Space Instrumentation:

Measuring Magnetic Fields in Space

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… the next 45 Minutes

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

The Magnetic field

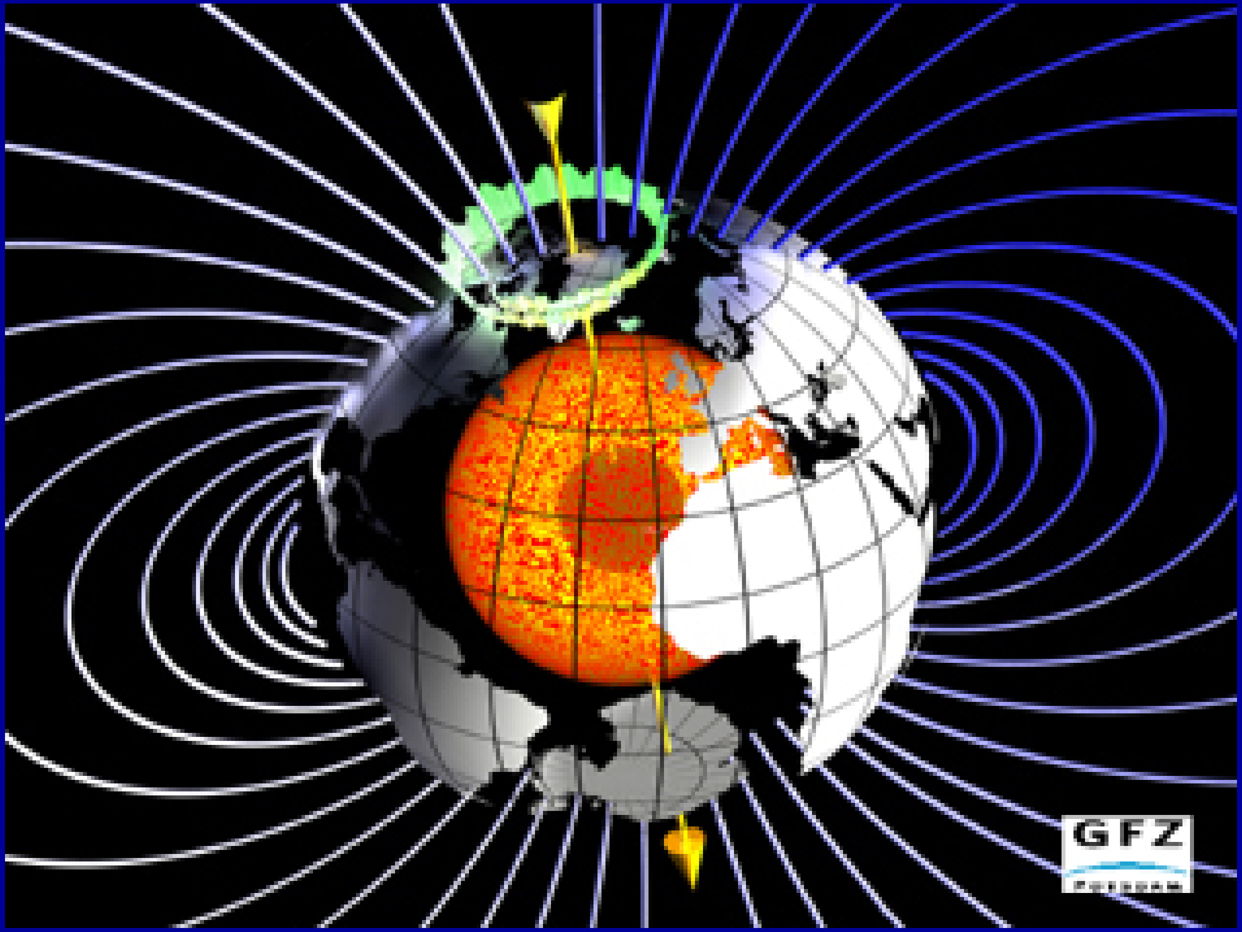
The Magnetic field

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

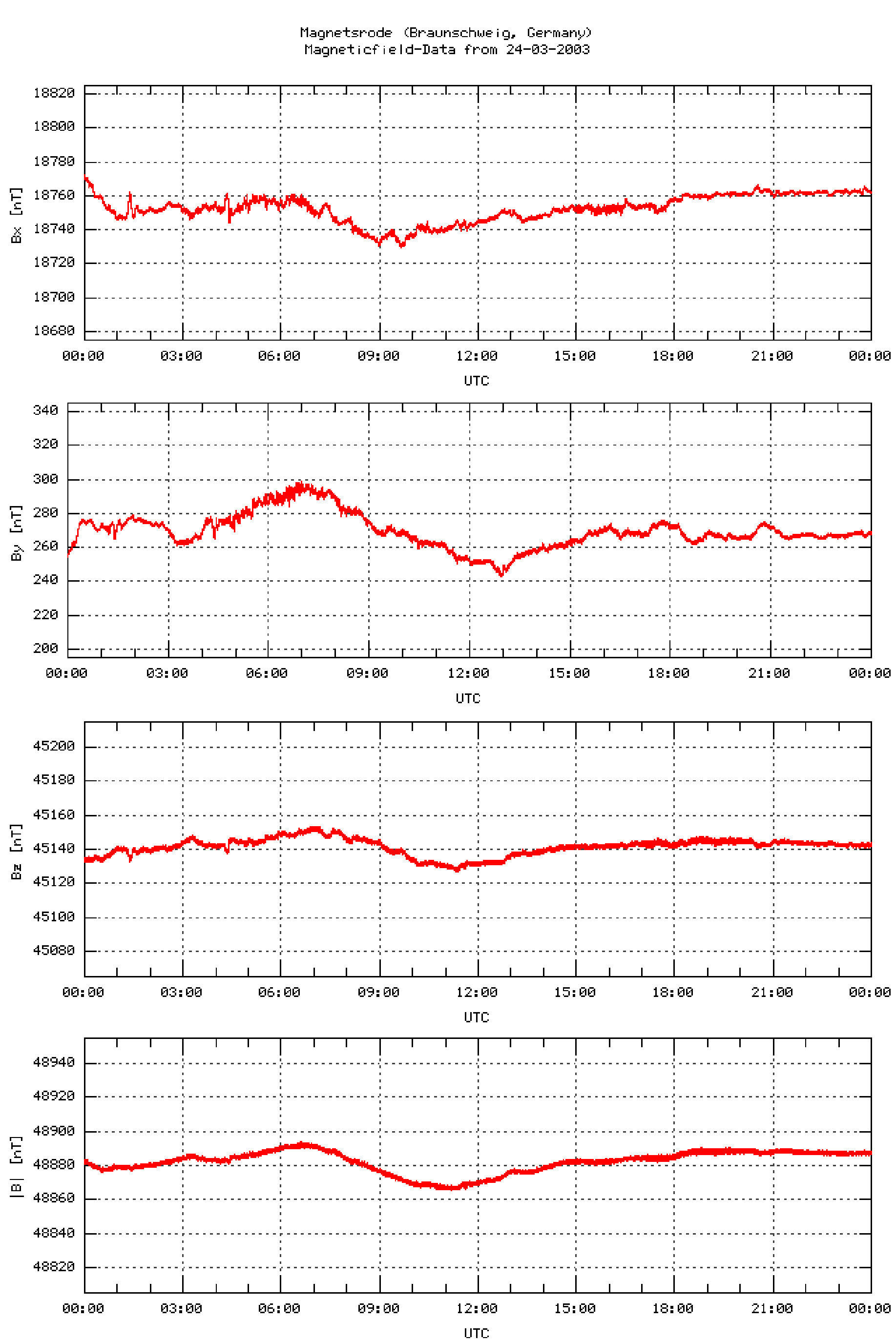
Declination

Inclination

The Magnetic field

Ground Observations- I

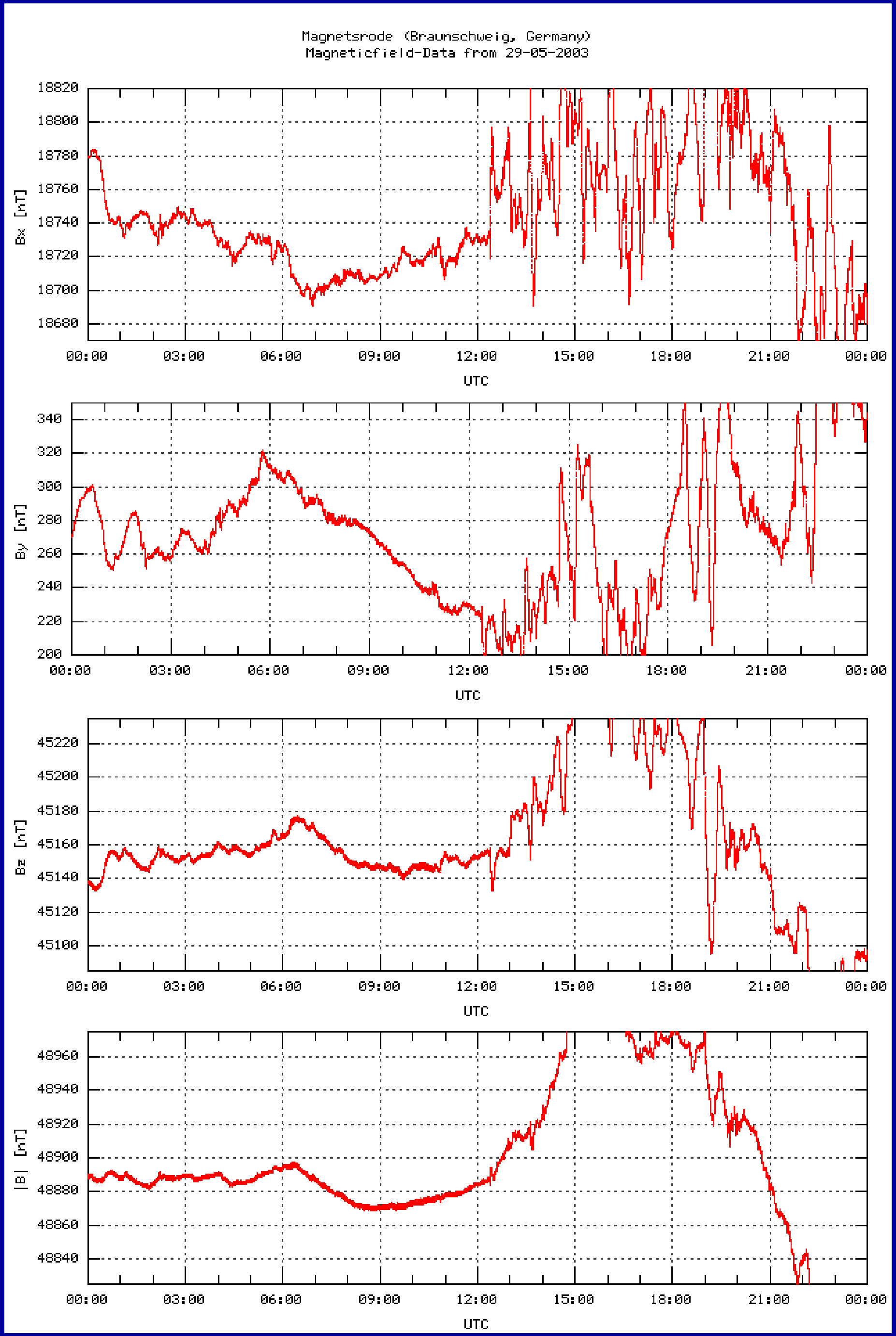
... a calm day



The Magnetic field

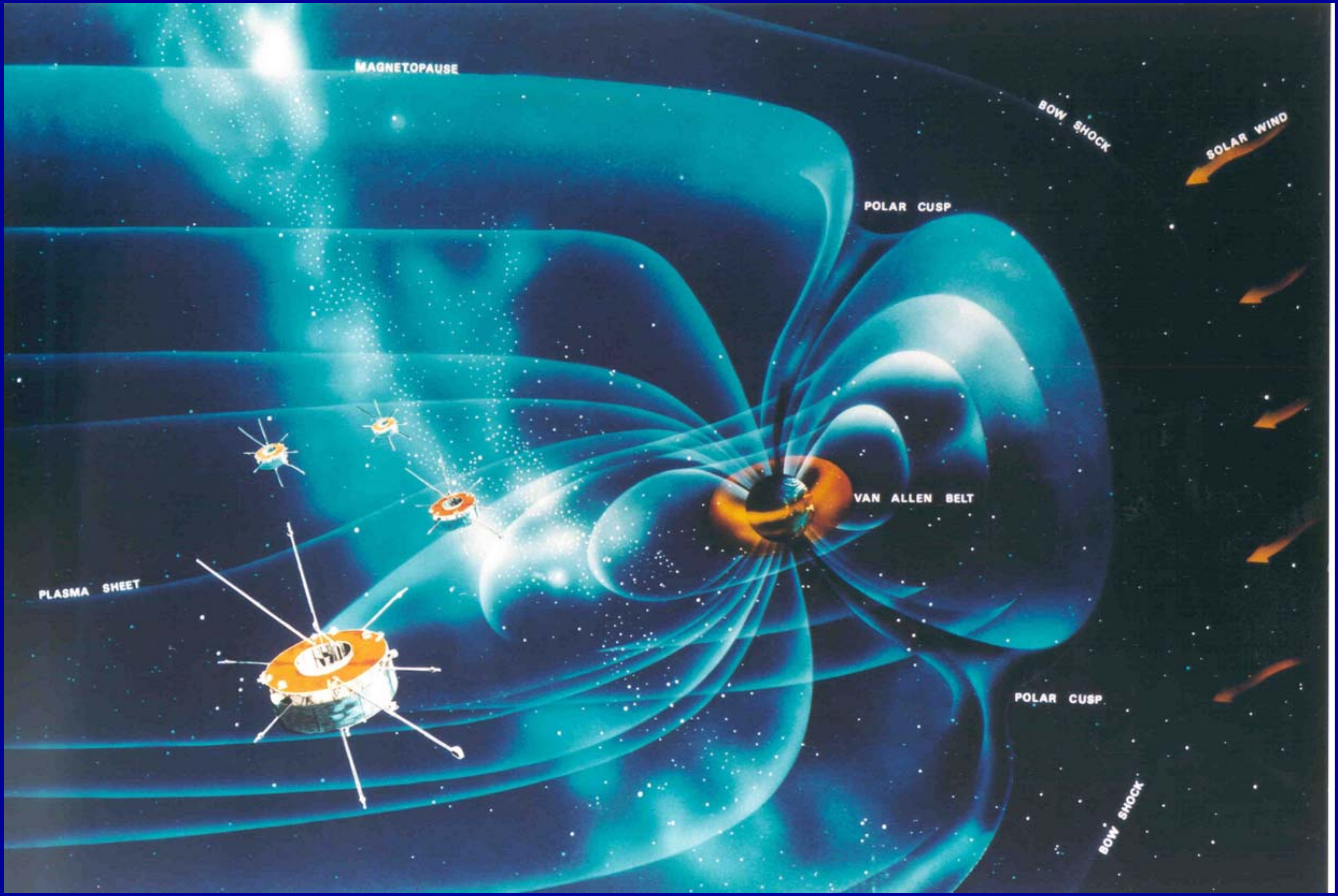
Ground Observations- II

... a disturbed day



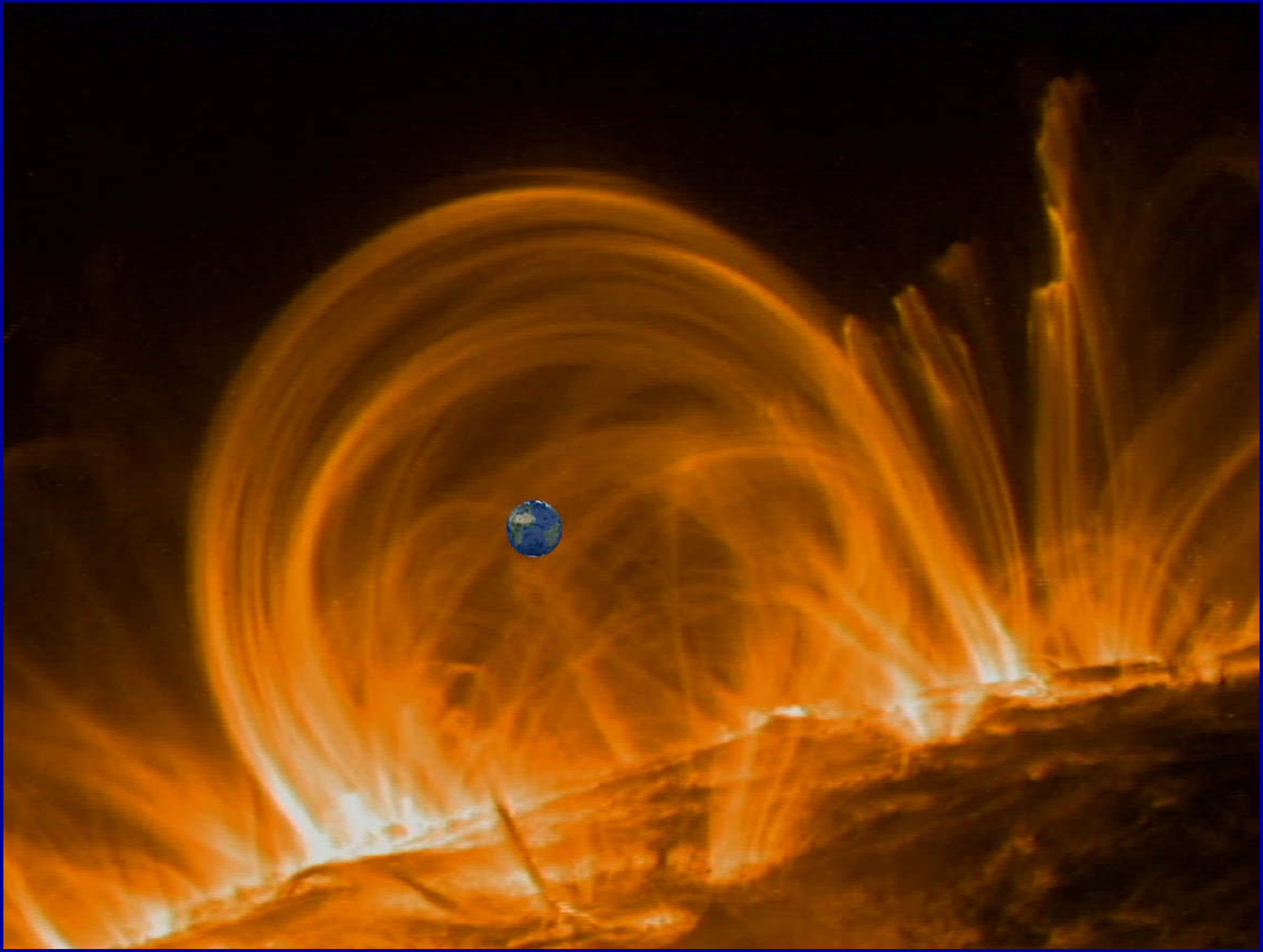
The Magnetic field

The real Earth



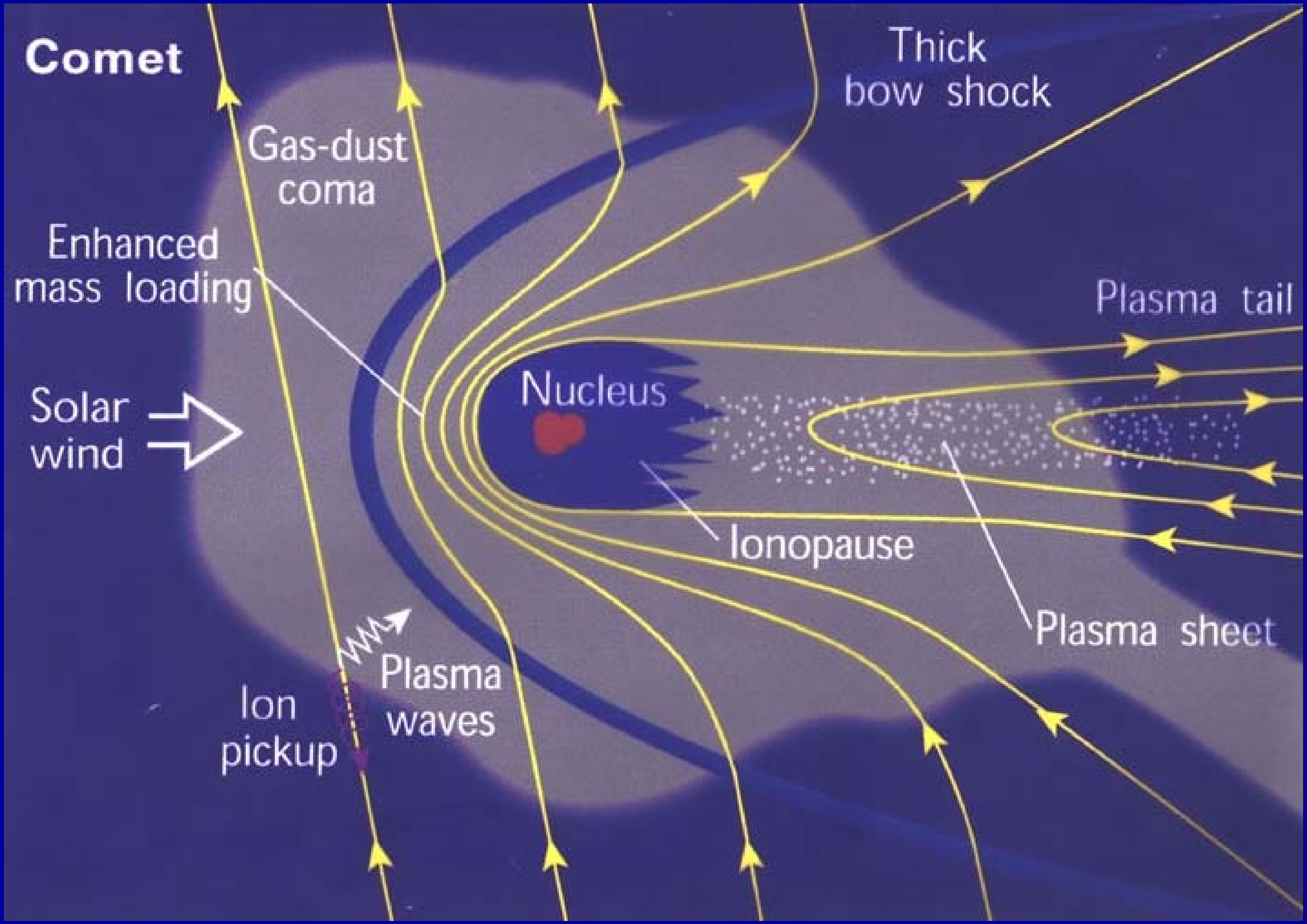
The Magnetic field

The Sun



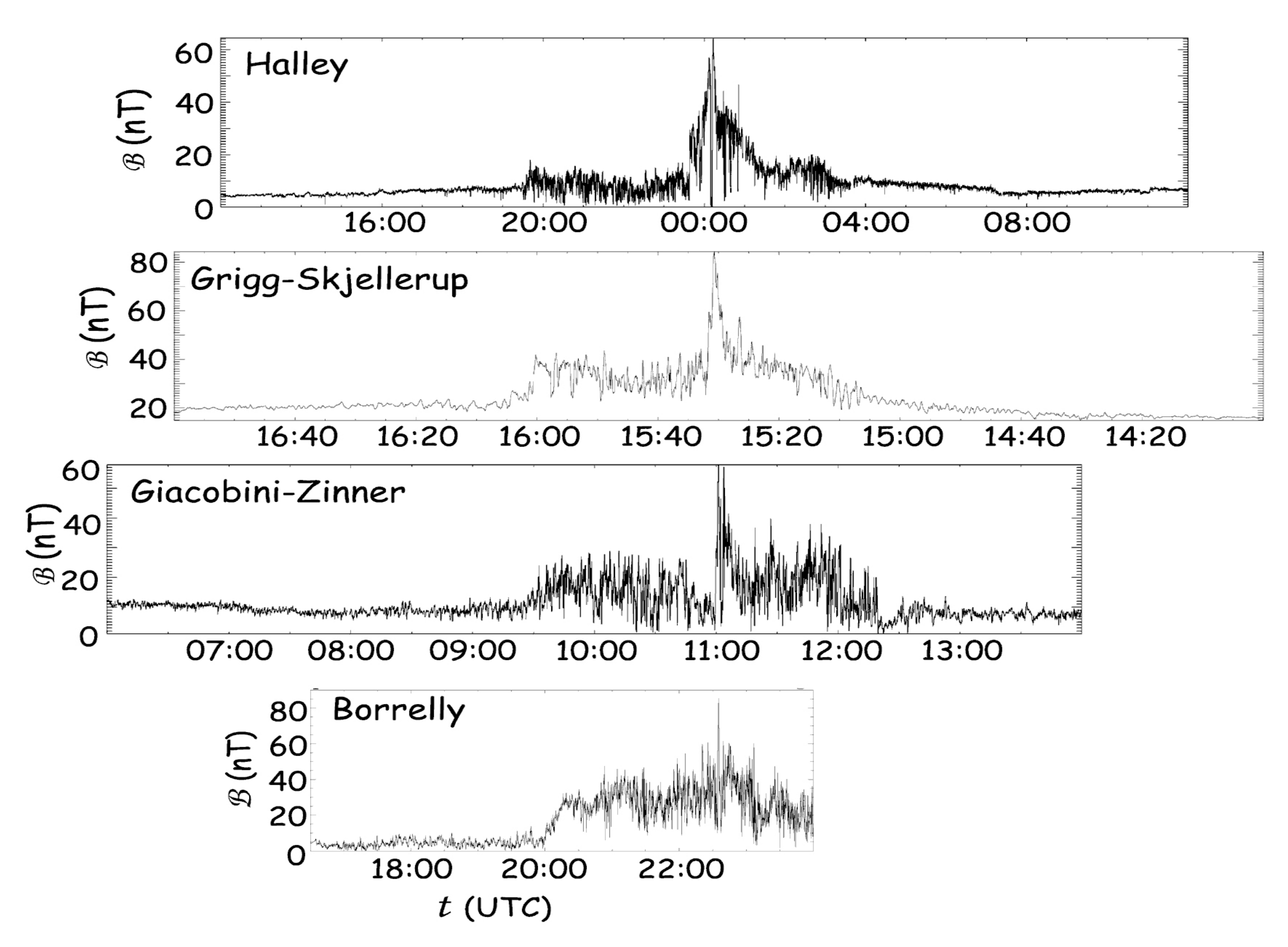
The Magnetic field

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

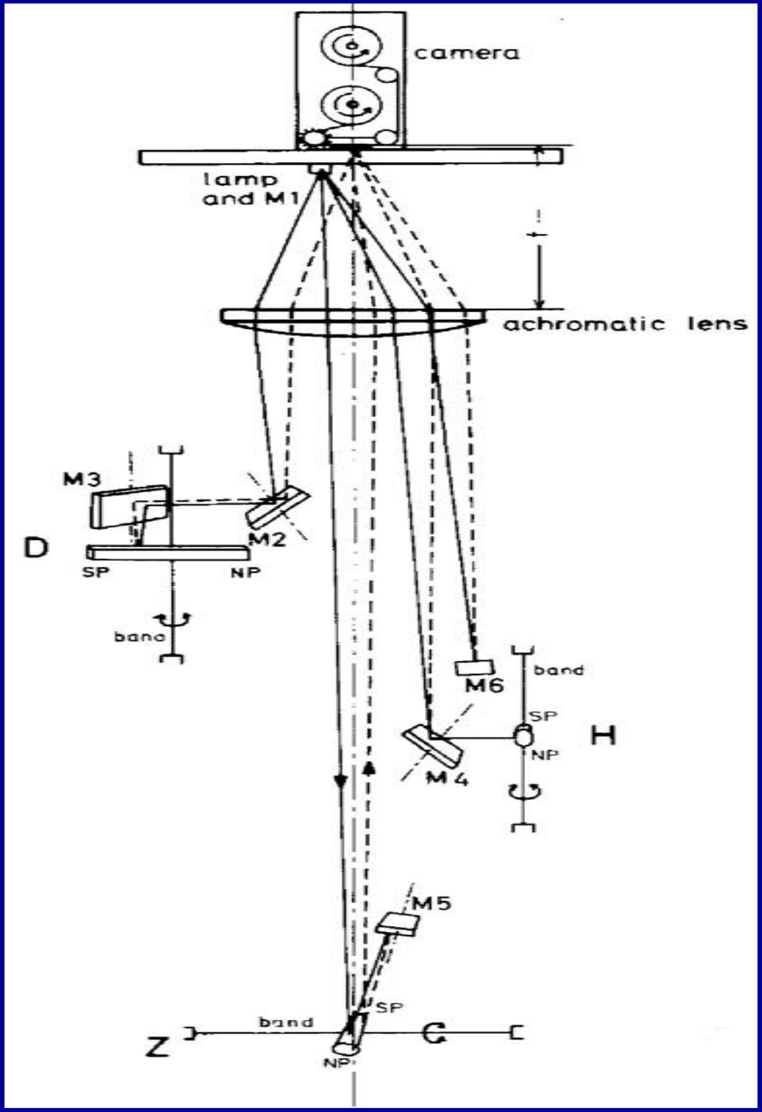
Magnetometers

Overview

- Direction
  - Mechanical
    - Compass
- Scalar
  - Optical Pumped
    - Scalar-He
  - Atomic Constants
    - Proton-Mag.
    - Overhauser
- Vector Components
  - Optical Pumped
    - Vector- He
  - Mechanical
    - Torsional Mag.
    - Field-Balance
  - Electrical
    - Fluxgate
    - Magneto Resistive
    - Hall Sensor
    - Searchcoil

Torsional Magnetometer

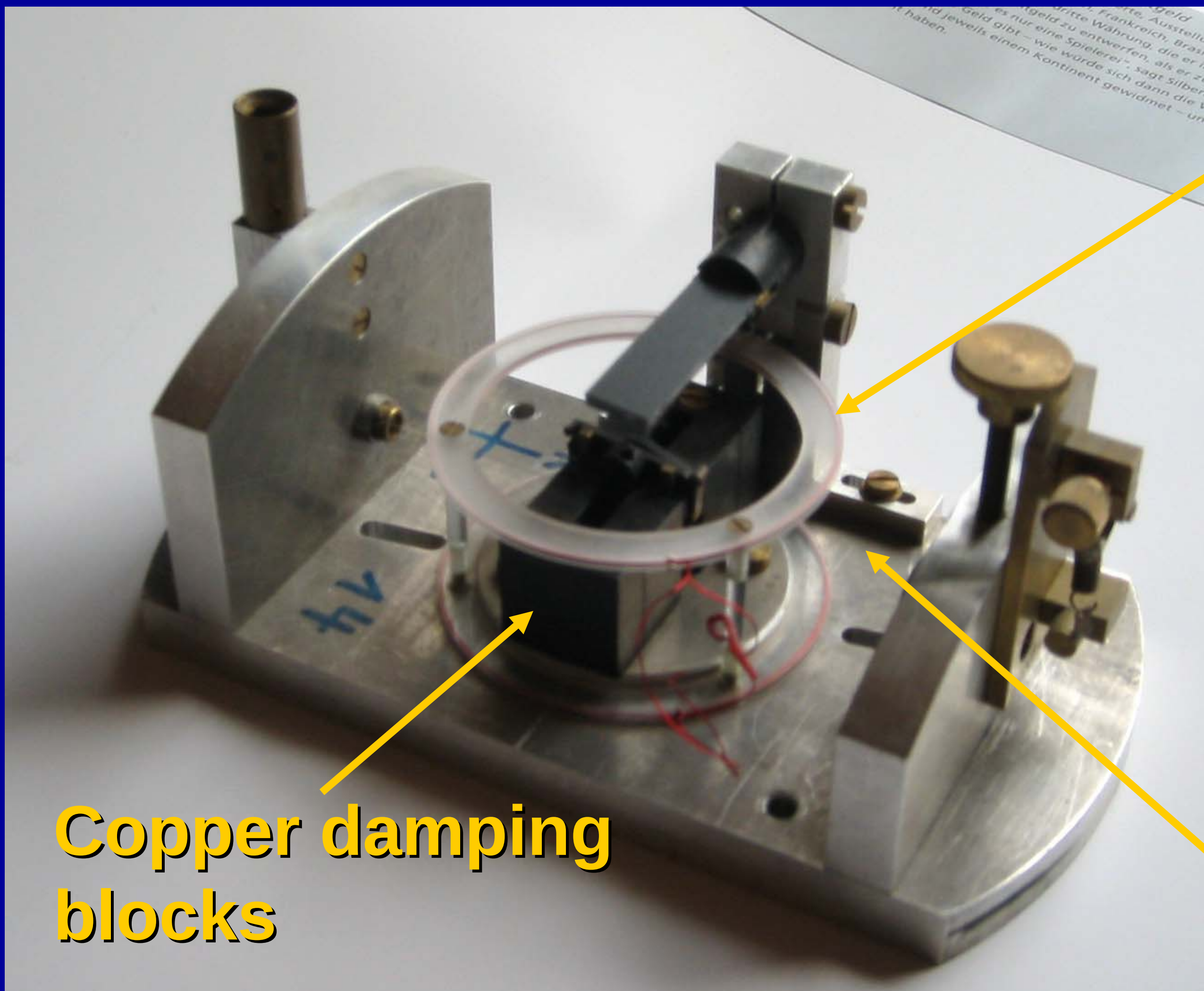
A Classical Instrument



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

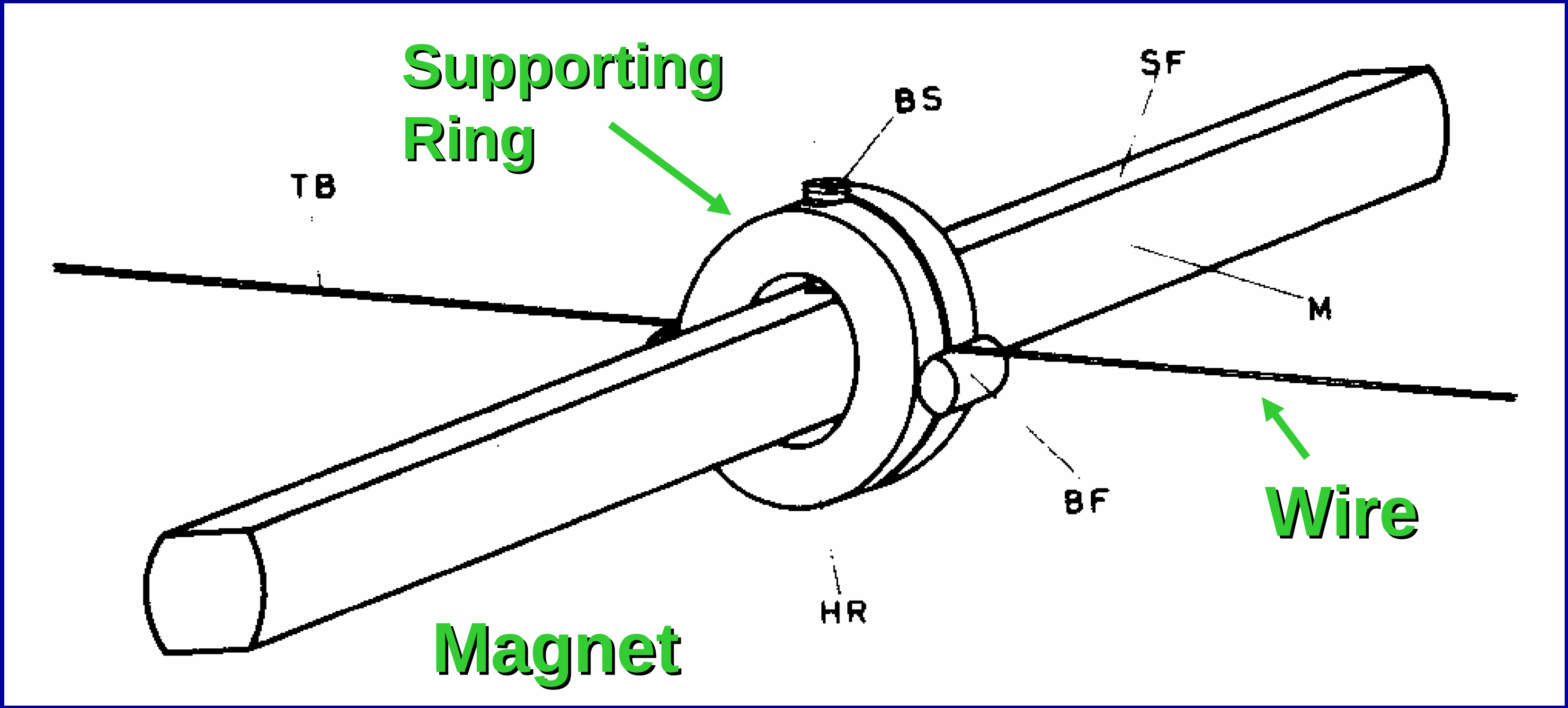
Torsional Magnetometer

The z-Component of the Gough-Reitzel Magnetometer



Torsional Magnetometer

Magnet and Suspending Wire



Torsional Magnetometer

Torque 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 torque balance equation reads:

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

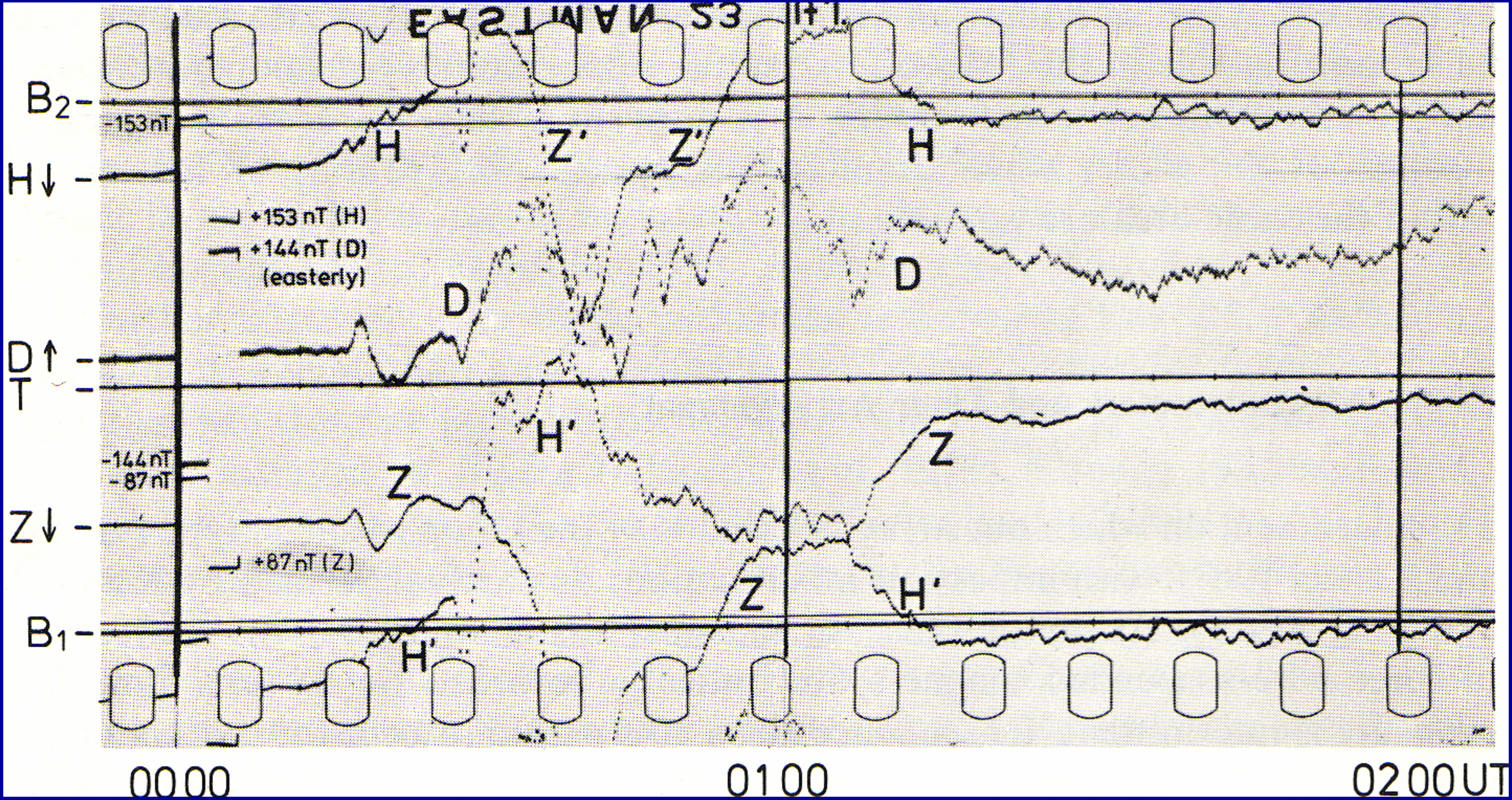
where M is the magnetic moment, H_Z the vertical component of the field, D the torsional module, and a the torsional angle. It follows

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

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

Torsional Magnetometer

A Sample Record



Torsional Magnetometer

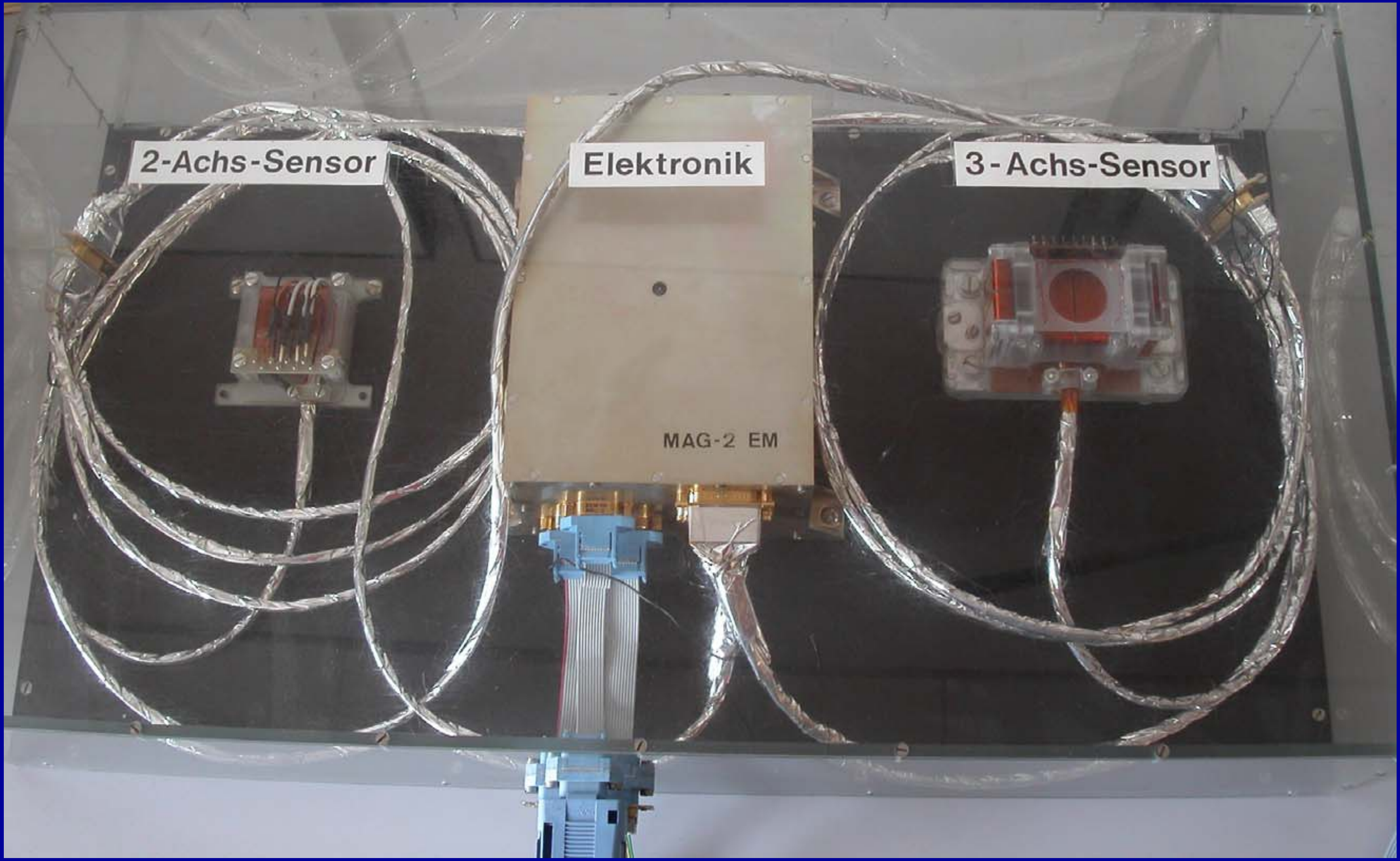
Characteristics

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



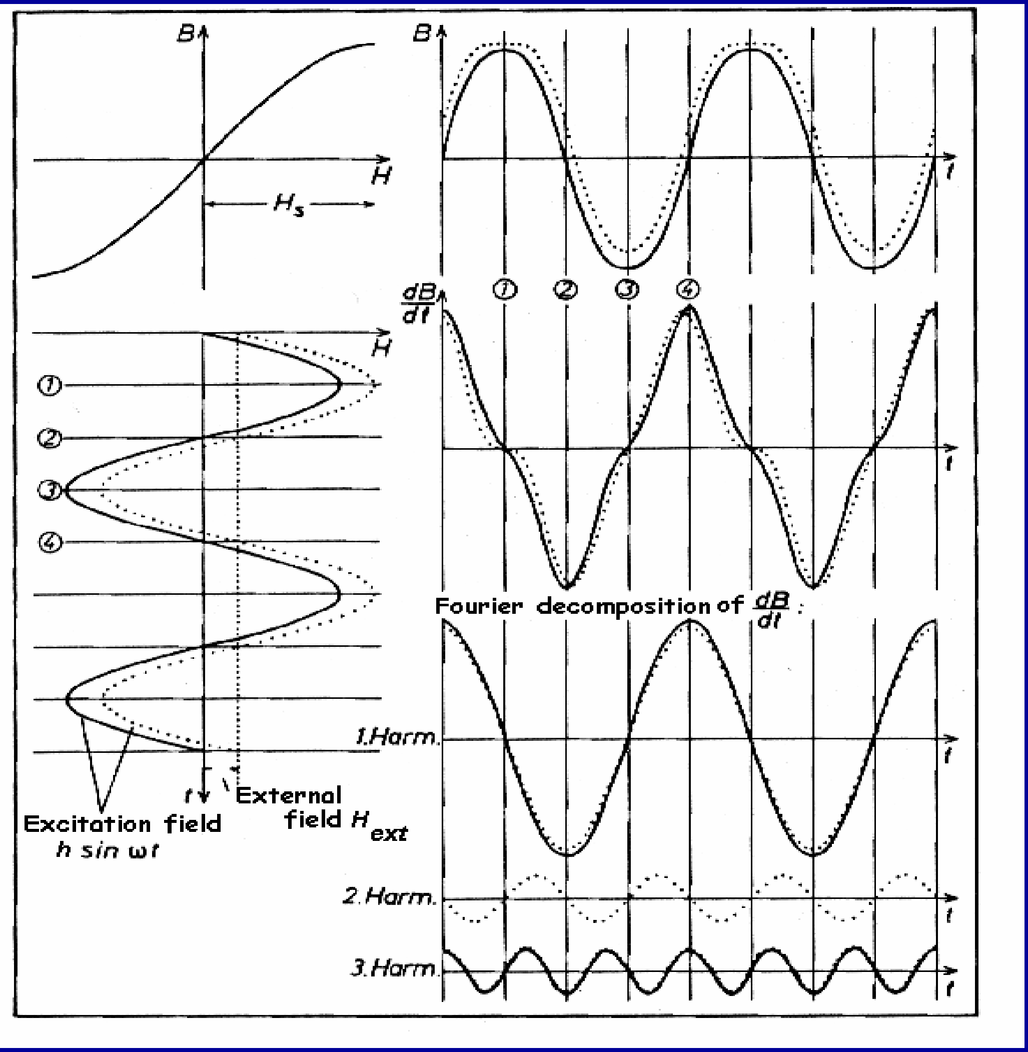
Fluxgate - Magnetometer (FGM)

Classification

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

Fluxgate - Magnetometer (FGM)

Characteristic Curve, Excitation and Output Voltage



Characteristic curve:

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

Excitation:

$$H(t) = H_{ext} + h \sin(\omega\, t)$$

Induced voltage at the secondary coil:

$$Ui \sim dB/dt$$

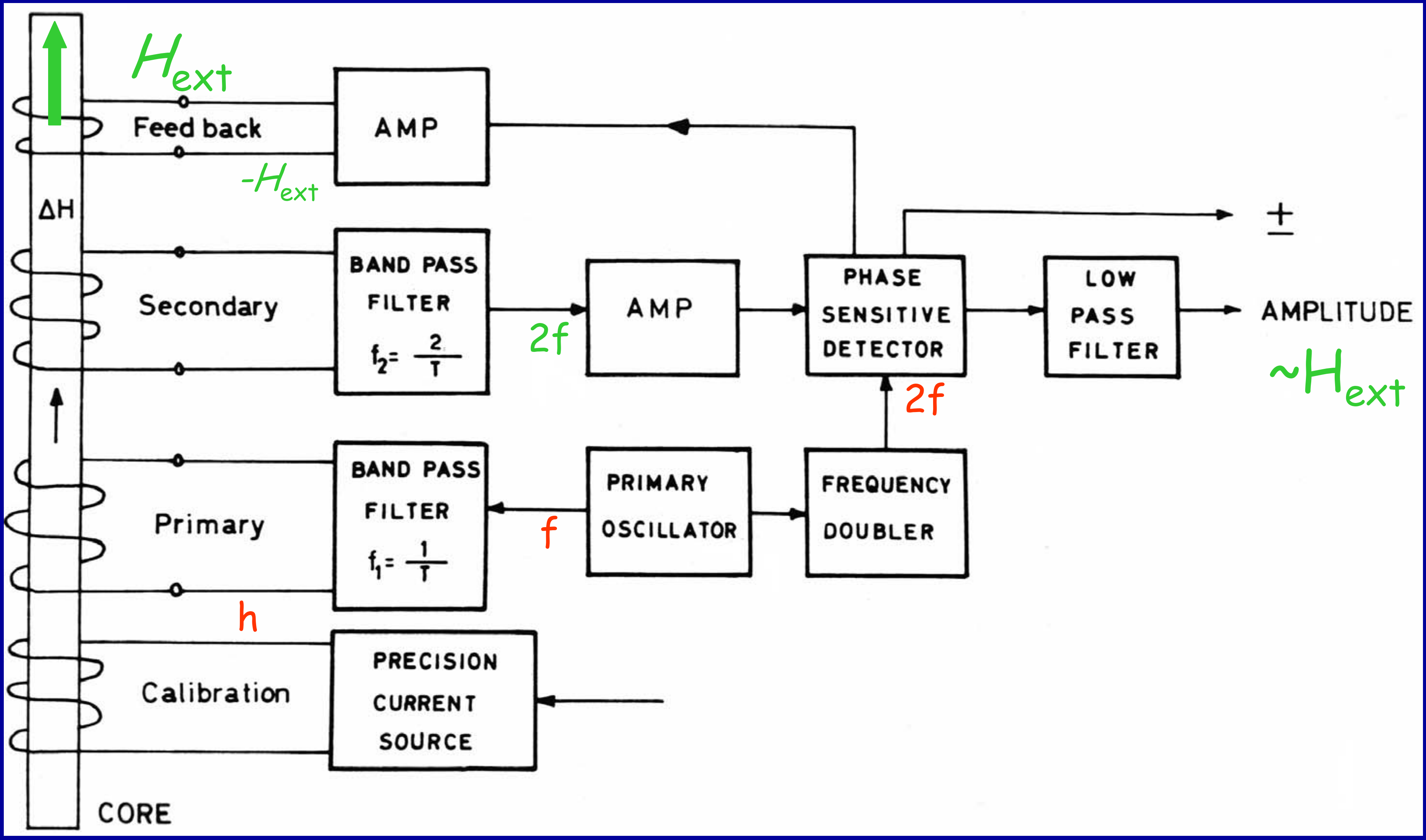
$$= 3\,h\,(1 - H^2_{ext} - 1/4\,h^2)\,\omega\,\cos(\omega\, t)$$

$$-3\,H_{ext}\,h^2\,\omega\,\sin(2\,\omega\, t)$$

$$+3/4\,h^3\,\omega\,\cos(3\,\omega\, t)$$

Fluxgate - Magnetometer (FGM)

Schematic Construction



Fluxgate - Magnetometer (FGM)

Functional Principle: Summary

- Non-linear magnetization curve is driven into saturation by periodic excitation (f)
- Pulsed excitation ⇨ less power consumption
- External field $\underline{H}_{ext}$ ⇨ ($2f$)
- Lock-in ($2f$), PSD, Integration $\rightarrow$ $\langle U_{2f} \rangle \sim B_{ext}$
- Feedback using $-\langle U_{2f} \rangle$ ⇨ Zero field and reduction of non-linearities

Fluxgate - Magnetometer (FGM)

Sensor Design

Problem:

Decoupling of small 2^{nd} harmonic from the excitation signal

Solution:

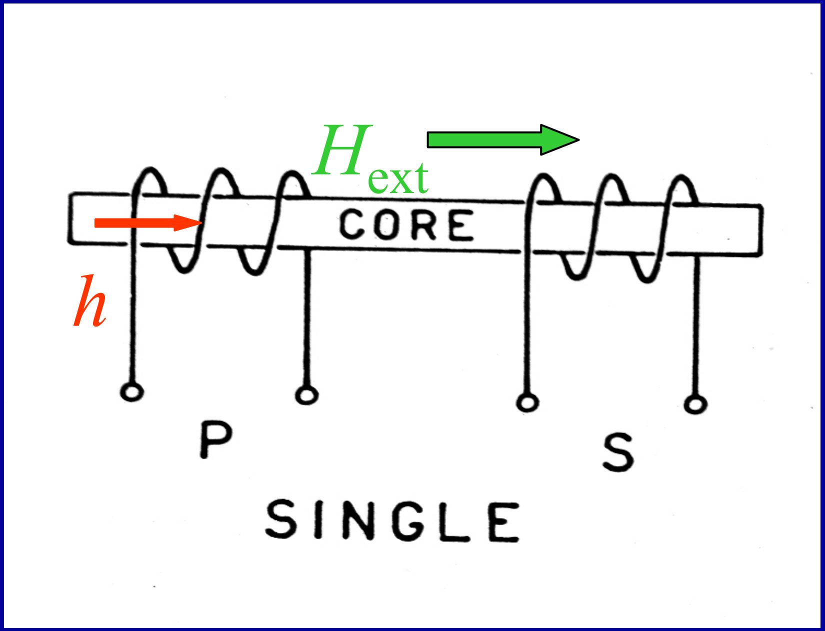
Suitable sensor geometry for suppression of odd harmonics

Fluxgate - Magnetometer (FGM)

Sensor Design:

Rod Core

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

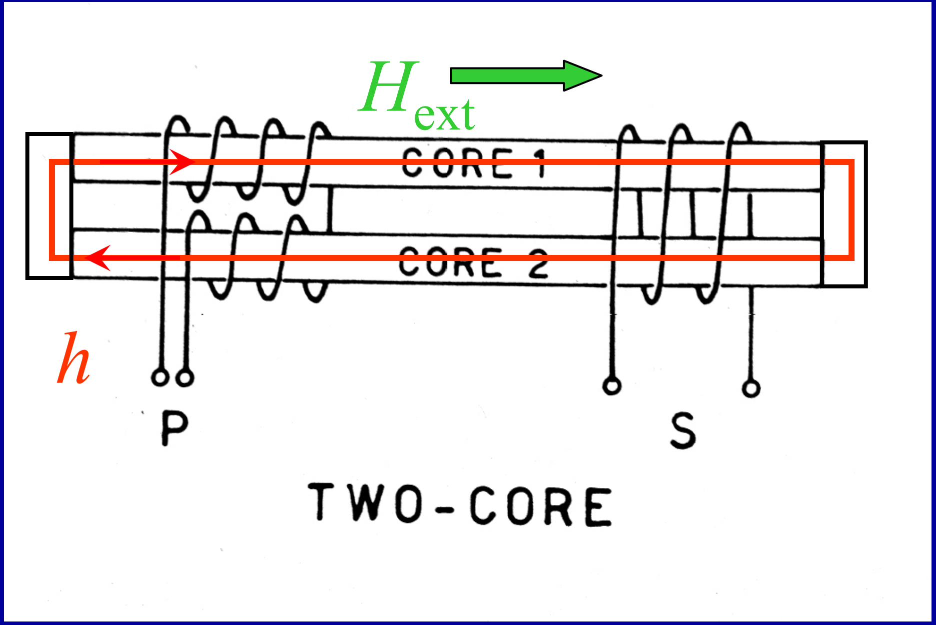


Fluxgate - Magnetometer (FGM)

Sensor Design:

Double Rod Core

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

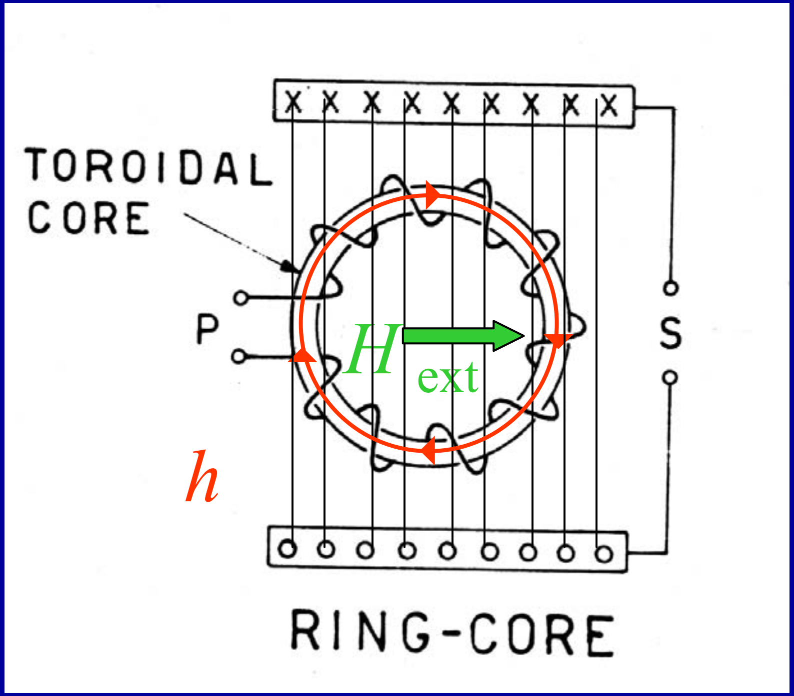


Fluxgate - Magnetometer (FGM)

Sensor Design:

Ring Core

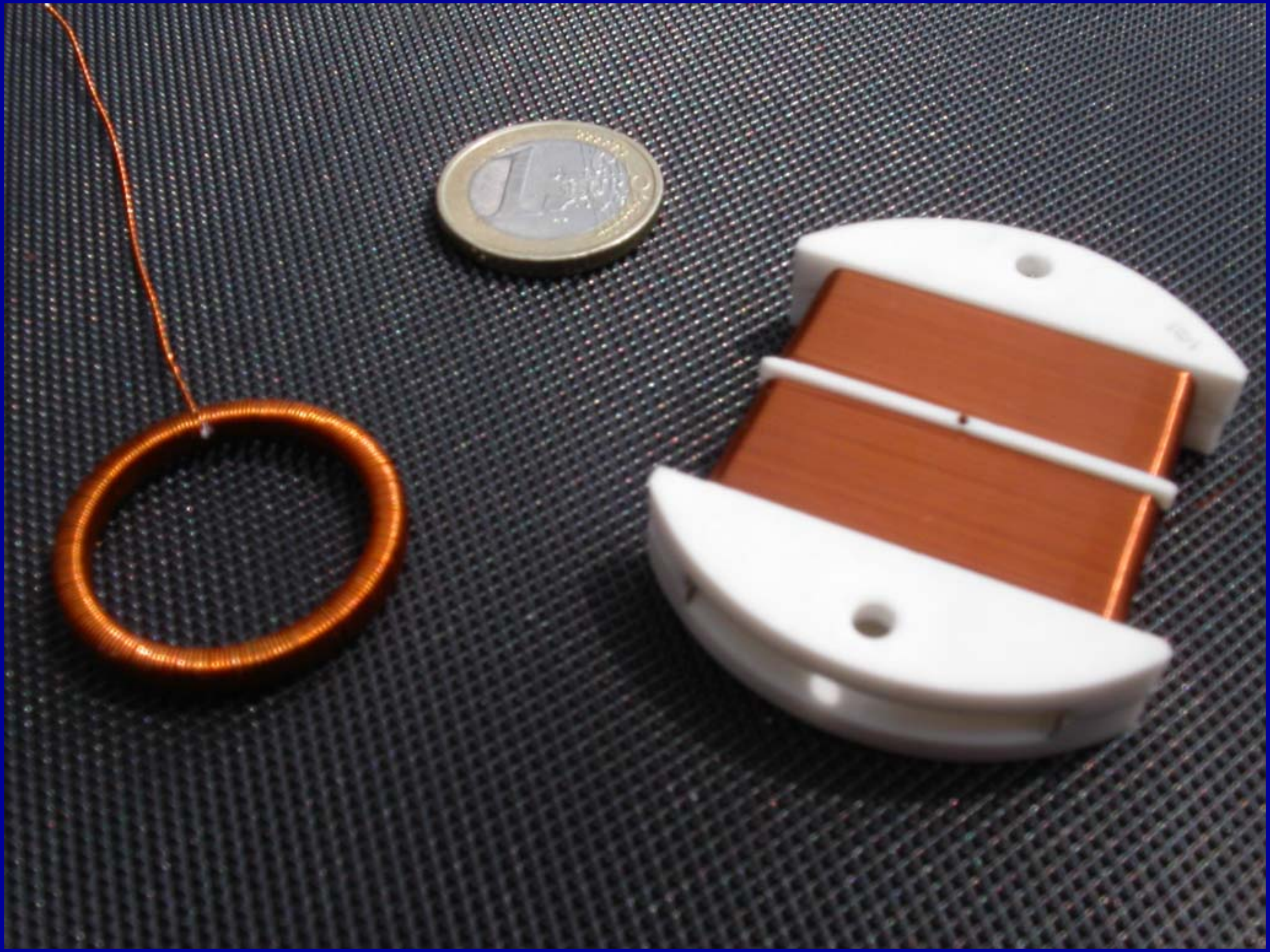
Further development of the Double Rod Core with same advantages.
Common outer rectangular secondary coil
⇨ Only even harmonics



Fluxgate - Magnetometer (FGM)

Examples

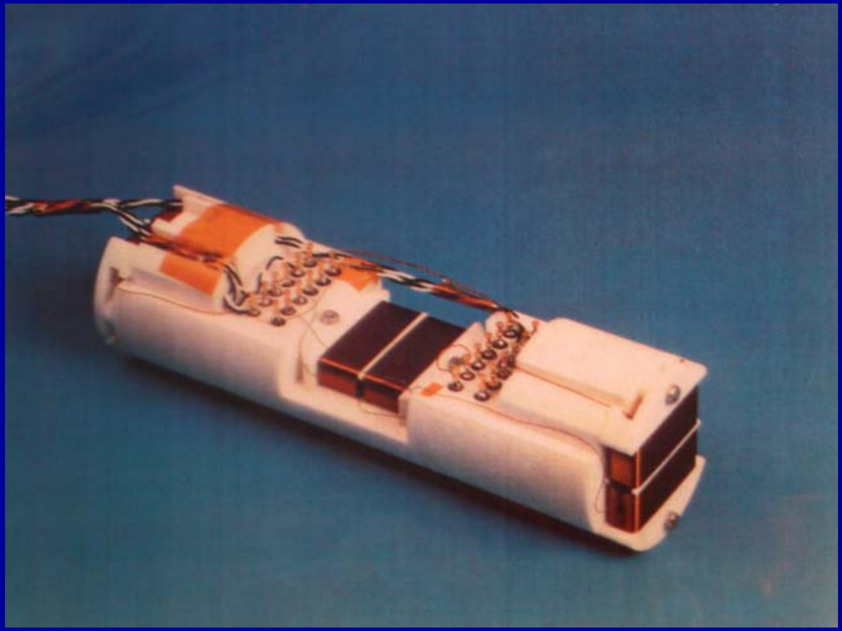
1- Axis Ring Core Sensor

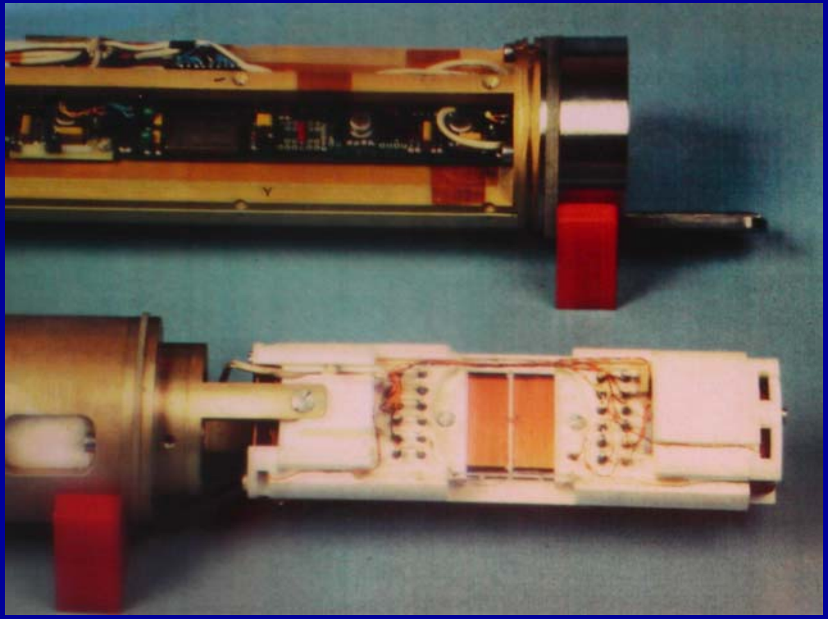


Fluxgate - Magnetometer (FGM)

Examples

3 Axes FGM KTB Borehole Sensor

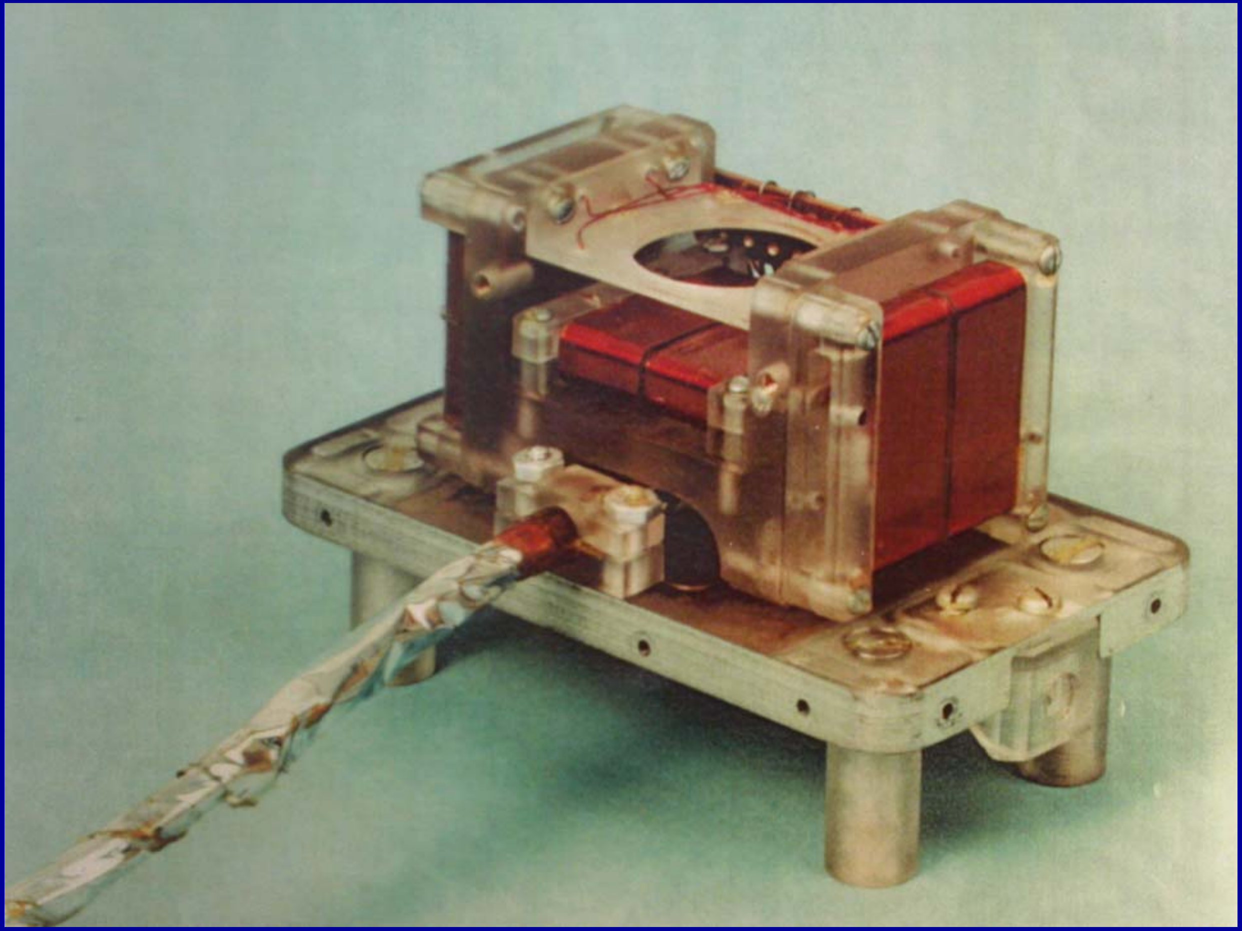




Fluxgate - Magnetometer (FGM)

Examples

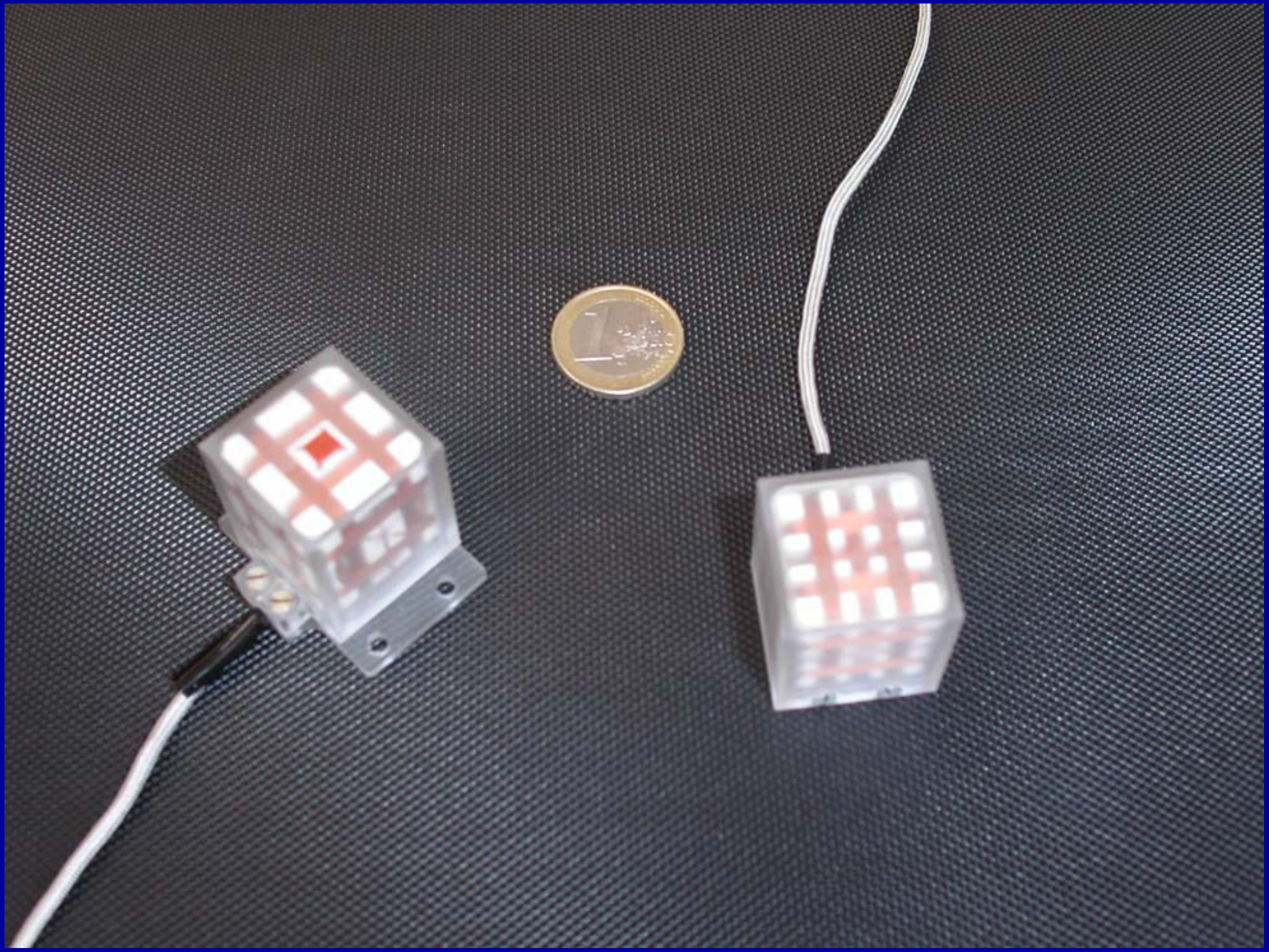
3 Axes CLUSTER FGM Sensor



Fluxgate - Magnetometer (FGM)

Examples

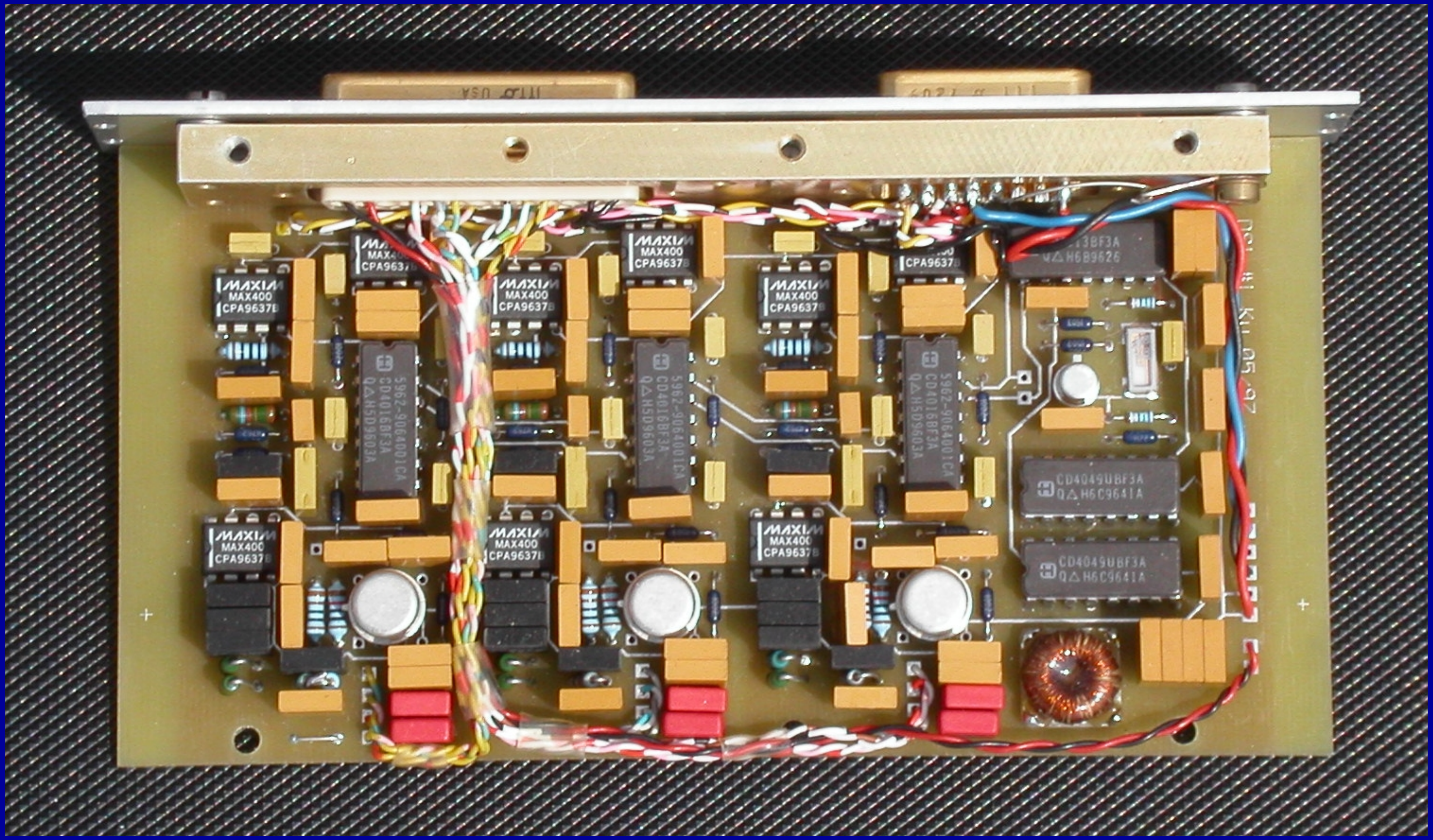
3 Axes ROSETTA / DS 1 FGM Sensors



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
  ⇨ AC-field measurements only
- Frequency spectrum mHz ... MHz
- Vector measurements with 3 orthogonal coils

SearchCoil - Magnetometer

Functional Principle

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

⇨ $U_{ind} = -\, n \;\; d\,(\underline{F} \bullet \underline{B}_{\perp}) / dt$

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

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

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

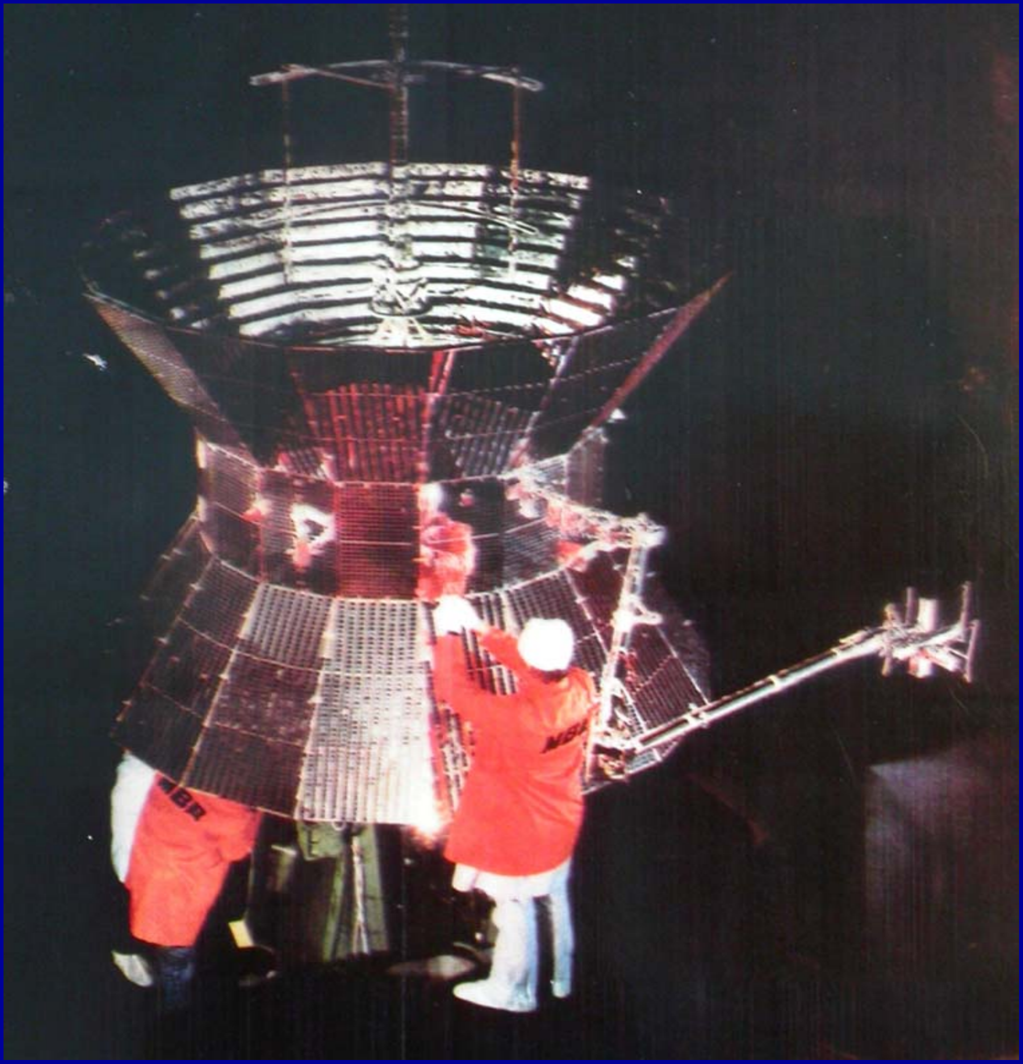
Real Sensors-Overview

Application	Axes	Wdgs.	Frequency Range [Hz]	Dimensions l x r [cm]	Sensitivity [µV/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	3	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

Example

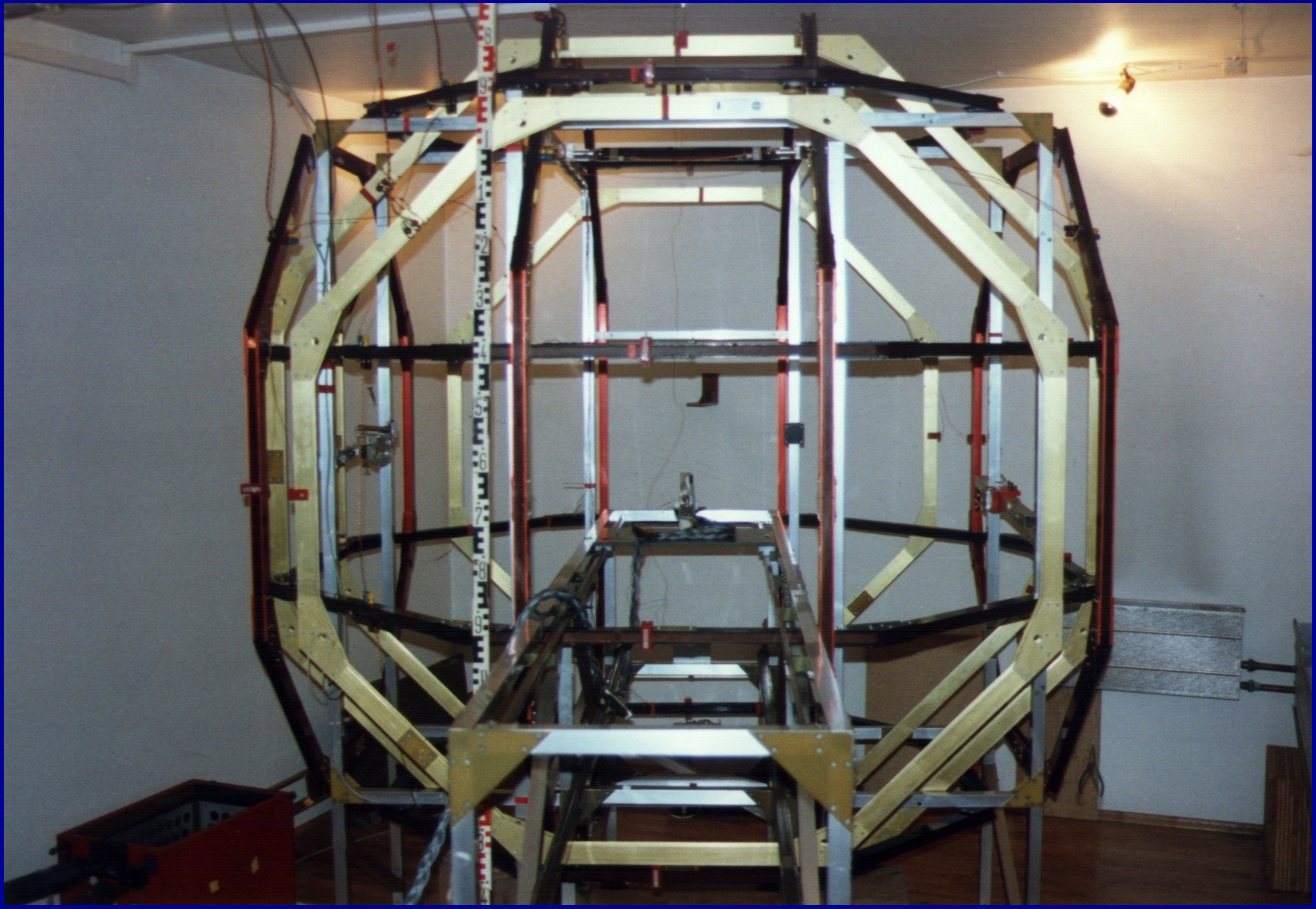
Searchcoils onboard the Helios s/c



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
• Field - Sequence:	arbitrary, user defined
• Accuracy:	< 0.8 nT
• Temperatures:	-196°C ... +200°C

Magnetometer Calibration

Sensor Model

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

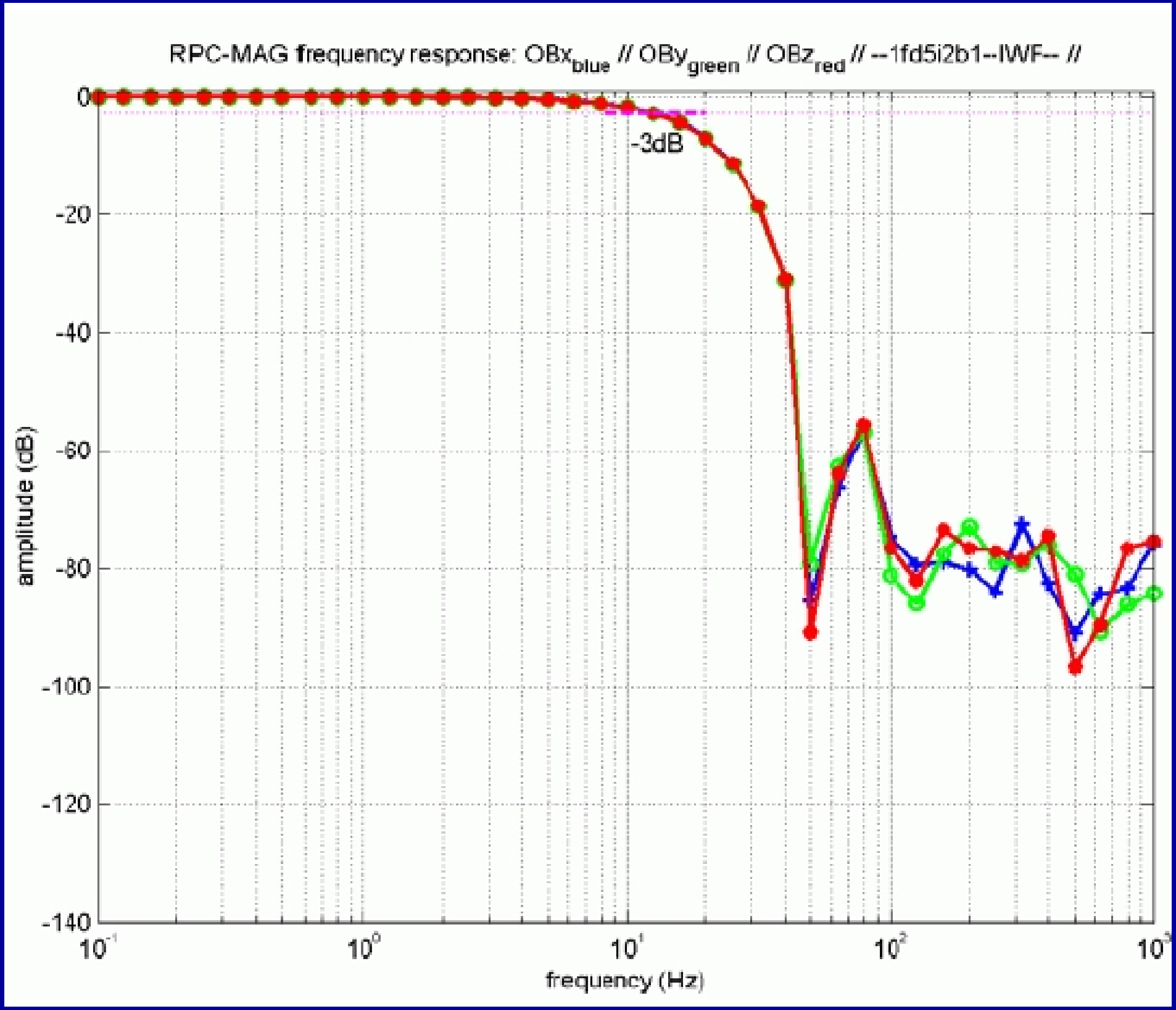
$$\underline{B}_c = \{\underline{\underline{R}}^{-1} \ \underline{\underline{M}}^{-1} \ \underline{\underline{S}}^{-1}\} (\underline{B}_r - \underline{B}_o - \underline{B}_{res})$$

Magnetometer Calibration

Parameters

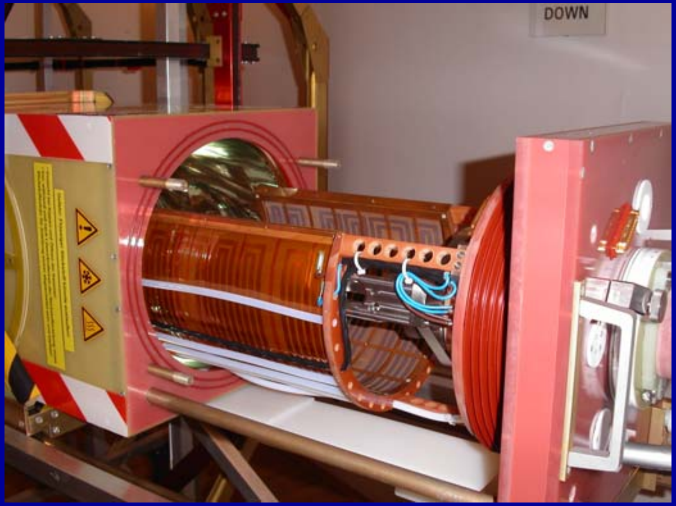
- Sensitivity $\underline{\underline{S}}$ $= \{S_{ii}\}$, $S_{ii} = S_{ii}(T)$
- Misalignment $\underline{\underline{M}}$ $= \{M_{ij}\}$, $M_{ij} = M_{ij}(T)$
- Offset $\underline{B}_O$ $= \{ B_{ox}(T), B_{oy}(T), B_{oz}(T) \}$
- Frequency Response

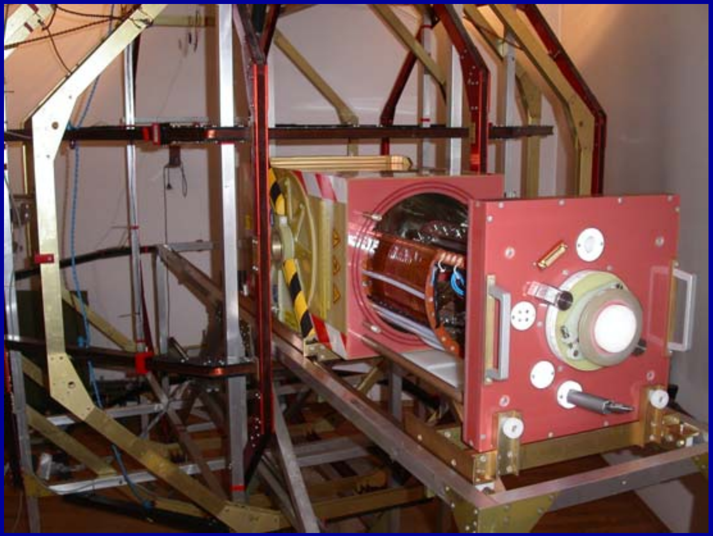
Magnetometer Calibration
Frequency Response

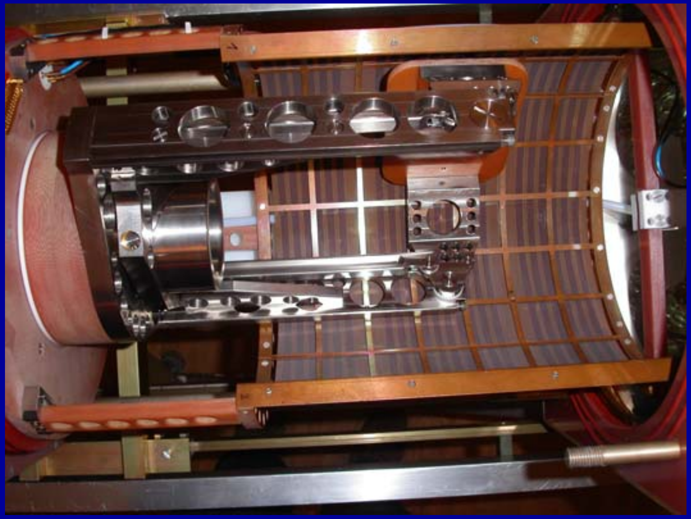


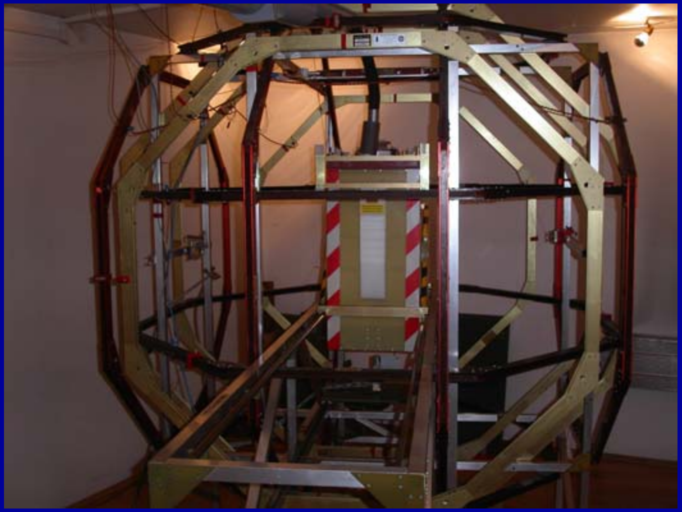
Magnetometer Calibration

Temperature Behavior









Magnetic Cleanliness

Magnetic Cleanliness

Basic Ideas

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

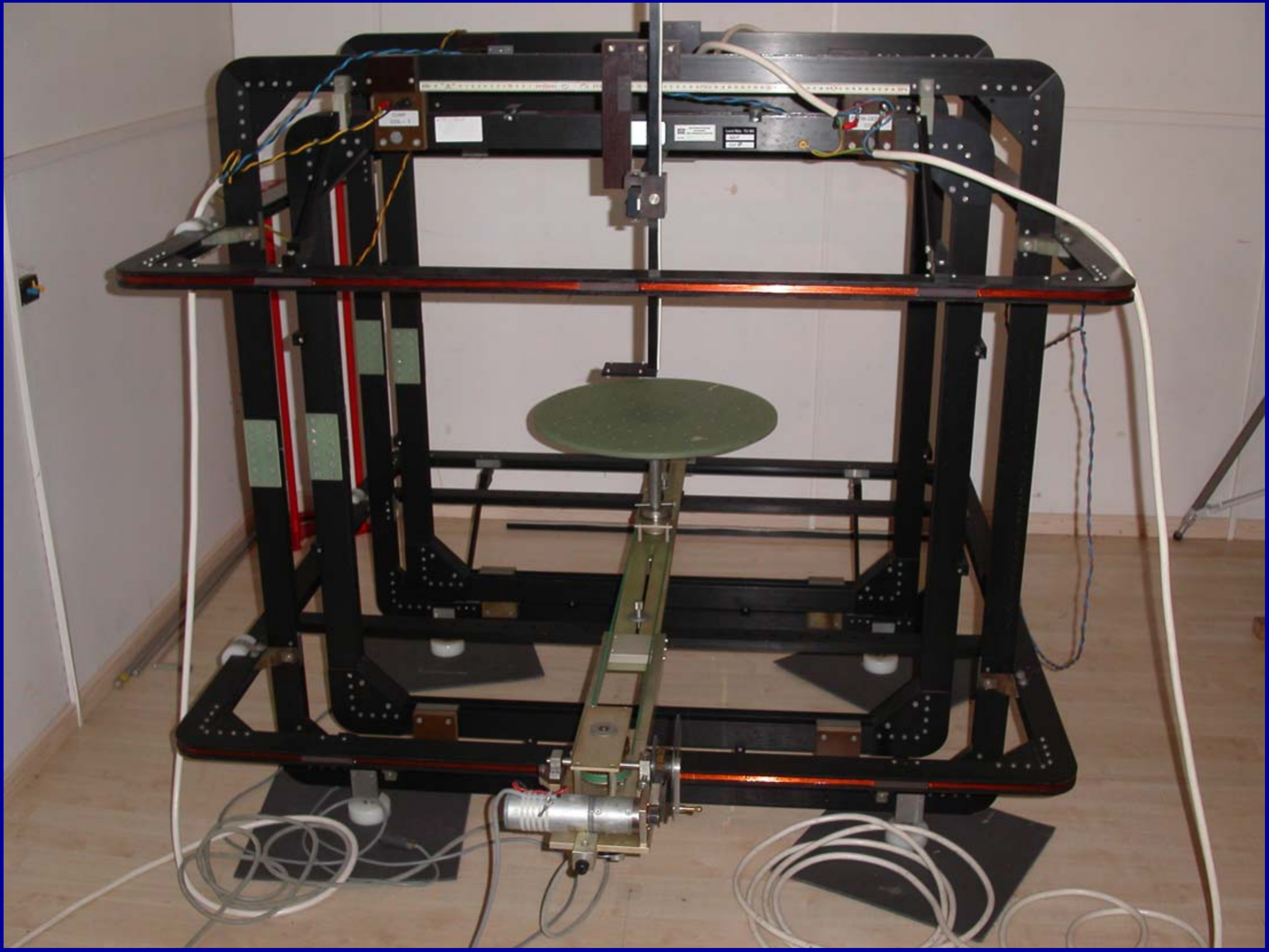
⇨Every unit has to be mapped before integration

- 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

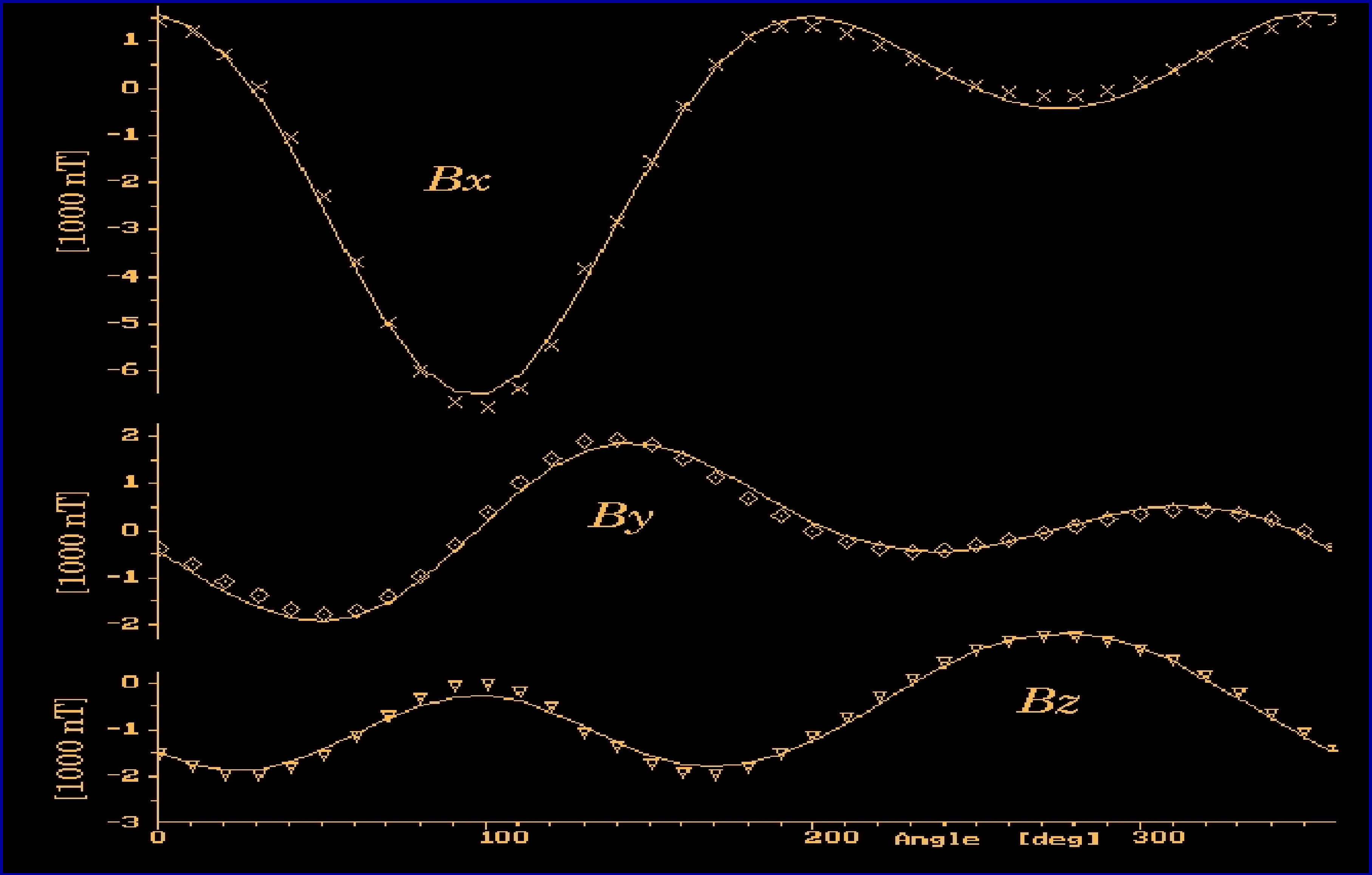
Magnetic Cleanliness

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, lightweight,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:

IGEP TU Braunschweig Institut für Geophysik und extraterrestrische Physik

- **Modern Magnetic Field Measurement Devices:**
  ftp.geophys.nat.tu-bs.de/pub/mrode/doc/mag_en_over.pdf

- **Daily Magnetic Field Data:**
  www.geophys.tu-bs.de/dienste/mrode/daten_en.html

- **Magnetsrode Calibration Facility:**
  www.geophys.tu-bs.de/dienste/mrode/magnetsrode_en.html