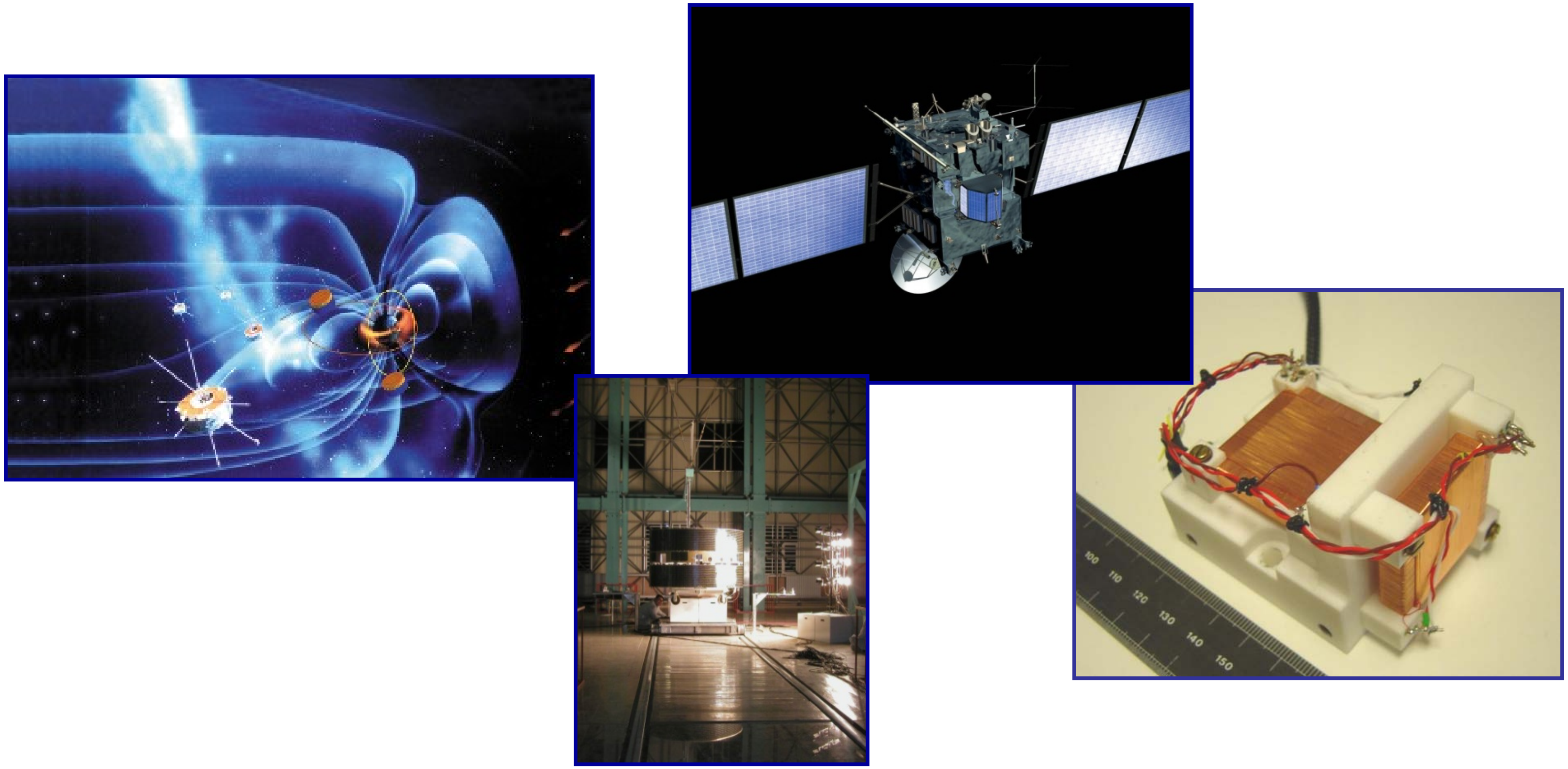
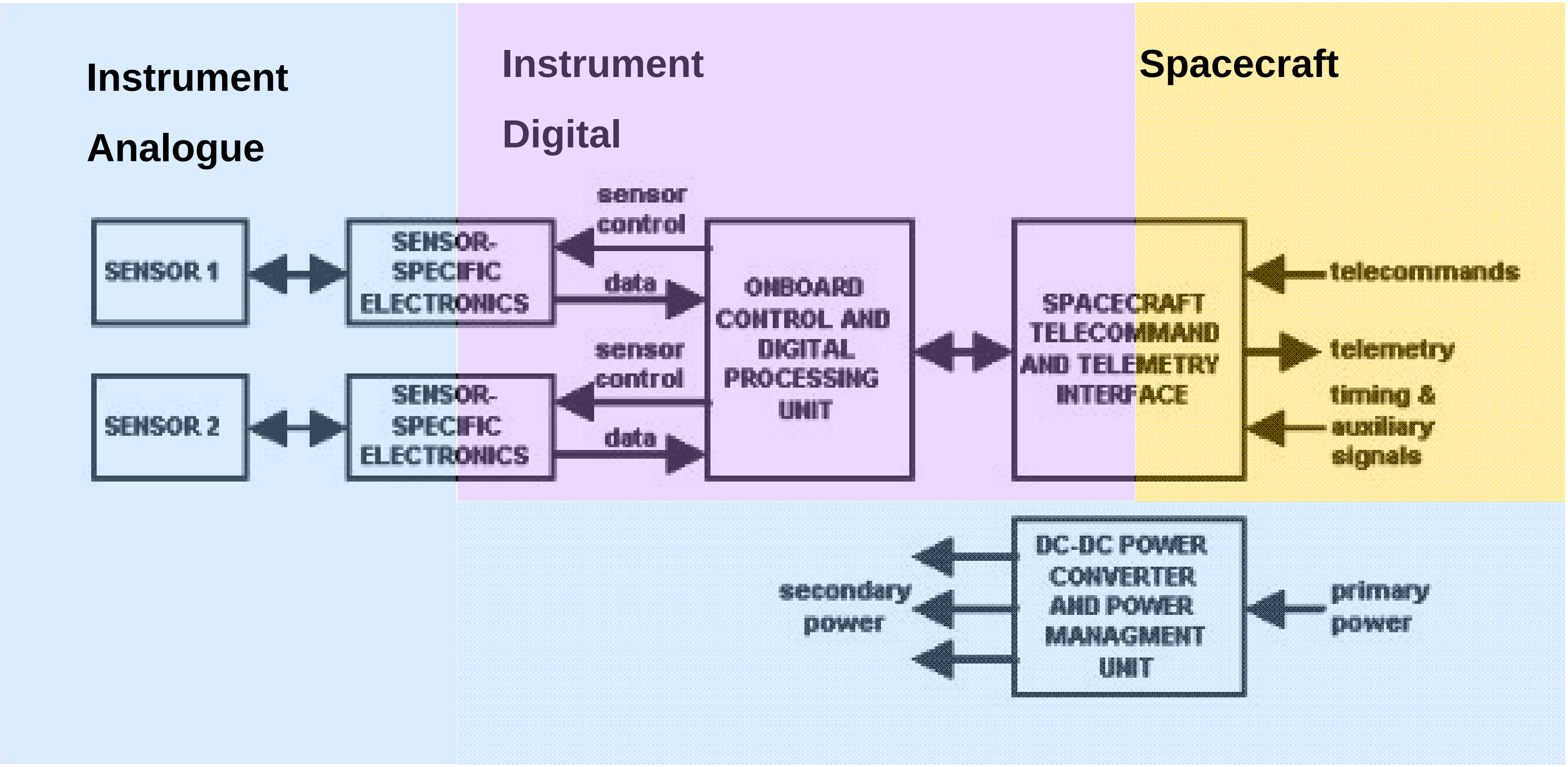
Instrumentation II
Magnetometers and Calibration



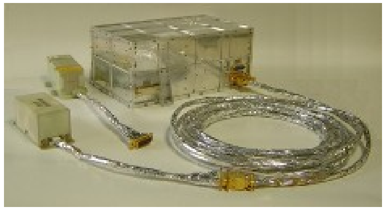
Generic Space Instrument

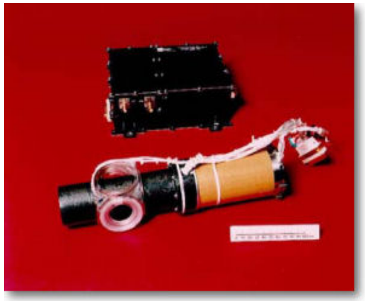


What do we mean by DC space magnetometer?

- Three B field components in range 0 - 30Hz
- Wide measurement range 0.01nT – 50,000nT
- Robust, reliable, high performance (low noise – stable offsets)
- Optimised for power, mass, radiation etc.
- Sensors fitted to a boom away from S/C magnetic disturbance

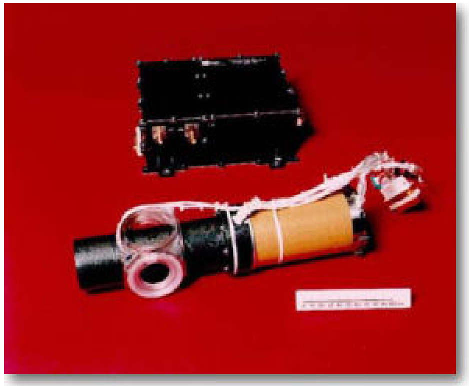
Sensor Technology	Range (T)	Suitable for space
SQUID	$10^{-14} – 10$	No – Cryostat needed
Optically Pumped	$10^{-14} – 10^{-4}$	Yes – **B** and |**B**|
Fluxgate	$10^{-10} – 10^{-4}$	Yes – **B**
Nuclear Precession	$10^{-11} – 10^{-2}$	Yes - |**B**|
Hall Effect	$10^{-3} – 10^{-2}$	No
Search Coil	$10^{-12} – 10^{6}$	Yes for **AC** fields



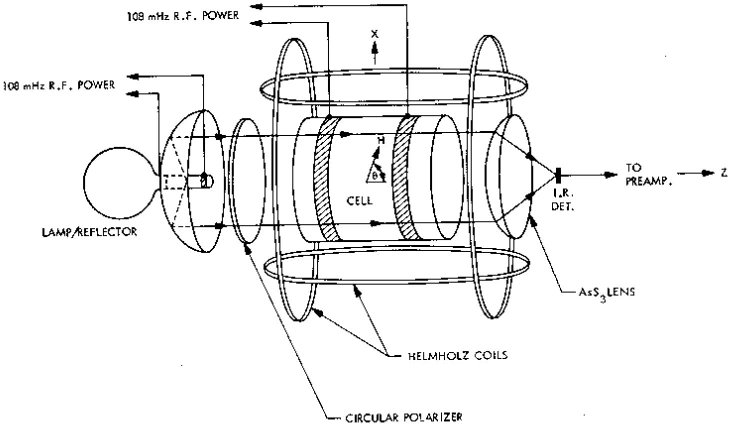


Optically Pumped Magnetometers

- **Heritage as a vector magnetometer**
- **Vector and Scalar Operation (on Cassini)**
- **Vector Mode**
  - RF discharge maintained in a He lamp – 1.08um
  - Creates radiation - channelled into a He absorption cell
  - He cell atoms are in meta-stable state also by RF discharge
  - Presence of ambient field causes Zeeman splitting
  - Emergent radiation is measured by IR detector
  - The measured absorption depends on efficiency of the optical pumping
  - Helmholtz coils around cell apply rotating sweep fields
  - Signal is obtained by measuring the modulation of rotating sweep fields applied by surrounding Helmholtz coils
  - Results in a sinusoid whose magnitude and phase give the size and direction of the field
  - Signal detected and fedback into the sensor coils



- **Scalar mode**
  - 1.08um radiation and frequency modulated AC field applied.
  - Absorption greatest when AC frequency = Larmor frequency.
  - Larmor frequency related to |**B**| by fundamental constants
  - Result is a very accurate measure of absolute field



Smith 1975

Proton Precession Magnetometers

- Proton rich material eg distilled water
- Surrounded by induction coil
- AC field induces proton precession
- Once induced field switched off
- Protons relax back to ambient field precession
- This induces a small AC signal in coil
- Proportional to ambient field
- Suitable for slow varying fields
- Used for absolute measurement of **B**
- Used on Earth mapping missions eg Oested, CHAMP

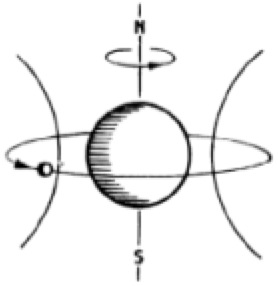


Fig. 1. Magnetic field around hydrogen proton produced by orbiting electron

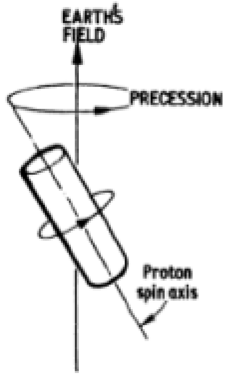


Fig. 2 Precession of proton relative to earth's field when acted upon by external magnetic influence

Fig. 3. Diminishing alternating voltage set up by precession frequencies from the detector coils

Huggard 1970

Induction Magnetometers

Faraday induction law →

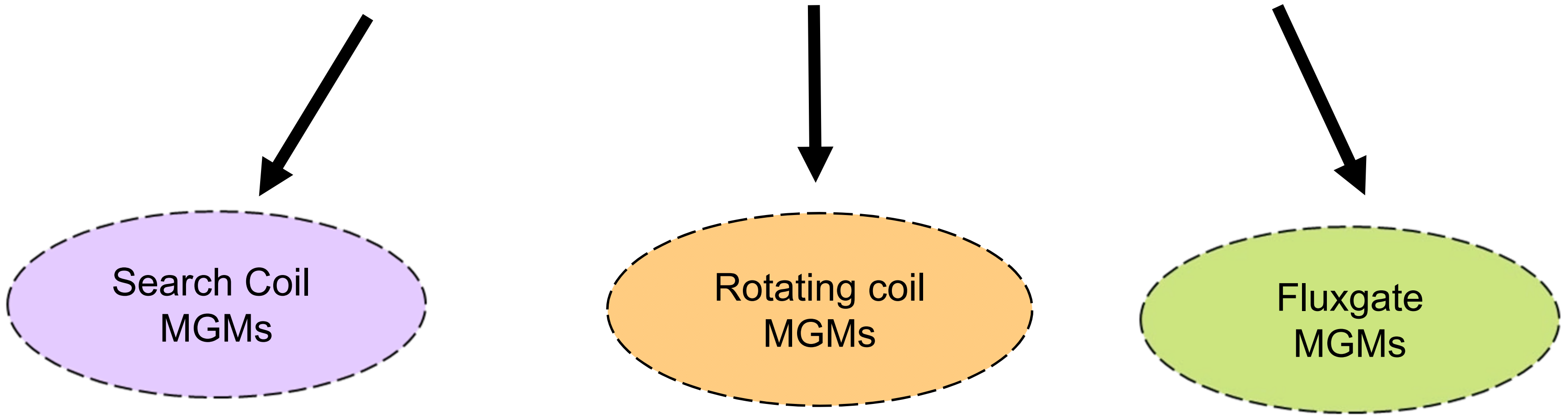
$$V_i = d\Phi / dt$$

$$\ldots = d(BA)/dt \qquad \text{Since } B = \mu_o \mu_r H$$

$$V_i = d(NA\mu_o\mu_r(t)H(t)/dt)$$

Expanded

$$V_i = NA\mu_o\mu_r dH(t)/dt + N\mu_o\mu_r H dA(t)/dt + NA\mu_o H d\mu_r(t)/dt$$



Search Coil MGMs

Rotating coil MGMs

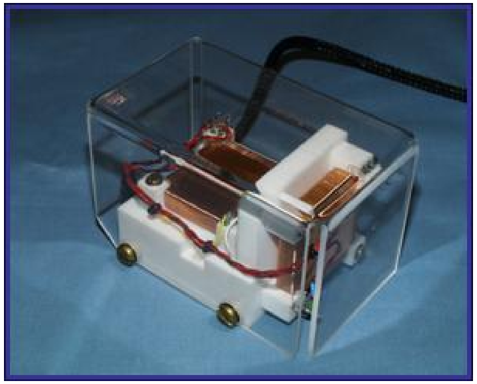
Fluxgate MGMs

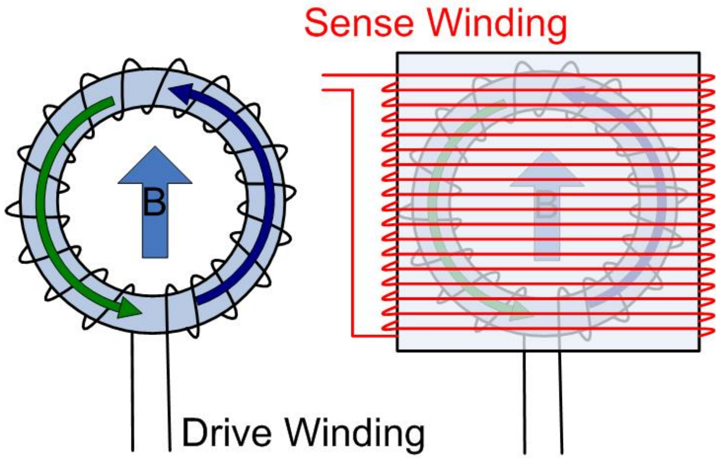
Anatomy of a Fluxgate

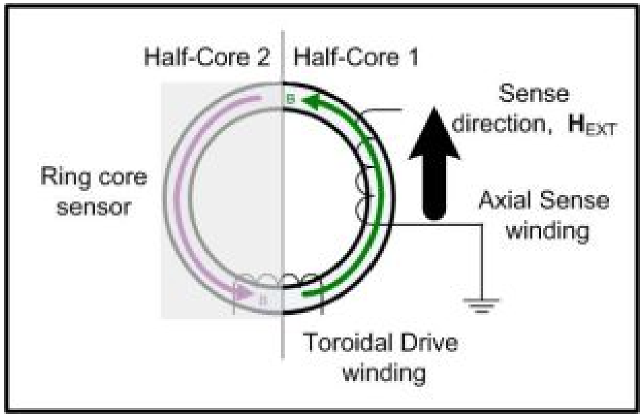
- **Operating Principle**
  - Soft permeable core driven around hysterisis loop
  - $\mathbf{H}_{\mathrm{EXT}}$ results in a net changing flux
  - Field proportional voltage induced in sense winding
  - Closed loop improves linearity

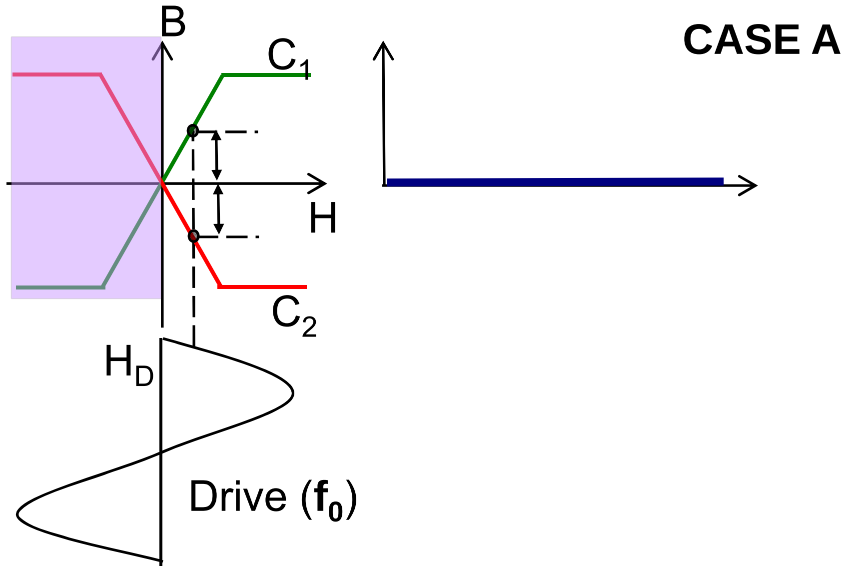
- **Advantages**
  - Low noise ~ 20pT/ √Hz @1Hz
  - Wide dynamic range
  - Mature technology
  - Relatively inexpensive

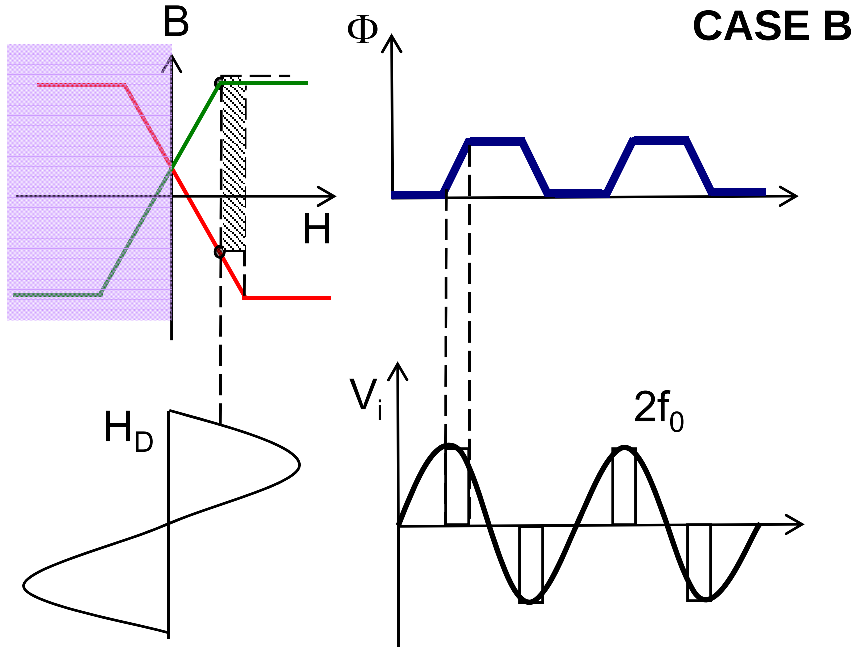
- **Disadvantages**
  - Sensor mass
  - Sensor offset
  - Power ~ 1W
  - In-flight calibration overhead









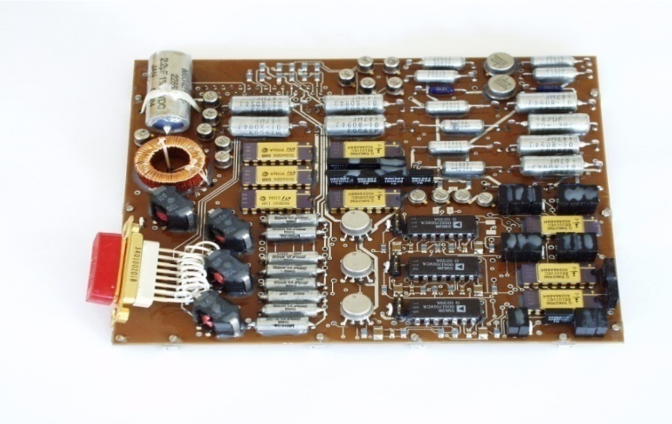


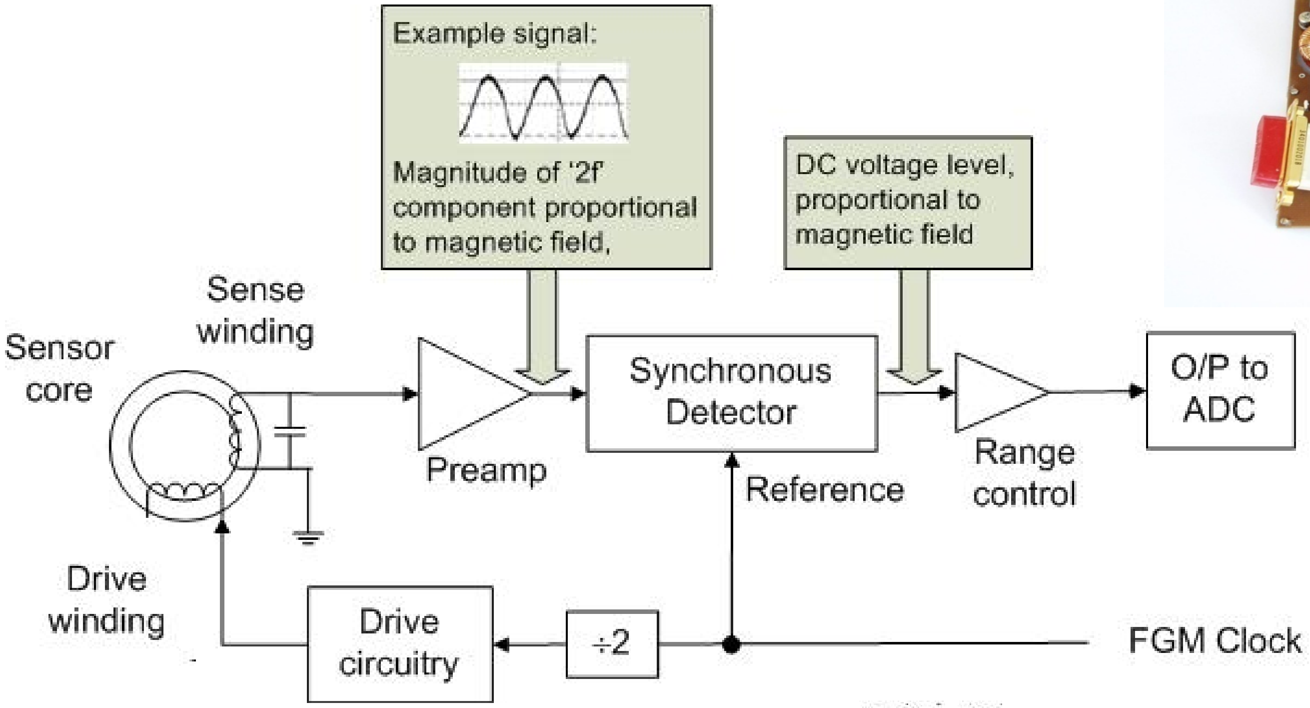
CASE A: Zero external DC field
Half cores saturate synchronously – no net change of flux **seen** by sense wining

CASE B: Non-zero external DC field
Half cores do not saturate synchronously – a net change of flux **seen** by sense wining

Change of flux in sense winding at the 4 crossing of the B-H infection points in each drive period → induced voltage at
2 x $\mathbf{f}_o$ according to Faraday

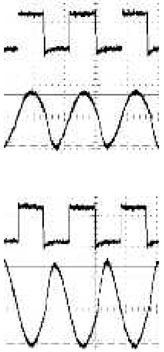
Fluxgate Control Electronics: Open Loop





Field magnitude determined by 2f magnitude

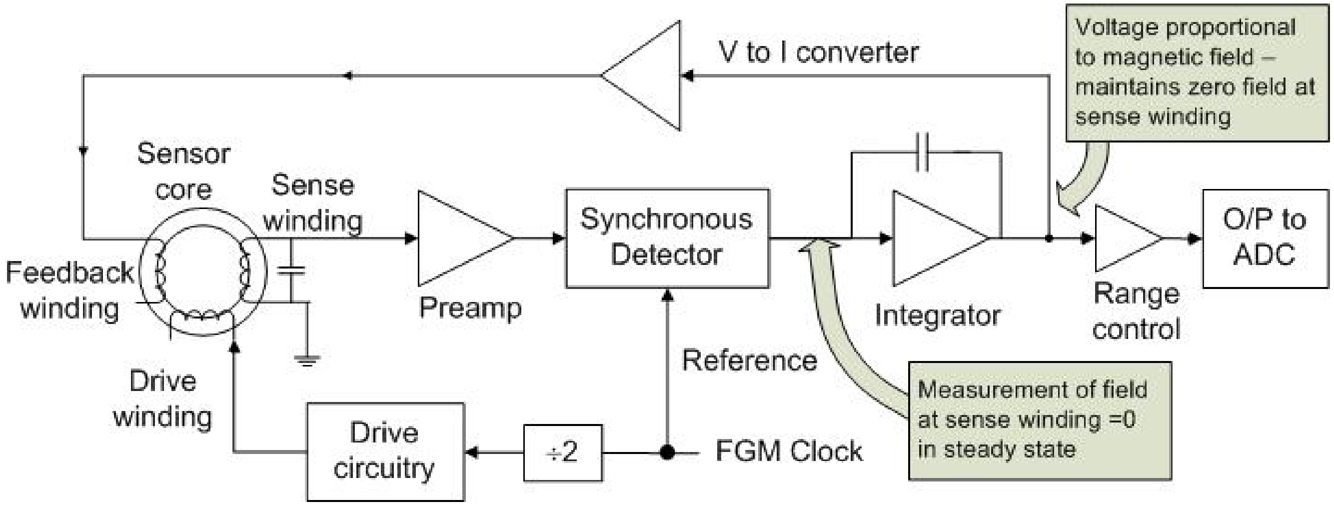
Field direction determined by 2f phase relative to reference



Measured 2f

Reference 2f

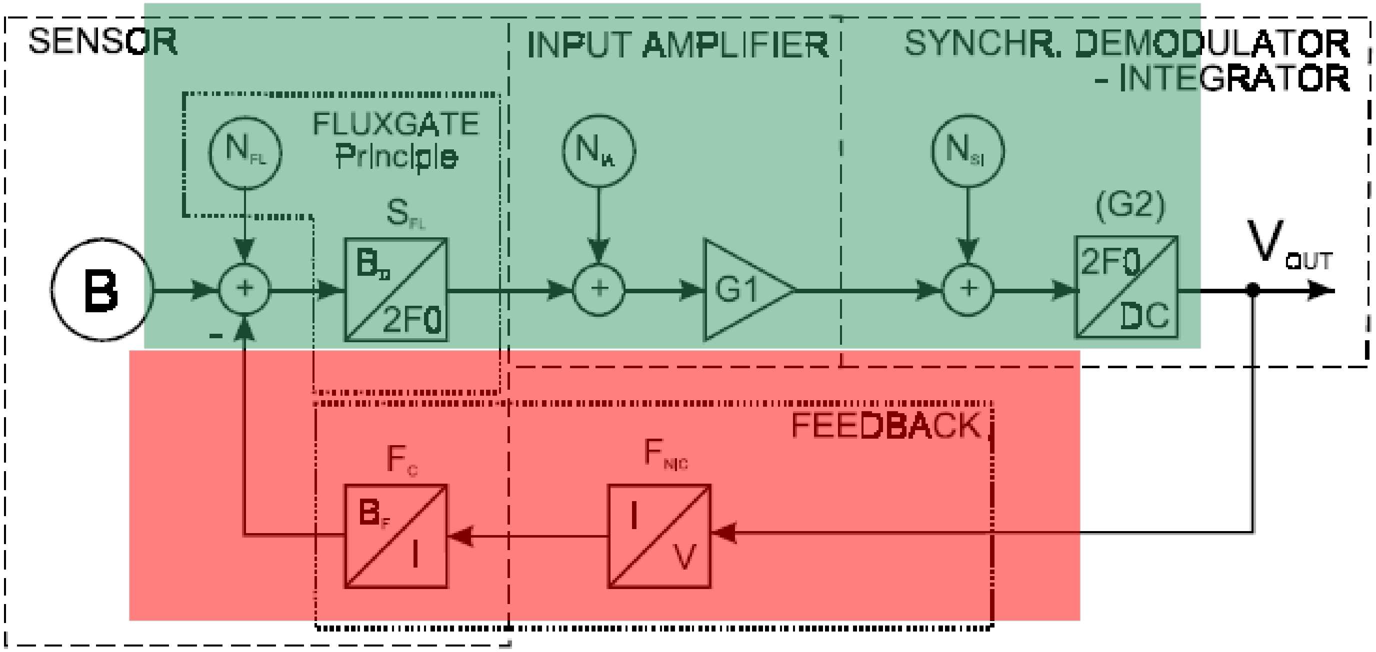
Fluxgate Control Electronics: Closed Loop



Benefits include improved linearity and temperature stability. Scale factor depends only on feedback resistor/gain stage and coil constant.

Considerable effort spent minimising even harmonics in drive signal
some odd harmonics due to transformer effect.

Includes anti-aliasing filter



(Magnes 1999)

B	external magnetic field [nT]
$B_D=B-B_F$	magnetic field within the sense coil
S_{FL}	sensitivity of the fluxgate sensor [µV/nT]
N_{FL}	noise of the fluxgate sensor [nT]
N_{IA}	noise of the input amplifier
G1, G2	amplification factors
N_{SI}	noise of the synchr. demodulator and integrator
F_C	coil factor of the sense coil [nT/µA]
F_{NIC}	conversion factor of the NIC [µA/V]
2F0	second harmonic measurement signal
B_F	magnetic feedback field

$$\left[\left[\left[(B+N_{FL}-B_F)\cdot S_{FL}\right]+N_{IA}\right]\cdot G_1+N_{SI}\right]\cdot G_2=V_{OUT}$$

🟩 Measured signal

$$B_F=F_{NIC}\,F_C\,V_{OUT}=k\,V_{OUT}$$

🟥 Feedback signal

Equating terms and re-arranging

$$V_{OUT} = B \cdot \frac{S_{FL} G_2 G_1}{1 + k S_{FL} G_2 G_1} + \frac{(N_{FL} S_{FL} + N_{IA}) \cdot G_2 G_1 + N_{SI} G_2}{1 + k S_{FL} G_2 G_1}$$

And if ***$kS_{FL}G_2G_1 >> 1$***

$$V_{OUT} = B \cdot \frac{1}{k} + \frac{N_{FL}}{k} + \frac{N_{IA}}{k S_{FL}} + \frac{N_{SI}}{k S_{FL} G_1}$$

Two conclusions

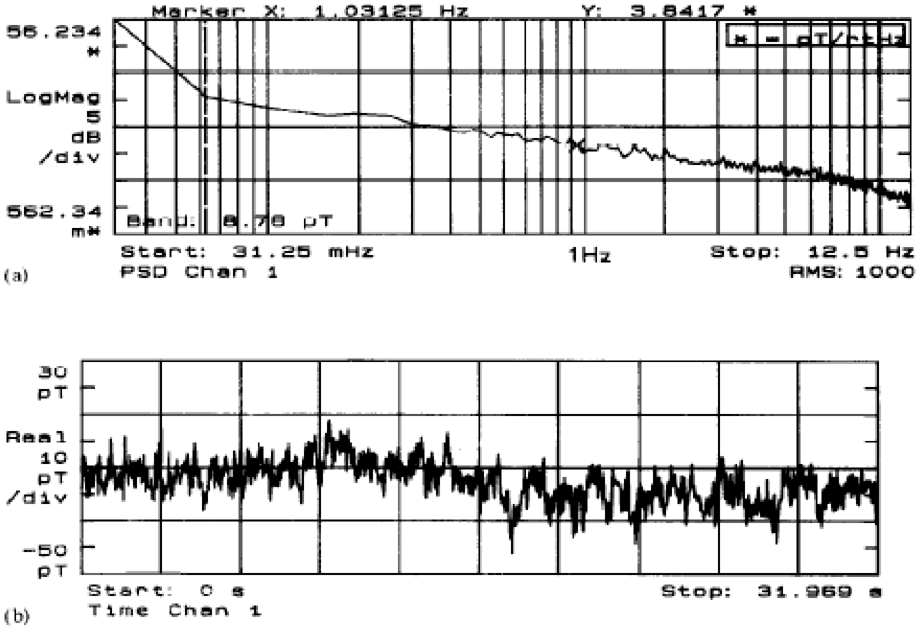
Measurement range only set by feedback circuit

Output noise is dominated by input amplifier and sensor noise only

(Very low noise analogue pre-amps available)

Fluxgate Noise

- Best expressed as a Noise Spectral Density (NSD) often at1Hz
- Characteristic typically has a 1/f fall off



Ripka (1998)

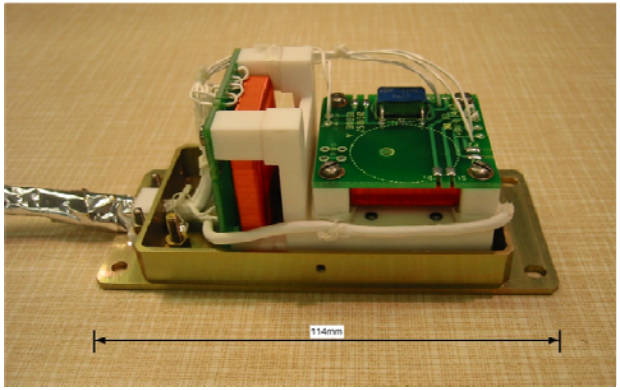
- Between 0 and Nyquist can use following expression to calculate RMS Noise

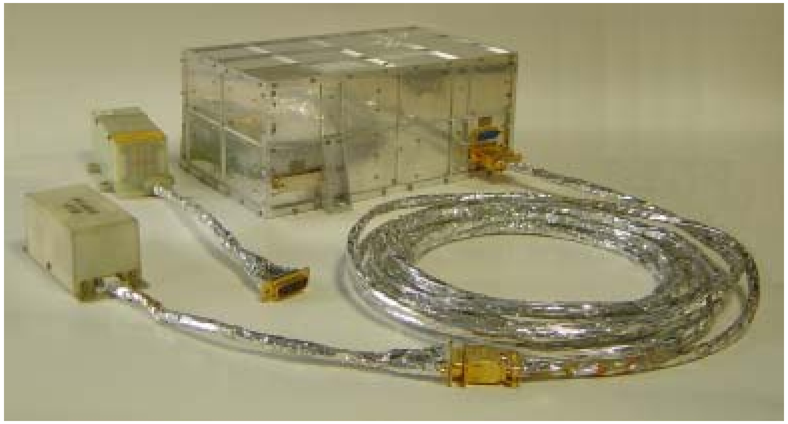
$$N_{\mathrm{rms}} = \left(\int_{f_L}^{f_H} P(f)\,dt \right)^{1/2} = (P(1)\ln(f_H/f_L))^{1/2}$$

- Above Nyquist noise will be flat (ie white noise) due to ADC quantization
- Best quality fluxgates have NSD ~5pT/Root Hz at 1Hz

Imperial fluxgate instrument performance

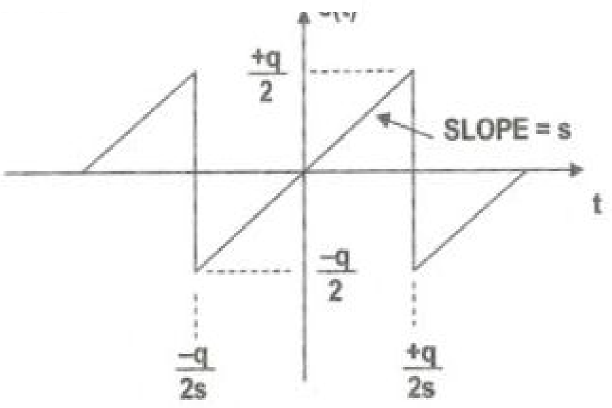
- Industrial partner - Ultra Electronics
- Cassini/Double Star Heritage
- Two core sensor
- Tuned second harmonic detection
- Dual sense and feedback windings
- Offset stability < 0.05 nT/°C
- Scale factor drift < 40 ppm/°C
- Noise density < 8pT/root Hz @1Hz
- Operating range
  - -80^{o}C to 70^{o}C (operational)
  - -130^{o}C to 90^{o}C (non-operational)

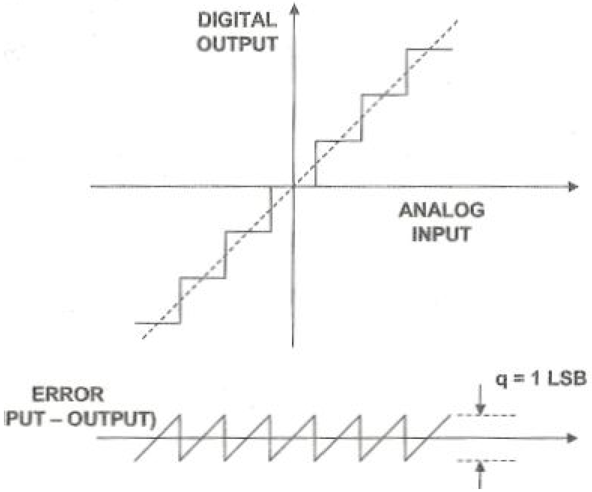




Importance of ADC: Quantization Noise

- Large number of bits N
- Ideal linearity
- No missing codes
- Radiation tolerance
- Ideal quantization noise

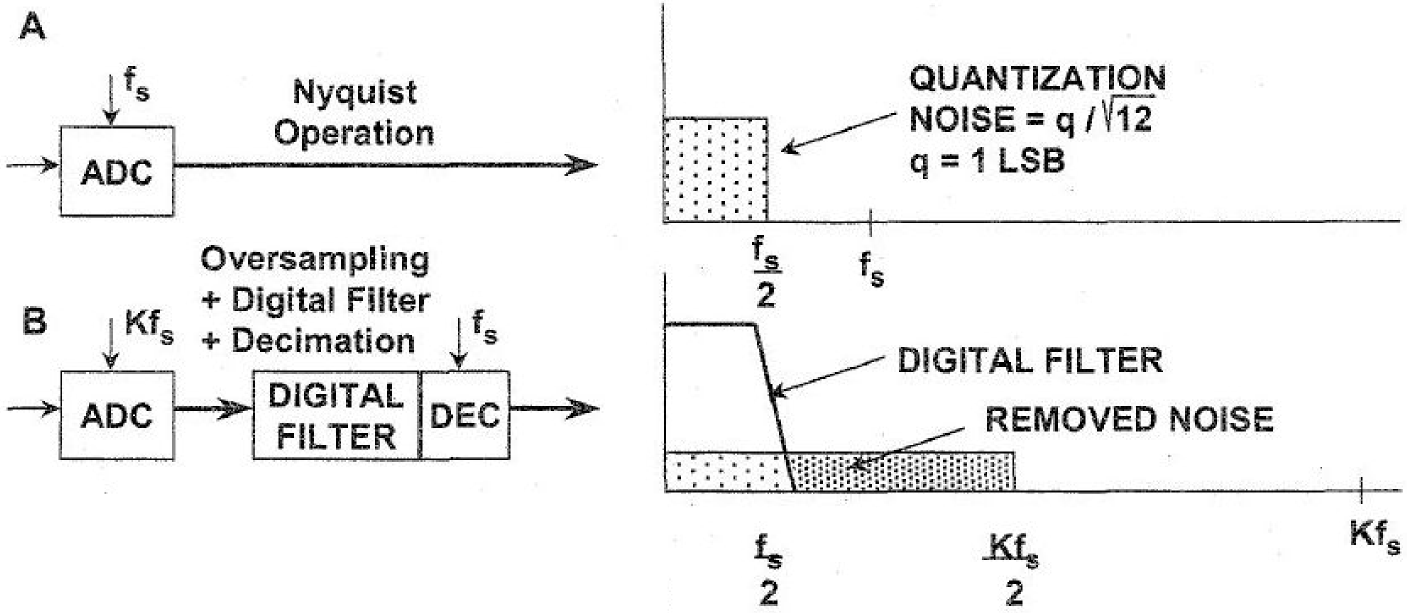




- ERROR = $e(t) = st, \quad \frac{-q}{2s} < t < \frac{+q}{2s}$
- MEAN-SQUARE ERROR = $\overline{e^2(t)} = \frac{s}{q} \int_{-q/2s}^{+q/2s} (st)^2 \, dt = \frac{q^2}{12}$
- ROOT-MEAN-SQUARE ERROR = $\sqrt{\overline{e^2(t)}} = \frac{q}{\sqrt{12}}$

Quantization Noise

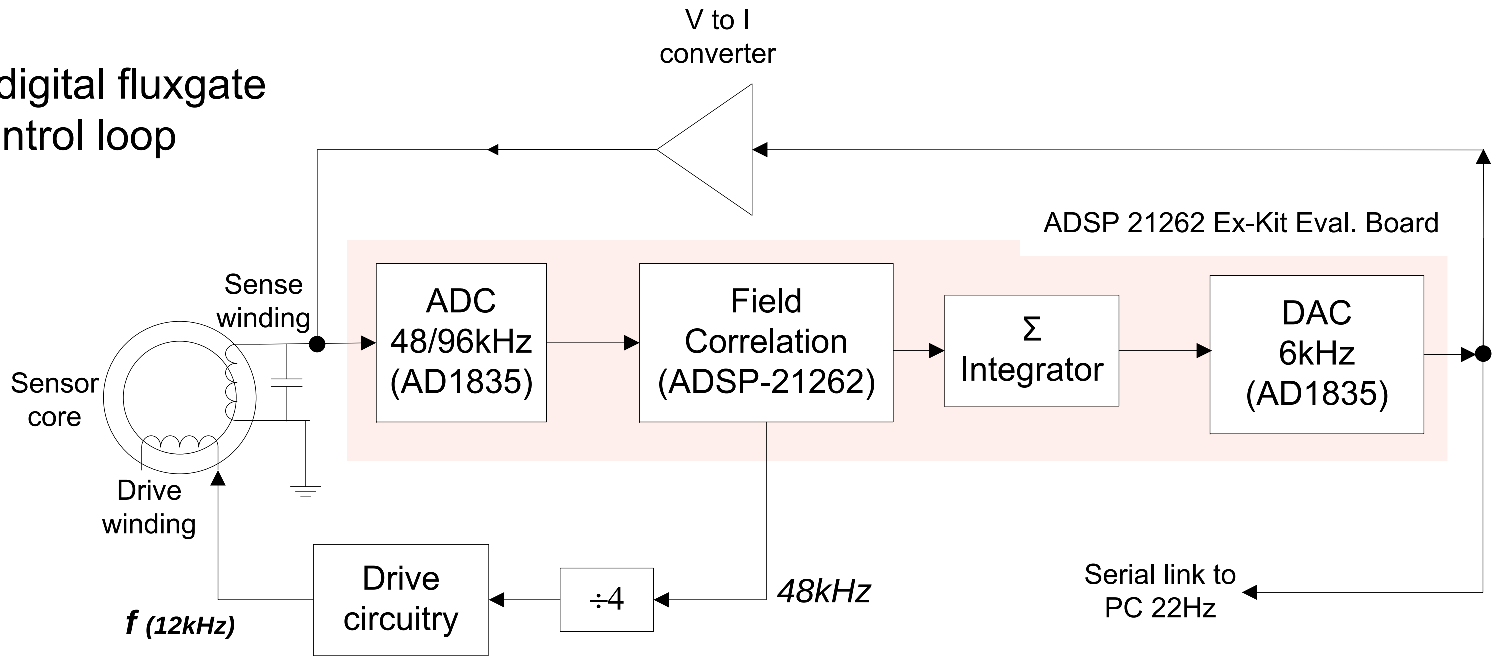
- Large N Rad-tolerant ADCs are a ‘big’ problem for all instruments
- Solution: MIL-STD devices with spot shields (N ~14)
- Traditionally a separate self contained card – Cluster, Rosetta, Cassini
- Use oversampling to reduce Q noise
- Q noise should be matched to intrinsic sensor noise based on desired range, resolution sensor scale factor and N and LSB



Digital Magnetometers

- Means migrating control loop into digital domain
- ADC **and** DAC utilised **within** sensor control loop
- Offers increased flexibility - programmable
- First Missions late 90s - ROMAP, VEX, Astrid, Oersted
- Shown to reduce analogue content and power consumption
- Numerous designs – still being played out - a very active field

A digital fluxgate control loop



Delta Sigma Fluxgates – A hot topic

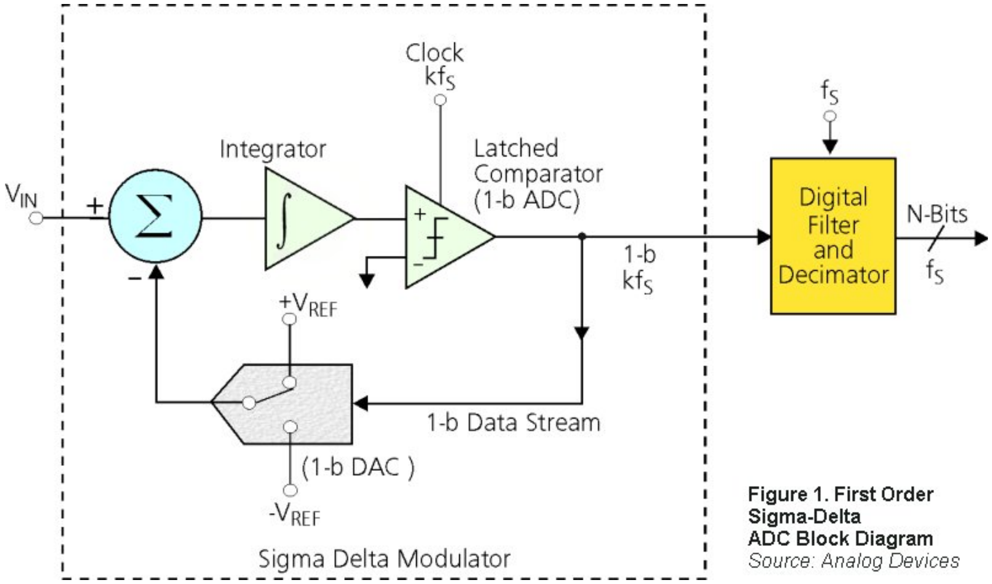


Figure 1. First Order Sigma-Delta ADC Block Diagram
Source: Analog Devices

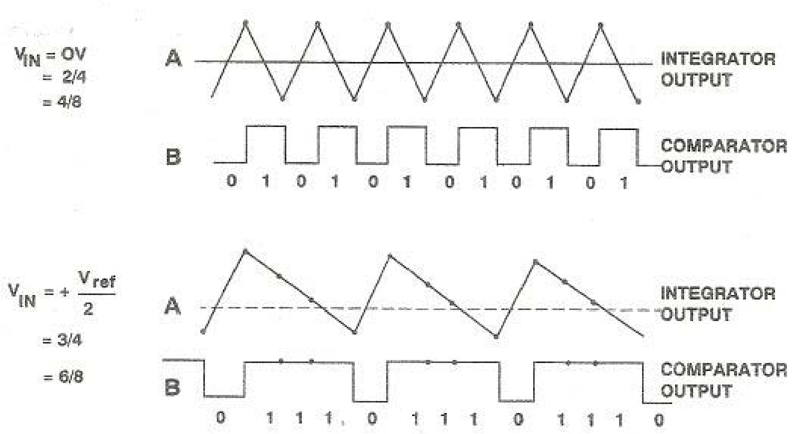
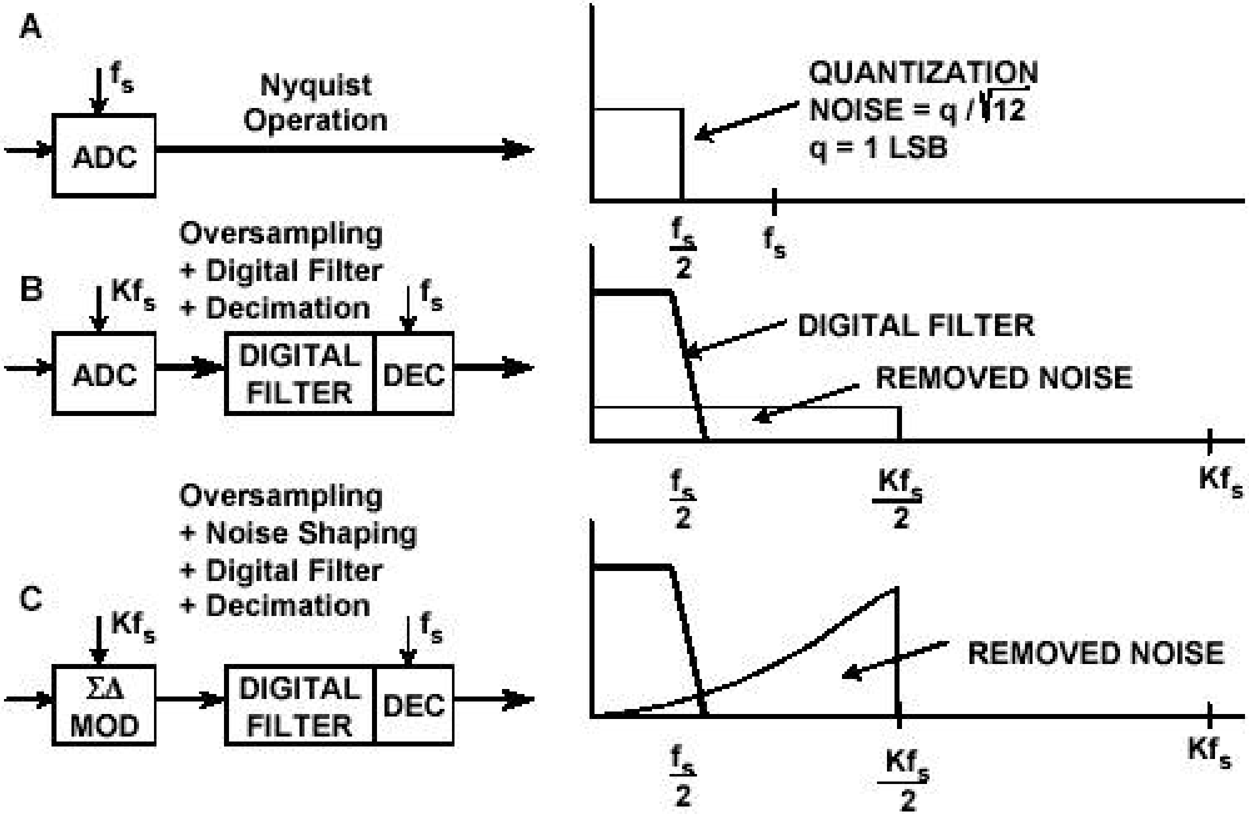


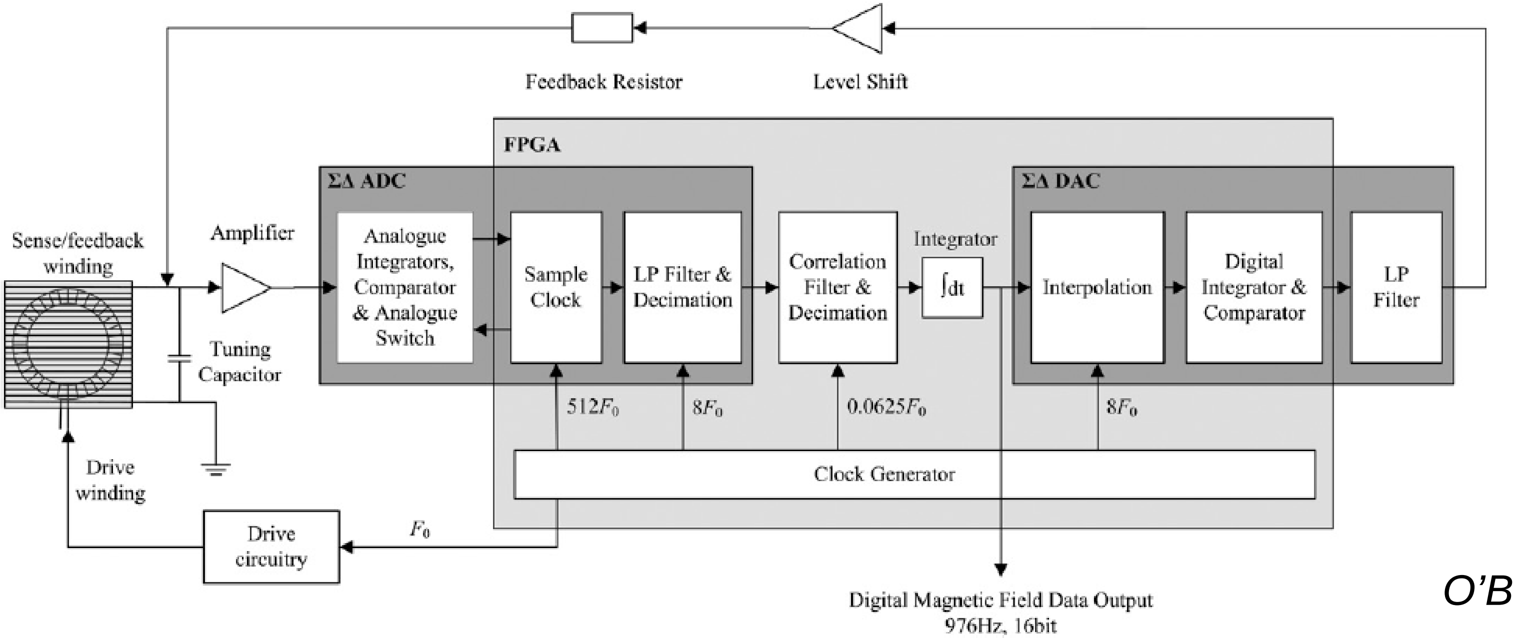
***Figure 3.127:** Sigma-Delta Modulator Waveforms*

- Single bit quantization at very high frequency– linear by definition
- Tracks **changes** in consecutive samples rather than absolute value
- ‘Ones’ density of the 1 bit data stream provides an average value of Vin
- Can be implemented with a rad-hard analogue discretes and rad-hard digital logic – mixed signal ASIC
- Additional gain due to noise shaping
- Eliminates need for old fashioned non rad-hard ADCs

Noise shaping effect

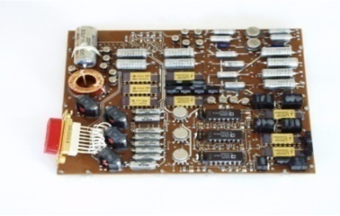


Delta-Sigma Magnetometer



O'Brien (2007)

Replace



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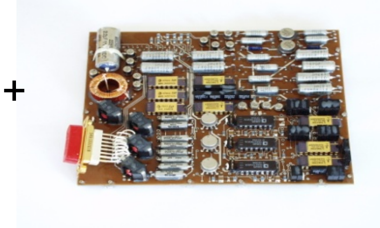

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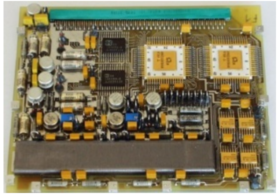

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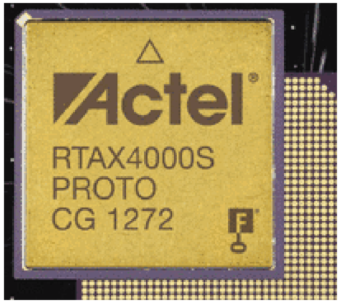
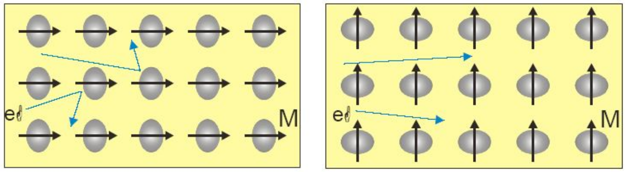
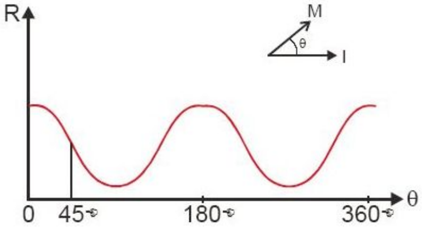


Anisotropic Magnetoresistance

- **Magneto Resistance Effect**
  - Change of resistance in magnetic field
  - AMR single layer permalloy,
  - AMR ΔR/Rmin of order 1- 2%
  - AMR has lowest noise floor
  - Johnson noise limited - no shot noise

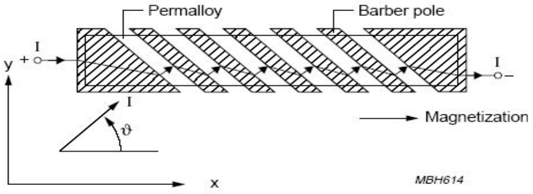
$$R = R_0 + \Delta R_0 \cos^2(\theta(H))$$

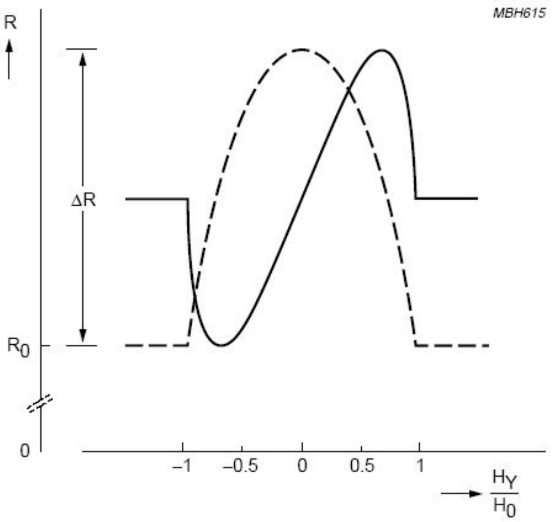




- **Barber Poles**
  - Max, sensitivity & linearity at **M** v **H** 45°
  - Conductive strips for linear operation

- **AMR Sensors**
  - Thin film solid state devices
  - Implemented as Wheatstone bridge
  - Mass <1g, Ceramic package
  - Sensitivity increases with increasing bridge voltage, V_B

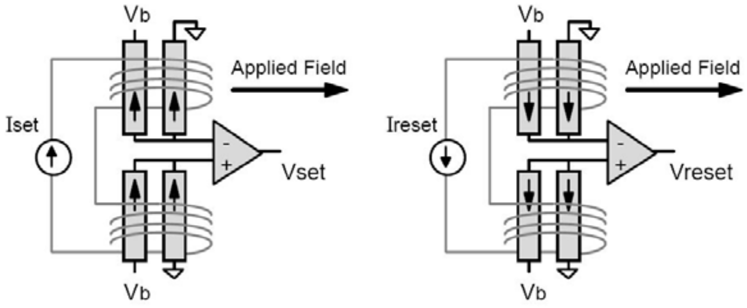




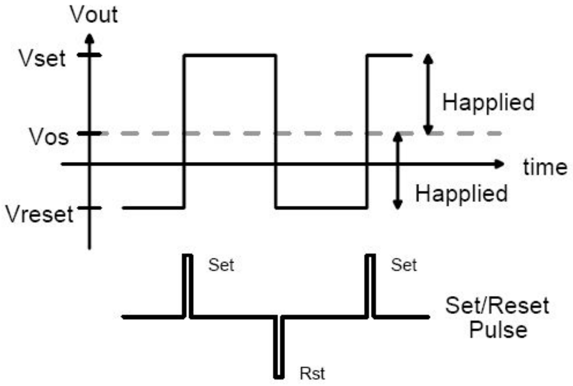
Philips

Integrated coils

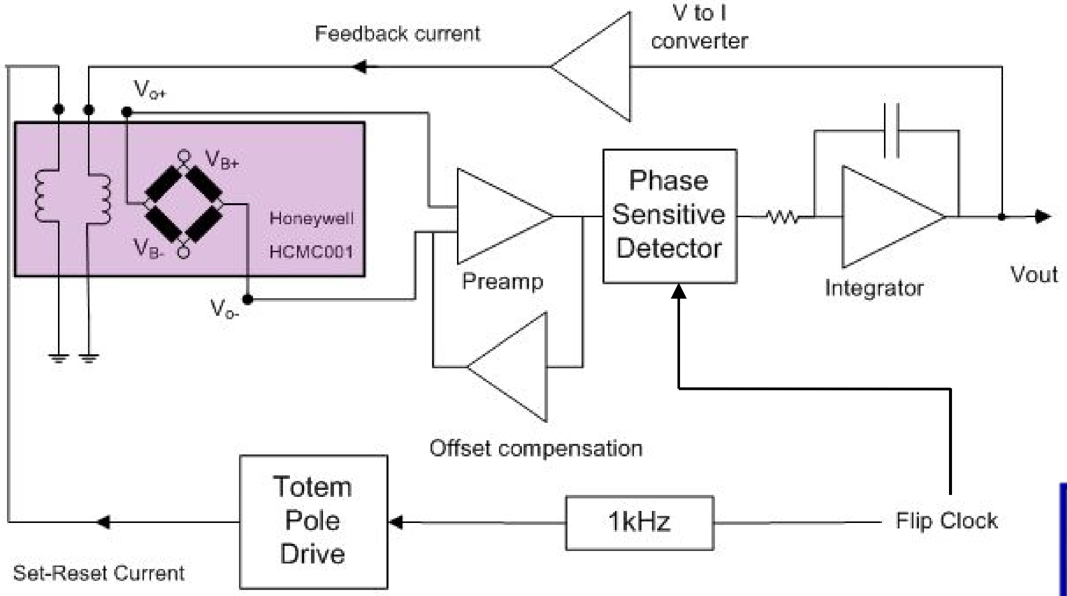
- **Set - Reset Coils**
  - Planar coils around each bridge resistor
  - Coil axis parallel to Easy axis
  - Used to re-align the anisotropic direction
  - Large current spike needed
  - Can extract sensor offset (unlike fluxgate)
  - Requires de-modulation to DC
  - Compensates for offset and offset drift
  - Improves sensor noise floor



- **Offset coils**
  - Integrated coils around the bridge
  - Coil axis parallel to Hard (sensitive) axis
  - Permits electromagnetic feedback
  - Used in closed loop back off measured field
  - Improves linearity and variation of sensitivity with temperature
  - Suppresses Barkhausen noise

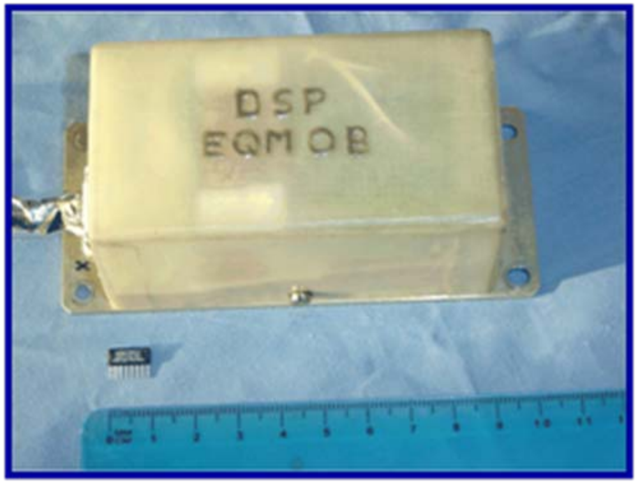


Single axis AMR magnetometer



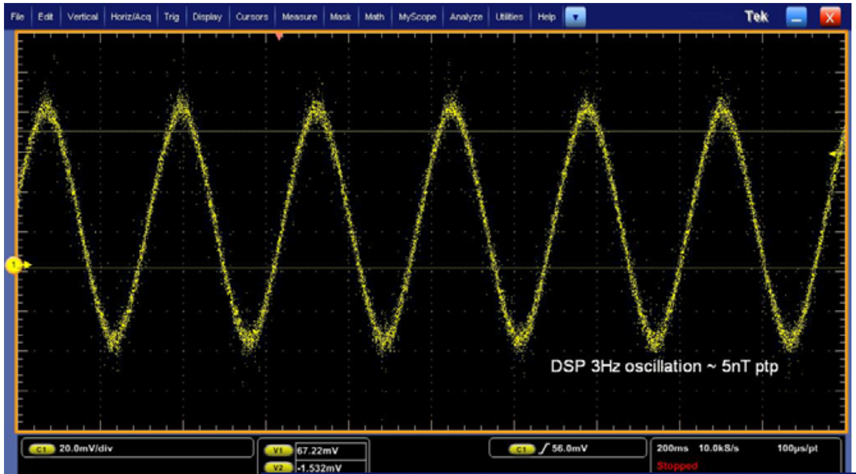
Analog build
Set-Rest 4A with 2μs τ_C
Sensitivity proportional to V_B
Closed loop

$$V_o = H_y \times \frac{R_{FB}}{A_{COIL}}$$



Stimulus measurement – Fluxgate vs AMR

DSP (20mV/div scale)



DSP 3Hz oscillation ~ 5nT ptp

C1 20.0mV/div

V1 67.22mV

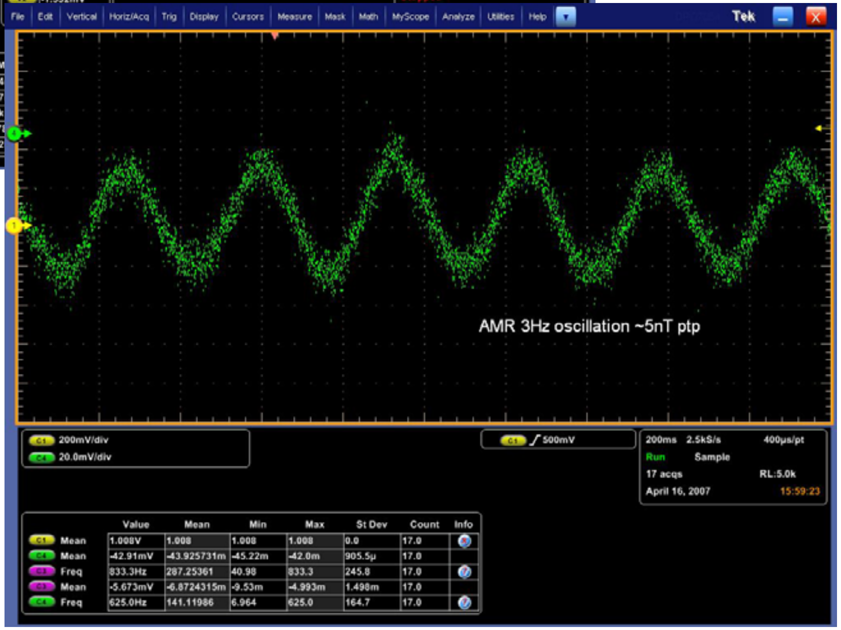
V2 -1.532mV

C1 56.0mV

200ms 10.0kS/s 100µs/pt

		Value	Mean	M
C1	Mean	21.05mV	20.993665m	20.94
C4	Mean	5.676mV	5.6362236m	5.597
C3	Freq	1.291kHz	1.2702697k	1.25k
C3	Mean	-10.21mV	-10.994548m	-11.7
C4	Freq	4.452kHz	4.7293464k	4.452

AMR (20mV/div scale)



AMR 3Hz oscillation ~5nT ptp

C1 200mV/div

C4 20.0mV/div

C1 500mV

200ms 2.5kS/s 400µs/pt

Run Sample

17 acqs RL:5.0k

April 16, 2007 15:59:23

		Value	Mean	Min	Max	St Dev	Count	Info
C1	Mean	1.008V	1.008	1.008	1.008	0.0	17.0	
C4	Mean	-42.91mV	-43.925731m	-45.22m	-42.0m	905.5µ	17.0	
C3	Freq	833.3Hz	287.25361	40.98	833.3	245.8	17.0	
C3	Mean	-5.673mV	-6.8724315m	-9.53m	-4.993m	1.498m	17.0	
C4	Freq	625.0Hz	141.11986	6.964	625.0	164.7	17.0	

- Three layer Mu-Metal shield
- 3Hz sine wave – 5nT ptp
- Optimal AMR configuration
- Closed loop, R_{FB}=9kΩ
- Bridge voltage 12V
- Offset compensation
- Flip frequency, 1.1kHz
- Sensitivity ~ 11mV/nT
- Sensitivity not linear with increasing R_{FB}
- Some residual offset in closed lop
- Temperature measurement outstanding

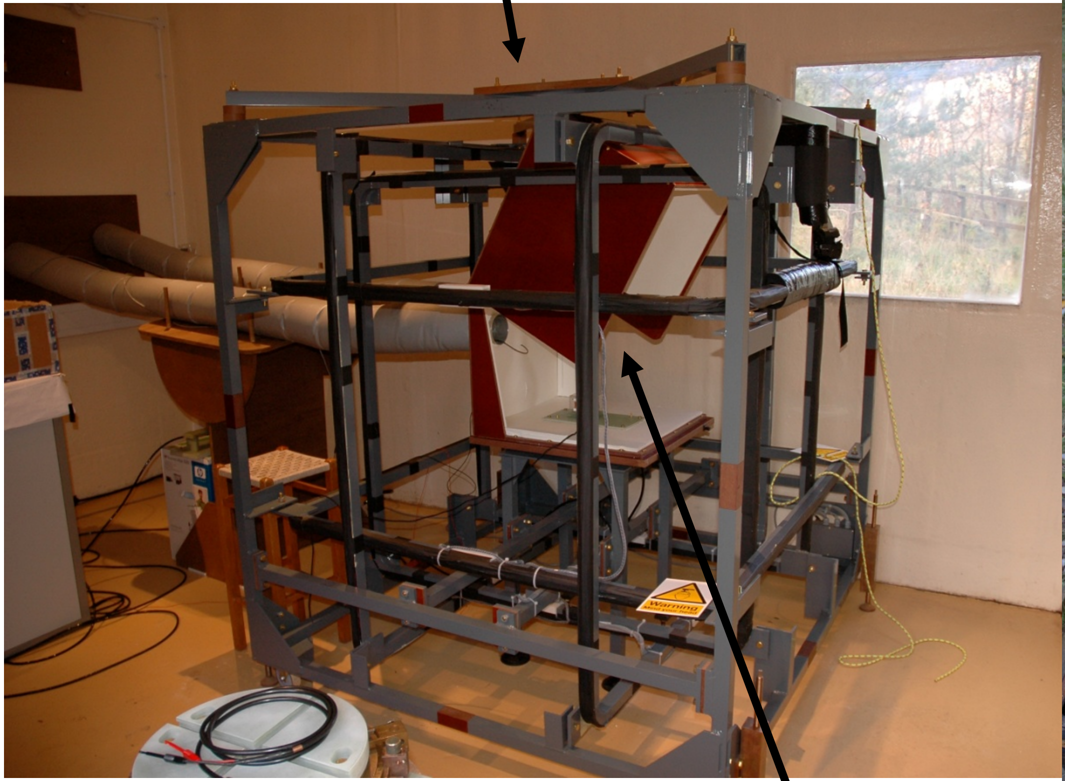
Imperial College London

Calibration equation for a vector magnetometer

- **Calibration Matrix** 12 paramaters needed to transform measured volts to accurate field components into a physically useful co-ordinate system eg GSE, GSM
  - Calibration Matrix
    - Sensor **gains** – convert from raw volts to nT
    - Sensor **mis-alignments** – correct from deviation from nominal sensor axis
    - Euler **angles** –transform othogonalised components into required system
  - Offset vector:
    - Sensor offset - correct for zero level readings (due to sensor, electronics or S/C)
  - Calibration Files
    - Text files with calibration matrix & offset vector for each sensor on a daily or orbit basis :

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{pmatrix} \begin{pmatrix} B_{S1} - O_1 \\ B_{S2} - O_2 \\ B_{S3} - O_3 \end{pmatrix}$$

Imperial's Magnetic Coil Facility



3 axis Helmholtz Coils

Sensor thermal chamber

Pit for long terms offset and noise measurement

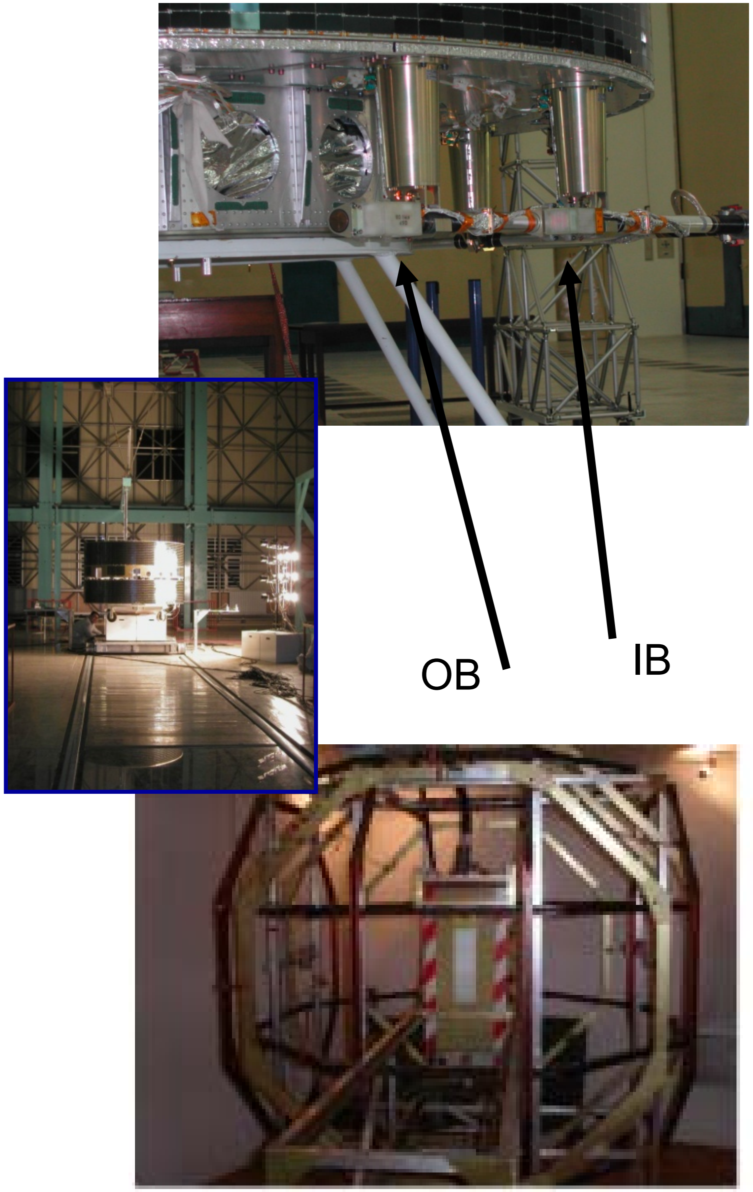
- Facility dynamically backs of Earth’s field using
  - Two Earth Field Reference Magnetometers (EFR) located either side of the hut

- EFR located in pits either side of test hut
- Sum (average) of EFRs used to cancel Earths field inside coil system

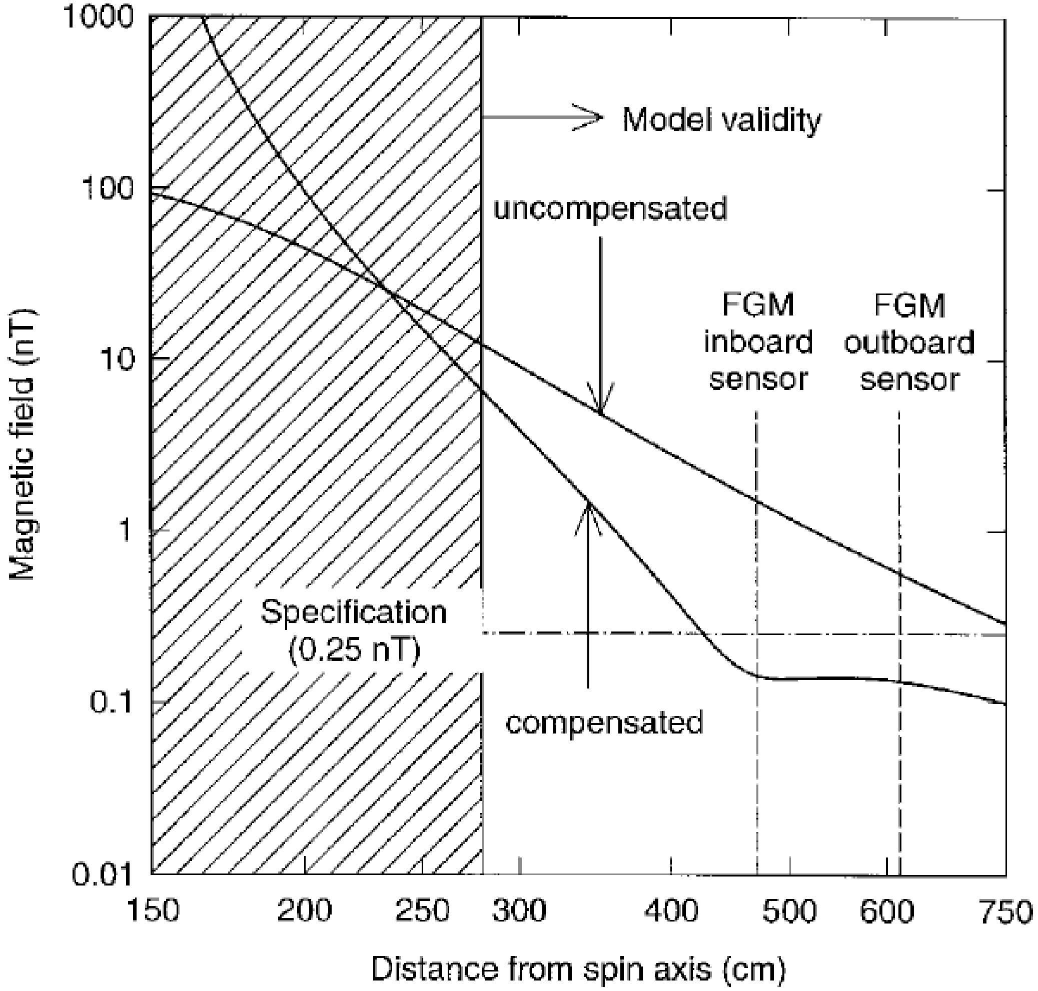
- Difference (gradient) of EFRs used for monitoring

Practical calibration models

- **Ground Calibration - we determine**
  - Sensor calibration parameters on ground,
  - Their associated temperature coefficients,
  - Their variations with input power
  - The sensor noise
- **Magnetic Cleanliness Program - includes**
  - Maximum length boom
  - Low field requirement at boom tip
  - Magnetic screening of materials and units
  - A spacecraft magnetic model
  - System level magnetic test
- **In-flight**
  - range switching, calibration steps
  - In-flight calibration techniques
  - Use of multiple sensors
  - Use of absolute and vector sensors
  - Use of dual-gradiometer modes



System Level Magnetic Test: Cluster Example

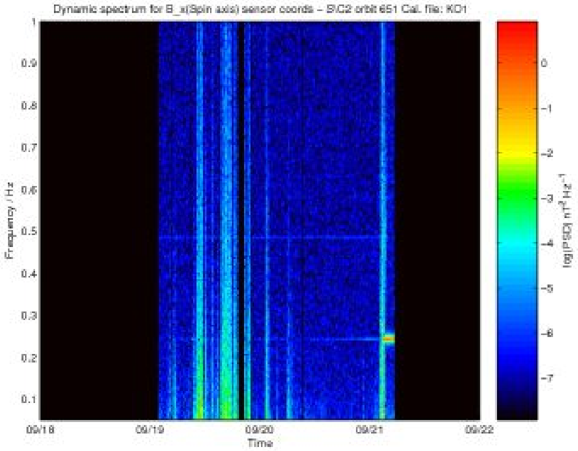


Cluster had a very rigorous (and expensive) magnetic cleanliness program

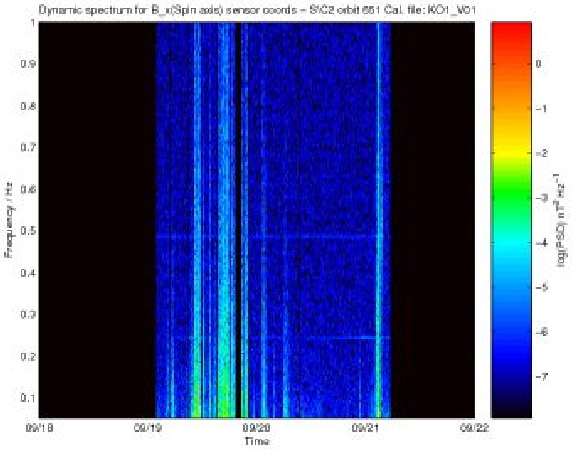
A S/C magnetic field of < 0.25nT is almost NOT the case on the vast majority of S/C

In-flight calibration techniques

- **Spin stabalised spacecraft**
  - Fourier analysis on spinning data
  - Permits recovery of 8 of the 12 cal parameters
  - Major error – spin axis offset
  - Residual spin tone indicates calibration error
  - Example Missions:
    - Cluster, Ulysses, Double Star, Equator-S, Themis

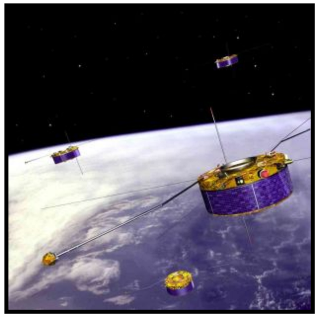


- **Three-axis stabalised spacecraft**
  - More difficult to calibrate
  - Utilise S/C rolls for offset measurement
  - Statistical analyses of solar wind data
  - Looks for correlations between **B** and B components
  - Additional absolute reference magnetometer useful
  - Example Missions
    - Cassini, Rosetta, Oersted, Venus Express

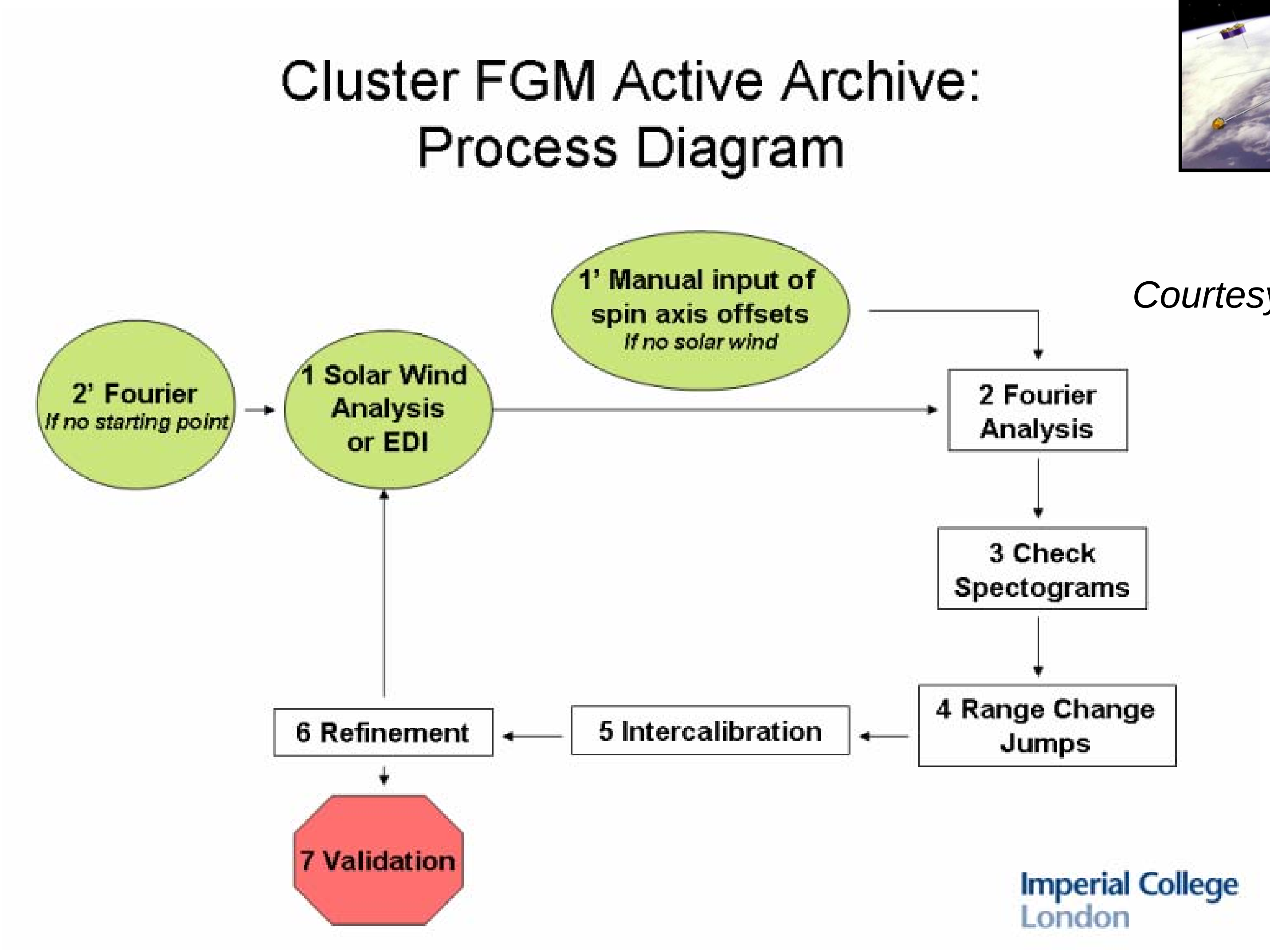


- **Multiple spacecraft missions = multiple calibration references**

Multi-S/C Calibration – Cluster Example



Courtesy J. Gloag



Cluster FGM Active Archive: Process Diagram

2' Fourier
If no starting point

1 Solar Wind Analysis or EDI

1' Manual input of spin axis offsets
If no solar wind

2 Fourier Analysis

3 Check Spectograms

4 Range Change Jumps

5 Intercalibration

6 Refinement

7 Validation

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Dual Magnetometer Mode

- Used in cases where S/C field contaminates measurement
- IB and OB sensor used as a gradiometer
- Ambient field same at both IB & OB
- S/C field NOT same at IB & OB
- Number of sensors is proportional to multipole moment that may be extracted
- Two sensors limit model to a dipole of fixed position
- Other techniques utilising pattern recognition in operation
- Relative sampling of both sensors important especially on spinning S/C
- Usually results in reduced data rates
- Example missions: Double Star, Venus Express

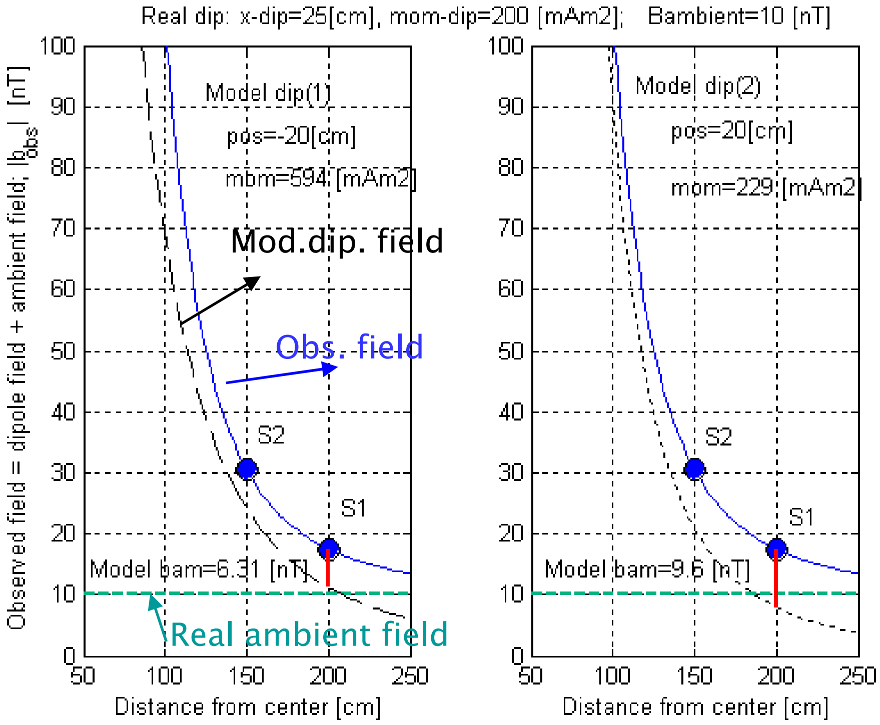


Figure courtesy Delva

Example (1 dim.):
Real **B**am=10 nT
Real SC dipole:
p =25 cm
m =200 mAm2

Solution 1:
p~ = – 20cm
m~=594mA^2

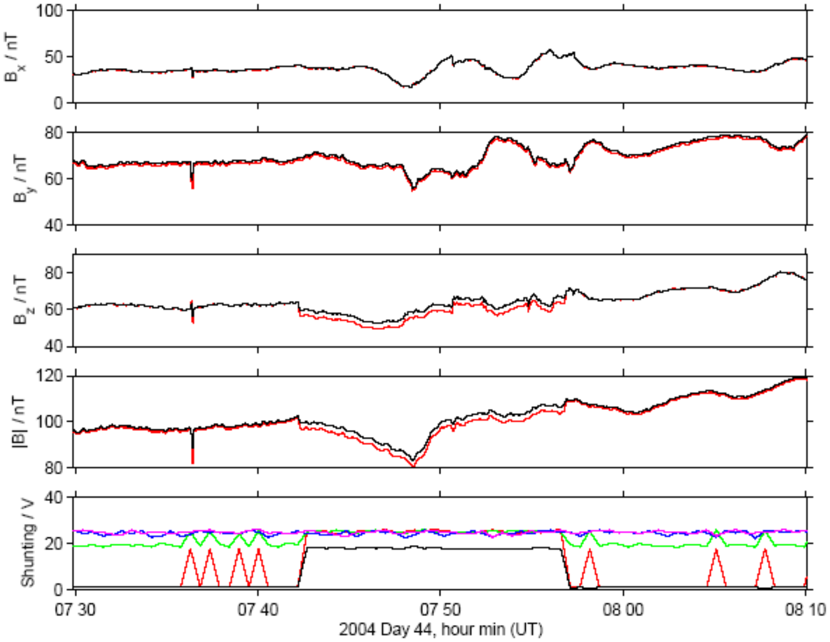
Bam~=6.31nT

Solution 2:
p~ =+20cm
m~=229mAm^2

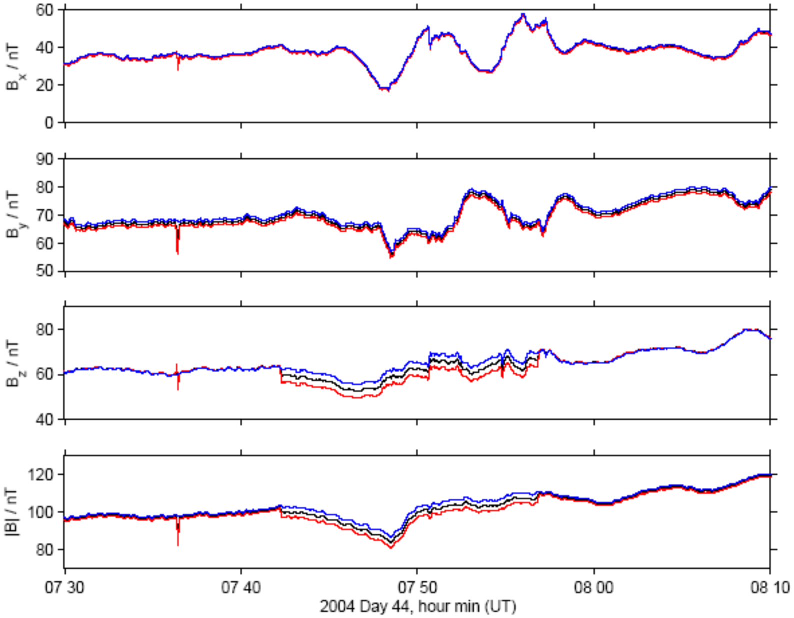
Bam~=9.6nT

Case Study. Double Star magnetometer

- OB sensor 5m, IB sensor 3.5m
- Spin synchronised disturbance due to unbalanced solar array current
- Amplitude varies with S/C shunting mode
- Data cleaned using gradiometer mode
- Resulting data set is spin averaged resolution (0.25Hz) compared to 11Hz on-board



Un-cleaned data and shunting modes

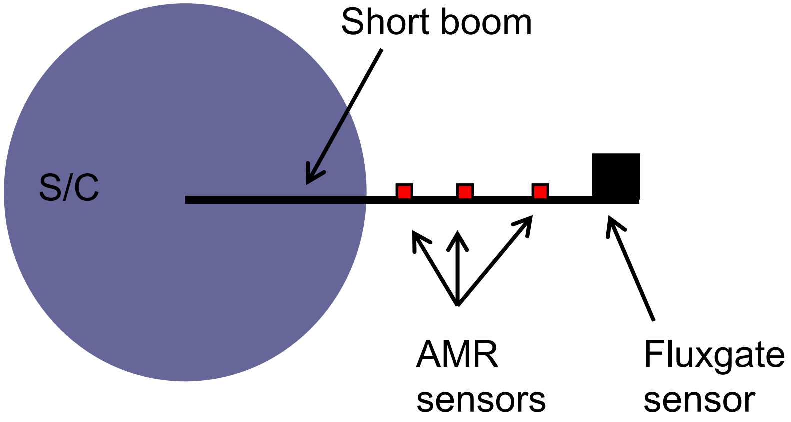


Un-cleaned and cleaned data

Carr (2005)

A new magnetometer model?

- Fluxgate - AMR combination
- Single fluxgate at end of a (shorter boom)
- Several AMR sensors inward of the fluxgate
- Permits multipole expansion of S/C field
- Accurate separation ambient field at instrument intrinsic data rate
- Precise tracking of fluxgate offsets
- Required for space plasma constellations
- Potential for automation
- Could be applied acoss missions
- Extendable to an array of AMR sensors



Question – How to validate concept ?

A magnetometer array

- **Imperial College student satellite program**
  - Milestone - Two spacecraft in LEO
  - 10cm cube, 1kg modules
  - Injection into LEO approx $30,000

- **Aims**
  - Measure ULF wave field in dayside magnetosphere
  - Flight qualify FPGA controlled AMR array
  - Validate S/C field rejection algorithms
  - Extract accurate magnetic field vector

- **Ground validation**
  - Mobile Coil Facility
  - ESTEC MDM to calculate E-box moments
  - Measure both S/C components and assembled S/C
  - Measured moments fitted to S/C model
  - Permits validation test of field rejection on ground

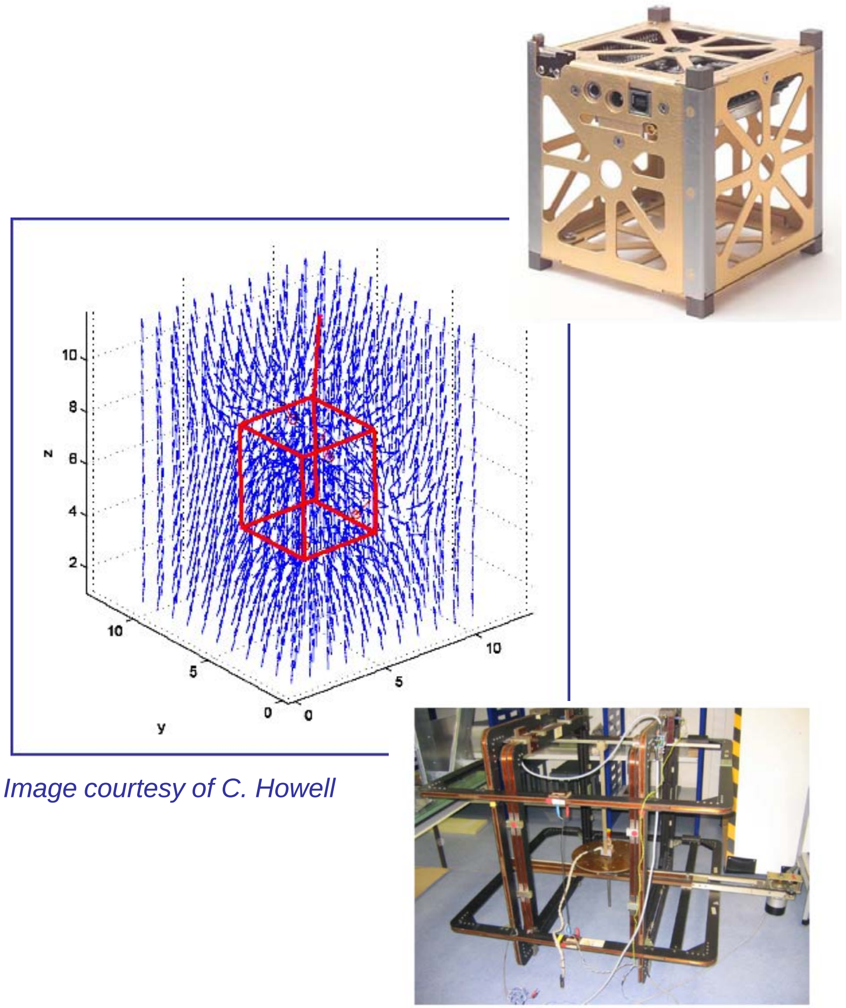
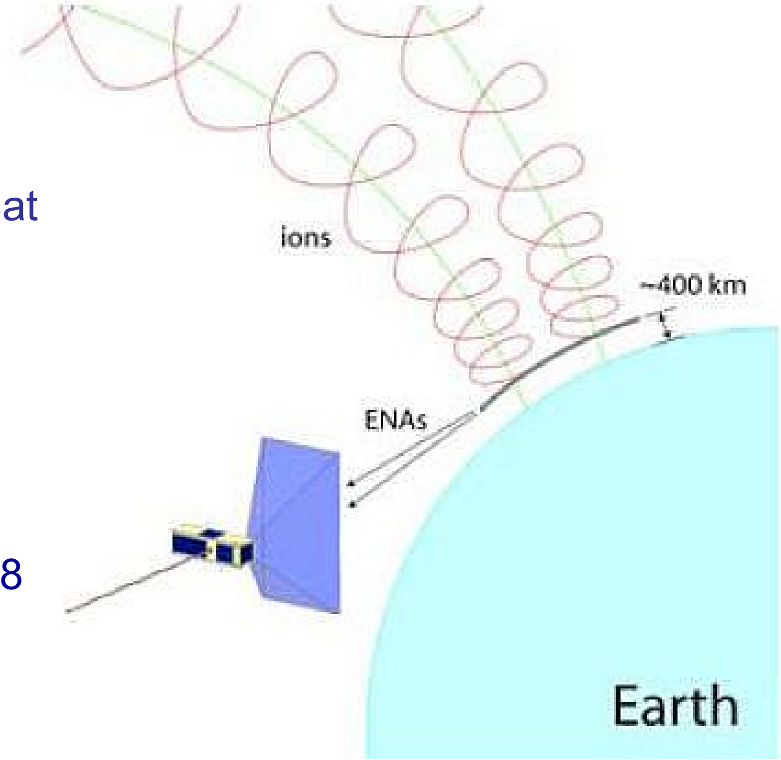


Image courtesy of C. Howell

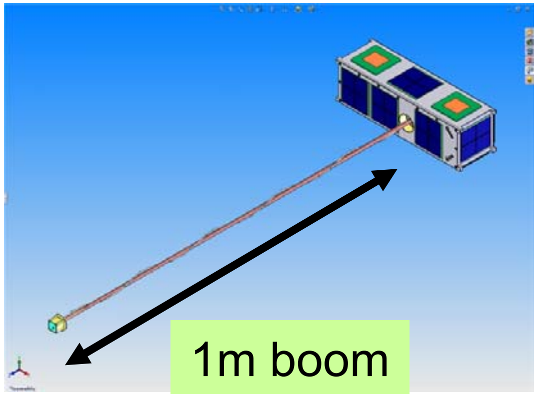
Potential Flight Opportunity 2010

CINEMA- CubeSat for measurement of ions, neutrals and magnetic fields

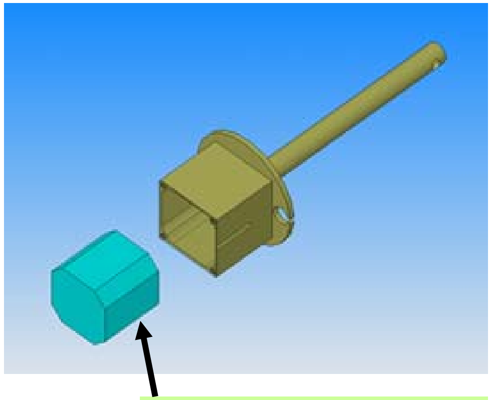
- Collaboration between UCB, IC & NASA AMES
- Space plasma science measurement on 3U CubeSat
- Led by UCB/SSL
- LEO with >65^o inclination (72^o nominal), 650km
- 1m deployable boom
- Spin stabalised at ~1rpm
- Two MAG sensors
- Submitted to NSF Space Weather Competition 2008
- To be re-submitted 2009
- Heritage: GeneSat & STEREO



CINEMA Magnetometer



1m boom



Magnetometer

1m extendable boom
Boom mass ~120g
MAG orientation not controlled
Determined by magneto-torquer pulse post deployment
Following de-tumble CubeSat spun up and spin axis aligned normal to ecliptic

MAGIC Magnetometer Modes

<u>Attitude Mode</u>

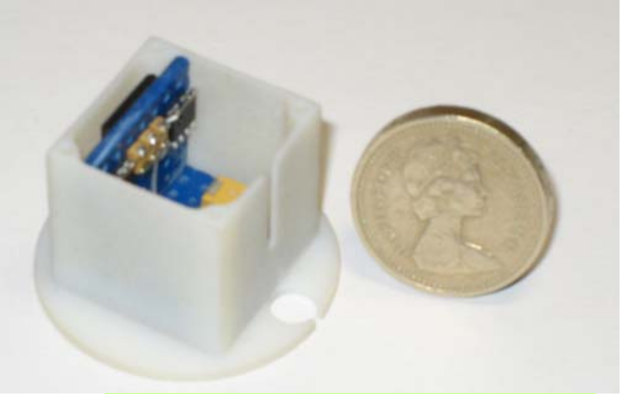
Accuracy <25nT, <150mW

<u>Science Mode</u>

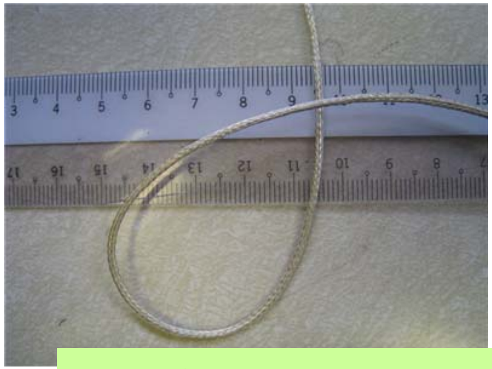
Accuracy <2nT, <750mW

Instrument Range +/-65536nT

Resolution: 0.25nT



MAGIC Sensor head



MAG Boom Harness