Interactive comment on “Building a Raspberry Pi School Magnetometer Network in the UK”

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Reviewer 1:

Author’s Response: Phil: Thank you for taking the time to review the manuscript. We have updated the manuscript as suggested and altered Figure 3 to be clearer. The detailed response is below.

1. Abstract - last sentence, system not systems. Response: changed

2. Introduction - "over periods" is ambiguous. Does this convey the time period i.e. 2 Pi/frequency or length of data window? Response: we meant the length of the data window over a time range of several minutes to several hours. Wording has been changed.

3. What is the actual price of one of the authors’ magnetometers? Only a relative value is given. This might be helpful for others to see how much it would cost to join their network. Response: The approximate cost is around 150 GBP at 2018 prices, though this is with a bulk-buy discount.

4. Section 2, l1 varies both <in> time.. Response: corrected

5. Section2, l14, temperature measurements of what? Please be more specific. Presumably you mean of the atmosphere, and direct measurements rather than by proxy? Response: It measures the ambient temperature of the air using a thermistor. The text has been updated.

6. l29 typo: seasonal Response: corrected

7. Section 3.1, l23 the current <difference> is .. Response: corrected

8. Section 2.1, l33 can be calculated, <which may also be expressed as> D, I... Response: changed

9. Section 3, l22 if the <calibration> magnetic field.. Response: I’ve left this as written because the resolution of each measurement is directly dependent on the field strength. Larger field strengths have lower resolution due to the limited range of the digisiter. In scientific observatories, the digitiser is 24-bit (rather than 16-bit) and the main field is ’backed off’ using another set of coils wrapped around the fluxgate magnetometers to reduce the magnetic field variation to +/- 4000 nT for this very reason. These systems can achieve resolution of around 0.1pT or better, though other noise is around 5-10pT in general.

10. Section 5. l4. Please make clear that X is the most sensitive component as the electrojet flows East-West. Response: I’ve amended the text.

11. Fig3. I found the bottom axis label confusing - it looks like its in units of nT/C. I suggest using a right axis, separating out the two quantities: i.e nT on the left axis, degrees C on the right. Also, you report only temperature variation - what is the baseline that you’ve used? i.e. what does zero temperature represent? Response: The Figure 3 plot has been changed to move the temperature variation scale to the right hand side. The scale is now in degrees C. The caption has been amended to state that the temperature varies around a baseline value of 18 degrees C, as the building was heated. The updated figure is shown below.

Reviewer 2:

C. Finlay (Referee)

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This manuscript presents details of a simple, low cost, magnetometer system suitable both for outreach activities in schools and for scientific monitoring of large amplitude geomagnetic disturbance events. A clear description is given of the measurement system and examples of data collected from a number of locations across the UK are presented. An illustration of the scientific value of the data in monitoring the impact of the September 2017 geomagnetic storm is given, along with a very nice movie that is available through you tube. The authors are to be commended for conceiving and carrying out this inspiring project! It provides a splendid example of how the public can be actively involved in real-world geoscience. Furthermore the pitfalls and challenges inherent in such a project are clearly set out; this will be of great aid to those contemplating similar activities. The manuscript is both well written and appropriately referenced. I recommend it be accepted once the minor points/suggestions listed below are addressed.

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Author's Response: Chris: Thank you for the positive comments on the work. We have taken your suggestions and provide a detailed response below.

1. Perhaps it may be useful to state the approx precision of the system and price (1.5 nT and 150 GBP?) of the system already in the abstract. This information is likely of great interest to many readers. Response: This was also commented by Reviewer 1. The manuscript has been updated to provide this information.

2. Section 2: Similar to a bicycle dynamo: please add a note that unlike a bicycle dynamo there is no permanent magnet in the core involved in generating the Earth's magnetic field, since the temperatures there are too high. Response: We have updated the text to clarify this point. Added in a reference to Lowrie (2007).

3. Section 2: 'the speed and density of the solar wind ... increases and energy is passed' -> 'the speed and density of the solar wind ... increases, and the interplanetary magnetic field is perturbed, resulting in energy being passed' Response: Text has been modified as requested

4. Section 2: 'generating large magnetic fields' -> generating relatively large magnetic fields (amplitudes up to 100-1000 nT) Response: Text has been modified

5. Section 2.1 ' The current is directly proportional to' -> 'the current needed to produce saturation is directly proportional to' Response: Text has been modified "The current difference is directly" as this was also noted by Reviewer 1.

6. Section 3: The magnetometer system consists of -> The Raspberry Pi school magnetometer system consists of Response: Text has been changed

7. Section 3. 'true accuracy' Do you mean precision? Is this not a variometer without absolute measurement accuracy? Response: Text has been changed to say precision. The relative accuracy over a few hours is good, but it is not a full field absolute instrument so, yes, the accuracy at any given time would be poor.

8. Section 3.1/ Fig 2. There is an offset in H between Rpi and GDAS1 early on 12th Sept of > 50 nT, any idea of the reason for this? Response: I'm not entirely sure. Most likely it is some manmade background that disappeared by the middle of the day (like on the 17th Sep) as the system was in an office in Murchison House. It may in part also be due to longer term temperature drift – there is a mean value subtracted from the Rpi data rather than a linear fit over the five days.

9. Section 3.1 'remove much of the error by backing-out the measured temperature through calibration. Has this been done? If so it might be nice to show the corrected version in Fig 3?

Response: Yes, I have played around with the temperature correction and made code and example data available in Python for the schools themselves to have a go. I used a least -squares fit to a second-order polynomial so get an offset (near zero), linear and second-order terms. The coefficients are quite dependent on the time-series selected though as the instrument response is non-linear with temperature. Hence, the best strategy in reality is to keep the temperature stable. For the data used in Figure 6, the temperature changes were 'backed out' as best as possible (though not fully in BGS03 for example at the end of the time-series), and the data from the BGS variometers were aligned to true north, again as best as possible (given the lack of orientation information). I have implemented a correction and placed an updated Figure 3 and the correction coefficients that were computed (Figure 1 below).

10. Section 4 'cover the UK in both latitude and longitude'. Perhaps a school in N. Ireland might also be of interest? Response: Although I didn't try too hard, I didn't meet anyone from a school in NI at any of the IOP fairs or come across one through other contacts.

11. Section 5 'the aurora moves as far south as LER' Do you mean the magnetic signature of the aurora or the aurora as seen in visual observations? Response: The aurora were visible across the UK (and photographed by the BGS Aurora Camera in ESK though it was raining in LER) but I've amended the sentence to be clearer.

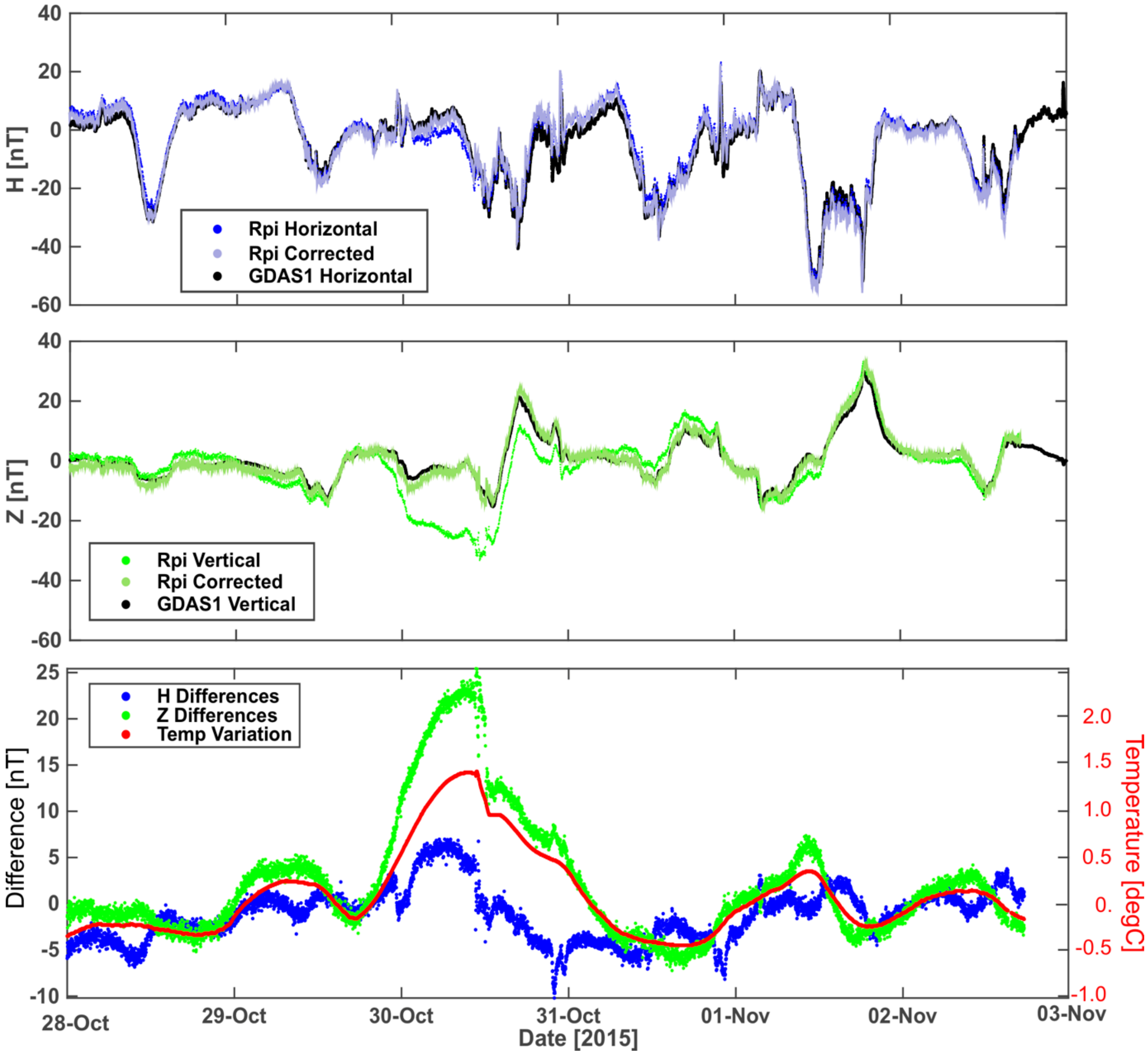

Fig 1. Updated version of Figure 3 in the paper with temperature-corrected curves for the H and Z component

Reviewer 3:

P. Coïsson (Referee)

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The article "Building a Raspberry Pi School Magnetometer Network in the UK" presents a very interesting outreach project to develop a network of low-cost magnetometers to deploy in schools. The details on the instruments a technological choices are described and a very interesting example of a major storm is presented providing the bridge between this citizen science and the research science. The article is informative, well organised and pleasant to read. It is acceptable for publication after very minor revisions.

Author's Response: Pierdavide: We thank you very much for reading through the manuscript and providing suggestions for improving it.

Some comments:

In the introduction it is described how the low-cost magnetometers and acquisition chains, can provide instruments useful for citizen science. It would be important to cite some other projects. Later in the manuscript the school seismometers are mentioned, it could be important to introduce these other outreach projects here. Also, other citizen science projects on magnetism could be cited (e.g. CrowdMag)

Response: Correct - there are a number of geophysical networks along the lines of this project particularly for citizen scientists and schools. We have amended the first paragraph as follows: "Over the past decade, the introduction of cheap reliable computing hardware and sensors, along with the ubiquity of high-speed Internet connections mean that it is now possible create low-cost open-science networks of geophysical sensors. This has encouraged the development of data-intensive networks, for example in climate studies (Weather Observation Website: wow.metoffice.gov.uk/), seismology (BGS School Seismology Project: www.bgs.ac.uk/schoolseismology/) or cosmic ray research (the TimPix Project: www.researchinschools.org/TIMPIX) where spatial and temporal gaps in the professional scientific networks may be filled or augmented. Some networks employ existing platforms such as mobile phones using in-built sensors to record data (e.g. CrowdMag, see www.ngdc.noaa.gov/geomag/crowdmag.shtml) while others create bespoke hardware with higher accuracy than general purpose systems. In geomagnetism, high-quality low-cost fluxgate sensors have become more widely available to allow accurate monitoring of the variation of the Earth's magnetic field over time ranges of several minutes to hours."

Section 2 presents the Earth magnetic field, its sources and the traditional observatories that are deployed for scientific research. There is very little information about the chains of magnetometers that exists, in many cases oriented for Space Weather applications. Some of them are used later in this work for the study of the September 2017 storm. It would be better to present them in this section, adding relevant references to these networks.

Response: I think that is perhaps too much detail for a general audience. We do note that "The global scientific magnetic observatory network fulfils this role. However, there are presently only around 200 magnetic observatories worldwide, with a very uneven spatial coverage biased towards the northern hemisphere, and Europe in particular Love (2013). Data are freely available from most of these observatories at the INTERMAGNET website (www.intermagnet.org).” So someone can look at that reference for more information or any other the other references like INTERMAGNET.

Since this is an educational article, I think it would be useful to include a figure that defines the magnetic components, in particular the definition of D and I are missing in the text.

Response: Again, I think people interested in the detail can look up that information for themselves in Lowrie (2007) or Reda et al. (2011), for example or online.

Some additional details on clock synchronisation could also be added: how often the Raspberry Pi synchronise its clock to an internet server? Can these setting be optimised for the need of the project (e.g. every 10 s in between the record of samples).Which is the expected drift of the clock when the internet connection is lost?

Response: The drift of the clocks is a few seconds per day in a random direction. In a test of 10 systems simultaneously running without a network connection for a week, none varied by more than plus or minus twenty seconds. A Raspberry Pi with a network connection checks a Network Time Protocol (NTP) server every two minutes as part of the background scheduling. Thus, even if the connection is lost for a couple of days, the time-stamp of the retrieved data will not be too far out. However, if the network connection is lost the data are placed into a file with ‘.bad’ in the name to differentiate them from data collected when the Rpi was correctly synchronised.

The text has been updated to read: “The Raspberry Pi is not fitted with a real-time clock and therefore it is important that it is connected to the internet in order to obtain and keep the correct time. The clock drift is on the order of several seconds per day, though a Network Time Protocol (NTP) server is polled every two minutes as part of the computer's routine job schedule. An internet connection is also required for the transfer of magnetic field data onto the web.”

It think it would be very important to give more information on the schools targeted by this project and the educational notes provided: were they prepared for elementary, high schools, college …?

Response: Table 1 has been updated to denote this. It’s a mixture of primary, secondary and university – mainly secondary (11-18 year old students).

A deeper discussion on the challenges of magnetometry could be extremely useful: traditionally magnetic observatory are located in isolated area, taking care that a sufficiently large radius around the sensor is preserved as much as possible from manmade noise. Schools clearly cannot meet this need. The focus could be put on the involvement of teachers and students on the project.

Response: A good point and we do note the reasons why this is only partially successful. In the UK, teachers are constantly being barraged with new requirements for planning and improving lessons which takes up much of their time. Unless they are very interested in the project then their attention will wander after a few months. It is a trade-off of access to quiet sites within a (non-ideal) school environment and visibility to the students and teacher. While we (as scientists) can advise what to do, if the school cannot achieve the quality we desire, there is not much we can really do. The project is a public outreach one as much as a scientific experiment, so we have to be flexible and fit in with the school’s capabilities.

From a different point of view, these installations can be analysed to develop strategies on geophysics data acquisition in environments where high level of man-made noise is expected. Strategies and algorithms to handle with the noise and retrieve geophysical signals could be developed.

Response: Very true, I completely agree. I imagine machine learning or clever quality checking algorithms (e.g. using wavelets) could be used to discriminate between manmade or natural signals. Likewise cross-correlation with local scientific observatories would be another good check of geophysical versus manmade signals. This is an entire project in itself and beyond the scope of this article though!

Add the definition of the acronyms GDAS: Geomagnetic Data Acquisition System. Response: Added in the acronym

Add a reference to IGRF 12 generation. Response: Reference to Thebault et al (2015) added

Figure 1: add a) and b) to make more explicit what stated in the article text. Other elements (thermometer, ADC...) could also be indicated more explicitly on the figure for instance with labels and arrows. Response: We've updated the caption text with much more detail. I'm not sure adding more text to the photo will work.

Figure 3: add right vertical axis to show the unscaled deltaT. Response: As suggested by Reviewer 1 too, we have changed the graph and moved the axis to the right

Figure 5: choose a different colour couple than orange/red that are hardly distinguishable on the figure. The video of the storm is very informative and could be added to the article as a supplement, in order to guarantee its availability over long time. Response: There's a wide variety of magnetic field changes over the course of the storm (±1000 nT) and I experimented with different colour scale limits. This version captures the essence of the electrojet moving south and north over time in the X component. I can use a different snapshot or place the other versions online if required?

Reviewer 4

M. Nair (Referee)

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Availability of low-cost electronics and spread of internet raise the possibility of filling up the spatial gaps in the environmental sensing. Add citizen science to this mix, and we get an exciting new way to collect data and to engage the public in science experiments at the same time. The authors describe development, testing and validation of a low-cost, easy-to-use vector magnetometer. They then deploy the magnetometer in 10 schools in the UK. They discuss the data collected during a geomagnetic storm and the lessons learned while working with the teachers and students. This paper is written clearly and it is easy to understand. I recommend publication of this paper in the "Geoscience Communication". I have only a few minor suggestions/questions on this paper.

Response: Manoj – we appreciate your time and efforts to read and comment on the manuscript. Please find our response to your queries and suggestions below.

Page 3: 1-5: Authors may also want to mention the geomagnetic substorm, which occurs almost on a daily basis at polar regions.

Response: We have added: 'On days without obvious magnetic activity, the solar wind loads the magnetosphere with energy over the course of several hours. This causes small `substorms' to form in the polar regions through a process called the Dungey cycle (Dungey, 1961).'

Page 5 Lines 5-10: Where did you place the magnetometer during your initial measurements? Do you have a recommendation for keeping the magnetometer in residential/school environments?

Response: During the initial measurements, the magnetometer was placed in an unused office on the fifth floor at the south end of the former BGS building (Murchison House) far away from the goods and passenger lifts. It was covered in insulation and placed in a box to reduce temperature changes.

We did recommend putting the system at the back of a classroom, away from time-varying magnetic sources (doors, metal cupboards, radiators or beside electrical ducting). The best location was in Oundle who put theirs in an equipment lab in the centre of the building. The temperature is very stable and the system is undisturbed in general. However, we can only make recommendations not dictate where the system goes.

Page 5 Lines 25-30: You mention that the updated magnetometer also collects temperature data. Are you using the temperature data to calibrate the fluxgate outputs? It would be great if you can write a few lines about this. How do you deal with power outages? Can the system work off a battery?

Response: I have produced an updated version of Figure 3 for Reviewer 2 (C. Finlay) which shows how the temperature can be corrected for (see https://editor.copernicus.org/index.php/gc-2018-10-SC1.pdf?_mdl=msover_md&_jrl=700&_lcm=oc108lcm109w&_acm=get_comm_file&_ms=69948&c=147023&salt=662352946305454882). I wouldn't say it is calibrated in the usual sense as the data are not absolute, but the temperature variation can be removed.

We have added in: "However, though the systems are very temperature-dependent, it is possible to remove much of the error by `backing-out' the measured temperature variation through calibration.

We demonstrate this using a second-order polynomial model to compute the least-squares best-fit coefficients between the magnetometer differences in each component (H and Z) and temperature variation. These model fits are also shown in Figure 3 denoted 'corrected'. The linear coefficients are of the order of 3.8 nT/°C for the H component and 12.6 nT/°C for the Z component. Table 2 gives all six coefficients."

The system is powered from the mains electricity. If the power goes out, then it stops working. We could add an in-line battery pack, but that requires more parts (charger, voltage regulator, battery) which would cost more money – but it is eminently possible, of course.

Page 6 Lines 10:15. How did you orient the magnetometer properly in your school deployments? Did you face challenges with students/teachers misaligning the magnetometers?

Response: In half the schools, the system was personally installed and we instructed the teacher-in-charge how best to align the system by nulling the Y-component. However, the systems tend to get moved every few months in which case the alignment has changed. The only way to deal with this is post-process the data by rotating the horizontal magnetic values back to their approximate model values or nulling the Y component using quiet time values. This is not ideal, but makes the data useable for analysis.

Page 6 Lines 15:20. Can the students access the data locally?

Response: Yes, they can either get the data from the AuroraWatch website or use a USB memory stick to collect the data from the Raspberry Pi directly. I've added a sentence to clarify that.

Page 7 Lines 10:15. Regarding the quiet-day signal removal. Did you use a model to remove the Sq variations? How was the long-term performance of the magnetometer systems? Did you face issues with sensor/components going bad?

Response: For the analysis of the September storm, the quiet time value was assumed to be the average of the magnetic field components between 02:00 and 03:00 on the 7th September prior to the storm. We did not remove the Sq variations from the data, though they are relatively small compared to the storm signal (20 nT versus >200 nT).

Thus far, there have been no electronic or electrical issues with the computer, digitiser or sensor themselves. They are surprisingly robust in that sense!

Page 8 Lessons Learned. You mentioned the challenges encountered during the long-term deployment in the school. A part of the issue is that the teachers have very little time to devote to this experiment. This is a common problem faced by many citizen science projects. Is paying teachers/students is an option?

Response: It's an interesting proposal but I don't think we'd get money under an educational or outreach grant from the UK funding bodies. As I understand it, other organisations like UK Met Office have a huge number of unpaid volunteers who send in weather readings for free, for example. There's usually plenty of interested people – it is finding them and providing them with suitable equipment and training that is the main issue.

Reviewer 5

C. Webster (Referee)

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I enjoyed reading the paper and feel it is important to share the use of low cost instruments such as the Raspberry Pi with students and researchers globally. Perhaps science centres and museums would also be willing to host a few of these instruments. The science presented in this paper is sound, well-structured, and acceptable for publication after minor revisions. It may be good to indicate the rough cost of building one of these magnetometers.

Response: Thank you for the review. The plans are freely available to the public through me and are easy enough to follow with some soldering skills, so are open to science centres for example should they be interested. The cost I have added to the text on the recommendation of yourself and the other reviews. It costs around £150 at 2018 prices for all the parts.

Below are a few minor comments on the text:

page 2 line 29 - seasonal* dependence or seasonally dependent*

Response: corrected

Page 3 line 12 - The geomagnetic field can be measured with an instrument generically

(I would delete "generically" as it is not really necessary) known as a magnetometer.

There are several types of instruments that can be used to* make a measurement...

Response: OK – sentences have been modified

page 3 line 33 - causing large electrical currents to flow. Flow where?

Response: added 'in the upper atmosphere'

Page 5 line 7 – the brackets need to be closed (H...

Response: brackets closed

Page 7 line 28 – use a dash between the time for consistency

Response: added a dash 12:00—18:00

Page 8 line 19 - there* is no

Response: Changed to 'there are no easy ways to '

Spell out all acronyms such as GDAS

Response: added in (Geomagnetic Digital Acquisition system or GDAS)

Where possible try not to end sentences with prepositions such as 'to' or 'in' etc

Response: I have changed the sentences where I found this.

Building a Raspberry Pi School Magnetometer Network in the UK

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Abstract. As computing and geophysical sensor components have become increasingly affordable over the past decade, it is now possible to design and build a cost-effective system for monitoring the Earth's natural magnetic field variations, in particular for space weather events. Modern fluxgate magnetometers are sensitive down to the ~~sub-nanotesla~~ sub-nanoTesla (nT) level, which far exceeds the level of accuracy required to detect very small variations of the external magnetic field. When the popular Raspberry Pi single-board computer is combined with a suitable digitiser it can be used as a low-cost data logger. We adapted off-the-shelf components to design a magnetometer system for schools and developed bespoke Python software to build a network of low-cost magnetometers across the UK. We describe the system and software and how it was deployed to schools around the UK. In addition, we show the results recorded by the ~~systems~~ system from one of the largest geomagnetic storms of the current solar cycle.

1 Introduction

Over the past decade, the introduction of cheap reliable computing hardware and sensors, along with the ubiquity of high-speed Internet connections mean that it is now possible ~~to make relatively robust and cheap magnetometer systems to accurately monitor~~ create low-cost open-science networks of geophysical sensors. This has encouraged the development of data-intensive networks, for example in climate studies (Weather Observation Website: wow.metoffice.gov.uk/), seismology (BGS School Seismology Project: www.bgs.ac.uk/schoolseismology/) or cosmic ray research (the TimPix Project: www.researchinschools.org/TIMPIX) where spatial and temporal gaps in the professional scientific networks may be filled or augmented. Some networks employ existing platforms such as mobile phones using in-built sensors to record data (e.g. CrowdMag, see www.ngdc.noaa.gov/geomag/crowdmag.shtml) while others create bespoke hardware with higher accuracy than general purpose systems. In geomagnetism, high-quality low-cost fluxgate sensors have become widely available allowing accurate monitoring of the variation of the Earth's magnetic field over ~~periods~~ time ranges of several minutes to hours. This prompted us to investigate the various types of ~~sensors available~~ commercial sensors and their ability to monitor the external magnetic field, and in particular their ability to record large geomagnetic storms.

The Raspberry Pi is a small single-board computer that typically runs the Linux operating system. Peripherals such as sensors may be directly connected to its general purpose input/output (GPIO) pins. Relatively cheap fluxgate magnetometer sensors are now available from a number of suppliers and analog-to-digital converters are also commonplace in the Raspberry Pi ecosystem. For around one-hundredth of the price of a conventional scientific-standard fluxgate magnetometer instrument we found that we could build a system with approximately one-hundredth the accuracy and resolution. (At 2018 prices, the Raspberry Pi magnetometer costs around £150 GBP.) Despite the lower accuracy, this is still easily sufficient to record the daily variation of the Earth's ionosphere and magnetosphere, in order to detect the rapid changes in the magnetic field during geomagnetic storms. As a combination of a citizen science experiment and an outreach and education programme in geophysics, we applied to the UK Science Technology and Facilities Council (STFC) in 2015 for a Small Public Engagement grant and were successful. In the application we bid for funding to build and deploy ten systems to schools across the United Kingdom.

In Section 2 of this paper we briefly describe the science of the magnetic field and what a sensor measurement consists of. In Sections 3 and 4 we outline how our system works and was deployed to create a school network. As an example of its utility for science, in Section 5 we show the results of combining the Raspberry Pi magnetometer network with measurements from the permanent magnetic observatory network in the UK to enhance our understanding of the spatial and temporal dynamics of a large geomagnetic storm on the 7–8th September 2017. Finally, we discuss some of the lessons learned from the project in terms of public engagement and interacting with schools.

2 The Earth's magnetic field

The Earth's magnetic field is a vector quantity with a strength and direction, which varies both in time and space (e.g. Merrill et al., 1996). It has an average strength on the surface of around 50,000 nT though this varies from 20,000 nT at the equator to 65,000 nT at the poles. Though the field is strong enough to move a small iron needle, it is, in fact, incredibly weak; ~~in reality the average~~ a standard fridge magnet is tens to hundreds of times stronger.

After temperature measurements, the magnetic field has one of the longest observational records available, dating back centuries (Jackson et al., 2000). The vast majority (>95%) of magnetic field is generated in the liquid iron outer core by the self-exciting geodynamo. Similar to a bicycle dynamo, the Earth's outer core converts energy from motion of the conductive liquid iron into electrical currents. ~~These electrical currents~~ However, unlike a bicycle dynamo, the core is far too hot (> 3500°K) to be permanently magnetized (e.g. Lowrie, 2007). The electrical currents in the core generate a long-lived magnetic field which is detectable on the surface of the Earth. In addition, remnant magnetisation of iron-bearing minerals in the upper crust act as another internal source but are small on average compared to the core field (typically <1 %). The remaining magnetic sources are external to the Earth's surface and include currents flowing in the conductive ionosphere (at altitudes of 100 – 1000 km) and in the large scale magnetosphere created by the interaction of the Earth's magnetic field with the conductive solar wind. External fields are generally small (<4%) but can rise locally to over 10% of the field strength at high latitudes during large geomagnetic storms (e.g. Kivelson and Russell, 1995).

When a measurement of the magnetic field is made on or above the surface of the Earth, the value obtained is the sum of all sources. Each source has a distinct temporal and spatial behaviour and, by measuring the field and its variation in many different places over time, the observations can be used to understand the individual geophysical systems. The crustal magnetic field changes on the slowest of time-scales – tens of millions of years on average. The core field changes on periods of around one year to millions of years, which includes global magnetic field reversals. The ionospheric magnetic field changes on a diurnal basis, driven by the effects of solar illumination and ~~seasonally~~ seasonal dependence on the solar elevation angle. Finally, the magnetospheric field varies on time-scales of seconds to days. On days without obvious magnetic activity, the solar wind loads the magnetosphere with energy over the course of several hours. This causes small 'substorms' to form in the polar regions through a process called the Dungey cycle (Dungey, 1961).

Occasionally, when magnetic activity on the Sun's surface increases, for example from a Coronal Mass Ejection (CME), the speed and density of the solar wind (the tenuous ionised 'gas' which permeates the space between the planets) increases and ~~energy is~~ the interplanetary magnetic field is perturbed, resulting in energy being passed into the magnetosphere and ionosphere causing large electrical currents to flow in the upper atmosphere. When this happens, intense auroral electrojets form and move from their usual position near the poles and expand toward the equator, generating relatively large magnetic fields (100–1000 nT) which can be detected on the ground. The magnetosphere becomes loaded with energy which it attempts to dissipate every few hours through a process called magnetic reconnection. This causes the magnetic field to vibrate or pulsate at certain frequencies. These 'pulsations' last between a few seconds to tens of minutes and can be readily measured on the ground.

As most of the source signals overlap in time and space, they are difficult to identify with a single measurement. Hence, we need many sensors in a large network running for a long time in many different locations to resolve the contribution of each source. The global scientific magnetic observatory network fulfils this role. These are sites chosen specifically to reduce disturbance from man-made electrical or magnetic noise and hence tend to be in rural locations away from cities and railways. However, there are presently only around 200 magnetic observatories worldwide, with a very uneven spatial coverage biased towards the northern hemisphere, and Europe in particular (Love and Chulliat, 2013). Data are freely available from most of these observatories at the INTERMAGNET website (www.intermagnet.org).

2.1 Magnetic field measurements

The geomagnetic field can be measured with an instrument ~~generically~~ known as a magnetometer. There are several types of instruments that can be used to make a measurement such as (a) a simple compass needle to measure angles, (b) a copper wire wound around a cylinder of iron known as a fluxgate magnetometer to measure strength in a particular direction or (c) a magneto-resistive etching on a silicon chip (as in mobile electronic devices), again able to measure directional strength. The type of instrumentation used in scientific observatories has evolved over the past century from essentially compass needles suspended on quartz fibres requiring manual intervention to modern automated fluxgate magnetometers ~~harnessing~~ harnessed to digital electronics.

For our systems we use fluxgate magnetometers which consist of a small cylinder of ~~magnetisable~~ magnetizable iron wrapped by a copper wire with a large number of turnings (Primdahl, 1979). A electrical current, controlled by an oscillator, is passed back and forward through the copper wire creating a magnetic field. The magnetic field from the electrical current ~~magnetises~~ magnetizes the core in one direction along its axis, then in the opposite direction. If a pre-existing magnetic field exists in the environment, such as the Earth's magnetic field, then it requires less current to magnetise the core along that direction. The current difference is directly proportional to the strength of the pre-existing magnetic field, meaning that fluxgate sensors can be calibrated to relate current to ~~the~~ magnetic field strength. Thus, a calibrated standard fluxgate sensor can measure the strength of the magnetic field along the direction of its axis and is sufficiently sensitive to the absolute level and variations down to the 1 Hz range of the field. The main drawback of fluxgates are their sensitivity to temperature change.

To measure the full magnetic field (as the magnetic field is a vector which has a strength and direction), three fluxgate coils set at right angles to each other are used. The convention (in geomagnetism) is to use an orthogonal Cartesian coordinate system (X, Y and Z) where the X-axis points toward geographical North in the horizontal plane, the Y-axis points to geographical East and the Z-axis points down towards the centre of the Earth. Thus, the strength and direction of a magnetic 'field line' passing through the sensor can be measured by how strong it is in each component. From the measurements of magnetic field strength made along each axis, a full set of all magnetic components can be calculated, ~~including~~ which may also be expressed as the declination (D) and inclination (I) angles and the strength of the horizontal (H) and total (F) field. Our system is a variometer which can only provide approximate values of the strength and the relative change of the field, as compared to scientific observatories which make highly-calibrated absolute measurements of the geomagnetic vector and strength (Reda et al., 2011).

3 Instrumentation: development and build

The Raspberry Pi school magnetometer system consists of (a) a sensor head which has three fluxgate magnetometers and (b) a Raspberry Pi computer with an separate internal analogue-to-digital converter (ADC) board. The sensor head is linked to the ADC board via a connecting wire. Both the board and the magnetometers are powered by the Raspberry Pi. A blue LED within the sensor head indicates that the system is receiving power (Figure 1). The FLC100 magnetometers (from Stefan Mayer Instruments, Germany) are extremely sensitive to small variations of the magnetic field, with an operating range of zero to around 100,000 nT.

As noted, a standard magnetic field sensor has three magnetometers which are orientated along the three orthogonal components: North (X), East (Y) and Down (Z). The fluxgate coils are mounted in a Perspex block with a plastic base and brass screws (which are all non-magnetic).The sensor head also has a thermometer to measure ~~background temperature~~ the ambient temperature of the air. As it is so sensitive to temperature change, the system should ideally be kept at a constant temperature. A cover prevents accidental physical damage and helps reduce the rate of temperature changes to which the sensors are exposed.

The fluxgate magnetometers have been calibrated to output a 1 V analogue signal for a magnetic field strength of 50,000 nT. The analogue voltage is converted into a digital signal by the ADC. The 17-bit ADC is connected to the Raspberry Pi's Inter-Integrated Circuit (I^2C) bus using the GPIO pins. A cable connects the three fluxgate coils and the temperature to the ADC. The analogue signals are wired as single-ended inputs and so cannot make use of the 17th signed bit, giving the system a digitization resolution of 2^{16} = 65,536 levels. Hence, the digitizer has a finite resolution which inherently limits the precision of the magnetometer.

As an example, the smallest resolution at 50,000 nT/65,536 = 0.76 nT, meaning the digitizer can only resolve a magnetic field change larger than 0.76 nT. However, if the magnetic field strength is reduced to 15,000 nT, then the resolution increases i.e. 15,000 nT/65,536 = 0.22 nT. In practice, there are various factors that limit the resolution of the system so that the true ~~accuracy~~ precision is around 1.5 nT. This is sufficient to detect all the external field phenomena that are of interest to us.

To make a magnetic field measurement, the ADC samples the ~~signals~~ voltage several times a second and then the Raspberry Pi averages the values measured over 5 or 10 seconds. Taking the average of a number of measurements has the effect of smoothing out the variation (from temperature changes, electronic noise and changes in the magnetic field) to give a mean value of the magnetic field over the short period. The Raspberry Pi is not fitted with a real-time clock and therefore it is important that it is connected to the internet in order to obtain and keep the correct time. The clock drift is on the order of several seconds per day, so a Network Time Protocol (NTP) server is polled every two minutes as part of the computer's routine job schedule. An internet connection is also required for the transfer of magnetic field data ~~onto the web~~to our remote server.

3.1 Operation and Testing

Our magnetometer system was designed to measure the external field variation rather than the core field. Although it also measures the strength and direction of the Earth's full magnetic field vector, the instrument is not stable enough over the long term (i.e. days to weeks) to be a useful instrument for studying ~~the longer term~~ main field changes. As well as temperature, the magnetometer is also sensitive to man-made magnetic fields from mobile phones, vehicles, or lifts in a building, for example. Consequently, we usually disregard the full field measurements and compute the variation of the Horizontal field $(H = \sqrt{X^2+Y^2})$ around a quiet-time value, usually considered to be around 02:00–03:00 local time.

We tested an initial prototype~~in Edinburgh .~~, placing it in an unused office at the BGS building in Edinburgh, over several months in 2014 and compared it to the data from the closest geomagnetic observatory in Eskdalemuir, Scotland. Figure 2 shows an example of six days of data recorded on the Raspberry Pi magnetometer in Edinburgh. The horizontal strength (H) was computed and the average value for the period was subtracted from the result to give the variation. The blue line shows the data from the Raspberry Pi. For comparison, the data recorded on a scientific instrument (called Geomagnetic Data Acquisition System or GDAS1) at the Eskdalemuir Observatory approximately 70 km to the south of Edinburgh is shown in black. The data from the Edinburgh system closely match the variation recorded at the observatory.

A number of different geomagnetic events were observed. On the 12th September there was a geomagnetic storm which caused the magnetic field to fluctuate from +125 nT to -125 nT. The storm ended on the 13th September when the variations became smaller. The storm was followed on by a series of smaller rapid wiggles (pulsations) which are the result of dissipation of energy from the magnetosphere. By the 14th September, these disappeared and the ionospheric solar quiet time (Sq) current became visible. This is seen as a daily fall and rise of about 20 nT, with its lowest point at noon when the Sun passes overhead, on the 15th, 16th and 17th of September. Finally, on the 17th of September there is a step down and then up during the day time. This is man-made, caused by someone changing the magnetic environment of the room (e.g. entering the room for a time and then leaving later in the day).

Further testing of the second iteration of the sensor design was carried out in late 2015. The updated magnetometer system was fitted with a solid-state temperature sensor and was deployed in Eskdalemuir for several weeks. It was placed in a non-temperature controlled building around 100 m from the GDAS1 system. Figure 3 (upper and middle panel) shows the variation of the horizontal and vertical components as compared to the Eskdalemuir GDAS1 system. The lower panel shows the difference between the two systems with the temperature ~~(scaled ×10)~~ plotted too. There is a strong correlation between the magnetic differences of the Raspberry Pi systems and the temperature changes recorded. The step during the 30th October is due to manual retrieval of the data, affecting the room temperature temporarily. However, though the systems are very temperature-dependent, it is possible to remove much of the error by ‘backing-out’ the measured temperature variation through calibration. We demonstrate this using a second-order polynomial model to compute the least-squares best-fit coefficients between the magnetometer differences in each component (H and Z) and temperature variation. These model fits are also shown in Figure 3 denoted ’corrected’. The linear coefficients are of the order of 3.8 nT/°C for the H component and 12.6 nT/°C for the Z component. Table 2 gives all six coefficients.

Overall these tests indicate that, provided the Raspberry Pi magnetometer system is kept in a magnetically quiet and stable temperature environment, it is quite capable of capturing genuine geophysical phenomena, including the geomagnetic storms in which we are most interested~~in~~.

4 Deploying the network

In order to promote the new magnetometers, we attended a number of professional development events run for secondary-level physics teachers to recruit potential schools around the UK. We also used contacts in the Institute of Physics and personal connections to find teachers who were interested in hosting ~~the~~ a magnetometer at their school.

As noted, on its own a single magnetic sensor system is not particularly useful, but it can provide an educational tool for physics, astronomy, geology and geography students. However, tied into a UK-wide network of sensors, it is a means to participate in a genuine scientific collaboration to study the detailed variation of the magnetic field over the UK, particularly during geomagnetic storms. This is the ‘pitch’ we used to encourage teachers to host a system at their school. We provided an explanation of the science and tutorial notes for the teachers and pupils to read. We also suggested ideas of how to use the data, including how to process it using Jupyter notebooks and Python scripts.

After our initial building and testing phases, we further developed the Python logging software to run the system automatically and pass the data back to the Internet. We sought to make the system as easy as possible to set up on site. To that end, the Raspberry Pi magnetometer software was set to start logging magnetic field data as soon as it is switched on. The system saves the outputs from the sensors to a file, containing the X, Y, Z magnetic field (in nT) and the temperature at the sensor head (in °C). The data are recorded every 10 seconds and placed into a comma separated value (.csv) file which can be read by Excel, Word or any other type of data processing software. The data are written to a particular directory on the Raspberry Pi which can be found under: `/data/bgs_sch/<site_name>/<Year>/<Month>/<site_name_YearMonthDay.csv>`

Two other files may also be created each day: a logging file (.log) and a bad data file (.csv.bad). The logging file has information about when the logging of data starts and ends. If there are problems with accessing the internet or time from ~~a Network Time Protocol (NTP)~~an NTP server then data are written to the .csv.bad file instead to indicate there are uncertainties in the time record. Once every five minutes a Linux ‘cron’ job runs on the Raspberry Pi to transfer the recently recorded data to the Lancaster University website. Real-time plots of the data can be viewed at http://aurorawatch.lancs.ac.uk/plots/. The data may also be accessed from the Raspberry Pi directly.

It took over a year to deploy most of the sensors. Figure 4 shows the final destinations of nine of the Raspberry Pi magnetometer systems across the UK. The aim was to cover the UK in both latitude and longitude and to complement the existing BGS and Lancaster networks. Benbecula in the Outer Hebrides is the most northerly and westerly point, Norwich is the most easterly point and Eastbourne is the most southerly point in the network. There is a cluster around Birmingham to tie in with a University of Birmingham cosmic ray experiment running at the Physics Department and in two local schools (Bordesley and King Edward’s). Table 1 gives the locations of the each sensor. One of the systems was sent to the University of Otago in Dunedin, New Zealand as an experiment to show how the magnetic field varies simultaneously on a global basis during a geomagnetic storm. New Zealand is at the same geomagnetic latitude as the UK in the southern hemisphere.

The first system began running in October 2016 and the network expanded over 2016 and 2017. In the next section, we show an example of a major storm which was captured by the magnetometers.

5 Measurements from the geomagnetic storm of September 2017

In September 2017 ~~,~~one of the largest storms of the current solar cycle hit the Earth. A CME left the Sun at midday on 6th September and reached Earth’s magnetosphere in around 36 hours. Starting around 23:30 UT on 7th September, the first and deepest part of the storm lasted for around 3 hours. Beautiful aurorae were visible all across the UK. Around 13:00 UT on 8th September a second burst arrived, though as it was during the day in the UK, the aurorae were not visible. The magnetic signature was detected by the Raspberry Pi magnetometer network. As the north (or X) direction is most sensitive to the auroral electrojet (which are created by east-west directed ionospheric electric current flows), we focus on this component in the plots shown.

To get a regional picture of the storm, data were collected from the Raspberry Pi magnetometers, as well as a number of other variometers and observatories around the UK, Ireland, Belgium, Germany and Norway. Figure 5 shows the location of the scientific observatories (INTERMAGNET), the BGS and Lancaster University AuroraWatch network of variometers (Case et al., 2017), a network in Ireland run by Trinity College Dublin (MagIE) and data from the Tromsø Geophysical Observatory (TGO) network.

The data were processed to remove the quiet time mean value of the X component at each site, using the value for 02:00–03:00 local time from the 7th September. Where the orientation of the sensor is unknown (as with the Raspberry Pi magnetometers) we rotated the horizontal components to match the estimated values of X and Y from a global magnetic field model (the International Geomagnetic Reference Field version 12 (Thébault et al., 2015)). In Figure 6, we show the change of the magnetic field over the three days covering the 7–9th September 2017. The observatories and variometers are arranged by geographic latitude. The first and second parts of the storm are clearly visible as large spikes in the northern stations, decreasing in intensity further south. This is the signature of the auroral oval moving south during the peak of the storm, then returning northwards. In the first burst of the geomagnetic storm, the magnetic signature of the aurora moves as far south as LER and SUM which are in the Shetland Islands. The Raspberry Pi data (BGSXX) complement the other variometer and observatory data, matching the magnitude and timing of the main phases of the storm though they are slightly noisier overall. Sadly, not all system data were available at the time, so we did not completely cover the UK (e.g. Benbecula and Eastbourne are missing).

The line plot data was turned into a map of the magnetic field variation across the UK for each minute, interpolated using a physics-based method called Spherical Elementary Currents (Amm and Viljanen, 1999). Figure 7 gives a snapshot of the X and Y external magnetic field components at 23:45 UT as the auroral electrojet moves southward across the UK. It extends south of Shetland as can be observed most clearly in the X component (left panel). A video of the storm can be seen at https://youtu.be/ueDvVNhNbIc. In the movie, several more bursts of activity can be seen later in the day ~~from~~ between 12:~~00 to 18~~00–18:00 UT. Without the new magnetometers, it would not be possible to distinguish such detail. These measurements will lead to a better understanding about how the magnetic field changes over regions smaller than 1000 km during large geomagnetic storms at mid-latitudes.

6 Lessons learned

The idea of a school magnetometer network was ~~in part~~ inspired by the long-running UK Schools Seismometer network, part-run by BGS. Having experimented with the Raspberry Pi, it was an obvious and capable device for attaching to all manner of sensors~~to~~. As with most projects, the concept and initial ideas of how it might work and operate differed strongly to the end results. After making a prototype sensor and then bidding for a larger grant to make ten systems, we found that the building and development of the hardware and software was the (relatively) easy part – after all, this is what we do professionally.

However, once the systems were built, the harder parts of the project were the actual engagement with the schools and deploying the systems out to them. For half of the schools, we personally delivered the systems and helped to set them up. ~~However, schools~~ Schools are busy places though and it is difficult to get teacher's time and to hold their attention for more than a few hours. More surprising was how tightly controlled school WiFi or Ethernet networks are. In fact, much of the set-up time was spent attempting to gain access to an open internet connection within the school. Many of the schools were unable to continuously meet the magnetically quiet environment criterion, making stable measurements (without steps or temperature drift) over a single day hard to achieve during the working school week. Some of the schools managed to place the sensor in a quiet location but this reduces the opportunity for students to observe the system or to notice it on a daily basis. Finally, once deployed, we found getting feedback from the teachers and schools was relatively slow. As the teachers rotate through different year classes after each ~~year~~term, the systems become unplugged or moved to noisier environments which further degrades their scientific usefulness. Hence, we monitor the data regularly and will contact the school to check if the data become poor or unusable.

Unfortunately, ~~here is no obvious way~~ there are no easy ways to combat many of these issues ~~—~~ – they are a function of the way schools operate. However, we hope at least some students have been inspired to consider geophysics as a future career based on their interaction with the sensors and data.

7 Conclusions

We have developed a Raspberry Pi magnetometer system using standard off-the-shelf sensors and materials. The system costs around 100 times less than a scientific-grade sensor (around £150GBP in 2018), but is sufficiently accurate to detect external magnetic field changes (at the nanoTesla level) from geomagnetic storms. We describe the build, testing and deployment of systems to schools around the UK to create a countrywide network. We also offer an example of how the data can be used to supplement the existing network of scientific observatories and analyse a large geomagnetic storm on the 7–8th September 2017. This is an excellent example of how falling hardware costs in combination with science outreach can provide an interesting geophysical sensor network which can be used for both science and education.

Code and data availability. Data are freely available at http://aurorawatch.lancs.ac.uk/data/. Code for running the magnetometers is available at https://github.com/stevemarple/. Instructions for building the hardware can be obtained by contacting the corresponding author.

Author contributions. CDB built, integrated and tested much of the hardware. SRM developed the software to run the systems and transfer the magnetic data to the AuroraWatch UK website. Both contributed to the writing of the manuscript.

Competing interests. The authors declare no competing interests.

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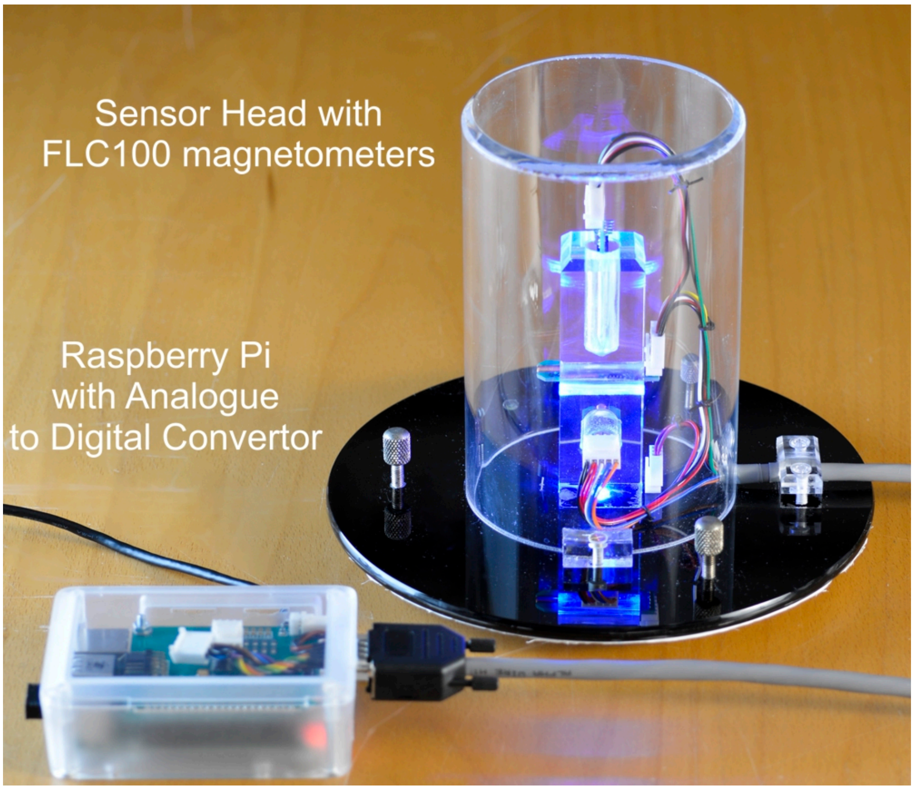

Figure 1. Raspberry Pi magnetometer system: the computer and digitiser board are in the small box in the lower left corner (enclosed in a transparent plastic box). The sensor head contains three orthogonal fluxgate sensors in the Perspex cube, again contained in a transparent case, which are connected by wires via the gray cable to the digitiser. A blue LED provides illumination to indicate the system is powered on. The thermistor is located at the base of the sensor (not visible). Brass feet and a bubble spirit-level embedded in the base are used to ensure the fluxgates are not tilted. The sensor head is approximately 15 cm high.

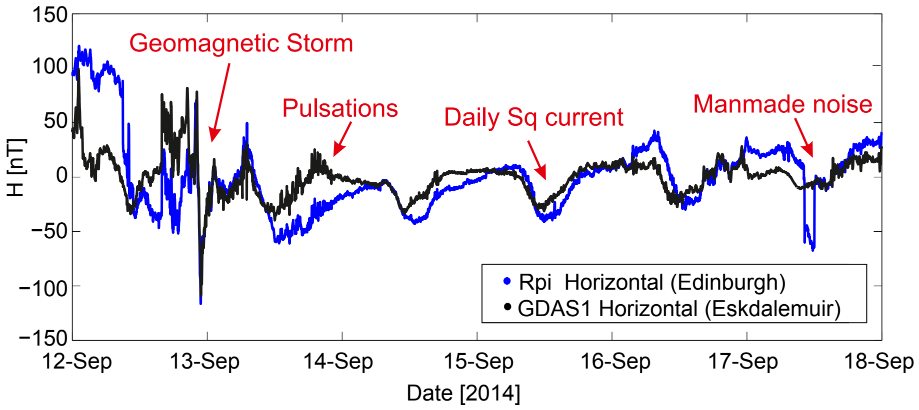

Figure 2. Horizontal field variation from 12-Sep-2014 to 18-Sep-2014. The blue line shows data from the Raspberry Pi magnetometer located in Edinburgh, UK. The black line is from the BGS GDAS1 system in the Eskdalemuir Geomagnetic Observatory (70 km south of Edinburgh).

Table 1. Identification number (c.f. Figures 5 and 6) and location of the ten Raspberry Pi systems.

ID	Latitude	Longitude	Location	Type of institution
BGS1	50.768	0.267	Gilredge, Eastbourne	Secondary
BGS2	-45.80	170.50	University of Otago, New Zealand	University
BGS3	52.450	1.929	University of Birmingham	University
BGS4	52.451	-1.925	King Edward's School, Birmingham	Secondary
BGS5	52.477	-1.857	Bordesley Green, Birmingham	Secondary
BGS6	57.426	-7.360	Sgoil Lionard, Benbecula	Secondary
BGS7	55.980	-4.583	Vale of Leven, Alexandria	Secondary
BGS8	55.940	-3.470	Kirkhill, Broxburn	Primary
BGS9	52.632	1.300	Norwich School, Norwich	Secondary
BGS10	52.481	-0.469	Oundle School, Peterborough	Secondary

Table 2. Correction coefficients for the temperature dependence in Figure 3.

Component	Offset [nT]	Linear [nT/°C]	2nd-Order [nT/°C^2]
Horizontal	-1.53	3.85	-0.16
Vertical	0.63	12.68	2.27

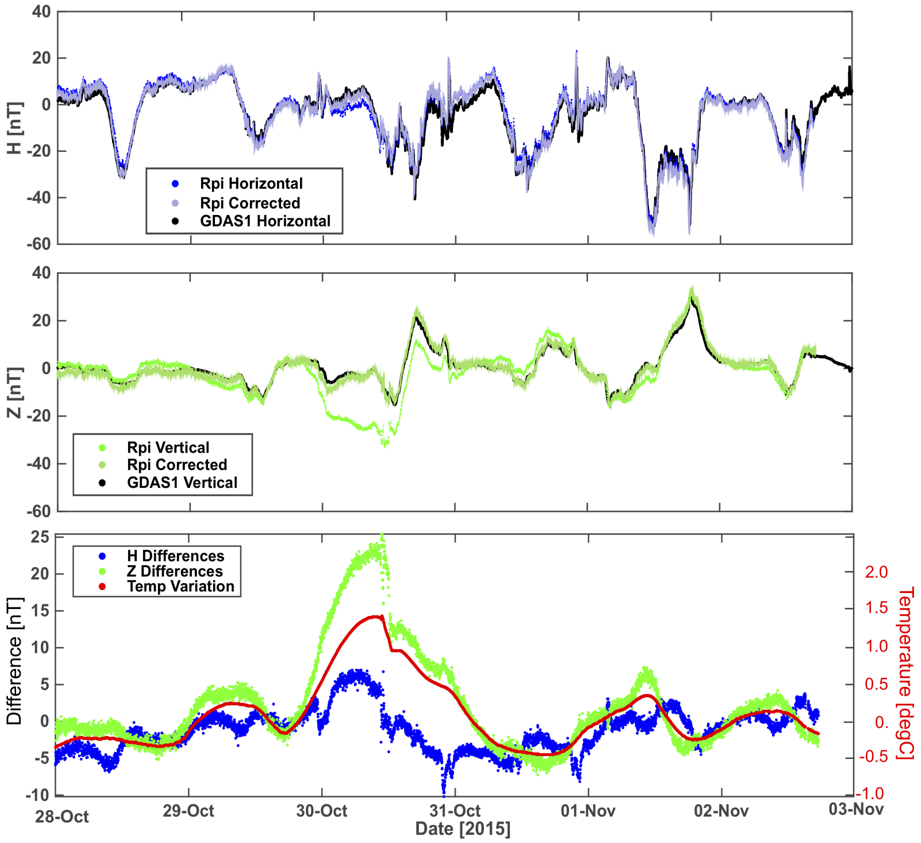

Figure 3. Comparison of the magnetic field variation between the Raspberry Pi magnetometer and Eskdalemuir GDAS1 system from 28-Oct-2015 to 03-Nov-2015. Upper panel: Horizontal component variation and a temperature-corrected data; Middle panel: Vertical component variation and a temperature-corrected data; Lower panel: Difference between the ~~two~~ Raspberry Pi and GDAS1 systems~~with the~~ , and temperature variation ~~(x10) also plotted~~around a baseline value of 18 °C.

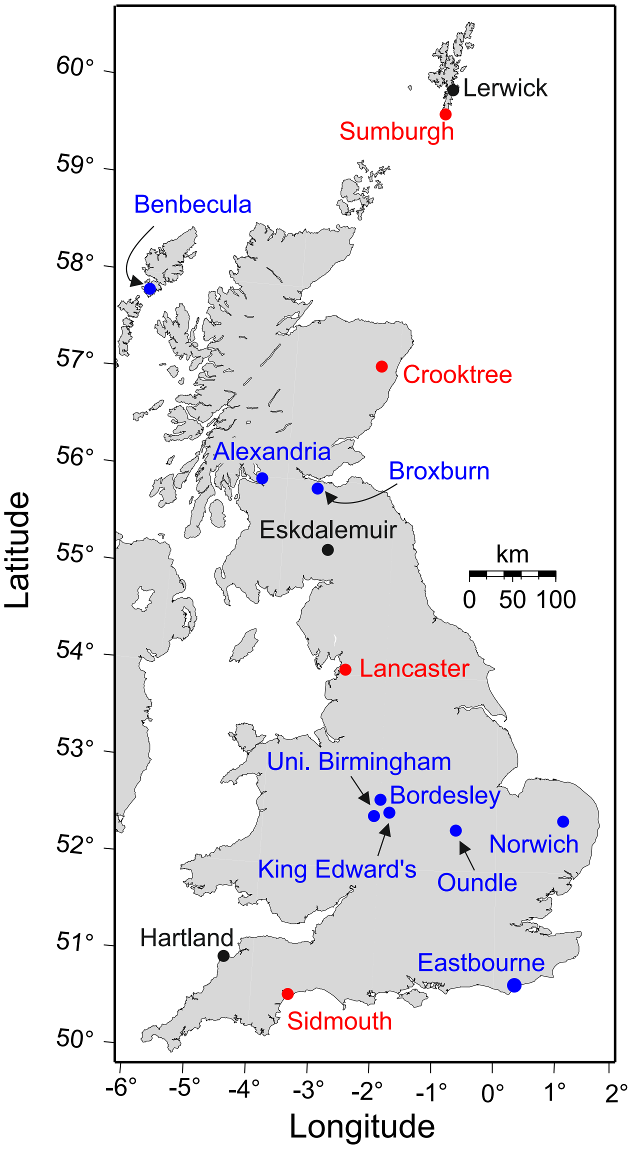

Figure 4. Map showing the locations of the Raspberry Pi magnetometers (blue), Lancaster University's AuroraWatch and SAMNET stations (red) and the BGS observatories (black).

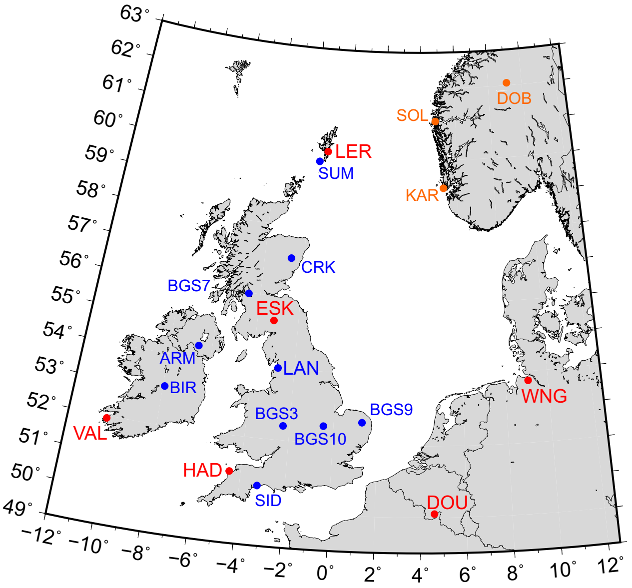

Figure 5. Map showing the locations of the variometer and observatory measurement sites available for the 7/8th September 2017. Red circles are INTERMAGNET observatories, orange circles indicated calibrated variometers (TGO) and blue indicate variometers including the Raspberry Pi (BGS) and the Lancaster AuroraWatch/SAMNET magnetometers.

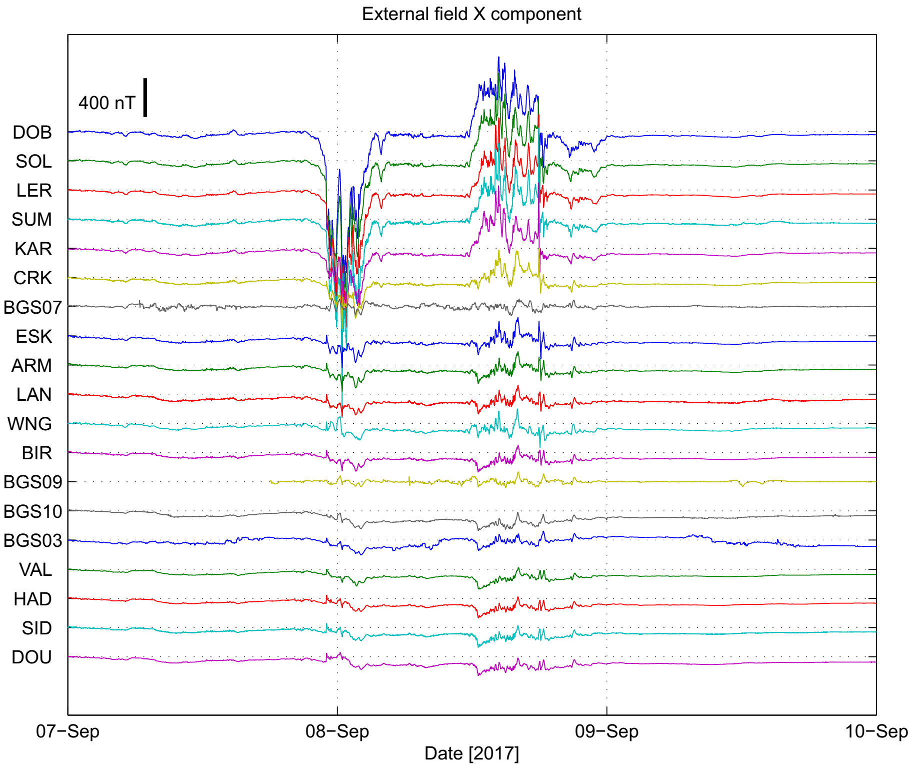

Figure 6. Stack plot of the variation of the X component over time at each measurement site from 00:00 UT 7th September to 00:00UT 10th September. Stations are ordered by geographic latitude. Note the initiation of the storm at midnight of the 7/8th September and the second phase beginning at 12:00UT on the 8th September. Scale bar denotes 400 nT change.

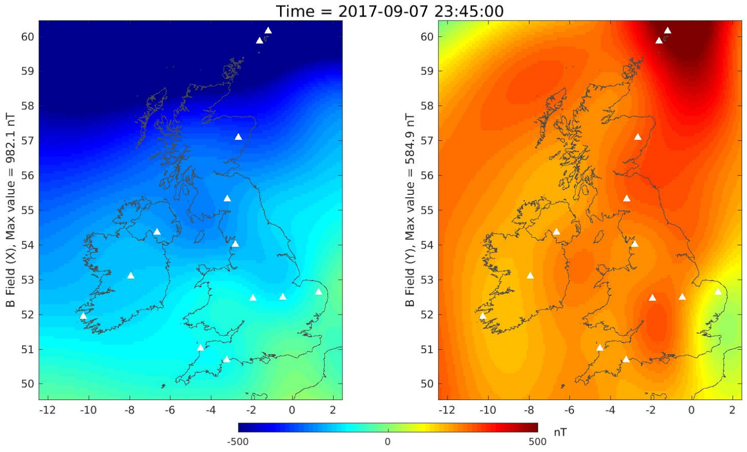

Figure 7. Snapshot of the two horizontal components of the magnetic field interpolated across the UK at 23:45 UT on the 7th September 2017.