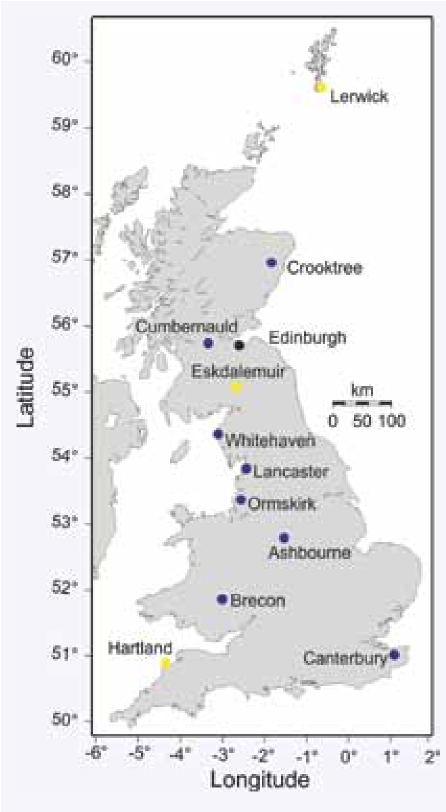
Space weather goes to schools

Ciarán D Beggan and **Steve R Marple** describe how they are using low-cost computers to develop a network of school magnetometers for measuring space-weather effects in the UK.

In December 2014, the British Geological Survey (BGS) and Lancaster University won an STFC Public Engagement grant to build and deploy 10 Raspberry Pi magnetometers to secondary schools across the UK. The primary aim is to encourage students from 14 to 18 years old to look at how sensors can be used to collect geophysical data and integrate it to give a wider understanding of physical phenomena such as space weather.

The launch of affordable yet powerful credit-card sized computers such as the Raspberry Pi has given rise to a new wave of interest in programming and self-built electronic systems. The cost of sensors and components for collecting astronomical or geophysical data has also fallen rapidly in the past decade. Taking advantage of these developments, we describe our efforts to build a three-axis magnetic field sensor, primarily designed for use in schools. It is based on high-quality fluxgate magnetic sensors and employs a Raspberry Pi to act as the data acquisition and logging system. An internet connection streams the data in near-real-time to a central website where the data can be visualized or downloaded and analysed. Extensive testing and comparison to scientific instrumentation shows that our new system can achieve a root-mean-square precision of better than 1 nanoTesla (nT) at a cadence of 5 s.

One of the reasons for doing this now is because, as a society, we are increasingly reliant on space-based technologies such as satellite global navigation systems and communication relays (e.g. Cannon *et al.* 2013). As a result, we have become more exposed to risks from so-called space-weather effects, which are primarily caused by the interaction between the Earth and the interplanetary magnetic field. Although there are visible effects during large geomagnetic storms, primarily the aurora, they



1 Location of the existing magnetic instruments in the UK. Yellow: BGS Absolute Observatories. Blue: SAMNET and AuroraWatch variometers. Black: Edinburgh test site.

are relatively difficult to observe in the UK because of our low geomagnetic latitude, clouds and light pollution. However, the change in the magnetic field can be measured at ground level.

On its own, a single magnetic sensor system (or magnetometer) is not particularly useful, but tied into a UK-wide network of sensors, such a system can provide an educational tool for physics, astronomy, geology and geography students. It is also 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. Thus, a second aim is to provide useful data on the spatial and temporal variation of the magnetic field across the UK during geomagnetic storms.

"One aim is to provide data on the magnetic field across the UK in geomagnetic storms"

The BGS runs three observatories in the UK, located in an approximately straight line from Shetland to Devon. Adding additional instruments across the breadth of the UK will help fill in the gaps as well as providing longitudinal coverage in the UK, allowing more detailed maps of the magnetic field variation to be made. The Lancaster University AuroraWatch UK programme has made an excellent start on this by offering a single-axis magnetometer to 10 schools across the UK. Our project adds to the existing network and enhances the sensor, changing it from being an aurora detector into a more fully fledged scientific instrument. The data can be analysed alongside existing data from the BGS absolute observatory (yellow) and University of Lancaster SAMNET variometer networks (blue) shown in figure 1.

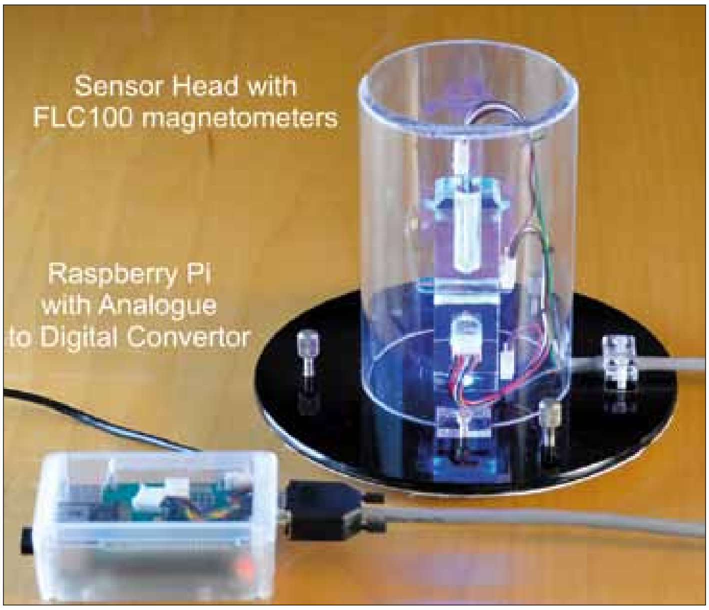
Instrumentation

Until recently, systems sensitive enough to detect the variations of the magnetic field arising from space weather (around 20 parts in a million) have only been available to the scientific community. The costs have typically been many thousands of pounds for dedicated instrumentation. However, with advances in computer and electronic technology, the parts required to build an instrument capable of recording data of almost scientific quality now cost less than £300. We have spent the past two years testing a number of different magnetic sensors and developing prototype systems before settling on the current configuration.

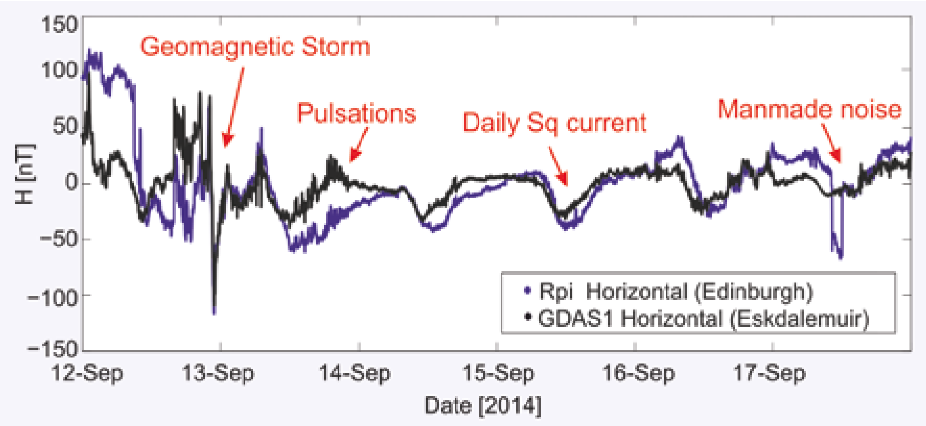
Our new Raspberry Pi magnetometer system consists of three main components: a sensor head, a data acquisition and logging system, and the software required to run, collect and transmit the measured data.

The sensor head consists of three FLC100 fluxgate coil magnetometers from Stefan Mayer Instruments in Germany. These miniature magnetometers are about 45 by 14 mm. They output a voltage proportional to the strength of the magnetic field and have an inherent accuracy of about 0.5 nT at 0.1–1 Hz.

A precision of 0.5 nT is around 1 part in 100 000 of the Earth's magnetic field strength in the UK. Thus the sensors can



2 Raspberry Pi three-axis magnetometer system.



3 Comparison of data from measurements made in Edinburgh and Eskdalemuir in September 2014.

easily measure: natural variations from the diurnal effect of the Sun on the ionosphere, called the Sq current (10–20 nT); pulsations of the magnetic field arising from energy redistribution (reconnection) in the magnetosphere (5–50 nT); and geomagnetic storms (typically 50–1500 nT). The instruments measure short-term variations very accurately, but the absolute level is only approximate. The magnetometers are mounted orthogonally – north (*X*), east (*Y*) and down (*Z*) – into a Perspex block and wired together to a common 5 V power supply and ground (figure 2).

The output connection from each magnetometer is wired back to an AB Electronics ADC+ 17-bit digitizer directly connected to a Raspberry Pi computer. The digitizer converts the analogue voltage output (where 1 V = 50 000 nT) to a digital value, which the Raspberry Pi records along with the time of acquisition. The Raspberry Pi requires an internet connection to an NTP (network time protocol) server to accurately timestamp the data.

As a result of the digitization precision of the analogue voltage, the complete system has a nominal sensitivity of around 0.8 nT, in each component direction (north, east and down). This is around 10 times lower than a current scientific-level instrument, but given the relatively low cost, it is an excellent price-to-performance ratio. The system also includes a temperature sensor chip with its analogue output connected to the ADC to measure ambient temperature, and an LED to show the unit is powered on.

"Given the relatively low cost, it is an excellent price-to-performance ratio"

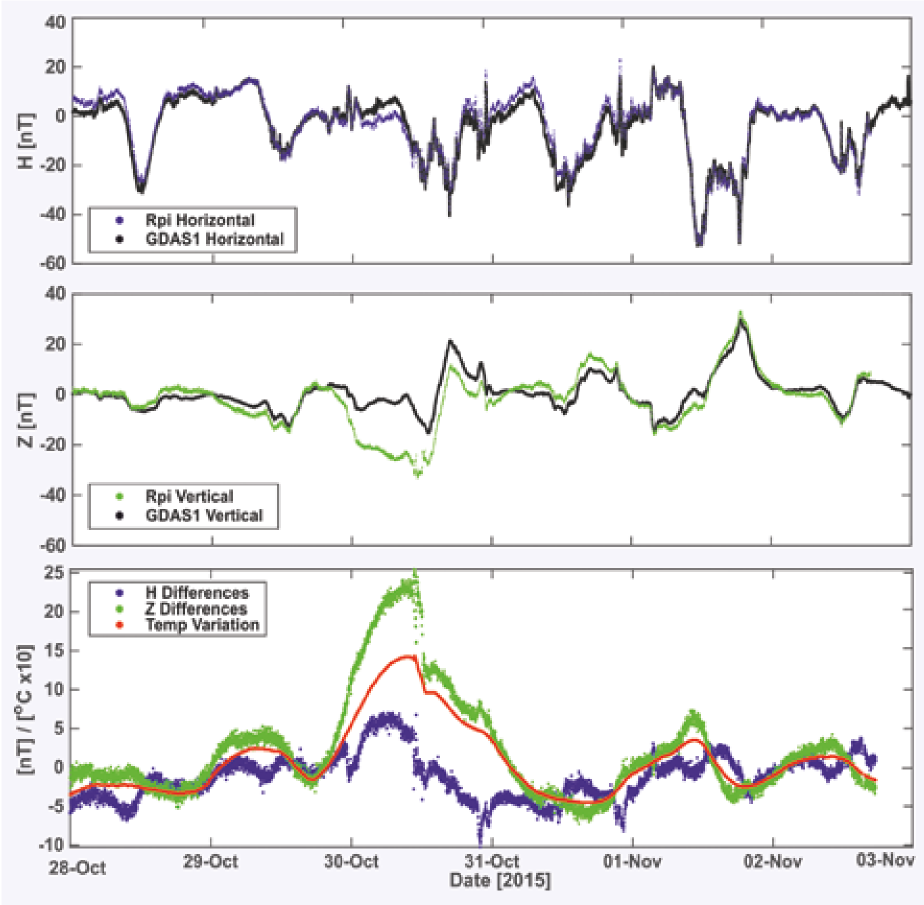
Software written in the Python programming language reads and records the values of the magnetic field from each component, along with the date, time and ambient temperature. The data are recorded to the internal SD card and transferred every few minutes to the Lancaster AuroraWatch UK website. Depending upon the policies of a school's network, two different upload protocols can be used. The simpler approach uses the standard rsync programme (Tridgell 1999) tunnelled through an SSH (secure shell) connection. Unfortunately, the restrictive nature of many school networks prevents SSH, even for outgoing access. In these cases a custom HTTP upload process can be used to transfer only the differences between the local file and the copy residing on the server.

As the sensor head cannot be accurately oriented to geographic north, it is not possible to measure the declination angle. But the two horizontal fluxgate coils are assumed to be (almost) orthogonally mounted, meaning that the horizontal strength of the magnetic field ($H = \sqrt{[X^2 + Y^2]}$) can be easily computed. The best method of achieving this is to orient the *X* sensor towards magnetic north, which in practice means nulling the output of the *Y* component so that it points to magnetic east. For the vertical axis we have included a bubble level to help with the levelling so the *Z* component is aligned downwards (i.e. along the gravity vector). Though we cannot guarantee the complete orthogonality of the sensors, given that we are mostly interested in the variation rather than the absolute value of the magnetic field, the effect of any misalignments is small.

Both the fluxgate magnetometers and the electronics are very sensitive to temperature. Great care and effort goes into controlling the temperature of scientific magnetic sensors in geomagnetic observatories, keeping variations to less than 0.1 °C over long periods. For our system, we have no control over the environment and so have included a thermocouple to measure ambient temperature. This allows temperature variations to be "backed out", i.e. removed in post-processing of the data.

Comparison to observatory data

An initial prototype was developed in 2014 based on a small "Engaging the Public" grant from NERC. In September 2014, the system was tested by using the Raspberry Pi magnetometer to record the horizontal variation in the BGS office in Edinburgh. These measurements were compared with the data from the primary scientific instrument at the Eskdalemuir Geomagnetic Observatory (called GDAS1) which lies approximately 70 km south of Edinburgh. Over the course of seven days, the Raspberry Pi detected geomagnetic phenomena including a storm, magnetospheric pulsations and the daily ionospheric solar quiet (Sq) current. It was also sensitive to local



4 Comparison of measurements made in Eskdalemuir for the horizontal (upper) and vertical (middle) components. The lower panel shows the difference between the *H* and *Z* measurements with the temperature variation also shown (exaggerated x10). The longer period variations are correlated with temperature.

(man-made) disturbances, which we minimized by placing it in an unused space. To minimize temperature variations, it was kept out of direct sunlight. The comparison between the horizontal data from Eskdalemuir and the Edinburgh site is excellent (figure 3) and gave us confidence that the system could be genuinely useful for scientific investigations.

Having built the new systems from the STFC award, all 10 systems were taken to the Eskdalemuir Non-Magnetic Laboratory in October 2015. Data from the magnetometers were recorded at a cadence of 5 s for several weeks. The laboratory is heated, though not particularly well insulated, so the temperature varied by a few degrees during the tests. The magnetometers were located about 100 m from the Eskdalemuir GDAS1 scientific instrument to which they were compared.

The variation and residuals (i.e. differences) between the data recorded by one of the Raspberry Pi systems (model 10) and the GDAS1 scientific instrument are shown in figure 4. The variation in the horizontal (*H*) and vertical (*Z*) components of the magnetic field for five days from 28 October to 2 November are shown in the upper panels. There were no major geomagnetic storms in this period, though there was some pulsation activity, and the daily Sq current is visible. Note that on 30 October the variation in the middle of the day was a result of disturbance when data was manually retrieved from the computer. The lower panel shows the difference between GDAS1 and Raspberry Pi sensors in the *H* and *Z* components. The temperature variation (exaggerated by a factor of 10) is also shown, with much of the long-period variation correlating with the change in temperature. The short-period fluctuations match very well – these are the signals that we are most interested in.

"The data gave us confidence that the system could be genuinely useful"

To compute the actual precision of the system, a rolling 10-minute average of data was computed and removed from the differences. The residuals (once the background average has been removed) show an approximately Gaussian distribution with standard deviation of less than 0.8 nT. This means the system is performing well within the nominal requirements we set (i.e. less than 1 nT) for signals between 2 and 100 mHz (10–500 seconds).

Conclusions

As a public engagement project, we have several target audiences. The primary audience is 14–18-year-old pupils studying physics, astronomy, geology, geography, IT or mathematics in secondary schools. We wish to interest them in the application of IT, physics and mathematics to real-world problems (as well as the study of physics) and to see science in a multidisciplinary manner – no one subject covers all the principles required to understand, build and run a magnetometer or network.

If such magnetometers were to be deployed across the UK, we could add to the existing capability of the AuroraWatch project at the University of Lancaster and expand our current science capability for the capture and analysis of data for space-weather research. In addition, we would like to encourage others to have a go at building their own system and contributing data to the network. ●

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WEBSITES

Raspberry Pi Magnetometer http://www.geomag.bgs.ac.uk/education/raspberry_pi_magnetometer.html
AuroraWatch http://aurorawatch.lancs.ac.uk

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