British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Geomagnetism *Review* *2013*

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Geomagnetism

Review 2013

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Front cover

Earth's protective shield - Earth & interplanetary space. Photo courtesy of ESA, © ESA/ATG medialab

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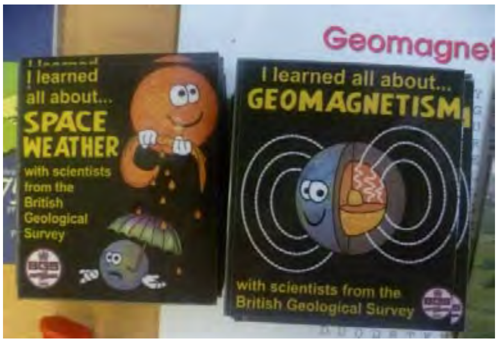


Explaining our science at the 'Bang Goes the Borders' science festival, 2013

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, alongside Earthquake Seismology, Earth and Planetary Observation and Monitoring, the Space Geodesy Facility and Volcanology.

EHO, in turn, is one of twelve BGS science themes that deliver the BGS science strategy. EHO sits 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 support from BGS Edinburgh Business Support and, on IT, from BGS Systems and Network Support.

The Geomagnetism team is primarily based in Edinburgh. In 2013 the team numbered 25 staff either fully or partly engaged in Geomagnetism work. In addition in 2013 we had one PhD student, co-supervised with the University of Edinburgh.

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, on Sable Island (Canada), at Port Stanley (Falkland Islands) and at King Edward Point (South Georgia). We also 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:

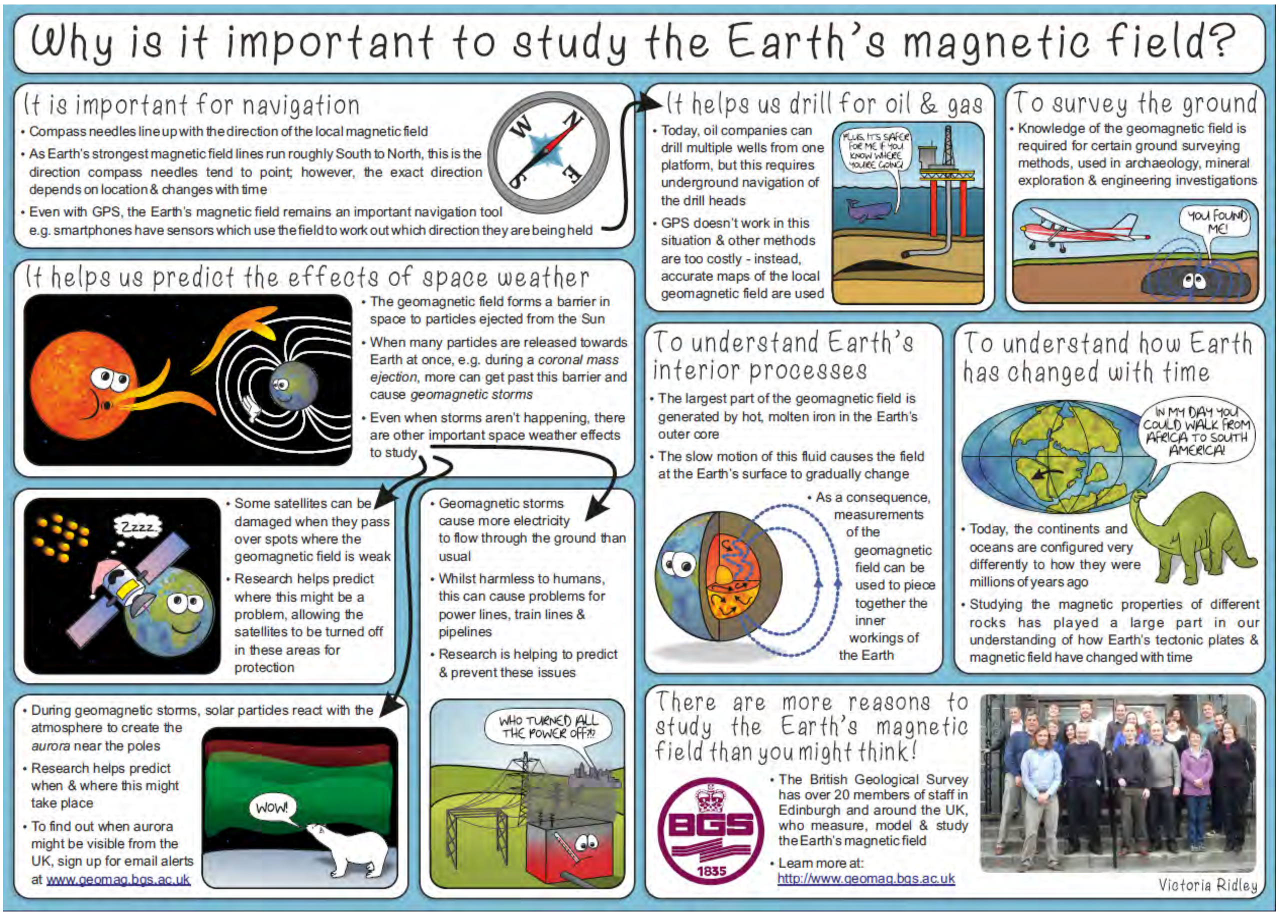
Long-term geomagnetic monitoring and allied research to improve our understanding of the Earth and its geomagnetic environment and hazards

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

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

We aim to be a world leader in

- Measuring, recording, modelling and interpreting the Earth's natural magnetic field and its sources
- Modelling and understanding the geomagnetic (space weather) hazard
- 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.



Winning poster in the December 2013 BGS poster competition (Victoria Ridley)

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Introduction

Sapper Hill, Port Stanley, during observatory service visit in 2013

Looking Ahead to 2014

The Geomagnetism team's scientific activities in 2014 will concentrate on research opportunities arising from the ESA Swarm magnetic survey mission, which was launched in late 2013. We will also continue to work with UK and international partners on the space weather hazard to technology. Other major activities will include continuing to operate the BGS magnetic observatories and the UK magnetic survey to international standards. We will also continue to produce academic and industry-standard geomagnetic models and data products.

Key Objectives

The Geomagnetism team will meet the aims of the new BGS and NERC strategies. For Geomagnetism science this will include activities such as:

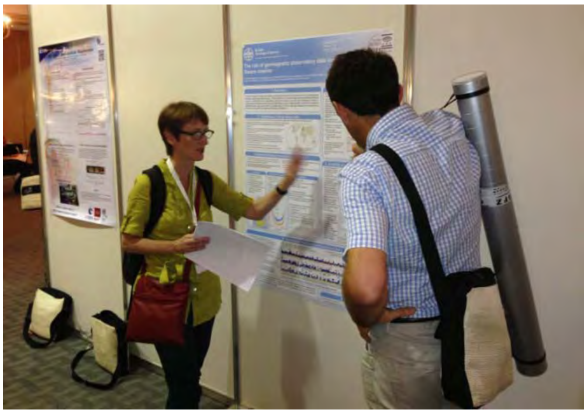
- Monitoring and probing of the deep Earth and near-space environments
- Maintaining and developing our network of magnetic sensors
- Working to improve society's resilience to the geomagnetic (space weather) hazard

Main Deliverables

Our specific deliverables for 2014 will be

- An INTERMAGNET-standard UK observatory network and an annual re-survey of sites in the UK magnetic repeat station network
- Operating to INTERMAGNET standards the BGS non-UK observatory network
- Supplying observatory data to INTERMAGNET, according to the timetable set by the INTERMAGNET organisation
- Delivering 'quasi-definitive' magnetic observatory data through INTERMAGNET for scientific and other use
- Publication of our observatory data and data products online, in the Monthly Bulletins series and in the Observatory Yearbooks series
- Supplying magnetic index products to the International Service for Geomagnetic Indices (ISGI), according to the timetable set by ISGI
- Operation of the World Data Centre for Geomagnetism (Edinburgh), including an annual 'call for data' and associated quality control activities

- Pursuing new scientific collaborations that address BGS aims and NERC themes
- Collaboration on existing international geomagnetic observatory (INDIGO) and survey programmes (MagNetE)
- Active participation (through presentations and organisation of sessions) in at least one major international scientific conference, e.g. the 2014 AGU meeting in San Francisco, the EGU meeting in Vienna, the UK National Astronomy Meeting, the COSPAR meeting in Moscow, the IAGA observatories workshop in India, and/or the AOGS conference in Sapporo.



Susan Macmillan explains her poster at the IAGA conference in Merida, Mexico

- Publication of two or more first-author papers in scientific and professional journals, and the writing of articles
- Operating and maintaining the BGS Swarm satellite 'level 2' models and data processing system for the ESA SCARF (Swarm Satellite Constellation Applications and Research Facility), to support the Swarm mission
- Publication of a Geomagnetism team annual report
- Provision of information and other data through the Geomagnetism web site, the main BGS site and by other electronic means. This will include 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

Artists view of the Swarm constellation in orbit. (Graphic courtesy of ESA)

- Working with UK Met Office as part of the Natural Hazards Partnership project, providing local and planetary magnetic indices and daily forecasts and magnetic data products

Exchange and training visit of Met Office staff member Chris Bulmer

- Monitoring and analysis of the geo-electric (telluric) measurements at the UK magnetic observatories
- Upgrading the Monitoring and Analysis of GIC (MAGIC) web tool, in association with National Grid

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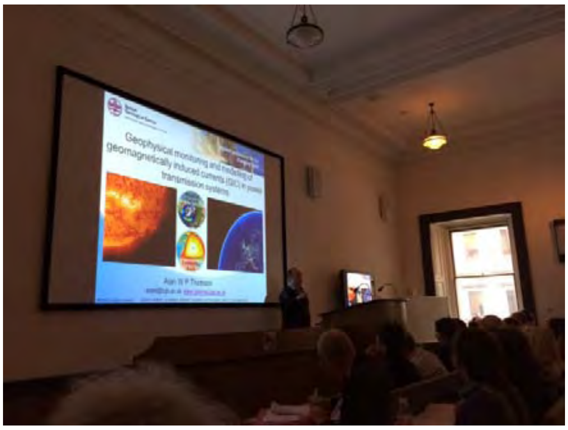
- Participation in UK space weather workshops, under the STFC 'SEREN' project, to develop research partnerships, particularly on space weather impacts on ground based technologies
- Organisation of two specific SEREN workshops on the geomagnetically induced current hazard to the UK power transmission system
- Carrying out geomagnetic data collection and processing ahead of World Magnetic Model and IGRF revisions in 2014-2015

Chris Turbitt making a magnetic survey at one of the UK repeat survey sites

- Producing the 2014 update of 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 IFR and IIFR services



Alan Thomson presenting at an RAS meeting on space weather in London

- Providing observatory facilities for calibration and testing of instruments
- Performing a re-survey of a number of the UK magnetic survey sites.
- Deriving the 2014 UK national magnetic model and delivery of customer report to Ordnance Survey
- Delivering a share of lectures to 4th year undergraduates at Edinburgh University on 'Geomagnetism'; set/mark exam questions; run tutorials; set/supervise student projects
- Delivering lectures to 3rd year undergraduates at Edinburgh University on 'Planetary Geophysics'; set/mark exam questions; run tutorials; set/supervise student projects

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Headline Numbers from 2013

Here are some key numbers, which help to put in perspective the team's outputs as a whole for 2013.

- Field reference data supplied for 730/130 IFR/IIFR wells
- 100% (>99%) UK (overseas) observatory data coverage
- 97 Ordnance Survey map compass references
- 96 magnetic bulletins published
- 27 field set-ups for IFR services
- 17 journal and conference proceedings papers, 15 scientific meetings, 42 presentations/posters
- 15 oil industry customer reports
- 6 articles on space weather for RIN 'Navigation News'
- 6 positions on scientific and technical geomagnetism bodies
- 5 observatory tours
- 3 post-doctorate research assistants
- 2 geomagnetic models (UK reference model and BGGM2013)
- 2 undergraduate courses taught
- 1 radio interview, 1 podcast and a number of newspaper and web articles and quotes
- 1 PhD student
- 1 MSc student

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Technical, Observatory and Field Operations

Surveying the new absolute observing pillar using differential GPS at Port Stanley Observatory, Falkland Islands

UK and Overseas Observatories

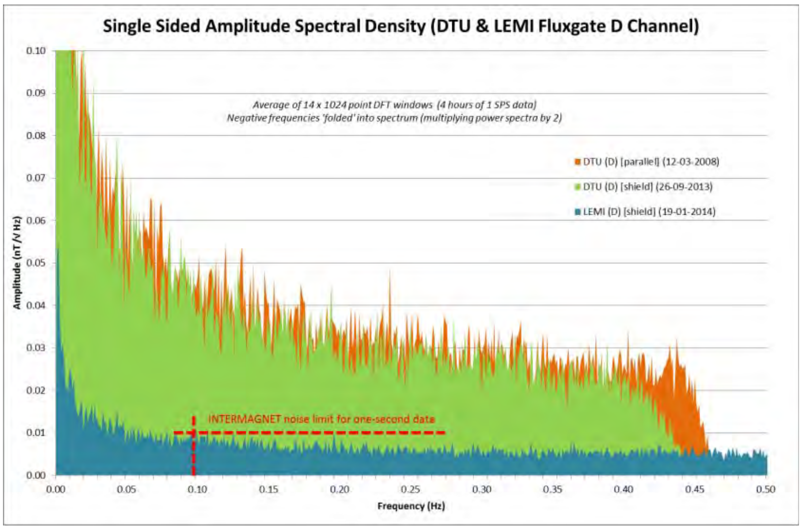
BGS operates three absolute geomagnetic observatories in the UK and five overseas to supply high quality, real-time measurements for research and services. We also take a leading role in expanding the global observatory network, to improve global modelling and for local applications. The UK observatories achieved 100% continuous data supply in 2013.

Technical Developments

Preparations continued through 2013 for the introduction of instrumentation to meet the new INTERMAGNET standard for one-second data. As well as specifying a higher sample rate, the standards demand that magnetometers operate with lower noise in order to resolve lower amplitude signals in the extended frequency band.

As shown in the figure below, testing with the five-layer mu-metal shield at Eskdalemuir Observatory verified noise estimates of a standard one-minute magnetometer (the DTU FGE) that had previously been made using a parallel instrument technique. Further tests on a LEMI-025 magnetometer showed that these newly-acquired instruments surpass the one-second INTERMAGNET standard and confirm the shield's ability to attenuate the natural field.

These tests pave the way for long-term



Noise tests results on two models of fluxgate magnetometer at Eskdalemuir Observatory (orange (2008) and green (2013) are from DTU instruments and blue is from the proposed new LEMI instrument). The INTERMAGNET limit for one-second data is 0.01 nT/√Hz at 0.1 Hz (red dashed line)

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stability testing of the LEMI-025 at Eskdalemuir. To support this testing, a major revision of the in-house data acquisition software was completed and rolled out to the observatories. This revision is based on an upgrade to the QNX operating system. Replacement of recording PCs is expected to be completed by the end of 2014.

The resilience of the back-up data communications between the observatories and Edinburgh was improved using an adaptable network architecture (VPN and Dynamic DNS). The performance of the entire real-time network is now more accurately supervised through an independent, external monitoring service.

Magnetic Observatories

Construction on the new office at Lerwick Observatory started early in the year and all BGS equipment was transferred in late summer. This was successfully co-ordinated with the Met Office to prevent any disruption, or data loss, during building or changeover.

Increasing artificial noise at Port Stanley Observatory over a number of years led to a decision to move the absolute observing site. This year a new position was established and surveyed. The measurement series at the new and old sites were overlapped by six months to establish transfer coefficients and therefore continuity of data.

A training course was held at Hartland Observatory on instrumentation and observing practice. This helped prepare a new member of staff from the British Antarctic Survey to operate the South Georgia observatory on behalf of BGS, during his deployment at King Edward Point.

The installation of two-component electric field monitors at the UK observatories was completed by April 2013 and real-time data are now available on the Geomagnetism web site.

UK Repeat Station Network

The 2013 magnetic repeat station programme covered nine measurement locations in the North of Scotland & Western Isles, West Wales & the Shropshire Hills and the North of England. 2013 was the third successive year when a differential GPS system was used in preference to a north-seeking gyroscope to determine the azimuth of true north when making declination measurements.

Global Network

BGS continues to be active on the INTERMAGNET committee and in the INDIGO project. The objective of INDIGO is to increase the number of INTERMAGNET-quality digital observatories around the world. BGS ran a training course for two observers from the Argentinian Servicio Meteorológico Nacional. This covered all aspects of running an observatory from instrument to final data production. This followed the admission of the INDIGO-supported Base Orcadas and Pilar Observatories into INTERMAGNET.

The GDASView processing application was redeveloped during 2013 to simplify the production of definitive and quasi-definitive magnetic observatory data. GDASView is used extensively by overseas institutes, including Gan Observatory (Maldives), which also joined INTERMAGNET this year.

Another new INTERMAGNET observatory is Cheongyang (South Korea). The observatory was advised on data production and the INTERMAGNET application process during a BGS staff visit to the operating institute, KRISS.

Technical, Observatory and Field Operations

The BGS Contribution to INTERMAGNET

Participants of the INTERMAGNET EXCOM/OPSCOM Meeting at the Danish Technical University in Lyngby, Denmark. October 2013

BGS continues to make significant contributions to the INTERMAGNET programme (www.intermagnet.org). INTERMAGNET is a consortium of world-wide institutes and observatories that make measurements of the Earth's magnetic field to agreed quality standards. 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 infrastructure.

New data products

In the run up to the launch of the ESA Swarm satellites, we have mounted a campaign to encourage observatories to submit preliminary absolute data to INTERMAGNET in a timely manner. This new data type is known as quasi-definitive (QDD). QDD was described at length in the 2012 annual report.

One role for QDD is providing independent data for validating Swarm models, for example by comparing measurements made by the satellite magnetometers with the ground based observations of the magnetic field during a Swarm 'over-pass'. Another role is for QDD to be combined with Swarm data for deriving global magnetic models.

In the Figure overleaf (top) we see that there has been a gradual rise in the number of observatories providing QDD. (The tail off in QDD provision towards the end of the report period is expected, since the data are required to be reported within three months of recording.) Work is continuing to convince other INTERMAGNET observatories of the growing importance of providing this data type.

Improved real-time performance

INTERMAGNET continues to encourage observatories to contribute 1-second data. We are also working with observatories to improve the speed at which they forward their data to INTERMAGNET.

The figure overleaf (at bottom) shows minimum (blue bars), mean (green) and maximum (red) lag times for those observatories that contributed 1-second data to INTERMAGNET in the

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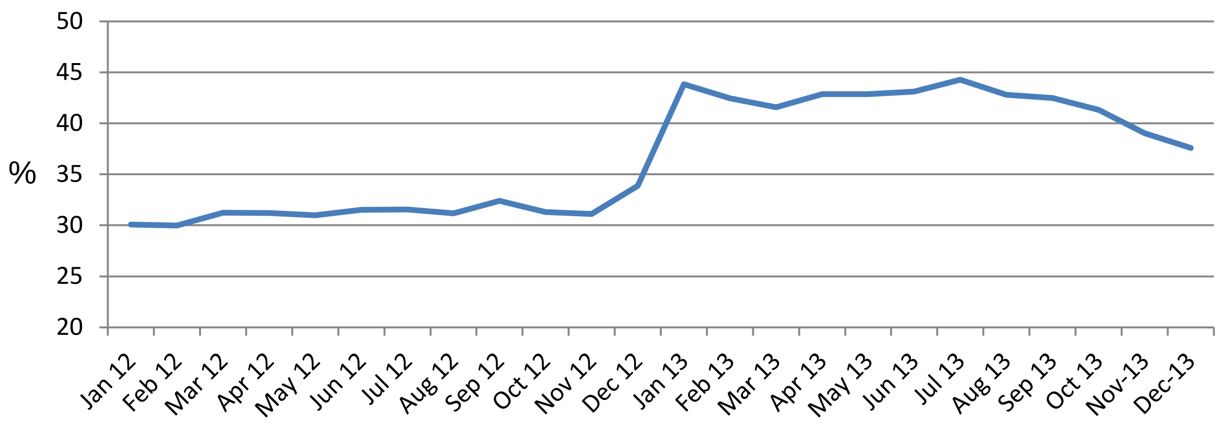
month of September in 2013 (as an example of capability).

Lag times are calculated by taking the difference between the current time and the time of the data sample immediately before a data update is received. This therefore represents the longest time a user would have to wait to receive real-time data.

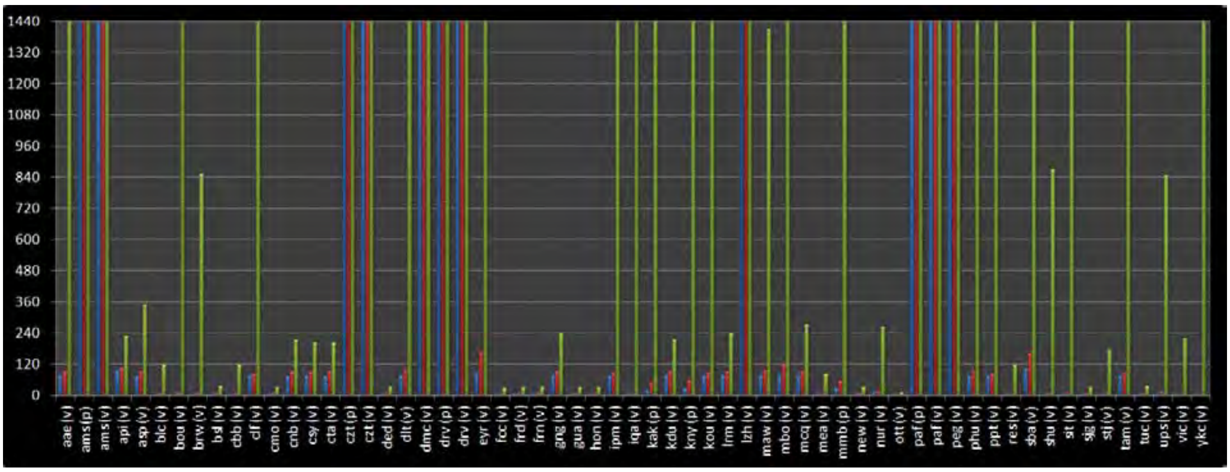
A number of observatories are starting to regularly achieve the current INTERMAGNET goal of making data available within 20 minutes of recording (the previous INTERMAGNET requirement was 72 hours).

The performance of the Canadian and American observatories is good in this respect: the Canadians since they also operate the INTERMAGNET data centre; and the Americans since they operate a real-time data collection network (based on the seismic 'Earthworm' software).

For other observatories the 20 minute target is more of a challenge, but, with encouragement and help, more observatories are starting to achieve it.



The number of observatories contributing quasi-definitive data to INTERMAGNET (as a percentage of the total number of observatories in INTERMAGNET) between January 2012 and December 2013



Minimum (blue bars), mean (red) and maximum (green) lag times, in minutes, for those observatories that contributed 1-second data to INTERMAGNET in September 2013. Observatories are identified by IAGA code along the lower axis

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Britain and Ireland at night, seen from space (Figure courtesy NASA/ISS)

The European Risk from Geomagnetically Induced Currents (EURISGIC)

Over a three year project lifetime the EURISGIC consortium developed the first ever model of the flow of hazardous geomagnetically induced currents in the European electrical transmission system. A prototype forecast system was also constructed and possible worst case and extreme event hazard scenarios for the grid were examined. As this project ends we summarise BGS activities and outputs.

BGS, together with colleagues at institutes across Europe, Russia and the US, was funded from 2011 to the end of 2013 by the European Union's Seventh Framework Programme to study the geomagnetically induced current (GIC) hazard to Europe's power transmission system.

The project had a number of strands to it, including modelling GIC in the European system and understanding the possible extremes that the system could face. These project strands were represented by nine distinct work packages:

- The construction of the first ever European power transmission grid model and update of the UK model
- The development of detailed conductivity models for Europe and, separately, the UK
- The building of geomagnetic, GIC and related science databases
- The production of a GIC risk map for Europe
- The investigation of worst case scenarios and extremes in the grid model
- The development of the NASA 'Solar Shield' magnetospheric and solar wind model for use in the European context
- The enhancement of a prototype GIC and geomagnetic forecast system for Europe
- The making of geomagnetic, geoelectric and GIC measurements to enhance our knowledge and validate models
- The education of the public and other stakeholders through scientific papers and other materials.

To assess and guide progress on the project a team of industry advisors was assembled. These advisors included senior power engineers from major electrical transmission system operators from across Europe, including National Grid in the UK.

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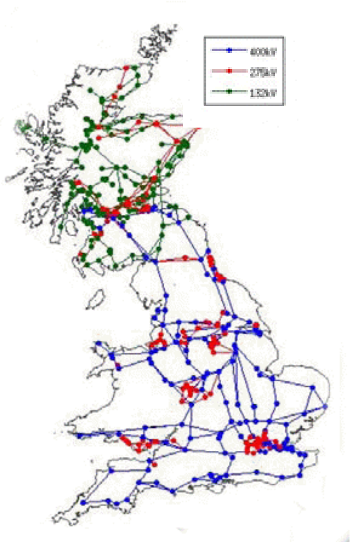
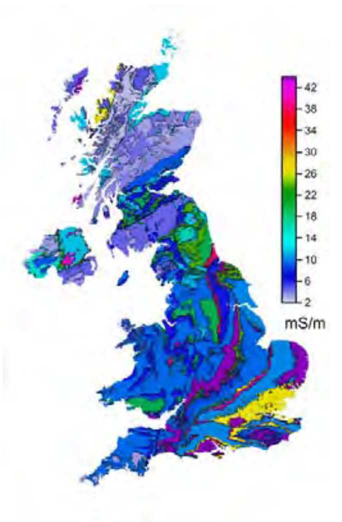
The BGS geomagnetism team led activities that modelled the UK grid (with National Grid), developed a new UK 3D conductivity model, quantified extreme events and measured the geo-electric field in the UK.

The transmission system model for the UK was upgraded to include more detailed line and transformer specifications. We also added the 132 kV system of Scotland to the existing 410 kV and 275 kV transmission models for Great Britain. This new model has now been incorporated into services for National Grid.



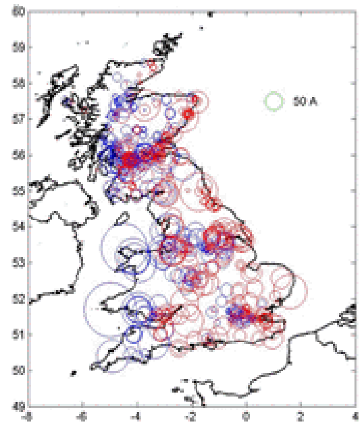
The updated UK model of the high voltage transmission system



The 'geological-conductivity' model of the UK based on the 1:625000 BGS geological map

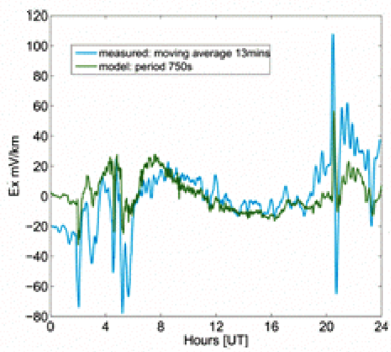
A highly detailed UK 'geological-conductivity' model was developed, based on airborne HiRes active electromagnetic sounding of the shallow sub-surface.

The new grid and conductivity models were tested in respect of previously recorded severe geomagnetic storms and hypothetical events, including an estimate of the 1 in 100-200 year worst case.



Estimated 1 in 200 year extreme GIC in the transmission system. Spot size is proportional to current into (red) or out of (blue) the ground. Spots are summed GIC at transformer substations

Geo-electric field measurement hardware was installed at the UK observatories during 2012 and 2013. The measured data have since been used to validate the surface electric field models that BGS have used in estimating GIC in the UK grid. But the results also show where improvements may yet be made – an activity that will extend well beyond the end of the EURISGIC project.



Measured (blue) and modelled (green) geoelectric field at Eskdalemuir for the storm of 2nd October 2013. Differences are in part due to local induction effects. Electric field in the north direction is shown

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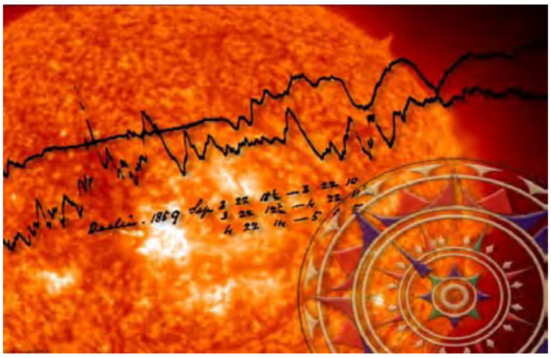
Science



Solar activity – the source of space weather and geomagnetic storms (solar image courtesy of ESA)

14 Years of Space Weather Forecasts: Have We Done a Good Job?

Since the 1990s, every Monday to Friday morning, a three-day geomagnetic activity forecast is issued by one of a team of space weather forecasters in BGS. By comparing these forecasts with observed activity levels we have made an analysis of the performance of the forecasting team over 14 years, more than one solar cycle. By using appropriate metrics, feedback can now be given to both the forecasters and to the various forecast users, on the value of the daily forecast.

The BGS Space Weather forecasts are:

- Predictions of globally averaged geomagnetic activity levels
- Issued every weekday before noon (weekends are not included as this is not a commercially funded service)
- Noon to noon (UT) forecasts for 1-3 days ahead. Noon to noon is more likely to capture storms in the local UK night time sector

BRITISH GEOLOGICAL SURVEY: NATIONAL GEOMAGNETIC SERVICE
GEOMAGNETIC ACTIVITY FORECAST FOR SPERRY DRILLING

Forecast Interval (GMT)	Forecast Global Activity Level
Noon 28-OCT-2003 to Noon 29-OCT-2003	ACTIVE
Noon 29-OCT-2003 to Noon 30-OCT-2003	MINOR-STORM
Noon 30-OCT-2003 to Noon 31-OCT-2003	MINOR-STORM

The daily activity forecast issued on the morning of 28th October 2003

The forecasts make use of public domain space weather observations, models and alerts, tapping into the specific expertise of our own and various groups around the world.

The forecasts are given in terms of one of four activity levels, based on the *Ap* magnetic index, as shown below:

ACTIVITY CLASS	Daily Planetary Activity Level (Ap)
QUIET – UNSETTLED	<=15
ACTIVE	16-29
MINOR STORM	30-49
MAJOR STORM	>=50

Over the years the recipients of the service have included:

- Met Office (UK), as part of the 'National Hazards Partnership' Daily Hazard Assessment, intended to inform the UK

Cabinet Office Civil Contingencies Secretariat and emergency responders

- Power companies concerned about Geomagnetically Induced Currents (GIC), e.g., Scottish Power and National Grid
- Oil industry companies using directional drilling techniques, e.g. Halliburton Sperry Drilling and Baker Hughes
- Geophysical prospecting companies
- Organisations working on instrument calibrations, e.g. , National Physical Laboratory and Bartington Instruments
- The general public interested in aurora alerts; and
- Geomagnetism colleagues and other partners planning for field work or absolute observations at observatories

Forecast Verification

At first glance it would appear to be a straightforward enough task to verify a forecast – each prediction is either right or wrong. However for space weather forecasts of this type the climatological distribution of the classes needs to be accounted for. It is not simply a question of obtaining the percentage correct values, since the highest scores would be achieved by predicting the most frequent class (Quiet-Unsettled, QU) every day: a forecast needs also to be of value to a user.

A skill score for space weather forecasts should be:

- Equitable
- Discouraging of hedging
- Useful faced with rare events

There is no single measure designed (so far) that is strong in all three. Therefore a few Skill Scores (SS) have been assessed and a selection of preliminary results is shown. For a SS also to be meaningful it needs to be compared against the equivalent SS of some benchmark forecast.

For this benchmark we chose a forecast based on the average of activity levels 1 and 27 days before. This provides a prediction based on some physical properties of geomagnetic activity, that of persistence and recurrence, and taken in equal proportions. A meaningful prediction of this type provides a good target for the forecasting team to beat.

Two-Category Equitable Skill Scores

Binary contingency tables can be used to investigate ‘Storm’ and ‘No-Storm’ results. ‘Storm’ is defined as either Minor Storm or Major Storm, and ‘No-Storm’ is the sum of Quiet-Unsettled and Active.

2x2 contingency table		Magnetic Storm Observed		Marginal Total
		Yes	No	
Magnetic Storm Forecast	Yes	A	B	A + B
	No	C	D	C + D
Marginal Total		A + C	B + D	n (A+B+C+D)

Benchmark		Storm Observed		Marginal Total
		Yes	No	
Storm Forecast	Yes	62	111	173
	No	140	3312	3452
Marginal Total		202	3423	3625

Geomag Forecasters		Storm Observed		Marginal Total
		Yes	No	
Storm Forecast	Yes	63	74	137
	No	139	3349	3488
Marginal Total		202	3423	3625

2x2 contingency tables – the general scheme (top), and the actual benchmark (middle) and forecasters (bottom) performance for the period 2000 to 2013

These tables can be created very easily and the values used to compute various SS. One such is the Heidke skill score (HSS), defined in terms of the entries in the tables above.

$$HSS = (A+D-E)/(n-E)$$

where E is a correct random forecast, given by

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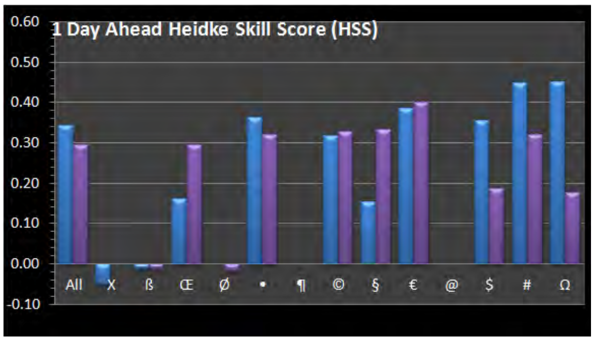
E = [(A+B)(A+C)+(B+D)(C+D)]/n

The HSS results for the 1-day ahead forecasts are shown below.



HSS for all forecasters together (far left) and individually (left to right), compared with the benchmark forecast over the same periods. Forecaster scores are anonymous (symbols) and in blue, benchmark scores are purple

The forecasting team overall has a higher SS than the benchmark. However a few forecasters have a lower score. We also see that for some, both scores are either very low, negative or not computed. This highlights a weakness of this type of SS: volatile results resulting from low values of *n*. Some forecasters may not have been making forecasts for long and so *n* is low.

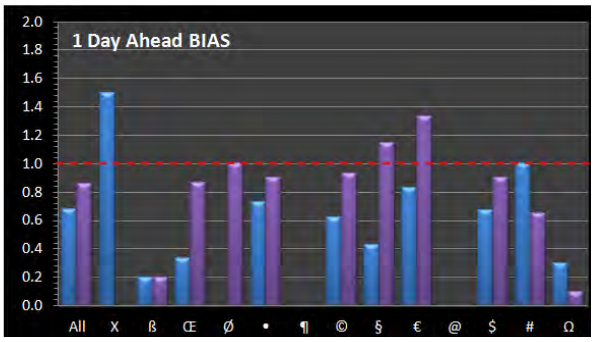
Whilst useful the HSS does not provide a complete evaluation of performance. A simple metric to complement HSS is the bias score or frequency bias.

BIAS=(A+B)/(A+C)

A comparison of bias scores is shown on the right (top). The benchmark typically has higher bias, which shows its limitations.

Multi-Category Equitable Skill Scores

Gandin and Murphy (1992) and Gerrity (1992) between them devised a way of extending equitable skill scores (ESS) to more than two categories using *kxk*



BIAS for all forecasters' together and individually compared (both blue) with the benchmark forecast BIAS (purple) over the same periods

contingency tables. The general formula is

$$ESS = \sum_{i=1}^{k}\sum_{j=1}^{k} p_{ij}s_{ij}$$

where p_{ij} are the elements in the probability contingency table (P), s_{ij} are the elements in a corresponding scoring matrix (S).

4 x 4 contingency matrix		Forecast Category				Marginal Total
		Q-U	ACTIVE	MINOR	MAJOR	
Observed Category	Q-U	3604	422	96	31	4153
	ACTIVE	414	169	46	9	638
	MINOR	96	55	22	9	182
	MAJOR	51	24	11	6	92
Marginal Total		4165	670	175	55	5065

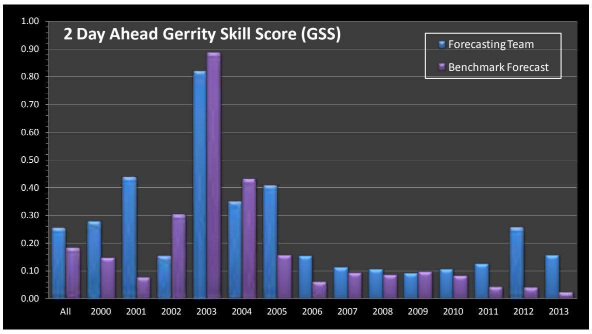
4 x 4 Probability matrix (P)		Forecast Category				Climatological probability
		Q-U	ACTIVE	MINOR	MAJOR	
Observed Category	Q-U	0.7115	0.0833	0.0190	0.0061	0.8199
	ACTIVE	0.0817	0.0334	0.0091	0.0018	0.1260
	MINOR	0.0190	0.0109	0.0043	0.0018	0.0359
	MAJOR	0.0101	0.0047	0.0022	0.0012	0.0182
Forecast probability		0.8223	0.1323	0.0346	0.0109	1.0000

4 x 4 reward-penalty or scoring matrix (S) as per Gerrity (1992)		Forecast Category			
		Q-U	ACTIVE	MINOR	MAJOR
Observed Category	Q-U	0.0984	-0.3081	-0.6605	-1.0000
	ACTIVE	-0.3081	1.5431	1.1907	0.8512
	MINOR	-0.6605	1.1907	7.3525	7.0130
	MAJOR	-1.0000	0.8512	7.0130	25.3645

4x4 contingency tables – forecasters (top), probability (P) matrix (middle) and scoring (S) matrix (bottom) for the period 2000 to 2013

The Gerrity Skill Score (GSS) covering all four forecast categories has been derived. The values in the S matrix show that higher rewards are generally obtained for correct forecasts (diagonal). However since the probability of occurrence is also highest in the top left box of the probability matrix, much lower rewards are given in the S matrix. Significantly higher rewards are given for those elements where the probability of occurrence is low – bottom right and neighbouring cells. This rewards correct forecasts of the rarest events the most. Rewards are also high for missing the rarest events by one category.

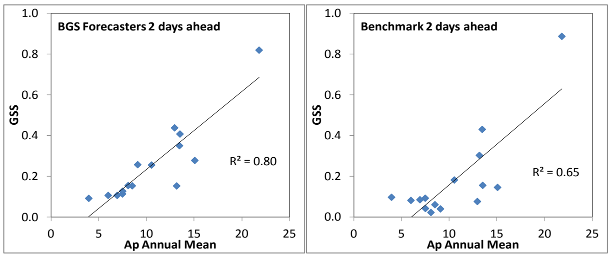
Results for the forecasting team for each of 1, 2 and 3 day-ahead forecasts over the 14 years studied compared to the benchmark have been derived. The results for the 2 day-ahead forecasts are shown here (below).



Annual 2-day GSS for both forecasts computed with the fixed S-matrix

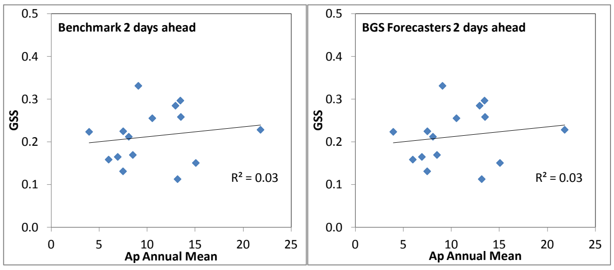
Overall the forecasting team have a higher SS than the benchmark in most years. In some years both SS are much greater than in other years: some dependence on geomagnetic activity levels is therefore possible, which would imply a non-equitable SS. To test this we plot the annual GSS results against the annual mean *Ap* as shown (top right).

The degree of correlation indicates a clear dependency of the SS on activity levels. A new S matrix has therefore been derived for each year in question, based only on the climatology of that year, as opposed to the complete 14 year data set.



Correlation between GSS and Ap for both forecasts with fixed S matrix

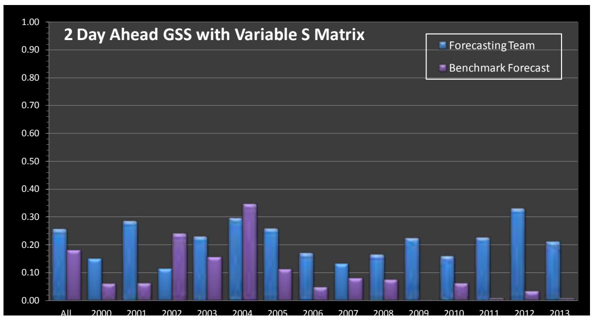
The new GSS is then computed based on the new, variable S matrices. The revised results of the regression analysis (below) suggest that the solar cycle dependence is successfully removed.



Correlation between GSS and Ap for both forecasts computed with variable S matrix

The revised GSS is therefore shown below with the year to year variations now much less. The GSS values are now smaller overall than those obtained with the fixed S matrix. However the absolute level is not as important a metric as the relative levels between methods. The benchmark model now scores better than the team in only 2 out of the 14 years analysed as opposed to 4 out of 14 with the fixed S matrix.

So, have we done a good job of forecasting? These preliminary statistics suggest that we have made a difference, though accurately forecasting geomagnetic activity remains a hard problem.



Revised annual GSS for both forecasts computed with variable S matrix

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Science

Digitised, One-Minute Geomagnetic Data for the Carrington Event

The Greenwich magnetogram for 1st September 1859 is shown on BBC 'Stargazing Live' in January 2014

The geomagnetic storm of early September 1859 is widely regarded as the most severe ever recorded. Dubbed the 'Carrington event', after the astronomer Richard Carrington who observed its precursor solar flare, it suggested a link between solar and geomagnetic activity.

Although few magnetic observatories were operating at this time around the world, there were two working in the London area – Kew (KEW) and Greenwich GRW). Both observatories were recording continuous magnetic variations on photographic paper and both captured large parts of the 1859 storm. The Carrington and other analogue magnetic records held by BGS have now been scanned in a campaign which began in 2007.

As part of the European Risk from Geomagnetically Induced Currents (EURISGIC) project, we looked to provide digital scientific data for the most extreme historical geomagnetic events. Some of the most powerful geomagnetic storms of the last 150 years have therefore now been digitised, including the data from the Carrington event.

This digitisation process started with selecting and implementing a program to enable the tracing of the scanned images. In-house and open-source 'Engauge Digitize' (ED) software were considered for the task. ED was chosen due to its relative user-friendly and stable graphical interface, enhanced viewing facility and adaptability to handle the types of traces typical of magnetograms.

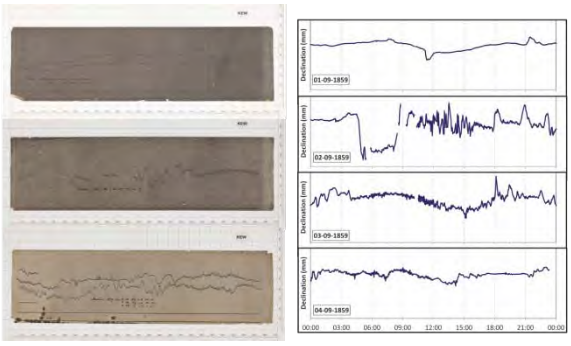
Despite the advantages of ED, the digitisation of storm-time magnetograms proved both time-consuming and complex due to the age and quality of the records. Converging and crossing components, missing traces due to 'clipping', indiscernible lines during rapid field movement and record quality due to original photo processing, storage and handling have all proved challenging.

However the magnetograms for the Carrington event were not too problematic and an almost complete digital record for the relevant days now exists. But gaps do occur at the peak of the storm when the variations recorded at both observatories were off scale (literally off-page) and therefore missed.

The project included the development of in-house software to process the ED output, which are sets of coordinates given in pixels. This software was used to process the ED digitised curves along with start and end times and other relevant metadata to obtain scaled, baseline adjusted, time-stamped values.

At both GRW and KEW, *H* and *Z* were recorded in 'parts of the whole'. Therefore, in order to compute values, scale and baseline further information had to be found from observatory yearbooks.

In the case of the Carrington event for KEW, uncertainty remains over this metadata. Therefore annual means were used for the baselines and the scale determined from the previously published magnitudes of the solar flare effect (*sfe*) at 11.15 UT on 1 September 1859.

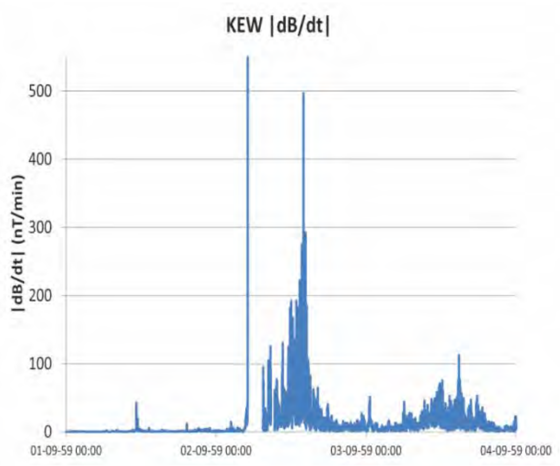


Kew Declination magnetograms for the Carrington storm. Photographed/scanned original images (left) and digitised data (right)

Verification of the digitised magnetograms required comparison between the GRW and KEW results. We found that, for *D* and *H*, KEW variations were greater than GRW by a factor of 1.1. Possible sources of this error are scale information, the digitisation process or original measurement error. The fact that GRW variations in *Z* were far greater than those at KEW prompted further re-examination and indications of an unnatural diurnal drift were detected. As this is observed in the original magnetograms, where the variation clearly dwarfs the *sfe* (Sept 1), it is likely to be an error in the original instrument set-up, rather than with the digitisation process. Further analysis is required and results here are therefore preliminary.

Additional verification of the data was achieved by computing hourly means from the digitised GRW and KEW data and comparing these with hourly spot values from Russian observatories at St Petersburg (STP) and Barnaul (BAR) as well as with hourly mean values from Helsinki (HEL), Finland. The results show a reasonable correspondence between the UK, Finnish and Russian data.

The time rate of change of the horizontal magnetic field (d*H*/dt) at both London sites was also calculated (d*H*/dt is the main factor in creating Geomagnetically Induced Currents in the electrical power transmission system). While data are unavailable at the peak of the storm, information given in a paper by the then Kew Director, Balfour Stewart, indicates that the maximum deviation was in excess of 700nT. Our analysis shows that, at the point where the *H* trace leaves the photographic paper, |d*H*/dt| is ~500 nT/min.

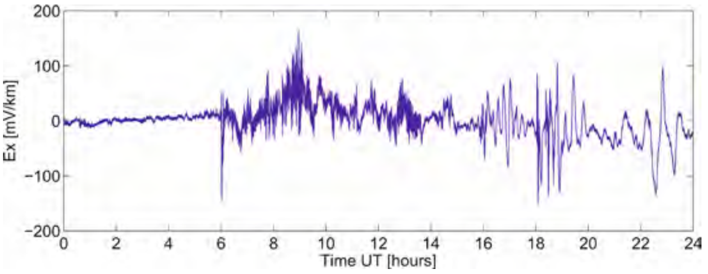


KEW |dB/dt| 1-4 September 1859

For context, at a modern day observatory (Hartland) of similar geomagnetic latitude to that estimated for London at this time (~51.5º N), the maximum measured |d*H*/dt| in the digital era has been 327 nT/min. Additionally, a published BGS statistical study on extremes estimated that the 100 and 200 year return level for |d*H*/dt| to be ~600 and ~800 nT/min respectively for this latitude.

In conclusion, the estimated |d*H*/dt| indicates individual events during the Carrington storm of nearly twice the peak of the March 1989 storm in the South of England. But we will probably never know just how big |d*H*/dt| was 'in the gaps'.

Science



Measured geo-electric field in mV/km at Eskdalemuir observatory, for a magnetically stormy day in 2013 (north component shown)

Extreme Values in Geoelectric Fields

Since 1957 the Nagycenk Széchenyi István Geophysical Observatory, Hungary, has made continuous geo-electric field (telluric) measurements. Knowing the geo-electric field is important as it directly determines the space weather hazard to power grids. Given this unique and long continuous record, the Nagycenk data are therefore ideal for estimating extremes in the electric field due to severe space weather. Here we provide an initial assessment of the one in 100 and one in 200 year extremes, using an extreme value statistical analysis.

Nagycenk observatory (IAGA code: NCK), lies on thick conductive sediment and is situated within a National Park; the latter helping to reduce the effects of man-made electromagnetic noise. Potential differences are measured in the North-South (*E*x) and East-West (*E*y) directions, using low polarization, lead electrodes, buried 2m deep. The electrode spacing is 500 m and data are recorded at 1 sec and 10 sec sampling intervals. Data resolution is about 6.1 μV/km. Data have been digitally recorded since 1994: data prior to this are in paper form and are currently being scanned and digitised.

In a preliminary survey of these data, using the technique of extreme value statistics (EVS), we analysed approximately 19 years (Feb 1994 to Aug 2013) of digital 10-second geo-electric data in *E*x and *E*y,as well as the 3-hour NCK *K* index (geomagnetic activity measure) and the three-hour *T*-index (geo-electric activity measure). We selected only data where the NCK observatory *K* index > 7, which provided 106 days for analysis. Then, for each day, we made a least squares fit, to estimate the daily baseline, and removed this baseline to leave the variations. Finally we analysed the variations using the ‘eXtremes’ software toolkit through the *R* statistical package.

The maximum 10-second values per 3 hour time block were used as our basic data set. This provided a manageable reduction in data size, from around 1 million samples to approximately 53,000 data. A second data set of the maximum 10-second values per day were also analysed for comparison and consistency with the first data set.

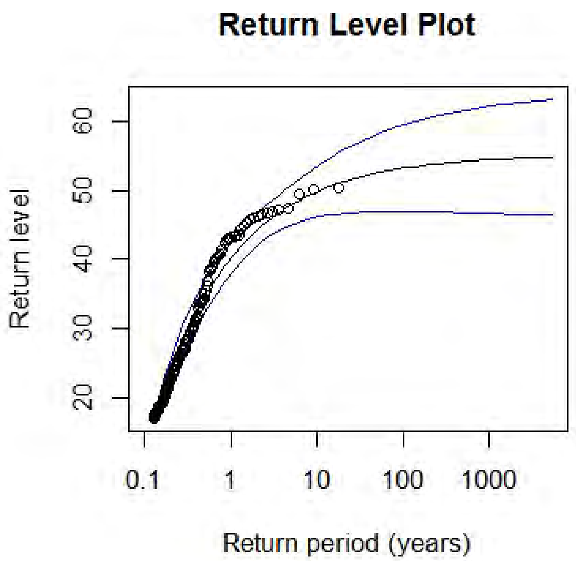
The maxima in both *E*x and *E*y were determined for the time-span of data. The projected generalised Pareto distribution (central to the EVS method) for periods of 100 and 200 years were then computed and 95% confidence levels were estimated.

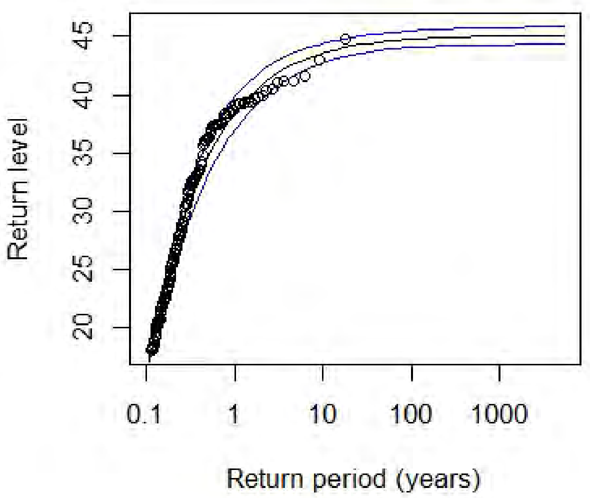
Referring to the two plots on this page, what we found was that:

- For *both* the 100 and 200 year return periods, the anticipated levels for the geo-electric data are about the same at 45 mV/km and 54 mV/km, for *E*x and *E*y respectively. These are small levels of geoelectric field, compared to measurements made at Eskdalemuir observatory, and may reflect the latitude of the observatory, or the geological nature of the region and its more conductive nature
- The return level curves therefore tend to 'saturate' above about a 10 year return period, meaning that such 'extremes' are already in the data set. This is unexpected and indicates that further work is required
- Using the daily maxima of 10-second data produces similar results (the second data set referred to earlier and not shown here)
- There is a sensitivity of the results to the choice of threshold (currently set at ~33% of the peak level, which is substantially less than for similar treatments of geomagnetic data). More work is therefore needed on the threshold selection.

Future work will include:

- Repeating the analysis by including days when the local *K* index is at least 6 (adding ~500 days more for processing and analysis), or through better correction of baselines, jumps and spikes in the data
- Repeating the analysis with scanned, digitised, and quality checked telluric data for more of the 50 years in the NCK record
- Re-computing the NCK *T* index with an unbounded upper limit and analyzing this data set via EVS
- In 2012, geoelectric monitoring equipment was installed at the three UK geomagnetic observatories. Data are now being recorded at these sites with the intention, over the long term, of comparing with the Nagycenk data, to provide a wider European scale view of surface geo-electric fields and their extremes.





Return level plots in Ex (above) and Ey (top) for Nagycenk. Units for the return level are mV/km. 95% confidence limits are shown in blue. Circles denote measured data

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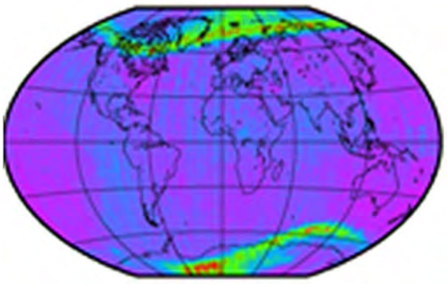
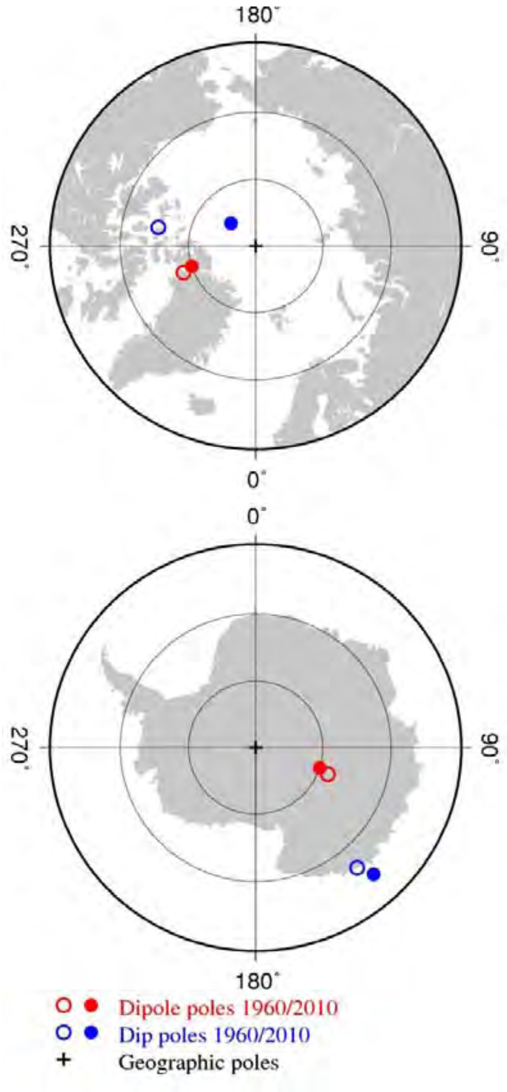
Science

Secular Change in Auroral Oval Locations



The two auroral zones are clearly identified (green/red) in this map of satellite magnetic measurements, where a model of the internal field has

A decline in the strength of the dipolar component of the Earth's magnetic field is expected to result in equatorward shifts in both auroral zones. It is also expected that the auroral zones should become wider. Although solar cycle and other long-term changes in the Sun and solar wind are the main drivers for changes in the locations of the zones over decadal timescales, it is conceivable that the internal field also has a detectable effect. This could affect the frequency and strength of magnetic storms in the UK.



In a study to test the impact of decadal changes in the internal magnetic field on the auroral zones, we first chose satellite vector magnetic data collected in 1979-1980 (by the US Magsat satellite) and during 2000-2010 (by the German CHAMP satellite) under similar magnetic activity and other conditions.

Data for times when the CHAMP satellite was in orbit during the same local times as Magsat (dawn-dusk) and within the same altitude range were then selected. The polar crossings in both the selected Magsat and CHAMP data were binned according to a proxy that represented solar wind conditions.

For each crossing in each bin the geomagnetic latitudes of the pole-ward and equator-ward boundaries (two of each) were identified in the magnetic vector data. The averages in the north and the south for each bin were first compared in the Magsat data to check that the north-south asymmetry in the polar magnetic field was apparent.

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We found that the auroral zone equator-ward boundary, especially on the dusk side, was closer to the dipole pole in the northern hemisphere, than it was in the south. This is consistent with the influence of the dip pole, which is closer to the dipole pole in the northern hemisphere. Although the scatter in the geomagnetic latitudes for the poleward boundaries meant that their results were less robust, this test did give some reassurance that the method used to detect the boundaries was working.

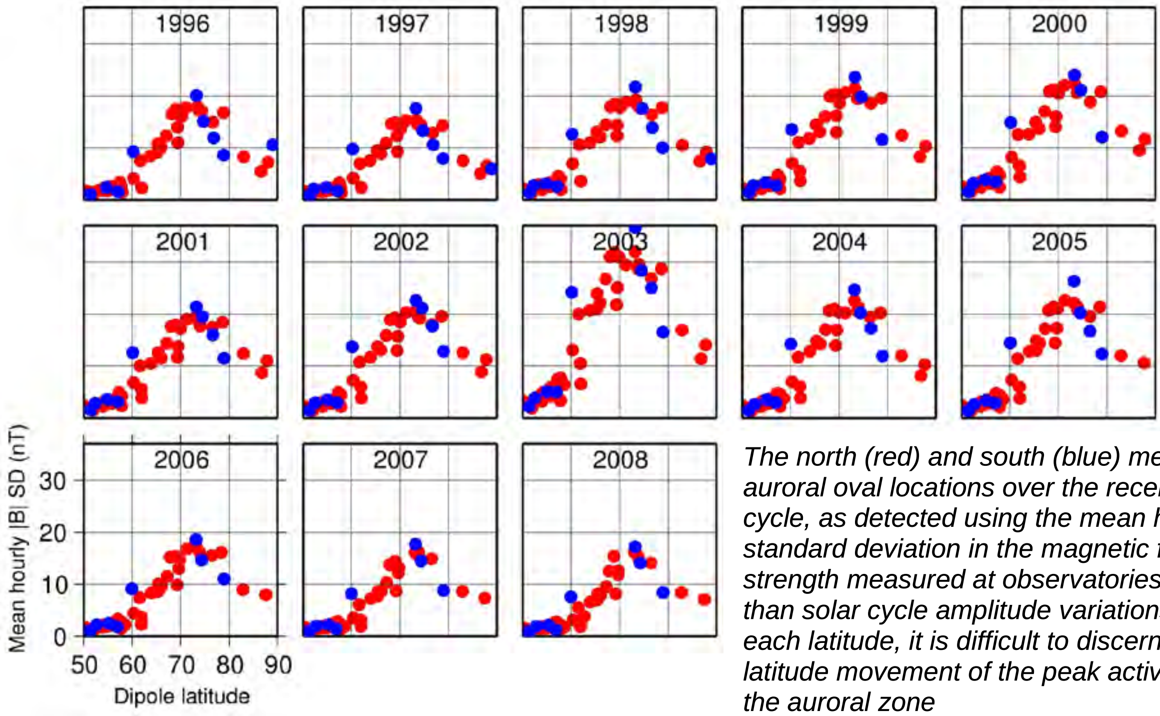
The next step was to compare the results between the two satellites, i.e. epochs. The equator-ward boundaries tended to be further north for CHAMP than for Magsat but the pole-ward boundaries were further south. Thus, as the dipole moment has become weaker, it may be the case that the auroral ovals are actually becoming narrower and, moreover, any equator-ward shift of the ovals is not detectable.

However in this work it is important to back out any effects of the solar cycle and effects due to the solar wind. These effects are clearly visible in a similar study to pinpoint the auroral zone using observatory data (see figure below). Any north-south asymmetry is not apparent in the observatory data, although the relatively poor data coverage in latitude (compared to that from satellites) doesn't help in detecting small changes.

In a related study, we looked at the change over time in the average magnetic flux over the two polar regions. This change has been found to be much greater in the south than in the north.

This reduction in the flux in the southern polar region means that the minimum altitude at which charged particles injected from space bounce back out to space is decreasing. This could affect the location of the auroral zone and the impact of space weather in the southern hemisphere.

However the spatial gradients of the magnetic field (and the changes over time in these gradients) are also different between the two polar regions. This makes a definitive interpretation difficult.



The north (red) and south (blue) mean auroral oval locations over the recent solar cycle, as detected using the mean hourly standard deviation in the magnetic field strength measured at observatories. Other than solar cycle amplitude variations at each latitude, it is difficult to discern any latitude movement of the peak activity, i.e. the auroral zone

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Artists view of the ESA Swarm satellite constellation. Swarm will aid development of better models for directional drilling (Illustration courtesy of ESA)

Directional Drilling

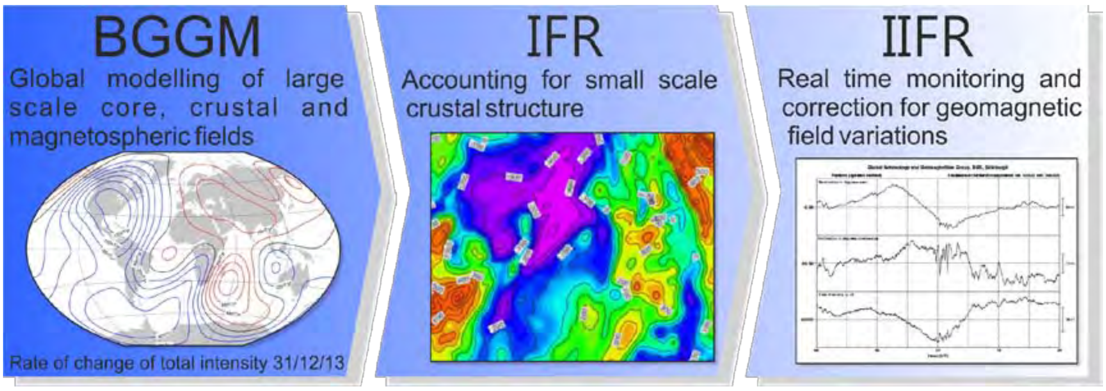
Extended reach and horizontal wells are becoming ever more common in oilfields around the world, with oil platforms now capable of sourcing targets greater than 10 km away. Navigating these wells through the subsurface, where GPS can't be used, commonly employs a technique known as magnetically referenced Measurement While Drilling (MWD). Throughout 2013, BGS continued to aid MWD efforts around the globe by providing a comprehensive geomagnetic referencing service to industry. Also in 2013, our research focused on developing and refining this service.

Determining the direction of the wellbore using the MWD technique requires knowledge of how the local magnetic field is changing both through the ground and over time. In order to unravel this complex relationship and provide the most accurate information to customers, the BGS geomagnetic referencing service models the field in three complementary ways: the BGGM, IFR and IIFR (summarised in the figure below).

BGS Global Geomagnetic Model (BGGM)

The largest scale and magnitude field is modelled by the BGGM, a global representation of the field arising in the Earth's outer core, the crust and magnetosphere.

Every year the BGGM is updated with new data and features. Alongside satellite data from previous years, BGGM2013 incorporated more recent measurements from the global network of geomagnetic observatories; the same will be true of BGGM2014.



From left to right: the BGGM, IFR and IIFR models and services provide increasingly finer scale representation of magnetic field variations in space and time.

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Further enhancements of the BGGM in 2013 included a more advanced method for predicting how the core field will change over the coming years.

Large scale crustal field sources of greater than ~350km are readily captured by BGS models, such as the model from which the BGGM is derived, but smaller scale features are difficult to constrain using satellite and observatory data alone. (No global field model is currently capable of resolving features smaller than ~55km.) However successful MWD operations require accurate knowledge of more complex, local magnetism

In-Field Referencing (IFR)

The BGS IFR service therefore accounts for the local field by combining large-scale field values from the BGGM with higher resolution models of the local crustal field. In creating these models, BGS transform scalar data from aeromagnetic or ship-borne surveys, carried out during the early phases of oil field exploration, to provide estimates of the vector field. The result is an accurate, site specific, representation of how the magnetic field strength and direction varies over a range of depths. In 2013 BGS provided magnetic field referencing for over 730 wells and set up 27 new locations for IFR.

When applied correctly, the current *'spectral'* IFR method has excellent accuracy with small, well-constrained errors. However, the assumptions underlying the technique do not hold in every situation where IFR is required. To deal with these cases, a new '*equivalent source*' approach has been developed.

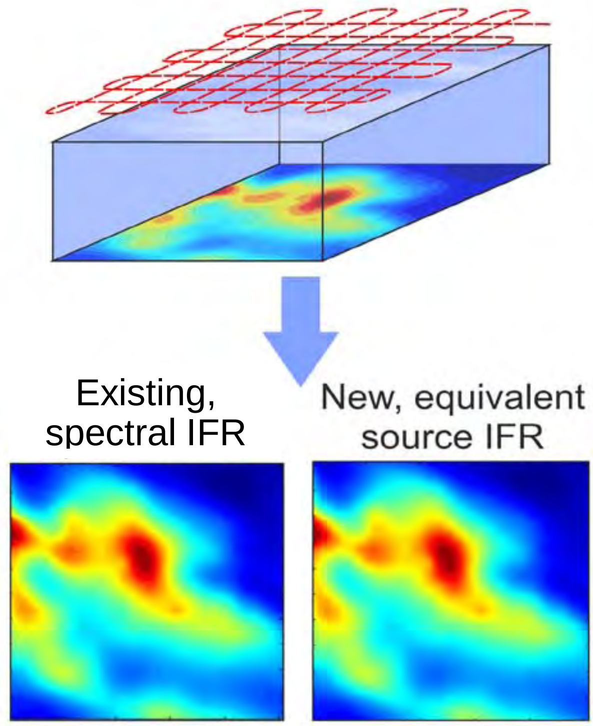
The approach is based on inverse modelling techniques, similar to those employed by the BGGM, and achieves results and errors comparable to the current spectral method (see Figure below). In contrast to the existing method, more initial work is required to set up a new locality for equivalent source modelling. However the output of results is more rapid. This makes the equivalent source method more appropriate for on-demand services. In the future, the new product will be incorporated into BGS's on-line IFR Hypercube calculator.

Interpolation In-Field Referencing (IIFR)

At higher latitudes, estimates of the core field and local crustal field may not be sufficient to estimate the field accurately at a given location. The main source of any discrepancy arises from Earth's complex and rapidly changing external field, which cannot be modelled accurately.

The IIFR service provided by BGS uses data from observatories to monitor these changes and project a '*virtual observatory'* to a drilling site. As the external field may vary considerably on a timescale of minutes, it is vital that IIFR data are provided in near real-time; only then can critical well-steering decisions be made quickly enough.

In 2013, BGS delivered nearly 100% of processed data products within the measurement-to-delivery target interval, with IIFR being supplied to over 130 wells.



Different but equally accurate representations of measured magnetic fields via spectral and equivalent source methods

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Science

Dr Robert Shore gives a presentation on his PhD research at BGS Edinburgh

Student and Research Associate Activities

The Geomagnetism team supports the wider education and training of undergraduate, postgraduate and post-doctoral researchers. We have links with UK and overseas universities and research institutes, and host a number of students and researchers each year. In addition, we jointly supervise PhD research students and are active within the NERC Doctoral Training Partnership. In this section, we summarise some teaching activities in the past year.

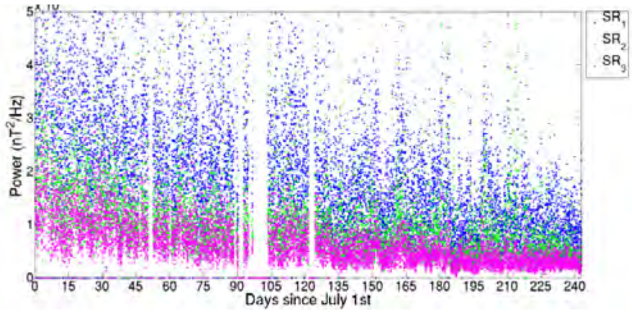
Dr Robert Shore, based at the University of Edinburgh, finished his PhD thesis in June 2013. Robert had been researching a number of topics related to magnetic satellite data, including investigating the so-called ‘virtual-observatory’ technique and the application of Ampère’s integral to data from near-simultaneous over flights of the Ørsted and CHAMP satellites, to resolve the ionospheric currents passing between the two satellites’ orbits. A paper describing the results from Robert’s Ampère integral research was published in the Journal of Geophysical Research in 2013.

Robert’s work suggested that there are a number of poorly understood electrical current systems in the ionosphere that are either not being correctly modelled or simply ignored. This may have an impact of the assumptions used in making global magnetic field models, such as the BGGM. Robert graduated in December 2013 and is now employed as a PDRA at the British Antarctic Survey in Cambridge.

Claire Allmark was a 4th year undergraduate geophysics student at the University of Edinburgh. She undertook a three month research project supervised by BGS to study the relationship between the amplitude of the Schumann Resonances, an electromagnetic phenomena occurring in the Earth-ionosphere electromagnetic cavity, and the Madden-Julian Oscillation (MJO), a mode of tropical atmospheric intra-seasonal variability.

Eight months of data from the BGS induction coil magnetometers at Eskdalemuir Magnetic Observatory were used in her study. The analysis Claire undertook confirmed the existence of a relationship between the Schumann Resonances and the MJO. This relationship occurs because the MJO promotes enhanced lightning activity over continental Africa on a quasi-periodic 30 to 60 day basis. The project helped to prove that the data from the induction coils can produce high-quality science and that BGS can successfully monitor long term trends in the global lightning system.

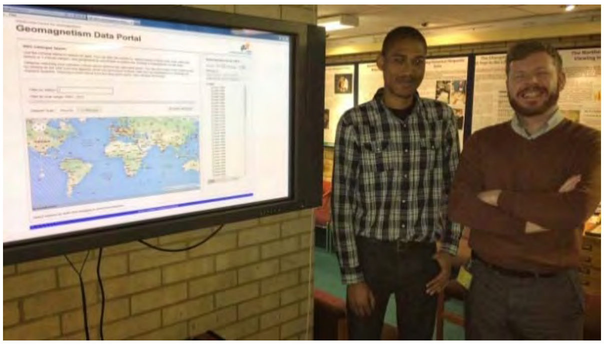
Clare accepted a PhD studentship in seismology at the University of Edinburgh.



Average power of the first three Schumann resonances (blue, green, purple) showing typical seasonal decrease for winter. Within this time-series are subtle signals related to the Madden-Julian Oscillation

Ikechukwu Nkisi-Orji is a Master's degree student at Robert Gordon University. For the industrial placement portion of his Information Systems course, Ike spent 11 months in Edinburgh working with the Geomagnetism Team on improvements to the data management and delivery systems used by the World Data Centre for Geomagnetism (WDC). The WDC is a BGS-hosted member data centre of the International Council for Science's World Data Systems programme.

One major output was the Geomagnetism Data Portal, a website providing researchers with access to the vast repository of data managed by the WDC. The new Data Portal makes use of the latest web technologies to make finding and accessing geomagnetic observatory data as easy as possible.



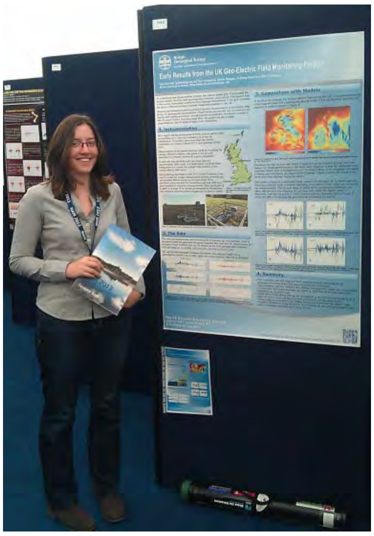
Ikechukwu Nkisi-Orji (left) with BGS supervisor Ewan Dawson (right)

Ines Gil & Chino Gusman

Under the aegis of the INDIGO Project, BGS hosted a one-week training course in Murchison House and Eskdalemuir Observatory for two magnetic observers from the Argentinian Servicio Meteorlógico Nacional. The course was given by several members of staff from the Geomagnetism Team to exchange knowledge and experiences in observatory practice, data processing and magnetic surveying. Ines and Chino represent the Argentinian observatories of Pilar and Orcadas del Sur; two observatories that have recently become members of the INTERMAGNET real-time observatory network following support from INDIGO; a project that aims to improve the global coverage of absolute, digital observatory data for science.

Ines Gil (centre) & Chino Gusman (left) with BGS supervisor Chris Turbitt (right)

Science



Dr Gemma Kelly, with her poster, at the National Astronomy Meeting (NAM) 2013 in St. Andrews

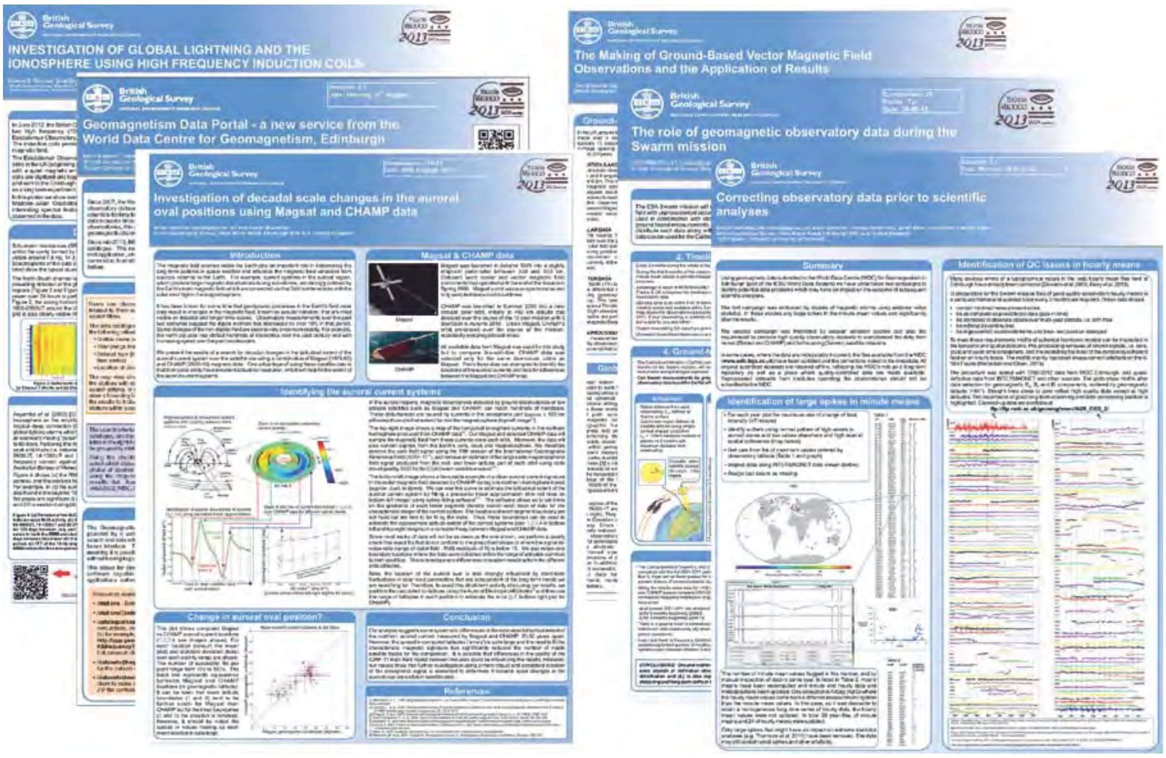
Conferences

The Geomagnetism team continued its long-running contribution to various UK, European and international science meetings. The biennial meeting of the International Association of Geomagnetism and Aeronomy (IAGA) was held in Merida, Mexico in July, while the Living Planet Symposium organised by the European Space Agency (ESA) took place in Edinburgh in September. Geomagnetism staff also attended the European Space Weather Week (ESWW) in Belgium. Throughout the year, smaller meetings took place in St. Andrews and London to which team members contributed.

IAGA 2013, Merida, Mexico

The biennial meetings of IAGA showcase geomagnetism science, attracting researchers from across the globe to meet and present their findings. The 2013 meeting, held in Mexico from 26-31 August, attracted 450 international participants with 870 presentations and posters. BGS were represented by four staff members who gave six talks and displayed nine posters.

Ciaran Beggan spoke about his research into the potential effects of extreme Geomagnetically Induced Currents on the UK power grid, the usefulness of core flow modelling to forecast the changes of the main magnetic field and the application of spherical Slepian functions to the separation of the crustal field between the ocean and continents. Ellen Clarke described BGS efforts in digitising and analysing our archive magnetograms, while Susan Macmillan showed results from her research on the impact of magnetic field strength decline on the South Atlantic Magnetic Anomaly. Alan Thomson summarised the installation of electric field measuring instruments at our three UK observatories and the initial results from the data. In addition, posters on topics ranging from observatory measurements and data quality control to the secular change of the position of the auroral zones were displayed throughout the week of the conference (see Figure).



Collage of the posters displayed at the IAGA 2013 meeting.
All the talks and posters from these conferences are available via the NERC Online Research Archive (NORA)

As chair of IAGA Division V (observatories, surveys and models), Alan Thomson attended several business meetings and reported to the IAGA executive. All staff attended working group meetings to discuss and coordinate future research projects such as the International Geomagnetic Reference Field (IGRF) model, due for release in 2015.

NAM and RAS Meetings

BGS staff presented three posters at the National Astronomy Meeting in St. Andrews in July and three posters at various special meetings of the Royal Astronomical Society in London throughout the year.

We also had a strong presence at the ESWW in Antwerp, Belgium at which two talks (Ellen Clarke and Gemma Kelly) and three posters were given.

ESA Living Planet Symposium, Edinburgh UK

As BGS is heavily involved with data processing for the recently launched ESA Swarm mission, staff attended the ESA organised Living Symposium meeting in September 2013 held in Edinburgh. At the meeting, we discussed the background work for the science related to the Swarm mission and our collaboration with European colleagues. Two posters were presented by BGS staff (Brian Hamilton and Victoria Ridley) while another two posters were presented on behalf of the Swarm Satellite Constellation Applications and Research Facility, a European consortium of which BGS is a member.

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Geomagnetism staff helping out at the 'Bang goes the Borders' science festival

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 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 Space*, Vol. 65 (No. 11), pp. 1345-1353, doi:10.5047/eps.2013.08.004

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

Beggan, C. D., D. Beamish, A. Richards, **G. S. Kelly**, and **A.W. P. Thomson** (2013), Prediction of extreme geomagnetically induced currents in the UK high-voltage network, SpaceWeather, 11, doi:10.1002/swe.20065

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,* Boletín Roa No. 03/13, ISSN: 1131-5040, pp 74-78

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*, Vol. 65 (No. 11), pp. 1363-1374, doi:10.5047/eps.2013.10.001

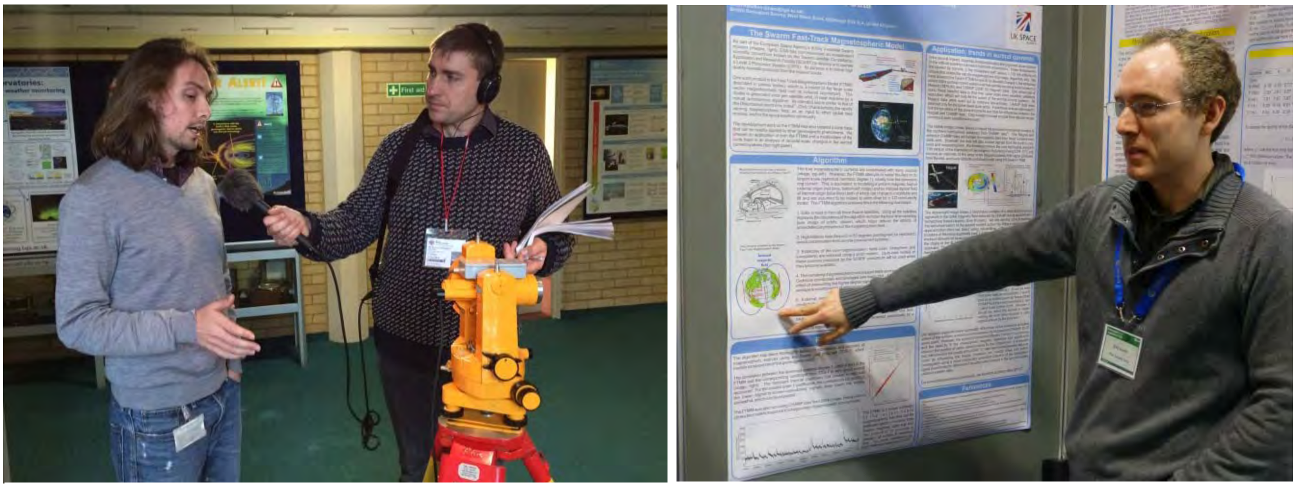
Dawson, E., Lowndes. J. and Reddy, P. (2013) The British Geological Survey's new geomagnetic data web service. *Data Science Journal, Volume 12*, WDS75-WDS80 dx.doi.org/10.2481/dsj.WDS-010

Hamilton, B. (2013) A rapid model of the large-scale magnetospheric field from Swarm satellite data, *Earth Planets and Space*, Vol. 65 (No. 11), pp. 1295-1308, doi:10.5047/eps.2013.09.003

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

Linthe, H.-J., Reda, J., Isac, A., Matzka, J. and **Turbitt, C**. 2013. Observatory Data Quality Control – 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*, Boletín Roa No. 03/13, ISSN: 1131-5040, pp 173-177

Olsen, N.; Friis-Christensen, E.; Floberghagen, R.; Alken, P.; **Beggan, Ciaran D**.; Chulliat, A.; Doornbos, E.; da Encarnação, J. T.; **Hamilton, Brian**; Hulot, G.; von den IJssel, J.; Kushinov, A.; Lesur, V.; Lühr, H.; **Macmillan, Susan**; Maus, S.; Noja, M.; Olsen, P. E. H.; Park, J.; Plank, G.; Püthe, C.; Rauberg, J.; Ritter, P.; Rother, M.; Sabaka, T.; Schachtschneider, R.; Sirol, O.; Stolle, C.; Thébault, E.; **Thomson, Alan W.P.**; Tøffner-Clausen, L.; Velímský, J; Vigneron, P.; Visser, P. N. . (2013) The Swarm Satellite Constellation Application and Research Facility (SCARF) and Swarm data product, *Earth, Planets and Space*, 65 (11). 1189-1200. 10.5047/eps.2013.07.00



Left: *Tom Shanahan talks to Richard Hollingham for the NERC Planet Earth podcast, December 2013.* ***Right:*** *Brian Hamilton discusses his poster at ESA's Living Planet Symposium, September 2013*

Macmillan, S. & Olsen, N. 2013. Observatory data and the Swarm mission (2013) *Earth Planets Space*, 65, 1355–1362, doi:10.5047/eps.2013.07.011

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*, Boletín Roa No. 03/13, ISSN: 1131-5040, pp 65-68

Shore, R. M., K. A. Whaler, **S. Macmillan, C. Beggan**, N. Olsen, T. Spain, and A. Aruliah (2013), Ionospheric midlatitude electric current density inferred from multiple magnetic satellites, J. Geophys. Res. Space Physics, 118, 5813–5829, doi:10.1002/jgra.50491.

Stolle, C., Floberghagen,R., Lühr, H., Maus, S., Knudsen, D. J., Alken, P., Doornbos, E., **Hamilton, B.**, **Thomson, A. W. P.**, and Visser, P. N. (2013) Space Weather opportunities from the Swarm mission including near real time application. *Earth Planets Space*, Vol. 65 (No. 11), pp. 1375-1383, doi:10.5047/eps.2013.10.002

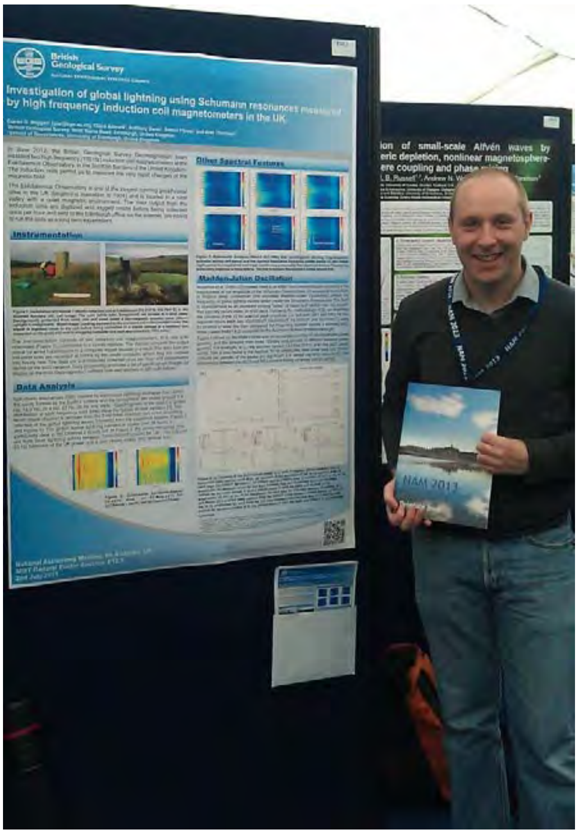
Thomson, A. W. P. 2013 Space Weather Applications of Geomagnetic Observatory Data. *Proceedings of XVth IAGA Workshop on Geomagnetic Observatory, Instruments, Data Acquisition and Processing, San Fernando, Spain, 4-14th June 2012,* Boletín Roa No. 03/13, ISSN: 1131-5040, pp 193-196

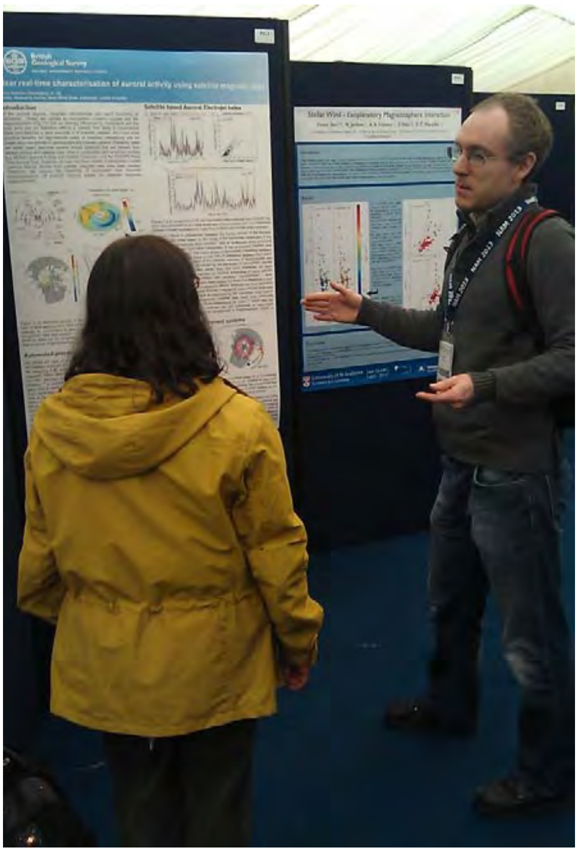
Turbitt, C., Matzka, J., Rasson, J., St-Louis, B. and Stewart, D. 2013. An Instrument Performance and Data Quality Standard for Intermagnet One-Second Data Exchange. *Proceedings of XVth IAGA Workshop on Geomagnetic Observatory, Instruments, Data Acquisition and Processing, San Fernando, Spain, 4-14th June 2012*, Boletín Roa No. 03/13, ISSN: 1131-5040, pp 186-188

Submitted, Accepted and to Appear 2014 (at March 2014)

Thomson, A. W. P., 2014. Geomagnetic Observatories: Monitoring the Earth's Magnetic and Space Weather Environment. *Weather* (submitted)

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 (accepted)





Presenting posters at the National Astronomy Meeting in St Andrews
***Left**: Ciarán Beggan* ***Right:** Brian Hamilton.*

Other Publications

3 BGS Reports: "2012 Annual Review", "Technical Note on Steady Flow and Acceleration Modelling", "Technical Note on Steady Flow Modelling"

Contribution to Royal Academy of Engineering report "Extreme Space Weather: impact on engineered systems and infrastructure":
https://www.raeng.org.uk/news/publications/list/reports/space_weather_summary_report.pdf and
https://www.raeng.org.uk/news/publications/list/reports/space_weather_full_report_final.pdf

Article for *Innovation International* "Current Crisis"

18 Customer Reports (UK survey & OS; oil industry services; ESA)

96 Observatory Monthly Bulletins: 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'

Contribution to BGS's GeoBlogy – 'Does the Ionosphere really hum?', by Ciaran Beggan:
britgeopeople.blogspot.co.uk/2013/06/does-ionosphere-really-hum-by-ciaran.html

Conference Presentations, Posters and Related Activities

RAS Specialist Discussion Meeting: 'Integrated Atmospheric and Space Science', London, UK, January

1 poster

IET 'Extreme Electromagnetics: The Triple Threat to Infrastructure', London, UK, January

1 presentation (Beggan)

BGA 'Geophysics in Future Energy Challenges', London, UK, February

1 presentation (Macmillan)

EU Science: Global Challenges, Global Collaboration, Brussels, Belgium, March

1 presentation (Thomson)

US Space Weather Week, Boulder, Colorado, USA, April

1 presentation (Thomson)

Institute of Engineering and Technology seminar on Solar Storms, London, April

1 presentation (Thomson)

Geomagnetism Advisory Group annual meeting, Edinburgh, May

6 presentations (Clarke, Flower, Macmillan, Turbitt, Thomson)

MagNetE workshop, Prague, Czech Republic, June

1 presentation (Shanahan)

Various working group meetings

RAS NAM/MIST, St. Andrews, UK, July

3 posters

Geneva Association Insurance Workshop, Berlin, Germany, July

1 presentation (Thomson)

IAGA Scientific Assembly, Merida, Mexico, August

5 talks (Beggan, Clarke, Macmillan, Thomson)

9 posters

ESA Living Planet Symposium, Edinburgh UK, September

4 posters

EU Joint Research Centre Workshop on Geomagnetically Induced Currents, Ispra, Italy, October

1 presentation (Thomson)

ISCWSA (SPE wellbore positioning) meeting, New Orleans, USA, October

1 Presentation (Beggan)

European Space Weather Week 10, Antwerp, Belgium, November

2 presentations (Clarke, Kelly)

3 posters

'Space weather fair' demonstations & splinter meetings

RMetSoc National Meeting: 'Space Weather: The importance of observations', London, December

1 poster

RAS Discussion meeting: 'Space Weather: a Dialogue between Scientists and Forecasters', London, UK, December

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1 presentation (Thomson)

Geomagnetism Team seminars, Edinburgh

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

Earth Hazard and Observatories programme seminars, Edinburgh

1 presentation to the wider EHO programme

Some Other Notable Outputs

Dr David Kerridge, BGS Geohazards science director, was made an Honorary Member of IAGA by its Conference of Delegates for outstanding service to IAGA

www.iugg.org/IAGA/iaga_pages/pdf/Newsletters/IAGAnews_50.pdf

Geoelectric field measurements made available on the geomagnetism team website.

www.geomag.bgs.ac.uk/data_service/space_weather/geoelectric.html

Geomagnetism Data Portal for accessing the World Data Centre for Geomagnetism, Edinburgh's digital data holdings was developed.

www.wdc.bgs.ac.uk/dataportal/

Software to digitise analogue magnetograms was developed and is being used in-house to analysis significant historical magnetic storms.

Software and web interface for Met Office and the Natural Hazards Partnership for new 3-hour activity predictions, production of a new 'Kuk' index and code for real time plotting

Establishment of a geomagnetism real time data 'operations room'

Observatory tours

Edinburgh University School of Geoscience visited Eskdalemuir Observatory in February.

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

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 lecture)

Educational and training activities. including participation at the BGS Edinburgh Open Day (Geomagnetism Team), the 'Bang Goes the Borders' public science event (Kelly and Ridley), and Dunbar Science festival (Flower).

Press Releases in July" Electric field measurements help defend grid against space weather" at RAS NAM meeting. Podcast recorded for the Naked Scientists

www.thenakedscientists.com/HTML/content/interviews/interview/1000292/

Press release in November for Swarm Launch. Radio interview for BBC Good Morning Wales.

Media interviews about space weather events

7 Feb – for the Guardian

3 Mar – for the Irish Times

Podcast for NERC Planet Earth (recorded in December)

planetearth.nerc.ac.uk/multimedia/story.aspx?id=1584

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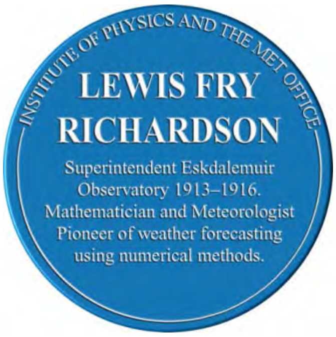
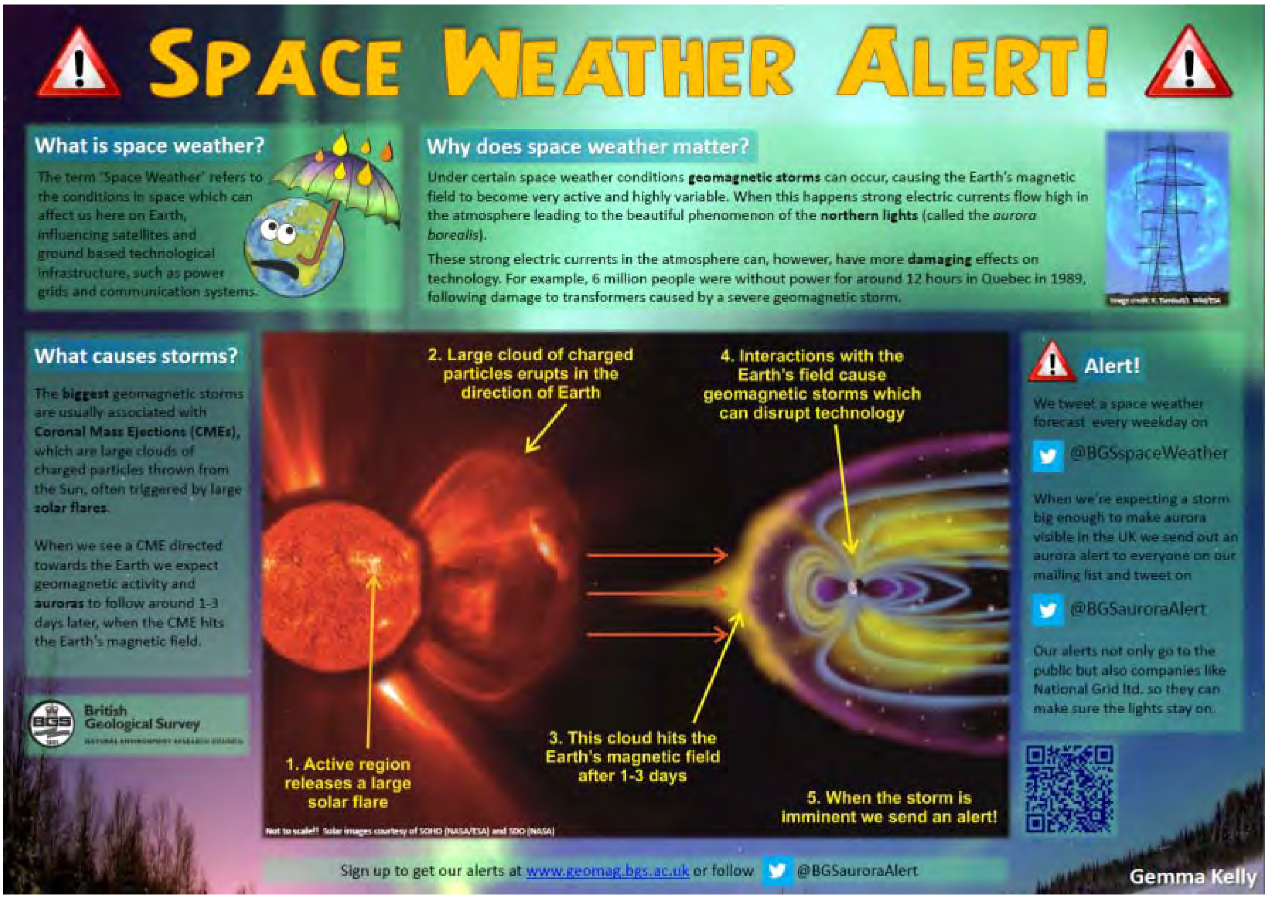
A blue plaque was unveiled at Eskdalemuir Observatory celebrating the centenary of Lewis Fry Richardson, the 'father of modern weather forecasting', arriving at the observatory. An event was held at the observatory, attended by local MSPs and Institute of Physics and Royal Meteorological Society members. BBC 'Reporting Scotland' reported from the observatory on the day, including broadcasting the evening weather report from the observatory grounds.



Left to Right: Richardson 'Blue Plaque'; being unveiled by IOP Director Paul Hardaker & Met Office Operations Director Rob Varley; David Kerridge addressing the assembly

Two first prizes awarded to Gemma Kelly and Victoria Ridley in May & December at BGS poster competitions. Victoria's poster is on page 2.



***Above**: Prize winning poster in the May 2013 BGS poster competition, by Gemma Kelly*

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Selected Glossary, Acronyms and Links

AOGS	*Asia Oceania Geosciences Society (http://www.asiaoceania.org)*
BBC	*British Broadcasting Corporation (www.bbc.co.uk/)*
BGGM	*BGS Global Geomagnetic Model (www.geomag.bgs.ac.uk/bggm.html)*
BGA	*British Geophysical Association (www.geophysics.org.uk/)*
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/)*
COSPAR	*Committee on Space Research*
Dip Pole	*The points on the Earth's surface where the magnetic field is vertical*
Dipole Pole	*The points on the Earth's surface where the best fitting centred dipole (bar magnet) approximation to the measured field passes through the Earth's surface*
DNS	*Domain Name System*
DTU	*Danish Technical University. (www.space.dtu.dk/English.aspx)*
EGU	*European Geophysical Union. (www.egu.eu/)*
Earthworm	*Seismic data acquisition and processing software (http://www.earthwormcentral.org/)*
EHO	*The Earth Hazards and Observatories science theme of BGS*
Engauge	*Digitising software (http://digitizer.sourceforge.net/)*
ESA	*European Space Agency (www.esa.int/esaCP/index.html)*
ESWW	*European Space Weather Week. (sidc.oma.be/esww6/)*
EU	*European Union (europa.eu/)*
EURISGIC	*European Risk from Geomagnetically Induced Currents (www.eurisgic.eu/)*
EXCOM	*Executive committee of INTERMAGNET*
EVS	*Extreme value statistics*
FGE	*Fluxgate magnetometer*
GIC	*Geomagnetically Induced Currents (a natural hazard to power systems and pipeline networks).*
GPS	*Global Positioning System. (www.gps.gov/)*
GSS	*Gerrity Skill Score*
HSS	*Heidke skill score*
IAGA	*International Association of Geomagnetism and Aeronomy (www.iugg.org/IAGA/iaga_pages/index.html)*

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IGRF	*International Geomagnetic Reference Field. (www.ngdc.noaa.gov/IAGA/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/)*
IOP	*Institute of Physics*
ISCWSA	*Industry Steering Committee on Wellbore Survey Accuracy. (iscwsa.org/)*
ISGI	*International Service for Geomagnetic Indices (www.icsu-fags.org/ps06isgi.htm)*
ISS	*International Space Station.*
JGR	*Journal of Geophysical Research*
KRISS	*Korean Research Institute of Standards and Science*
MAGIC	***"M**onitoring and **A**nalysis of **GIC**". A service for the National Grid.*
MAGSAT	*A NASA satellite mission to sample the vector magnetic field (1979 -1980)*
MagNetE	*European magnetic repeat station network (e.g. 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/)*
MJO	*Madden-Julian Oscillation (atmospheric climate mode)*
MSP	*Member of the Scottish Parliament*
MWD	*Measurement While Drilling – a technique used in the oil and gas industry.*
NAM	*National Astronomy Meeting (www.ras.org.uk/)*
NASA	*National Aeronautic and Space Administration (www.nasa.gov/)*
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/)*
PDRA	*Post Doctoral Research Associate*
QDD	*Quasi-definitive (magnetic observatory) data*
QNX	*UNIX-like real-time operating system*
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)*
SS	*Skill score*
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/)*
USGS	*United States Geological Survey (www.usgs.gov/)*
VPN	*Virtual Private Network*
WDC	*World Data Centre (www.wdc.rl.ac.uk/wdcmain/, www.wdc.rl.ac.uk/wdcmain/europe/edinburgh.html)*

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.

Alan Thomson would like to thank Ciarán Beggan, Gemma Kelly and Sarah Reay for their comments on this review. He also thanks the Geomagnetism team as a whole for their enthusiasm, dedication and hard work in 2013.

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).

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Dr Laurence Billingham	*Geomagnetic Research*
Ellen Clarke	*Geomagnetic Research and Data Processing*
Ewan Dawson	*Geomagnetic Research, Data Processing and IKE*
Paul Dickson	*Geomagnetism Business Account Support*
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Ted Harris	*Geomagnetic Data Processing and IKE*
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Thomas Humphries	*Geomagnetic Data Processing*
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British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Cover: Earth's protective shield - Earth & interplanetary space. Illustration courtesy of ESA,© ESA/ATG medialab