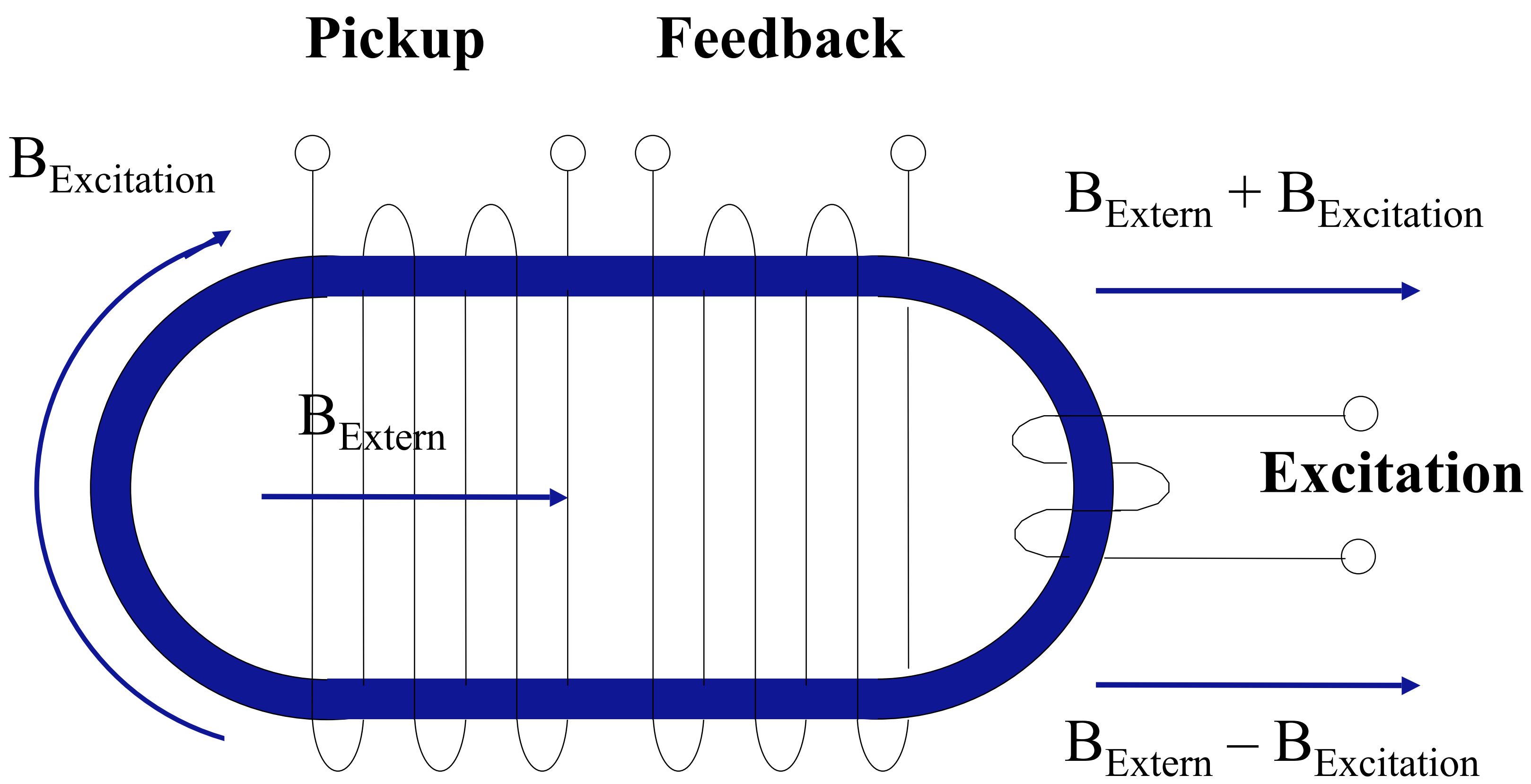
Fluxgate, Design and Calibration

- Design of Fluxgate Magnetometer for Space application
  - Operation Principle
  - Sensor design
  - Electronics options

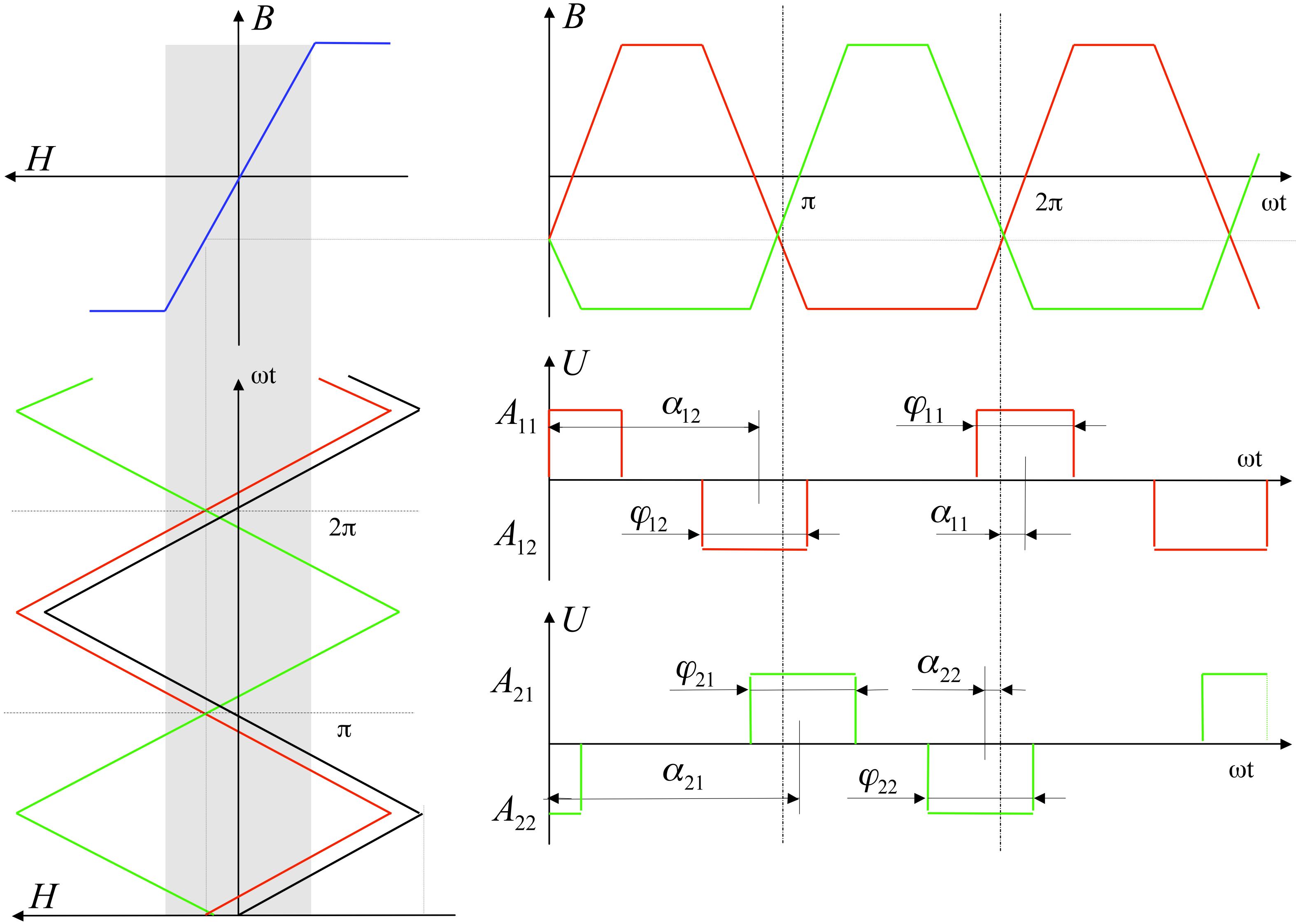
- Calibration of Fluxgate Magnetometer
  - On Ground Calibration:
    Parameter, Methods and Facilities
  - Inflight Calibration:
    Inputs, Methods and Procedure

Operation Principle (1)



$$U = \frac{d\Phi}{dt} = \frac{d\left(nA\mu_0\mu_r(t)H(t)\right)}{dt}$$

Operation Principle (2)



Operation Principle (3)

$$f(t)=\frac{2A_{11}}{\pi}\left\{\frac{\varphi_{11}}{2}+\frac{\sin(\varphi_{11})}{1}\cos(\omega t+\alpha_{11})+\frac{\sin(2\varphi_{11})}{2}\cos(2\omega t+2\alpha_{11})+\frac{\sin(3\varphi_{11})}{3}\cos(3\omega t+3\alpha_{11})+\ldots\right\}$$
$$+\frac{2A_{12}}{\pi}\left\{\frac{\varphi_{12}}{2}+\frac{\sin(\varphi_{12})}{1}\cos(\omega t+\alpha_{12})+\frac{\sin(2\varphi_{12})}{2}\cos(2\omega t+2\alpha_{12})+\frac{\sin(3\varphi_{12})}{3}\cos(3\omega t+3\alpha_{12})+\ldots\right\}$$
$$+\frac{2A_{21}}{\pi}\left\{\frac{\varphi_{21}}{2}+\frac{\sin(\varphi_{21})}{1}\cos(\omega t+\alpha_{21})+\frac{\sin(2\varphi_{21})}{2}\cos(2\omega t+2\alpha_{21})+\frac{\sin(3\varphi_{21})}{3}\cos(3\omega t+3\alpha_{21})+\ldots\right\}$$
$$+\frac{2A_{22}}{\pi}\left\{\frac{\varphi_{22}}{2}+\frac{\sin(\varphi_{22})}{1}\cos(\omega t+\alpha_{22})+\frac{\sin(2\varphi_{22})}{2}\cos(2\omega t+2\alpha_{22})+\frac{\sin(3\varphi_{22})}{3}\cos(3\omega t+3\alpha_{22})+\ldots\right\}$$

$$A_{i1}=\frac{B_{Sat}}{H_{Sat}}\frac{2\hat{H}_{Err}}{\pi},\quad A_{i2}=-\frac{B_{Sat}}{H_{Sat}}\frac{2\hat{H}_{Eerr}}{\pi}$$

$$\varphi_{ij}=\frac{\pi}{2\hat{H}_{Err}}H_{Sat}$$

$$\alpha_{11}=\frac{\pi}{2\hat{H}_{Err}}H_{Ext},\quad \alpha_{12}=\pi-\frac{\pi}{2\hat{H}_{Err}}H_{Ext},\quad \alpha_{21}=\pi+\frac{\pi}{2\hat{H}_{Err}}H_{Ext},\quad \alpha_{22}=-\frac{\pi}{2\hat{H}_{Err}}H_{Ext}$$

$$f_1(t)=\frac{2A_{11}}{\pi}\sin(\varphi_{11})\{\cos(\omega t+\alpha_{11})-\cos(\pi+\omega t-\alpha_{11})+\cos(\pi+\omega t+\alpha_{11})-\cos(\omega t-\alpha_{11})\}$$
$$=0$$

$$f_2(t)=\frac{A_{11}}{\pi}\sin(2\varphi_{11})\{\cos(2\omega t+2\alpha_{11})-\cos(2\pi+2\omega t-2\alpha_{11})+\cos(2\pi+2\omega t+2\alpha_{11})-\cos(2\omega t-2\alpha_{11})\}$$
$$=\frac{A_{11}}{\pi}\sin(2\varphi_{11})\{2\cos(2\omega t+2\alpha_{11})-2\cos(2\omega t-2\alpha_{11})\}=\frac{-4A_{11}}{\pi}\sin(2\varphi_{11})\sin(2\alpha_{11})\sin(2\omega t)$$

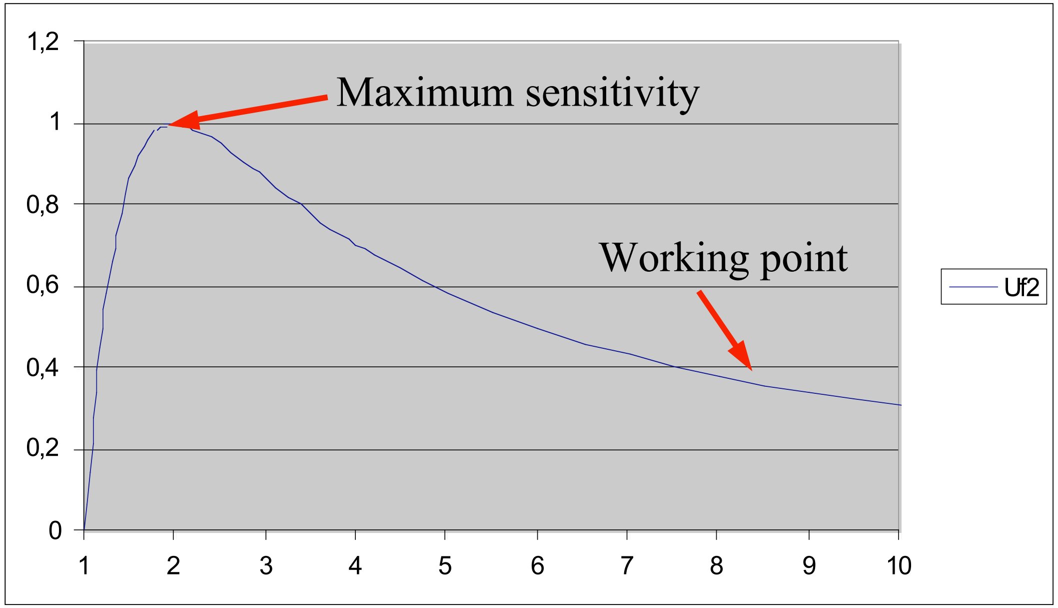
Operation Principle (4)

$$f_2(t) = -4\,\frac{B_{Sat}}{H_{Sat}}\,\frac{2\hat{H}_{Err}}{\pi^2}\,\sin\left(\pi\,\frac{H_{Sat}}{\hat{H}_{Err}}\right)\,\sin\left(\pi\,\frac{H_{Ext}}{\hat{H}_{Err}}\right)\,\sin(2\omega t)$$

$$\textit{für}\quad H_{Ext} << \hat{H}_{Err}\quad \textit{gilt}:$$

$$f_2(t) = -\frac{8}{\pi}\,\frac{B_{Sat}}{H_{Sat}}\,H_{Ext}\,\sin\left(\pi\frac{H_{Sat}}{\hat{H}_{Err}}\right)\,\sin(2\omega t)$$

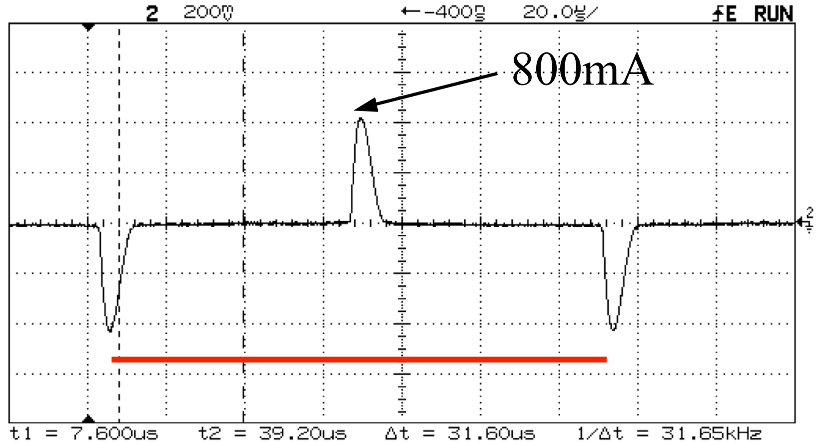
$$U_2(t) = -\frac{8}{\pi}\,n\,A\,\omega\,\mu_0\,\frac{B_{Sat}}{H_{Sat}}\,H_{Ext}\,\sin\left(\pi\frac{H_{Sat}}{\hat{H}_{Err}}\right)\,\sin(2\omega t)$$

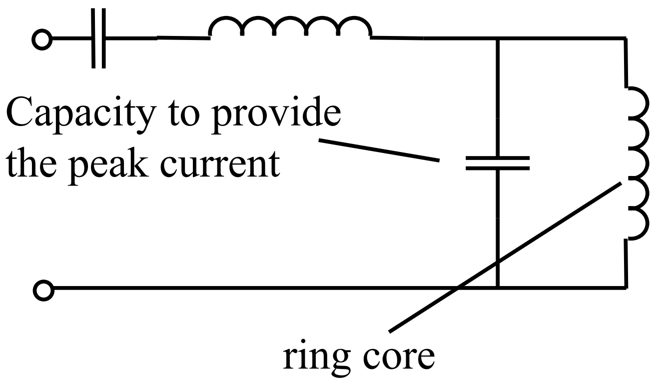


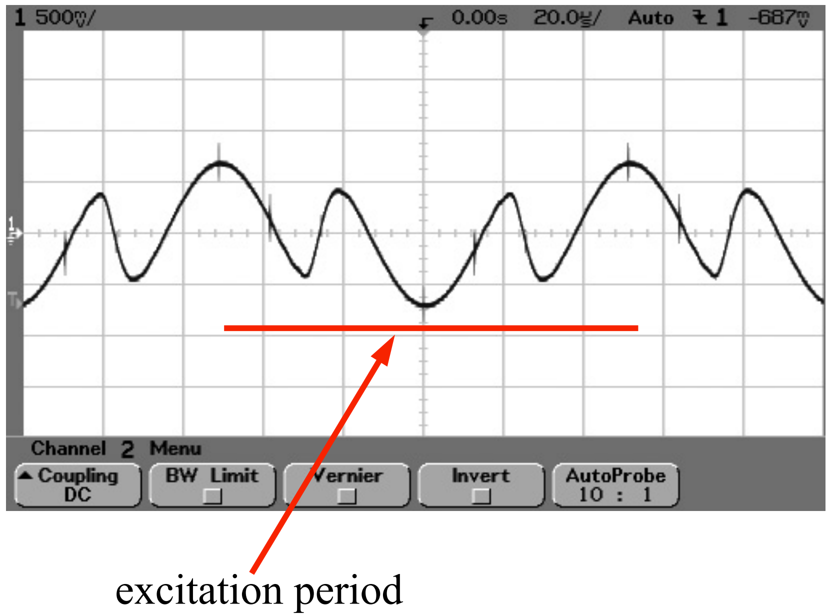
Amplitude U_{2f0} vs. H_{Err}/H_{Sat}

Excitation

- Excitation current is dominated by field dependent impedance of soft magnetic material
- Excitation frequency: 8-10kHz
- Symmetry: 70dB
- Power: 200mW, only 20% is consumed in sensor

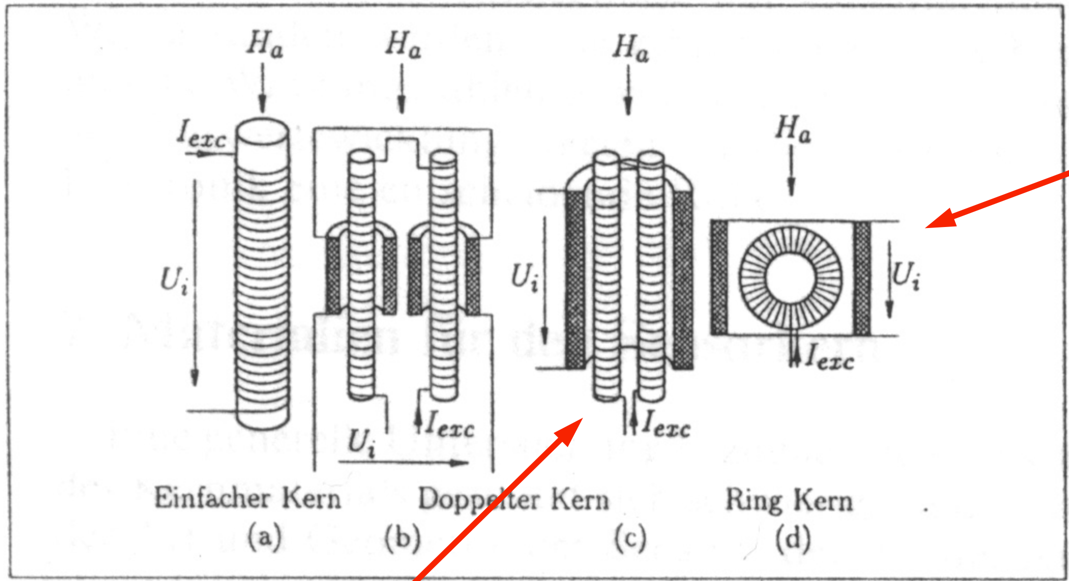






Types of Sensors

Bild 10: Parallele Sensortypen. (a) Einfacher Kern. (b) und (c) Doppelter Kern. (d) Ring-Kern.



- Ring Core
  - Acuna
  - Fornacon
  - Afanasev
  - Primdahl

☺ Low demagnetisation for excitation field

- Double Rod
  - Förster
  - Rasmussen

☺ Low demagnetisation for external field

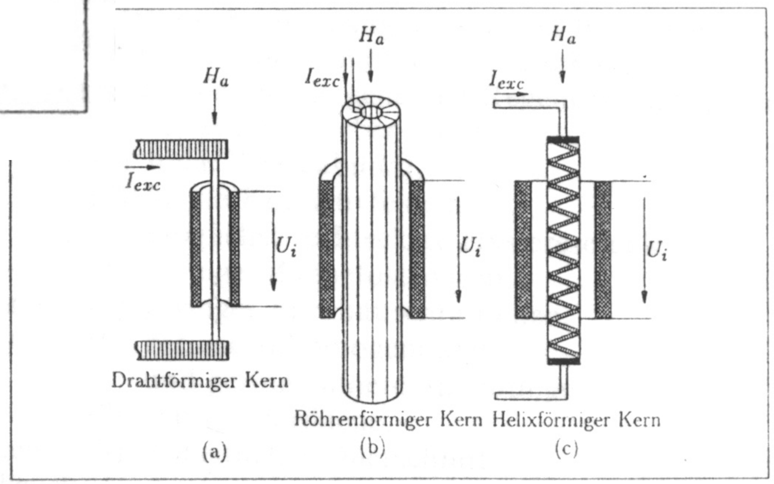
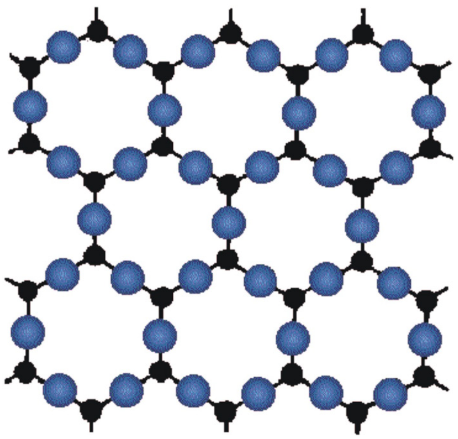
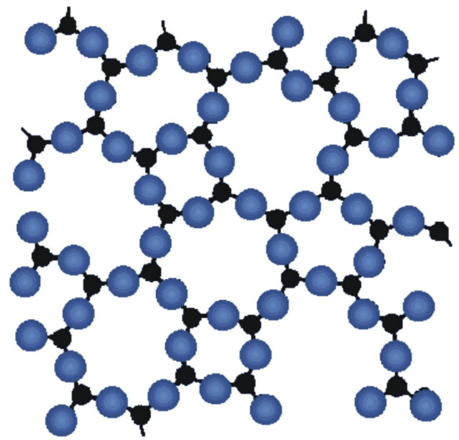


Bild 11: Orthogonale Sensortypen. (a) Kern aus ferromagnetischem Draht. (b) Röhrenförmiger Kern. (c) Helixförmiger Kern.

Magnetic Materials





- Crystalline Material

  NiFe-Alloy

☺ well processible

☺ high permeability

(80 % Ni ca. 300 000)

- Amorphous Material

  Fe- or Co-Alloy

☺ Isotrop

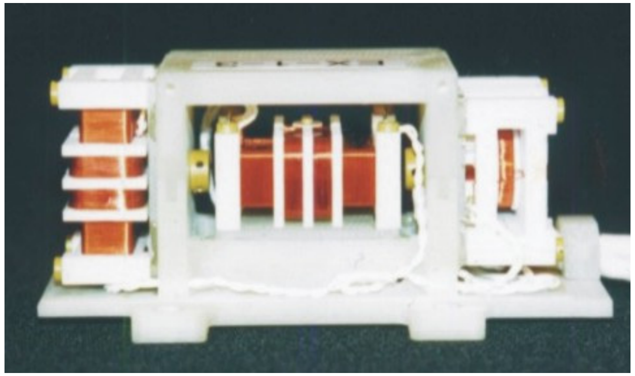
☺ Low coercivity (low magnetisation losses)

☹ low Curie - temperature

Ringcore Technology

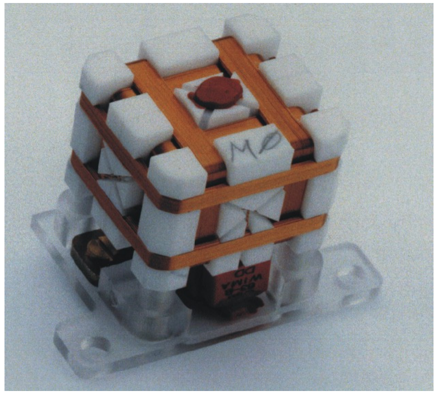
- Selection of „best“ alloy
  - $Fe_{94-x}Ni_xMo_6$ x: 76...83
- Manufacturing of soft-magnetic band
  - Hot and cold rolling up to 10µm thickness
  - Cutting to 2mm width
- Manufacturing of ring cores
  - Accommodation of band on bobbin
  - Isolation by Magnesiumoxide
- Thermal treatment
  - Under vacuum or hydrogen atmosphere
  - temperature: 900..1200°C

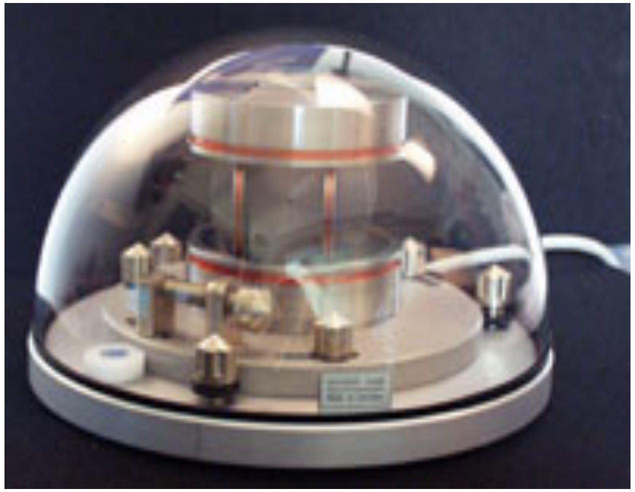
Examples of Sensors



Mars96, Equator-S,
Double Star,
240g

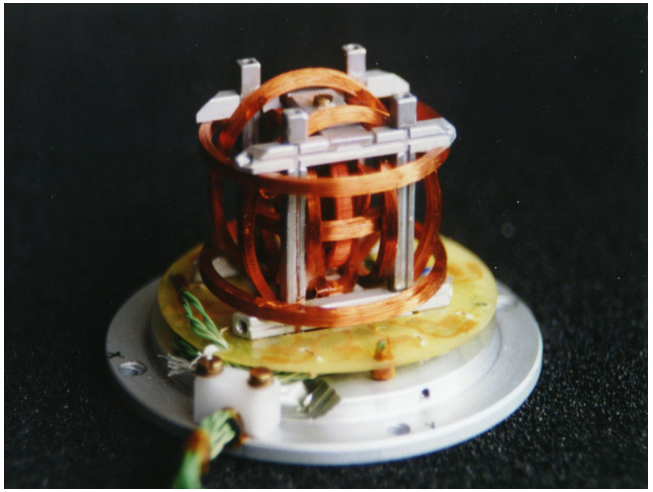
Rosetta Orbiter, DS1,
<50g, <10cm³



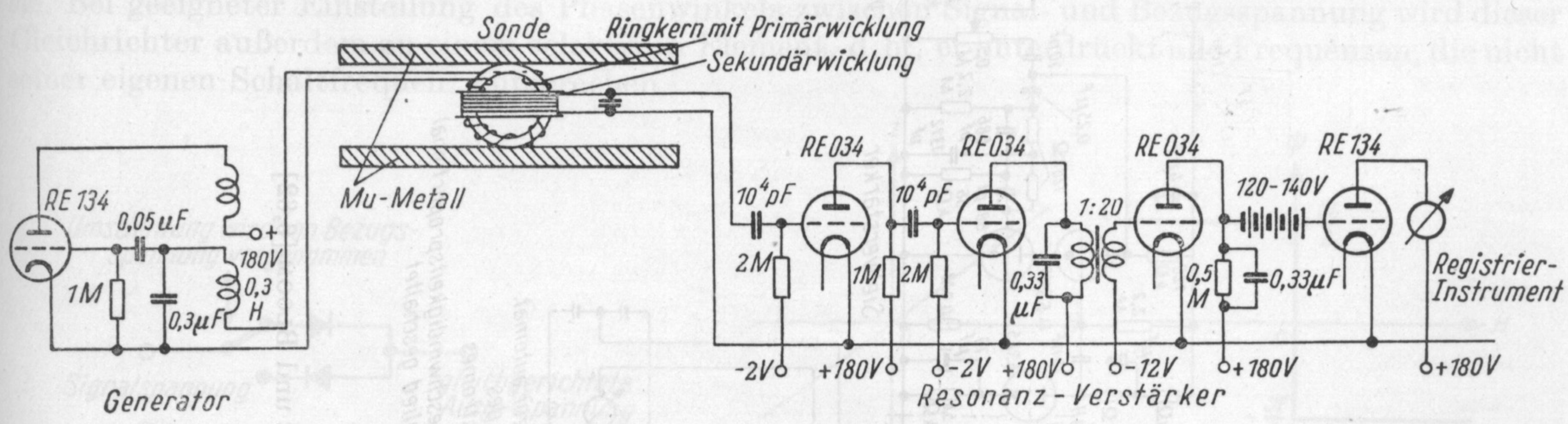


Observatories, MC,
applied Geophysics
3kg

Rosetta Lander, VEX,
Themis, BepiColombo.
<50g



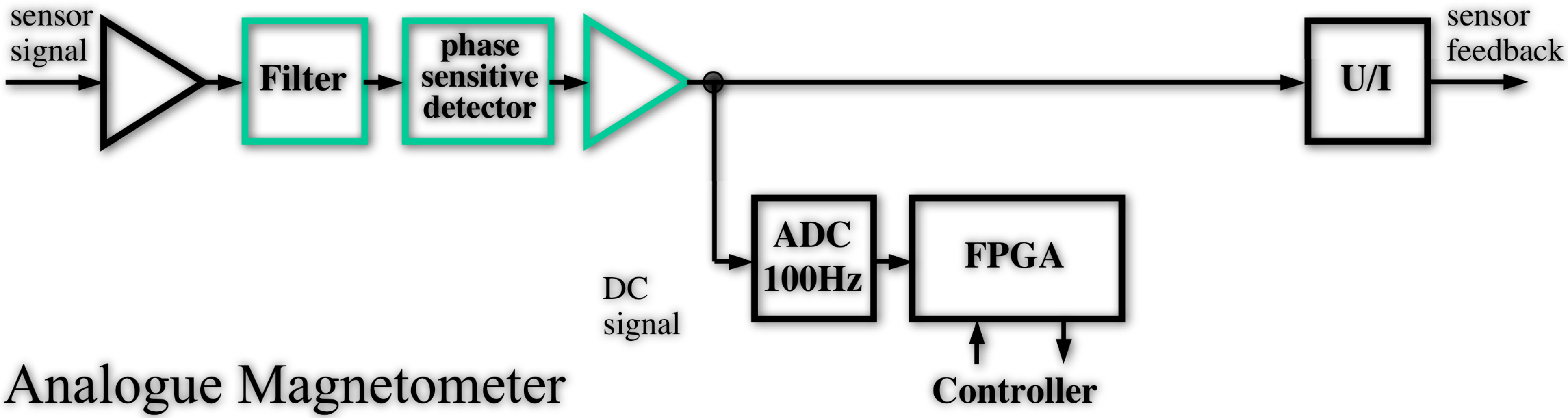
First Fluxgate Magnetometers



6,120 Schaltung des ersten, zur Registrierung des Erdfeldes benutzten SK-Sondengerätes nach ASCHENBRENNER und GOUBAU [6,35]

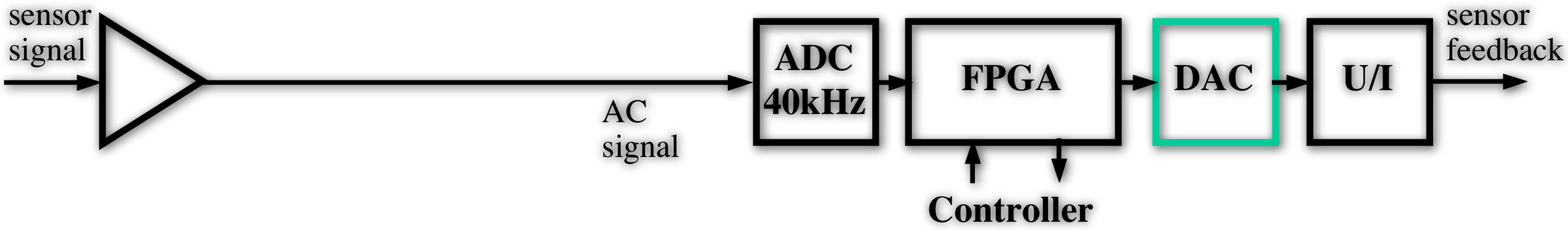
- Excitation Frequency: 700Hz
- Soft magnetic material: annealed wire
- Resolution: 0.3nT

Signal Processing Options

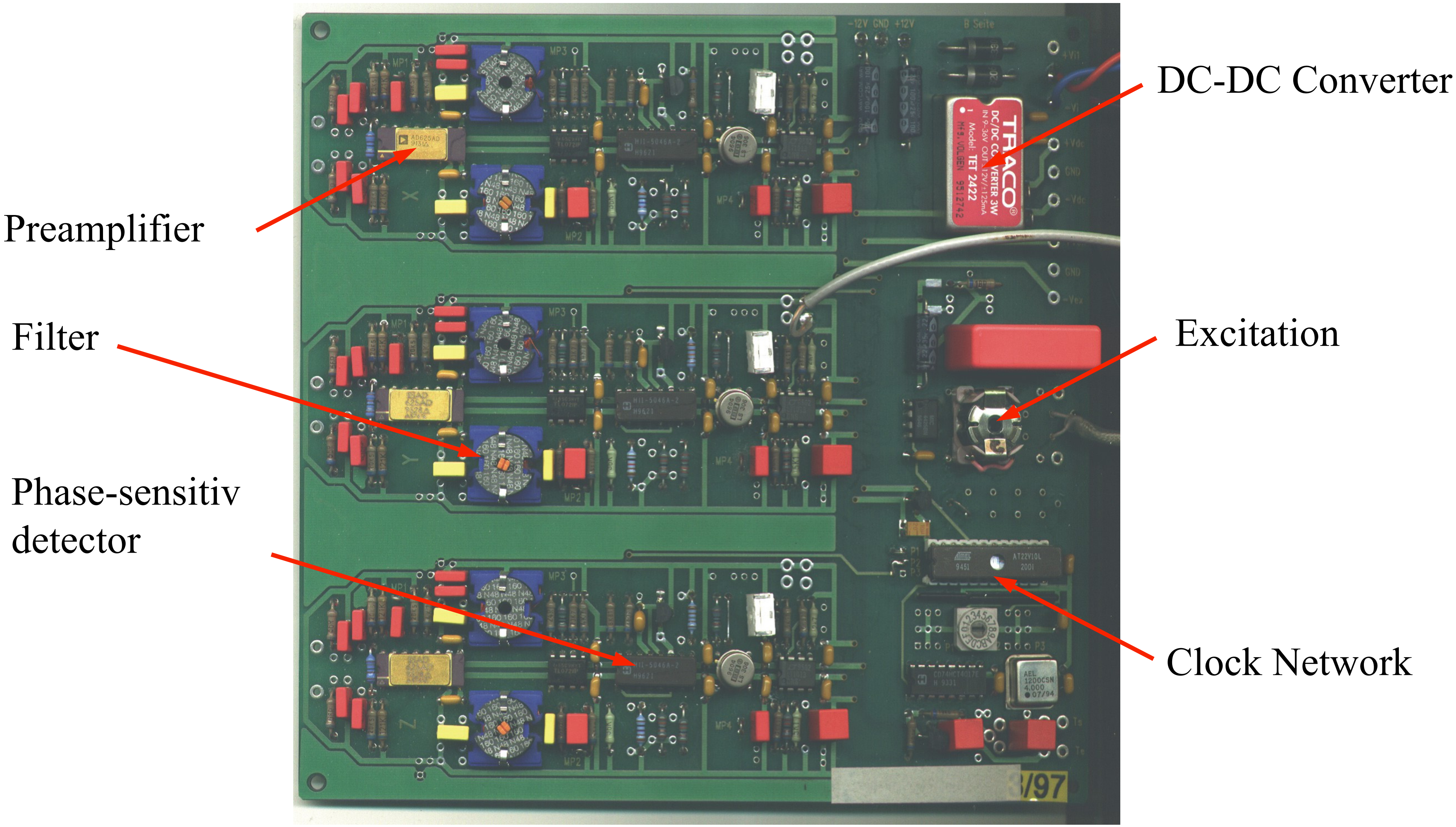


Analogue Magnetometer

Digital Magnetometer

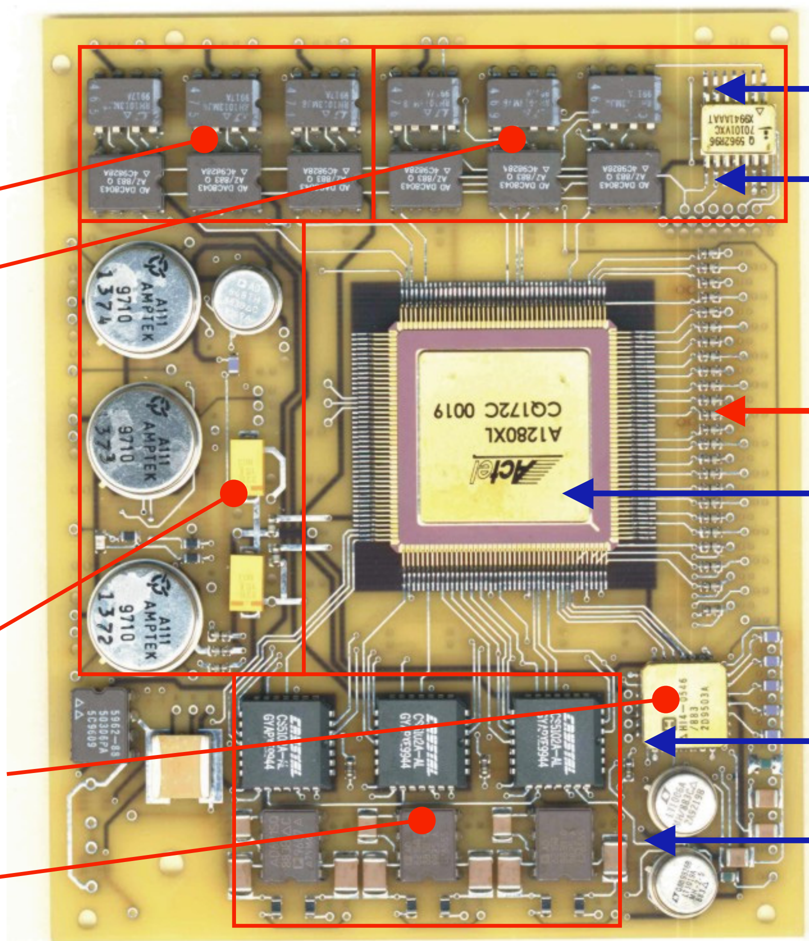


Example Analogue FGM



Example Digital FGM

ROMAP: Magnetometer (MAG) + Plasmamonitor (SPM)



Board size: 120mm x 100mm

Fluxgate Design References

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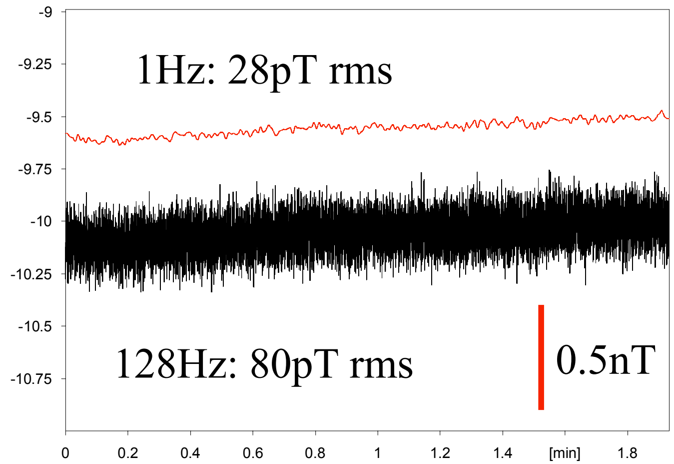
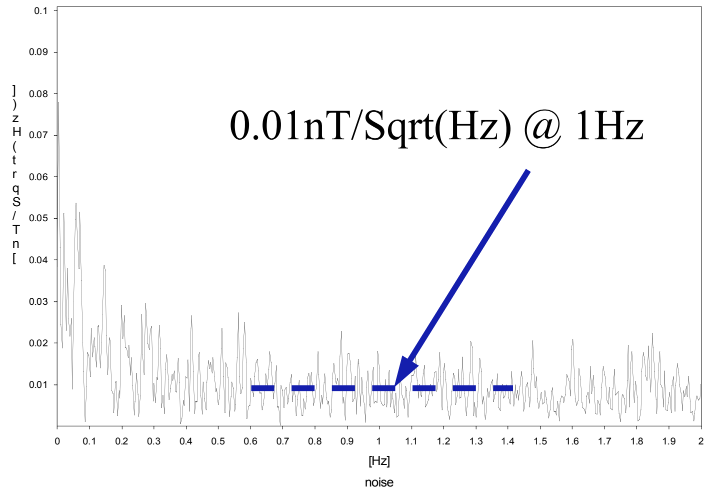
Calibration Parameters

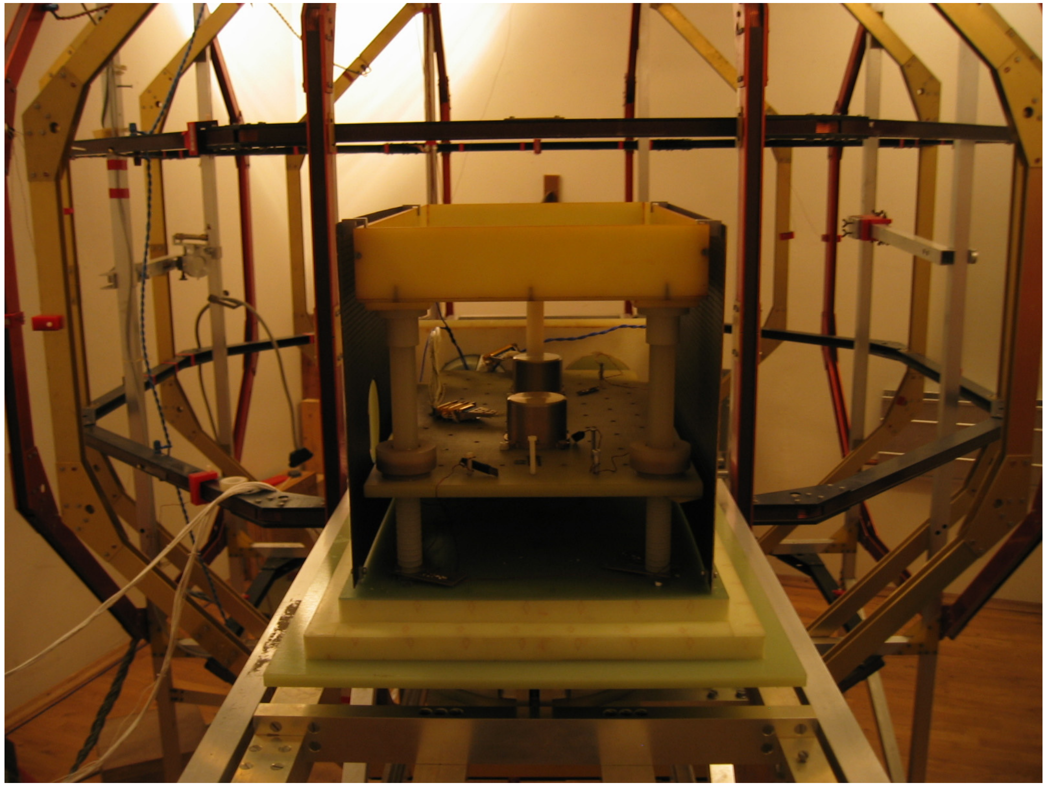
Parameter	**Error Source**	**typ. value**
Offsets (output at zero field) depends on time and temp.	asymmetry of sensor and excitation offsets of DC electronics, ADC ...	0-10nT 0.2nT/day; 0.05nT/°C
Scale value depends on temperature	scale value shall depends on feedback circuitry only – current source & feedback coil system	10^{-4} 1-30ppm/°C
Non linearity	at low fb factors: 2f0 non linearity at high fb factors: feedback circuitry non linearity	10^{-4}
Orthogonality	vector compensated: depends on fb coil system single sensors depends on ringcore /pick up coil	10^{-4}
Bandwidth	frequency behavior depends on analogue or digital filter. Has to be switched with telemetry rate	
Noise	should be ringcore property (no contribution of electronics), depends on frequency	10pT/Sqrt(Hz) at 1Hz





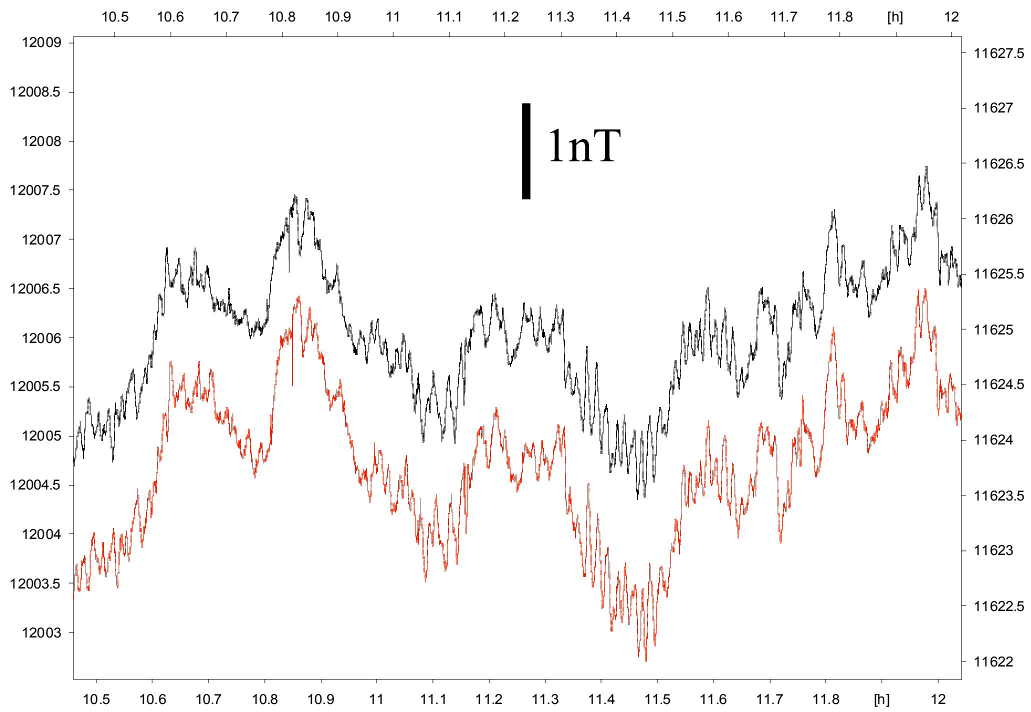
Ground Calibration Methods (1)

- Using well controlled, synthesized test fields
  - Sensor placed in coil systems
  - quiet environment required, Earth field variations as well as technical disturbances under control
  - Precise measurement / setting of coil currents
  - Air conditioning necessary
  - Calibration of coil system by (absolute) scalar magnetometer possible
  - Example: Magnetsrode close to Braunschweig



Ground Calibration Methods (2)

- Using the Earth field measured by a independent magnetometer
  - Sensor placed on a stable (non magnetic) pillar
  - Registration of Earth field in parallel to standard observatory instruments (or between flight models)
  - Noise can be checked by short term registration of pulsation
  - Drift can be checked after days-weeks registration
  - Most of the observatories offer this service

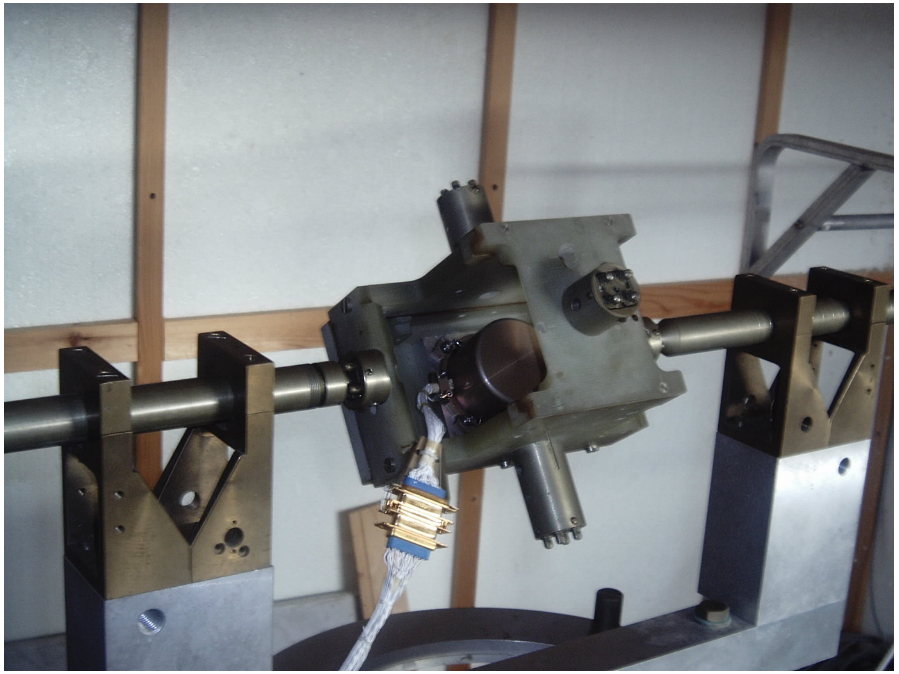


Ground Calibration Methods (3)

- Using „zero“fields
  - Sensor placed in ferromagnetic can which shields the Earth field
  - Noise and offset stability can be checked
  - If sensor can be rotated offsets in components perpendicular to rotation can be determined
  - Example: transportable mu-metal can, equipped with temperature chamber (Graz)

Ground Calibration Methods (4)

- Using a controlled motion of the sensor in the Earth field
  - Rotation about a well defined axis perpendicular to the Earth field
  - Misalignment rotation and magnetic axis results in a sine function
  - Misalignment can be absolutely derived by amplitude and phase
- Using an arbitrary motion of the sensor in the Earth field
  - Assuming a linear transfer function, 9 of 12 elements (offset, scale values, orthogonality) can be derived by comparison with the Earth field magnitude



Inflight Calibration

- Aim of inflight calibration
  - Determination of 12 elements of transformation $\mathbf{B}_M$ to $\mathbf{B}_{SC}$
  - Assumption: transformation is linear
  - $\mathbf{M}_{Cal}$ Calibration Matrix; $\mathbf{O}_{Cal}$: Calibration Offset

$$\mathbf{M}_{Cal} \left(\mathbf{B}_M - \mathbf{Z}_{Cal}\right) = \mathbf{B}_{SC}$$

- Calibration Matrix $\mathbf{M}_{Cal}$ shall be split up in three quantities
  - **S:** represents **scale values** with elements in the main axis
  - **O:** represents the **non orthogonality** (triangular matrix)
  - **R:** represents the orientation of the orthogonal system versus S/C system (rotation matrix)

$$\mathbf{O} \ \mathbf{S} \left(\mathbf{B}_M - \mathbf{Z}_{Cal}\right) = \mathbf{R} \ \mathbf{B}_{SC}$$

Calibration Inputs

- Calibration methods are based on the following relevant inputs
  - No spin and double spin tone in field magnitude
  - Field properties (Earth field model, Alfven waves, …)
  - Knowledge of preflight calibration and MC results
  - Experiment specifics, mode and housekeeping information
  - Independent field measurements
  - Inter-calibration: using spacecraft comparisons (B1=Bn, RotB=0, DivB =0) to level all instruments errors

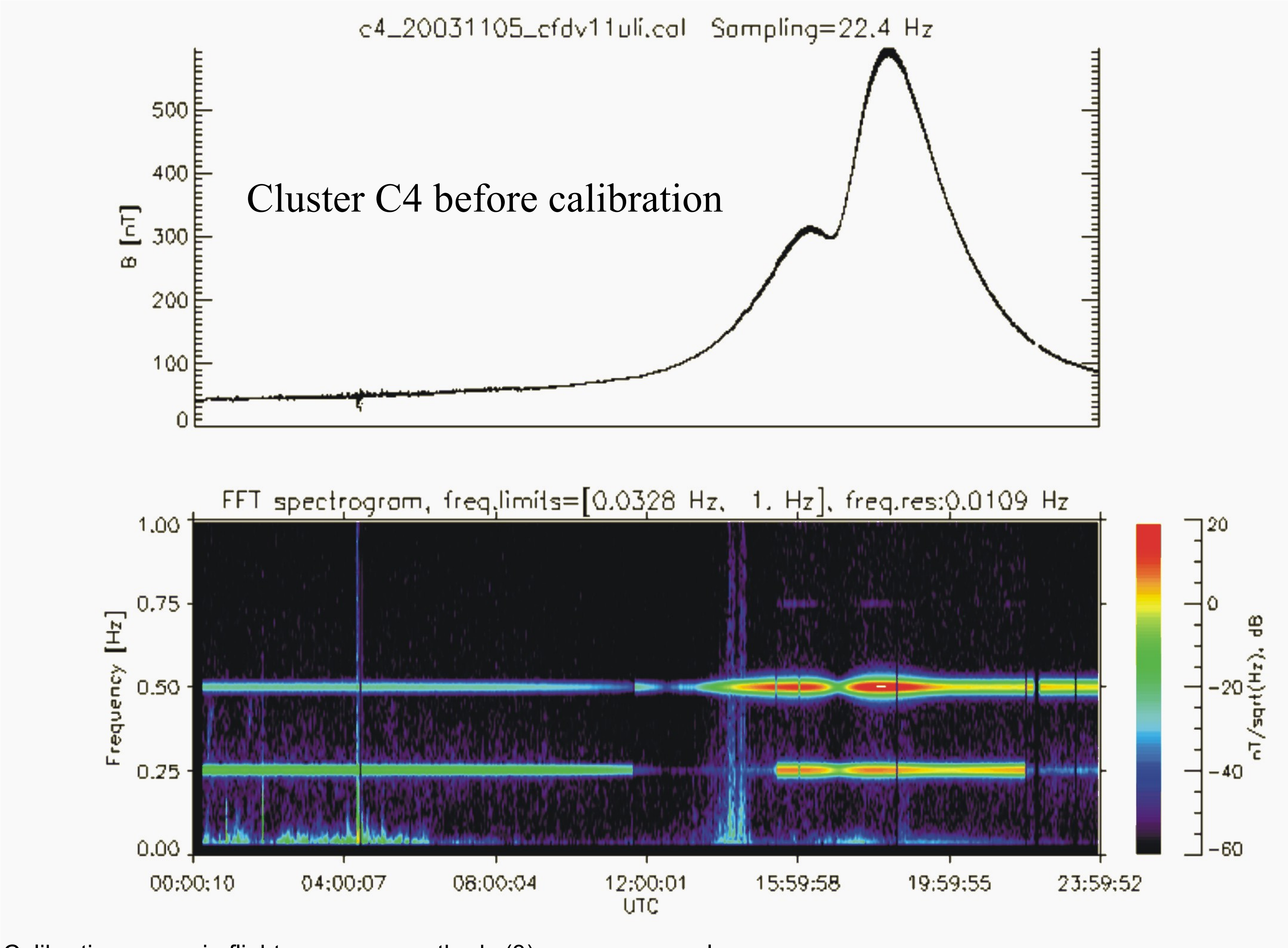
Methods (1)

Field magnitude has to be independent from sensor motion

$$\frac{\partial\left(\left|\mathbf{O}\ \ \mathbf{S}\ \left(\mathbf{B}_M - \mathbf{Z}_{Cal}\right)\right|\right)}{\partial\left(\mathbf{R}\right)} \overset{!}{=} 0$$

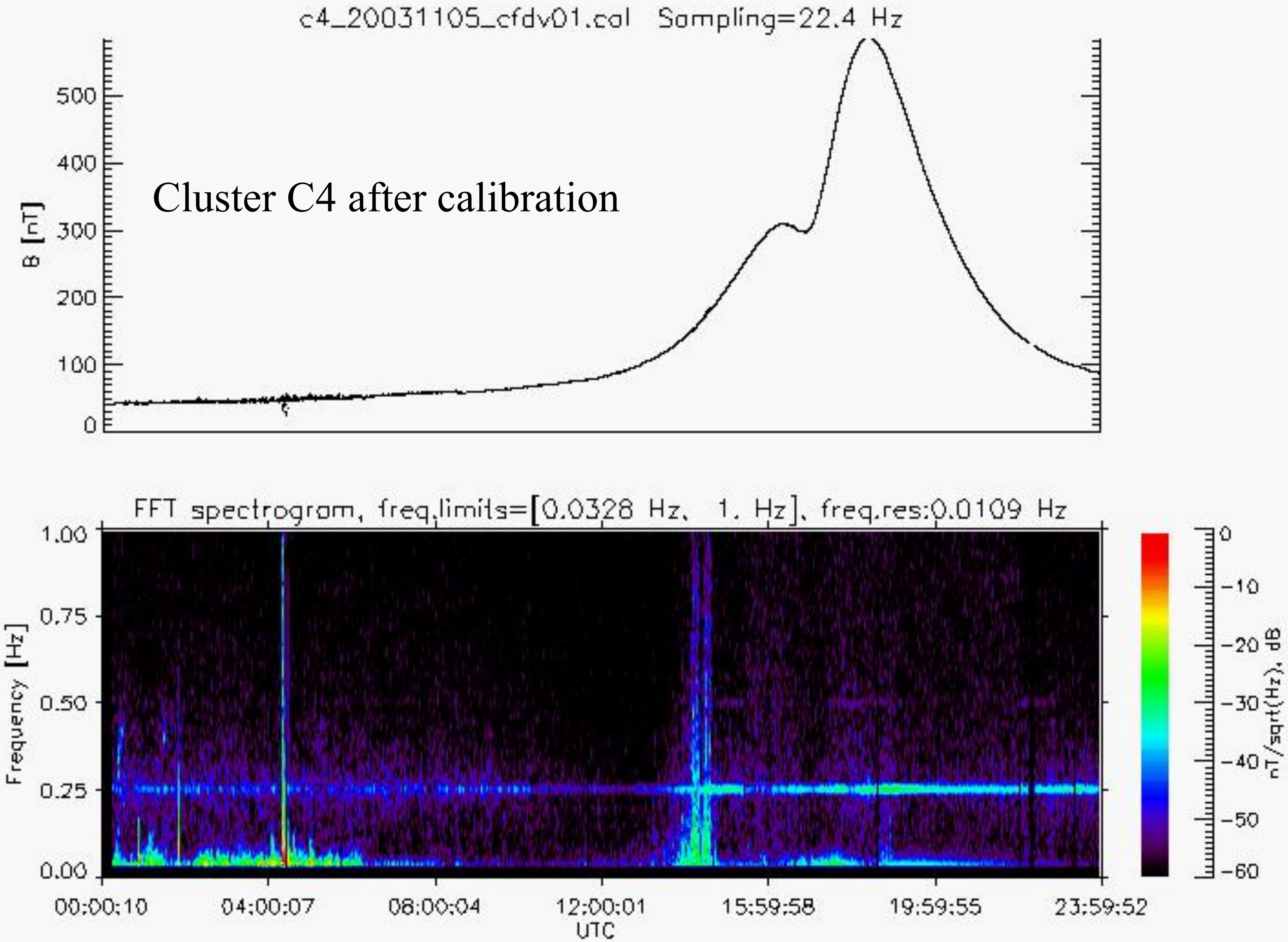
- Conditions:
  - $\mathbf{B}_{\mathrm{external}}$ → constant
  - $\mathbf{R} = R(\varphi, \psi, \vartheta)$ → variable
  - $\mathbf{O},\ \mathbf{S},\ \mathbf{Z}_{\mathrm{Cal}}$ → doesn't depend on time and external field
- Effects assuming S/C rotation as motion
  - spin and double spin tone in field magnitude (4 equations)
  - All three angle of orthogonality affected
  - Offsets and scale values perpendicular to rotation axis affected

Example



Calibration - in flight - methods (3) - example

Example


c4_20031105_cfdv01.cal Sampling=22.4 Hz
Cluster C4 after calibration
B [nT]
FFT spectrogram, freq.limits=[0.0328 Hz, 1. Hz], freq.res:0.0109 Hz
Frequency [Hz]
nT/sqrt(Hz), dB
UTC
00:00:10
04:00:07
08:00:04
12:00:01
15:59:58
19:59:55
23:59:52

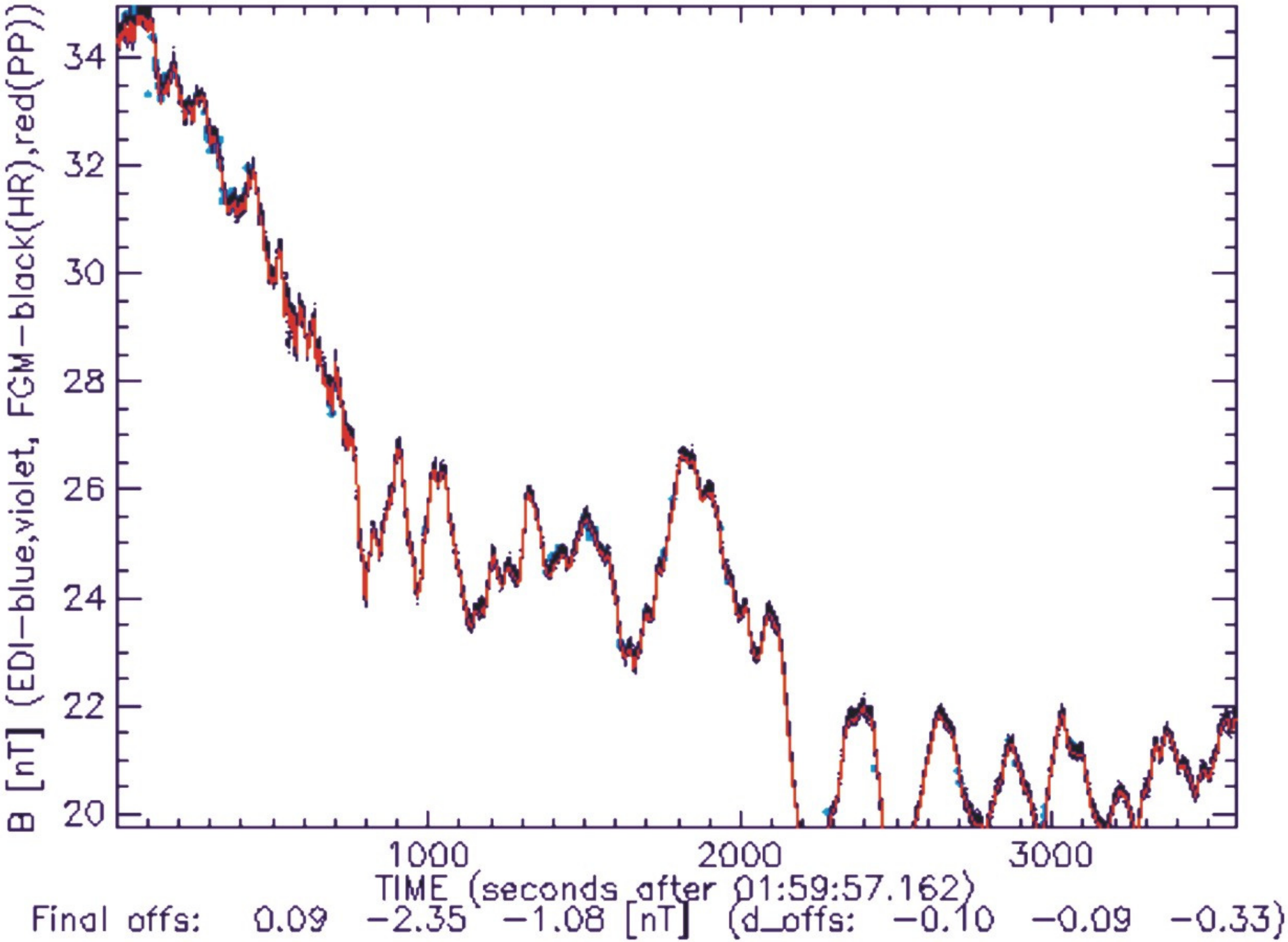
Methods (2)

Field magnitude has to be equal to the magnitude measured by an independent (scalar) magnetometer

$$\left|\mathbf{O}\;\;\mathbf{S}\;\left(\mathbf{B}_M - \mathbf{Z}_{Cal}\right)\right| = \left|\mathbf{R}\;\;\mathbf{B}_{SC}\right| \overset{!}{=} B$$

- Conditions:
  - $\mathbf{B}_{\text{external}}$ → shall be variable
  - $\mathbf{R}$ → can be arbitrary
  - $\mathbf{O}$, $\mathbf{S}$, $\mathbf{Z}_{\text{Cal}}$ → doesn't depend on time and external field
- Examples
  - Proton magnetometer on board satellites investigating the Earth magnetic field (low orbits, e.g. Magsat, Oersted, Champp)
  - EDI onboard Equator-S, Cluster and MMS

Example



Calibration - in flight - methods (2) - example

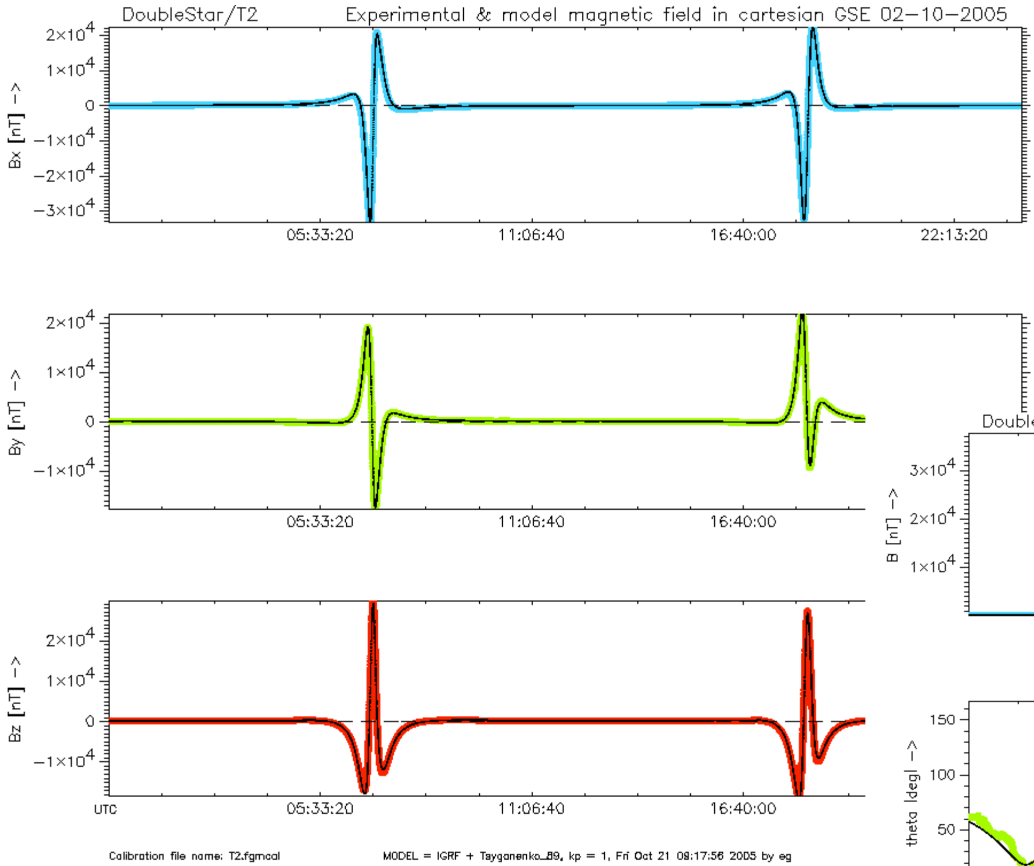
Methods (3)

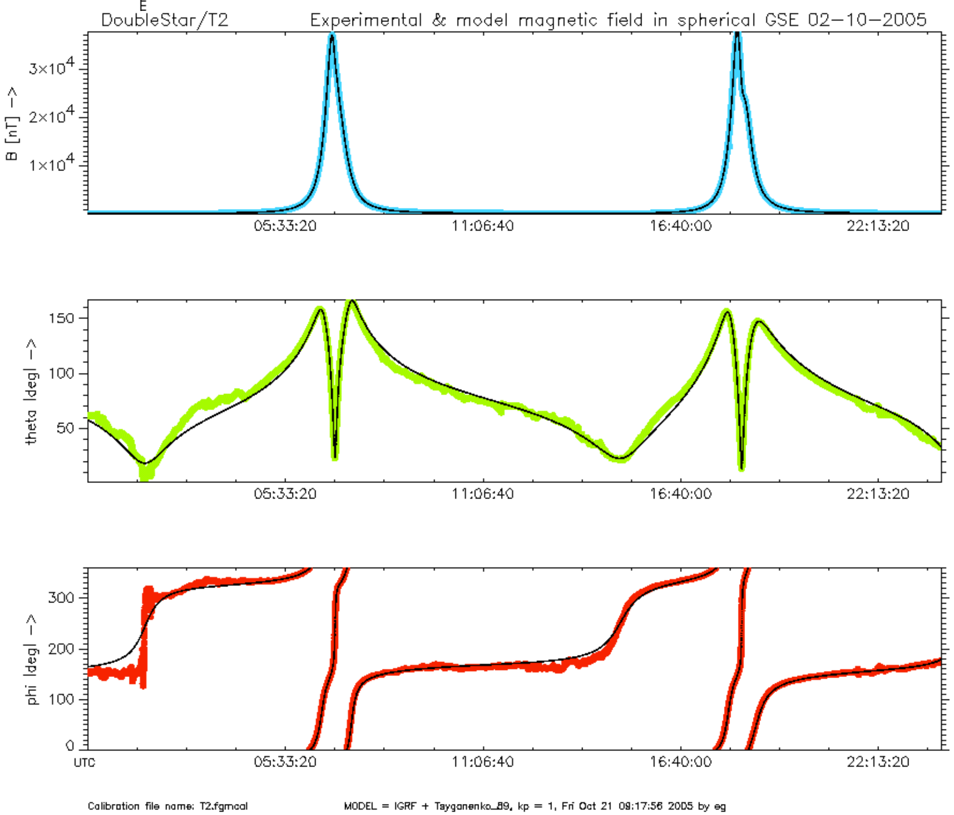
Measured field vector has to be in agreement with known physical features

$$f\left(\mathbf{O}\;\;\mathbf{S}\;\;\left(\mathbf{B}_{M}-\mathbf{Z}_{Cal}\right)\right)\overset{!}{=}\text{Expectation}$$

- Conditions:
  - $\mathbf{B}_{\mathrm{external}}$ → shall be variable
  - $\mathbf{R}$ → can be arbitrary
  - $\mathbf{O}$, $\mathbf{S}$, $\mathbf{Z}_{\mathrm{Cal}}$ → doesn't depend on time and external field
- Examples
  - In agreement with Earth field models
  - Alfven waves in solar wind
  - Divergence B=0, Cavity of Comets ...

Example


DoubleStar/T2
Experimental & model magnetic field in cartesian GSE 02–10–2005
Bx [nT] ->
By [nT] ->
Bz [nT] ->
UTC
05:33:20
11:06:40
16:40:00
22:13:20
Calibration file name: T2.fgmcal
MODEL = IGRF + Tayganenko_89, kp = 1, Fri Oct 21 09:17:56 2005 by eg


DoubleStar/T2
Experimental & model magnetic field in spherical GSE 02–10–2005
B [nT] ->
theta [deg] ->
phi [deg] ->
UTC
05:33:20
11:06:40
16:40:00
22:13:20
Calibration file name: T2.fgmcal
MODEL = IGRF + Tayganenko_89, kp = 1, Fri Oct 21 09:17:56 2005 by eg

Calibration Procedure

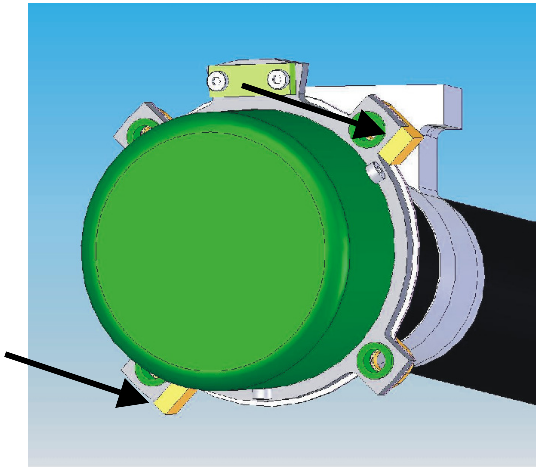
Non orthogonal sensor system

scale, offset, non orthogonality
range, mode

update of sensor parameters

Orthogonal sensor system

sensor alignment
boom alignment



removing of S/C generated offsets

S/C system

S/C moments of inertia

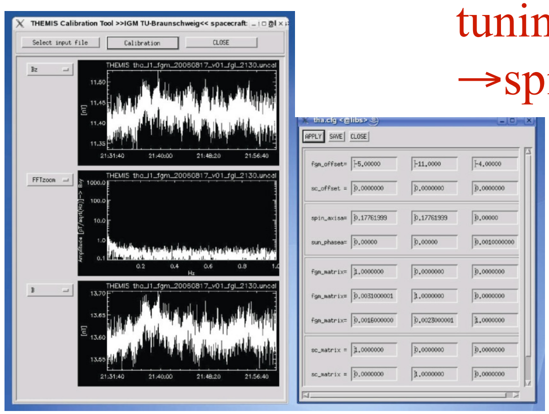
tuning of spin alignment
→spin tone in spin axis

Spin aligned S/C system

sun sensor align.
filter type

tuning of phase alignment
→ comparison with IGRF

Spin and sun aligned system



Calibration - in flight - procedure

Calibration References

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Outlook Computer Session

- Visualisation and Calibration of Ground Calibration Data
  - Plot of uncalibrated data
  - 9 parameter Fit on known (constant) field magnitude
  - Plot of calibrated data
  - Check of sensitivity of method versus parameter
- Visualisation and Calibration of Cluster data
  - Plot of uncalibrated data
  - 4 parameter Fit on unknown constant field magnitude
  - Plot of calibrated data
  - Introducing of calibration errors and checking of influence on spin and double spin tone in magnitude