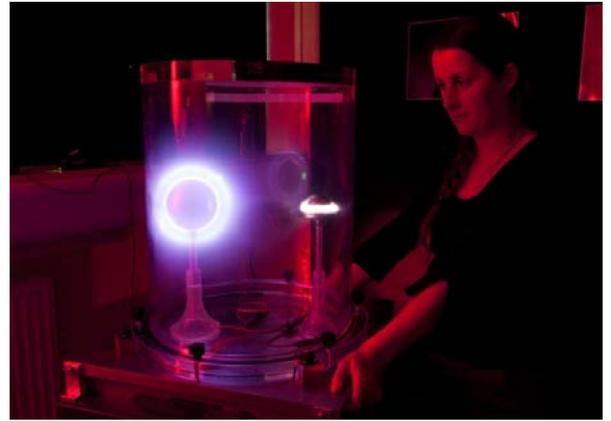


Near real-time delivery of K indices from UK observatories

Highlights of some other space weather related activities during 2012 include:

- Organising a session on 'Space Weather' at the British Science Festival in Aberdeen.
- Contributions to the draft UK Space Weather Strategy, led by STFC-RAL and the NERC Hazards theme leader.
- A paper on extreme geomagnetic storms placed in the top eight submissions to the Lloyd's 'Science of Risk' 2012 prize.
- Attendance and presentation made in plenary session at the 9th European Space Weather Week, on our work with National Grid.
- A presentation to Belgian power research institute SCK-CEN and Royal Observatory of Belgium on our work on the space weather hazard to power systems. Subsequently there was an enquiry from a second Belgian company ELIA (the transmission operator) for a presentation.
- Participation in the 'Severe Space Weather' workshop organised by GO-Science on behalf of government chief scientific advisor to the Prime Minister.
- A paper presented at the IET event on 'Extreme Electromagnetics: The Triple Threat to Infrastructure', covering the threat to the UK power grid from space weather.
- Contribution to the Royal Academy of Engineering report into space weather impact on engineered systems (see www.geomag.bgs.ac.uk/raeng_report.html).
- Participation in the second and third workshops in a series of joint US-UK space weather meetings, sponsored by government. The focus was on the scientific infrastructures our two countries need to better develop and coordinate to monitor space weather hazard, and on future space weather policy in our two nations.
- An invitation to represent the FP7 consortium project 'EURISGIC', on the North American Electrical Reliability Council's 'Geomagnetic Disturbance Task Force', where the science contribution is being led by NASA.
- A successful application for funding to STFC as collaborator on "SpacE weather REsearch Network (SEREN) - securing UK space weather capabilities", led by RAL. This will fund a series of networking workshops on space weather.
- Discussions with NERC colleagues on future UK involvement in the space weather segment of ESA's space situational awareness program. Comments provided on briefing paper(s) for NERC SISB and UKSA on advantages for NERC science, looking forward.
- Continued data exchange with the US National Oceanographic and Atmospheric Administration's Space Weather Prediction Centre (SWPC), in Colorado.

Outreach and Knowledge Exchange



Dr Gabby Provan (University of Leicester) demonstrates a planeterralla as part of the Geomagnetism display at the BGS Open Day

A wide variety of outputs are produced by the Geomagnetism team, including papers in scientific journals, commissioned reports, posters, talks and presentations. Here we list many of our outputs for 2012.

Scientific Journal Publications

Published 2012

Beggan, C. and S. McLay (2012), Interpolation of Magnetic and Electric fields using Spherical Elementary Current Systems, Proceedings of IRST 2012, Institution of Engineering and Technology.

Shanahan, T. J. G., Swan, A. P. and Macmillan, S. 2012. UK 2009-2010 repeat station report. *Annals of Geophysics*, 55, 6 ; doi:10.4401/ag-5439

Pulkkinen, A, Bernabeu, E, Eichner, J, **Beggan, C.** and **Thomson, A.** 2012. Generation of 100-year geomagnetically induced current scenarios. *Space Weather* 10, S04003, doi:10.1029/2011SW000750

Submitted, Accepted and to Appear 2013 (at April 2013)

Beggan C., Macmillan, S., Hamilton, B and A.W.P. Thomson (2013), Independent Validation of Swarm Level2 Magnetic Field Products and 'Quick Look' for Level1b data, *Earth Planets and Space* (submitted)

Beggan, C., Saarimäki, J., Whaler, K. and F. Simons (2013), Spectral and spatial decomposition of lithospheric magnetic field models using spherical Slepian functions, *Geophysical Journal International*, 193, 136-148

Cabrera E., **Turbitt, C. W.,** Rasson, J. L., Gianibelli, J. and Riddick, J. C. 2013. The Upgrade of Base Orcadas Magnetic Observatory. *Proceedings of XVth IAGA Workshop on Geomagnetic Observatory, Instruments, Data Acquisition and Processing, San Fernando, Spain, 4-14th June 2012* (submitted)

Clarke, E., Baillie, O., Reay, S.J. and Turbitt C.W. (2013) A method for the real-time production of quasi-definitive magnetic observatory data, *Earth Planets Space* (submitted)

Dawson, E., Lowndes. J. and Reddy, P. 2013. The British Geological Survey's new geomagnetic data web service. *Data Science Journal*

Hamilton, B. (2013) A rapid model of the large-scale magnetospheric field from Swarm satellite data, *Earth Planets and Space* (submitted)

Hamilton, C.W., **Beggan, C.D.**, Still, S., Beuthe, M., Lopes, R.M.C., Williams, D.A., Radebaugh, J., Wright, W., 2013. Spatial distribution of volcanoes on Io: Implications for tidal heating and magma ascent. *Earth and Planetary Science Letters* 361, 272–286

Linthé, H.-J., Reda, J., Isac, A., Matzka, J. and **Turbitt, C.** 2013. Observatory Data Quality Check – The Instrument to Ensure Valuable Research. *Proceedings of XVth IAGA Workshop on Geomagnetic Observatory, Instruments, Data Acquisition and Processing, San Fernando, Spain, 4-14th June 2012* (submitted)

Macmillan, S. & Olsen, N. 2013. Observatory data and the Swarm mission. *Earth Planets Space* (submitted)

Reay, S.J., Clarke, E., Dawson, E., and Macmillan, S. 2013. Operations of the World Data Centre for geomagnetism, Edinburgh. *Data Science Journal* 12. WDS47-WDS51. doi:10.2481/dsj.WDS-005

Shanahan, T., Turbitt C., and Flower, S. 2013. Experiences in Designing a Low-Cost Temperature Controlled Variometer Enclosure. *Proceedings of XVth IAGA Workshop on Geomagnetic Observatory, Instruments, Data Acquisition and Processing, San Fernando, Spain, 4-14th June 2012* (submitted)

Shore, R. M., Whaler, K. A., **Macmillan, S. Beggan, C.**, Olsen, N., Aruliah, A., and T. Spain. 2013, Ionospheric midlatitude electric current density inferred from a magnetic satellite constellation, *Journal of Geophysical Research (Space Physics)* (submitted)

Thomson, A. W. P. 2013 Space Weather Applications of Geomagnetic Observatory Data. *Proceedings of XVth IAGA Workshop on Geomagnetic Observatory, Instruments, Data Acquisition and Processing, San Fernando, Spain, 4-14th June 2012* (accepted)

Turbitt, C., Matzka, J., Rasson, J., St-Louis, B. and Stewart, D. 2013. An Instrument Performance and Data Quality Standard for Intermagnet One-Second Data Exchange. *Proceedings of XVth IAGA Workshop on Geomagnetic Observatory, Instruments, Data Acquisition and Processing, San Fernando, Spain, 4-14th June 2012* (submitted)

Wintoft, P., Buresova, D., Bushell, A., Hejda, P., Innocenti, M. E., Lapenta, G., Núñez, M., Perrone, L., Qahwaji, R., **Thomson, A. W. P.**, Tsagouri, I., Valach, F. and Viljanen, A. 2013. Verification of space weather models. *Journal of Space Weather and Space Climate* (submitted)



Left: Sarah Reay and delegates at the DEVEX conference, May 2012. **Right:** Tom Shanahan explaining observatory operations to a tour party at Eskdalemuir Observatory, May 2012.

Other Publications

1 BGS Report: 2011 annual review

29 Customer Reports (UK survey & OS; oil industry services; National Grid)

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

ESA's Let's embrace space, volume II - Space Research achievements under the 7th Framework Programme: bookshop.europa.eu/en/let-s-embrace-space-pbNB3111420/

Bi-monthly column on Space Weather for Royal Institute of Navigation's 'Navigation News'

Conference Presentations, Posters and Related Activities

'Magnetic Relaxation 2012' . Liverpool, UK, <u>Jan</u>	<i>1 poster</i>
RAS NAM/MIST , Manchester, UK, <u>Mar</u>	<i>1 presentation (Thomson)</i>
	<i>1 poster</i>
European Geophysical Union Meeting , Vienna, <u>Apr</u>	<i>1 poster</i>
ISCWSA meeting , Edinburgh, UK, <u>May</u> (SPE wellbore positioning)	<i>1 Presentation (Macmillan)</i> <i>Tour of Eskdalemuir Observatory</i>
DEVEX 2012 , Aberdeen, UK, <u>May</u>	<i>1 poster</i>
IET Ionospheric and Radio Systems Techniques , York, <u>May</u>	<i>1 poster</i>
IAGA Observatories Workshop , San Fernando, Spain, <u>Jun</u>	<i>3 presentations (Thomson/Turbitt,</i> <i>4 posters</i> <i>/Swan)</i>
SEDI , Leeds, UK, <u>Jun</u>	<i>2 posters</i>
Conference on Mathematical Geophysics , Edinburgh, <u>Jun</u>	<i>1 poster</i>
Predicting deep Earth processes and impacts on space climate , Leeds, <u>Jun</u>	<i>2 presentations</i> <i>(Macmillan/Beggan)</i>
1st Swarm Calibration Science Meeting . Frascati, Italy, <u>Jun</u>	<i>1 presentation (Macmillan)</i>
Geomagnetism Team Development Day , Pitlochry, <u>Oct</u>	<i>20 presentations by team members</i>
European Space Weather Week 9 , Brussels, Belgium, <u>Nov</u>	<i>1 presentation (Thomson)</i>
NSGG Recent work in Archaeological Geophysics , London, UK, <u>Dec</u>	<i>1 poster</i>

AGU Fall Meeting, San Francisco, USA, Dec

*1 presentation (Thomson)
2 posters*

Geomagnetism Team seminars, Edinburgh

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

Some Other Notable Outputs

Observatory tours

Eskdalemuir visit by attendees of the oil industry related ISCWSA meeting. (30 attendees)

Eskdalemuir visit by Leeds University Deep Earth group

University of Edinburgh Innovative Learning Week, Tour of Eskdalemuir (19 attendees)

Historical data

Re-discovery of geomagnetic data from Scott's 1912 final expedition to Antarctica.

Edinburgh University Undergraduate Lecture Series (September-April)

4th Year Honours Course on 'Geomagnetism', by Ciaran Beggan & Brian Hamilton (16 lectures)

3rd year Geophysics course on Earth and Planetary Structure by Ciaran Beggan, K. Goodenough & B. Baptie (18 lectures)

Public Lectures, Presentations and Demonstrations

British Science Festival, Aberdeen, UK (September) including 2 presentations (Thomson, Beggan); and 1 press conference

Educational and training activities, including presentation "The Earth's Magnetic Field" given at BGS Open Day.

Beggan, C., Computation of GIC in the UK power grid, SCK-CEN Belgium on behalf of the Royal Observatory Belgium, 7th Dec 2012,

Media Interviews following major space weather events

24 Jan – Interviews for Guardian, BBC News online, Stornoway Gazette.

7-8 Mar – Interviews for BBC Radio Scotland, Guardian, Telegraph, BBC News online, Yahoo! News

9 Oct – Interviews for Telegraph, Guardian

Reuters (UK) interview: 'Lost in migration: Earth's magnetic field overdue a flip' (October)
uk.reuters.com/article/2012/10/03/us-science-earth-magneticfield-idUKBRE8920X620121003

(>75 syndicated articles)

Podcast for NERC Planet Earth

planetearth.nerc.ac.uk/multimedia/story.aspx?id=1130

YouTube video tour of Eskdalemuir Observatory

youtu.be/W186Jk9c3hU

High frequency magnetometer data on the BGS website:

www.geomag.bgs.ac.uk/research/inductioncoils.html

Short-listed poster on extreme geomagnetic events presented at Lloyds Science of Risk Prize, London, UK (October)



Geomagnetism at the British Science Festival 2012

The Geomagnetism team took part in two events that showcased our work to the public at the 2012 British Science Festival in Aberdeen. Presentations were made and exhibits shown to enthusiastic audiences on the topics of 'Space weather: a new hazard for a modern world' and on 'May the force be with us: what does the magnetic field do for us?'

The British Science Festival (BSF) is an annual event organised by the British Science Association (BSA). The BSA is an organisation whose history stretches back to the British Association for the Advancement of Science (BAAS), which was founded in York on 27 September 1831. In the early 19th century both the BAAS and the Royal Society of London were instrumental in encouraging and funding international efforts in the fledging science of global Geomagnetism.



Dr Ciarán Beggan presenting at the "May the force be with us" event.

The 2012 meeting of the BSF was held at the University of Aberdeen between 4th and 9th September 2012 with the title of 'Energising Minds'

(www.britishecienceassociation.org/britishecience-festival/aberdeen-2012).

The first event we took part in was "May the force be with us: what does the Earth's magnetic field do for us?" This was organised by the Geological Society of London's Earth Science Communicator, Sarah Day. The theme was magnetic reversals: what we know about them, what actually happens during one, and what are the consequences.

Over ninety minutes, Professor Kathy Whaler (University of Edinburgh) explored how the Earth's magnetic field is generated. Dr Conall Mac Niocaill (University of Oxford) explained how the magnetic field has helped uncover some of the most fundamental principles of Earth science. Finally, Dr Ciarán Beggan (BGS) considered when the next reversal could be, and what its effects might be on the Earth. The event was chaired by Dr Alan Thomson (BGS) and attracted some 150 people.



Dr Lucie Green presenting at the "Space weather" event.

The second event was organised by the BGS Communication Team of Sarah Nice, Lauren Noakes and Sarah Reay and was supported by Dr Kate Lancaster of the Physics & Astronomy section of the BSF. This event was titled "Space weather: a new hazard for a modern world". The event was appropriate for this year's festival as the Sun is reaching its maximum magnetic activity, giving rise to more dramatic space weather. (It is also interesting to note that the last time Aberdeen hosted the BSF was in 1859, the year of the famous 'Carrington Event', which is believed to be the most extreme space weather event of the last 160 years or more.)

During the event Dr Lucie Green (Mullard Space Science Laboratory, University College



Dr Alan Thomson being interviewed by the BBC for the 'Reporting Scotland' news programme.

London) discussed what a coronal mass ejection (CME) is, what a 'large' one looks like, how we observe solar activity, such as CME. Dr Jim Wild (University of Lancaster) then discussed the Earth's magnetosphere, the role it plays in space weather and how it causes the northern lights during space weather. Dr Alan Thomson (BGS) talked about how the solid Earth responds to space weather, what technologies we have that are affected by space weather and why. He also discussed what an extreme storm could be like and what might happen to our power grid. Ahead of the space weather event we held a press conference which generated media interest and we gave an interview to the BBC which was broadcast on 'Reporting Scotland'.



The presenters, chairs and organisers of the two geomagnetism events at the British Science Festival. Left to right: Sarah Day, Sarah Nice, Sarah Reay, Conall MacNiocall, Alan Thomson, Kate Lancaster (hiding), Jim Wild, Ciarán Beggan, Lauren Noakes, Lucie Green.

Acknowledgements

The Geomagnetism team would like to acknowledge the support of team stakeholders, such as the Geomagnetism Advisory Group, BGS management and the Natural Environment Research Council.

The team also thank the BGS photographic and records quality control teams lead by Fergus MacTaggart and Bob McIntosh for the incredible job of digital capture of the analogue magnetogram and yearbook data sets. This has been a tremendous feat that has provided the geomagnetism community with a whole new set of data for research.

Alan Thomson would like to thank Ellen Clarke for her comments on this review. He also thanks the Geomagnetism team as a whole for their enthusiasm, dedication and hard work in 2012.

Geomagnetic and other data provided by scientific institutes and scientific bodies around the world are gratefully acknowledged.

This report is published with the approval of the Executive Director of the British Geological Survey (NERC).

Selected Glossary, Acronyms and Links

AGU	American Geophysical Union (www.agu.org/)
AUX_OBS	Swarm magnetic observatory database
BAAS	British Association for the Advancement of Science
BBC	British Broadcasting Corporation (www.bbc.co.uk/)
BGGM	BGS Global Geomagnetic Model (www.geomag.bgs.ac.uk/bggm.html)
BGS	British Geological Survey (www.bgs.ac.uk/)
BSA	British Science Association (www.britishtscienceassociation.org)
BSF	British Science Festival (www.britishtscienceassociation.org/british-science-festival)
CHAMP	German magnetic survey satellite. (www-app2.gfz-potsdam.de/pb1/op/champ/)
DEOS	Delft Institute for Earth-Oriented Space research (www.lr.tudelft.nl/en/research/research-institutes/deos/)
DTU	Danish Technical University. (www.space.dtu.dk/English.aspx)
EirGrid	Electrical transmission operator for Republic of Ireland (www.eirgrid.com/)
EHS	The Earth Hazards and Systems science theme, part of BGS
ELIA	Electrical transmission operator for Belgium (www.elia.be/)
ERASMUS	EuRopean community Action Scheme for the Mobility of University Students
ESA	European Space Agency (www.esa.int/ESA)
ESEO	Graduate School of Engineering (www.eseo.fr)
ESRIN	European Space Research Institute (www.esa.int/About_Us/ESRIN)
ETH Zurich	Swiss Federal Institute of Technology Zurich (www.ethz.ch/index_EN)
EU	European Union (europa.eu/)
EURISGIC	European Risk from Geomagnetically Induced Currents (www.eurisgic.eu/)
FMI	Finnish Meteorological Institute (en.ilmatietaenlaitos.fi/)
FP7	European Commission - The Seventh Framework Programme (ec.europa.eu/research/fp7/index_en.cfm)
GB	Great Britain
GFZ	Helmholtz centre, Potsdam, Germany (www.gfz-potsdam.de/)
GGRI	Geodetic and Geophysics Institute, Hungary (www.ggki.hu/en/)
GIC	Geomagnetically Induced Currents (a natural hazard to power systems and pipeline networks).
GO-SCIENCE	UK government office for science (www.bis.gov.uk/go-science)
GPS	Global Positioning System. (www.gps.gov/)
IAGA	International Association of Geomagnetism and Aeronomy (www.iugg.org/IAGA/iaga_pages/index.html)
ICSU	International Council for Science (www.icsu.org/)
IET	The Institution of Engineering and Technology (www.theiet.org/)

IGRF	International Geomagnetic Reference Field. (www.ngdc.noaa.gov/AGA/vmod/igrf.html)
IIFR/IFR	Interpolated In-Field Referencing/In-Field Referencing. (www.geomag.bgs.ac.uk/documents/estec_iifr.pdf)
IKE	Information and Knowledge Exchange
INTERMAGNET	International magnetometer network: a global network of magnetic observatories operating to common standards. (www.intermagnet.org/)
INDIGO	(Described in the publication on pubs.usgs.gov/of/2009/1226/)
IPGP	Institut de Physique du Globe de Paris (www.ipgp.fr/index2.php?langue=1)
ISCWSA	The Industry Steering Committee on Wellbore Survey Accuracy. (iscwsa.org/)
ISGI	International Service for Geomagnetic Indices (www.icsu-fags.org/ps06isgi.htm)
L1b	Level 1b - Swarm calibrated data
L2	Level 2 - Swarm products
MAGIC	“ M onitoring and A nalysis of GIC ”. A service for National Grid.
MagNetE	European magnetic repeat station network space.fmi.fi/MagNetE2009/?page=welcome).
Met Office	UK meteorological office. (www.metoffice.gov.uk/)
MIST	Magnetosphere, Ionosphere, Solar-Terrestrial (Physics). (www.mist.ac.uk/)
MMA	Swarm fast-track magnetospheric model
MOD	Ministry of Defence (www.mod.uk/)
NAM	National Astronomy Meeting (www.ras.org.uk/)
NASA	National Aeronautic and Space Administration (www.nasa.gov/)
National Grid	National Grid plc (www.nationalgrid.com/)
NATO	North Atlantic Treaty Organization (www.nato.int/)
NERC	Natural Environment Research Council (www.nerc.ac.uk/)
NHP	Natural Hazards Partnership
NOAA/NGDC	National Oceanic and Atmospheric Administration /National Geophysical Data Center (www.ngdc.noaa.gov/).
OS	Ordnance Survey (www.ordnancesurvey.co.uk/oswebsite/)
PDGS	Payload Data Ground Segment
PDRA	Post Doctorate Research Assistant
Ørsted/Oersted	Danish magnetic survey satellite. (web.dmi.dk/projects/oersted/)
Prague University	(www.cuni.cz/UKENG)
Pulsation	Narrow frequency band oscillations in the magnetic field due to magnetospheric sources (also called ‘micropulsations’)
QD	Quasi-definitive (magnetic observatory data)
QL	Swarm Quick-Look model
RIN	Royal Institute of Navigation. (www.rin.org.uk/)
RAS	Royal Astronomical Society. (www.ras.org.uk/)

Royal Society	UK National Academy of Science. (royalsociety.org/)
RAL	Rutherford Appleton Laboratory (www.stfc.ac.uk/home.aspx)
SAN	Storage area network.
SAMNET	Sub-Auroral Magnetometer Network. (www.dcs.lancs.ac.uk/iono/samnet/)
SCARF	Swarm Constellation Analysis and Research
SCK-CEN	The Belgian Nuclear Research Centre (www.sckcen.be/sckcen_en/)
SISB	NERC Science & Innovation Strategy Board
SIL	'Scientist in the loop'
SMART	Swarm Magnetic and Atmospheric Research Team Facility
SPE	Society of Petroleum Engineers (www.spe.org/spe-app/spe/index.jsp)
STFC	Science and Technology 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/)
UKSA	UK Space Agency (www.bis.gov.uk/ukspaceagency/)
USGS	United States Geological Survey (www.usgs.gov/)
VAL	Swarm L2 products validation model
WDC	World Data Centre (e.g. www.wdc.bgs.ac.uk)
WDS	World Data System (www.icsu-wds.org/)

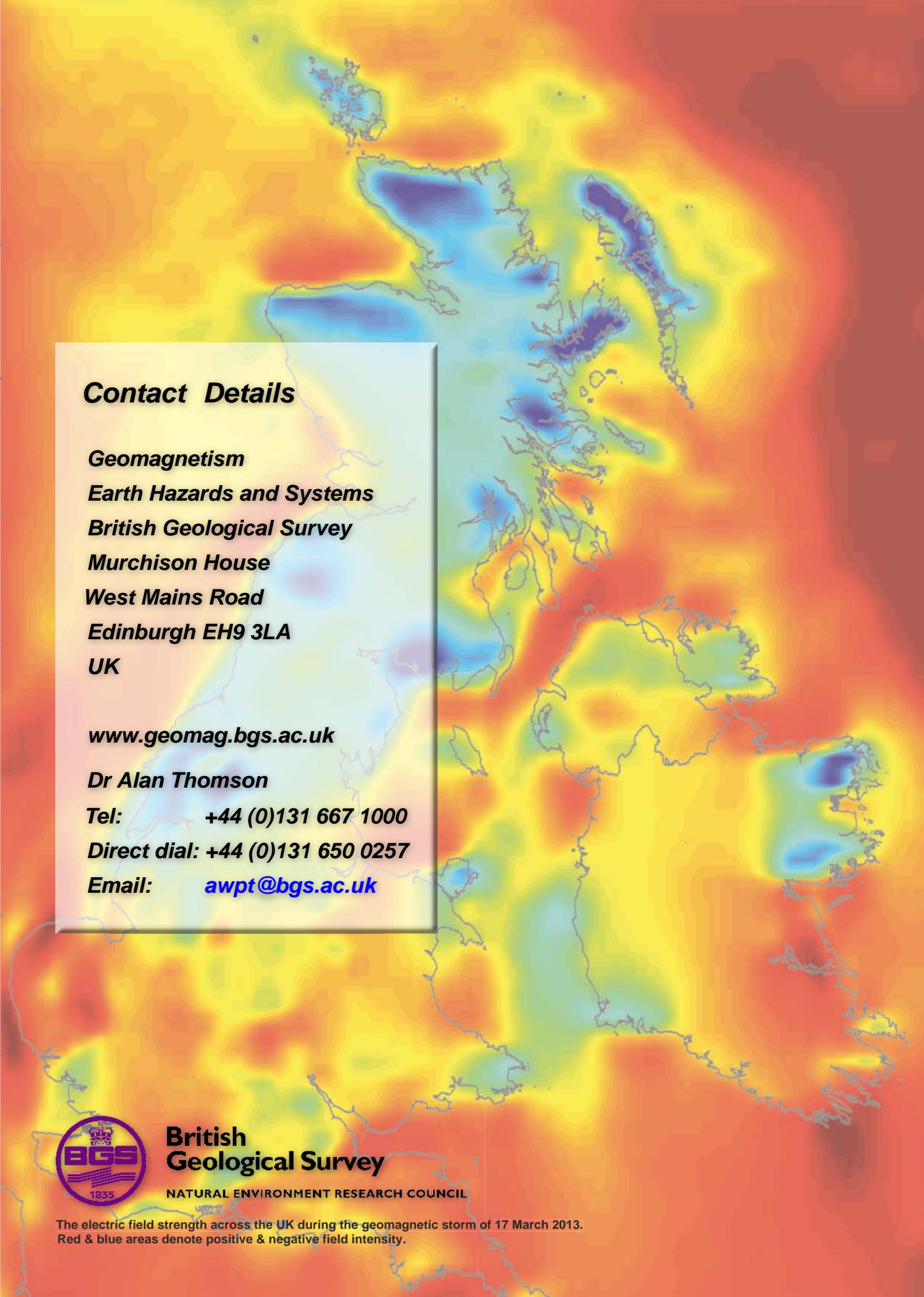
The Geomagnetism Team in 2012

Orsolya Baillie	<i>Geomagnetic Research and Data Processing</i>
Brian Bainbridge	<i>IT and Software Support</i>
Dr Ciarán Beggan	<i>Geomagnetic Research</i>
Dr Laurence Billingham	<i>Geomagnetic Research</i>
Ellen Clarke	<i>Geomagnetic Research and Data Processing</i>
Ewan Dawson	<i>Geomagnetic Research and Data Processing</i>
Paul Dixon	<i>Geomagnetism Business Account Support</i>
Jane Exton	<i>IT and Software Support</i>
Simon Flower	<i>Technical, Observatory Operations and IKE</i>
Dr Brian Hamilton	<i>Geomagnetic Research</i>
Ted Harris	<i>Geomagnetic Data Processing and IKE</i>
Sandy Henderson	<i>Geomagnetic Data Processing</i>
Thomas Humphries	<i>Geomagnetic Data Processing</i>
Dr Gemma Kelly	<i>Geomagnetic Research</i>
Dr David Kerridge	<i>Geomagnetic Research and Head of Science, Earth Hazards & Systems</i>
Dr Susan Macmillan	<i>Geomagnetic Research</i>
Colin Pringle	<i>Manager, Eskdalemuir Geomagnetic Observatory</i>
Sarah Reay	<i>Geomagnetic Research and Data Processing</i>
Dr Victoria Ridley	<i>Geomagnetic Research</i>
David Scott	<i>IT and Software Support</i>
Tom Shanahan	<i>Technical, Observatory Operations & Field Survey</i>
Tony Swan	<i>Technical, Observatory Operations & Field Survey</i>
Dr Alan Thomson	<i>Geomagnetic Research and Geomagnetism Team Leader</i>
Stephen Tredwin	<i>Manager, Hartland Geomagnetic Observatory</i>
Chris Turbitt	<i>Technical, Observatory Operations & Field Survey</i>



This page intentionally blank

This page intentionally blank



Contact Details

**Geomagnetism
Earth Hazards and Systems
British Geological Survey
Murchison House
West Mains Road
Edinburgh EH9 3LA
UK**

www.geomag.bgs.ac.uk

Dr Alan Thomson

Tel: +44 (0)131 667 1000

Direct dial: +44 (0)131 650 0257

Email: awpt@bgs.ac.uk



**British
Geological Survey**

NATURAL ENVIRONMENT RESEARCH COUNCIL

The electric field strength across the UK during the geomagnetic storm of 17 March 2013.
Red & blue areas denote positive & negative field intensity.