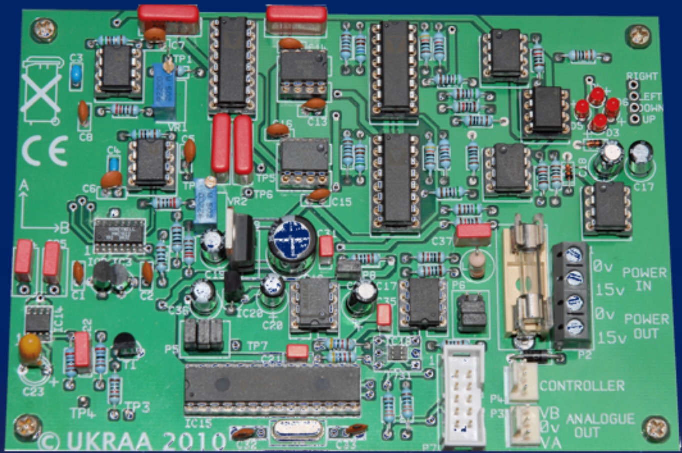
UK Radio Astronomy Association

Dual Axis Magnetometer

User Manual



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UK Radio Astronomy Association

Acknowledgements

Design Team

The UKRAA Magnetometer design is a combination of public domain material and original improvements by John Cook and David Farn. The circuit board layout was undertaken by John Cook.

Testing Team

The Magnetometer was tested by Paul Hyde, Martyn Kinder, Andrew Lutley and Alan Melia.

Production Team

The initial batch of the Magnetometers was produced by Andrew Lutley, Alan Melia and Norman Pomfret.

Contributors

The following authors have contributed to the Magnetometer User Manual: John Cook, Andrew Lutley, Alan Melia, Dr Laurence Newell, Whit Reeve.

Cover Photograph

The cover photograph of an auroral display is reproduced by kind permission of Graeme Whipps, a member of the BAA Aurora Section. The photograph shows active rayed bands with both oxygen and nitrogen emissions, and was taken on 2010-04-11, in Chapel of Garioch, Aberdeenshire.

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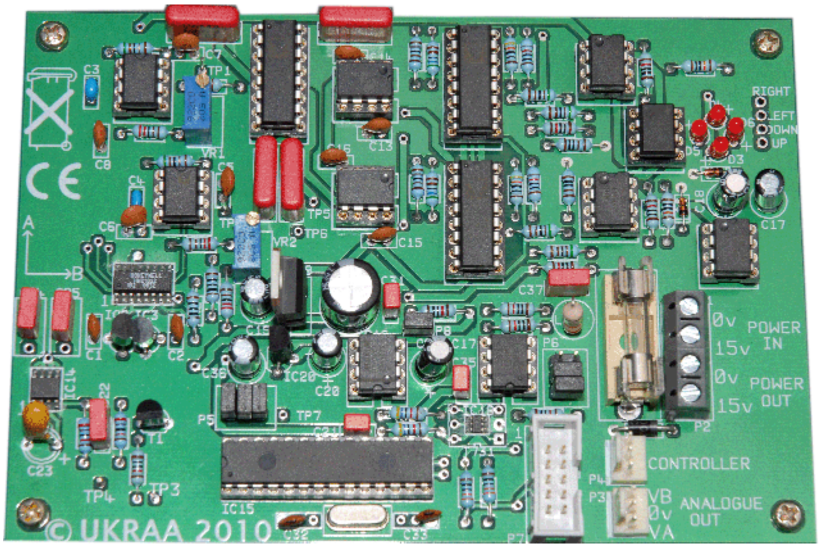
Introduction

UKRAA

The UK Radio Astronomy Association (UKRAA) is a non-profit-making charitable company limited by guarantee. It was established by the Radio Astronomy Group of the British Astronomical Association (BAA) to facilitate the production and sale of radio astronomy products.

Any suggestions or recommendations for improvement of this Manual would be appreciated. See the Contacts page for further details.

The UKRAA Magnetometer



The UKRAA Magnetometer Circuit Board

The UKRAA Magnetometer is a dual-axis solid state magnetometer, intended for monitoring the Earth's magnetic field. It can be used to gauge solar activity and help predict the possibility of auroral displays. It has been designed with thermal stability in mind, and should not drift significantly with temperature over at least 10..30C. Four gain settings are provided to allow for the differing circumstances in which it might be used. In an area where there are unavoidable magnetic disturbances a lower gain setting can be used, while higher gain can be selected if a site is available which is free from such disturbances. In practice, the default (gain step two) is usable in a domestic setting with vehicle traffic nearby.

A digital output is provided for connection via a UKRAA controller to the UKRAA Starbase control and logging software, (provided free of licensing charges by UKRAA), allowing observations to be stored centrally and shared with other observers.

The analogue outputs are voltages varying with time (0...5V), which may be fed to any data logger or digital multimeter. The Magnetometer is also compatible with the popular Radio Sky Pipe data logging software, but extra components will be required.

Magnetometer System Requirements

Data Logging

The magnetometer output can be monitored using the alignment lamps, although these are intended only for initial alignment. In order to make useful long-term observations, some sort of logging device is needed, and this is discussed in a later section.

Power Supply Considerations

In the standard configuration, a 15V regulated DC power supply is required, and should be kept at least 2m away from the sensor. This can either be a battery or a mains adapter, in each case capable of supplying 15V DC at 90mA. For instance, UKRAA can supply a power supply part number UKR022.

It is important to ensure that the **positive** output of the power supply is connected to the 2.5mm central **socket**.
All UKRAA modules are standardised to use this type of supply.

Make sure that the power supply is not covered in any way; it should run only slightly warm to the touch.

It is also possible to use a 12 V sealed Lead-Acid Accumulator by connecting a jumper on link **P8**. This mode of operation may be useful when the magnetometer is used some distance from mains supplies, perhaps when investigating sources of noise, or during calibration.

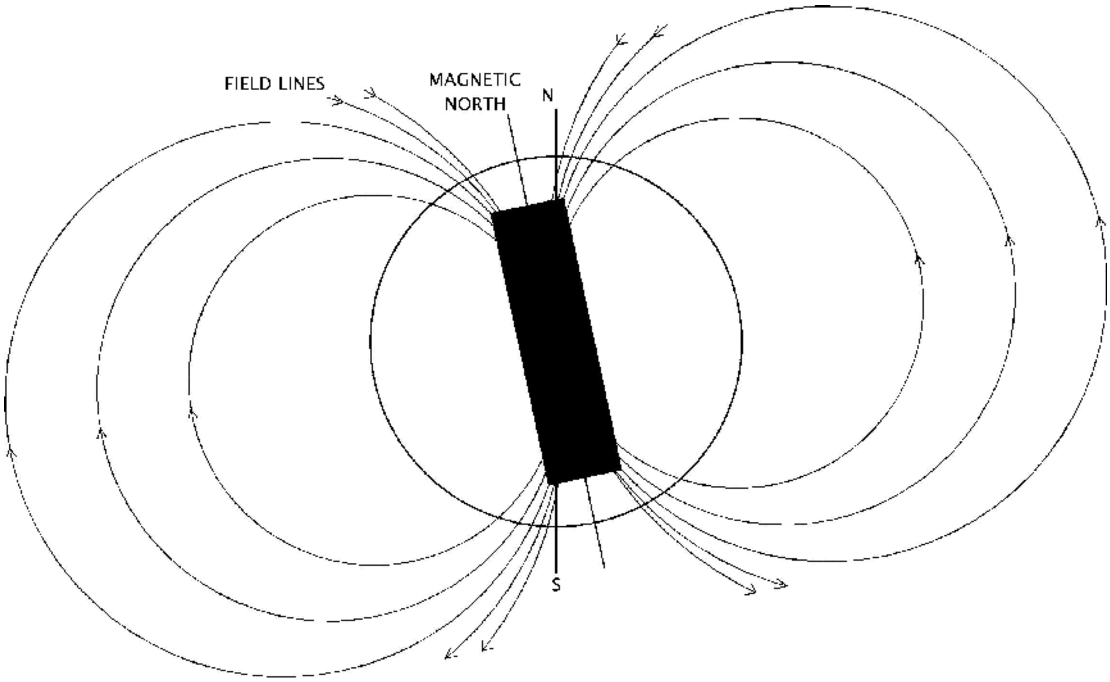
Support

All users of the Magnetometer system are encouraged to make use of the support available from UKRAA for setting up and operation. Please see the Contacts section for details.

Introduction to Magnetometry

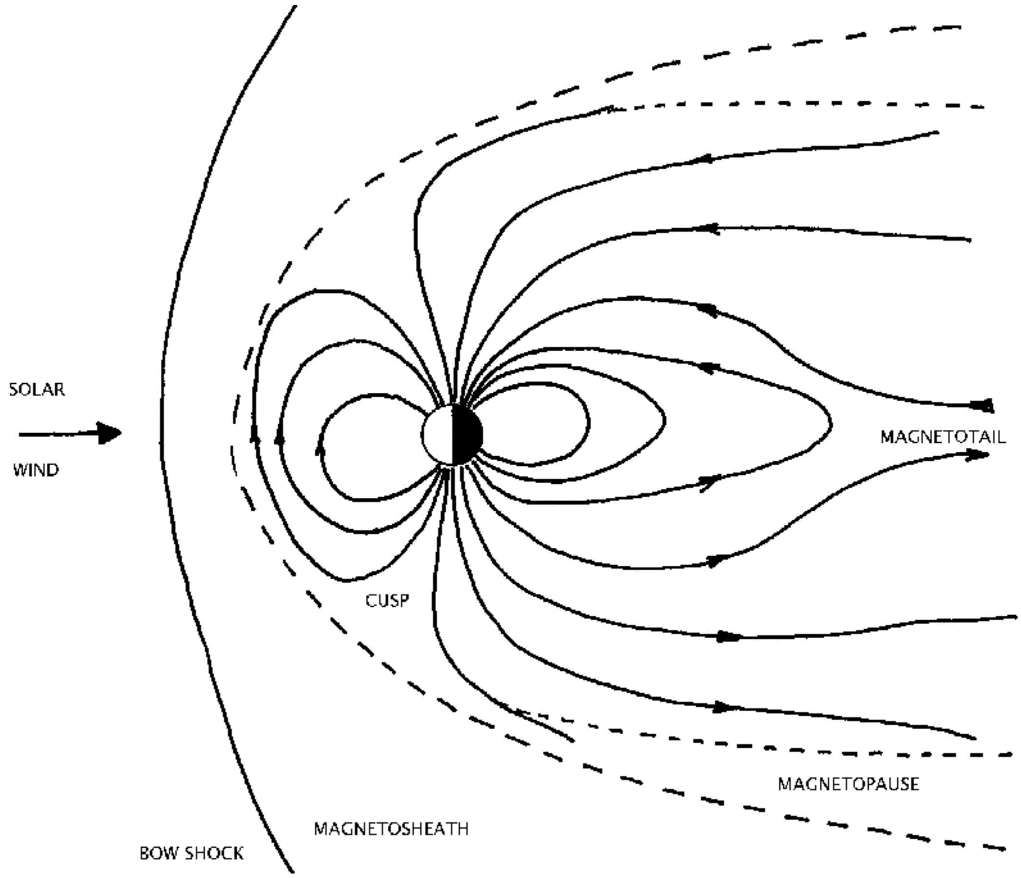
This section gives a brief introduction to the Earth's magnetic field and its measurement. A more in-depth treatment is given in the Appendix written by Whit Reeve.

The Earth has a dipole magnetic field, appearing as if a large bar magnet were buried near its centre and aligned roughly north - south. A look at any Ordnance Survey (UK) map will show a diagram indicating the difference between true north and magnetic north. The hypothetical bar magnet is offset from the Earth's rotation axis, and moves with time. This means that any magnetic observatory will have a magnetic latitude and longitude that is different from its ordinary geographic latitude and longitude. Although this difference is important, the alignment lamps on the UKRAA magnetometer will automatically allow for it. If the Earth were alone in space, then its magnetic field would remain stationary and uniform over the short term; however, we are quite close to the Sun.



The Earth's magnetic field

The Sun, a G2v star, has its own magnetic field, as well as a particle wind that flows through the solar system. The solar wind is ionised and carries the Sun's magnetic field with it, distorting its dipole pattern. Where it encounters the Earth's magnetic field (the magnetosphere) there is a magnetic pressure between the two. The solar wind then carries its field around the minor obstruction caused by Earth, and continues to flow onwards away from the Sun. Our magnetosphere is therefore compressed on the sunlit side, and drawn out on the night side into a long magnetotail. At ground level in equatorial latitudes, the normal strength of the Earth's field is about 30uT (micro-Tesla)



Earth-Sun Magnetic Interactions

As the Earth rotates about its axis each day, the distorted magnetosphere remains fixed relative to the Sun. A magnetic observatory will therefore see its local magnetic field pushed around as the Sun moves through the sky. A magnetometer records this daily movement as the normal diurnal variation. See the results section below for typical recordings.

The magnetic field lines curve downwards as they approach the magnetic poles, in a way familiar from experiments with iron filings and a bar magnet. Aligning the magnetometer sensor with the local field thus allows both horizontal components to be measured.

Turbulence in the solar wind results in turbulence at the interface between it and the magnetosphere. The field at ground level moves in response to this turbulence and thus gives some indication of solar activity. Severe turbulence results in field lines becoming tangled at the interface, and reconnection events within the field. This allows particles from the solar wind direct access to the Earth's magnetic field, which they follow towards either magnetic pole. When they reach the upper region of the atmosphere (80..100km) oxygen and nitrogen atoms become ionised by the injected particles, and begin to give off the light that we see as an aurora.

Turbulence in the solar wind can be due to solar flare activity, coronal mass ejections and coronal holes, so even in the very quiet conditions of solar minimum, there is magnetic activity to monitor. In more active periods, the disturbances can saturate the magnetometer even on the default gain setting.

Magnetometer Technical Description

Please refer to the Magnetometer circuit diagram in an Appendix.

The heart of the magnetometer is IC1, a Honeywell Anisotropic Magneto Resistive (AMR) sensor. It has two sensing bridges (A and B on the circuit diagram), arranged at 90 degrees to each other. It is designed for use in magnetic direction-finding and compasses. It also includes features that make it ideal for sensing small changes in the Earth's magnetic field. Each sensor bridge has a permalloy strap included which can be used to reset its sensitivity and cancel out errors and offsets.

IC2 and IC3 provide a stable reference voltage of +/- 2.5V for each bridge, regulated from the system +/- 5V supplies. Each bridge output is a voltage proportional to the magnetic field strength in its sensitive direction. With a 5V supply, its output is 50nV/nT. Variations of the order of +/-100nT are to be detected for a useful magnetometer, and so a large amount of gain is required. Following through a single channel, IC4 is an instrumentation amplifier with a gain set to 1000, the sensitivity at its output being 50uV/nT. Following IC4 is a chopper-amplifier based on instrumentation amplifier IC7 and the switches in IC6. Returning to IC1, the permalloy strap over the sensing bridge is driven with a series of high current pulses, alternating positive and negative (SRA and SRB on the circuit). In time with these pulses, anti-phase square waves drive the analogue switches in IC6. The high current pulse in the permalloy strap has the effect of resetting its sensitivity with an opposite polarity. For a constant applied field, the bridge output alternates positive and negative with each pulse while the switches route these voltages to the inputs of IC7. Capacitors C9 and 10 hold the voltage steady for the brief period while its switch is open so that IC7's output is the arithmetical sum of the voltages on C9 and C10. In a zero field, the output of the bridge will be due to temperature and offset effects, and so the voltages on C9 and C10 will be equal and opposite. IC7's output would thus be zero, and would remain at zero even if changing temperature causes minor bridge changes. This switching provides a gain of two, while IC7 has an additional gain set by the gain setting resistors selected by IC12 (50 at the nominal gain setting). See the timing chart on the circuit diagram.

Following the signal chain, IC9b provides a further gain of two, and an offset provided by IC9a. As the bridge is driven symmetrically about 0V, the chopper-amplifier output is also symmetric about 0V. For data logging and recording a unipolar output is far better, and so IC9a provides the required voltage shift. A zero field will now give an output of +2.5V, with changes in field strength increasing or decreasing the voltage. R20 and C17 give a one second time constant to remove unwanted switching noise, while D1 prevents the signal from going negative. IC21b is a unity gain buffer to drive the recording equipment.

The potentiometer VR1 allows any offsets from the high gain of IC4 to be nulled out, such that zero field strength does give 0V out via the controller, or 2.5V (mid range) out via the uni-polar DC output connector P3.

Please note that VR1 and VR2 balance the amplifier input offsets, and will be preset in manufacture and should not need further adjustment unless IC2 or IC4 are replaced. The adjustment requires the use of an oscilloscope, and is described in the next section.

Alignment LEDs D3 and D4 are driven by IC11a. The output of IC7 directly drives the inverting input of IC11a, such that zero field strength on the bridge results in 0V out of IC11a. Any imbalance (*i.e.* a magnetic field) drives IC11a output either positive or negative, illuminating the appropriate LED.

IC15 provides all of the timing signals for the permalloy straps and analogue switches (via T1 and IC14), as well as analogue to digital conversion of the outputs (pins 2 and 3). It also includes the software interface for a Starbase controller. The temperature sensor (IC18) and configuration memory (IC17) provide Starbase compatibility. IC16, 19 and 20 provide the necessary regulated supplies.

A small serial memory (EEPROM) is included in the Magnetometer to ensure compatibility with the UKRAA Starbase system, This stores identification and configuration details for the module (as XML), allowing the Starbase Observatory to automatically identify which instruments are connected. The Magnetometer module also contains a temperature sensor, allowing calibration of the response with variations in ambient temperature.

Setting up the Magnetometer System

The UKRAA Magnetometer is provided set up and ready to use. Should it become necessary to check or adjust the settings, then the following tools will be needed.

Tools Required

Multimeter

Small brass or ceramic-bladed screwdriver (i.e. non-magnetic)

Voltage and Waveform Checks

Supply voltage = 15V on P1

- IC2 cathode = +2.5V
- IC3 anode = -2.5V
- IC19 output = +5V
- IC20 output = -5V

IC15

- Pin 25 is a 2kHz square wave, 5V amplitude
- Pins 24 & 23 are negative pulses
- Pins 4 & 7 are positive pulses,
  as shown in the timing diagram on the circuit

Input Stage Balance

With the above checks complete, the input balance potentiometers need to be adjusted.

Connect an oscilloscope to test point 1 (TP1) which is the IC4 output (pin 6), and rotate the entire board to minimise the square wave amplitude. Adjust the balance potentiometer (VR1) to give a 0V DC output on the oscilloscope. Repeat for TP2, which is IC5 pin 6 and adjust VR2, again rotating the entire board to minimise the square wave amplitude. The ground connection of the scope probe may be connected to the tab on the 7805 regulator which is at ground potential.

Operation

At initial switch-on as received, the gain will be set to step 2. The gain settings, which at present can only be changed via a UKRAA Controller, are:

- 1 x0.4
- 2 x1
- 3 x2
- 4 x4

Note that when in use the magnetometer will remember the last commanded gain setting, and will power up with that setting. Gain setting 2 should be adequate for most purposes, and gain setting 4 can only really be used in a location which is magnetically very quiet, and free from nearby human activity.

Rotate the entire unit in 3-dimensions to minimise the brightness of all four LEDs. From this position, moving a small steel object (such as a screwdriver) adjacent to the sensor will illuminate the LEDs in turn as the magnetic field is disturbed. Once settled in, do not move the magnetometer! If there is a lot of local magnetic disturbance, then set the gain to step 1. If conditions allow, steps 2 or 3 can be used to increase sensitivity. As a guide to likely auroral activity, step 2 is adequate, and can produce a saturated output under storm conditions. Higher gain will allow examination of smaller disturbances.

Mounting and Installation

The complete Magnetometer unit can be mounted in an aluminium box, with connectors for the signals, and alignment LEDs mounted at one end. It can also be mounted in a sealed plastic box, using cable glands for the signal and power connections (a suitable box, with tilt mechanism, cable gland and cable is available from UKRAA – part no UKR034). Ensure that the alignment LEDs are visible, and mount the unit where it will not be moved, and where magnetic disturbance is likely to be minimised. Avoid locations close to iron and steel objects, or anything containing magnetic circuits. Experience will guide its final placement.

Careful consideration should be given to the location of the Magnetometer, as there are many sources of magnetic disturbance and interference in most domestic situations. Using the default gain setting, an indoor location in a spare room should be suitable. Higher gain settings may well require an outdoor location, well away from roads, vehicles and other ferrous objects that may move. The movement of any ferrous object (such as a steel-bodied car) will alter the local magnetic field, and therefore be detected by the magnetometer. Some experimentation will be required. In practice, the Earth's natural magnetic field will move slowly compared with 'domestic' objects, and so such interference is easily seen and rejected from the observations. If an outdoor location is to be used, make sure that the magnetometer is screened from direct sunlight. Even in winter, a full Sun can provide quite a lot of heat, and summer sunshine could cause the internal temperature to reach damaging levels.

If a single axis is required, then the magnetometer can be put on a flat surface and rotated to simply point at magnetic north. It is worth spending some time with the magnetometer held in the hand to see how the alignment lamps work.

If the full two-axis Magnetometer is to be used, it must be aligned in three-dimensions with the local magnetic field, as described in detail in the next section. This must be done in a way that holds the sensor rigidly in place, and prevents any movement. The alignment lamps should help in this process, correct three-dimensional orientation being when all four lamps are at a minimum brightness.

If the direction of North is not known, then identify it with an ordinary magnetic compass. With the magnetometer powered up, start by rotating it in a horizontal plane such that the alignment lamps face North. At some point the **Left** (marked D5) and **Right** (marked D6) lamps will swap, indicating magnetic North. Careful fine adjustment should result in left and right lamps at a minimum. If both lamps remain bright together, then there may be a local interfering magnetic field (such as from a mains transformer). Such a site would not be suitable for the magnetometer. The magnetometer can now be tilted (north end upwards) so that the local field becomes normal to the sensor. The **Up** (marked D4) and **Down** (marked D3) lamps will now swap, the null position of minimum brightness again being the correct point. Having established this orientation, a means of fixing the magnetometer in space can be devised.

An Example Magnetometer Mounting

The photograph below shows one way of installing the Magnetometer. Here a waterproof enclosure is used, with room to house a Magnetometer and a UKRAA Controller, which can be mounted at a distance from any electrical interference. Note the simple plastic hinge assembly to allow the Magnetometer to be tilted for 'nulled' alignment, as described in this section. This enclosure is available from UKRAA either with a Magnetometer (part number UKR033) or as a separate item (part number UKR034).

Enclosure containing a UKRAA Magnetometer (lid not shown)

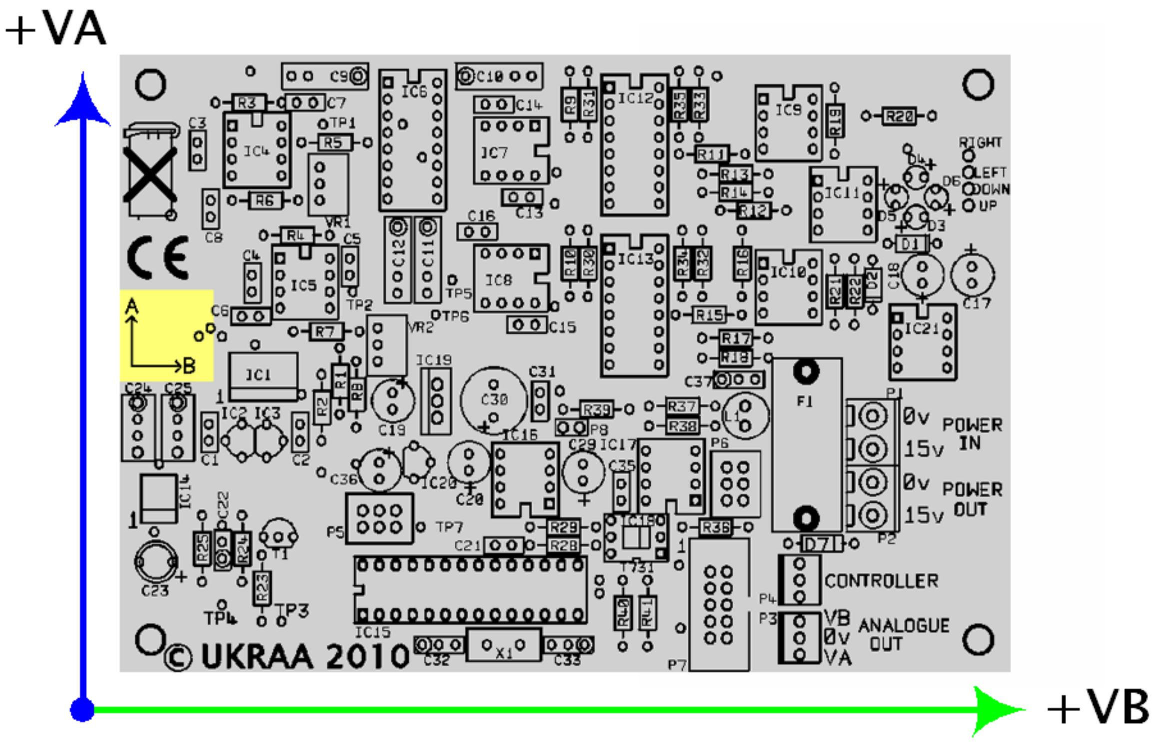
All cables pass through a sealed cable gland, to ensure the enclosure remains watertight. The box has a clear lid so the user can see the alignment lamps.

If you decide to make your own enclosure, make sure that you use only non-magnetic components, such as plastic or brass. Note that some types of stainless steel can be magnetic!

Orientation of the Magnetometer

You will have realised from the previous section that there are several ways in which the magnetometer may be mounted and still be sensitive to the magnetic field. However, to ensure that your observations can be reliably compared with those from other observers, it is recommended that you follow the orientation described here. There are several variables in three dimensions and it is wise to try to standardise them as much as possible!

Firstly, the Honeywell magnetic sensor device on the circuit board has two defined axes of sensitivity; the manufacturer has labelled these 'A' and 'B', and we have chosen to follow the same nomenclature to avoid confusion. The diagram below shows how these axes relate to the board orientation. Both axes are equally sensitive – the sensor is completely symmetrical in its operation. Each output can go positive or negative, and the conventional direction for the *positive* voltage output is shown (+VA and +VB). The highlighted area shown is printed on the circuit board for ease of reference.



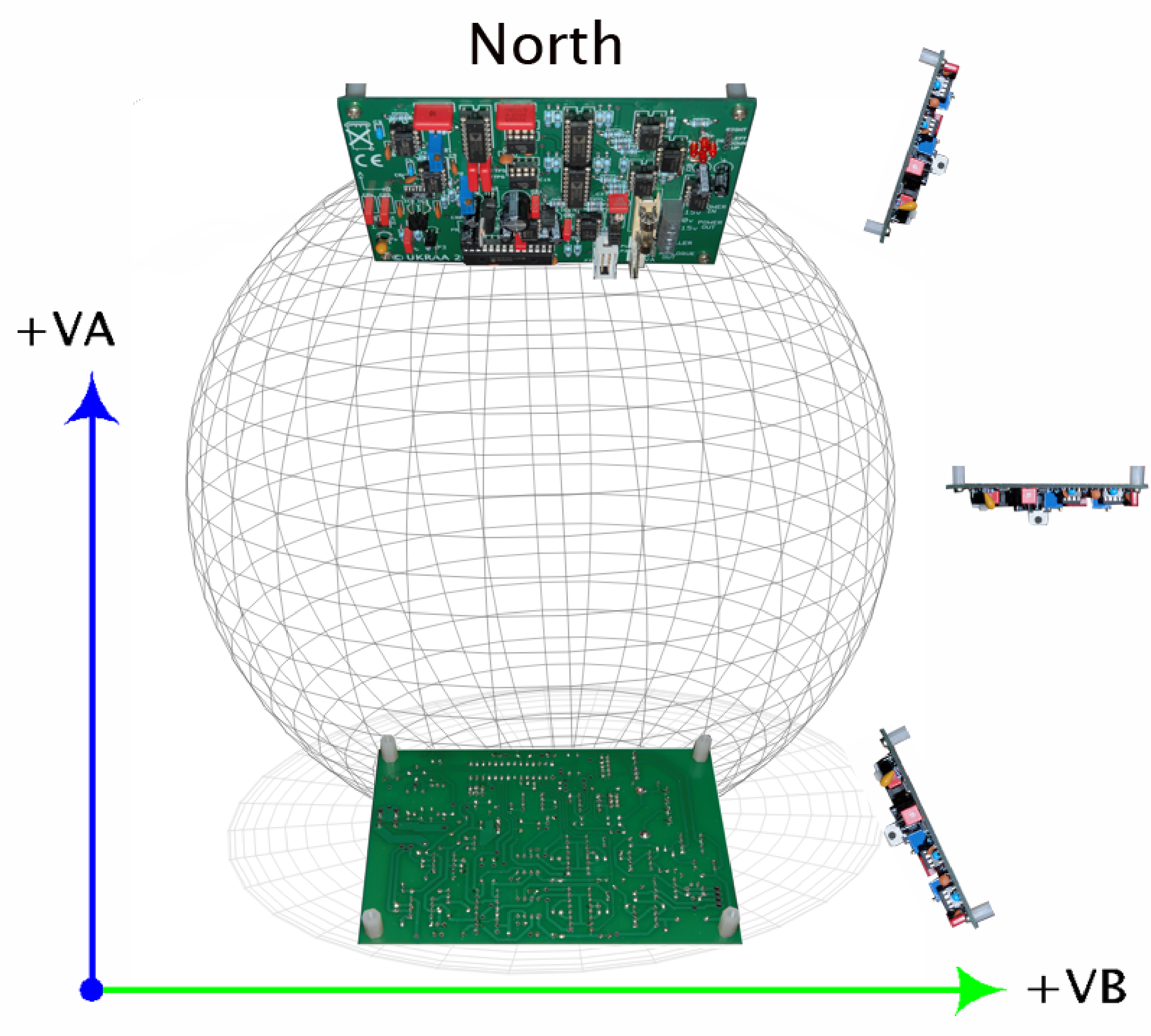
Showing the relationship of the board orientation with sensor axes A and B

The analogue outputs from the Magnetometer (VA and VB) are available on P3 in the lower right corner of the circuit board. The digital outputs from the PIC controller analogue to digital converter are available via the I^2C bus on P4.

The corresponding *Starscript* commands for the `MagnetometerPlugin` when used with a Starbase Controller are:

`MagnetometerPlugin.getAAxis()`	Gets the output of the A axis sensor
`MagnetometerPlugin.getBAxis()`	Gets the output of the B axis sensor

The second level of standardisation is to ensure that the circuit board is always mounted in the same orientation with respect to the Earth's field, regardless of the location on the surface. The diagram below shows how the board should be mounted in both hemispheres. Holding the board so that the text can be read, the lower (slightly longer) edge is the 'hinge', and is always in an East-West direction. In the northern hemisphere the top edge of the board leans *away* from the Equator towards the *North* Pole. Remember that the field vector has to pass through the board normal (at right angles) to the sensor device (assuming 'nulled' alignment), so the actual angle will depend on the observatory's magnetic latitude. In the southern hemisphere the top edge leans *away* from the Equator towards the *South* Pole.



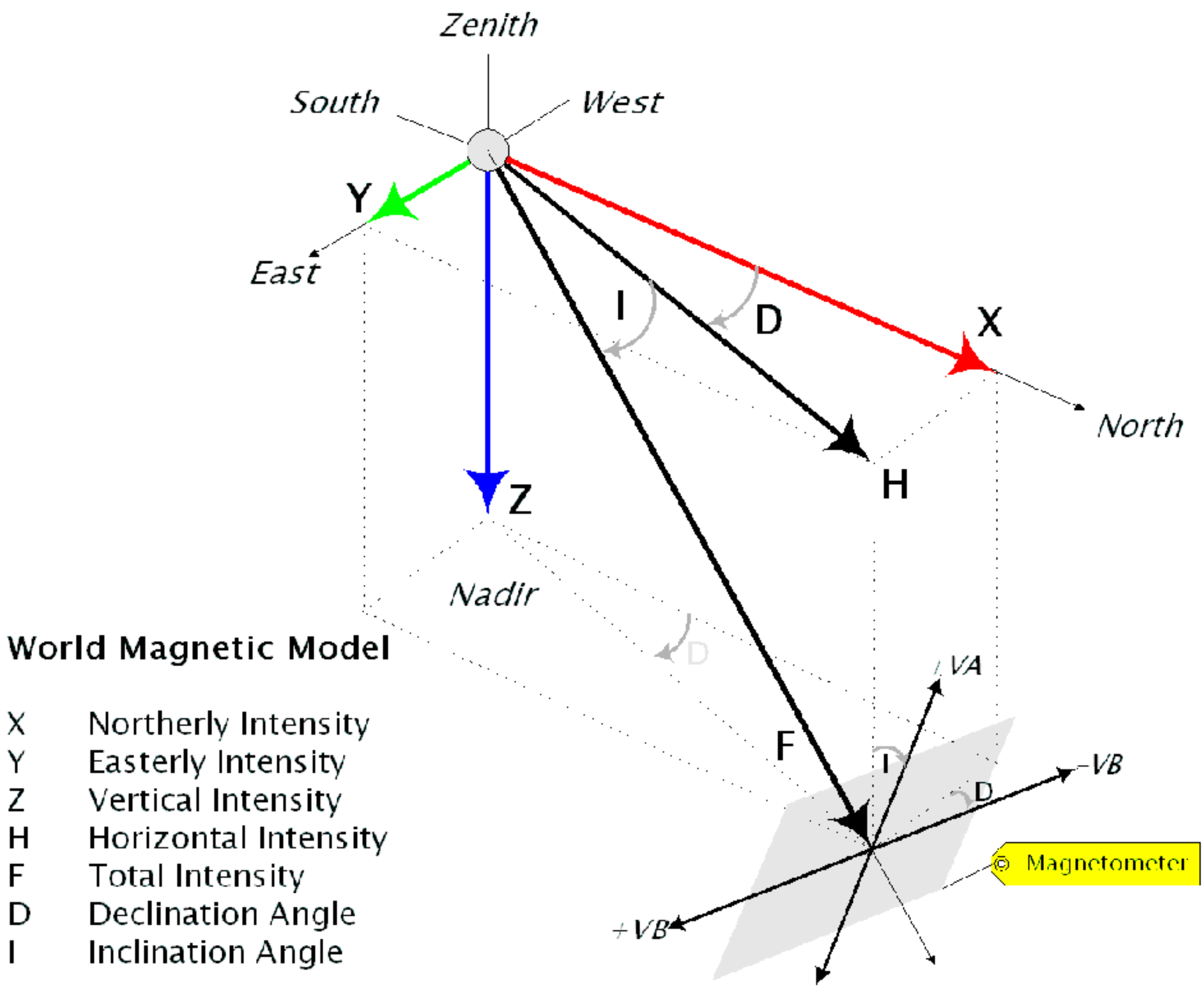
Standardisation of Magnetometer orientation

Clearly if an observatory is precisely on the Equator, then the Magnetometer should be mounted vertically, *i.e.* the board is standing upright. It would be interesting to hear if anyone tries this!

Please take care with orientation! There are several ways to mount the Magnetometer and appear to obtain a useful signal. It is not easy to test if your A and B axes are reversed, or have the opposite sign to our convention above.

The final (and in some ways the hardest) step is to relate the Magnetometer A and B axes to the conventional notation for recording the magnetic field. The A and B components are components of the field in a plane normal to the undisturbed field *at the time of alignment*, and so do not directly relate to the more intuitive North-South axis of the Earth's field. The diagram below shows this (complex) relationship in more detail. The coordinate system shown is the World Magnetic Model (WMM), a joint product of the United States' National Geospatial-Intelligence Agency (NGA) and the United Kingdom's Defence Geographic Centre (DGC). The WMM was developed jointly by the National Geophysical Data Center (NGDC, Boulder CO, USA) and the British Geological Survey (BGS, Edinburgh, Scotland). The link below gives more information:

http://www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml



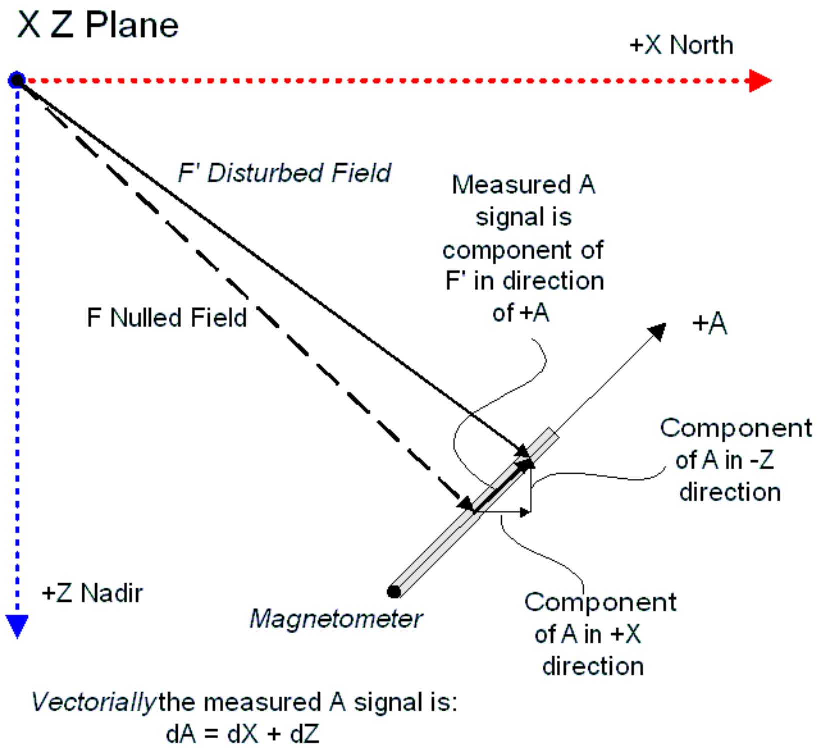
The Magnetometer orientation in relation to the World Magnetic Model

Starbase users can add the specific details of the WMM to an observation at their location ('topocentric') with the *Starscript* command:

```
DataProcessor.addToposWMMMetadata()
```

This command uses the observatory Latitude and Longitude, and calculates each of the WMM parameters given above, adding them as metadata items to the data record.

This final diagram shows a slice through the WMM diagram above, but only in the X-Z plane. Its purpose is to show that relating (A, B) to (X, Y, Z) is difficult, but not impossible!



The relationship of the WMM X-Z Plane to the Magnetometer A Component

In practice it is not necessary to derive the (X, Y, Z) components, since observers are usually looking only for changes to the undisturbed levels. You may however like to experiment with different ways of presenting these data. The A and B vector components provide the instantaneous direction of the current field relative to the field *at the time of alignment*. In principle this resultant direction can be plotted against time, as a polar or 'radar' plot, so showing the movement of the field vector during a disturbance, in the same way that a weather station might show the history of the wind direction and magnitude over time, with a 'wind rose' plot. It could be that particular types of disturbance have their own 'signatures' on such a radial plot.

Troubleshooting

Possible installation problems include:

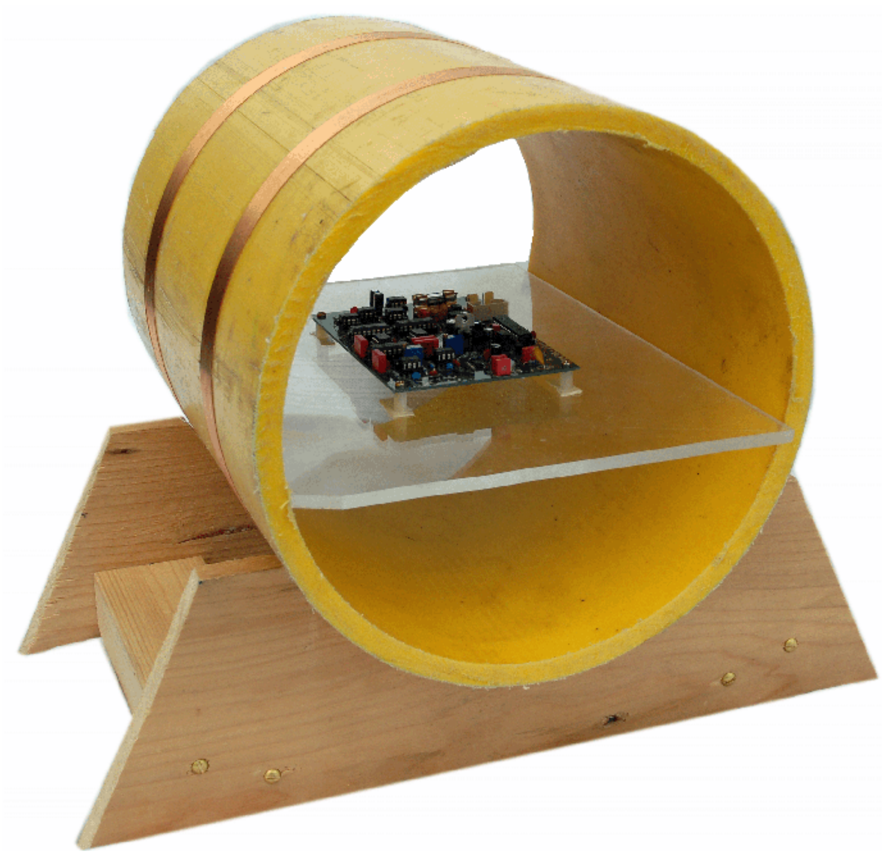
- If all four alignment lamps glow brightly together, then there is probably a local AC magnetic field. This may be from a mains transformer or motor.
- Short bursts of fast oscillation on the recording may be produced by the motor of a hair dryer or vacuum cleaner.
- Sudden steps in the output voltage are most likely to be due to a ferrous object moving in or out of range. Such effects are caused by parked cars, loudspeakers, metal furniture *etc.*

Sensitivity and Calibration

As you gain more experience using the Magnetometer, you may wish to try to calibrate its response against a known magnetic field intensity. This section gives some suggestions as to how this might be achieved.

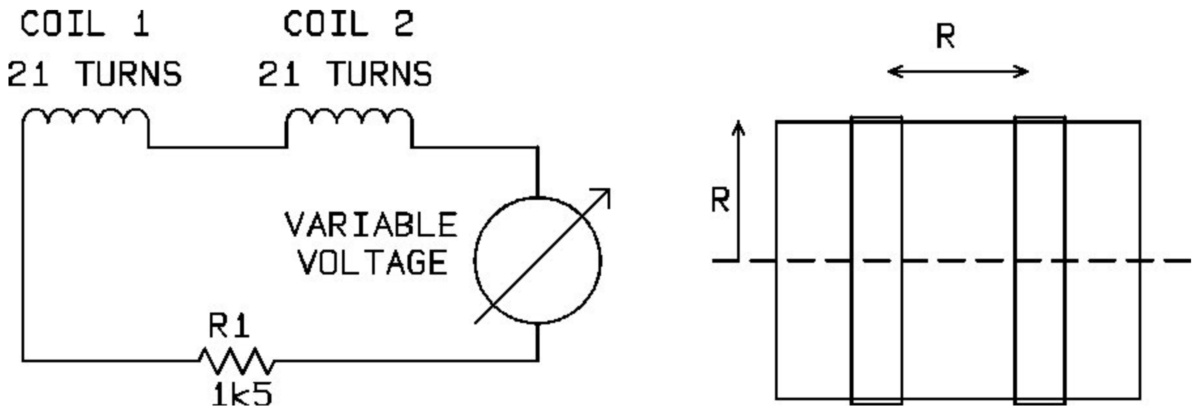
Sensitivity and calibration are very different, and need to be borne in mind when using a magnetometer. The sensitivity in terms of nT (nano Tesla) change in flux density per mV change in output voltage can be measured, while calibration against an absolute standard cannot. The Earth's magnetic field is ever present and cannot be easily removed to make any sensible calibration possible. Sensitivity can be checked regardless of the local field, provided that care is taken: it is a tricky procedure at the best of times.

The principle involved in checking sensitivity is that of the Helmholtz coil. An electric current flowing in any coil will produce a known magnetic field within the coil (a solenoid), but it will vary with position within the coil. By placing two identical coils a distance apart with a common axis, the field can be made constant on-axis. Placing the magnetometer within the coil thus allows sensitivity to be checked by measuring the output voltage while changing the current in the coils.



Magnetometer in Helmholtz coil.

http://en.wikipedia.org/wiki/Helmholtz_coil



Circuit of Helmholtz coil.

The coil diameter (2R, in the diagram above) needs to be just large enough to contain the magnetometer board. The tube in the picture is 180mm outside diameter. Each coil is 21 turns of 0.4mm wire, close wound, spaced half the coil diameter apart, 90mm in this case. Secure the coils with double-sided tape so that they cannot move. Dress the lead-out wires so that they too are fixed out of the way. A platform can be made to slide the board into the tube such that the sensor chip is on axis, in the centre of the two coils. If the second magnetometer axis is also to be measured, then a much larger diameter coil will be required in order to take the full width of the board.

Start by setting a coil current of about 1mA. As already noted, the Earth's field cannot be removed, and so a position for the coils must be found that biases the magnetometer output just above 0V. The coil current can then be increased in small steps and the output voltage noted each time. Stop when the output gets close to 5V, and use the formula below to convert the current into flux density:

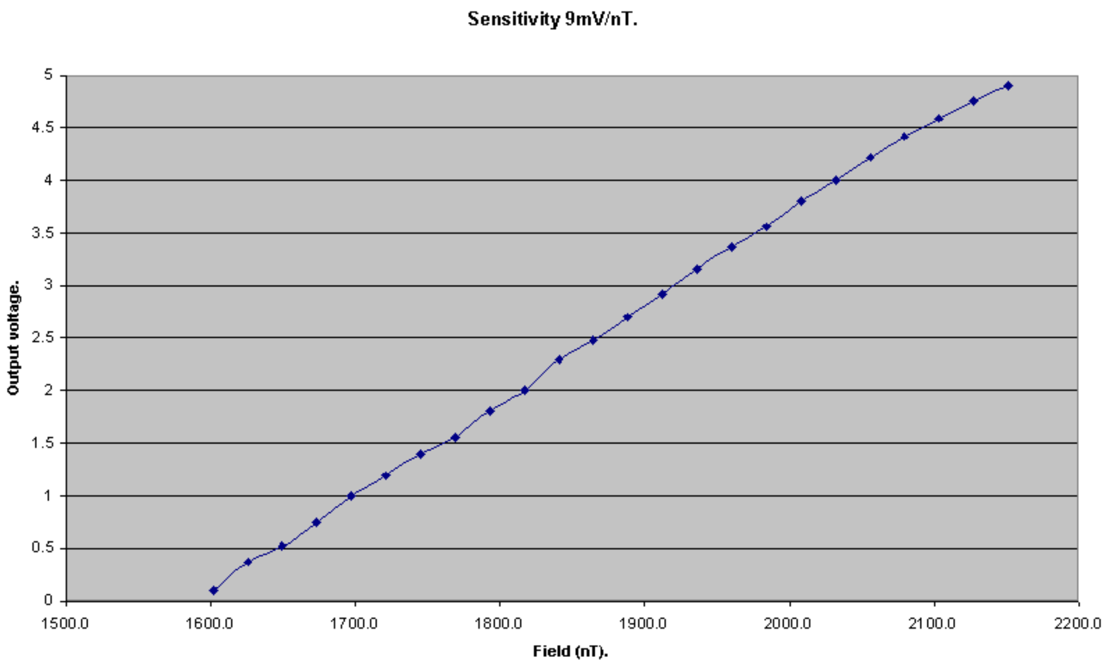
$$B= (8.9917 \times 10-7 \times N \times I)/R \quad \text{(Tesla)}$$

N= number of turns

I= current (Amps).

R= coil radius (metres).

When making these measurements, care needs to be taken that all magnetic materials are moved well away (at least one metre, preferably more), and that nothing magnetic can move (including moving-coil meters) during the test. Care also needs to be taken in construction of the test fixture, so that alignment can be set and maintained whilst adjusting the coil current and checking the output voltage. These are not easy measurements! Once a series of measurements has been made over the range of output voltage, the result can be plotted to measure the slope in nT/mV.



Graph obtained with prototype magnetometer at gain setting two.

Note that the output will be non-linear close to each end of the range (near 0v and 5V) , but should have a nearly linear region over which the sensitivity remains constant. Given the difficulty in making these measurements, a straight line is unlikely to be obtained, but an average slope can be determined.

Classification and Interpretation of Results

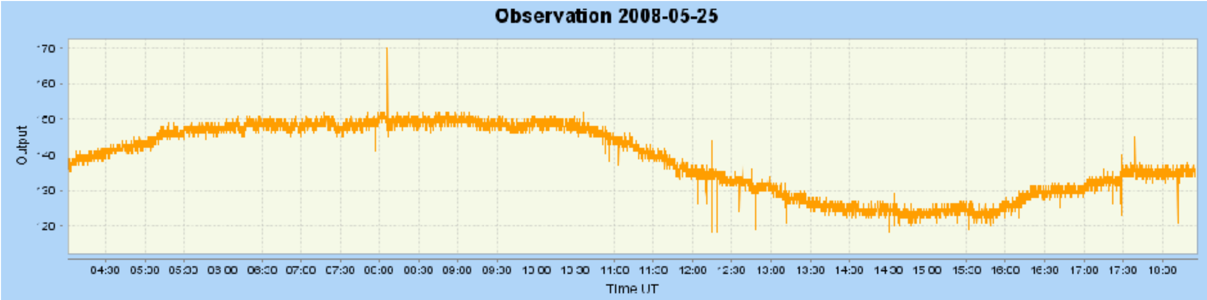
With the tilted and rotated alignment ('nulled'), the output voltage will be about mid-scale (2.5V). Moving small ferrous objects (such as a screwdriver) nearby will alter the output and also show as a change in brightness of the alignment lamps. Periodic visual checks will show changes in the local magnetic field, but cannot distinguish domestic interference from genuine solar effects. Connection of a Starbase controller or other logging software should enable more useful observations to be made.

Recordings made over a 24 hour period should show the diurnal variation due to the Earth's rotation. The magnetosphere is pushed away by the solar wind, and so the field direction appears to sway from side to side each day. When the Sun is quiet, this effect is easily seen. On top of this slow variation, there are likely to be steps recorded, due to local 'domestic' interference. Steel garage doors and moving vehicles or steel framed furniture are most likely to be recorded. Turbulence in the solar wind will buffet the magnetosphere, and so be recorded as a disturbance to the local magnetic field. These disturbances are often larger than the diurnal variation, and occur over much shorter periods. The disturbance may last less than an hour, or continue for longer. The amplitude recorded will depend on the degree of turbulence in the solar wind; a major coronal mass ejection (CME) may well saturate the sensor at times of high solar activity.

While smaller (minor) disturbances are quite common, even at times of low solar activity, major disturbances can be used to warn of possible auroral conditions. If there has been a significant particle injection into the magnetosphere then an aurora may become visible as the auroral oval moves in our direction, light pollution permitting.

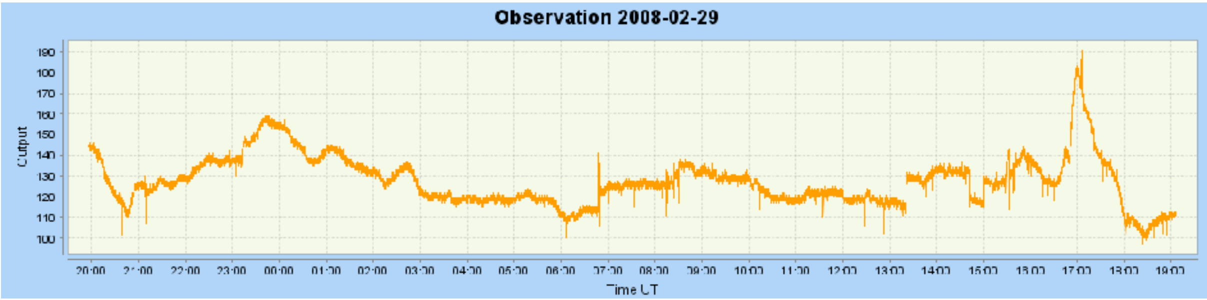
Magnetic observations can be simply stated as quiet, disturbed or active, based on previous recordings from a particular magnetometer. While this is sufficient for most needs, a record of the K-index can be made. This requires that the sensitivity of the magnetometer is known, and that a means of calibrating observations against other observers is available. Users interested in this aspect are advised to look at various geomagnetism web sites for suitable advice and comparisons. The technical Appendix by Whit Reeve gives more information.

The following charts show typical recordings from one channel of the magnetometer.

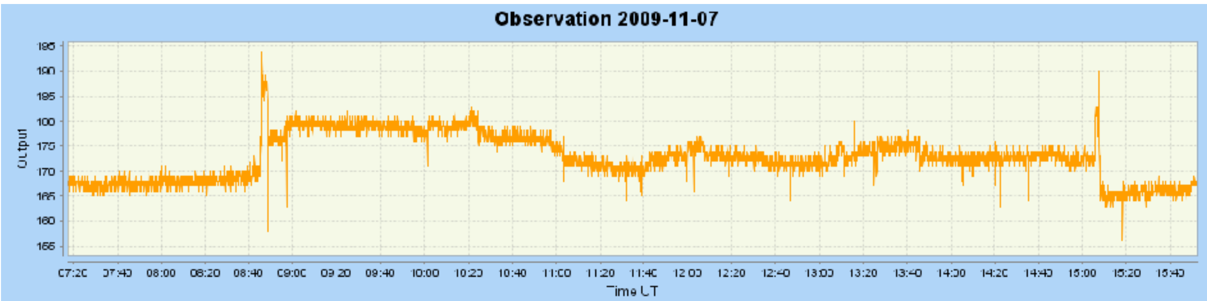


The normal diurnal curve on a quiet day in 2008 May

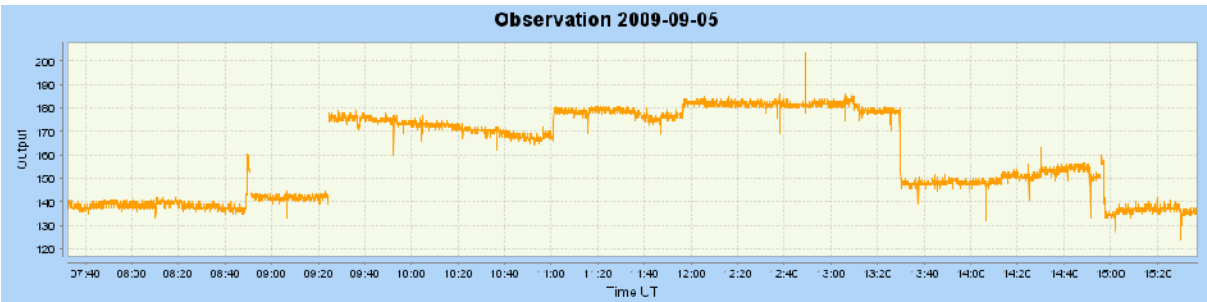
Ideally this curve should appear almost sinusoidal. Averaging over several quiet days will help to determine the curve for your location.



Genuine solar disturbances recorded on 2008 February 29



Steel garage door and small car



Large commercial vehicle parked nearby.

Using the UKRAA Magnetometer

This section describes some of the various options available for logging the output of the Magnetometer:

- **Starbase**
  UKRAA's preferred data capture option is to connect the Magnetometer via a UKRAA Controller to the Starbase Observatory software.

- **Data Loggers**
  Digital Multimeters (DMM) with computer outputs or other custom recording devices may be used. Starbase can import the comma-separated or tab-separated data formats produced by these loggers.

- **Radio-SkyPipe**
  The UKRAA Magnetometer may be used with the popular Radio-SkyPipe (RSP) software. This mode of operation requires an external analogue-to-digital converter (ADC) such as a LabJack or a custom circuit using the MAX186 device (a MAX 186 ADC is available from UKRAA on request part number UKR021). Starbase can import RSP files.

UKRAA Starbase

If you have also purchased a UKRAA Controller module, the Magnetometer can be installed as an instrument in the Starbase Observatory. The Controller is a "stand-alone" microprocessor card with a substantial amount of memory and only requires a low voltage power supply, which could be a battery for remote locations. It is capable of recording and storing data in its on-board memory that is sufficient for many thousands of readings. In addition to supporting data logging, Starbase enables you to compare your observations with those from a wider community. The Observatory is supplied as Java software, available as a free download from www.ukraa.com.

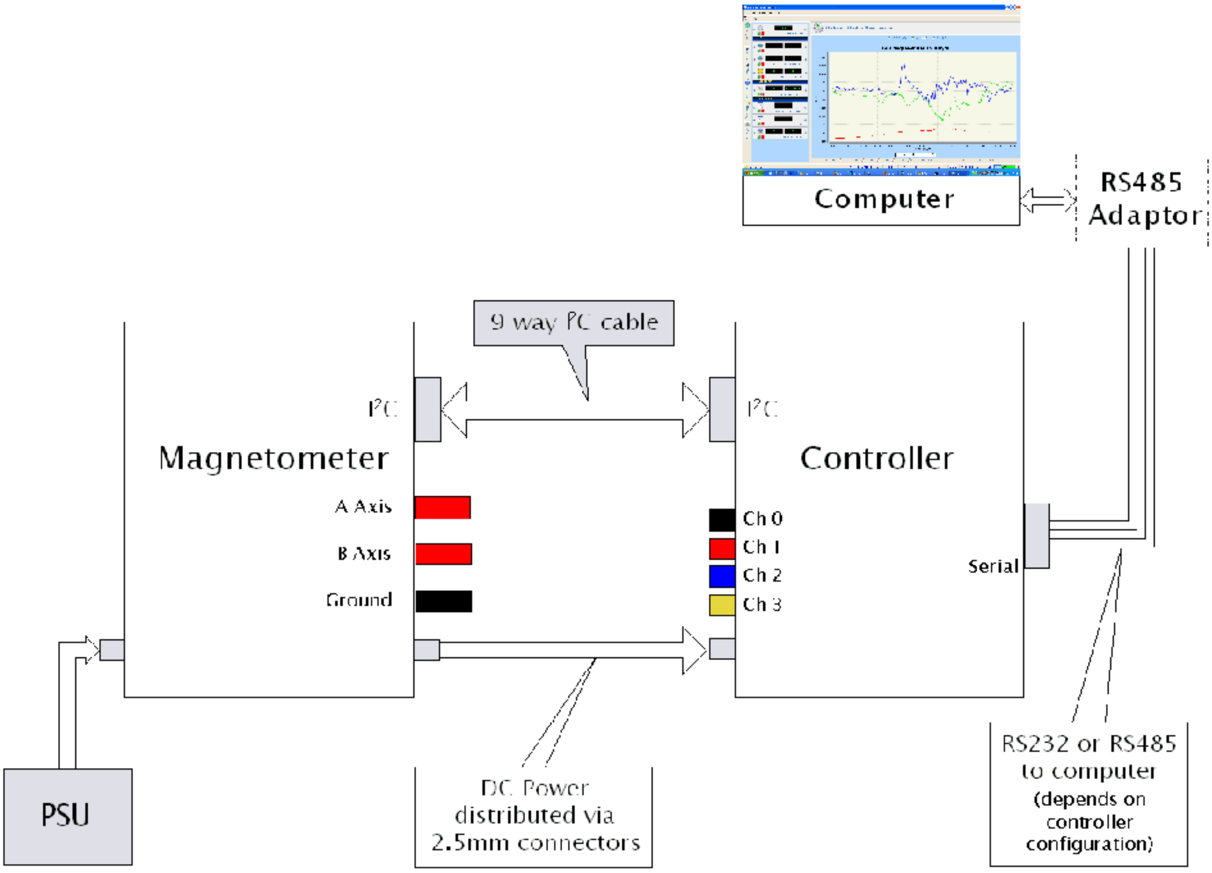
Getting Started

In order to use the Magnetometer with Starbase, first connect the UKRAA Controller module to the Magnetometer, using a suitable cable (10way to 10way IDC connector ribbon cable). This is inserted in the box header marked I^2C Bus.

If a controller is used it is recommended that the power be applied to the 2.5mm socket on the Controller board and the Magnetometer be supplied by a lead with 2pin white polarised free socket inserted into the header adjacent to the power plug on the Controller, and connected to the screw terminals on the Magnetometer.

If a controller is *not* used then power should be supplied direct to the appropriate screw terminals P1 (take care to observe the correct polarity). Application of reverse polarity will blow the adajcent fuse (250mA) but this may not fully protect the components.

The Controller may then be connected to your computer; the type of connection will depend on the type of controller, but will usually be via an RS232 or RS485 cable. You may require an RS485 to USB adaptor, if your computer does not have an RS485 port. You may wish to use an adaptor with an electrically isolated connection, to protect your computer from electrical interference from the instruments in your observatory (or *vice versa*!).



Magnetometer used in Starbase mode

RS232 or RS485?

The choice between using RS232 or RS485 depends on your local environment and your future plans for your observatory.

Using RS232 restricts you to locating the Controller no more than 5 metres away from the computer. The number of available communication ports on your computer will limit the number of instruments that can be connected and monitored consecutively by Starbase.

On the other hand, using a single RS485 port will allow instruments to be located several hundreds of metres away from the Starbase computer and additionally, allow many different instruments to be daisy-chained together. RS485 is also much more tolerant to environmental 'noise' that can cause data loss or corruption. The UKRAA recommends that you adopt RS485 as the interface for your Magnetometer and Controller.

Your Observatory user manual will describe how to set up the data connection, and to test the link with the Controller. You should prove that *e.g.* the `ping()` command completes correctly before continuing.

Data Logging

The Starbase Observatory Magnetometer Instrument

There are two main modes of operation that will be useful to you: firstly, the Controller may be set up as an off-line data logger. This means that once the logging operation has started, you can turn off the computer, and leave the Controller active for a long time. The recording time may be several days even at the fastest sample rate. The data you have collected are then retrieved the next time you use your computer. The second mode is in 'real time', *i.e.* you can see each data sample as it is taken, and watch the progress of the recording on the Observatory, in much the same way as using a chart recorder. You may then save the data to a file on the computer when your observation is complete. This mode is most useful for testing and setting up, when it is helpful to see the effects of changes in the system.

Offline Logging Mode

Perform the following steps to capture data in offline logging mode. Please refer to your Starbase User Guide if these terms are unfamiliar to you.

`Core.reset()`	Ensure the Controller starts in a known state. This is always good practice, for all instruments. WAIT for 10 seconds!
`Core.ping()`	This confirms that you can communicate with the Instrument.
`DataCapture.getSpace()`	Ensure 100% of data memory is available. If not, there may be earlier data still to be downloaded.
`DataCapture.setRate(1)`	Set the sample rate, here 1 second as an example.
`DataCapture.capture(true)`	Start the capture operation. Most commands will now return a CAPTURE_ACTIVE status until capture is stopped.
Allow time to pass!	The computer does not need to be connected again until the next step.
`DataCapture.capture(false)`	Stop the capture operation. All commands may now be executed again.
`DataCapture.getDataBlockCount()`	(Optional) Check to see how many data blocks have been recorded. This will show how long the download is likely to take.

`DataCapture.getData(Staribus, PassThrough)`	Read the data from the Controller into Starbase Observatory. This may take some time on a slow connection when the memory is full. See the later comments about the choice of Filter (`PassThrough` used here).
Now view the data on the Chart, or the RawData and ProcessedData tabs.	Do not turn off the Controller until you are sure that the data are saved on the computer.
`Exporter.exportRawData(filename, timestamp, dataformat)`	Save the RawData to a specified filename, in the format of your choice (initially Stardata XML).
`Exporter.exportChart(filename, timestamp, format, width, height)`	(Optional) Save the chart as an image, in the format of your choice (e.g. PNG works well). Remember that you cannot reload the data from a chart, only from the RawData file.

Take some time to become familiar with the capturing and downloading process, and then experiment with processing and storage options. For instance, the ProcessedData tab shows the effect of filtering the RawData. The optional filter is enabled during the getData() download. The first release of the software includes a `SimpleIntegrator`, a filter which just averages a number of data samples over a period specified by the configuration property `DAO.TimeConstant`. (Found in `Magnetometer-properties.xml`) In hardware terms, the effect is the same as applying an RC low pass filter to the voltage output. You may export the ProcessedData independently of the RawData. The chart shows the ProcessedData, so if you do not want to filter your data, remember to set the filter parameter to `PassThrough`.

Realtime Logging Mode

This mode is run with a single command, as below.

`Core.reset()`	WAIT for 10 seconds!
`DataCapture.captureRealtime(sampleinterval, captureperiod, filter, update, logging)`	All logging parameters are entered in the single command.
View the samples on the Chart or the data tabs, as they are accumulated.	In order to save memory, the data are 'decimated' when there are too many to fit precisely on the graph. This does not affect the underlying RawData, it is purely to improve display efficiency.
`Exporter.exportRawData(filename, timestamp, format)`	Export your data to a file on your computer.
Allow the capture to run to completion after the specified `captureperiod`, or use Abort.	

The remarks under `capture()` concerning RawData and ProcessedData also apply to `captureRealtime()`.

Please note: if you use the `captureRealtime()` command for long periods at high sample rates, the number of data samples may mean high demands on the memory allocated to the Observatory. This will be indicated by an increase in the Memory Usage indicator, at the right hand end of the status bar. Eventually you may find that performance suffers, and the computer becomes progressively more unresponsive. If this happens, save your data (with `export()`) and close down Starbase.

`captureRealtime()` is not intended as a substitute for offline logging!

Advanced Topics

It is possible to read the physical temperature of the Controller and Magnetometer modules, using the `Utilities.getTemperature()` and `MagnetometerPlugin.getTemperature()` commands. These may be useful if you suspect variations in output due to variations in ambient temperature. If this does occur, it may indicate a hardware fault, or suggest that calibration may be advised. The Temperature channel is included in the logged data for the `capture()` and `captureRealtime()` commands. The Temperature channel can be turned off on the Chart display.

The configuration of the Controller-Magnetometer combination is stored in XML files on the computer. (Later releases will hold the XML in ROM devices on the modules themselves.) A certain amount of customisation is possible, and you may like to experiment with this. For instance you could change the name of the Chart legend displayed in Starbase, or even the name of the instrument. Your Starbase User Guide will contain further information on this topic.

The Magnetometer instrument in the Observatory has a RegionalMap tab, which shows the PointsOfInterest (POI) described in the instrument XML file, or in a separate POI file. You may add to the list of POIs, for instance the locations of other observers, or magnetic field observatories. You may even change the map itself, by generating new map image from data provided by NOAA at http://rimmer.ngdc.noaa.gov. Note that the map is slightly unusual in that it is a linear projection of Longitude and Latitude, so that the location of the cursor is more easily calculated. The area represented by the map is described in the `Frameworks.xml` file. The map may be saved as an image using the `Exporter` commands.

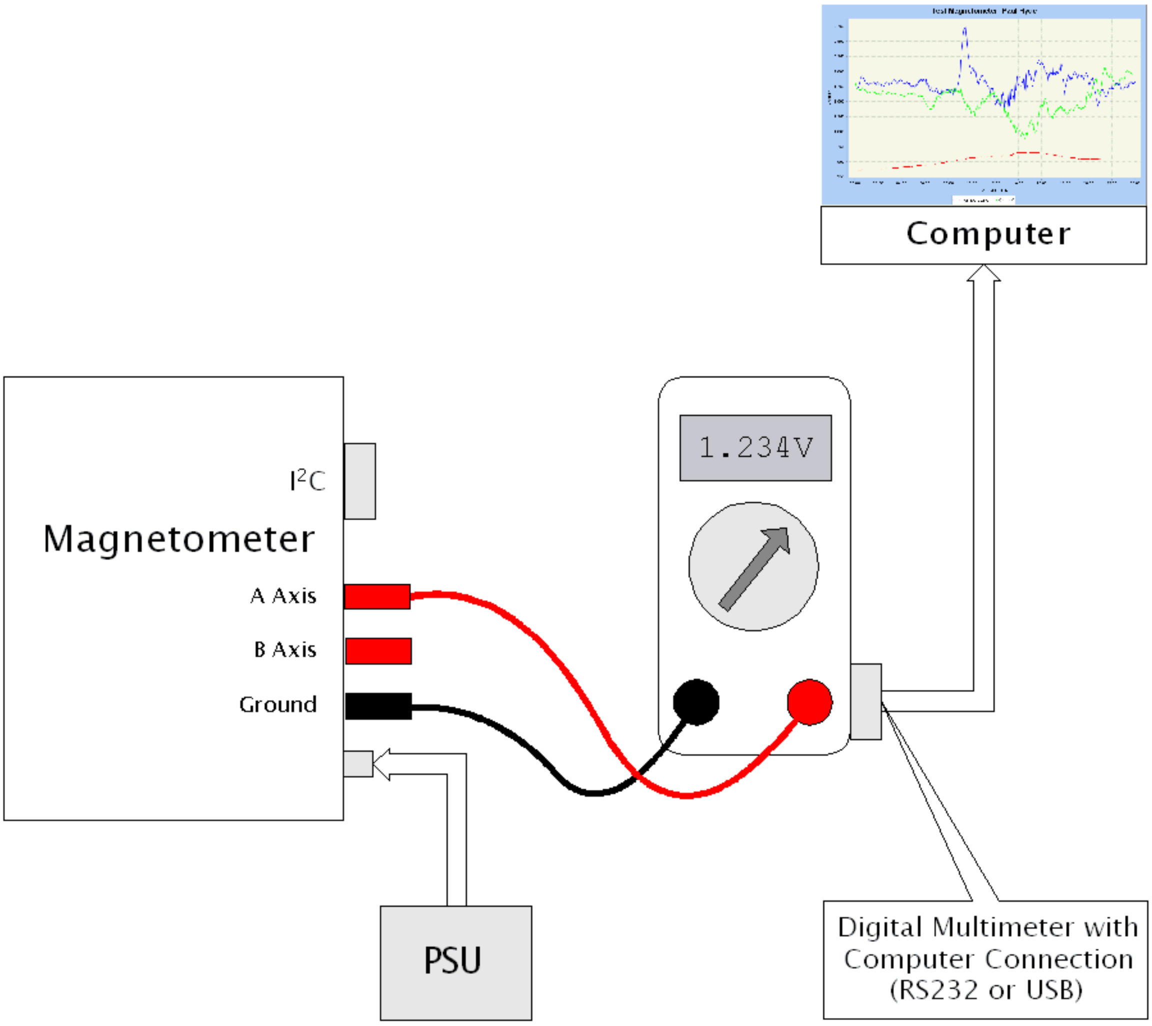
Data Loggers

The outputs from the Magnetometer sensor are two varying voltages, one for each axis, that are proportional to the strength of the local magnetic field in the appropriate direction. A continuous record of these voltages is required to indicate the presence of a magnetic disturbance and thus a Solar Flare. In the days before readily available computers the output would have been recorded using a chart recorder ('strip chart') that would trace the signal level on a long strip of graduated paper using a pen. These were fun to use but refilling the ink reservoirs could be messy. These instruments can still be found on the vintage test equipment market and are still capable of doing the job. Their disadvantage is that one cannot re-analyse the data without carefully and laboriously reading it off, and it is not easily possible to compare two events or two days recordings in detail.

The development of digital measuring instruments in the 1960s laid the foundation for what became known as data-loggers. These are instruments that autonomously take measurements and record the values digitally, often against some form of time-stamp. The data can then be input to a digital computer for analysis, scaling, smoothing or filtering, display, publication, and finally archive storage.

There are several ways of recording the results from the Magnetometer using data-loggers. For instance, there is a wide range of hand-held Digital Multimeters (DMM) on the market, and some can transfer their measurements to a computer, usually with an RS232 or USB connection. UK examples are from Maplin (Ref: N56FU) and one of the Digitek DMMs from CPC (Ref: IN02513).

The multimeter in conjunction with appropriate (usually provided) software may be used as a single-channel data-recording device or data-logger. The software included should allow a chart-recorder emulation display or some form of plotting routine, together with a way of storing a batch of readings with vital extra information like date, time and what was being measured (the observation metadata). This can be somewhat limited for longer term study, but you can also import the data into a spreadsheet application such as Excel. Whilst you can use the OpenOffice spreadsheet application for this, it is very slow when dealing with the large amount of data produced from a typical day's observing. Note that many spreadsheet applications are limited to 64,000 lines, which means that you cannot accommodate sampling at a rate faster than about 1.5 seconds if you want to capture 24 hours of data. In practice this is not a problem since 3 or 5 second sampling intervals are quite adequate for magnetic field monitoring, and the inherent time constant of the Magnetometer itself is longer than a second.



Magnetometer used in Data Logger mode (single channel)

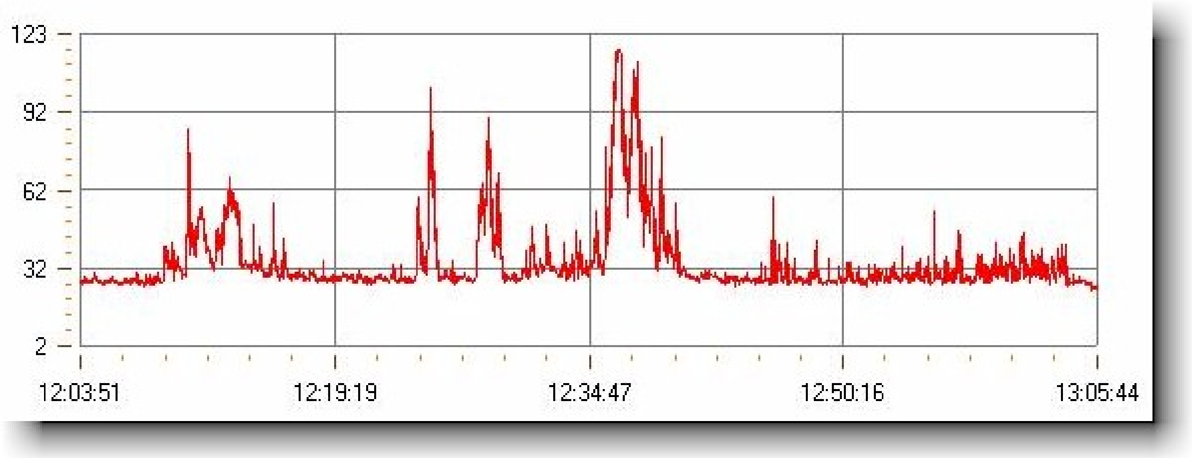
There are also a number of stand-alone accessories that interface to a computer with software provided to do the same job but not needing the flexibility of a hand held multimeter. One UK vendor of these is Pico Technology of St Neots, in Cambridgeshire.

It is not possible for UKRAA to provide any detailed assistance on third party data-loggers or software, but there are many offerings available. The output ports on the Magnetometer give a 0 to 5 Volt range: this should suit a wide range of generally available data-loggers.

Radio Sky Pipe

Radio-SkyPipe is a widely-used successor to the old 'stripchart' recorders. Full details of this free software application can be found at the link below. Please note that some features of the program are available only for chargeable licences.

http://www.radiosky.com/skypipeishere.html



Sample Radio Sky-Pipe chart

Installing Radio Sky-Pipe

Use the instructions on the Radio-SkyPipe website to install the latest version on your computer. Please see the Radio-SkyPipe Support desk at

http://www.radiosky.com/support.html

for all queries related to the installation and operation of this application.

Connecting to Radio-SkyPipe

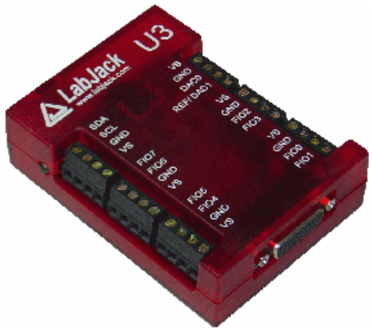
The UKRAA Magnetometer produces an analogue output signal for each of the two sensor axes A and B. Radio Sky-Pipe requires a digital input signal. In order to enable Radio Sky-Pipe to process the signals from your Magnetometer you will need an Analogue to Digital Converter (ADC). Two types of ADC which may be appropriate are described below; the choice will depend on the available sockets on your computer, and on the number of channels you wish to record. Note that it is not necessary to record both A and B axes simultaneously, but if you can do so, you will enhance the usefulness of your observations.

- If your computer has a standard 25-way printer socket (see picture below), you can use the UKRAA Radio Sky-Pipe single channel ADC (UKR030). Contact UKRAA for further details of this product.

25-way printer socket

- If your computer has a USB socket (see picture below), you can use the LabJack U3. The U3 is a 12-bit data logger that can be configured for a variety of input, output, timing and control applications. It comes in two versions, LV, with maximum input levels of ± 2.44 Volts and HV with maximum input levels of ± 10/20 Volts. Go to http://www.audon.co.uk/u3.html for further details of this product.

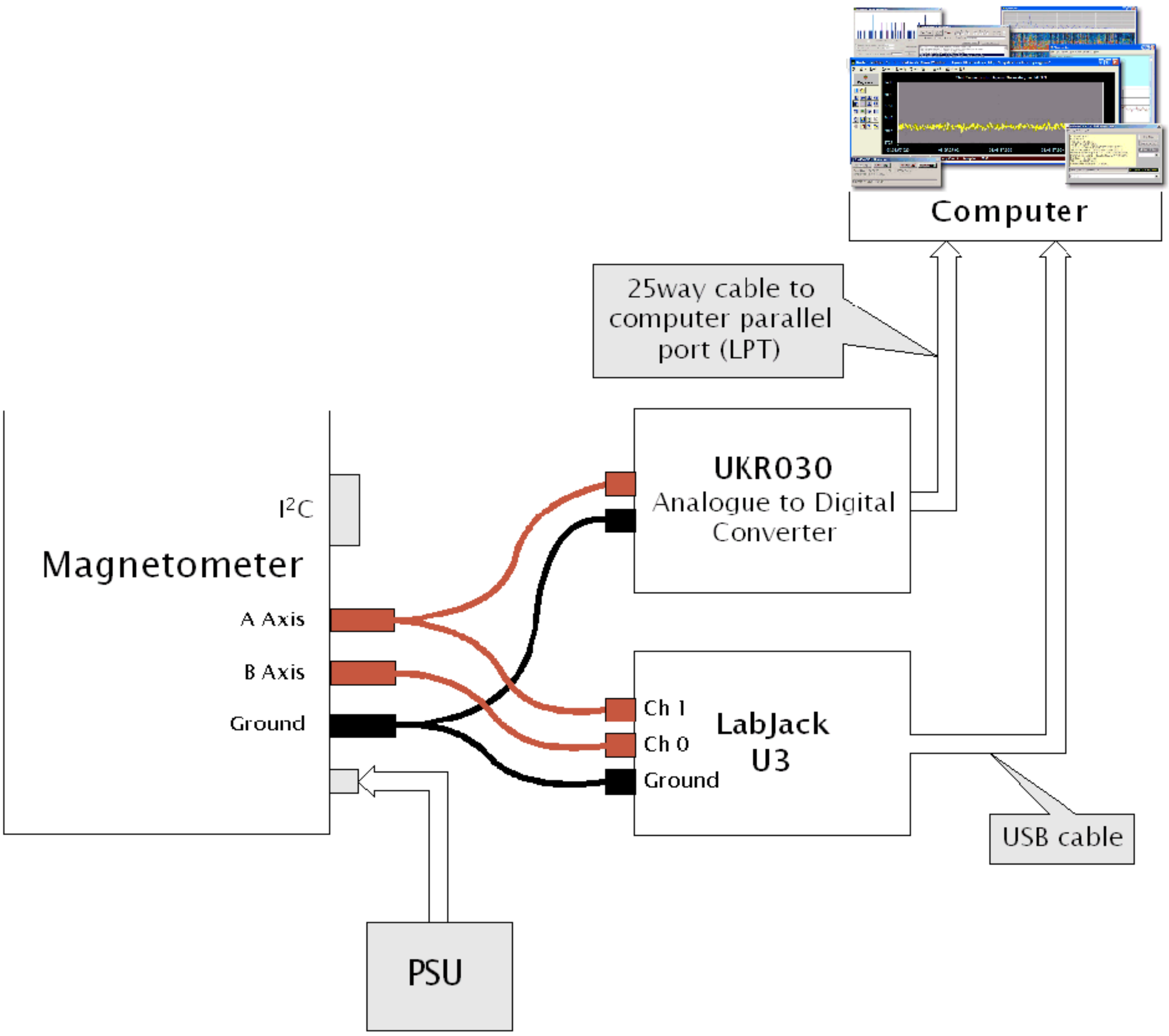
USB socket



LabJack U3

Configuring Radio Sky-Pipe

You will need to configure the RSP application to work with the Magnetometer. The most important step is to select the OPTIONS tab at the top of the main screen and set Data Source CH1 to be **`MAX186 ADC CH1`** and Data Source CH2 to be **`MAX186 ADC CH2`** (if using the UKRAA Radio Sky-Pipe single channel ADC – available on request) or LJ U3 ADC and Source CH to 1 and 2, according to which input channel on the LabJack you are using. The Stripchart settings can then be set to average ten readings taken every 0.2 seconds (giving a time constant of 2 seconds), to help average out any noise. A default Chart Width of 86,400 seconds will plot a full day's data on the screen. If you then use the Logging tab to restart charting at midnight, Radio-SkyPipe will create daily files that you can archive and review at leisure.



Magnetometer used in Radio SkyPipe mode with two example adaptors

Use a standard 25-way printer cable to connect from the Magnetometer to your computer and ensure that the Magnetometer is switched on. Clicking on the 'Start Chart' button will then set things running, though with the above settings it may take a minute or so before the trace becomes visible on the chart.

UKRAA Starbase is able to read Radio Sky-Pipe data files, and convert them to other formats. The simplest instrument to use for this purpose is called `GenericInstrument`.

Glossary

ADC	Analogue to Digital Converter
ATU	Aerial Tuning Unit
BAA	British Astronomical Association
BNC	Bayonet Neil Concelman (connector)
CDROM	Compact Disc Read Only Memory
EEPROM	Electrically Erasable Programmable Read Only Memory
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
I2C	Inter IC Control Bus (also IIC bus)
ITU	International Telecommunications Union
LW	Long Wave
MW	Medium Wave
NATO	North Atlantic Treaty Organisation
NOAA	National Oceanic and Atmospheric Administration
POI	Point Of Interest
RAG	Radio Astronomy Group
RF	Radio Frequency
RoHS	Restriction of Hazardous Substances
RS232	Electronics Industry Association Communications Protocol Standard
RS485	Electronics Industry Association Communications Protocol Standard, differential transmission
RSGB	Radio Society of Great Britain
RSP	Radio Sky Pipe
SID	Sudden Ionospheric Disturbance
SW	Short Wave
UKRAA	The UK Radio Astronomy Association
URL	Uniform Resource Locator
USB	Universal Serial Bus
UT	Universal Time
UV	Ultra Violet

W/m^2	Watts per square metre
WEEE	Waste Electrical and Electronic Equipment
XML	Extensible Markup Language

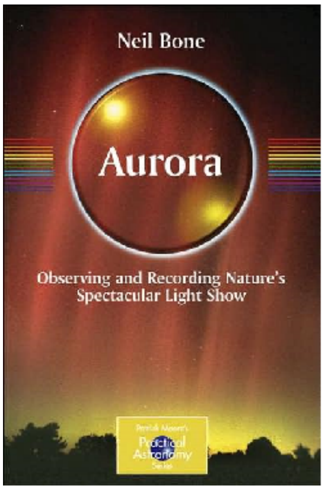
Auroral oval	The oval shaped zones around each magnetic pole at roughly 67 degrees north and south. They mark the location at which auroral activity is most likely to occur, and are often visible in satellite images of the polar regions. Strong magnetic activity pushes the auroral oval away from its pole, and towards mid-latitude observers.
Bow Shock	Similar to the bow wave in front of a moving ship. There is a sharp decrease in solar wind velocity as it meets the Earth's magnetic field.
Declination	The angle between true north (the rotation axis) and magnetic north for any northern hemisphere observer, or true south and magnetic south for southern observers.
Dipole	Having two poles. A magnetic field with a single north and a single south pole.
Diurnal variation	The natural change in the direction of magnetic north (or south) caused by the Earth's rotation against the solar wind.
Inclination	The angle of the local magnetic field to the horizontal.
K index	The maximum fluctuation of the horizontal components of the magnetic field relative to a quiet day, measured over a 3 hour period. The fluctuation seen varies between observers at different geomagnetic latitudes, a local conversion factor is required to convert nT to K index. This can only be calibrated by reference to the index reported by other observers.
Magnetic North	The direction to which a compass needle will point. The direction in which the magnetometer will null.
Magnetopause	The region in which the Sun's and Earth's magnetic fields meet. Where the magnetic pressure is sufficient to deflect the solar wind around the Earth.
Magnetosheath	The region downwind of the Bow Shock where the Solar Wind becomes turbulent on meeting the Earth's magnetic field.
Magnetotail	The long drawn-out tail to the Earth's magnetic field produced as the solar wind is deflected at the sunlit side around to the night side.
Tesla (T)	The SI unit of magnetic flux density. 1 Tesla = 10^4 Gauss. 1nT = 10^{-9} T.
True North	The northern point of the Earth's rotation axis.

References

Internet URLs

www.ukraa.com	UKRAA
www.britastro.org/radio	BAA Radio Astronomy Group
www.ukraa.com/www/starbase	Starbase information
www.sec.noaa.gov/today.html	GOES satellite data & space weather
www.britastro.org/aurora	BAA Aurora Section
www.dcs.lancs.ac.uk/iono/aurorawatch	Lancaster University Aurora Watch
www.geomag.bgs.ac.uk/observatories.html	British Geological Survey
www.i2c-bus.org	I2C Bus
www.rs485.com/rs485spec.html	RS485 Specification
www.aavso.org/solar-sids	American Association of Variable Star Observers (SIDs)
www.radiosky.com	Radio Sky Publishing

Books

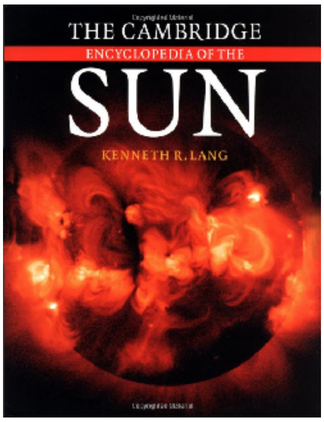


The Aurora, Sun-Earth interactions
Neil Bone

ISBN-13: 9780387360522

Published 2007

Paperback 182 pages

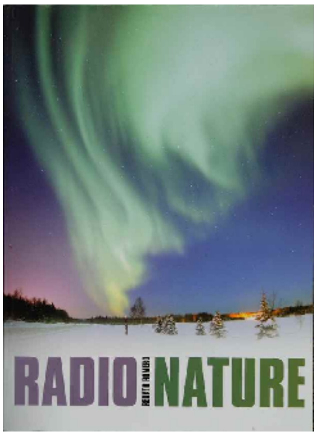


The Cambridge Encyclopedia of the Sun
Kenneth Lang

ISBN-13: 9780521780933
ISBN-10: 0521780934

Published August 2001

272 pages 276 x 219 mm



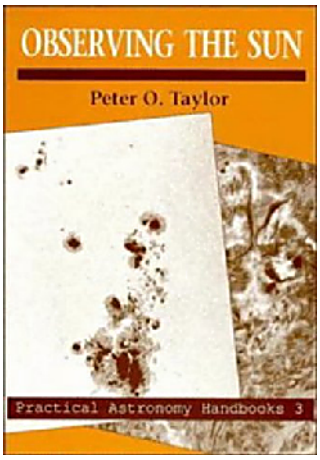
Radio Nature

Renato Romero

ISBN 9781-9050-8638-2

Published 2008

220 pages 240 x 175 mm



Observing the Sun

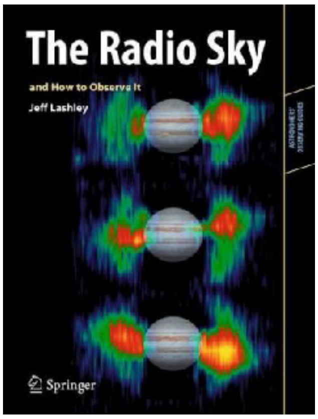
Peter Taylor

ISBN-10: 0521401100

or ISBN-13: 9780521401104

Published November 1991

173 pages 279 x 215 mm



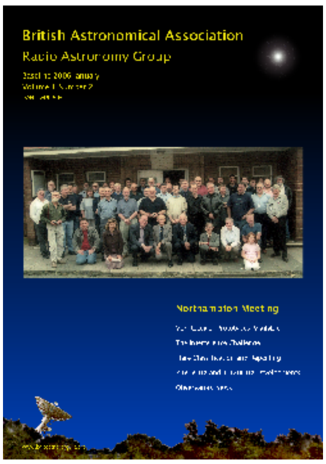
The Radio Sky and How to Observe It

Jeff Lashley

ISBN 978-1-4419-0882-7

Published 2010

236 pages 235 x 178 mm



BAA Radio Astronomy Group *Baseline*

Volume 1, Numbers 1 to 4

Download from www.britastro.org/radio

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Website: www.ukraa.com/www/starbase

BAA Radio Astronomy Group

Website: www.britastro.org/radio/

Appendix 1 – Geomagnetism Tutorial

This Introduction to Geomagnetism has been reproduced here by kind permission of the author, Whitham D. Reeve of Alaska USA. Whit Reeve has a lot of experience of radio astronomy and geomagnetism, and is also the US distributor of UKRAA products. This material is also available on Whit's website at www.reeve.com. Some minor changes have been made to ensure consistency of style with this User Manual.

Introduction

This tutorial is written for amateur radio astronomers and amateur radio operators who wish to understand the causes and characteristics of the Earth's magnetic field and how it is affected by solar activity.

In 1600 William Gilbert published the first scientific study of the Earth's magnetic field in *De Magnete*. [Gilbert] However, in spite of this and a huge amount of subsequent work, and the practical use of the Earth's magnetic field for compass navigation for perhaps a thousand years, our understanding of the origin of the Earth's magnetic field still is incomplete. We call the study of the Earth's magnetic field the study of *geomagnetism* and the field is measured with *geomagnetometers*. The results of our measurements are shown on *magnetograms* (Fig. 1).

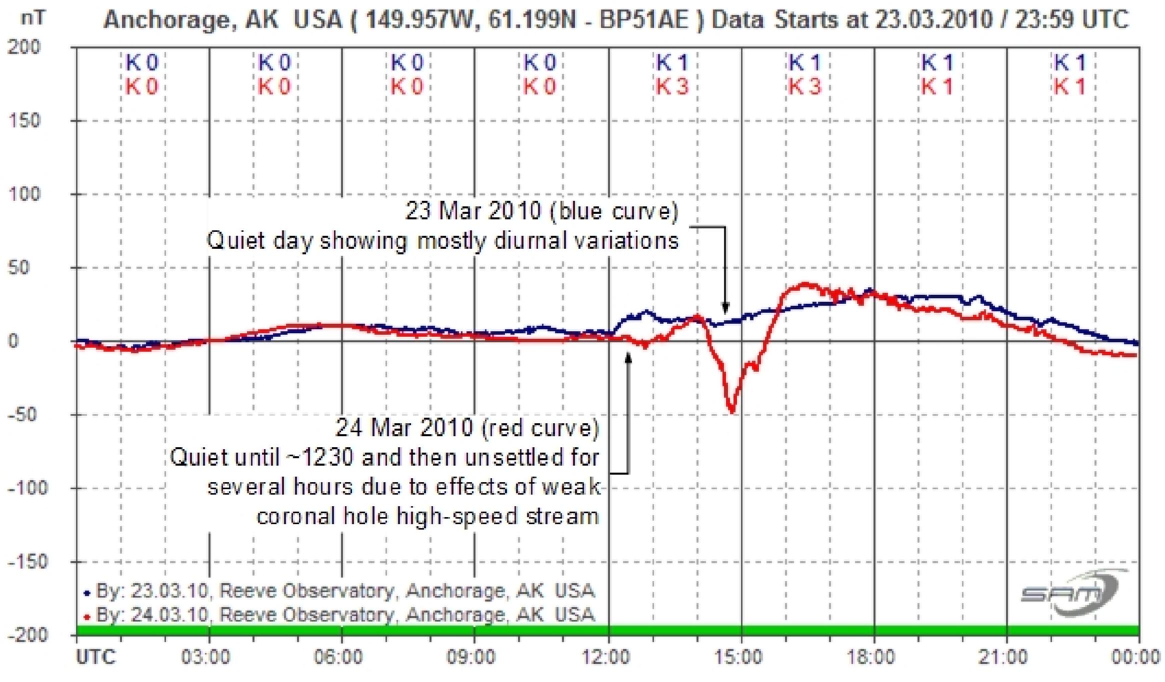


Fig. 1 A Typical Magnetogram

A magnetogram shows the magnetic field amplitude on the vertical scale with respect to time on the horizontal scale. This particular magnetogram shows two consecutive days in 2010 March, at Anchorage, Alaska USA indicating a magnetically quiet day followed by disturbances due to a coronal hole high-speed stream. Annotations have been added to indicate events

Amateur radio astronomers can study the Earth's magnetic field and its variability by using instrumentation well within their financial reach and technical capabilities. At least one magnetometer system has alarm capabilities that can be used to indicate aurora viewing and radio propagation opportunities associated with geomagnetic storms and disturbances. Live magnetometer data can be viewed online.[1]

Magnetic Quantities and Units of Measure

There are two basic magnetic quantities and one constant from which all other magnetic quantities are derived: [NBS]

- Magnetic induction, ***B*** (often called magnetic flux density).
  This measures the mechanical force experienced by a current-carrying conductor in a magnetic field
- Magnetic field strength, ***H*** (often called magnetizing force, magnetizing field or magnetic intensity).
  This measures the ability of an electric current to produce magnetic induction at a given point
- Magnetic constant, Γ_m (for air or vacuum, $\Gamma_m = \mu_0 = B/H$).
  This is the ratio of the magnetic induction to the corresponding magnetic field strength in a material or in a vacuum. The magnetic constant also is called *permeability*, and μ_0 is the permeability of free space.

The units of measure for these magnetic quantities are given in Table 1. One of the unfortunate results of early studies of magnetism was the naming of these units of measure. The name magnetic field strength for H probably is more appropriate to B, the magnetic induction. Magnetic field sensors actually measure the induction of the field. A typical sensor can be thought of as the secondary of a transformer in which the Earth's core is the primary.

Another difficult legacy arises from the various systems of units. In the CGS (centimetre, gram, second) system, H and B have identical values but, of course, different units. In the SI (International System of Units), B and H are in the ratio of $4\pi \cdot 10^{-7}$ H/m. One of the additional problems associated with the use of magnetic units is that the simple ratio relationships mentioned here are true only in air and vacuum and where ferromagnetic materials are not involved.

[1] For example, see www.reeve.com/SAM/SAM_simple.html and www.sam-magnetometer.net/

Table 1 – Magnetic quantities and units of measure

Quantity	Common unit	Alternate units and remarks	Dimensions
B	tesla (T)	gamma (= 1 nT = 10^{-9} T) weber/m^2 (= 1 T) gauss (= 100,000 nT)	$M \cdot T^{-2} \cdot I^{-1}$
H	ampere-turn/meter (A/m)	oersted (= $10^3/4\pi$ A/m)	$I \cdot L^{-1}$
Γ_m	henry/metre (H/m)	In air or vacuum, $\Gamma_m = \mu_0 = 4\pi \times 10^{-7}$ H/m	$L \cdot M \cdot T^{-2} \cdot I^{-2}$

Table notes:

1. Confusion often arises in the use of units for magnetic induction B and magnetic field strength H. In the science of geomagnetism, the magnetic field strength frequently is expressed in units of gauss despite international agreement in the International System of Units (SI) to use ampere-turn/meter. Also, in geomagnetism a smaller unit, lower-case gamma (γ) frequently is used with long-term (secular) and transient variations. 1 γ = 1 nT
2. Dimensions are mass (M), time (T), current (I), and length (L)

The Magnetic Dipole

Theoretical and experimental studies have shown that the magnetic properties of materials result from the motions of electric charges within them, either rotation in orbits or spins about their axis. These motions constitute electric currents and thereby produce magnetic fields.

In electricity the simplest structure is the isolated charge. If two opposite charges are placed near each other, they form an electric dipole, characterized by an electric dipole moment. The electric dipole moment indicates the orientation of the charges. In magnetism, isolated magnetic poles apparently do not exist, and the simplest magnetic structure is the magnetic dipole, characterized by a magnetic dipole moment, or just magnetic moment. The Earth's magnetic field, as measured at the surface, is very similar to the field from a magnetic dipole (Fig. 2).

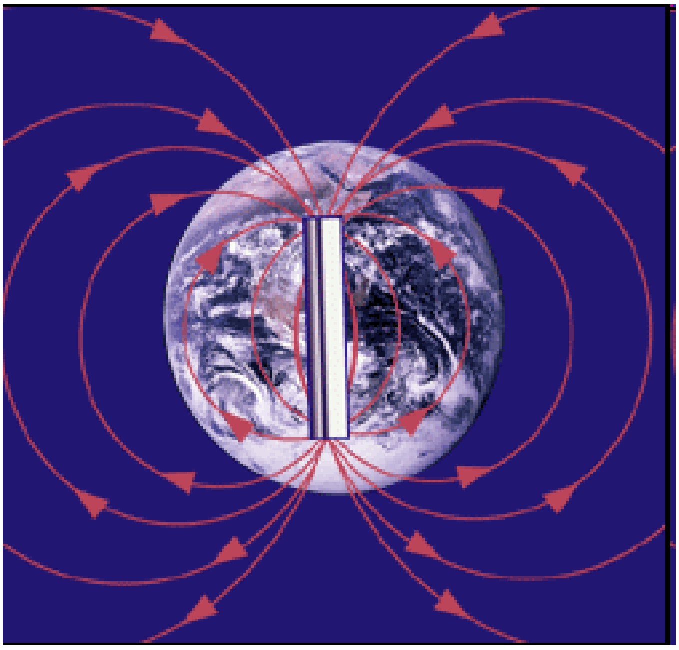


Fig. 2
Earth's magnetic field at the surface is much like a magnetic dipole indicated by the bar magnet at the Earth's center. Image source: NASA

The magnetic moment is a vector pointed along the spin axis or normal to the orbital plane. Its magnitude is the product of the equivalent current and the area enclosed by its path. The magnetic moment of a body is the vector sum of its internal moments. Various symbols have been used for the magnetic moment including *M*, *m* and μ. The units are ampere-meter^2 (A-m^2) and dimensions are $I \cdot L^2$.

A loop of wire or solenoid carrying an electrical current and a bar magnet are examples of magnetic dipoles. The magnetic induction, B, due to a dipole at a distant point along its axis in line with the magnetic north and south poles, in terms of the dipole moment, is

$$B = \frac{\mu_0 \cdot M}{2 \cdot \pi \cdot r^3}$$

where B = magnetic induction (T)

μ_0 = magnetic constant (H/m)

M = magnetic moment (A–m^2)

r = distance from dipole center (m)

The magnetic induction at a distant point along a magnetic dipole's perpendicular bisector (magnetic equator) is

$$B = \frac{\mu_0 \cdot M}{4 \cdot \pi \cdot r^3}$$

The foregoing equations show that the magnetic induction drops quite rapidly with distance from the magnetic dipole center. For example, if we double the distance, the magnetic induction is reduced by a factor of 1/8. We can rearrange the second equation to calculate the approximate dipole moment of the Earth's field at the equator. The average magnetic induction (B) at the equator is approximately 31,000 nT and the Earth's radius is approximately 6,378 km. Substituting these values

$$M = \frac{4\pi \cdot r^3 \cdot B}{\mu_0} = \frac{4\pi \cdot \left(6.378 \cdot 10^6\right)^3 \cdot 3.1 \cdot 10^{-5}}{4\pi \cdot 10^{-7}} \approx 8 \cdot 10^{22} \text{ A–m}^2$$

If we assume the outer core is a single turn conductive iron loop, we can calculate the current in that loop from

$$I = \frac{M}{\pi \cdot r_{OC}^2}$$

where M was previously calculated and r_{oc} is the radius of the Earth's outer core, around 3,000 km. With these simplifying assumptions, the current in the core is on the order of $2.8 \cdot 10^9$ A (2.8 billion amperes).

The Magnetic Environment

In our universe, magnetic field amplitudes range over many orders of magnitudes (Table 2). Although our main concern is the Earth's magnetic field, it is interesting and instructive to also consider extraterrestrial magnetic fields. In the far reaches of outer-space, the inter-stellar medium (ISM), a small magnetic field exists due to the polarization of light by magnetically oriented dust particles. The magnetic induction is on the order of 1 nT, or about one-billionth that of the strongest permanent magnets on Earth.

Within the solar system, the inter-planetary medium (IPM), the Sun's magnetic field is on the order of 5 nT at a distance of 1 astronomical unit (AU), the average distance of the Earth to the Sun (approximately 150 million km). This magnetic field is caused by the plasma – neutral hydrogen atoms, protons and electrons – that makes up the solar wind. The orientation of this field is away from or toward the Sun and is heavily influenced by solar activity such as sunspots, coronal mass ejections (CME), coronal hole high-speed streams and certain types of solar flares.

Table 2 – The magnetic field environment

Environment	B (T)
Surface of neutron stars	10^{8}
Pulsed electromagnets	10
Strongest permanent magnets	1
Refrigerator magnet	10^{-2}
Sun's magnetic field at poles	10^{-2}
Jupiter's magnetic field at poles	10^{-3}
Earth's magnetic field at poles	10^{-4}
Stray fields from electric machinery	10^{-5}
Urban magnetic noise level	10^{-6}
Inter-stellar medium	10^{-9}
Magneto-cardiograms	10^{-10}
Heartbeat	10^{-11}
Human brain	10^{-12}

The Earth's main magnetic field creates a volume called the *magnetosphere* in the space surrounding the Earth (Fig. 3). Without the solar wind, the shape of the magnetosphere would be the shape of the undisturbed dipole field in space. However, the solar wind compresses the side toward the Sun to about 10 Earth radii and stretches it like a tail on the other side to more than 100 Earth radii. The magnetosphere deflects the flow of most solar wind particles around the Earth. However, some charged particles are trapped and guided by the magnetosphere causing aurora in a halo-shaped region around the poles (*auroral zone*). The magnetic induction in the magnetosphere varies from around 10 nT to 60,000 nT.

Closer to the Earth, the Van Allen radiation belts extend from around 3 to 10 Earth radii and consist of a torus of charged particles (protons and electrons) that move along the Earth's magnetic field lines and are reflected back and forth by the high-intensity fields near the north and south poles. The outer Van Allen belts derive their energy from the solar wind. The system circulates along the geomagnetic equator causing a *ring current*. These currents generate their own magnetic field, which can be as strong as 80 nT. [Backus]

The ring current systems are called *electrojets*, an analogy with the jet streams in the stratosphere. Equatorial electrojets are associated with quiet solar magnetic variations (termed *Sq*) and lunar daily magnetic variations (termed *L*) and are considered to be special features of the transient magnetic variations in the Earth's equatorial region.[Chapman]

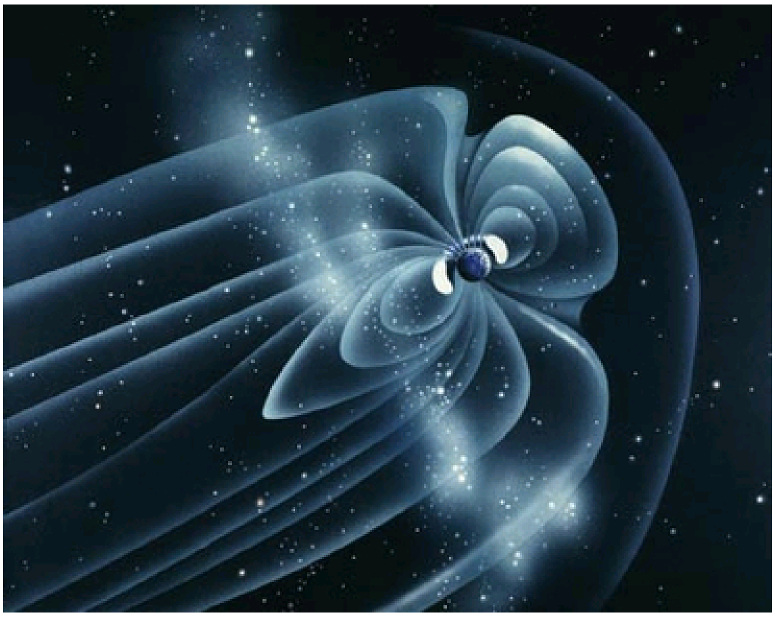


Fig. 3

The Earth's magnetosphere and effects of the solar wind. The Earth is the small globe in the middle-right. The Sun (not shown) is approximately 150 million kilometres away. The magnetosphere is compressed by the solar wind shock wave on the sunlit side (from upper-right corner). The magnetosphere's tail is pushed out on the night-time side around 100 Earth radii (toward lower-left corner). The Van Allen belt is the white torus around the Earth. (Image source: NASA)

Even closer to the Earth, the Sun's ultraviolet light ionizes the outer regions of the Earth's atmosphere on its sunlit side causing it to be much more conducting than the nighttime side. The *ionosphere* extends from as low as 50 km to as high as 1000 km above the Earth's surface. Strong electric currents circulate in the sunlit hemisphere with a westward drift. On the Earth's surface, the current system associated with this component of the magnetic field follows the Sun as it passes overhead.

On the Earth's surface, the field consists of several components, the largest of which is the *main field* or dipole field generated within the Earth itself. This ranges from around 20,000 to 65,000 nT depending on the location. Other components, which can make up as much as 10% of the total measured field at the surface, are described later. Under the surface, the magnetic field gets stronger as the observer moves toward the Earth's core, the source of the main field.

Time Scales

The Earth's magnetic field varies over an extraordinary large span of time scales, from femtoseconds ($10^{-15}s$) to millions or billions of years (10 petaseconds, or $10^{15}s$). The very short time variations are due to sunlight and are of little interest in the study of geomagnetism.

Our interest starts with a time period on the order of milliseconds ($10^{-3}s$). The magnetic field sporadically oscillates with amplitude of a few nanoteslas and frequency in the kilohertz range. The induced electric emissions from these oscillations can be fed into a speaker or headphones and are found to have a falling tone. Because of this tonal nature, they are called *whistlers*. Each whistler is the result of a lightning stroke at the other end of the magnetic field lines passing through the observer's detector. The lightning produces a radio wave pulse in the ionosphere that travels along the field line. The frequency components of the pulse disperse as it propagates and its higher frequencies arrive first followed by progressively lower frequencies.

The solar wind excites charged particles in the magnetosphere at their resonant frequencies. These are called *micropulsations* and they have periods of 1 to 300 seconds. Micropulsations can last for several hours and have amplitudes of a few nanoteslas.

As mentioned previously, ring currents follow the Sun as it moves through the sky. An observer at a fixed location would measure a daily variation in the magnetic field. This *diurnal* variation is particularly noticeable on magnetically quiet days. There also are seasonal variations due to the change in the Sun's position, as seen by a fixed observer on Earth, as the Earth orbits the Sun. These variations are quite subtle and required years of observation and study to find.

Observers notice that measurements of the Earth's magnetic field vary with a period of about 27 days, corresponding to the average rotation rate of the Sun itself. In particular, when there are active sunspots, the Earth's field may experience wild gyrations due to coronal mass ejections and other activity on the Sun. These tend to recur with a 27 day period as sunspots and coronal holes rotate with the Sun. Depending on the location and the intensity of the solar activity, the magnetic field variations at the Earth's surface can reach 2,000 nT. The number of sunspots visible on the Sun follows an approximate 11-year cycle (Fig. 4-left). A new 11 year sunspot cycle begins when the magnetic polarity of the sunspots has reversed from the previous cycle. The polarity reversal cycle requires 22 years to complete and is called the solar magnetic cycle (Fig. 4-right). Observers see variations in the Earth's magnetic field corresponding to these periods.

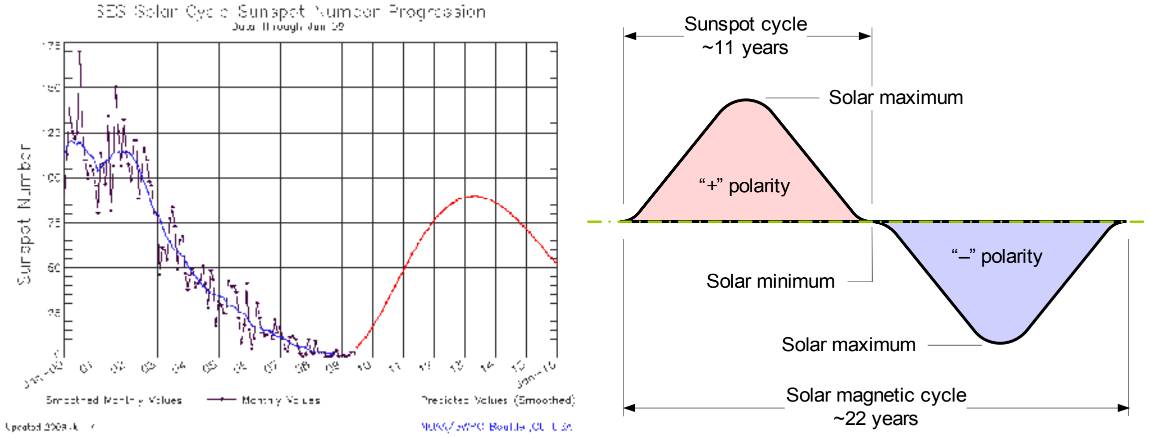


Fig. 4

(Left) Most recent 11 year sunspot cycle and predicted next cycle. (Right) 22 year solar magnetic cycle. Sunspot cycles vary in length and intensity

All magnetic field variations discussed so far are related to solar or lightning activity and, with the exception of the sunspot cycle and solar magnetic cycle, have periods less than one year (Fig. 5). The Earth's magnetic field also varies over longer time periods due to sources within the Earth. These are called *secular variations* and are observed as a steady increase or decrease of magnetic field amplitudes at an observatory amounting to a few nanoteslas per year. Secular variations can be modeled by a quadratic polynomial in time.

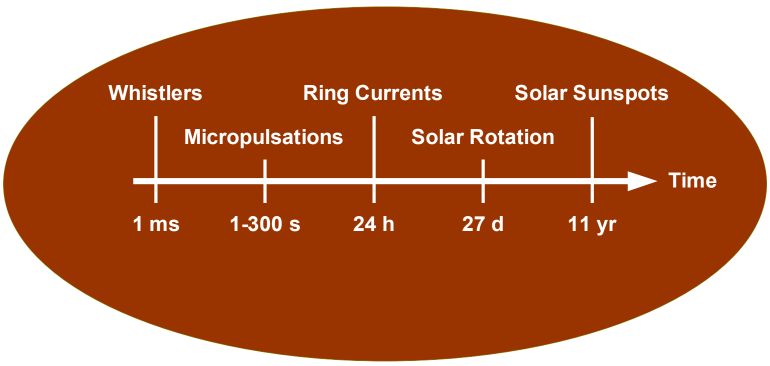


Fig. 5

Geomagnetic field time scales for external geomagnetic field influences

Occasionally, the slope of the secular drift changes rather suddenly; that is, the change takes place in a time period less than one year (Fig. 6). These *magnetic jerks* do not occur periodically, the most recent occurred in 1969, 1979, 1992 and 2003. It is thought they may be caused by differential movement between the Earth's core and the outer crust. The 1969 magnetic jerk was not a global phenomenon. It was quite clear in Europe but undetectable at most observatories in North America.

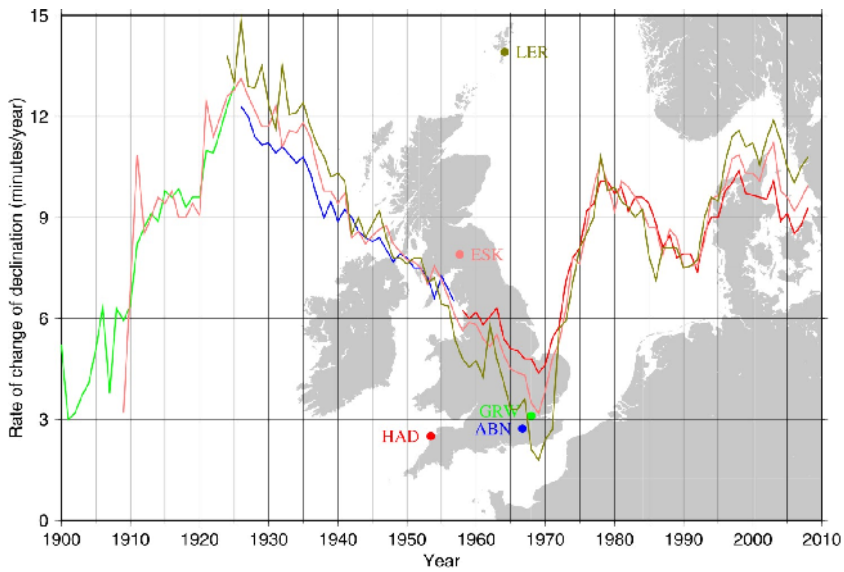
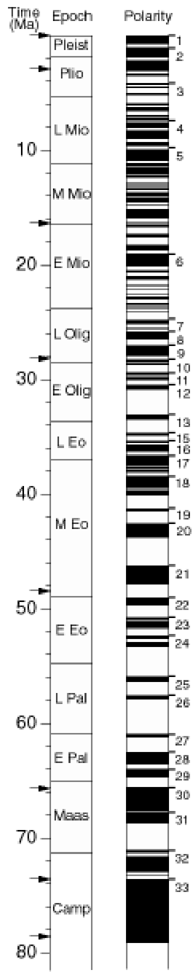


Fig. 6

Secular variations and magnetic jerks. The magnetic field slowly drifts but occasionally the drift direction changes suddenly (within a one year time period) as shown here for three observatories in the United Kingdom. Image source: British Geological Survey

The Earth's field experiences a slow westward drift. The drift rate corresponds to a complete circuit around the Earth in about 700 to 2000 years (depending on who is making the calculation), although it is unlikely that any individual feature of the field survives that long. The Earth's field also changes in such a way that its polarity reverses at apparently random times (Fig. 7). The reversals have occurred as frequently as every 10,000 years and as infrequently as every 50 million years. Over the last 25 million years reversals have had an average period of about 100,000 years. However, geological evidence indicates the rate has increased and decreased with a characteristic time of around 100 million years.

Fig. 7 (right) Geomagnetic field reversals over the last 80 million years. Geomagnetic field reversals during the last 25 million yr have occurred at an average rate of about once every 100,000 yr. Image source: US Geological Survey



Basic Characteristics

The Earth's magnetic field consists of *internal* and *external* components. The internal, or main, magnetic field is fairly steady when measured over time periods of days or months but its changes are quite significant when measured over periods of years and centuries. The Earth's field also includes external components that represent up to around 10% of the total field measured at the Earth's surface.

The external field is considered to consist of three separate components: 1) magnetospheric current systems at the magnetopause (boundary between the magnetosphere and the surrounding inter-planetary medium or plasma); 2) magnetospheric currents at the surface that separate the two lobes of the magnetosphere's tail; and 3) a current system above the Earth's equatorial region (ring current). Investigators believe the ring current is caused by charged particles in the solar wind that are trapped by the geomagnetic field, enhancing the plasma in the Van Allen belts. The charged particles spiral around and along the magnetic field lines between northern and southern latitudes. Their net motion is mainly westward and equivalent to an electric current in a ring around the Earth.[Chapman]

The external field varies diurnally on the order of a few tens of nanoteslas (Fig. 8) and also experiences seasonal variations. It is the external field that is most affected by solar activity. Magnetic storms associated with the external field last minutes to days with variations of hundreds to thousands of nanoteslas. Some variations are so subtle that they were detected or put on a firm basis only by very detailed and pioneering statistical analysis by S. E. Forbush over a period of many years. [Van Allen]

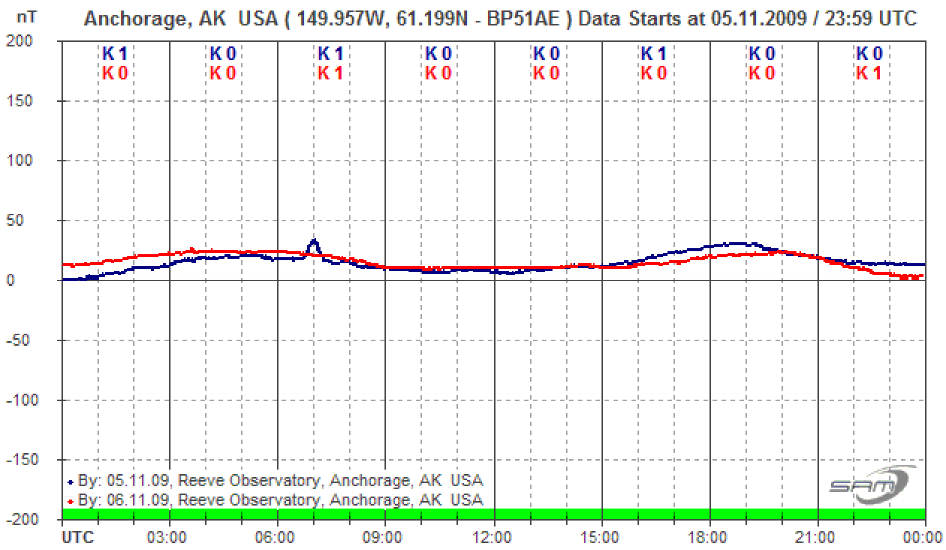


Fig. 8

Diurnal variations in the geomagnetic field on magnetically quiet days in November 2009 at Anchorage, Alaska USA. The "swelling" of the field in the sunlit hemisphere is apparent from around 1600 to 2200 UTC. sunrise and sunset on the days shown were approximately 1640 and 0045 UTC, respectively. The daytime peak migrates back and forth with the seasons.

Another component of the Earth's magnetic field is the anomalous, induced magnetic field. This is magnetization induced in the Earth's crust by the main and external fields and also remnant magnetization in ferromagnetic materials in the upper crust (for example, iron ore deposits). In most places, the induced field is considerably smaller than the other components, but there are locations, for example, along the Aleutian Islands and Southeast Alaska coasts where compass navigation is impaired due to the anomalous field (Fig. 9).

Fig. 9

Anomalous field on the south coast of Unalaska Island in Alaska's Aleutian Island Chain (see mariner warning at lower-right). Image source: US Geological Survey

The Earth's core is thought to consist of two layers of iron-nickel (Fig. 10-left). The inner core is solid due to the high pressure from gravity but the outer core, or layer, is liquid. The solid inner core rotates with respect to the outer core and mantle. The temperature gradient between the top and bottom of the outer layer is large enough to cause convection (Fig. 10-right).[Karttunen] The exact mechanism that produces the Earth's magnetic field is unknown, but all the components for producing it are in the core – a rotating conductor (inner core) and strong electrical currents (outer layer).

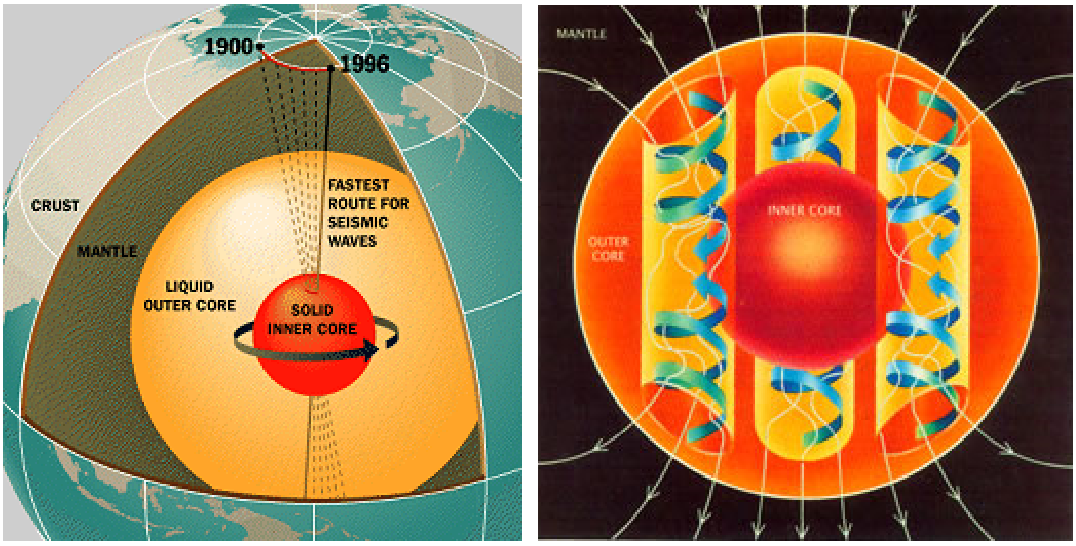


Fig. 10

(Left) Earth's core is thought to consist of two layers of iron-nickel. (Right) Convection currents in the Earth's core are thought to be part of the process that produces the geomagnetic field. Image source: NASA

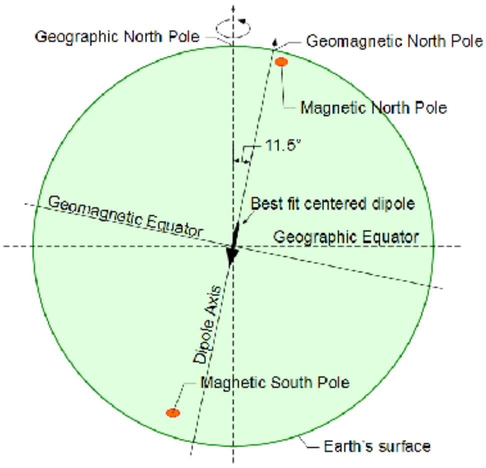


Fig. 11

Alignment of the best-fit centred dipole gives a tilt of 11.5 degrees. The difference between the field from a centred dipole and the Earth's actual field can be reduced by offsetting the dipole slightly. Note that the Magnetic North and South Poles are not collocated with the Geomagnetic North and South Poles based on the dipole model (see text).

As previously mentioned, the Earth's magnetic field is roughly equivalent to the field of a magnetic dipole. The dipole is not aligned with the Earth's geographic poles but is tilted. If the dipole is assumed to be at the Earth's centre, the best approximation is obtained with the dipole axis tilted about 11.5° (Fig. 11).

The dipole is not centred, and the geographic location of the magnetic North Pole is not on the exact opposite side of the Earth from the magnetic South Pole. The discrepancies between the centred dipole and the Earth's actual field can be reduced by fitting an eccentric dipole. In 2005 the location of the centre of the eccentric dipole, sometimes known as the magnetic centre, was at approximately r, ϕ', λ = 552 km, 22.2°N, 141.6°E, where r is the dipole's distance from the Earth's geographic centre, and ϕ' and λ are its geographic latitude and longitude.[2]

The Earth's magnetic north and south poles are not collocated with the north and south poles associated with the best-fit dipole field. The magnetic north and south poles are where the field lines are vertical (magnetic inclination is +90 degrees). This also is called the *magnetic dip pole*. The north and south poles associated with the best-fit dipole field are based on models such as the International Geomagnetic Reference Field (IGRF) models (for example, the Centred Dipole model and Eccentric Dipole model). These are *computed* pole positions and may be quite different than the actual measured dip pole.

The average magnetic induction at the Earth's equator is ~31,000 nT. Over the Earth's surface, the field varies from about 20,000 to 65,000 nT depending on the location (Fig. 12). As mentioned above, the field is not constant over time. It varies on a daily basis and on a long-term basis (secular variations). Long-term variations include complete reversals and wandering of the magnetic poles (Fig. 13). In 2001 the North Pole was moving northwest at a rate of about 40 km/yr. Between 2001 and 2005, the North Pole moved from 81.3°N : 110.8°W to 82.7°N : 114.4°W, a great circle distance of about 165 km. Of course, the South Pole wanders as well; however, its movement over long periods is not as well studied as the North Pole. An interesting animation of the field changes and pole wandering can be found at geomag.usgs.gov/faqs.php. Paleomagnetism studies have shown that, at least for the last 2,000 years, the average position of the geomagnetic poles is indistinguishable from the geographic poles.[3]

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[2] Calculations from www.ngdc.noaa.gov/geomag/faqgeom.shtml

[3] Paleomagnetism is the study of the magnetic properties of rocks and minerals

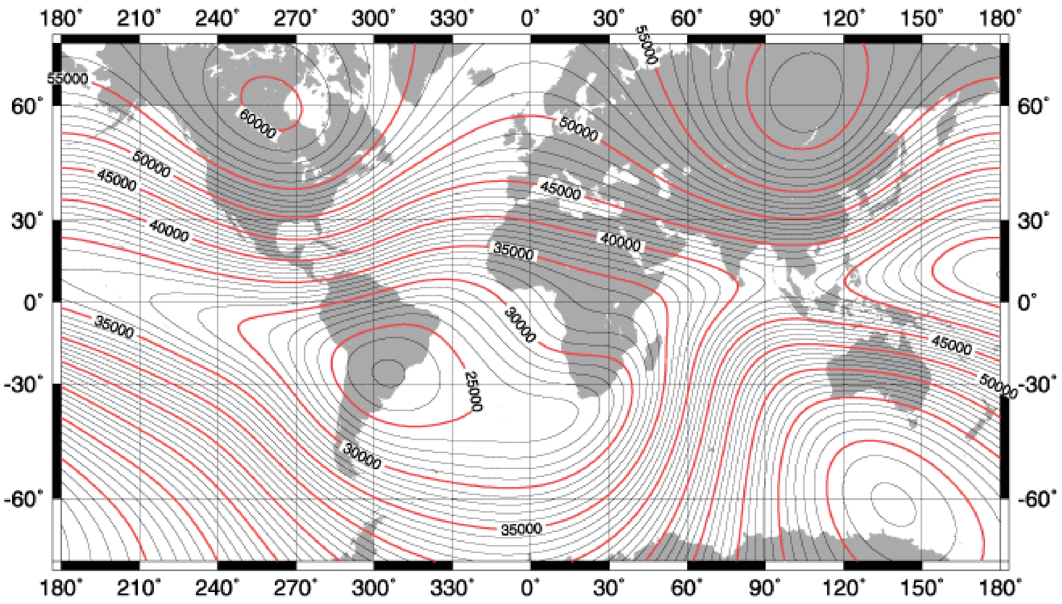


Fig. 12
Earth's Total Magnetic Field in nT in the year 2000. Note the geomagnetic equator passes through the middle of South America considerably south of the geographic equator and is north of the geographic equator in the Pacific Ocean. (source: National Geophysical Data Center, NOAA, www.ngdc.noaa.gov/geomag/)

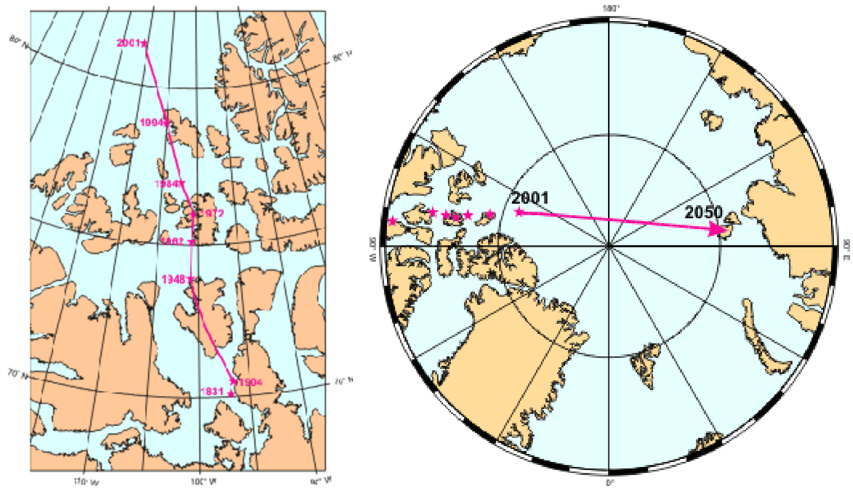


Fig. 13
(Left) Geomagnetic north pole movement through northern Canada between 1831 and 2001. (Right) Future estimate. In the right image, the converged black lines indicate the geographic North Pole. Image source: Geological Survey of Canada

Because the dipole's north and south poles presently are not in the same location as the Earth's geographic poles, geomagnetic and geographic coordinates on the Earth's surface are considerably different. To provide a consistent framework for study of the Earth's field, a system of geomagnetic coordinates has been defined based on the intersections of the dipole axis with the Earth's surface. The geographic coordinates of the geomagnetic north and south poles presently are 79.7 °N : 71.8 °W and 79.7 °S : 108.2 °E. Since the geomagnetic poles are slowly moving, the coordinates are redefined at 5 year intervals (based on the International Geomagnetic Reference Field, presently IGRF-10). A coordinate system converter can be found online.[4] For example, the geographic and geomagnetic coordinates for the Reeve Observatory at Anchorage, Alaska USA in June 2010 were

Geographic: 61.19928 °N : 149.95652 °W

Geomagnetic: 61.74 °N : 263.80 °E

Investigators noticed geomagnetic variations corresponded to the Sun's rotation period. The rotation period was first studied by Richard Carrington in the 1850s and found to be 27.2753 days. Since the Sun is gaseous, has no permanent points of reference and rotates differentially (upper latitudes rotate slower than lower latitudes), this period is an average.

Julius Bartels studied the correspondence between the Sun's rotation and the geomagnetic field and in 1934 conceived a system of rotation numbers based on an even 27-day period. [Bartels-34] He assigned Day 1 of Rotation 1 to February 8, 1832 (for reference, day 1 of Rotation 1001 was January 17, 1906 and day 1 of Rotation 2400 was June 12, 2009). He then plotted the Sun's activity based on the 3-hour K-index for each rotation number. This was called the Bartels Diagram, also called Bartels Musical Diagram because of its appearance (Fig. 14).

One problem with using the Bartels Rotation Number system is that it is like a calendar with no leap years – it falls out of synchronization over time. A more accurate rotation system is based on the Carrington period mentioned above. Carrington Rotation Number 1 started November 9, 1853.

[4] wdc.kugi.kyoto-u.ac.jp/igrf/gggm/index.html

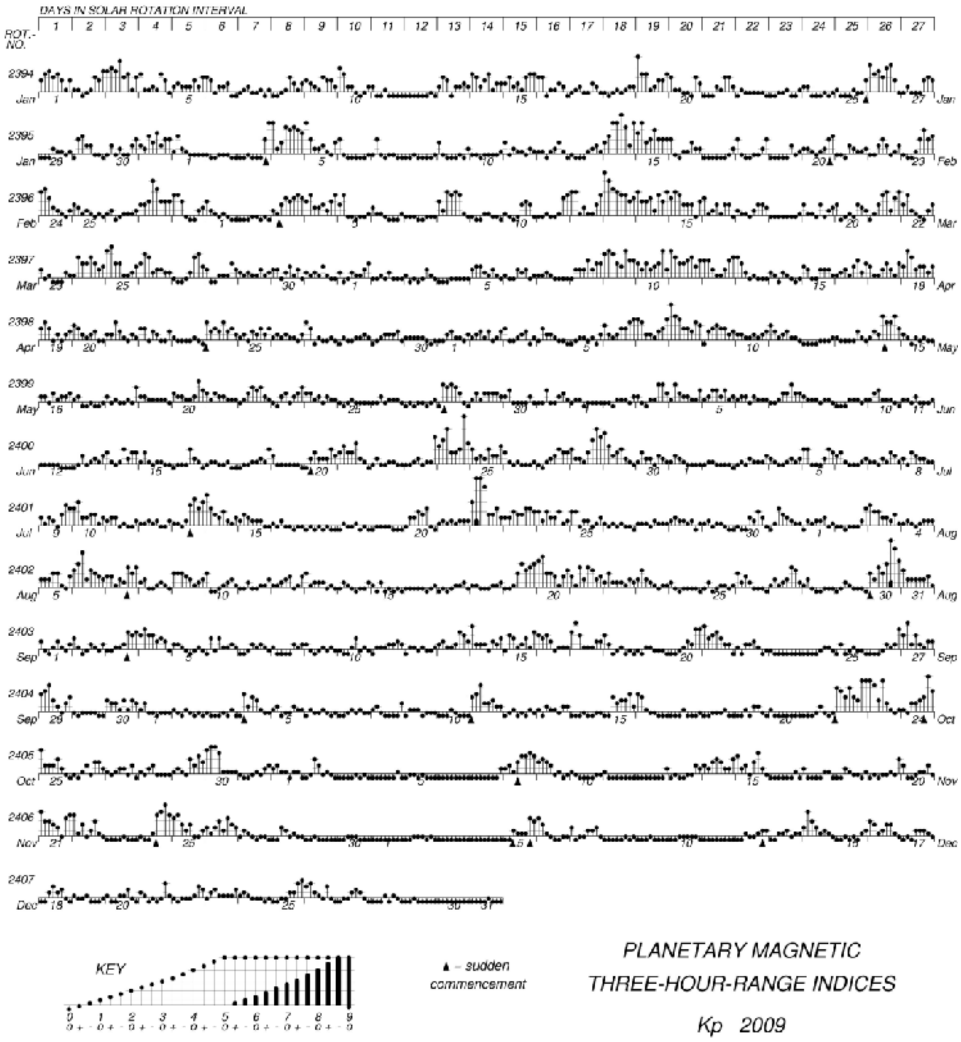


Fig. 14

Bartels Diagram for 2009. The 1st through 27th day of each rotation are shown at the top with the corresponding K-index value for each rotation in a column immediately below. Image source: wdc.kugi.kyoto-u.ac.jp/kp

Geomagnetic Field Parameters

According to the National Geophysical Data Center (NGDC)[5], the Earth's magnetic field is described by seven parameters (Fig. 15):

- Declination (*D*, + east of north, angular measurement in degrees)
- Inclination (*I*, + down, angular measurement in degrees)
- Horizontal intensity ($H = \sqrt{X^2 + Y^2}$, amplitude measurement in nT)
- North component of horizontal intensity (*X*, + north, amplitude measurement in nT)
- East component of horizontal intensity (*Y*, + east, amplitude measurement in nT)
- Vertical intensity (Z, + down, amplitude measurement in nT)
- Total intensity ($F = \sqrt{H^2 + Z^2} = \sqrt{X^2 + Y^2 + Z^2}$, amplitude measurement in nT)

Anyone who reads literature associated with geomagnetism soon realizes there are other, often confusing, parameters used to describe the Earth's field. For example, some observatories use D in nT to indicate the horizontal component aligned with geomagnetic East-West while others use D to indicate Declination in degrees. Geomagnetic literature often lacks symbol and parameter definitions and inconsistent use of units of measure, reflecting the confusion mentioned in Sect. II.

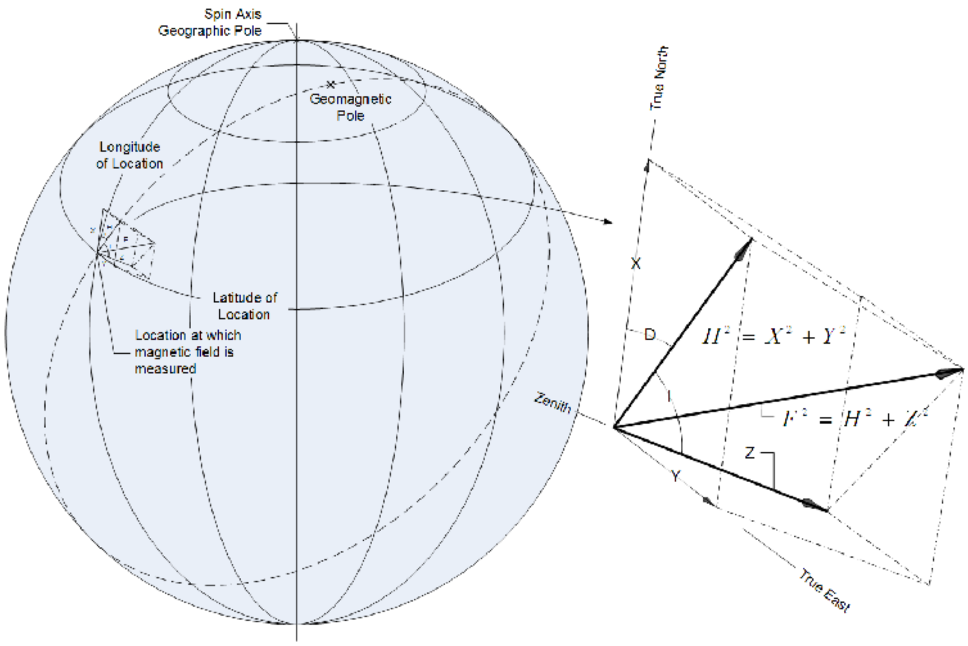


Fig. 15

Schematic of the seven magnetic field parameters defined by the NGDC

[5] www.ngdc.noaa.gov/geomag/faqgeom.shtml

The NGDC calculator gave the following values for March 2, 2010 at the Reeve Observatory in Anchorage (geographic coordinates 61.199 N : 149.956 W):

- Declination, D = 18.97° changing by –0.307 °/year
- Inclination, I = 74.144° changing by –0.012 °/year
- North component, X = 14,416.14 nT changing by +16.27 nT/year
- East component, Y = 4,955.46 nT changing by -80.63 nT/year
- Horizontal Intensity, H = 15,244.07 nT changing by –10.6 nT/year
- Vertical component, Z = 53,669.56 nT changing by +5.27 nT/year
- Total Intensity, F = 55,792.5 nT changing by +2.18 nT/year

As seen in this data, the vertical component at this observatory is, by far, the largest; the total intensity vector is only about 16° from vertical.

Anyone who reads literature associated with geomagnetism soon realizes there are other, often confusing, parameters used to describe the Earth's field. For example, some observatories use D in nT to indicate the horizontal component aligned with geomagnetic East–West while others use D to indicate Declination in degrees. Geomagnetic literature often lacks symbol and parameter definitions and inconsistent use of units of measure, reflecting the confusion mentioned in the section on Units of Measure.

Readers may encounter various coordinate systems:

- Geographic coordinates – North (X), East (Y), Vertical down (Z)
- Geographic coordinates – Horizontal intensity (H), Declination (D), Vertical down (Z)
- Geomagnetic coordinates – Magnetic north (H), magnetic east (D), Vertical down (Z)

Geomagnetic sensors typically are setup as follows: during initial setup the magnetic sensor axes are oriented in either the geographic or local magnetic coordinate system (that is, with respect to true north and east or with respect to local magnetic north and east). The vertical sensor axis always is exactly vertical.

The Earth's main (dipole) field is constantly changing so the geomagnetic coordinate system also changes over time. Using the two horizontal components the observatory determines a slowly varying time dependent declination angle and subsequently rotates the horizontal components into a local magnetic coordinate system for which the magnetic east component (E) is minimized and the magnetic north component (N) is maximized. Note that geomagnetic coordinates are labeled H, D and Z although the units of the D-component can be magnetic induction in nT or an angle in degrees. Also, the D-component is often found to have a significant offset due to changing field over time.

Geomagnetic Indices

Indices are used in the study of geomagnetism to summarize the large amounts of complex data associated with periodic observations. Many indices have been proposed over the years and several still are in use today. The indices differ in the time scale associated with their determination, for example, hourly, 3-hourly, daily, and so on. We will spend the most time discussing the K-index because it is the most common. We will discuss the related G-scale and Ap-index at the end of this section. An excellent description of geomagnetic indices is found in [Mayaud] and a more detailed description of indices derived from the K-index is found in [Menvielle].

The K-index is an approximately logarithmic measure of magnetic disturbances and consists of ten values, K0 through K9. It is related to the *peak-to-peak* fluctuations of the horizontal magnetic field component observed on a magnetometer during a three-hour interval relative to a quiet day. The vertical component (Z) is excluded from the K-index because it is more affected by underground-induced effects and by field sources farther from the station. The three-hour intervals correspond to Universal Coordinated Time (UTC) 0000 – 0300, 0300 – 0600, . . . , 2100 – 2400.

The conversion from maximum fluctuation in nT to K-index varies from observatory to observatory in such a way that the historical rate of occurrence of each K-index value is about the same at all observatories. The K-index was introduced in 1939 by Julius Bartels. [Bartels-39]

Observatories at higher geomagnetic latitudes routinely experience wider magnetic field fluctuations than lower-latitudes observatories (Fig. 16); therefore, the magnetic field amplitude range corresponding to each K-index value at these higher latitudes is wider. The K-index values also depend on magnetic longitude. Dirk Lummerzheim, Research Professor at Geophysical Institute, University of Alaska – Fairbanks, said "If an existing sensor station is moved across town, it would have a new K-index."[6] The K-index only can be determined from statistical analysis of data from a long observing period. There is no formula that can be used to determine the limits for the K-index values based on latitude and longitude.

[6] Personal communications May 8, 2009.

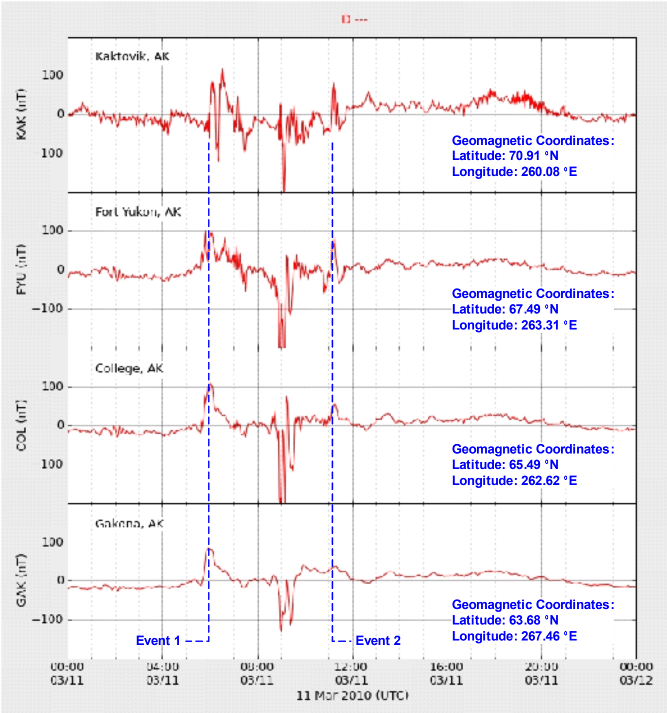


Fig. 16

Geomagnetic variations are more pronounced at high-latitude observatories. These magnetograms show the E-W component for some of stations in the Alaska Magnetometer Chain. The stations are at approximately the same longitude and separated in latitude by about 2 degrees. Two events are marked to illustrate the increase in activity with latitude. Also, it is apparent that the overall charted activity is noisier as latitude is increased.

A table is assigned to each observatory, giving the limits, or range, corresponding to each of the ten values of K. The lower limit for K = 9 is 100 times the upper limit for K = 0. The lower limit for K = 9 at a given station generally, but not always, has one of the following values: 300, 350, 500, 600, 750, 1000, 1200, 2000, or 2500.[7] The first applies to magnetically quiet very low latitude observatories, and the last applies to the most disturbed stations in the auroral zone at northern latitudes. The limit 500 is apprpriate for mid-latitude stations at about geomagnetic latitude 50°. The K-index table for this latitude is shown in Table 3, left panel.

[7] These values were used when the number of observatories was small. There are no apparent limitations in the use of intermediate values in modern magnetometer networks.

Table 3 - K-index values for various K9 limits

Mid-latitudes ~50 °N K9 > 500		Example K9 > 1000		College, Alaska ~65 °N K9 > 2500	
K	**Range (nT)**	**K**	**Range (nT)**	**K**	**Range (nT)**
K0	0 - 5	K0	0 - 10	K0	0 - 25
K1	5 - 10	K1	10 - 20	K1	25 - 50
K2	10 - 20	K2	20 - 40	K2	50 - 100
K3	20 - 40	K3	40 - 80	K3	100 - 200
K4	40 - 70	K4	80 - 140	K4	200 - 350
K5	70 - 120	K5	140 - 240	K5	350 - 600
K6	120 - 200	K6	240 -400	K6	600 - 1000
K7	200 - 330	K7	400 - 660	K7	1000 - 1650
K8	330 - 500	K8	660 - 1000	K8	1650 - 2500
K9	> 500	K9	> 1000	K9	> 2500

It can be seen that the ranges double for K = 0 through K = 3. The ranges then increase more slowly because, if doubled, the index would become too coarse and the higher indices, K = 8 and K = 9, never would be reached. For other geomagnetic latitudes, the range limits are scaled up or down proportionately to the lower limit for K = 9. For example, if the lower limit for K = 9 is 1000, then the K-index range is as shown in the middle panel of the table. For College, Alaska, at 65.48°N geomagnetic latitude, about 400 km north of the Reeve Observatory in Anchorage, the lower limit for K = 9 is 2500 and is shown in the right panel.

The weighted average of the K-index values for a network of geomagnetic observatories is used to derive a *planetary* K-index, or Kp-index. There are two Kp indices in use today. One is an estimated Kp-index determined by the Space Weather Prediction Center[8] and the other at the international level by the Helmholtz Centre in Potsdam[9].

The Potsdam Kp-index is based on 13 observatories around the world. It is not reported in real time and cannot be used for space operations where there is a need for immediate warning of geomagnetic disturbances related to solar events. Therefore, the Space Weather Prediction Center uses near real-time estimates from the US Air Force based on a network of observatories, most of which are in North America.

[8] www.swpc.noaa.gov/info/Kindex.html

[9] www-app3.gfz-potsdam.de/kp_index/index.html

Amateur radio astronomers may not be interested in or equipped to perform the detailed analysis required to develop a K-index for their stations. For that type of work an approximation is sufficient. A *local* K-index may be approximated from a nearby magnetometer station that already has a K-index. Alternately, a local K-index may be approximated by using field data from a nearby magnetometer station and working backward from the planetary Kp-index as follows:[10]

- Determine the Kp-index values for several 3-hour time periods over several days. If possible, find a dozen or so periods for each Kp-index value, Kp = 0 through Kp = 9. Days when Kp is high (Kp = 8 and Kp = 9) are relatively rare (a few days in an 11 year solar cycle) compared to lower Kp values, so it may not be possible to find very many times when the Kp-index is high
- Determine the field values (nT) at a nearby magnetometer station corresponding to the same time periods and days.
- For each Kp-index value, compare the range of corresponding field values to the range limits, or multiples of the range limits, described above (the multiple is the same for each Kp-index value and does not have to be an integer)
- Assign the appropriate range limits to each local K-index value so they resemble the Kp-index to the extent possible

The US National Oceanic and Atmospheric Administration (NOAA) simplified the K-index and Kp-index into a G-scale to help people involved in space programs to understand the significance of geomagnetic storms. Variations in the Earth's magnetic field, and particularly magnetic storms, can affect space operations in many ways (discussed in the next section).

The G-scale uses near-real time estimates of the Kp-index and contains five categories (G1 to G5) to indicate geomagnetic storms for space weather reporting purposes (Table 4). The G0 category corresponds to K = 0 to K = 4. It is a below-storm category and not reported. NOAA reports geomagnetic storms on the web.[11]

[10] Dirk Lummerzheim at the Geophysical Institute, University of Alaska Fairbanks suggested this procedure, and it is the one used at Reeve Observatory to set the K-index.

[11] www.swpc.noaa.gov/SWN/index.html

Table 4
NOAA space weather scale for geomagnetic storms. See original source for effects associated with the G-scale. (source: www.swpc.noaa.gov/NOAAscales/index.html#GeomagneticStorms)

Category		**Physical measure**	**Average frequency (1 cycle = 11 years)**
Scale	**Descriptor**		
G5	Extreme	Kp = 9	4 per cycle (4 days per cycle)
G4	Severe	Kp = 8 and 9-	100 per cycle (60 days per cycle)
G3	Strong	Kp = 7	200 per cycle (130 days per cycle)
G2	Moderate	Kp = 6	600 per cycle (360 days per cycle)
G1	Minor	Kp = 5	1700 per cycle (900 days per cycle)
G0	Below storm	Kp = 0 to 4	N/A

Another index that currently is used is the planetary A-index (Ap-index). It is based on the K-index and frequently is mentioned in propagation summaries and forecasts published by the American Radio Relay League (ARRL).[12]

The A-index indicates a daily average level for geomagnetic activity, but it is not a simple average of a set of K-indices because of the non-linear, quasi-logarithmic nature of the K-index. Instead, the K-index is converted to a linear scale called the "equivalent three hourly range" a-index (with a lowercase “a”). The daily A-index is the average of eight "a" indices. The following table illustrates the conversion between K-index and a-index.

K =	0	1	2	3	4	5	6	7	8	9
a =	0	3	7	15	27	48	80	140	240	400

[12] For example, see www.arrl.org/w1aw-bulletins-archive/

An example will illustrate the derivation of the A-index from the K-indices for one day. There are eight K-index values for each 24 hour period. The K-index for each period is converted to an a-index (note lower case) and the eight a-indices are then averaged to find the A-index. The planetary Ap-index takes into account a group of observatories (rather than just one) and actually is calculated as a running average of eight 3-hour periods.

Time period (UTC)	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24
K-index	3	5	7	4	3	2	1	1
a-index	15	48	140	27	15	7	3	3
A-index	(15 + 48 + 140 + 27 + 15 + 7 + 3 + 3)/8 = **32.25**							

The Ap-index and Kp-index are not the only indices used in the study of geomagnetism, but the K-index, by far, is the one most commonly used to describe geomagnetic activity.

Geomagnetic Storms and Disturbances

A geomagnetic storm occurs when there is a period of rapid magnetic field variation. Generally, there are two main causes:

- First, the Sun occasionally emits a *coronal mass ejection* (CME), which is a strong surge in the emission of charged particles with a resulting increase in the velocity and density of the solar wind (Fig. 17). A CME must be directed at Earth for it to disturb the geomagnetic field. When the surge hits the Earth's magnetosphere, usually 3 – 5 days after the solar event, the magnetic field is disturbed and oscillates. This in turn generates electric currents in the Earth's ionosphere and near-Earth space environment. The electric currents in turn generate additional magnetic-field variations. An example of CME impact on the geomagnetic field is shown later in this section;
- Second, large regions on the Sun's corona become cooler indicating that the Sun's magnetic field lines are stretching far out into the inter-planetary medium (Fig. 18). These field lines may directly link with the Earth's magnetic field, a process called *magnetic reconnection*. Charged particles can then travel along the magnetic field lines and enter the Earth's magnetosphere. The resulting current causes the geomagnetic field to vary. An example of the effect of coronal hole high-speed streams on the geomagnetic field was shown in Sect. I. Magnetic reconnection is an ongoing process and the magnitude of its effects depend on plasma pressure, the magnetic field and its direction and other factors. Sometimes the CME and direct linkage occur at the same time leading to a very large geomagnetic storm.

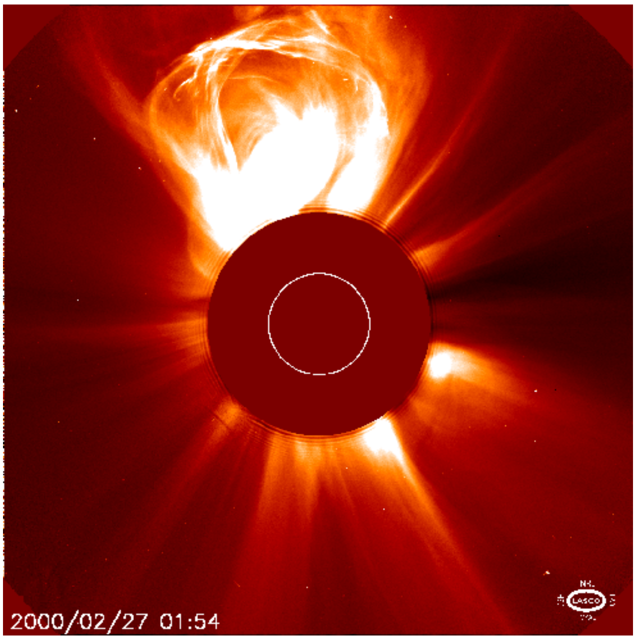


Fig. 17

Coronal mass ejection (CME) in upper part of image. A huge explosion on the Sun ejects charged particles that, when directed at the Earth, interact with and disturb the geomagnetic field. CMEs are often associated with large solar flares. The disk in the center is part of the imaging device, and the white circle in the middle corresponds to the Sun. Image source: NASA

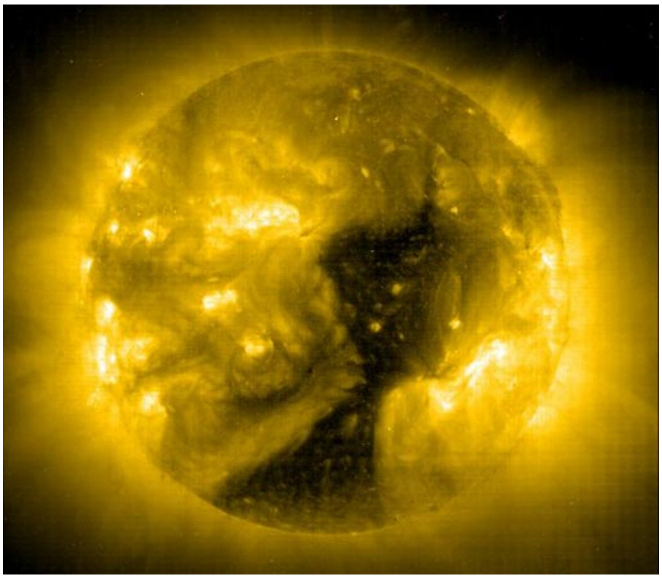


Fig. 18

Coronal hole high-speed stream. The large dark region in the image indicates less dense and colder plasma in the Sun's corona where the solar magnetic field lines are able to stretch far out into the inter-planetary medium. These field lines may connect with the Earth's magnetic field, causing a geomagnetic disturbance. During periods of sunspot minimum, the coronal holes usually are found in the Sun's polar regions, but as solar activity increases the coronal holes can be found at all latitudes. Image source: NASA sunspots indicate solar activity that also can affect the geomagnetic field (Fig. 19). While sunspots themselves do not cause geomagnetic storms (it is the solar activity associated with the sunspots), there is a direct correlation between the sunspot number and geomagnetic activity. sunspot cycles are numbered based on a somewhat arbitrary starting point. The cycles themselves probably have existed as long as the Sun but were not given numbers until the 1700s. Cycle 24 ended in late 2008. Aurora observers have long noted that the brilliance and frequency of aurora is related to the sunspot number.

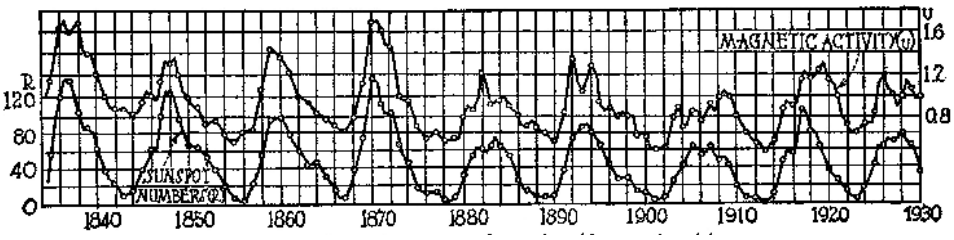


Fig. 19

Correlation between sunspot number and geomagnetic field variation, 1834-1930. This chart from 1934 shows how closely the geomagnetic field changes (upper curve and right-hand scale) correspond to the sunspot number (lower curve and left-hand scale), leaving no doubt that the Sun is responsible. In this chart, the geomagnetic activity is measured by the now obsolete U-index, which is reported in variations of tens of nT.

Image source: [Stetson] fig. 37

Amateur radio astronomers who study and listen for solar emissions and who also monitor the geomagnetic field can attempt to correlate their data; however, due to the varying delays from the time of a solar event to its effect on the geomagnetic field, correlation of individual events is very difficult, particularly when the Sun is active. The time between a solar event and its effect on the geomagnetic field depends on the solar wind speed.

The solar wind speed depends on many factors associated with the sunspot cycle. During the descending and minimum phases of the sunspot cycle, the solar wind is dominated by coronal hole high-speed streams, with speeds in the range of 500 - 800 km/s. The solar wind also has a denser low-speed component with a speed of around 300 km/s associated with the equatorial coronal streamer belt. The overall average speed is in the vicinity of 470 km/s.

The high- and low-speed components form alternating streams in the solar wind flow. They move outward into inter-planetary space in a spiral due to the Sun's rotation. As the streams travel away from the Sun, the high-speed streams overtake the slow-speed flows and create regions of enhanced density and magnetic field called *co-rotating interaction regions* (CIR). When these regions encounter the Earth, they trigger geomagnetic storms that recur with a 27-day period.

In the ascending and maximum phases of the sunspot cycle, the coronal holes shrink and the high-speed flows narrow and weaken resulting in a decrease in the average solar wind speed. At the same time, the ambient solar wind is increasingly disturbed by CMEs. CMEs reach a peak occurrence rate at sunspot maximum and cause non-recurrent geomagnetic storms. The speed of CMEs depends on their characteristics and relative directions to Earth and can vary from a few hundred km/s to over 1,500 km/s (Fig. 20). Therefore, a CME event observed on the Sun may take anywhere from 1 to 9 days to reach Earth, with the average being about four days.

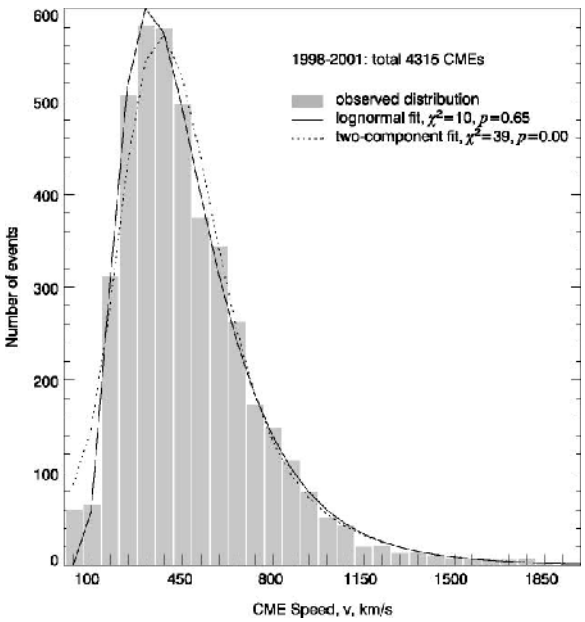


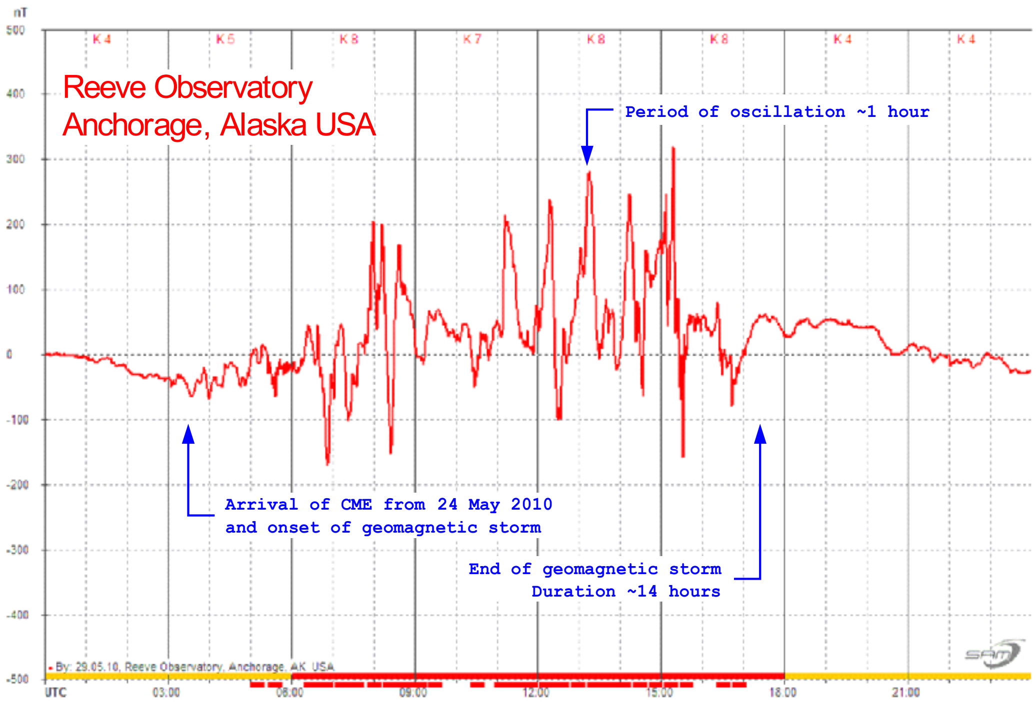
Fig. 20 (left)
Speeds of coronal mass ejections from a study of data from the Large Angle and Spectrometric Coronagraph Experiment on board Solar and Heliospheric Observatory (SOHO/LASCO) spacecraft. Image source: [Yurchyshyn]

From a technical standpoint, the principal defining property of a geomagnetic storm is the creation of an enhanced ring current formed by ions (mostly protons and oxygen ions) and electrons in the 10-300 keV energy range and usually located between 2 and 7 Earth radii. These produce a magnetic field disturbance which, at the equator, is opposite in direction to the Earth's main (dipole) field. The enhanced ring current is primarily caused by strong dawn-to-dusk electric fields associated with the movement of southward-directed inter-planetary magnetic fields (IMF), *Bs*, pass the Earth over a long time period. Energy is transferred from the solar wind by magnetic reconnection between the IMF and the Earth's magnetic field.[Gonzalez]

Geomagnetic storms are extraordinary variations in the Earth's magnetic field, which can last up to several days. The main feature of a storm is an unmistakable decrease of the field's horizontal intensity and its subsequent recovery. Such events are related to the way the magnetosphere interacts with the solar wind. Some geomagnetic storms, particularly larger ones, begin with the arrival of an interplanetary shock structure, called a *geomagnetic sudden commencement*. If the IMF associated with the arrival of a solar-terrestrial disturbance remains northward behind the shock then there usually is no subsequent storm, and the shock stands alone as a *geomagnetic sudden impulse*. If the IMF is directed southward (-Bz) behind the shock then a geomagnetic storm usually follows the sudden commencement. The storm event usually is the effect of enhanced solar-wind pressure associated with a coronal-mass ejection (CME) or coronal hole high-speed stream. For purposes of measurement, a geomagnetic storm occurs when the K-index reaches a threshold of 5 or greater.

At least one geomagnetometer (Simple Aurora Monitor, SAM) provides an alarm that is triggered by the K-index. When the peak-to-peak amplitude variations within a 3-hour interval reach a preset threshold (in the case of the SAM, the threshold can be set to any of nine K-index values), the alarm is triggered.

The amplitude variations associated with geomagnetic storms are apparent on magnetograms. One such storm occurred in May 2010 due to arrival of a CME from 24 May (Fig. 21). As for the geomagnetic sudden impulse, the variations are obvious but not nearly as great as for a storm (Fig. 22).



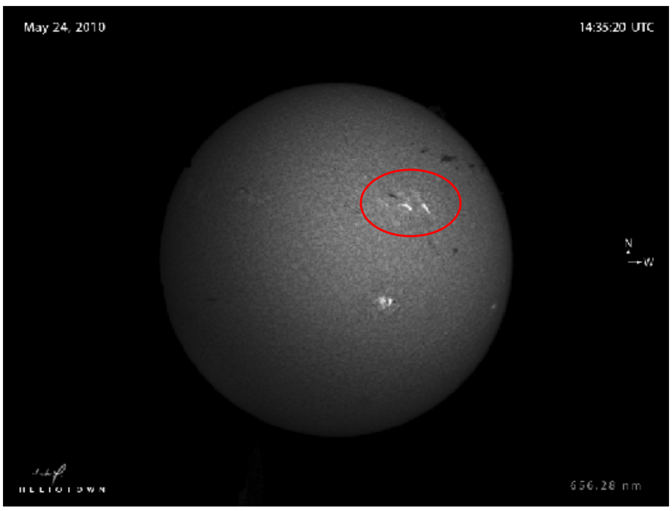
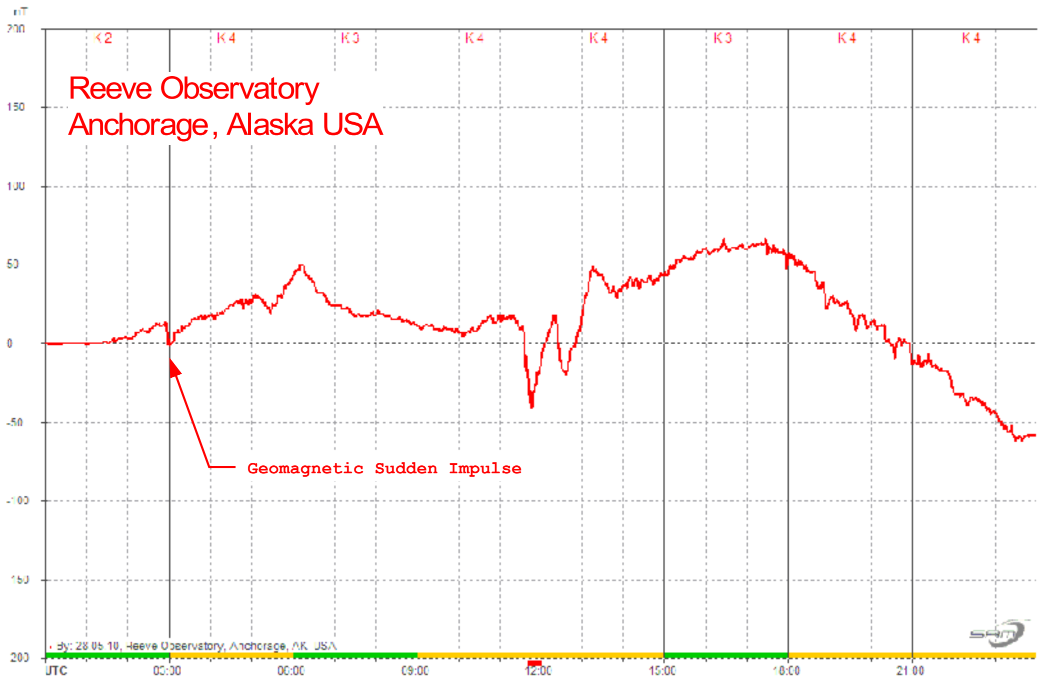


Fig. 21

(Upper) A strong geomagnetic storm was recorded 29 May 2010 at Reeve Observatory in Anchorage, Alaska USA. Compare the vertical scale to the quiet-day magnetogram in Sect. VI. Also, note the red K-index alarm bars along the horizontal axis. (Lower) The storm most likely was caused by a CME that occurred 24 May 2010 from the location on the Sun indicated (lower image courtesy of Thomas Ashcraft)

The geomagnetic sudden impulse is identified by its characteristic signature in terrestrial magnetometer data. It is most clearly seen at low latitudes, where the field variations are generally less complex than at high latitudes. This means that a sudden impulse can be difficult to identify at high latitude observatories because it may be overshadowed by normal activity. By coincidence, almost all sudden impulses in the 12 month period between May 2009 and May 2010 occurred during otherwise quiet periods and are clearly shown at the Reeve Observatory at 61°N latitude.



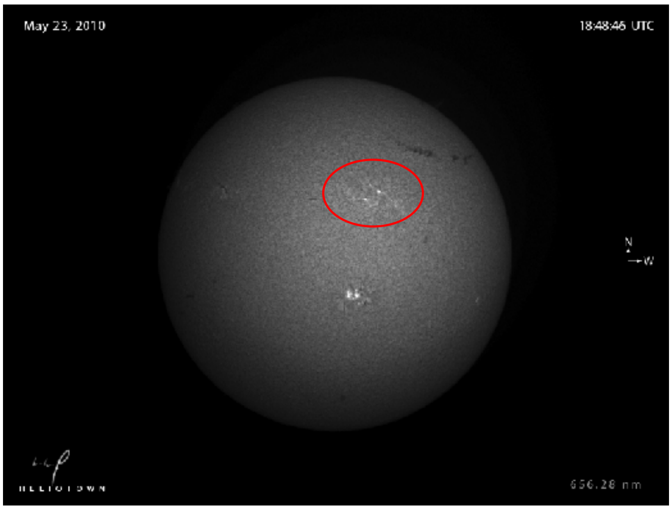


Fig. 22

(Upper) A geomagnetic sudden impulse was recorded at 0300 UTC, 28 May 2010 at Reeve Observatory in Anchorage, Alaska USA. The drop in amplitude was approximately 15 nT. This sudden impulse was identified by an alert issued by Space Weather Prediction Center. (Lower) The sudden impulse most likely was caused by a CME that occurred 23 May from the same location on the Sun as the storm previously described (lower image courtesy of Thomas Ashcraft)

A visible manifestation of a geomagnetic storm is *aurora* (Fig. 23a). Aurora is a luminous glow of the upper atmosphere (from as low as 80 to as high as 600 km) caused by energetic particles from the solar wind (mostly electrons but also protons) that enter the atmosphere from the magnetosphere along Earth's magnetic field lines. As they penetrate the upper atmosphere they collide with air molecules and oxygen and nitrogen atoms. The collisions transfer energy to the molecule or atom, which excites it. An excited atom or molecule returns to a non-excited state (ground state) by emitting a photon, that is, by making light.

Therefore, a geomagnetic storm indicates a good chance for viewing the aurora. Aurora viewing depends on geomagnetic activity and location, with higher latitudes (> 60°) being the best. However, during intense geomagnetic storms, aurora may be visible at much lower latitudes (Fig. 23b). There are several sources of information for aurora viewing; a few are listed in *Further Reading and Study*.

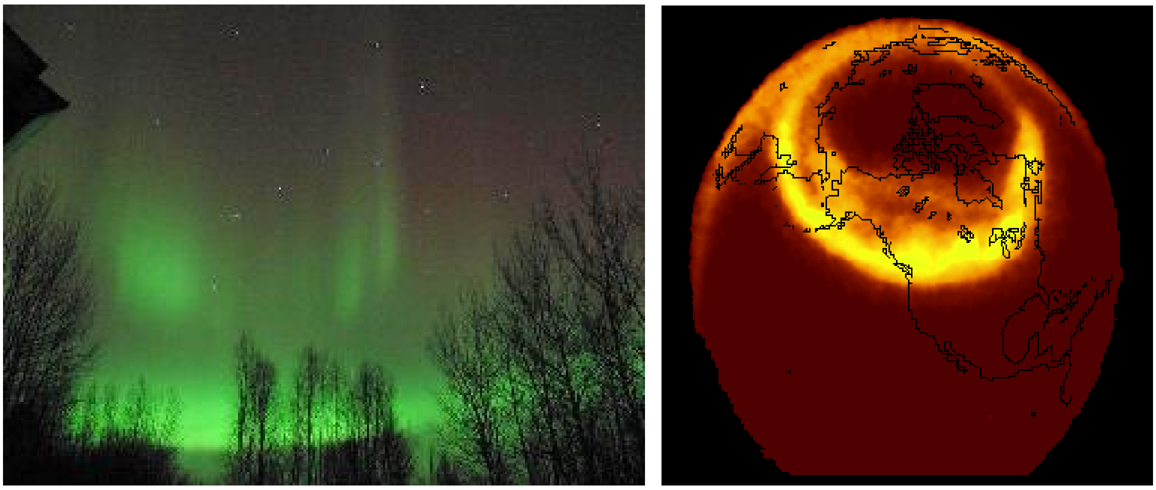


Fig. 23

a) Aurora is a visible manifestation of a geomagnetic storm as seen here at ground level. b) The aurora normally is seen at higher latitudes (> 60°) but during strong geomagnetic storms the auroral oval may extend considerably lower.

Image source: University of Alaska Geophysical Institute

A real time or near real time K-index could be helpful for radio propagation planning and prediction and aurora viewing. There are many public sources of K-index data available, but all of them come from the two sources mentioned above. The information is free and can be accessed by telephone, the internet and radio. Of course, amateur radio astronomers and amateur radio operators with their own geomagnetometer can determine the K-index at their location in real-time.

The effects of solar activity and geomagnetic storms go beyond amateur radio and aurora viewing and are largely deleterious (Fig. 24). Rapid variations in the magnetic field can affect high frequency ionospheric radio propagation and related military and commercial operations. Changes in the ionosphere can degrade the performance of global navigation satellite systems such as GPS, Galileo, Compass and GLONASS. Ionospheric expansion increases the drag on satellites, making their control more difficult, and can expose satellites to damaging static charge build-up and discharge. Varying magnetic fields can induce currents in metallic pipelines, increasing galvanic corrosion, and in electric power transmission lines causing voltage surges and blackouts.

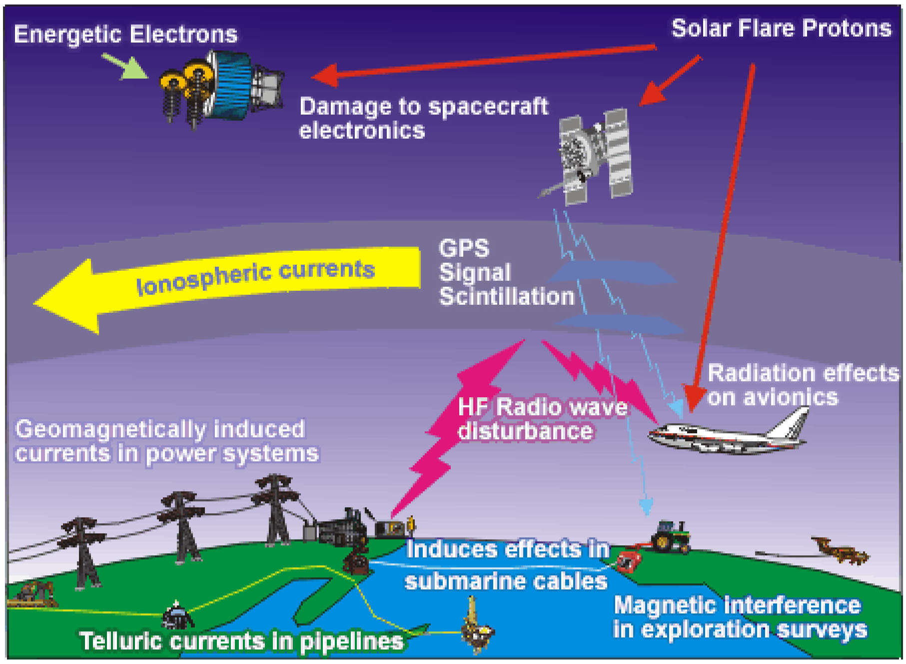


Fig. 24

Effects of solar activity and related geomagnetic storms. Image source: NASA

Radio Propagation Effects

Radio Aurora

Radio Aurora is ionospheric ionization associated with auroral disturbances that cause radio reflections.[Davies] Radio aurora reflects or refracts radio waves while the familiar visible aurora is caused by emitted visible and invisible radiation. Visible aurora and radio aurora are separate phenomena that do not necessarily occur at the same time and in the same space, but they do have the same basic origin.

Magazine articles appear frequently that are written about radio aurora from a radio amateur's perspective. See for example [Pocock], [Frank69] and [Frank74]. The solar activity that leads to the radio aurora also leads to geomagnetic field disturbances and thus may be detected by a geomagnetometer.

Ionospheric Storms

Ionospheric storms are conditions that last several days and are accompanied by additional ionospheric circulating currents and associated geomagnetic disturbances. During normal conditions at mid-latitudes, the variations are a few tenths of one percent of the total geomagnetic field but reach several percent during an ionospheric storm. Large geomagnetic storms are accompanied by ionospheric anomalies including depression of daytime critical frequencies of the F2 layer, radio blackout, and enhanced spread F and sporadic E propagation.[Davies] These effects and their duration depend on the sunspot cycle.

Polar Cap Absorption

Polar cap absorption (PCA) is ionization at northern latitudes that leads to radio blackouts on trans-polar paths. The blackouts last from hours to days depending on the latitude. PCA events usually are preceded by large solar flares but generally are not accompanied by noticeable changes in geomagnetic or auroral activity except toward the end when an auroral zone geomagnetic storm sets in. Thus, a geomagnetometer may or may not indicate conditions for PCA. The auroral zone is considered to be above 60° geomagnetic latitude and is oval shaped. The current shape and extent of the aurora is available online (Fig. 25).[13]

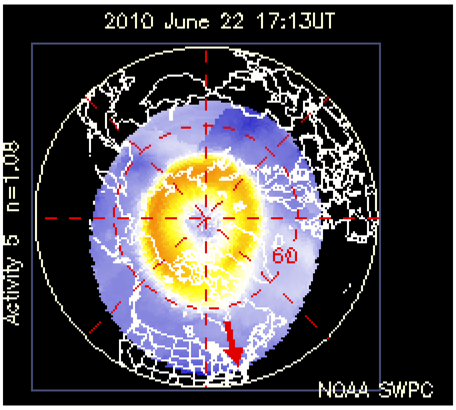


Fig. 25

The auroral oval expands and contracts with the makeup and speed of the solar wind. Manifestations of the associated geomagnetic activity are radio propagation anomalies. Image source: NOAA

[13] www.swpc.noaa.gov/pmap/

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Further Reading and Study

- Aurora Viewing Tips, www.swpc.noaa.gov/Aurora/
- The Aurora Watcher's Handbook, www.uaf.edu/uapress/book/displaysingle.html?id=32
- US Geological Survey National Geomagnetism Program, geomag.usgs.gov/
- National Geophysical Data Center, www.ngdc.noaa.gov/geomag/
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Author Biography

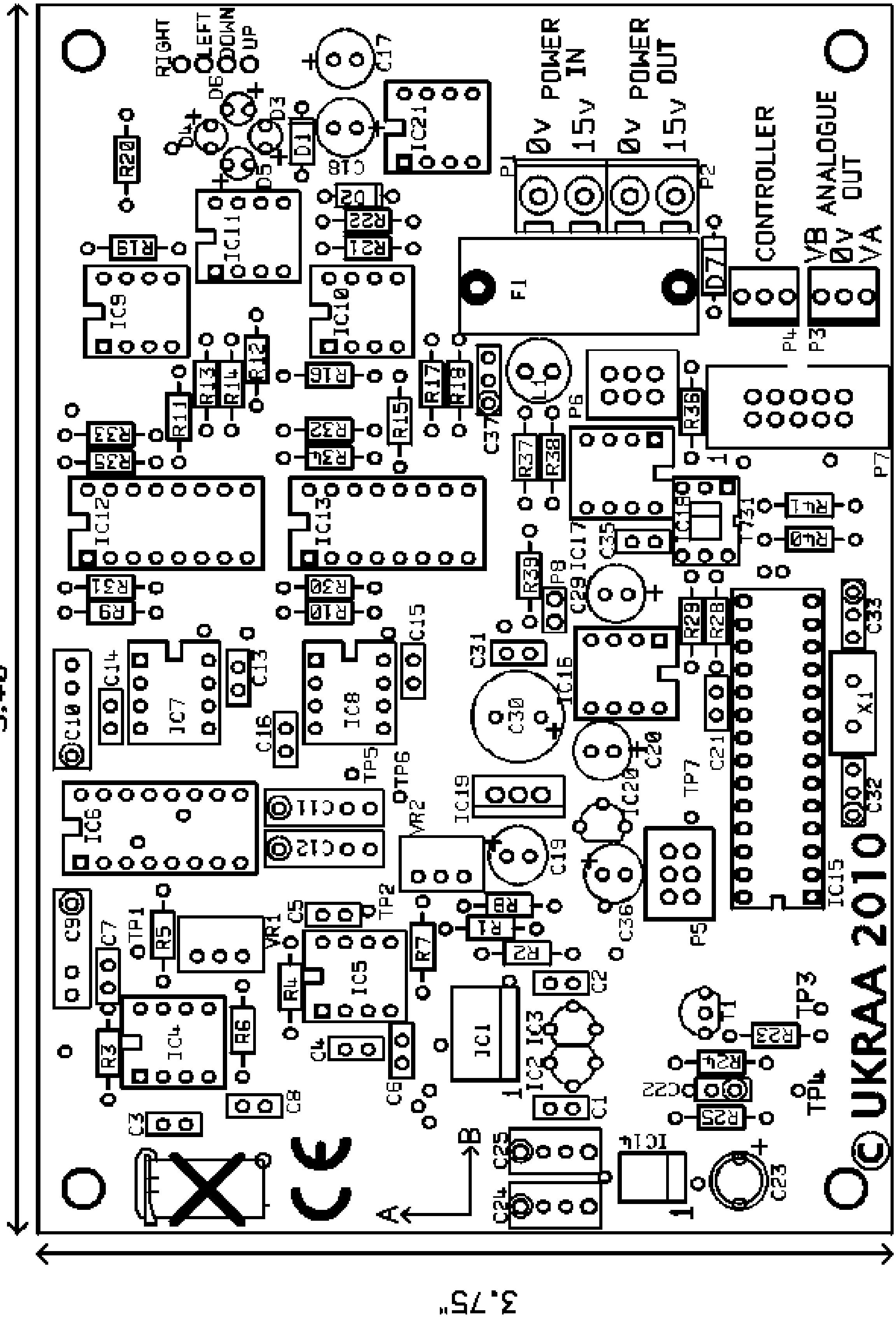
Whitham Reeve was born in Anchorage, Alaska and has lived there his entire life. He became interested in electronics in 1958 and worked in the airline industry in the 1960s and 1970s as an avionics technician, engineer and manager responsible for the design, installation and maintenance of electronic equipment and systems in large airplanes. For the next 36 years he worked as an engineer in the telecommunications and electric utility industries with the last 32 years as owner and operator of Reeve Engineers, an Anchorage-based consulting engineering firm. Mr. Reeve is a registered professional electrical engineer with BSEE and MEE degrees. He has written a number of books for practising engineers and enjoys writing about technical subjects. Recently he has been building a radio science observatory for studying electromagnetic phenomena associated with the Sun, Earth and other planets.

Appendix 2 – Magnetometer Specifications

Magnetic Field Sensor Device	Honeywell HMC 1022 Dual-Axis Magnetoresistive
Analogue Outputs (two channels)	0 to 5V
Gain (step 1)	0.4 (4mV/nT)
Gain {step 2)	1 (9mV/nT)
Gain (step 3)	2 (18mV/nT)
Gain (step 4)	4 (36mV/nT)
Time Constant (hardware)	1 second
Control Interface	I^2C Bus
Temperature Sensor Range	-40C *to* +150C
Temperature Sensor Resolution	11 to 14 bit *(11 bit in Starbase mode)*
Power Supply	15v DC at 90mA

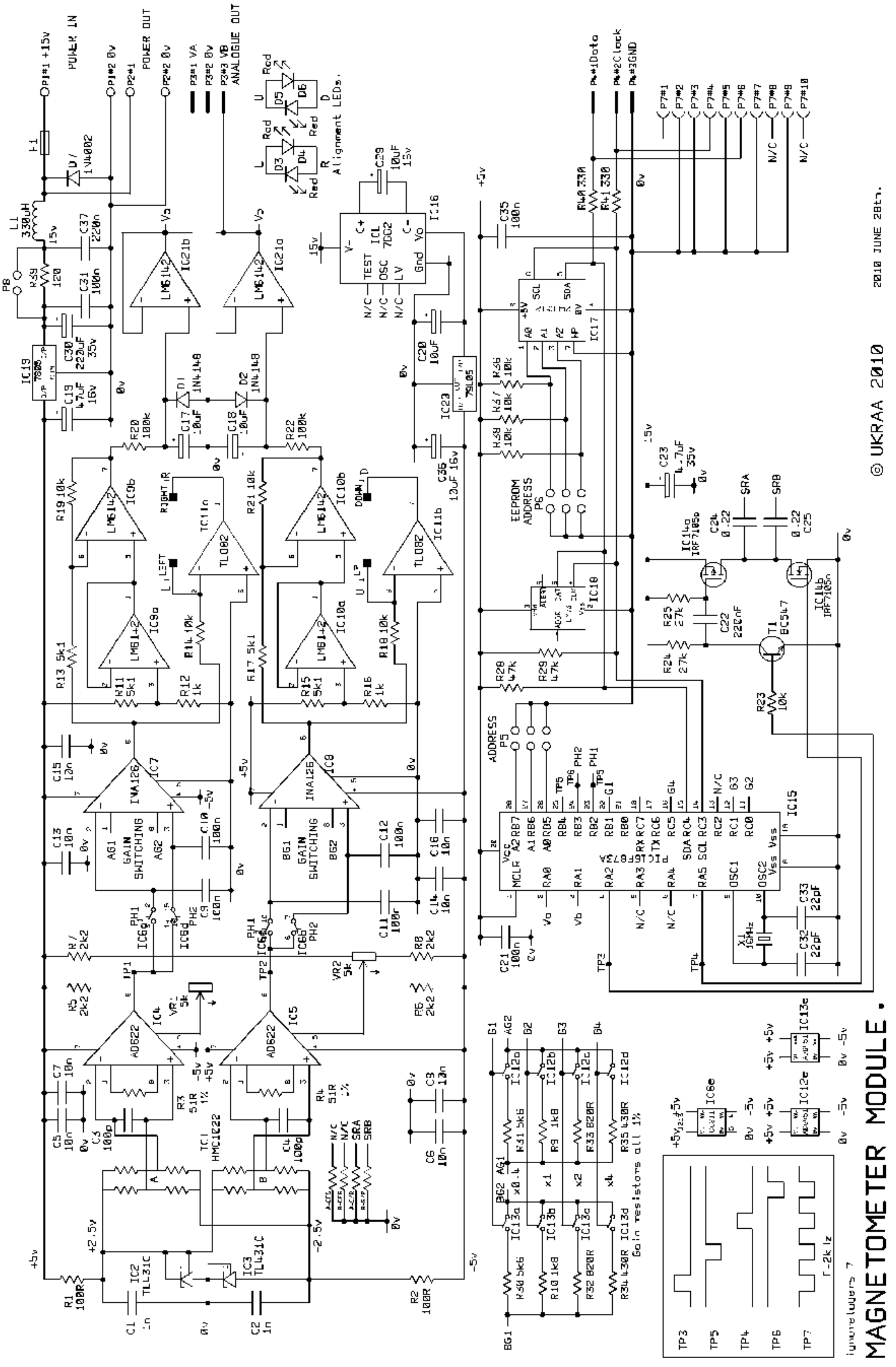
Please note that the calibration values given for gain *vs.* gain setting are only approximate, and will vary with specific hardware.

Appendix 3 – Magnetometer PCB Layout



Magnetometer Component Overlay

Appendix 4 – Magnetometer Circuit Diagram



Appendix 5 – I^2C Address Map

The PIC controller, temperature sensor and memory devices on the Magnetometer can respond to the following I^2C bus addresses:

Address *(binary)*	Address *(Hex)*	Function
0010 0000	20	Starbase: Read/Write to PIC: Gain control {01...04}
0010 0001	21	Starbase: Read from PIC: A axis high byte {00...03}
0010 0010	22	Starbase: Read from PIC: A axis low byte {00...FF}
0010 0011	23	Starbase: Read from PIC: B axis high byte {00...03}
0010 0100	24	Starbase: Read from PIC: B axis low byte {00...FF}
1001 1000	98	Starbase: Write to LM73 Temperature Sensor Pointer Register
1001 1001	99	Starbase: Read from LM73 Temperature Sensor Pointer Register
1001 1010	9A	Write to LM73 Temperature Sensor Pointer Register
1001 1011	9B	Read from LM73 Temperature Sensor Pointer Register
1001 1100	9C	Write to LM73 Temperature Sensor Pointer Register
1001 1101	9D	Read from LM73 Temperature Sensor Pointer Register
1010 0000	A0	Write to EEPROM
1010 0001	A1	Read from EEPROM
1010 0010	A2	Starbase: Write to EEPROM
1010 0011	A3	Starbase: Read from EEPROM
1010 0100	A4	Write to EEPROM
1010 0101	A5	Read from EEPROM
1010 0110	A6	Write to EEPROM
1010 0111	A7	Read from EEPROM
1010 1000	A8	Write to EEPROM
1010 1001	A9	Read from EEPROM
1010 1010	AA	Write to EEPROM
1010 1011	AB	Read from EEPROM
1010 1100	AC	Write to EEPROM
1010 1101	AD	Read from EEPROM
1010 1110	AE	Write to EEPROM
1010 1111	AF	Read from EEPROM

The I^2C bus address of the temperature sensor is always 98/99 (as shown in the table above), which is used by UKRAA Starbase to determine the temperature of the Primary Instrument Plugin.

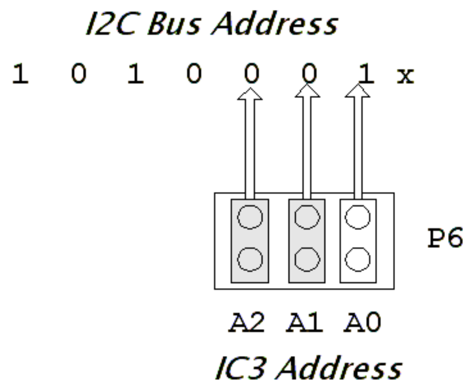
Greyed out options in the address table are used in different configurations with multiple plugins.

The corresponding *Starscript* commands for the `MagnetometerPlugin` when used with a Starbase Controller are:

getGain()	Gets the current gain setting
setGain(gain)	Sets the gain to 1, 2, 3 or 4
getTemperature()	Gets the Magnetometer temperature
getAAxis()	Gets the output of the A axis sensor
getBAxis()	Gets the output of the B axis sensor

Setting the Bus Address of the Configuration Memory

Note that the set of three links on P6 set the base address bits for the Configuration Memory EEPROM. For compatibility with Starbase, when using the Magnetometer as the Primary Instrument Plugin, the links must be set to give address **001** (binary), *i.e.* examining the circuit diagram, the IC17 address pins A2, A1, A0 should be <link> <link> <open>, as shown in the diagram below. (Address 000 is reserved for the Controller EEPROM.) If there is no legend on the PCB the A0 link is that closest to the 10-pin box socket.



Mapping IC17 addresses to I²C addresses using P6,
for use as Primary Instrument Plugin

Appendix 6 – I²C Bus Operation

This section is provided for those users who wish to write their own control software to make use of the Magnetometer I²C interface. The board may be used without using the I²C control, but the gain will be fixed at the default of setting 2.

The magnetometer uses an I²C two wire bus interface and presents itself as a slave device. Slave devices on an I²C bus each have a unique address and will only respond to messages with that address. I²C data is handled in 8 bit bytes, and the magnetometer has a fixed 7 bit address. Bit 0 of the address byte, sent at the start of a message, is set to '0' for a write operation, and to '1' for a read. The magnetometer thus has 2 addresses, 20H for writing and 21H for reading. This is normal I^2C practice. Fast mode, clock stretching and multi-master arbitration are not supported.

To access these registers, the sub-address is held in a pointer which must be set by a write operation, after the address byte and before the data byte. If a valid acknowledgement is received by the magnetometer from the I^2C bus master following its data read / write, the pointer is automatically incremented for a subsequent read / write. This is most useful to read the data for each axis as two consecutive bytes. The magnetometer will end a message sequence if a 'stop' condition is received, or if the master fails to acknowledge a read operation.

I^2C control message examples

To *write* to the gain control register, the following sequence is sent by the master:

- I^2C start condition
- Write address (20H)
- Pointer (00H)
- Data (01H to 04H)
- I^2C stop condition.

A data *read* is slightly more complicated. For example, to read the A axis high byte:

- I^2C start condition
- Write address (20H)
- Pointer (01H)
- I^2C stop (or another start, see I2C specification)

This has set the pointer to 01H, to *read* the associated data:

- I^2C start condition (Only if stop was previously sent, see specification)
- Read address (21H)
- 8 clock pulses to read the data byte from the magnetometer
- 9^{th}. clock pulse for the acknowledgement bit
- I^2C stop condition.

If the master does acknowledge the read operation, a stop is not strictly needed. The magnetometer will assume that the sequence has ended If the acknowledgement bit is sent by the master, this tells the magnetometer that another read operation will follow. Another train of pulses will be sent to read the next data byte. In the example above, this would be the A axis low byte as the pointer would have incremented to 02H.

Appendix 7 – Jumper Settings and Pinouts

Component	**Labelled**	**Function**
P1	Pin 1	Power In +15V DC
	Pin 2	Ground
P2	Pin 1	Power Out +15V DC
	Pin 2	Ground
P3	Pin 1	Analogue Output A Axis
	Pin 2	Ground
	Pin 3	Analogue Output B Axis
P4 *(Controller)*	Pin 1	I^2C Data (SDA)
	Pin 2	I^2C Clock (SCL)
	Pin 3	I^2C Ground
P5	Address	Sets the PIC I^2C Address **Not used in this version**
P6	A0	Sets the Configuration EEPROM Address See Appendix 5
	A1	
	A3	
P7 *(Controller)*	Pin 4	I^2C Clock
	Pin 6	I^2C Data
	Pins 2,3,5,7,9	I^2C Ground
P8	P8	Connect to allow +12 V DC operation rather than the standard +15 V DC.

Appendix 8 – Regulatory Compliance

RoHS

The Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment 2002/95/EC, (commonly referred to as the Restriction of Hazardous Substances Directive or RoHS) was adopted in February 2003 by the European Union. The RoHS directive took effect on 2006 July 1, and is required to be enforced and become law in each member state. This directive restricts the use of six hazardous materials in the manufacture of various types of electronic and electrical equipment. In speech, RoHS is often spelled out, or pronounced “rosh”.

The above paragraph was taken from the Wikipedia essay on RoHS.

The RoHS Directive restricts the use of the following six hazardous substances in electronic and electrical equipment products falling within the Directive:

- Lead
- Mercury
- Cadmium
- Hexavalent chromium
- Polybrominated biphenyls
- Polybrominated diphenyl ethers

UKRAA confirms that the suppliers of the components and materials used in the UKRAA Magnetometer have stated that such components and materials are RoHS compliant and that reasonable steps have been taken to confirm these statements.

WEEE

RoHS is closely linked with the Waste Electrical and Electronic Equipment Directive (WEEE) 2002/96/EC that sets collection, recycling and recovery targets for electrical goods and is part of a legislative initiative to solve the problem of huge amounts of toxic e-waste.

The Waste Electrical and Electronic Equipment (WEEE) Directive is designed to ensure the efficient collection and recycling of electrical and electronic equipment at end-of-life. If a customer purchases a new product from UKRAA which falls within the WEEE Directive to replace an existing one (of similar function to the one that has been sold) and intends to dispose of the existing one, then the customer can request that we take back the existing product and deal with the costs and logistics of recycling it. Any customer wishing to take advantage of this facility should contact us. Provided that the existing product comes within the scope of the WEEE Directive, we will make arrangements for its return or collection and will deal with its disposal.

Revision History

Revision	Date	Author	Status
Draft A	2010-07-18	L M Newell	Internal draft for peer review
Draft B	2010-08-08	L M Newell	Internal development draft
Draft C	2010-08-30	L M Newell	Added reviewer's comments and photos
Draft D	2010-12-13	A J Lutley	Corrections from supplied feedback
Issue 1	2011-03-03	L M Newell	Added feedback changes and corrections

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