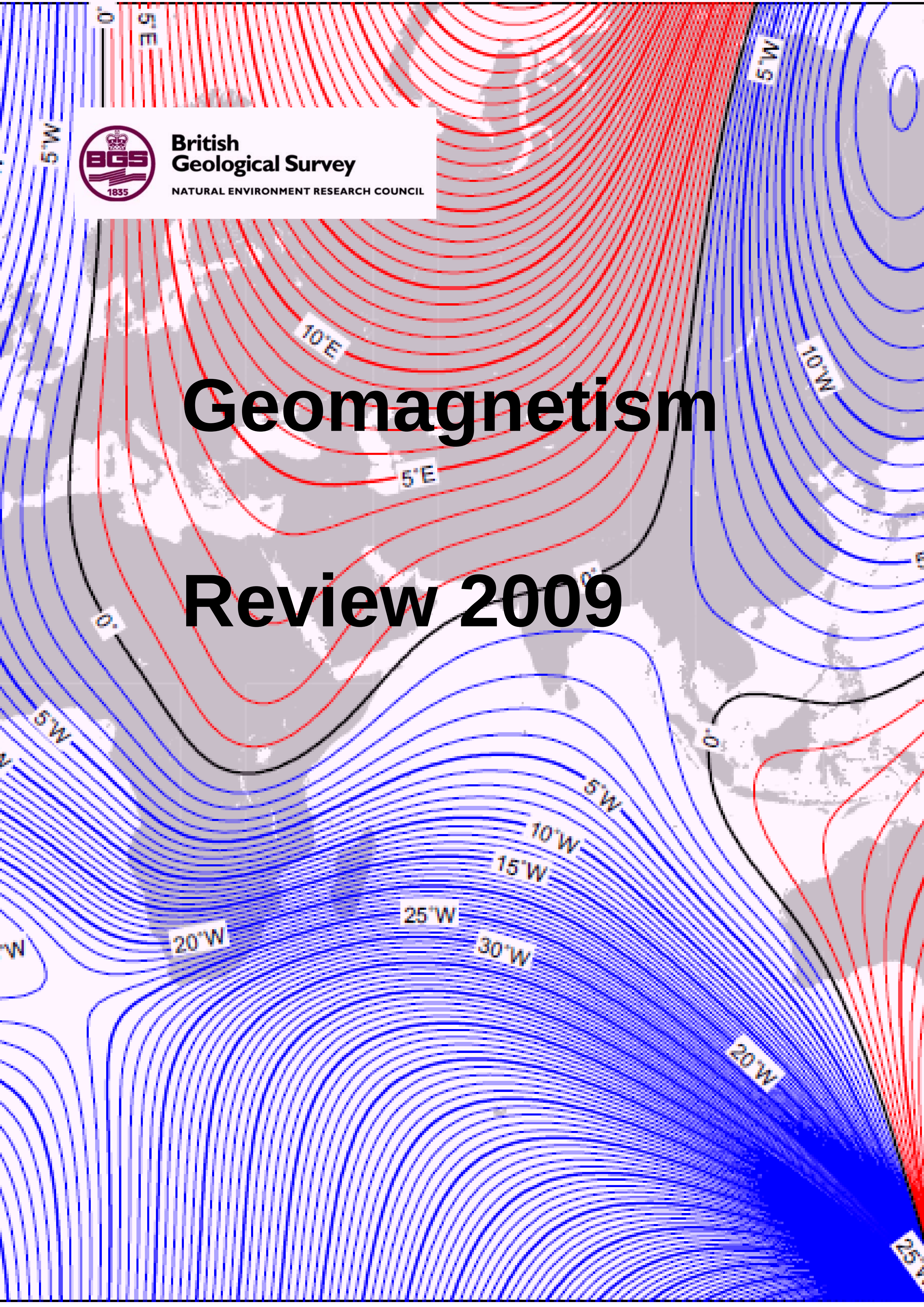

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Geomagnetism

Review 2009

BRITISH GEOLOGICAL SURVEY

OPEN REPORT OR/10/029

Geomagnetism

Review 2009

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Key words

Geomagnetism.

Front cover

Declination at 2010.0 from the World Magnetic Model (degrees from true north)

Bibliographical reference

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42pp.

Edinburgh British Geological Survey 2010

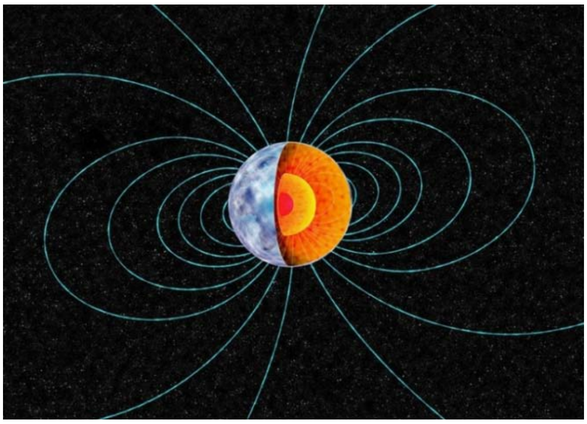
The Geomagnetism Team, December 2009

Back *(left to right): Thomas Humphries, David Kerridge, Orsi Baillie, Ted Harris, David Booth, Chris Turbitt, Sarah Reay, Alan Thomson, Ellen Clarke, Ciaran Beggan.*

Front *(left to right): Brian Hamilton, Tony Swann, Ewan Dawson, Brian Bainbridge, Susan Macmillan, Thomas Shanahan.*

Not present*: Jane Exton, Simon Flower, Sandy Henderson, Colin Pringle, David Scott and Stephen Tredwin.*

Contents



Measurements of the geomagnetic field reveal changes in the Earth environment, from the inner core out into space.

Introduction: The Year in Perspective

Who we are and What we do

The Geomagnetism team measures, records, models and interprets variations in the Earth's natural magnetic fields, across the world and over 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 the private sector.

The British Geological Survey (BGS) is the main Earth Science research centre for the UK and is funded primarily through the Natural Environment Research Council (NERC).

Geomagnetism science is represented in BGS as a team within the Earth Hazards and Systems (EHS) science theme, alongside Earthquake Seismology and Volcanology.

EHS is one of ten BGS science themes that deliver the BGS science strategy. EHS is supported by the Information and Knowledge Exchange (IKE), Administration, and Resources and Business programmes.

The Geomagnetism team is based in Edinburgh and in 2009 numbered twenty-two full and part-time staff. We receive additional support from BGS Edinburgh Business Support, Business Administration and System and Network Services.

For the purposes of continuous geomagnetic monitoring in the UK BGS operates three magnetic observatories. These are located (*see main Figure opposite*) in Lerwick (Shetland), at Eskdalemuir (Scottish Borders) and in Hartland (North Devon).

We also operate magnetic observatories overseas on Ascension Island and in Port Stanley (Falkland Islands). We oversee and maintain magnetic observatory operations on Sable Island (Canada) and in northern Alaska (USA).

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

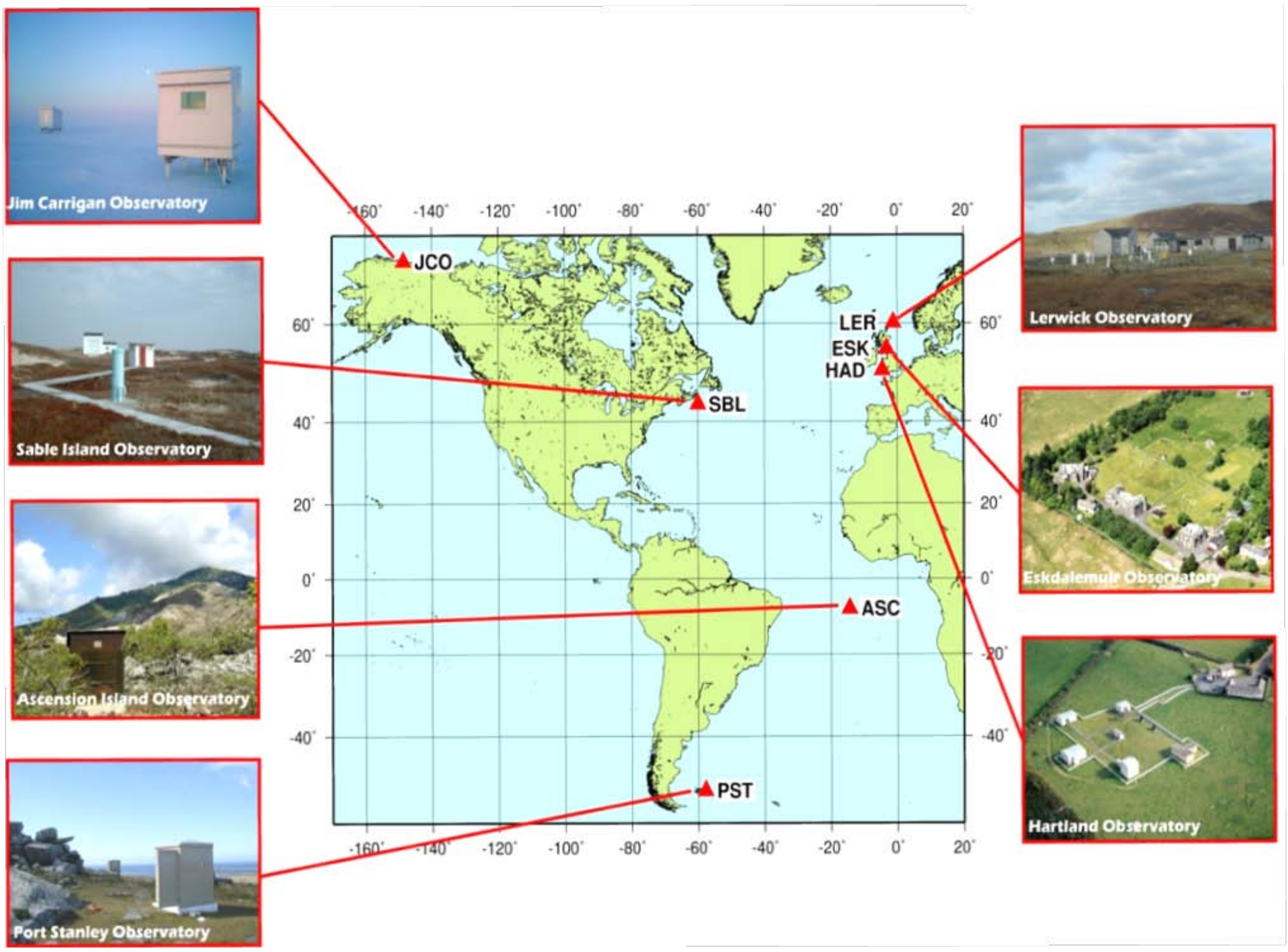
Long-term geomagnetic monitoring and allied research to improve our understanding of the Earth and its natural environment.

Other activities of the team are mathematical modelling of the geomagnetic field and its changes, 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

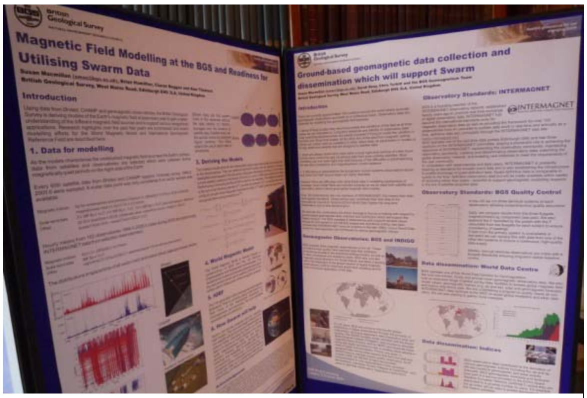
- Measuring, recording, modelling and interpreting the Earth's natural magnetic field and its sources;
- Delivering tailored geomagnetic data, products and services to academics, business and the public;
- Knowledge and information for all sectors of society on geomagnetism science: what it tells us about the Earth and how it can be used in practical ways.



The three UK and four overseas magnetic observatories operated by BGS

Introduction:

The Year in Perspective



Presenting Geomagnetism team science at a Royal Astronomical Society discussion meeting, October 2009

Objectives and Achievements

Geomagnetism team objectives for 2009 were developed in response to current NERC and BGS strategy and to customer requirements. We achieved our objectives through the NERC-funded National Geomagnetic Service (NGS) and our externally funded projects. In this section we provide an overview of the full range of our activities in 2009. In the rest of this report we describe in detail notable achievements during this past year.

Key Objectives

In autumn 2008 we set the following objectives for 2009.

- To operate the BGS magnetic observatories and the UK magnetic survey to the highest standards.

2009 service visits were made to Port Stanley and the other BGS magnetic observatories

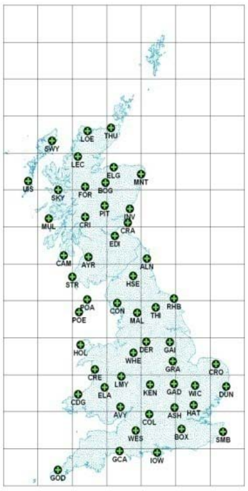
- To further develop the World Data Centre for Geomagnetism and to continue the back-up and the scanning of paper records of observatory data.
- To produce and publish mathematical models of core, lithospheric and other magnetic fields.
- To provide valued services and data products to academic and business customers and to assure the continuation of external income from our long-established customer group.
- To work to attract new external income, for example ESA funding, as a member of the 'Swarm' international magnetic science consortium, and for our space weather hazard activities.
- To actively pursue collaboration with UK universities and institutes on geomagnetism hazard and on magnetic field modelling science.
- To coordinate our IKE activities with relevant BGS IKE teams.
- To hold influential positions in scientific bodies such as INTERMAGNET and IAGA.

Key Deliverables and Achievements

These key objectives were fully realised through the following deliverables and achievements.

- Completion of the maintenance programme for the observatory network. The upgrading of environmental conditions and installations for backup sensors at the UK observatories.

- The occupation of nine sites in the UK magnetic repeat station network.



Sites in the UK repeat station network

- Upgrade of INDIGO overseas observatories (a developing country project) to include USB stick recorders and preparation of instrumentation for Pilar Observatory, Argentina.

- Completion of the first year of a programme of electronic scanning of the 256,000 UK observatory magnetograms held by BGS.

- Maintenance of the World Data Centre for Geomagnetism (Edinburgh), in accordance with the rules of the World Data Centre system.

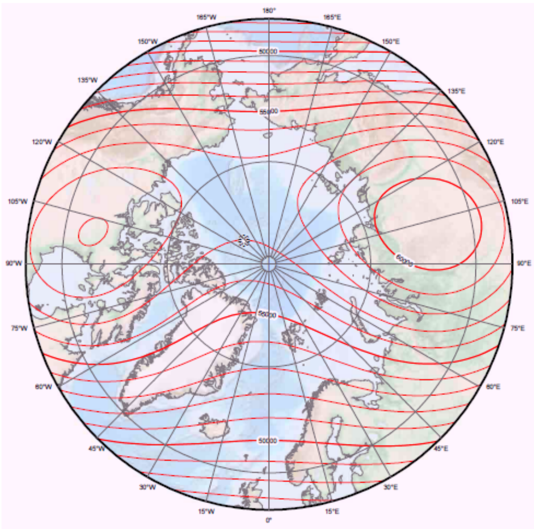
- The production of geomagnetic models:

  - A 2009 revision of the UK magnetic model.

  - A 2009 revision of the BGS global geomagnetic field model (BGGM), using the latest observatory and magnetic survey satellite data.

  - Candidate models submitted for the 11th generation of the International Geomagnetic Reference Field (IGRF).

  - Collaboration with the NOAA/NGDC in the USA on the 2010-2015 revision of the World Magnetic Model (WMM).



Vertical component of the new WMM at the Earth's surface (contours at 1000nT)

- The supply of data products to the International Service for Geomagnetic Indices (ISGI) (to the timetable set by ISGI) for the production of global geomagnetic activity indices.

- The delivery of real-time UK observatory data and data products via the Geomagnetism website www.geomag.bgs.ac.uk.

- The initial set-up for In-Field Referencing (IFR) at 27 new oil fields around the world and completion of 20 commissioned reports.

- Magnetic north data supplied for 95 OS map products.

- The delivery of definitive data from the UK magnetic observatories (to the timetable set by INTERMAGNET) for publication on the INTERMAGNET 2008 DVD.

- The publication of UK observatory data and data products in the BGS monthly bulletin series.

Monthly bulletins from the observatories

- 100% (99.9%) data coverage was achieved for the UK (Overseas) observatories and near real-time UK data was available to customers a few minutes after collection.

- Winning a (NERC) National Centre for Earth Observation (NCEO) grant (total value £200k over two years) to support activities during the ESA Swarm mission, with University of Liverpool (start date late 2010).

- Preparation of two consortium bids with colleagues at European institutes on a) the geomagnetic hazard to European power systems (FP7) and b) in response to an ‘announcement of opportunity’ to develop a Swarm mission ‘level 2 science products centre’ (ESA).

- The supervision of BUFI-supported PhD students at the University of Lancaster (on geomagnetic hazard), University of Liverpool (polar magnetism) and University of Edinburgh (satellite magnetometry and the ESA Swarm mission).

- The publication of 6 papers and articles in scientific and professional journals and educational and information material *(Figure below)*, e.g. for the BGS web site: www.bgs.ac.uk.

The Geomagnetism team on the BGS news website

- The preparation of the Geomagnetism team Annual Review.

- The delivery of 31 presentations and posters on BGS geomagnetic science at various scientific conferences.

- Convening of a WDC meeting during IAGA; the carrying out of organising committee, chair and co-chair duties at INTERMAGNET meetings, MagnetE workshops and IAGA Division 5 business meetings.

- David Kerridge was awarded the MBE in the New Years Honours List 2010, and the Geophysics Award of the Royal Astronomical Society, in April 2009, both for services to geophysics.

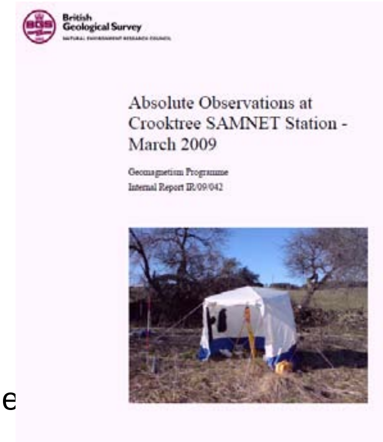
- One team member served on the science organising committees for the 2009 European Space Weather Week (ESWW6) and the 2010 National Astronomy Meeting (NAM-UKSP-MIST) in Glasgow.

Other Notable Achievements

However we achieved more, in terms of science, applications and outreach, than we set through our key objectives.

We briefly note these activities here, as they are not discussed elsewhere in this report. These activities are worth noting, both for current and future operations, and in terms of strategy development.

- Major infrastructure investment was made by BGS facilities management at Eskdalemuir and Hartland to safeguard buildings and hence operations for many more years.
- Preparations, planning and discussions with the British Antarctic Survey and the South Georgia government took place in advance of the installation of the new South Georgia magnetic observatory, scheduled for 2010-2011.
- Absolute magnetic measurements were made at Crooktree in Scotland to assess baseline standards of the SAMNET variometer systems, and the scope to upgrade these to quasi-observatory status (*see opposite*).



Support for SAMNET (University of Lancaster) operations

- The ne MagNetE (Magnetic Network of Europe) organising committee. We are helping coordinate group activities such as the proposal to produce a European Declination map for the epoch 2006.5. Currently data is being solicited and processed for the final map.

Some Key Figures at a Glance

100% (99.9%) UK (Overseas) observatory 1-minute data collection
4 geomagnetic models & software
6 journal papers; 12 scientific meetings, 31 presentations and posters
3 PhD students
Compass data for 95 OS maps
27 field set-ups for IIFR/IFR services and 20 customer reports
97,000 scanned archived magnetograms
84 magnetic bulletins published
6 articles on space weather for ‘Navigation News’
3 grant bids (1 success; 2 still in review)
1 MBE, 1 RAS ‘Services to Geophysics’ and 1 AGU ‘Outstanding Speaker’ award
Positions on 3 scientific and technical geomagnetism bodies

Introduction:

The Year in Perspective

The ESA Swarm satellite constellation (Image courtesy ESA)

A Look Ahead to 2010

The Geomagnetism team's major opportunities in 2010 (and beyond) arise from the ESA Swarm magnetic survey mission and from the funding of solar-terrestrial physics – space weather hazard - within NERC. With level BGS/NERC funding the team will continue to operate the BGS magnetic observatories and the UK magnetic survey to internationally recognised standards. We will produce magnetic models and publish results and all our activities will be in support of BGS and NERC objectives. The team will also work to secure continuation of its external income, during a time of general economic uncertainty, by developing appropriate services and data products for academics and customers.

Key Objectives

In 2010 we will maintain our high standards of operation in all current science and application areas. Our major objectives, through the National Geomagnetic Service (NGS) and our external income projects, are

- Uninterrupted magnetic observatory operations and continuation of the UK magnetic survey (This is identified as being in support of actions and deliverables of the 'BGS Science Strategy 2009-2014', under the category of "Observe and Monitor").
- Quality-assured geomagnetic data products (BGS Strategy: "Secure and Enhance the Geoscience Knowledge Base").
- Mathematical models of spatial and temporal variations in Earth's magnetic fields (BGS Strategy: "Model our Dynamic Environment").
- Geomagnetic information and knowledge exchange, scientific collaboration, publications and outreach, and leadership within scientific bodies concerned with Geomagnetism (BGS Strategy: "Exchange our Knowledge").

Main Deliverables

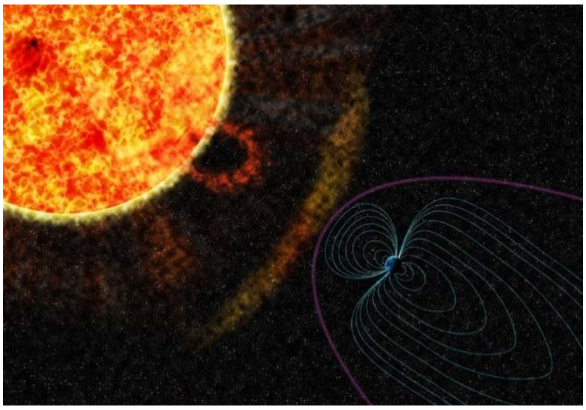
Our deliverables for 2010, in respect of our objectives, will be

- Maintenance of an INTERMAGNET-standard UK observatory network.
- Maintenance of our overseas observatories and the first year of a programme to establish a new magnetic observatory on South Georgia, to INTERMAGNET standards.

King Edward Point Research Station & Grytviken Whaling Station in Cumberland Bay, South Georgia. Looking South from high above the Bore Valley

Courtesy of British Antarctic Survey (NERC)

- Re-survey of ten sites in the UK magnetic repeat station network, a survey report and a revised UK magnetic model.
- Publication of observatory data and data products in the 2010 Monthly Bulletins and in the Observatory Yearbook series.
- Supply of 2009 observatory data to INTERMAGNET, according to INTERMAGNET's timetable.
- Supply of magnetic index products to the International Service for Geomagnetic Indices (ISGI), according to ISGI's timetable.
- On-line provision of real-time UK observatory data products through the BGS Geomagnetism website.
- Continuation of the scanning programme of UK observatory paper magnetograms and the development of an on-line database for academic and public research. Commence UK yearbook scanning program.
- Production of a 2010 revision of the global geomagnetic field model for, using the latest observatory and magnetic survey satellite data.
- Operation of the World Data Centre for Geomagnetism (Edinburgh), including an annual 'call for data' and associated quality control activities.
- Co-supervision of BUFI PhD students with the Universities of Edinburgh (satellite magnetometry and ESA Swarm mission), Lancaster (geomagnetic hazard) and Liverpool (polar magnetism).
- Pursuing of new scientific collaborations that address BGS challenges and NERC themes, e.g. through solar-terrestrial physics grant opportunities in the UK and Europe.



The Sun gives rise to the space weather and geomagnetic hazard to technology

- Collaboration in existing international geomagnetic observatory (INDIGO) and survey programmes (MagNetE).
- Active participation in at least one major scientific conference.
- Publication of at least two first-author papers in scientific and professional journals, the writing of articles, provision of information and educational material for the BGS web

site and publication of a team Annual Review for 2010.

Sable Island Observatory in 2009

Technical, Observatory and Field Operations

UK and Overseas Observatories

BGS operates three magnetic observatories in the UK. These provide the high quality, near-real-time data that underpin products provided to both commercial and academic users. The Geomagnetism team attained one hundred percent data coverage from the UK observatories in 2009. BGS also runs four overseas magnetic observatories and takes a leading role in the expansion of the global network of digital magnetic observatories, both for improved global field modelling and for local applications of the data.

The UK Observatories

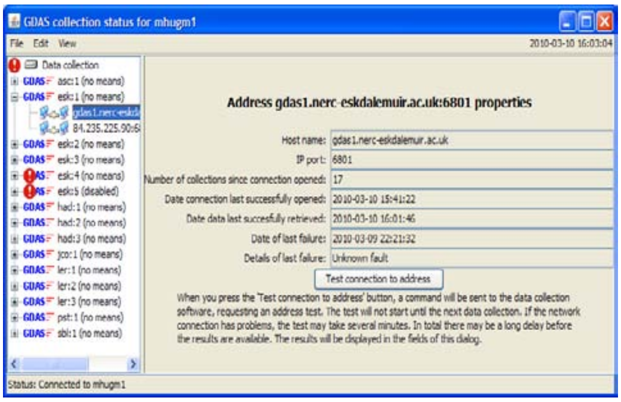
The installation of a small instrument enclosure at Lerwick Observatory completed this year's programme of upgrades at the UK observatories. These bespoke, non-magnetic, temperature-regulated enclosures are used by the team to distribute fluxgate magnetometers around each observatory site to minimise the risk of data loss from man-made interference.

Also in this year's programme was the laying of foundations, enclosures and cabling at Eskdalemuir Observatory, prior to the installation of two sets of induction coils, capable of measuring magnetic field variations in the band 10-1000 Hz. These sensors will be used as long-term monitors of atmospheric electromagnetic phenomena.

Although there were major infrastructure works during the year at the UK observatories – roofing works and boiler replacement at Eskdalemuir; site rewiring at Hartland – the redundancy and reliability measures in place have ensured that no data were lost from the observatories during 2009. The three UK observatories are therefore able to report 100% data coverage for the fourth consecutive year.

Broadband internet links were installed at Hartland and Lerwick Observatories to improve the data connection between the observatories and the main data processing hub in Edinburgh. The improved data link with Hartland also provides the infrastructure to establish a complete off-site data processing mirror at the observatory to ensure the reliability of real-time geomagnetic data supply from BGS, e.g. in the event of power failure in Edinburgh.

Key data transfer software (from the observatories to Edinburgh) was also upgraded to support the mirror data processing site at Hartland and to improve reliability and speed of data transfer. Reliability improvements have come from reduction in the number of hardware and software stages in data transfer and also in the use of fault reporting and diagnostic tools within the new software, particularly for the secondary communication links to the observatories.



User interface to data collection and monitoring

The Overseas Observatories

In addition to regular manual absolute measurements by local staff, BGS engineers visited the four overseas observatories during 2009 to make manual absolute measurements, calibrate instrumentation and upgrade equipment. Ascension and Port Stanley Observatories were serviced in February 2009 and additional earthing arrangements were added to the lightning protection at Port Stanley. Lightning protection measures at Port Stanley have proved very effective and both Port Stanley and Ascension have reported uninterrupted, INTERMAGNET-standard data for 2009, save for a short downtime during servicing.

A curtailed visit to Sable Island Observatory, Nova Scotia in May 2009 only provided sufficient time for routine calibrations and measurements, while a visit to Jim Carrigan Observatory, Alaska in the same month provided an opportunity to make scalar site measurements at a site to the east of the Prudhoe Bay oil field. These observations and forthcoming vector measurements in 2010 will be used to quantify the uncertainties in the provision of IIFR at high latitudes.

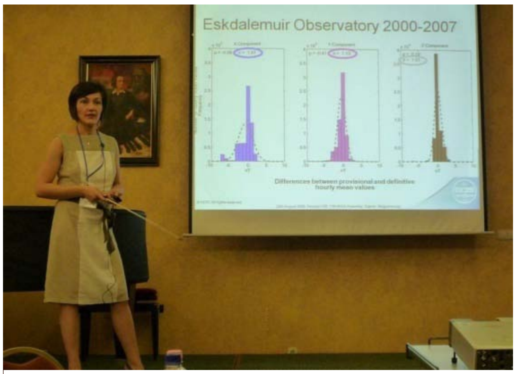
A permanent back-up satellite link was established between BGS Edinburgh and Jim Carrigan Observatory to reduce the frequency of data delays to the real-time IIFR service, improving the reliability of the BGS IIFR web service for the Prudhoe Bay fields.

Absolute observing position, Ascension

2009 saw the retirement of David Booth, science manager for the UK observatories, and also the appointment of Tony Swan as an observatory operations engineer.

BGS has some concerns for Lerwick Observatory due to a proposal by the site owner (Met Office) to sell a portion of land for private development and to relocate office facilities. However the redistribution of instruments and the establishment of an auxiliary absolute observing position are expected to mitigate any potential disturbance to the continuity and quality of the observatory data. NERC is also negotiating to purchase a land ‘buffer zone’.

Technical, Observatory and Field Operations



Presenting QDD results at the XI IAGA Scientific Assembly, 2009, Sopron, Hungary

Quasi-Definitive Observatory Data in Near Real Time

Over the past decade, the Geomagnetism Team has developed its observatory instrumentation, data acquisition and processing systems to the point that we are now able to produce quasi-definitive observatory data in near real time. These data are expected to support a wide variety of applications and science in the coming years.

What use are Quasi-Definitive Data (QDD)?

- There is an established oil industry need for high quality data to aid real time directional drilling.
- We anticipate future demand from the scientific community, particularly as a result of the research opportunities that will be created by the integration of observatory data with data from the ESA SWARM magnetic survey mission.
- We will be able to support more frequent updating of global geomagnetic field models.
- Accurate near real-time data will aid space weather and geomagnetic hazard assessment and support decision making by industry and government, for example in understanding risk to the power grid.
- Production of QDD is in line with modern professional practice for magnetic observatory operations, as determined by INTERMAGNET.

How do we produce QDD?

BGS operates three observatories in the UK and four overseas. At each of the UK observatories three identical systems with vector and scalar instruments record the magnetic field direction (at 1 Hz) and magnitude (at 0.1 Hz). At each of the overseas observatories we operate a single system.

Our standard baseline-corrected data are subject to high levels of quality control. For the UK observatories quality control involves comparisons between different systems in each field component to identify corrupt data. Such data may then be replaced with data from an unaffected dataset during the working day. In the case of the overseas observatories, total field comparisons assist in identifying any corrupt data, which are corrected the following day.

Good quality control also depends on good, regular absolute observations. Two absolute observations are therefore made per week at the UK observatories; two per month are made at the overseas stations, and additional observations are made during service visits.

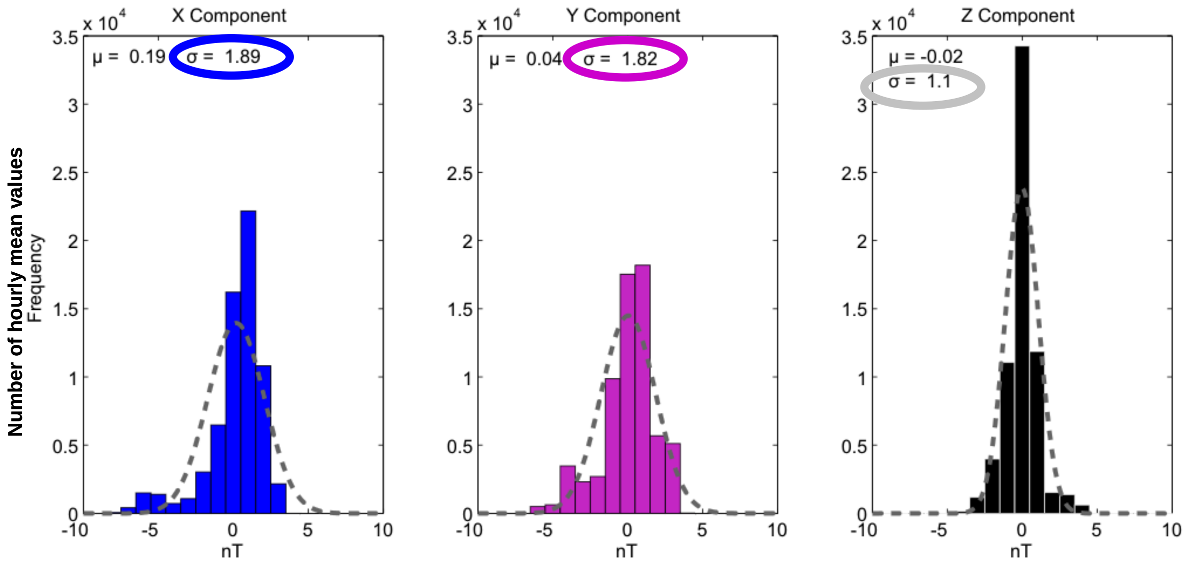
Our observatory baselines are updated monthly by fitting piecewise polynomials to spot values. Daily extrapolated baseline values, derived from these baseline fits, are combined with real-time variometer data by the automatic data processing software to produce the QDD.

How close to definitive are our QDD?

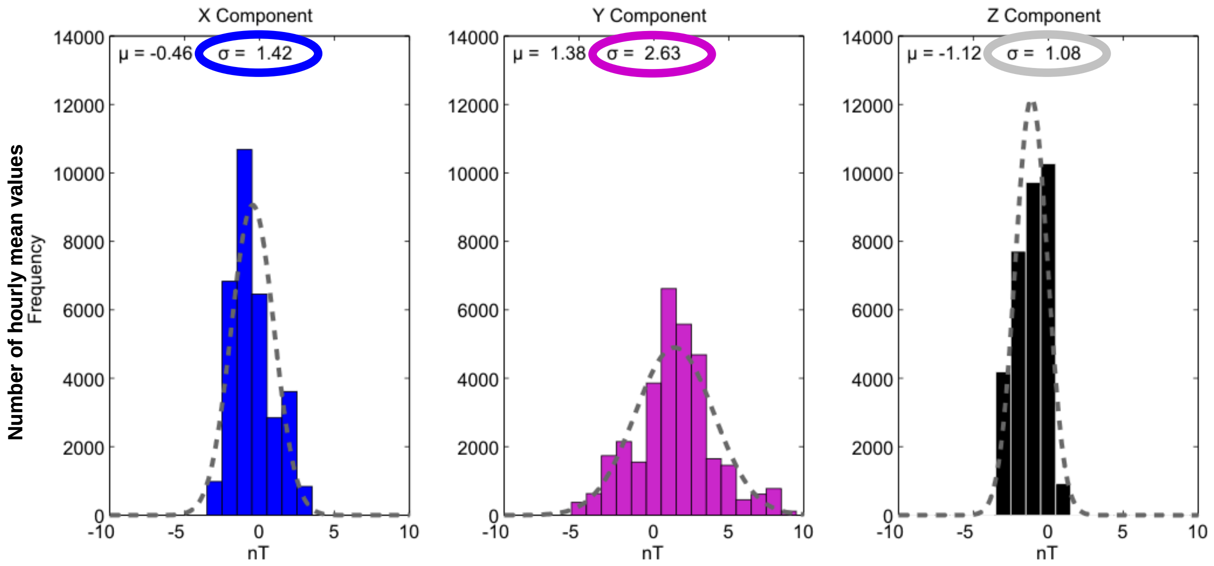
We have carried out a study in which we compared quasi-definitive hourly mean values, made available on-line on a next day basis, with the definitive published data, not normally available until the following year.

The results show that the quasi-definitive data are almost always within 5nT of the definitive values, in line with the INTERMAGNET target accuracy for definitive data.

These results were first presented at the XIst IAGA scientific assembly, where a new IAGA resolution encouraging all observatory operators to produce QDD was adopted.



Hartland 2000-2007: Differences between provisional and definitive hourly mean values. The standard deviation in the difference is highlighted.



Ascension Island 2004-2007: Differences between provisional and definitive hourly mean values. The standard deviation in the difference is highlighted

World Data Centre for Geomagnetism

The World Data Centre system, established by the International Council of Scientific Unions

The Geomagnetism Team operates a World Data Centre (WDC) for Geomagnetism. We hold digital records from around 280 magnetic observatories worldwide, on a number of time-scales, along with various magnetic survey, model and activity index data. The operation of this dynamic data centre contributes towards our own global modelling efforts and provides a valuable service to the worldwide research community.

Throughout 2009 our WDC increased its data holdings of observatory minute, hourly and annual mean values and global magnetic survey and repeat station data. We obtained data via direct data submission, through our annual 'call-for-data' and by data exchange with other WDCs.

In 2009 we developed new quality control procedures for all new and current datasets within the WDC.

With our new procedures we discovered that a large number of the quality control issues that were found in our hourly mean datasets resulted from formatting and typographical mistakes. (The core principle of WDC data quality control policy is that WDCs should not make any change to the data it receives, beyond the correction of obvious formatting or typographical errors.)

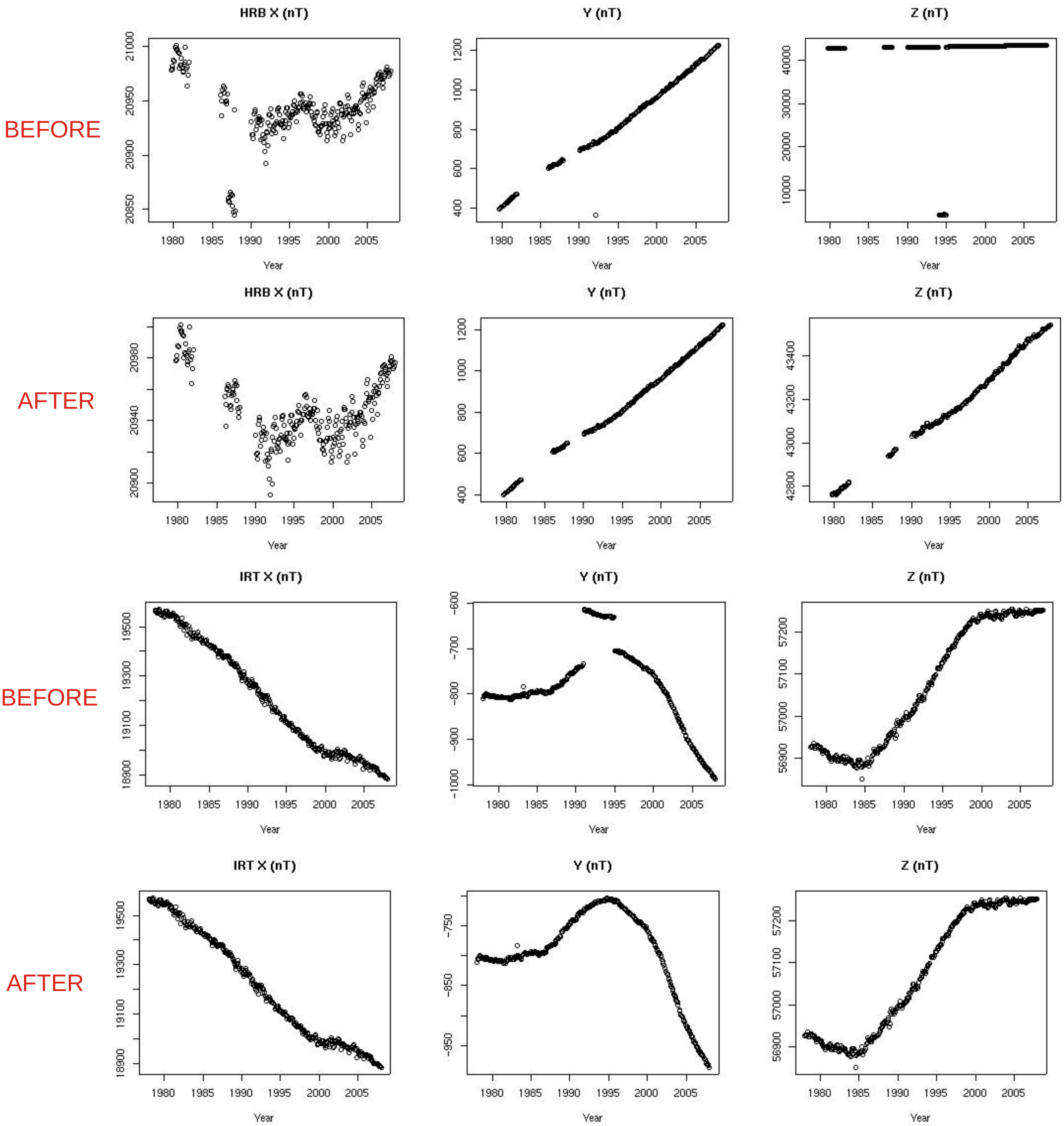
In the past year we therefore embarked on a programme of quality assessment of our hourly mean datasets spanning 1968-2008. We identified and corrected errors within over 80 observatory-years of data. We are now in the process of checking all annual mean values for typographical and formatting errors and plan similar work for minute means.

These improvements to data quality within the Edinburgh WDC are motivated primarily by the benefits that will be gained in the future by the geomagnetic modelling community. However any improvements will benefit other users of the WDC and this work will also help maximise the science return from the forthcoming ESA Swarm magnetic survey mission.

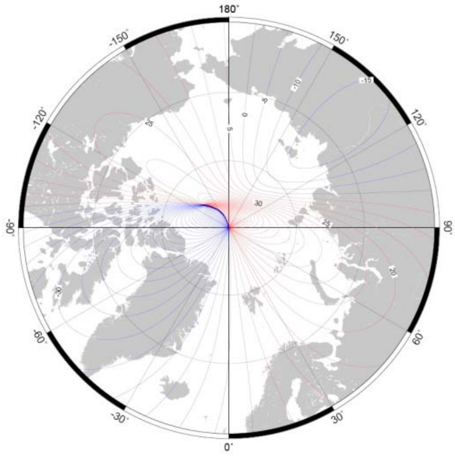
The importance of gathering and sharing metadata (information about data) along with our data holdings was also reinforced this year. During our annual 'call-for-data' we requested basic metadata on instrumentation etc. from data providers to begin the process of building this important dataset.

The issue of metadata was presented and discussed at the IAGA scientific assembly in Sopron, Hungary, and a new IAGA resolution was agreed and adopted, encouraging the preservation of metadata.

A second WDC meeting was held during the Sopron assembly, with representatives from WDCs in the UK, USA, Japan, Russia and India in attendance. Since this meeting we have established new data mirroring relationships with the Kyoto and Boulder WDCs and we hope to develop these relationships further in the coming year.



Plots of the monthly means for two selected observatories (Hurbanovo and Irkutsk) 'before' and 'after' quality-control of gross typographical and formatting errors



Declination over the North Pole at 2010.0 from WMM2010. Red – east, blue - west, black – zero. Contour interval is 5°

Science

Global Geomagnetic Models: WMM2010, IGRF-11 and BGGM2009

The World Magnetic Model (WMM), the International Geomagnetic Reference Field (IGRF) and the BGS Global Magnetic Model (BGGM) were all revised in 2009. The WMM model is the result of UK/US collaboration and provides a reference magnetic field for government, military and business. The IGRF is the product of international collaboration between geomagnetists on behalf of IAGA and provides a magnetic model standard for both public and academic use. The BGS Global Magnetic Model (BGGM) is a dedicated BGS product in support of drilling operations.

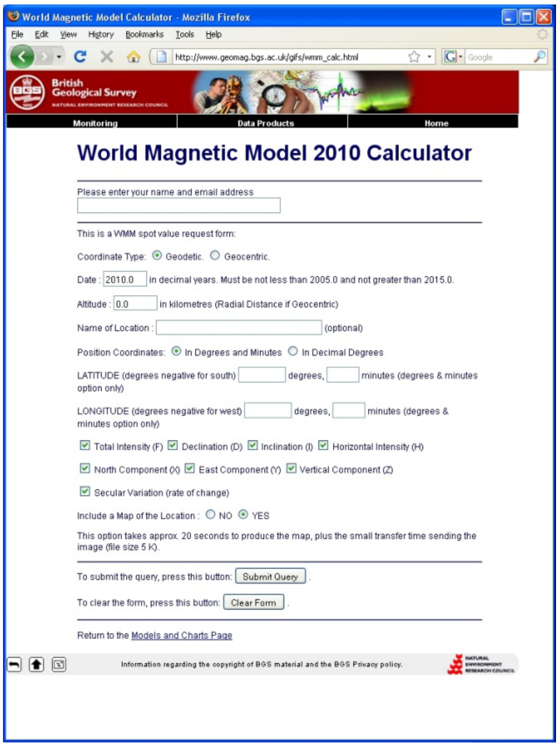
World Magnetic Model

The WMM is a standard model of the core and large-scale crustal magnetic field. It is used extensively for navigation and in attitude and heading referencing systems by the UK Ministry of Defence, the US Department of Defense, the North Atlantic Treaty Organization and the International Hydrographic Organization. It is also used widely in civilian navigation and heading systems.

Irregular changes in the Earth's core field limit the lifetime of any predictive model such as the WMM. For this reason a revision (WMM2010) was released in December 2009, valid until 2015. This model was produced by BGS in collaboration with the US National Geophysical Data Center (NGDC), with funding from the Defence Geographic Centre in the UK and the US National Geospatial-Intelligence Agency.

WMM2010 consists of a degree 12 spherical harmonic model of the Earth's main field (MF) at 2010.0 produced by NGDC and a mean rate of change estimate (called secular variation, SV) over the period 2010.0 to 2015.0 produced by BGS.

In order to construct a SV model we wanted data with as much coverage in space and time as possible. We therefore used data from the CHAMP and Ørsted magnetic survey satellites spanning 1999 to 2009, at a 20 second sampling interval.


World Magnetic Model Calculator - Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://www.geomag.bgs.ac.uk/gifs/wmm_calc.html
British Geological Survey
Monitoring | Data Products | Home

World Magnetic Model 2010 Calculator

Please enter your name and email address

This is a WMM spot value request form:

Coordinate Type: Geodetic. Geocentric.

Date : 2010.0 in decimal years. Must be not less than 2005.0 and not greater than 2015.0.

Altitude : 0.0 in kilometres (Radial Distance if Geocentric)

Name of Location : (optional)

Position Coordinates: In Degrees and Minutes In Decimal Degrees

LATITUDE (degrees negative for south) degrees, minutes (degrees & minutes option only)

LONGITUDE (degrees negative for west) degrees, minutes (degrees & minutes option only)

Total Intensity (F) Declination (D) Inclination (I) Horizontal Intensity (H)

North Component (X) East Component (Y) Vertical Component (Z)

Secular Variation (rate of change)

Include a Map of the Location : NO YES

This option takes approx. 20 seconds to produce the map, plus the small transfer time sending the image (file size 5 K).

To submit the query, press this button: Submit Query

To clear the form, press this button: Clear Form

Return to the Models and Charts Page

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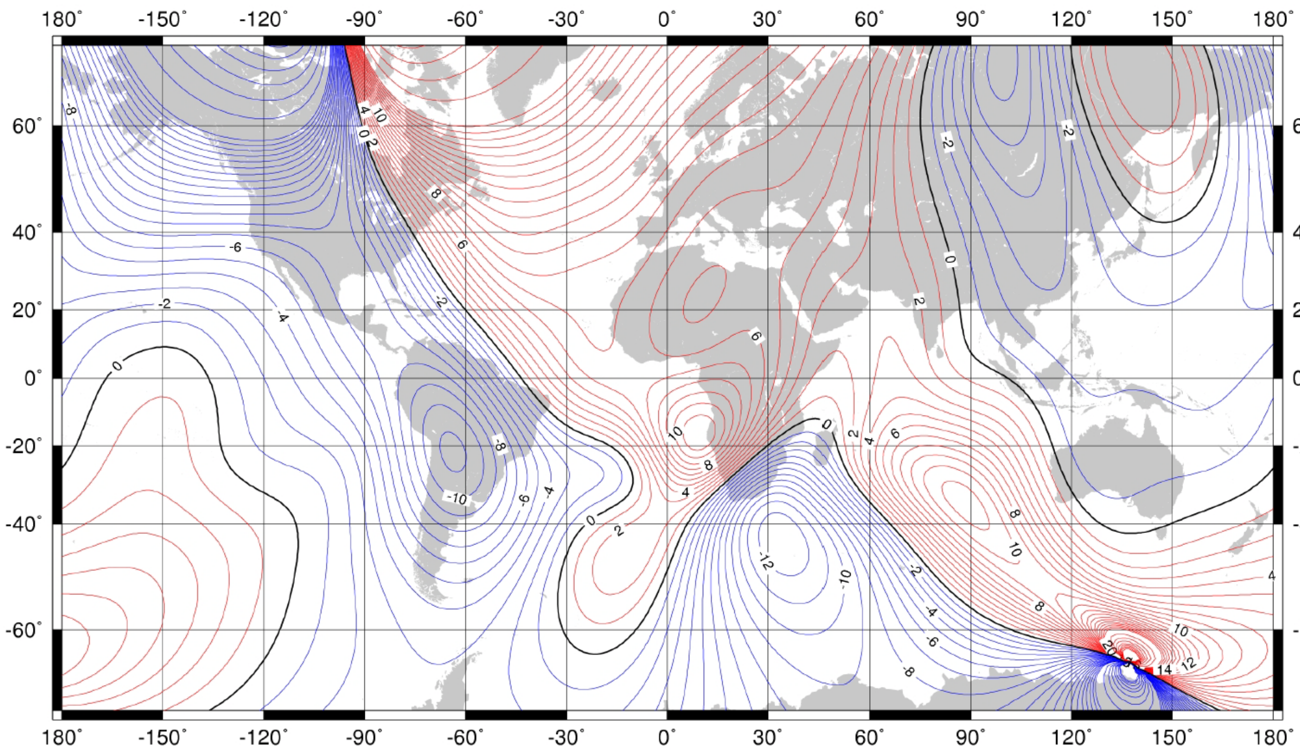
Web form on BGS website used to calculate the WMM2010 field components: *http://www.geomag.bgs.ac.uk/gifs/wmm_calc.html*.

A similar BGS web form also exists for IGRF-11: *http://www.geomag.bgs.ac.uk/gifs/igrf_form.shtml*.

The WMM is a model of the core and large-scale crustal fields only. However the satellite data contain unwanted signals such as small-scale crustal, external ionospheric and magnetospheric and their induced counterparts. These fields would have added noise to the WMM2010 SV model and could have biased its estimates.

BGS employed two techniques to avoid the contamination caused by external magnetic fields.

Firstly we rejected those data most contaminated by these sources, as identified by a combination of local time, geomagnetic indices and solar wind data. However, this had an unwanted side effect in leaving temporal gaps in the data. This would have had a detrimental effect on the quality of the SV estimates. We therefore ameliorated this effect by including similarly selected data from 152 land-based observatories which have the property of a more continuous temporal coverage.



Annual rate of change of declination for 2010.0 to 2015.0 from the World Magnetic Model (WMM2010). Red –easterly change, blue – westerly change, black – zero change. Contour interval is 1'/year (sixtieth of a degree) up to ±20'/year, thereafter 5'/year, and projection is Mercator

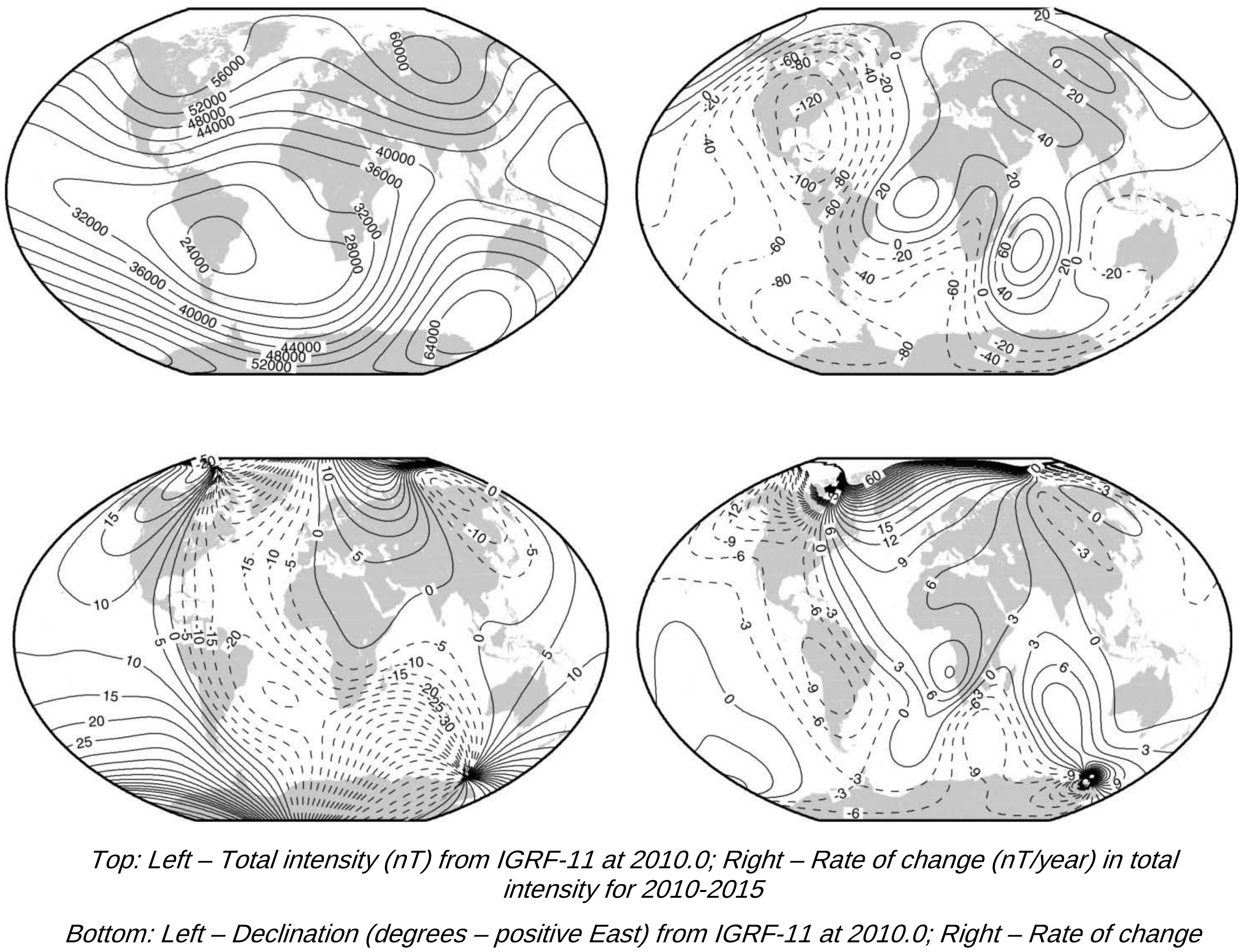
Our second technique was to initially model the larger unwanted sources that we could not easily reject. We therefore constructed what we called a ‘parent model’ for the WMM, including these extra sources, before removing the unwanted components to finalise the WMM. For example, our parent model extended to spherical harmonic degree 60 - a minimum wavelength in the magnetic field of around 660 km - to capture smaller scale crustal features. The WMM parent model also included harmonic terms for large-scale magnetospheric field variations and their induced components.

As well as producing the WMM SV model, BGS also validated the final model and software, co-authored the report and prepared customer-specific deliverables.

International Geomagnetic Reference Field

In October 2009 BGS contributed MF and SV models for the 11th generation of the International Geomagnetic Reference Field (IGRF). The IGRF is a collaborative model produced by geomagnetists from around the world and endorsed by the International Association of Geomagnetism and Aeronomy (IAGA).

The IGRF is a common tool of survey geophysicists and space scientists as a good quality reference model. The IGRF dates back to around 1970 and grew out of discussions that took place within IAGA in the 1960s following the World Magnetic Survey and International Geophysical Year of 1957-1958.



Top: Left – Total intensity (nT) from IGRF-11 at 2010.0; Right – Rate of change (nT/year) in total intensity for 2010-2015

Bottom: Left – Declination (degrees – positive East) from IGRF-11 at 2010.0; Right – Rate of change (min-arc/year) in declination for 2010-2015

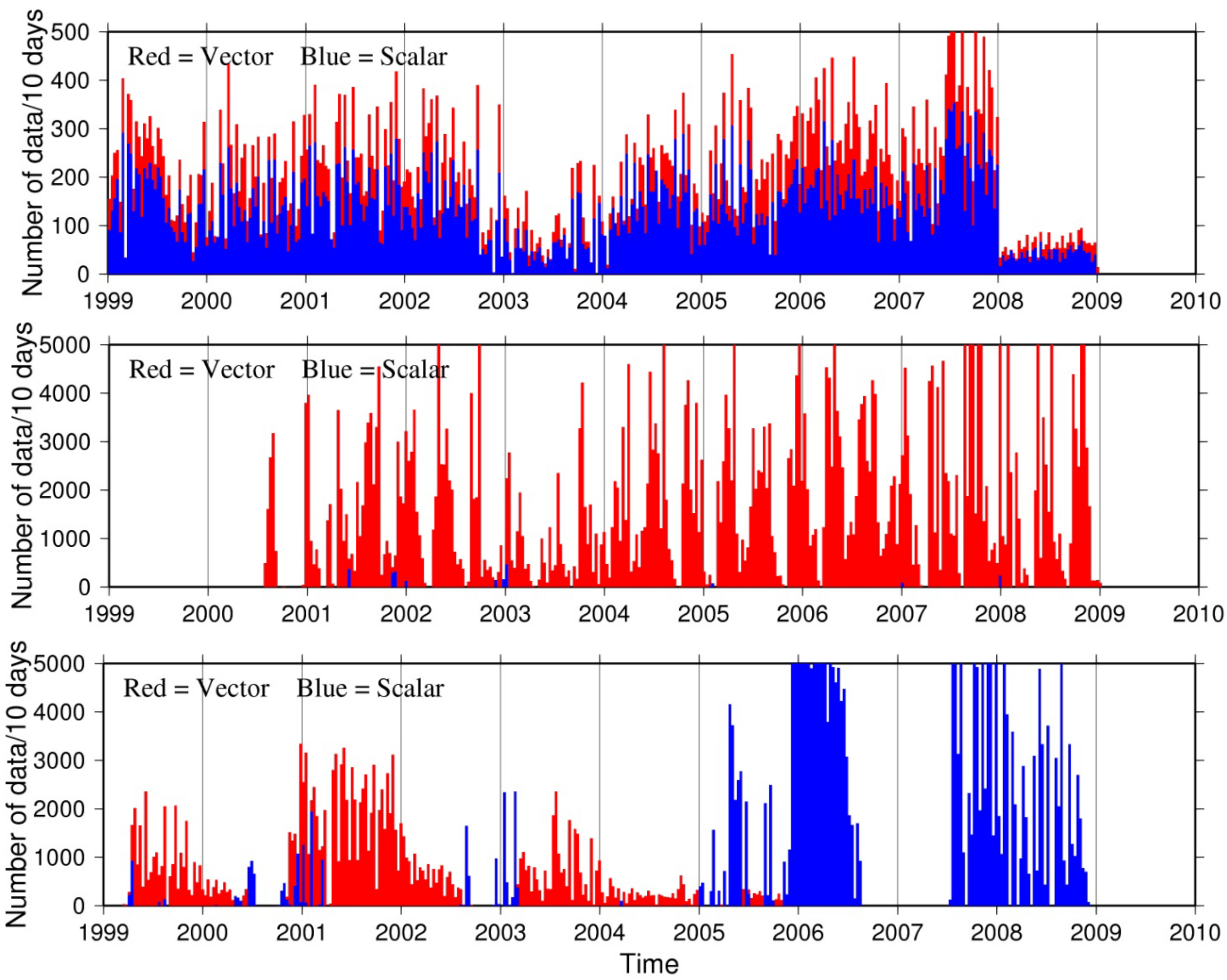
The BGS IGRF candidate models were evaluated alongside those from the other contributing institutes (US, Germany, Denmark, Russia, France). In December 2009, the BGS models for the 2010 MF and 2010-2015 SV models were both accepted and incorporated into IGRF-11.

Currently the IGRF is a spherical harmonic degree 13 model, with maximum harmonic degree 8 for the SV component. Prior to 1995 the IGRF only extends to harmonic degree 10, because of the less dense data distribution that was typical of the pre-Ørsted and pre-Champ satellite eras. The models up to and including 2005 are now designated as 'definitive' models (i.e. known as DGRFs), in that the potential for further improving these is regarded by IAGA as slight.

BGS Global Magnetic Model

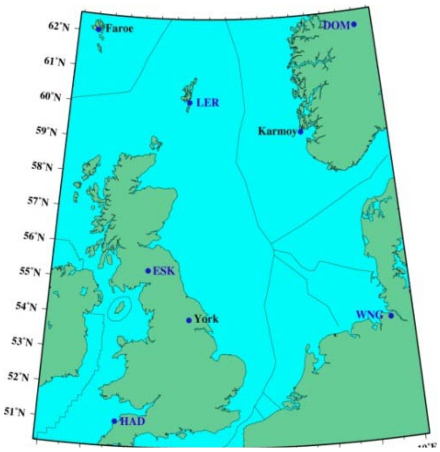
In spring 2009 we completed an update of the BGS Global Magnetic Model (BGGM) for the oil industry. This model is used to correct down-hole magnetic surveys. The 2009 BGGM incorporated all data made available since the last revision in 2008, when the model's maximum spherical harmonic degree was increased and the executable software was updated.

The BGGM has excellent quality control and traceability since, unlike other public models, the BGGM is entirely a BGS effort. Annual updates of the BGGM ensure that the MF and predictive SV models remain high-quality reference models for detailed studies.



Distribution in time of selected data from satellites (top) and observatories (bottom) used in BGGM2009

Science



The eight magnetic observatories (upper case) and variometer stations (lower case) around the North Sea, used in studying improved ionospheric field models

Improving Estimates of Regional Ionospheric Magnetic Fields

The main magnetic field of the Earth and local crustal fields are well characterised in existing BGS global field models and change only slowly with time. However, electrical currents in the ionosphere can produce significant magnetic fields which vary rapidly in time, on the order of seconds to hours. We aim to improve our ability to estimate these regional fields using real-time magnetic observatory and variometer station data.

The magnetic field measured at any point on the surface of the Earth is a combination of the global main field, generated in the core, local fields from crustal rocks, and other effects, including electrical currents that flow in the ionosphere at heights above 100km. The magnetic variations due to these ionospheric currents vary in strength and can be very large, particularly during a geomagnetic storm.

In many applications of geomagnetism it is important to have good estimates of the magnetic field strength and direction at locations distant from geomagnetic observatories, for example for directional-drilling of oil wells deep underground or for detecting the presence of potentially damaging geomagnetically induced currents in the UK power grid.

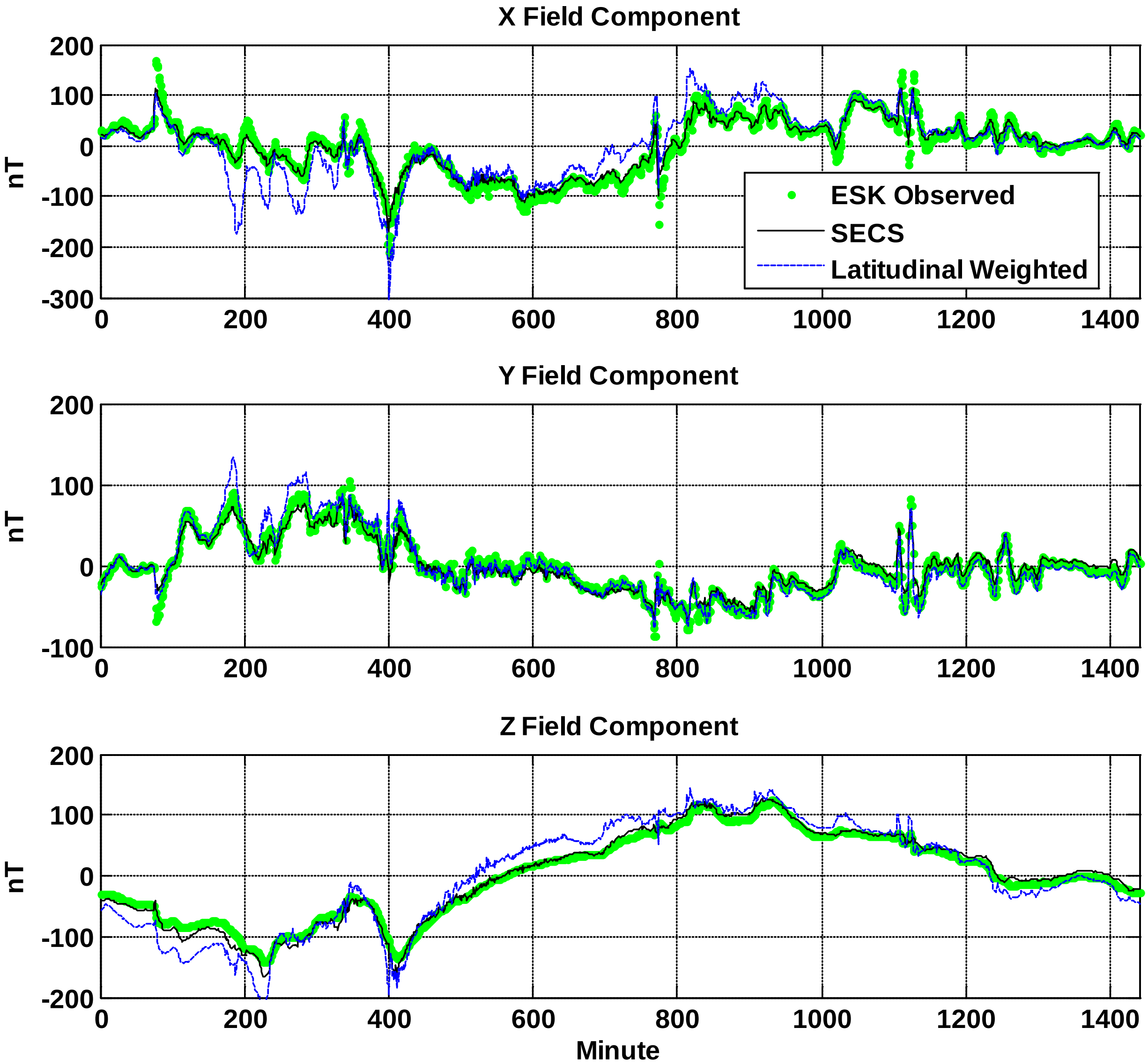
Currently, to estimate the magnetic field due to the ionosphere at a point on or below the Earth's surface, the BGS uses data measured from two magnetic observatories – one to the north and the other to the south of the point of interest. At the point of interest the observatory measurements are averaged, weighted by the latitudinal difference of the sample point from each observatory.

However we have been investigating the potential of another method of estimating the magnetic field generated by the ionosphere. This is a technique known as 'Spherical Elementary Current Systems' (SECS).

The SECS method employs mathematical equations to represent the ionosphere as a grid of point current systems, which interact with each other at a height of 110km. The magnitude of each of the individual current systems is deduced from data from a regional network of magnetic observatories and variometer stations surrounding the point of interest.

This method should work well in the North Sea basin which has a large number of observatories and variometer stations (*see map on previous page*). For example we have compared how well the SECS method and the present method estimate the field at a location where we have measured data (*see the case study below, where we compare measured Eskdalemuir magnetic data with the results of the two methods*).

We have found that on very magnetically disturbed days, when the ionospheric contribution to the total measured field at an observatory is relatively large, the SECS method outperforms the traditional method; on quieter days the two methods are comparable in accuracy. Further studies, for different parts of the world are planned.



Estimation of the magnetic field produced from ionospheric currents: *The disturbance of the magnetic field on a particularly disturbed day (11th September 2005) as observed at Eskdalemuir. The average strength of the magnetic field in the X, Y and Z components has been subtracted for clarity, leaving the deviation from the mean (green line). Overlain (black line) is an estimate of the magnetic field using the SECS method. The data for the SECS method were gathered from seven other stations in the North Sea area. The mismatch between the two curves is small. For comparison, the traditional method of estimation using latitudinal weighting of Lerwick and Hartland data is shown (blue dashed lines)*

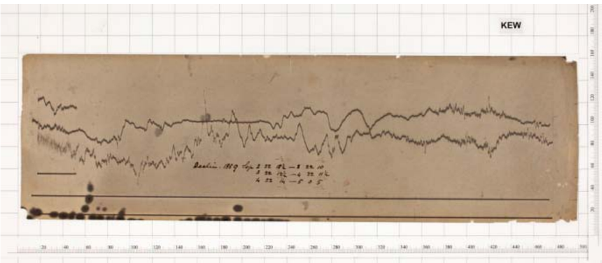
Science

Browsing the magnetogram archive, Murchison House, Edinburgh

Historical UK Geomagnetic Records

Continuous geomagnetic monitoring is important in the analysis of solar-driven regular and irregular field variations. In order to investigate changes in the character of these variations, over decades to centuries, the data sets of most value are those that can be derived from the longest-running series of observatories. Thus, the historical observatory records held in the BGS archive are of fundamental importance.

Protecting the legacy and exploiting the resources left to us by our predecessors is, in many ways, as important a task as the on-going operations of the observatories today. Magnetograms (*e.g. as below*) and yearbooks from UK observatories dating back to 1848 are held in the BGS archives and urgently need to be safeguarded.



Four main priorities were identified for these original paper records. These were to:

- maintain a secure and safe storage environment
- generate a digital back-up copy
- improve accessibility
- extract digital values

The majority of the records are now stored in the Murchison House archive, Edinburgh; a temperature and humidity controlled environment that provides optimum long-term storage conditions to help preserve historic scientific documents. Plans have also been made to transfer the remaining magnetograms from Hartland in 2010. In 2008 the programme of work began to capture digital images of the magnetograms, generating the essential back-ups

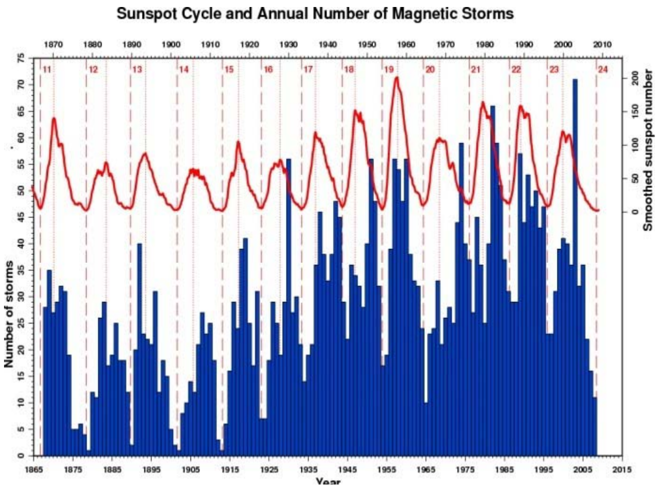
required. The system (*photo above*), designed and developed by BGS photographic services in Edinburgh, includes a 21 megapixel resolution camera. It uses a flat plane macro lens to minimise distortion and a fixed focal length.

The capture of the first two data sets, the Kew and Greenwich magnetograms, which were considered most at risk, is now complete. The second stage is to provide global access to this largely untapped data so the digital images will soon be available on-line as part of the BGS *OpenGeoscience* service (http://www.bgs.ac.uk/opengeoscience/).

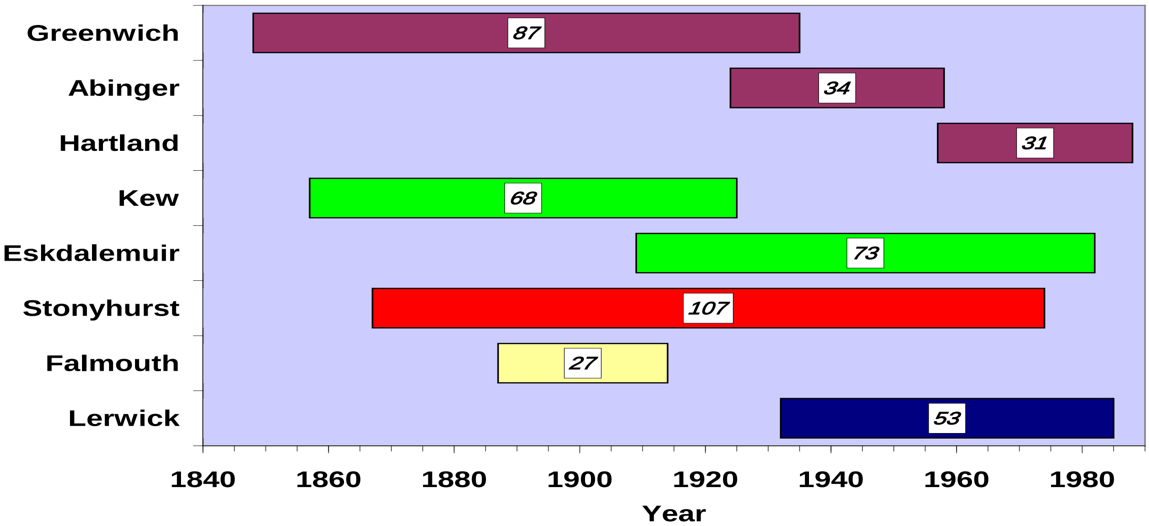
In addition to the magnetograms, plans have been made to photograph the complete set of UK observatory yearbooks. This will provide valuable on-line metadata to accompany the magnetograms, as well as being an additional data resource in its own right.

A Java program is being developed to extract digital data from the magnetogram images. It is intended that this software, which makes use of recent advances in image processing techniques, will enable data to be obtained by a semi-automated process.

Currently the longest running digital geomagnetic data set is the 3-hour *aa* index, which extends back to 1868. A global geomagnetic activity index that is much used in long-term climatological studies, the *aa* can for example be used to identify geomagnetic storms (*below*).

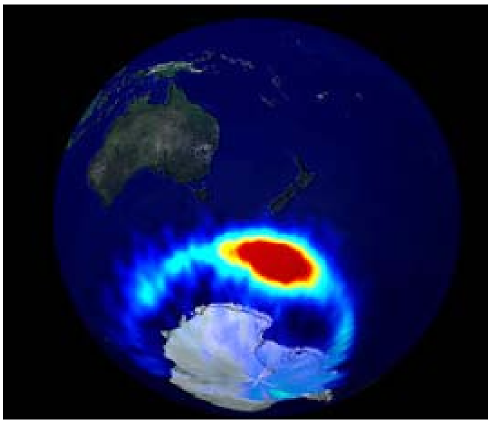


Digitisation of historical analogue data will enable the derivation of other similarly long or even longer data sets providing researchers with the tools to find additional evidence of long term trends and variations.



The UK magnetogram archive consists of photographic records from eight observatories. Only three are still in operation today. Some observatories were forced to move to alternative sites as local infrastructure affected magnetic field measurements; others fell into disuse over time as personnel moved on

Science



Auroral and polar electrical currents (highlighted) affect high-latitude magnetic field models (Picture courtesy NASA)

Geomagnetism Students

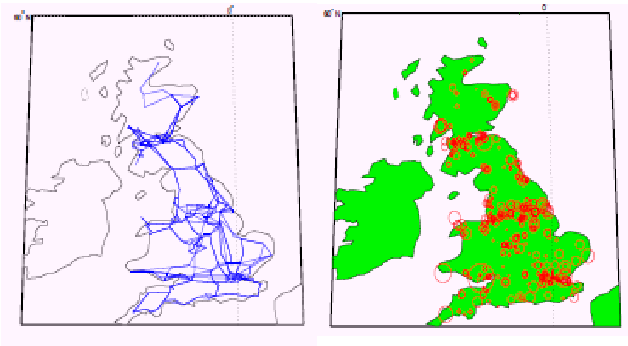
The team currently has three PhD students, studying various aspects of geomagnetism. All are part-funded by the BGS-Universities Funding Initiative (BUFI) and by NERC and EPSRC. Our students have produced papers and posters and made presentations at numerous meetings and conferences in 2009.

Katie Turnbull is in the third year of her PhD in the Department of Communication Systems at the University of Lancaster, studying 'Geomagnetically Induced Currents (GIC) in Power Systems' supervised by Alan Thomson and Dr Jim Wild of the University of Lancaster.

Katie is the lead author on a paper recently published by Annals of Geophysics on "Characteristics of variations in the ground magnetic field during substorms at mid latitudes."

In this paper it is argued that an improved knowledge and understanding of how the different phases of geomagnetic sub-storms affect the magnetic field will ultimately help to better understand how GIC arises in power grids. Using a list of sub-storm expansion phase onsets, derived from auroral observations by the IMAGE-FUV satellite, Katie and co-workers examined 553 individual sub-storm onsets and summarised their characteristics.

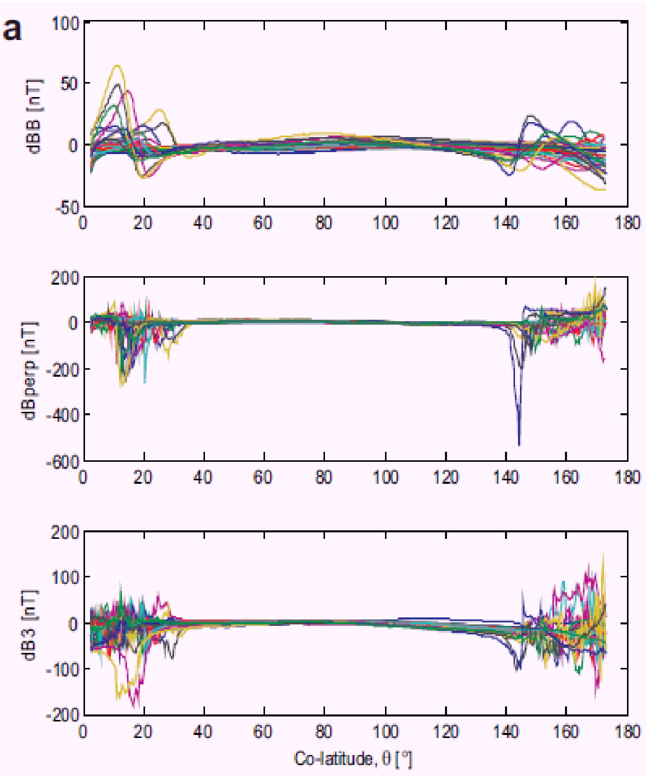
Katie has also constructed a new high-voltage power grid model for the UK mainland and is currently examining how it responds to both hypothetical and historical examples of geomagnetic storms (*see Figure below*).



High voltage grid of the UK at 2008 (left) and GIC flowing at major transformers (right) for a hypothetical east-west surface electric field of 1V/km

Gemma Kelly is currently in the second year of her PhD, studying 'Polar Geomagnetism' at the University of Liverpool and co-supervised by Alan Thomson and Dr Richard Holmes of the University of Liverpool.

During the last year Gemma has been investigating magnetic field residuals between satellite data (Ørsted and CHAMP) and well-known geomagnetic field models (e.g. 'Tsyganenko 01' and 'CHAOS-2'), particularly in the northern high latitude region. The data investigated are for night time only during periods of quiet geomagnetic indices.



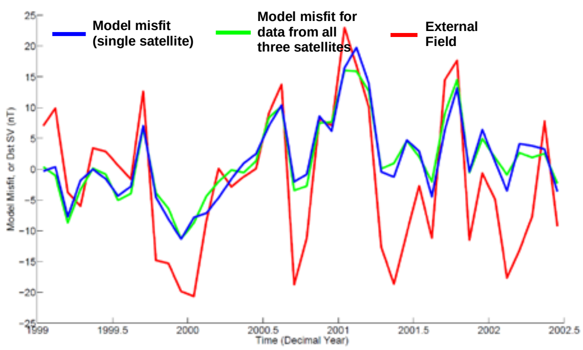
Data-Model vector field residuals (nT) for night-side CHAMP satellite data, ordered by co-latitude, on 15-16 March 2001, with one axis (top) aligned to the ambient magnetic field direction

In order to look for patterns and consistent signals in the data she has been studying the residuals on an orbit by orbit basis. By looking at the residuals in this way we can identify features which are constant in time, and begin to get an idea of possible electrical current sources that produce large magnetic residual values. Results indicate that existing models – commonly used in the global field modelling community – do not capture the variability in real data. This has implications for polar field modelling, which Gemma will explore next year.

Rob Shore began his PhD in September 2009, at the University of Edinburgh, supervised by Susan Macmillan and Professor Kathy Whaler of the School of GeoSciences at the University of Edinburgh. Rob is studying 'Satellite magnetometry and the new ESA SWARM constellation'.

Rob's project will help to improve our capabilities in quantifying the sources of the Earth's magnetic field. He aims to derive models of the core and lithospheric fields that are less contaminated by time-varying ionospheric and magnetospheric fields at all latitudes. Following from this we should also be able to improve our understanding of how the core field evolves with time and improve our short-term predictions of it.

In the first few months of the project Rob has been using simulated Swarm satellite data. He is investigating whether applying the "virtual observatory" technique to data from a constellation of satellites results in models less contaminated with time-varying external fields as compared to models from single satellite data sets.



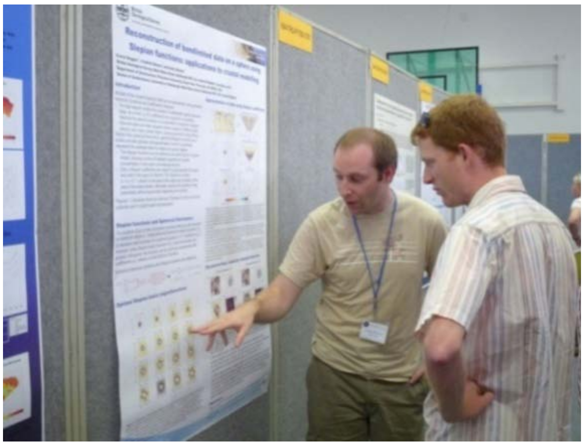
Correlation of model misfits with external field *signal. Models fitted to simulated Swarm satellite constellation data*

Explaining the INTERMAGNET programme to scientists at the IAGA assembly in 2009 in Hungary

Outreach and Knowledge Exchange

Geomagnetism science remains an active research area. A decade of continuous sampling of the magnetic field by satellites has just been completed. These data, together with measurements from the global network of magnetic observatories, have enabled us to study the Earth's magnetic field at a finer resolution than before and therefore to increase our basic knowledge of the Earth. The Geomagnetism team has been active in basic research and in communicating the exciting new developments and why they matter.

Our outreach and IKE activities take the form of talks, presentations, demonstrations, observatory 'tours', university teaching, web-articles and, of course, paper publications.



Poster session at the IAGA assembly 2009

One regular annual activity for the team is participation in the BGS 'Open Day' held in Edinburgh every September, intended for the general public, and the 'Schools Week', for school children.

We also contributed to a regular bi-monthly column, on 'space weather and navigation' published in the Royal Institute of Navigation's 'Navigation News'.

The team was a major contributor at the IAGA conference in Sopron, Hungary in August (*see Figures on this page*).

Much of our science activities in the year were focussed on this major event in geomagnetism science. Presentations were also made at, for example, the EGU and Space Weather Week conferences and the MagnetE and ESA Swarm science workshops, as detailed below.

Scientific Journal Publications

Published 2009

Beggan, C. D., Whaler, K. A., 2009. Forecasting change of the magnetic field using core surface flows and ensemble Kalman filtering, *Geophysical Research Letters*, 36, L18303. doi:10.1029/2009GL039927

Beggan, C.D., Whaler, K. A., Macmillan S., 2009. Biased residuals of core flow models from satellite-derived 'virtual observatories', *Geophysical Journal International*, 177, 463-475. doi:10.1111/j.1365-246X.2009.04111.x

Macmillan, Susan; Chris Turbitt and Alan Thomson, 2009. Ascension and Port Stanley geomagnetic observatories and monitoring the South Atlantic Anomaly. *Annals of Geophysics*, **52**, 83-96.

Matzka, J., Olsen, N., Fox Maule, C., Pedersen, L. W., Berarducci, A., Macmillan, S., 2009. Geomagnetic observations on Tristan da Cunha, *Annals of Geophysics*, **52**, 97-105.

Simons, F.J., Hawthorne, J.C., Beggan, C., 2009. Efficient analysis and representation of geophysical processes using localized spherical basis functions, in Proceedings of the International Society for Optical Engineering (SPIE). Wavelets XIII, Goyal, V.K., Papadakis, M., Van De Ville, D. (Eds.), vol. 7446, 74460G. doi:10.1117/12.825730

Turnbull, K.T., Wild, J. A., Honary, F. Thomson, A. W. P. and McKay, A. J., 2009. Characteristics of variations in the ground magnetic field during substorms at mid latitudes. *Ann Geophys*, **27**, 3421-3428.

Submitted, Accepted and to Appear 2010 (at April)

Beggan, C., Whaler, K., 2010. Forecasting secular variation using core flows, *Earth Planets Space* (submitted).

Beggan, C., Hamilton, C.W.. 2010. New image processing software for analyzing object size-frequency distributions, geometry, orientation, and spatial distribution, *Computers and Geosciences*, 36. doi:10.1016/j.cageo.2009.09.003 (in press).

Hamilton, B., Macmillan, S., and Thomson, A, 2010. The BGS magnetic field candidate models for the 11th generation IGRF, *Earth, Planets, Space*, Special Issue on International Geomagnetic Reference Field — the eleventh generation (submitted).

Thomson, A.W.P., Hamilton, B., Macmillan, S. and Reay, S., 2010. A Novel Weighting Method for Satellite Magnetic Data and a New Global Magnetic Field Model, *Geophys. J. Int.*, 181, 250-260, doi: 10.1111/j.1365-246X.2010.04510.x..

Thomson, A.W.P. Gaunt, C.T., Cilliers, P., Wild, J. A., Opperman, B., McKinnell, L-A., Kotze, P., Ngwira, C. M. And Lotz, S. I., 2010. Present Day Challenges in Understanding the Geomagnetic Hazard to National Power Grids, *Adv. Sp. Res*. doi: 10.1016/j.asr.2009.11.023 (in press).

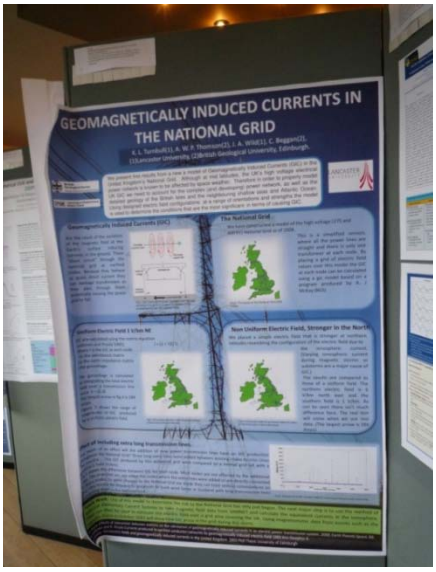
Other Publications

4 BGS Reports (BGS observatory service visits; 2008 annual review; Crooktree survey)

20 Customer Reports (UK survey & OS; oil industry services; overseas observatories)

84 Observatory Monthly Bulletins: www.geomag.bgs.ac.uk/bulletins/

Geomagnetism activities on BGS website (via BGS web search facility):
www.bgs.ac.uk/news/result.cfm?action=textsearch&userTxt=geomagnetism&newsSearchBtn=++go++&code=NEWS&code=VACANCY&code=UPDATES&code=DIARY&code=ANNOUNCEMENT
and www.bgs.ac.uk/news/ns_home.html



Left: *Poster on the geomagnetic hazard to the UK power network: European Space Weather Week Six, November.* ***Right***: *The GEOSPACE six-monthly consortium meeting, January.*

Conference Presentations, Posters and Related Activities

GEOSPACE consortium science meeting, January, Edinburgh

1 Presentation (Beggan); 2 Posters; A BGS-organised meeting at Murchison House

NERC Data Management Workshop, February, Swindon

1 Poster

SPE/IADC Drilling Conference, Amsterdam, Netherlands, March

1 Presentation (Macmillan)

European Geophysical Union, Vienna, Austria, April

1 Poster

COST ES0803 Action on ‘Space Weather Services’, Frascati, Italy, April

1 Presentation (Thomson & Clarke); UK management delegate (Thomson)

Swarm 2nd International Science meeting, Potsdam, Germany, June

3 Posters

MagNetE Workshop, June

2 Presentations (Shanahan); MagNetE organising committee member (Shanahan)

International Association for Geomagnetism and Aeronomy, Sopron, Hungary, August

6 Presentations (Baillie, Beggan, Clarke, Macmillan, Reay, Thomson); 7 Posters; INTERMAGNET Exhibitor Stand; Division 5 co-chair (Thomson)

RAS/BGA Discussion Meeting on 'Swarm', London, UK, October,

4 Posters

BGS Technology Forum, Keyworth, Nottingham, October

1 Presentation (Turbitt)

BGS-Universities Funding Initiative (BUFI) Student Meeting, Keyworth, Nottingham October

2 Posters

European Space Weather Week 6, Bruges, Belgium, November

Scientific Organising Committee Member & Splinter Group Presenter (Thomson); 2 Posters

Assembly of the International Association for Geomagnetism and Aeronomy in Hungary, August 2009. (Picture courtesy IAGA)

Other Notable Outputs

AGU Outstanding Speaker Award (from December 2008)

Ciaran D Beggan, Trans. AGU, 89(53), Fall Meet. Suppl., Abstract GP53B-07

RAS Geophysics Prize (April) and The Queen's New Year Honours List (December)

Dr David J Kerridge MBE

Edinburgh University Undergraduate Lecture Series(September-December)

4th Year Honours Course on 'Geomagnetism', Ciaran Beggan and Alan Thomson

Public Lectures, Presentations and Demonstrations

Educational and training activities with customer groups, student groups, societies.

Acknowledgements

Alan Thomson would like to acknowledge the support of his colleagues, Geomagnetism team stakeholders and the Geomagnetism Advisory Group, BGS management and the Natural Environment Research Council.

He would also like to thank Susan Macmillan and David Kerridge for their contributions to this review. The Geomagnetism team as a whole is thanked for all their activities and hard work in 2009.

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

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

Selected Glossary, Acronyms and Links

BAS. British Antarctic Survey. (http://www.antarctica.ac.uk/)

BGGM. BGS Global Geomagnetic Model (http://www.geomag.bgs.ac.uk/bggm.html)

BGA. British Geophysical Association. (http://www.ras.org.uk/index.php?option=com_content&task=view&id=936&Itemid=2)

BGS. British Geological Survey (http://www.bgs.ac.uk/)

BNSC. British National Space Centre. (http://www.bnsc.gov.uk/)

BUFI. BGS-Universities Funding Initiative. (http://www.bgs.ac.uk/research/who.html)

CHAMP. German magnetic survey satellite. (http://www-app2.gfz-potsdam.de/pb1/op/champ/)

DGRF. Definitive Geomagnetic Reference Field. See **IGRF**.

DTU. Danish Technical University. (http://www.space.dtu.dk/English.aspx)

EGU. European Geophysical Union. (http://www.egu.eu/)

ESA. European Space Agency (http://www.esa.int/esaCP/index.html)

ESWW. European Space Weather Week. (http://sidc.oma.be/esww6/)

IAGA. International Association of Geomagnetism and Aeronomy (http://www.iugg.org/IAGA/iaga_pages/index.html)

IIFR/IFR. Interpolated In-Field Referencing/In-Field Referencing. (http://www.geomag.bgs.ac.uk/documents/estec_iifr.pdf)

IGRF. International Geomagnetic Reference Field. (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html)

INTERMAGNET. International magnetometer network: a global network of magnetic observatories operating to common standards. (http://www.intermagnet.org/)

INDIGO. (http://pubs.usgs.gov/of/2009/1226/)

ISCWSA. The Industry Steering Committee on Wellbore Survey Accuracy. (http://iscwsa.org/)

ISGI. International Service for Geomagnetic Indices (http://www.icsu-fags.org/ps06isgi.htm)

IUGG. International Union of Geodesy and Geophysics. (http://www.iugg.org/)

GEOSPACE. NERC consortium of UK universities and institutes studying geomagnetism. (http://www.geos.ed.ac.uk/research/geospace/)

GFZ. Helmholtz centre, Potsdam, Germany, (http://www.gfz-potsdam.de/portal/-?$part=CmsPart&docId=1346494)

GPS. Global Positioning System. (http://www.gps.gov/)

MagNetE. European magnetic repeat station network (e.g. http://space.fmi.fi/MagNetE2009/?page=welcome).

Met Office. UK meteorological office. (http://www.metoffice.gov.uk/)

MIST. Magnetosphere, Ionosphere, Solar-Terrestrial (Physics). (http://www.mist.ac.uk/)

NAMAS. National Measurement and Accreditation Service. (http://www.ukas.com/)

NERC. Natural Environment Research Council (http://www.nerc.ac.uk/)

NCEO. National Centre for Earth Observation (http://www.nerc.ac.uk/research/areas/earthobs/nceo.asp)

NGS. National Geomagnetic Service (http://www.geomag.bgs.ac.uk)

NOAA/NGDC. National Oceanic and Atmospheric Administration/National Geophysical Data Center (http://www.ngdc.noaa.gov/).

Ørsted/Oersted. Danish magnetic survey satellite. (http://web.dmi.dk/projects/oersted/)

OS. Ordnance Survey. (http://www.ordnancesurvey.co.uk/oswebsite/)

RIN. Royal Institute of Navigation. (http://www.rin.org.uk/)

RAS. Royal Astronomical Society. (http://www.ras.org.uk/)

Royal Society. UK National Academy of Science. (http://royalsociety.org/)

SAMNET. Sub-Auroral Magnetometer Network. (http://www.dcs.lancs.ac.uk/iono/samnet/)

SPE. Society of Petroleum Engineers (http://www.spe.org/spe-app/spe/index.jsp)

Swarm. Proposed three-satellite ‘mini-constellation’ for magnetic field surveying. (http://www.esa.int/esaLP/LPswarm.html)

SWENET. Space weather network (ESA) (http://www.esa-spaceweather.net/swenet/index.html)

WDC. World Data Centre (http://www.wdc.rl.ac.uk/wdcmain/,
http://www.wdc.rl.ac.uk/wdcmain/europe/edinburgh.html)

WMM. World Magnetic Model
(http://www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml)

The Geomagnetism Team in 2009

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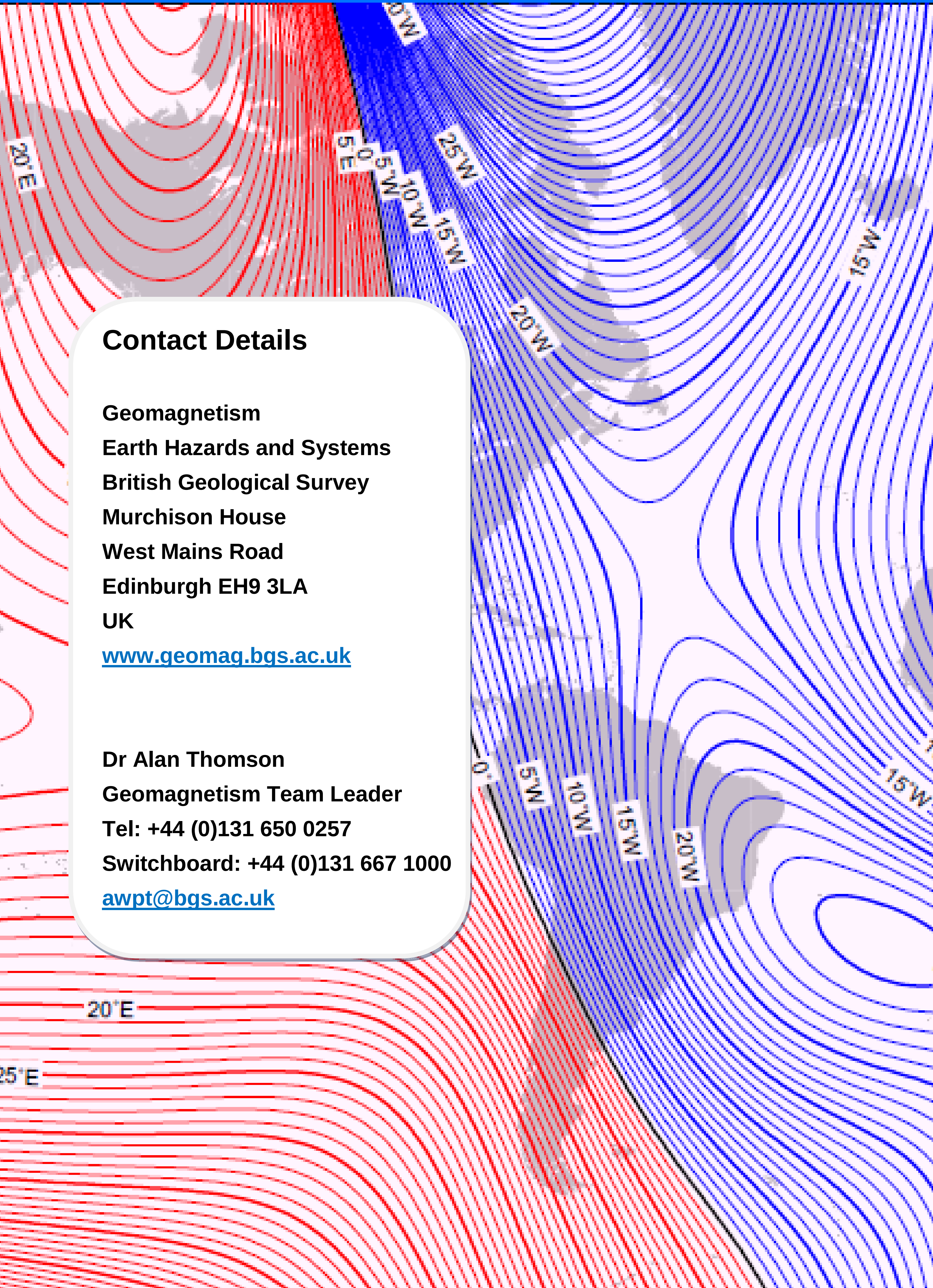

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