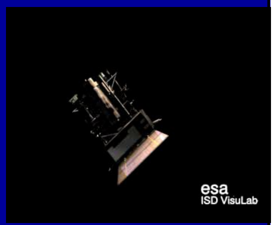
Space Instrumentation (6)

Lectures for the IMPRS June 23 to June 27 at MPAe Lindau
Compiled/organized by Rainer Schwenn, MPAe,
supported by Drs. Curdt, Gandorfer, Hilchenbach, Hoekzema, Richter, Schühle

Wed, 25.6., 14:00 Measuring magnetic fields in space (Richter, TU Bs)



Space Instrumentation:

Measuring Magnetic Fields in Space

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Institute for Geophysics and Meteorology
TU- Braunschweig

MPAe Lindau 25.6.2003

… the next 45 Minutes

- The Magnetic field
- Magnetometers:
  - Torsional Magnetometer
  - Fluxgate-Magnetometer
  - Searchcoil Magnetometer
- Magnetometer Calibration
- Magnetic Cleanliness

The Magnetic field

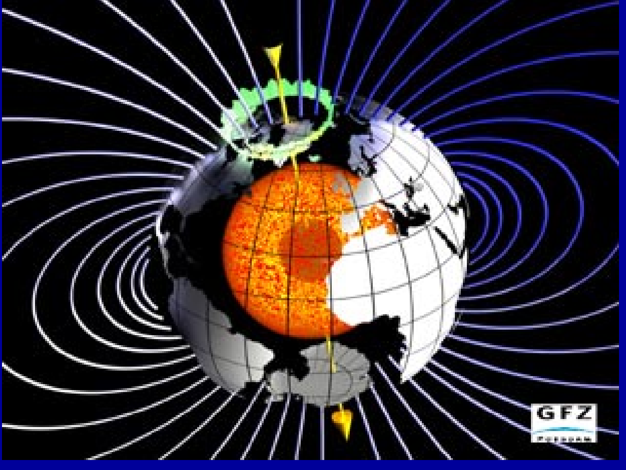
The Magnetic field

Maxwell Equations

Name or Description	SI
Faraday's law	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampere's law	$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$
Poisson equation	$\nabla \cdot \mathbf{D} = \rho$
[Absence of magnetic monopoles]	$\nabla \cdot \mathbf{B} = 0$
Lorentz force on charge q	$q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
Constitutive relations	$\mathbf{D} = \epsilon \mathbf{E}$ $\mathbf{B} = \mu \mathbf{H}$

The Magnetic field

The pure Earth



The Magnetic field

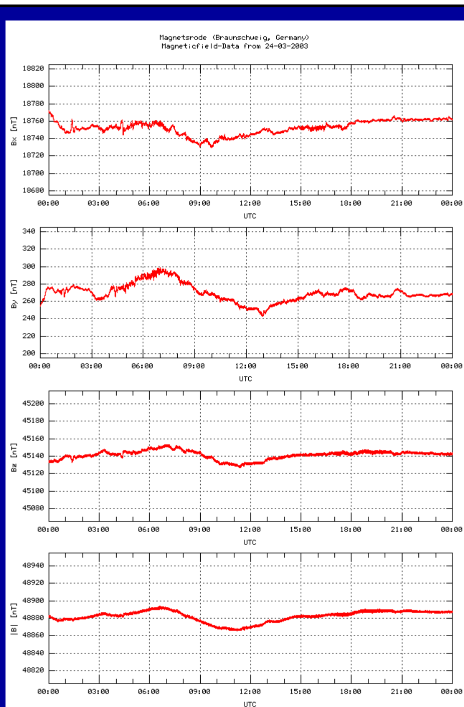
Horizontal and Vertical components

Declination   Inclination

The Magnetic field

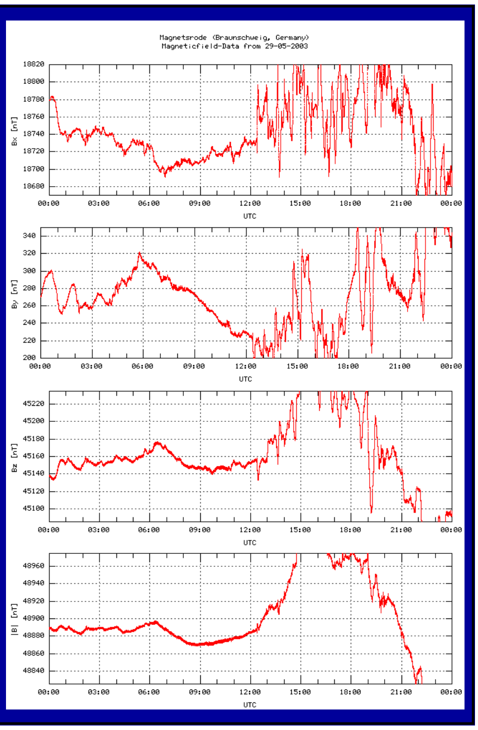
Ground Observations- I

… a calm day

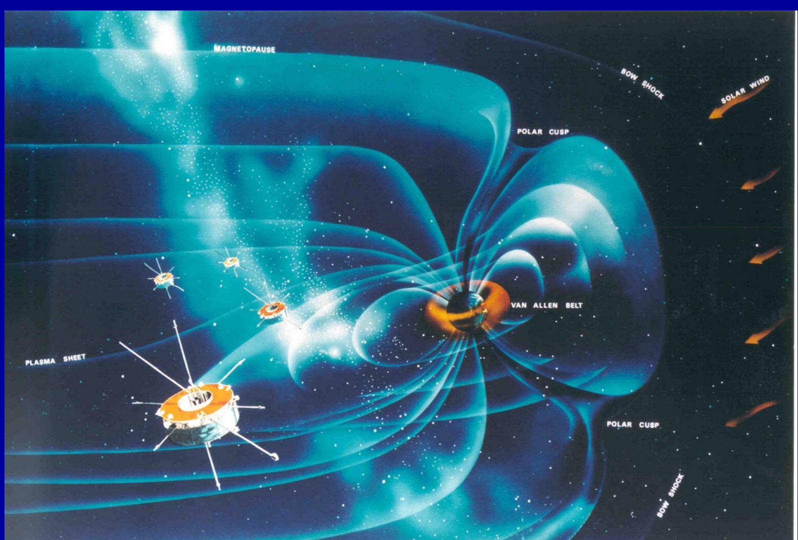


The Magnetic field
Ground Observations- II

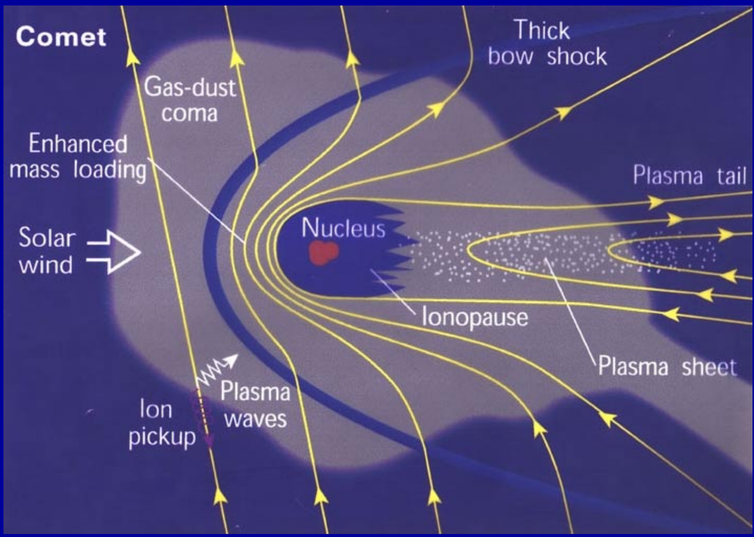
... a disturbed day



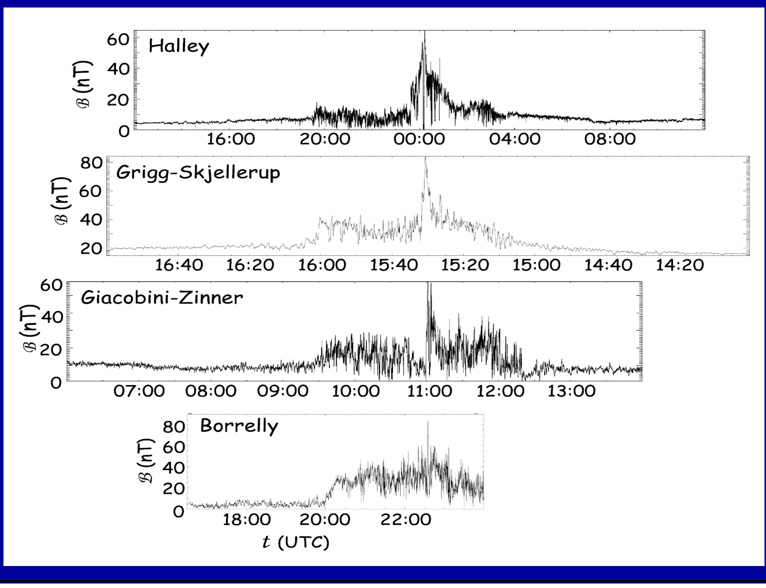
The Magnetic field
The real Earth



The Magnetic field
Comets



The Magnetic field
Cometary Structures



Magnetometers

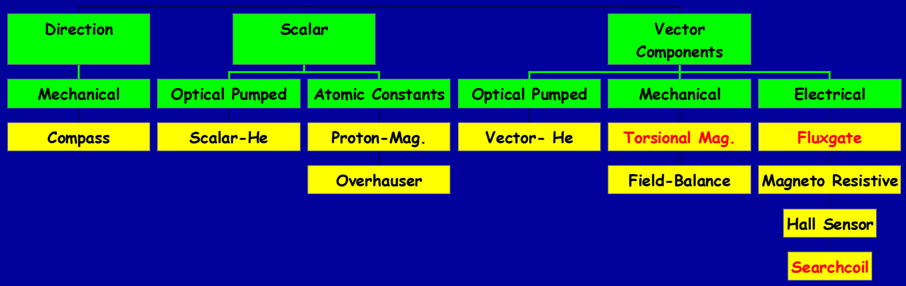
Magnetometers

Design Criteria for s/c Magnetometers

- Long term Stability
- Range (SW, Planetary fields)
- Resolution (ADC)
- Vector Rate, TM-Budget
- Filters (Aliasing, Order, Cut off)
- Commanding
- Power & Mass (Size)
- Position

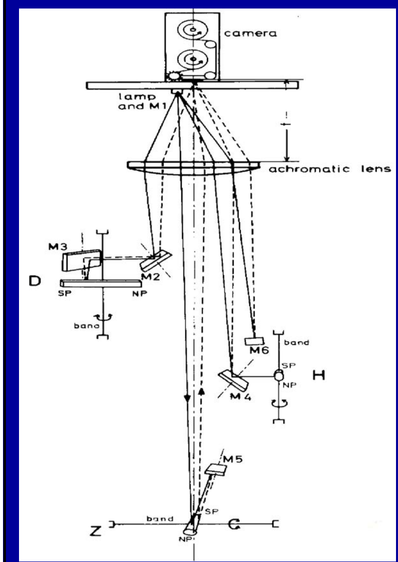
Magnetometers

Overview



Torsional Magnetometer

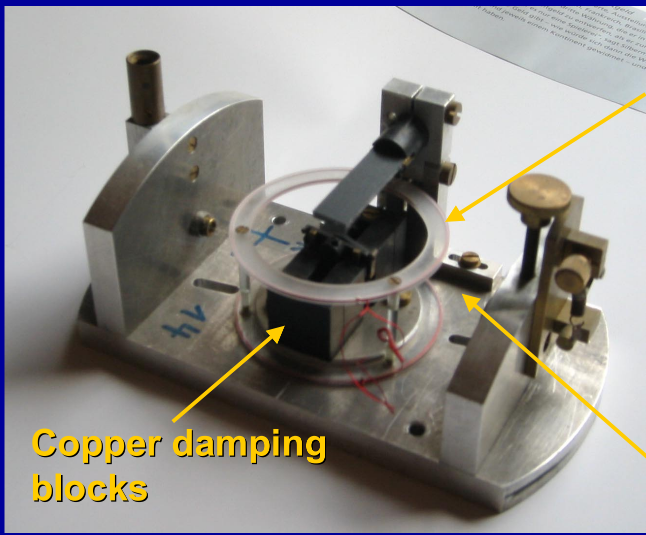
A Classical Instrument



The idea:
A magnet, suspended by a torsional wire, is rotating under the action of the Earth magnetic field. The rotational position of the magnet is deter-mined by a light pointer and recorded on a normal film

Torsional Magnetometer

The z-Component of the Gough-Reitzel Magnetometer



Torsional Magnetometer

Angular Momentum Balance for the z-component

The x-axis is aligned with the wire, the z-axis is vertical, and Y completes the system. Thus the angular momentum balance equation reads:

$$M \cdot H_Z - D \cdot \alpha = 0$$

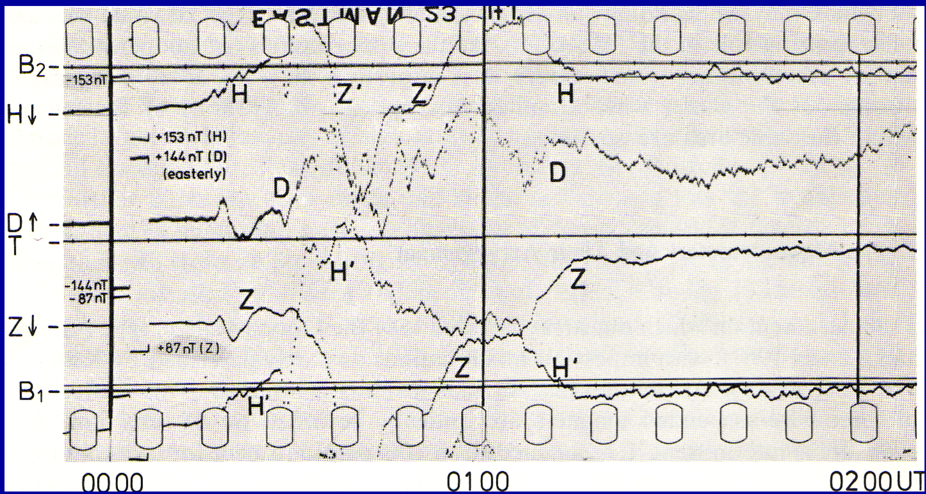
where M is the magnetic moment, H_Z the vertical component of the field, D the torsional module, and ♋ the torsional angle. It follows

$$H_z = \frac{D}{M}\alpha$$

Calibration determines D/M. Similar equations for H_X and H_Y.

Torsional Magnetometer

A Sample Record



Torsional Magnetometer

in Action...

Torsional Magnetometer

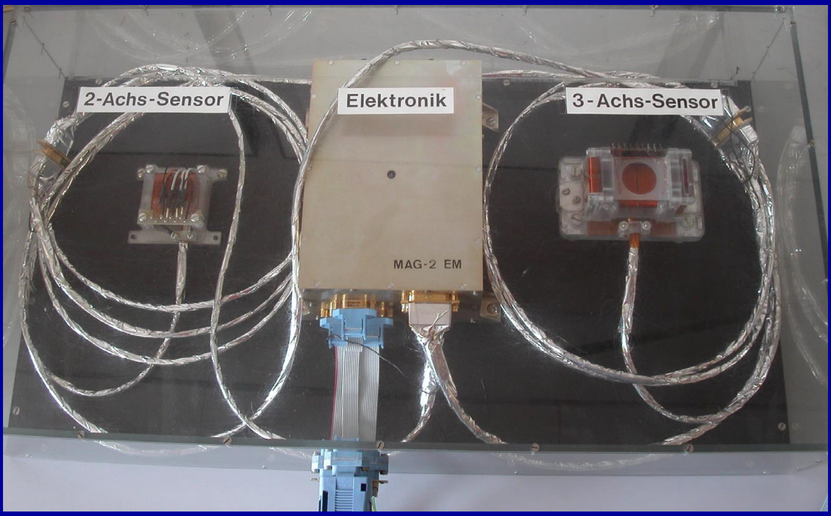
Characteristics

Weight:	10 kg
Power:	40 mW
Operating period:	70 days
Sampling:	0.2 vectors/s
Resolution:	1 nT
Dynamics range:	1500 nT

Fluxgate - Magnetometer (FGM)

Examples

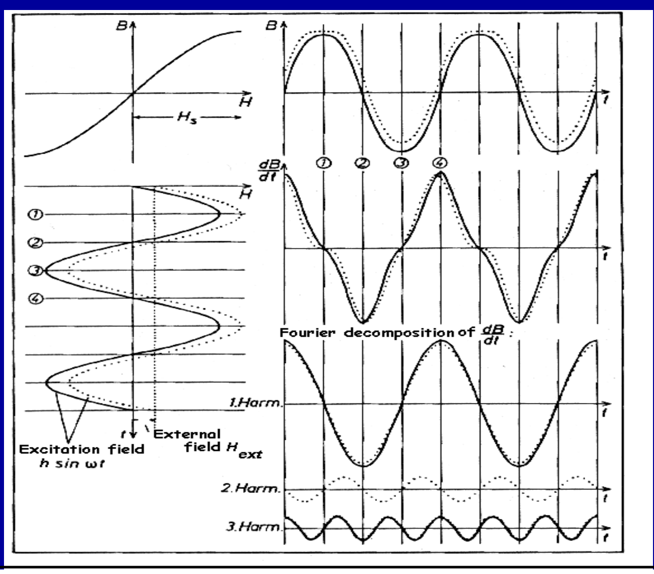
GIOTTO FGM System



Fluxgate - Magnetometer (FGM)
Classification

- Saturated-Core-Magnetometer
- Vector measurements possible
- No absolute measurements
- Lightweight, compact construction
- Low power consumption
- Qualified for space applications

Fluxgate - Magnetometer (FGM)
Characteristic Curve, Excitation and Output Voltage



Fluxgate - Magnetometer (FGM)

Characteristic Curve, Excitation and Output Voltage

- Characteristic curve:

  $B(H(t)) = 3\,H(t) - H(t)^3$

- Excitation:

  $H(t) = H_{ext} + h\,\sin(◆\,t)$

- Induced voltage at the secondary coil:

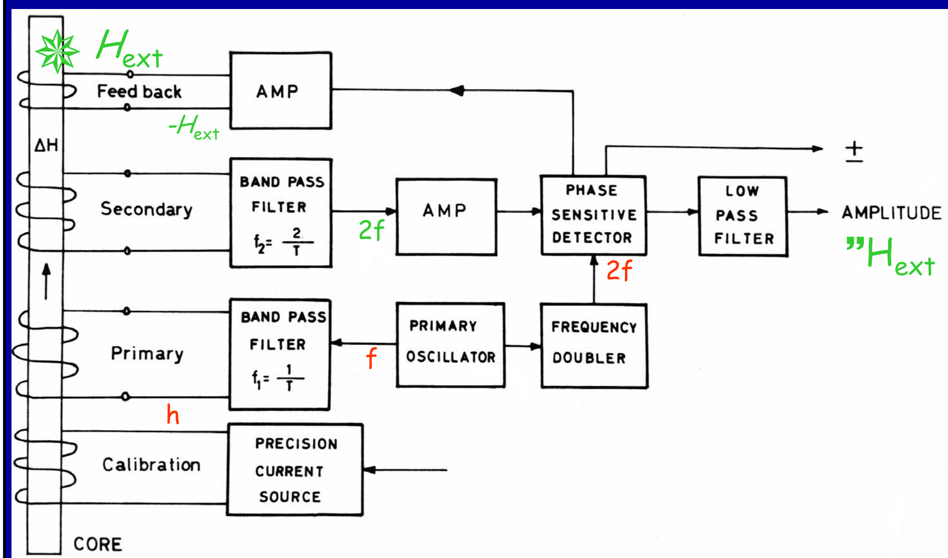
  U_i ” $dB/dt = 3\,h\,(1 - H_{ext}^2 - 1/4\,h^2)$ ◆ $\cos(◆t)$

  $-3\,H_{ext}\,h^2$ ◆ $\sin(2$ ◆$t)$

  $+3/4\;\;h^3$ ◆ $\cos(3$ ◆$t)$

Fluxgate - Magnetometer (FGM)

Schematic Construction



Fluxgate - Magnetometer (FGM)

Functional Principle: Summary

- Non-linear magnetization curve is driven into saturation by periodic excitation (f)
- External field H_{ext} ⇒ ($2f$)
- Lock-in ($2f$), PSD, Integration → $\langle U_{2f} \rangle \propto B_{ext}$
- Feedback using $-\langle U_{2f} \rangle$ ⇒ Zero field and reduction of non-linearities
- Symmetric core excitation ⇒ DC-offset reduction
- Pulsed excitation ⇒ less power consumption

Fluxgate - Magnetometer (FGM)

Sensor Design

Problem:

Decoupling of small 2nd harmonic from the excitation signal

Solution:

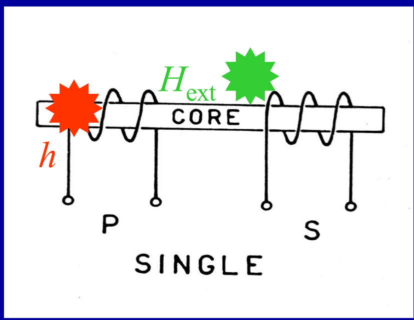
Suitable sensor geometry for suppression of odd harmonics

Fluxgate - Magnetometer (FGM)

Sensor Design:

Rod Core

Simple excitation coil, simple secondary coil
➔ No suppression of odd harmonics

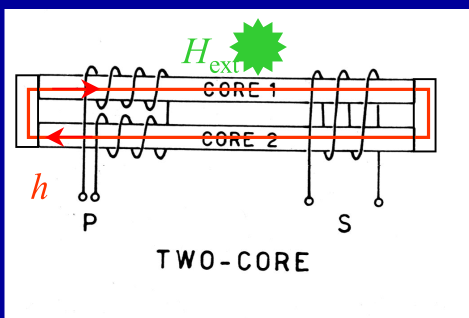


Fluxgate - Magnetometer (FGM)

Sensor Design:

Double Rod Core

Two individual excitation coils, common secondary coil
➔ Only even harmonics



Fluxgate - Magnetometer (FGM)

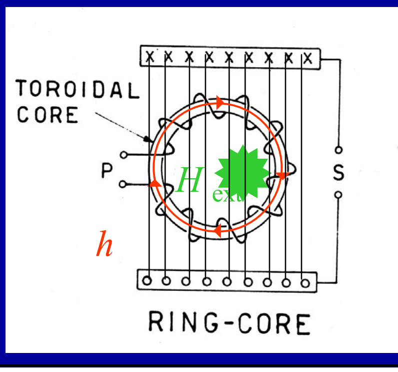
Sensor Design:

Ring Core

Further development of the Double Rod Core with same advantages.

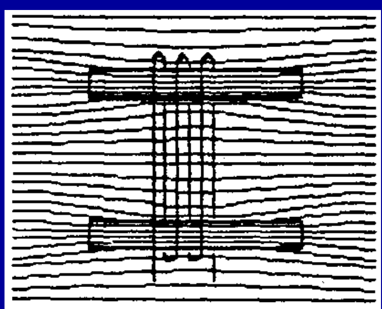
Common outer rectangular secondary coil

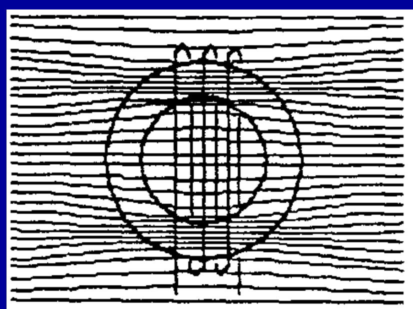
⇒ Only even harmonics



Fluxgate - Magnetometer (FGM)

Flux Distribution





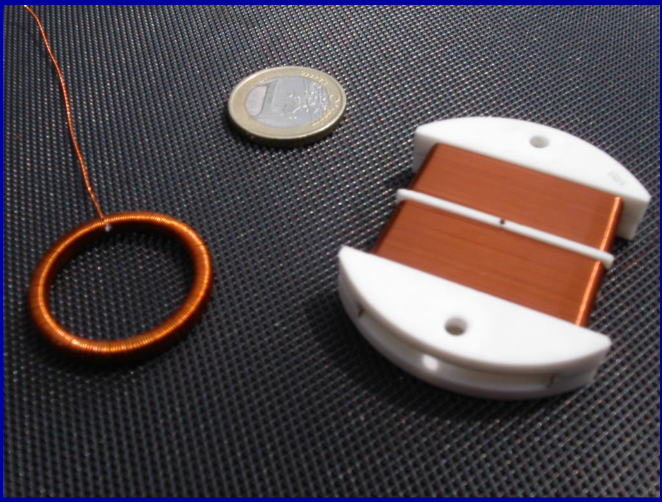
Double Rod Core and Ring Core

show equivalent flux distribution

Fluxgate - Magnetometer (FGM)

Examples

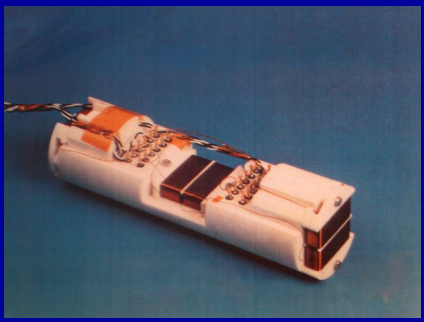
1- Axis Ring Core Sensor

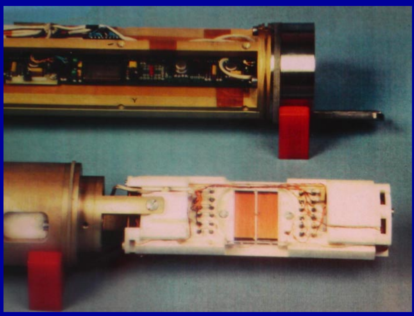


Fluxgate - Magnetometer (FGM)

Examples

3 Axes FGM KTB Borehole Sensor

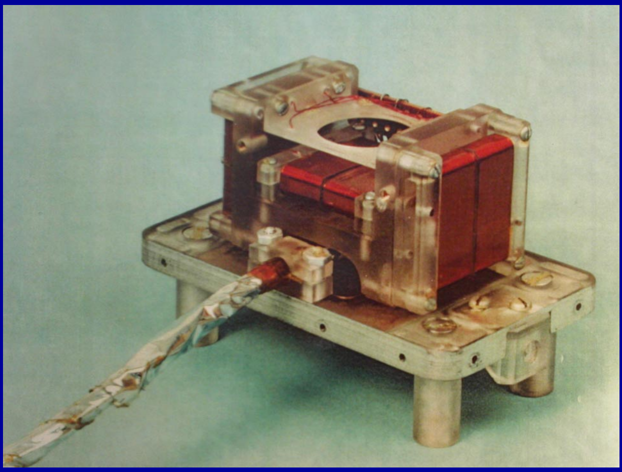




Fluxgate - Magnetometer (FGM)

Examples

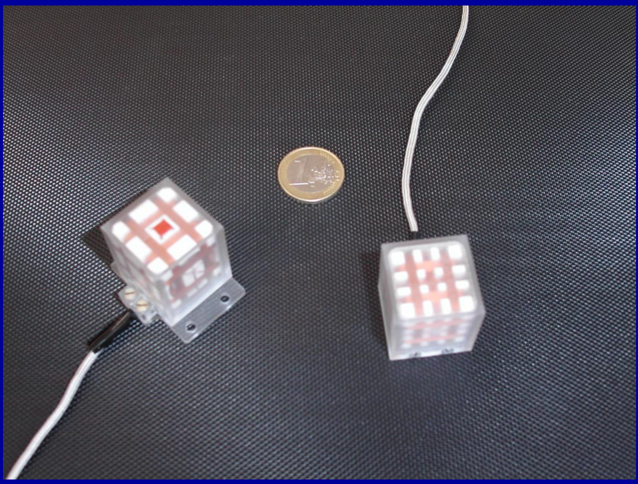
3 Axes CLUSTER FGM Sensor



Fluxgate - Magnetometer (FGM)

Examples

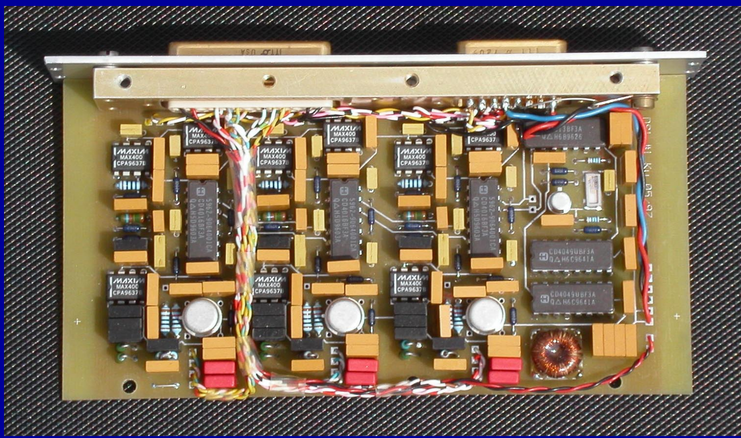
3 Axes ROSETTA / DS 1 FGM Sensors



Fluxgate - Magnetometer (FGM)

Examples

DS 1 FGM Analog Electronics



Fluxgate Magnetometer (FGM)

Characteristics

e.g. ROSETTA

Weight (sensor):	30 g
Power:	500 mW
Operating period:	15 years
Sampling:	20 vectors/s
Resolution:	0.04 nT
Dynamics range:	16000 nT

SearchCoil - Magnetometer
Classification

- Induction-Coil-Magnetometer
  - $\Rightarrow$ AC-field measurements only
- Frequency spectrum mHz ... MHz
- Vector measurements with 3 orthogonal coils

SearchCoil - Magnetometer
Functional Principle

- Induction law: rot $\underline{E} = - d\underline{B} / d\,t$
- Induced Voltage: $U_{ind} = \oint \underline{E} \bullet d\underline{s}$

$\Rightarrow$ $U_{ind} = - n \; d\,(F \; B_{\gamma}) / dt$

- Harmonic fields $B = \hat{B}$ sin(ωt) and constant area F

$$\Rightarrow \hat{U}_{ind} = + n \; F \, \omega \; \hat{B}$$

SearchCoil - Magnetometer
Characteristics

•Voltage rises linear with frequency & amplitude

•Signal in case of

* rotation of coil in constant field
* fixed coil in time varying field
* temporally varying coil geometry (Temperature!) in constant field

Result: Interpretation in unknown field is difficult if magnetometer (s/c!) is in motion

SearchCoil - Magnetometer
Real Sensors-Overview

Application	Axes	Wdgs.	Frequency Range [Hz]	Dimensions l x r [cm]	Sensitivity [❍V/nT Hz]
Micro-pulsations	3	200000	1m ...10	200 x 1.25	700
Magneto-telluric (MT)	1	40000	0.3m... 300	120 x 1.15	73
Audio MT	1	10000	1 ... 20k	90 x 1.1	8.6
Helios S/C	1	60000	5 ...2.2k	35 x 0.3	6
Galileo S/C	1	1500	0.1 ... 100k	30 x 0.25	0.18

SearchCoil - Magnetometer

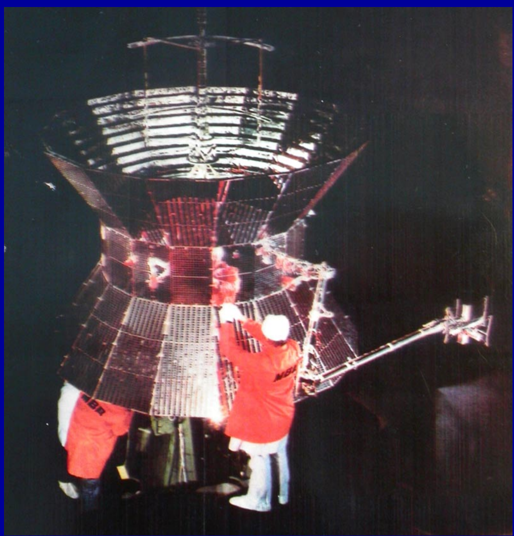
Real Sensors-Overview

Frequency Range [Hz]	Low 0.3m … 200	Medium 1 … 20k	High 10 .. 600k
Spectral noise density [pT / ⌦Hz]	0.1 @ 1Hz	0.01 @ 1kHz	0.002 @50 kHz
Length [m]	1.1	0.4	0.5
Weight [kg]	15	0.45	0.07

SearchCoil - Magnetometer

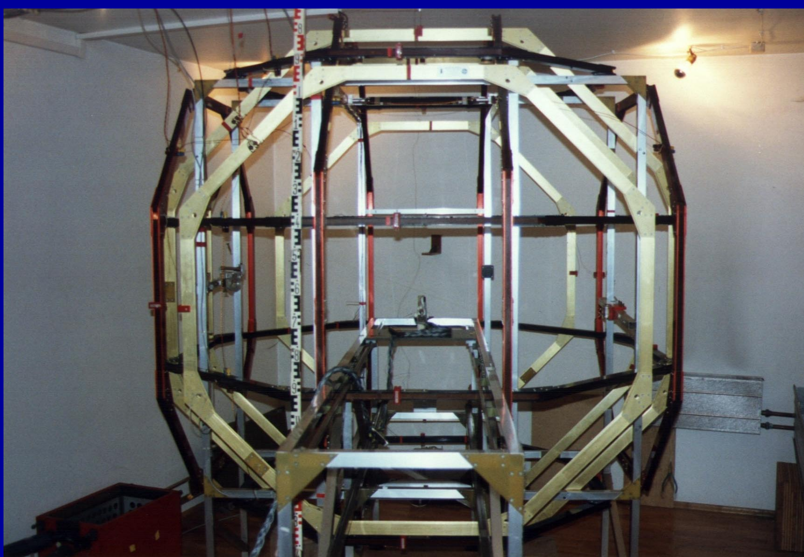
Example

Searchcoils onboard the Helios s/c



Magnetometer Calibration

Magnetometer Calibration
Magnetsrode - MCF



Magnetometer Calibration

Magnetsrode – Characteristics

- Compensation: Dynamic
- Field - Range: -100000 nT ... +100000 nT
- Field - Direction: any, 3 components
- Field -Type : DC, AC, Arbitrary
- Accuracy: < 0.8 nT

Magnetometer Calibration

Sensor Model

$$\underline{B}_c = \underline{\underline{F}}^{-1} \underline{B}_m$$

$$\underline{B}_c = \{\underline{\underline{R}}^{-1} \underline{\underline{M}}^{-1} \underline{\underline{S}}^{-1}\} (\underline{B}_r - \underline{B}_o - \underline{B}_{res})$$

Magnetometer Calibration
Parameters

- Sensitivity $\underline{\underline{S}}$ $= \{S_{ii}\}$, $S_{ii} = S_{ii}(T)$
- Misalignment $\underline{\underline{M}}$ $= \{M_{ij}\}$, $M_{ij} = M_{ij}(T)$
- Offset $\underline{B}_O$ $= \{ B_{ox}(T), B_{oy}(T), B_{oz}(T) \}$
- Frequency Response

Magnetometer Calibration
Parameters - Sensitivity

$$(S_{ii})^{-1} = \sigma_{0,i} + \sigma_{1,i} \cdot T$$

ROSETTA:

$\sigma_{0,x}$ [1]	$\sigma_{0,y}$ [1]	$\sigma_{0,z}$ [1]
1.09070	1.09434	1.09413

$\sigma_{1,x}$ [1/K]	$\sigma_{1,y}$ [1/K]	$\sigma_{1,z}$ [1/K]
-1.42E-005	-9.30E-006	-8.55E-006

Magnetometer Calibration
Parameters - Misalignment

$$(\underline{\underline{M}})^{-1}(T)=\begin{pmatrix} 1 & \cos(\xi_{xy}(T)) & \cos(\xi_{xz}(T)) \\ 0 & \sin(\xi_{xy}(T)) & \frac{\cos(\xi_{yz}(T))-\cos(\xi_{xy}(T))\cdot\cos(\xi_{xz}(T))}{\sin(\xi_{xy}(T))} \\ 0 & 0 & \sqrt{\sin^2(\xi_{xz}(T))-((\underline{\underline{M}})^{-1}_{12})^2} \end{pmatrix}$$

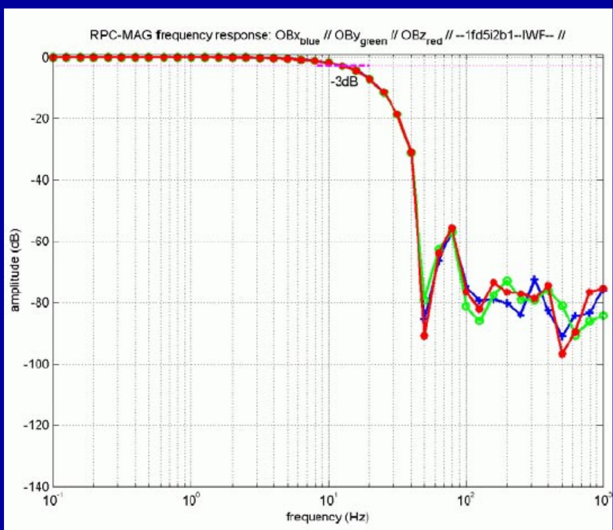
$$\boxed{\xi^1_{ij}(T)=\xi_{0,ij}+\xi_{1,ij}\cdot T}$$

ROSETTA:

$\xi_{0,xy}$ [°]	$\xi_{0,xz}$ [°]	$\xi_{0,yz}$ [°]
90.0348	89.9587	89.9433

$\xi_{1,xy}$ [°/K]	$\xi_{1,xz}$ [°/K]	$\xi_{1,yz}$ [°/K]
8.54E-005	3.71E-005	1.20E-004

Magnetometer Calibration
Frequency Response



Magnetic Cleanliness

Magnetic Cleanliness
Basic Ideas

- Magnetic properties of the s/c have to be known to perform excellent measurements in space

  ⇓ Every unit has to be mapped before integration

- S/C is represented by a model of *n* Dipoles
- Usage of Compensation-Magnets

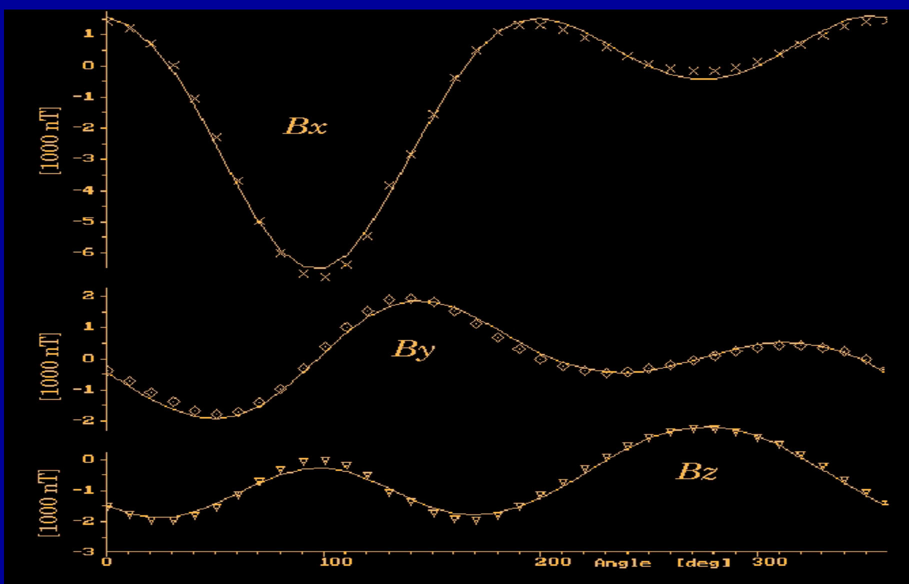
  ⇓ Magnetic field at the location of the MAG can be minimized

Magnetic Cleanliness

A mobile Coil Facility – (MCF)

Magnetic Cleanliness

Example: A **CLUSTER** Thruster



Magnetic Cleanliness
Example: A **CLUSTER** Thruster

REPORT (UNIT LEVEL MODEL)
========================

DUT-NAME: 10 Newton Thruster s/n 485

SCS (Spacecraft Coordinate System)

	Position [cm]			Moments [mAm2]			
	x	y	z	Mx	My	Mz	Mtot
1.	22.18	112.21	85.48	327.53	-384.85	-16.20	505.62
2.	28.47	100.32	86.69	-1105.86	-2189.66	334.80	2475.80
3.	25.90	101.97	86.78	729.64	2505.89	-276.60	2624.57

Total Moment spec: 9.50

Total Moment : -48.68 -68.62 42.00 94.03

Pos FGM0 (x,y,z) [cm] : 124.65 -600.19 52.59

Field FGM0 spec (x,y,z,tot) [pT]: -0.7 5.2 0.3 5.3

Field FGM0 (x,y,z,tot) [pT]: 23.1 -33.0 -14.4 42.8

Summary

- Magnetic field measurements in space are exciting and interesting due to complex, temporally varying plasma interactions between SW, celestial bodies
- Instrumentation: FGM is standard s/c application (low power, leightweight,reliable,remote controlled, radiation hard, long term stable, high resolution...)
- Careful calibration necessary for serious science
- Extensive Magnetic Cleanliness program guarantees known measurement conditions

More Information:

- Modern Magnetic Field Measurement Devices:
  ftp.geophys.nat.tu-bs.de/pub/mrode/doc/mag_en_over.pdf
- Daily Magnetic Field Data:
  www.tu-bs.de/institute/geophysik/dienste/mrode/daten_en.html
- Magnetsrode Calibration Facility:
  www.tu-bs.de/institute/geophysik/dienste/mrode/magnetsrode_en.html