Technical University of Denmark

FLUXGATE MAGNETOMETER

Suspended version

Model FGE version K2
Manual

Fluxgate sensor SE. S0387,
Fluxgate electronic box SE. E0493

(Revision 01/4-2014)

DTU Space
National Space Institute

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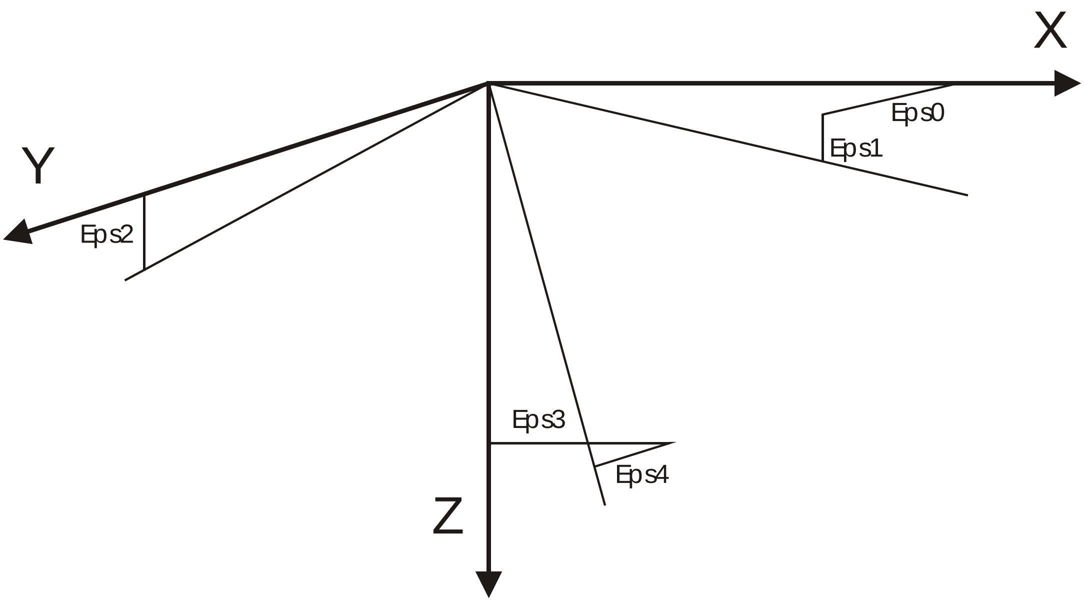
1. General Description.

The fluxgate magnetometer model FGE is a tri-axial magnetometer, based on commercially available fluxgate sensors. In order to improve long term stability as well as temperature stability these sensors are at DTU Space supplied with compensation coils wound on quartz tubes in order to obtain a sensor drift of less than a few nT per year and a temperature coeff. of 0.25 nT/°C or less, which makes the magnetometer very well suited for use in magnetic observatories.

Two versions of the magnetometer are available. The normal type in which the three fluxgate sensors are mounted on a 12x12x12 cm^3 marble cube placed on a three legged aluminium base.
For the best possible baseline stability a second version is available, in which the marble cube is suspended in two crossed phosphor-bronze strips to compensate any tilt of the sensor foundation. With this version baseline drift of less than 2-3 nT/year has been obtained even at places where a normal fluxgate magnetometer would have shown drifts of 100 nT/year or more.
The suspended version is recommended for all observatories seeking very low baseline drift.

Each sensor unit is calibrated at the Danish geomagnetic observatory Brorfelde (BFE) to determine the sensitivity and the misalignment of the sensors. The results of this test are given in the calibration certificate which follows each magnetometer.



As frame of reference for these calibrations, we use an orthogonal coordinate system X,Y,Z, where the Y-axis is horizontal and lies in the same vertical plane as the magnetic axis of the Y- (D-) sensor. The X-axis is also horizontal and perpendicular to Y. Z is pointing downwards.
The figure shows the frame of reference and the five angles of misalignments which are given in the certificate. In the standard instrument these angles are smaller than 2 mrad or 7 min of arcs. An optional alignment to 1 mrad is available.

Using these misalignment angles one gets the following expression for the magnetometer outputs V_x, V_y and V_z (in V):

$$S_X * V_X = O_X + B_X + \varepsilon_0 B_Y + \varepsilon_1 B_Z - X_{BIAS}$$
$$S_Y * V_Y = O_Y + B_Y + \varepsilon_2 B_Z - Y_{BIAS}$$
$$S_Z * V_Z = O_Z + B_Z + \varepsilon_3 B_X + \varepsilon_4 B_Y - Z_{BIAS}$$

where S is the instrument sensitivity in nT/V, the O's are instrument offsets in nT, B_x, B_y and B_z are the magnetic field components along the axis of our reference coordinate system and the epsilons are the misalignment angles from the certificate. The BIAS terms indicates that a constant magnetic field is subtracted by stable BIAS-currents.
Both the offset terms and the misalignment terms are small and may be included in the BIAS-terms for most purposes. The expression above may therefore be reduced to:

$$S_X * V_X = B_X - X_{BIAS}$$
$$S_Y * V_Y = B_Y - Y_{BIAS}$$
$$S_Z * V_Z = B_Z - Z_{BIAS}$$

The instrument sensitivities are determined by the sensor coil sensitivities and the scaling resistors in the electronics. We have:

$$S_X = \frac{C_X}{R} nT / mA$$

Where the R's are the three resistors in the electronics box setting the instrument sensitivity and the C's are the sensor sensitivities (nT/mA) which are given in the calibration certificate.
The formulas given above are useful during installation and also if one wants to change the sensitivity (or range) of the instrument.
The electronics are made using high quality and high precision components so that no adjustments are necessary.
As the sensitivity of each sensor coil is given in the calibration certificate the scale values of the instruments may be changed by changing the scaling resistors.

The electronics consists of three main blocks:

A. The power supply.

B. Sensor amplifiers and phase detectors.

C. Magnetic field biasing circuit. This circuit makes it possible to compensate the main magnetic field in extremely precise steps. Using the build in DIP-switches (or rotary switches) the biasing field may be adjusted in 255 steps of approx. 150 nT each, giving a maximum range of 38000 nT for the biasing field. In order to compensate larger fields a fixed bias of approx. 38000 nT may be installed for the X and Z components in addition to the variable biasing. *(see 7.2)*
The biasing circuit is extremely stable but is usually not calibrated, so that the actual value of the biasing field has to be determined by absolute measurements at the observatory after the installation of the instrument.

The biasing electronics allow only for biasing positive values of the magnetic field components. If the magnetometer is to be used in places with large negative magnetic field components such as the Z-component in the southern hemisphere, it will be necessary to record X, Y and -Z. In order to change the polarity of the Z-sensor one should remove the cover from the fluxgate sensor and swap the two wires to the Z-sensor. Indication of which wires should be swapped is shown on the label on top of the sensor, where the wires comes in.
Also if you want to compensate negative Y-components you will have to record –Y by swapping the two wires to the Y sensor on top of the sensor.

One advantage using a model FGE magnetometer is that all critical components may be kept in the variometer house at constant temperature.
As the magnetometer only outputs the variations of the magnetic field, the choice of datalogger equipment/AD-converter is not critical and will in general not influence the overall stability of the baseline values of the magnetometer.
To fully utilize the magnetometer, it's recommended to use the optional built-in 16-bit AD-converter. The ADAM4017 digitizer gives the following possible combinations of range and resolution:

Range	+-6400 nT	+-3200 nT	+-1600 nT
Resolution	0.2 nT	0.1 nT	0.05 nT

The choice will often depend on the location of the magnetic observatory. At high latitude one will choose a large range in order to record the large magnetic storms seen there, while observatories at lower latitude will look for high resolution.

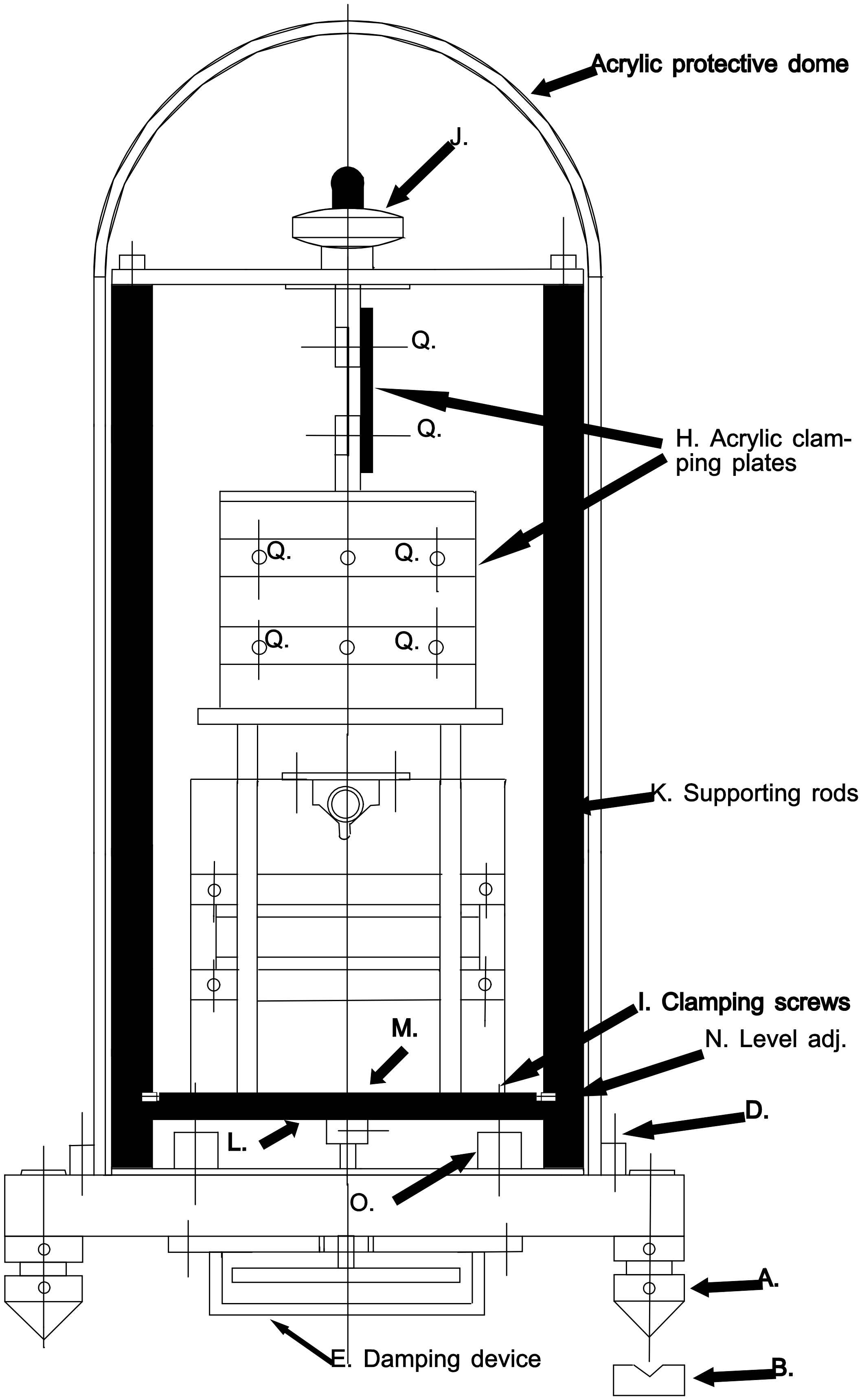
2. Installation.

In order to obtain the best stability the sensor unit and electronic box should be installed in a house, which is temperature controlled.
Since any fluxgate magnetometer is extremely sensitive to tilt, it is usually very important to use an instrument pier which is founded deep in the ground or build on rock. The suspended fluxgate magnetometer will however compensate for small tilt of the sensor.
Before installing the suspended fluxgate magnetometer in the variometer house it is important to check that the X- and Y-sensors in the marble block are horizontal, when the pendulum is hanging freely in the middle of the instrument. This is most easily done on a spare pier with a smooth surface (e.g. marble).

2.1 Unpacking and installation.

Place the fluxgate magnetometer (cf. figure) on the pier with each of the three feet (A) in the supplied supports (B).
The protective acrylic dome (C) may now be removed by unscrewing the three screws (D) in the bottom plate of the magnetometer.
The **two acrylic clamping plates** marked with red tape (H) protecting the suspension brass bands during transport are removed by unscrewing the eight finger screws (Q) fixing the clamping plates.
Then the **four clamping screws** (I) marked with red ink, fixing the pendulum to the bottom plate are removed.
Finally the pendulum is lifted by turning the two large black knobs (J) on top of the instruments until the pendulum reaches the top plate. Tighten the knobs.
Lifting the pendulum one also releases the damping device (E) on the bottom of the instrument. This device which is filled with silicone oil is closed with a plug during transportation. **When lowering the pendulum for transportation of the instrument see that this plug goes into the hole in the bottom plate and closes the damping device.**
It is important that the pendulum is hanging in the middle of the instrument during recording. To ensure this one should adjust the three supporting feet (A) until this is accomplished.(Check for instance the distance between the four supporting rods (K) and the plate on which the marble block is mounted (L).These distances must all be the same for all four rods.)
It should be noted that this adjustment is also necessary every time the instrument is rotated during test of the instrument

Now place the electronics box at least 1 m away from the sensor and connect the electronics to the sensor.


Acrylic protective dome
J.
Q.
Q.
H. Acrylic clam-
ping plates
Q.
Q.
Q.
Q.
K. Supporting rods
I. Clamping screws
N. Level adj.
M.
D.
L.
O.
A.
E. Damping device
B.

Suspended Magnetometer sensors in workshop

2.2 Check of levelling.

When the sensor has been installed on a suitable pier one can proceed with the levelling check. This is done by measuring the output from the instrument in the four positions where the X- and Y-sensors are pointing toward magnetic north and magnetic south.

Position 1: X-sensor pointing towards magnetic north.

In this position the BIAS-switches for Y-sensor should be in the OFF-position (or 0-position), while the BIAS-switches for the Z-sensor should be adjusted so that the Z-output is less than
± 100 nT. *(for ajusting large field components see 7.2 on page 18)*

The Z-switches should now be kept unchanged during the measurements in all four positions.
The sensor is now turned until the X-sensor is pointing towards magnetic N. The bottom plate has an "N" engraved which may be used for a coarse adjustment. For the fine adjustment use nulling of the Y-output (Y< ±50 nT) to determine the correct position.
When the X-sensor is pointing towards magnetic N, adjust the X-switches until X-output is less than ±1 V. Check finally that the pendulum is positioned in the middle of the instrument and also that the Y-output is still < ±50 nT.
Now read the **X-output, V_{X1}** and the **Z-output, V_{Z1}**.

Position 2: X-sensor pointing towards magnetic south.

In the second position "X-sensor pointing towards magnetic south" also use the Y-sensor to determine the correct position, by rotation of the sensor until the Y-output is less than 50 nT. Again check that the pendulum is in the middle of the instrument, if necessary adjust the feet.
As the BIAS-generator can only compensate positive magnetic fields it is necessary to reverse the polarity of the X- and Y-sensors in the two positions where these sensors are pointing S. A small connector is therefore placed on the top of the instrument, which should be moved when the instrument has either the X- or the Y-sensor pointing south. Use the "GREEN" end of the connector in the normal direction, pointing north and the "RED" end of the connector when pointing south. In older models of the magnetometer a special test cable is supplied to be inserted between the electronics and the sensors in order to reverse the polarity of the X- and Y-sensors.
The X-switches should be set in the same positions as with X pointing N.
Now read the X**-output, V_{X2}** and the **Z-output, V_{Z2}**.

Position 3: Y-sensor pointing towards magnetic north.

In this position the X-switches are in the OFF-position (0-position) and the X-output is nulled to find the correct position. Use the "GREEN" end of the RED/GREEN connector. Set the Y-Switches until Y is less than ±1V (or as small as possible if H is larger than 38000 nT) .
Read the **Y-output, V_{Y3}** and the **Z-output, V_{Z3}**.

Position 4: Y-sensor pointing towards magnetic south.

In the final position the X-switches should also be OFF (0-position) and nulling of the X-output is used to find to position where Y is pointing south. Use the "RED" end of the RED/GREEN connector. The Y-switches should not be changed from position 3.
Read the **Y-output V_{Y4}** and the **Z-output**, **V_{Z4}**.

Finally restore the RED/GREEN connector to the "GREEN" end.

The misalignment of the sensors may now be calculated from the following equations, where the V's are the measured magnetometer outputs, the O's are magnetometer offsets, H and Z the actual horizontal and vertical field components, the ε's are the misalignment angles in radians (indicated in the figure above) and the S's are the scale values of the instrument in nT/V. The BIAS terms are the fixed bias-field set by the switches.

$$S_X * V_{X1} = O_X + H_1 - X_{BIAS} + \varepsilon_1 * Z_1$$
$$S_Z * V_{Z1} = O_Z + Z_1 - Z_{BIAS} + \varepsilon_3 * H_1$$

$$S_X * V_{X2} = O_X + H_2 - X_{BIAS} - \varepsilon_1 * Z_2$$
$$S_Z * V_{Z2} = O_Z + Z_2 - Z_{BIAS} - \varepsilon_3 * H_2$$

$$S_Y * V_{Y3} = O_Y + H_3 - Y_{BIAS} + \varepsilon_2 * Z_3$$
$$S_Z * V_{Z3} = O_Z + Z_3 - Z_{BIAS} + \varepsilon_4 * H_3$$

$$S_Y * V_{Y4} = O_Y + H_4 - Y_{BIAS} - \varepsilon_2 * Z_4$$
$$S_Z * V_{Z4} = O_Z + Z_4 - Z_{BIAS} - \varepsilon_4 * H_4$$

From these equations one gets the following:

$$\varepsilon_1 = \frac{S_X(V_{X1} - V_{X2}) - (H_1 - H_2)}{2Z}$$

$$\varepsilon_2 = \frac{S_Y(V_{Y3} - V_{Y4}) - (H_3 - H_4)}{2Z}$$

$$\varepsilon_3 = \frac{S_Z(V_{Z1} - V_{Z2}) - (Z_1 - Z_2)}{2H}$$

$$\varepsilon_4 = \frac{S_Z(V_{Z3} - V_{Z4}) - (Z_3 - Z_4)}{2H}$$

Please notice that in the Southern Hemisphere where the polarity of the Z-sensor is reversed so that –Z is recorded rather than Z, the formulas for ε3 and ε4 should have a minus sign in front of the scale value Sz.

As can be seen from the equations it is possible to determine four of the five misalignment angles by this simple test. The fifth angle ε_0 i.e. the non-orthogonality of the X and Y sensor may only be determined by more complicated means.

2.3 Adjustment of the levelling.

Normally adjustment of the levelling is not necessary even after transporting the magnetometer from one place to another. If the check of the levelling gives values which deviates significantly from the values given in the certificate an adjustment may be considered.

Before starting an adjustment of the levelling it is recommended to contact DTU Space for further instructions.

Correction of the levelling is done by moving the marble block and its supporting aluminium plate (M) in respect to the plate (L). One should be very cautious doing this as only very small adjustments normally are necessary.
From the equation given above, one can see that the readings of the magnetometer in position N and S should be the same, when the sensors are levelled properly. Also one should notice that the reading of magnetometer when properly levelled should be the mean of the readings N and S during the initial test. It is therefore not necessary to rotate the instrument during the levelling in one direction. One only has to adjust the position of the marble block until the output of the specific sensor is the mean value of the readings during the initial test.
To move the aluminium plate (M) in respect to the aluminium plate (L) one should loosen the four screws which fix the two plates together. Thereafter it is possible to move the marble block in the X- or Y-direction by loosing and tightening of two sets of four brass screws (N). Before any adjustment of these screws and also when loosing the four screws fixing the two plates together one should lower the pendulum until it rests on its four supporting cylinders (O) used during transport.

After adjustment of the levelling remember to fasten the four screws mentioned above. Also one could repeat the test procedure described above to make a final determination of the four misalignment angles.

2.4 Installation of the suspended fluxgate magnetometer.

After testing and possible adjustment of the magnetometer has been finished the magnetometer may be installed in its final position in the variometer house.
During transport of the instrument from one house to the other, it's necessary to lower the pendulum and fix it to the bottom plate using the four clamping screws.
Please see that the plug closing the damping mechanism gets into its hole in the bottom plate.
It is not necessary to use the two acrylic transportation clamps for transportation between houses.
When the magnetometer is placed on its pier in the variometer house, the clamping screws have been removed and the pendulum been raised, one should rotate the instrument until the sensor head is in the correct orientation.

2.4.1 HDZ-orientation.

Installation of the suspended fluxgate magnetometer is the HDZ orientation is very simple as one only have to rotate the sensor until the D (Y)-output is close to zero:

A. Place the sensor unit on the instrument pier with the X-sensor pointing towards magnetic north. Place the electronic box at least 1 m away from the sensor unit and connect the electronics to the sensor unit.

B. Set all the biasing switches on the electronics to zero.

C. Adjust the three foot screws until the pendulum is hanging freely in the middle of the instrument

D. Rotate the sensor until the Y-output is close to zero (less than +-100 nT). This is most easily done using a digital voltmeter to measure the analogue Y-output from the electronics. Another possibility is to get the digital output of the Y-channel from the datalogger.

E. Set the X- and Z-biasing so that the X- and Z-outputs are close to zero (less than ±150 nT).

F. Repeat D and E if necessary.

F. Fasten the three supporting foot screws using the three nuts.

Using this orientation of the sensor, absolute measurements of for example D, I and F will determine the baseline values. (The azimuth of the Y-sensor D_0 as well as the baseline values for H and Z).

2.4.2 XYZ-orientation.

If XYZ-orientation is wanted, one should also use the Y-output to find the correct orientation. In order to so one should of course know the actual value of the Y-component on the pier where the sensor is going to be mounted. The installation is as for HDZ-orientation except that the Y-output should not be close to zero but close to the value of the Y-component on the pier.

As for the HDZ orientation one can use a digital voltmeter to measure the analogue Y-output. Or one can use the digital Y-output from the datalogger.

A. Place the sensor unit on the instrument pier with the X-sensor pointing towards geographic north. Place the electronic box at least 1 m away from the sensor unit and connect the electronics to the sensor unit.

B. Set all the biasing switches on the electronics to zero.

C. Adjust the three foot screws until the pendulum is hanging freely in the middle of the instrument

D. Rotate the sensor until the Y-output is close to actual value of the magnetic field. This is most easily done using a digital voltmeter to measure the analogue Y-output from the electronics. Another possibility is to get the digital output of the Y-channel from the datalogger. (At some observatories the Y-component may be larger than +-3200 nT, so that the datalogger can only be used if the range of the ADAM-module is changed from 5V to 10 V.)

E. Set the X-, Y- and Z-biasing so that all three outputs are close to zero (less than ±150 nT). As the magnetometer can only bias positive magnetic fields it may be necessary to change the polarity of the Y-component at the observatories where Y is negative. One will then record X, -Y and Z. In order to change the polarity of the Y-sensor one will have to remove the acrylic dome from the sensor and swap the wires to the Y-sensor on the top of the sensor assembly.

F. Repeat D and E if necessary.

F. Fasten the three supporting foot screws using the three nuts and mount the acrylic protection dome.

3. Connection of the magnetometer to the data logging system.

There are five analogue outputs from the magnetometer, X-, Y- ,Z- and the temperatures of the sensor and of the electronics.

The magnetometer analogue outputs have a dynamic range of ±10 V.

The scale value for the outputs from the temperature sensors is 10.0 mV/°K. (3.00V ~ 300 Kelvin)

3.1 Analogue Output connector.

A.	GND
B.	X-sensor output
C.	Y-sensor output
D.	Z-sensor output
E.	Sensor temperature output T1
F.	Electronics temperature output T2

3.2 The Adam 4017 AD-converter module.

The optional build-in AD-converter should be configured and the data read by the data logging software.

Please notice that in order to utilize the full 16 bit resolution the ADAM 4017 should be configured to use a +-5 V dynamic range.

The ADAM 4017 module can only convert 5 different input channels every second. It is therefore necessary to limit the number of active input channels to five.

Finally remember to configure for 50/60Hz operation to avoid noise from power lines.

The following commands should be used:

%AANNTTCCFF, which can be used to configure the module. (50/60 Hz, Range, Baud rate, Data format).

$0151F , which will activates the first five input channels

#AA , which will read all channels

Please read the ADAM manual for more information.

The digital output from the magnetometer electronics should be connected to an ADAM 4520 RS485/RS232 converter module through a twisted pair cable, which may have a length of several hundred meter.

Please notice that a terminating resistor 120 ohm is mounted inside the magnetometer.

3.3 Digital Output connector.

The digital data connector has the following pin connections:

A.	Data +
B.	Data -
C.	nc.
D.	nc.

4. Adjustment of range.

The range (or sensitivity) of the magnetometer is user specified and preset at delivery of the instrument.
As described in section 1 the sensitivity of each component X, Y and Z is given by a formula:

$$S_E = \frac{C_E}{R_E}$$

Where the C's are the sensor sensitivities determined by the initial calibration at Brorfelde Observatory. These numbers are given both in the certificate and on a paper label fixed to the marble cube.
The R_E's are fixed resistors in the electronics box.

The sensitivity of the magnetometer may be changed by changing the three resistors R44, R144 and R244 (See the circuit diagram). The accuracy of these resistors are 0.1%.
The scale values can be calculated from the sensor coil data found on the sensor and the value of the scaling resistors.

The scale values in nT/V is given by:

S (nT/V) = C (nT/mA) / R (kohm)

Example: Sensor S0289 has the following coil constants:

C_X: 37998 nT/mA
C_Y: 37747 nT/mA
C_Z: 37787 nT/mA

Using an electronics with identical scaling resistors of f. ex. 118.0 kohm one gets :

S_X = 37998 nT/mA / 118.0 kohm = 322.0 nT/V
S_Y = 37747 nT/mA / 118.0 kohm = 319.9 nT/V
S_Z = 37787 nT/mA / 118.0 kohm = 320.2 nT/V

These scale values should be calculated for each set of sensor/electronics.
These numbers should be used by the data logging software to change from voltage to nT.
If one have to record negative fields like Z in the southern hemisphere or a negative Y-component, the scale value should be used with have a minus sign.

5. Specifications.

Analogue output:	±10 V
Analogue dynamic range:	Approx. +-3200 nT
Range of bias:	+76000 nT for X and Z, +38000 nT for Y
Bias step:	150 nT (steps not calibrated)
Misalignment of sensors:	< 2 mrad (7 min of arcs)
Long term drift:	< 3 nT/year
Temp. coeff.	<0.25 nT/°C
Band pass:	DC to 1 Hz
Temperature sensor output:	10 mV/°K

For fluxgate sensor SE. S0387 and fluxgate electronic box SE. E0493 together:

X-coil constant:	C_X:	37145 nT/mA
Y-coil constant:	C_Y:	36890 nT/mA
Z-coil constant:	C_Z:	37345 nT/mA
X-scale value:	S_X:	314.8 nT/V
Y-scale value:	S_Y:	312.6 nT/V
Z-scale value:	S_Z:	316.5 nT/V
Scale resistors:		118.0 kohm 0.1%

Specification of optional suspension:

Range of tilt compensation:	±0.5 °
Tilt compensation factor:	> 500

General information:

Size of suspended sensor:	25x25x55 cm^3, 18 kg
Size of electronics:	16x40x10 cm^3, 3 kg
Power supply:	12 V DC, 3W
Operating temperature:	-10 to +40°C

6. Calibration Circuit.

The magnetometers are equipped with a calibration facility, which enables you to test the magnetometer and the data logger from time to time.
Using the calibration switch on the electronics box very accurate currents (0.02500 mA +-0.2 o/o) are sent through the scaling resistors.

The changes in the output voltages may be calculated:

dX (V) = 0.0250 mA * 118.0 kohm = 2.95 V +- 0.2%
dY (V) = 0.0250 mA * 118.0 kohm = 2.95 V +- 0.2%
dZ (V) = 0.0250 mA * 118.0 kohm = 2.95 V +- 0.2%

The same changes in the output measured in nTesla through the aquisition system with the right **scale values**:

dX (V) = 0.0250 mA * 37145 nT/mA = **928.6 nT** +- 0.2%
dY (V) = 0.0250 mA * 36890 nT/mA = **922.2 nT** +- 0.2%
dZ (V) = 0.0250 mA * 37345 nT/mA = **933.6 nT** +- 0.2%

The facility should be used to check your magnetometer and your data logger system.
If you observe any changes in these values you should try to find the reason for the error.

7. Change of instrument wiring

7.1 Recording negative field components.

The magnetometer is from the manufacturer set to operate in the Northern Hemisphere.
Since the Bias-system only works with positive magnetic field components it is not possible to measure the Z-component in the Southern Hemisphere. Instead one has to measure -Z.
In order to do so the user has to change the polarity of the Z-sensor. This is easily done. First one should remove the plastic protective house from the sensor. Then one has to swap the two wires going to the Z-sensor.
On the top of the magnetometer is shown how the 10 coloured wires should be connected in the two hemispheres.
If one wish to record a places where the Y-component is negative and biaz is needed one also have to use the same procedure for the Y-sensor. Simply to swap the two wires on top of the magnetometer leading to the Y-sensor.

7.2 Recording large field components

Since the adjustable BIAS-circuit compensates the magnetic field components in 255 steps of 150 nT, it is necessary to add a fixed bias (38000 nT) at higher fields like the Z-field at mid and high latitude.
This is done using the two switches on the circuit board (one for X and one for Z)
At high latitude (Z>38000) the Z-switch must be ON.
At lower latitude (Z<38000) the Z-switch must be OFF. (See picture)
The X-switch is only used in equatorial regions where X is larger than 38000 nT.