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Instrumentation for Space Physics

PG Lecture, 5th December 2017

Chris Carr

Imperial College London

Outline

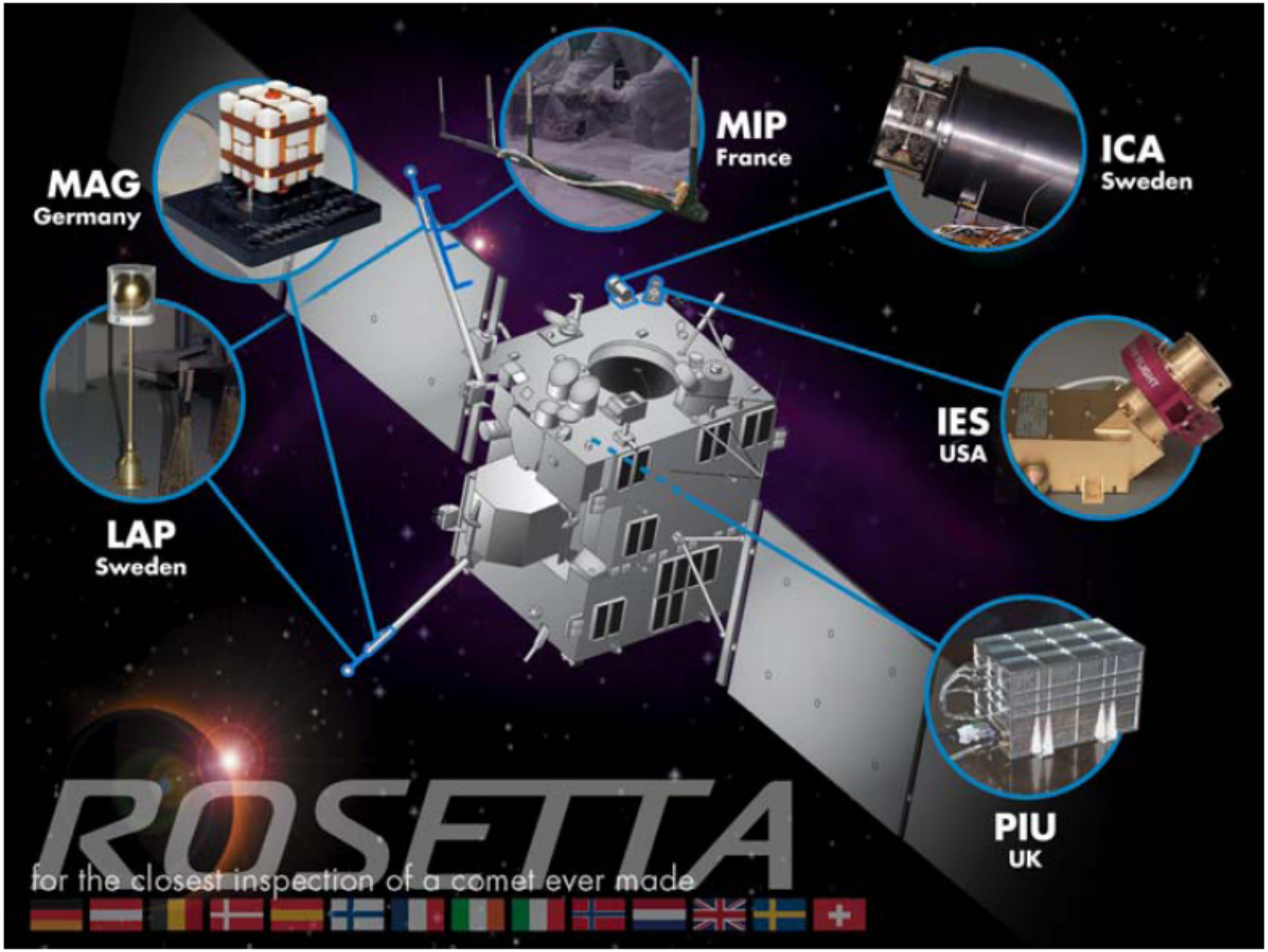
Objectives

- To provide an overview of instrumentation for space plasma physics
- To describe the basic principles behind the most frequently used measurement techniques
- To outline the particular difficulties encountered in building instruments for the space environment

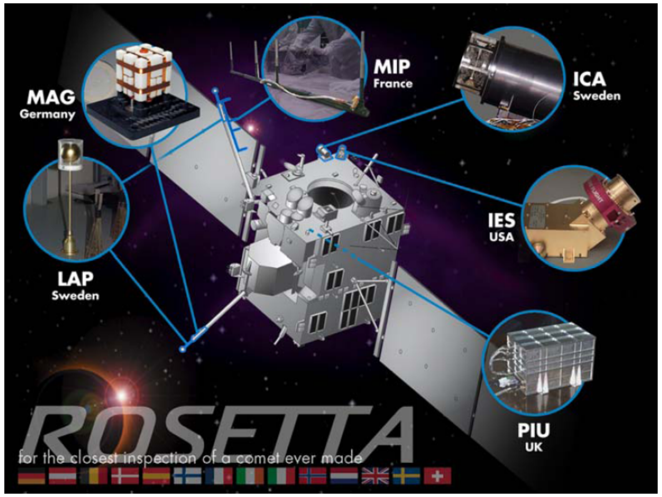
The lecture is in 7 sections

1. Instrumentation for Space Physics
   - » e.g. The Rosetta Plasma Consortium
2. Techniques for Fields
3. Techniques for Particles
4. Performance, Characterisation and Calibration
5. Designing for the Space Environment
6. Digital techniques
7. Future developments

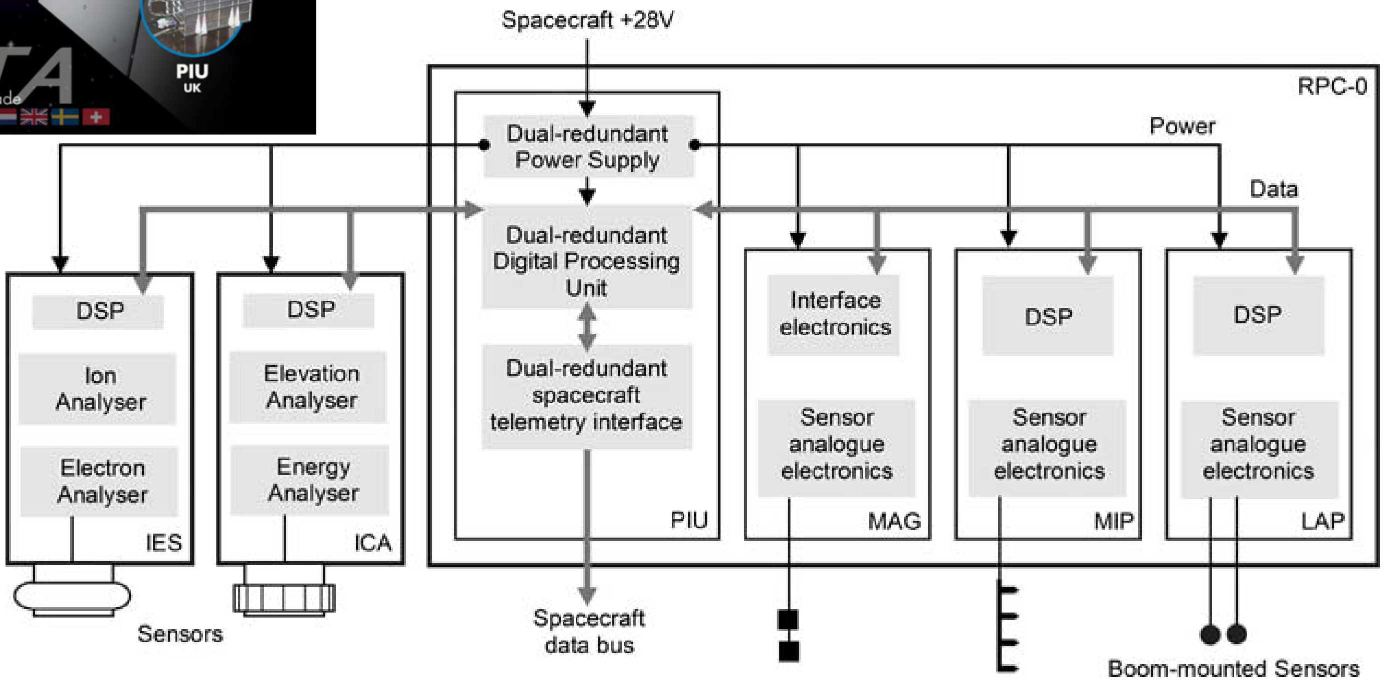
1. Instrumentation for Space Plasma Physics: The Rosetta Plasma Consortium (RPC)



Rosetta Plasma Consortium (RPC)



Mass	7.5 kg
Power	12 W
Telemetry	350 to 5200 bits/s



Carr et al., 2007

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Performance Parameters for RPC

SENSOR	Parameter	Range
IES - 3D Ion & Electron Distribution with Field of View 90° x 360°	Energy Range	4 eV to 22 keV
	Energy Resolution	ΔE/E= 0.04
	Angular Resolution (el)	5° x 22.5°
	Angular Resolution (ions)	5° x 5° & 5° x 45°
ICA - 3D Ion Distribution with Mass Resolution and Field of View 90° x 360°	Energy Range	10 eV to 40 keV
	Energy Resolution	ΔE/E= 0.07
	Angular Resolution	5° x 45°
	Mass Range	Cometary atomic & molecular ions
LAP - Langmuir Probes (2x) Plasma Density, Temperature, Flow velocity, LF waves	Electron density and variations	1 to 10^6 cm^{-3}
	Electron temperature	10 K to 10^5 K
	Flow velocity	0-10 km/s
	Spacecraft potential	± 10 V
MIP - Mutual Impedance Probe Plasma Density, Temperature, Flow velocity; HF waves	Electron density and variations	2 to 10^5 cm^{-3}
	Electron temperature	30 K to 10^5 K
	Flow velocity	0.1 to 1 km/s
	Plasma waves	7kHz to 3.5 MHz
MAG - Dual Magnetometer Magnetic field vector	Bandwidth	0 to 10 Hz
	Resolution	31 pT
	Dynamic range	± 16384 nT

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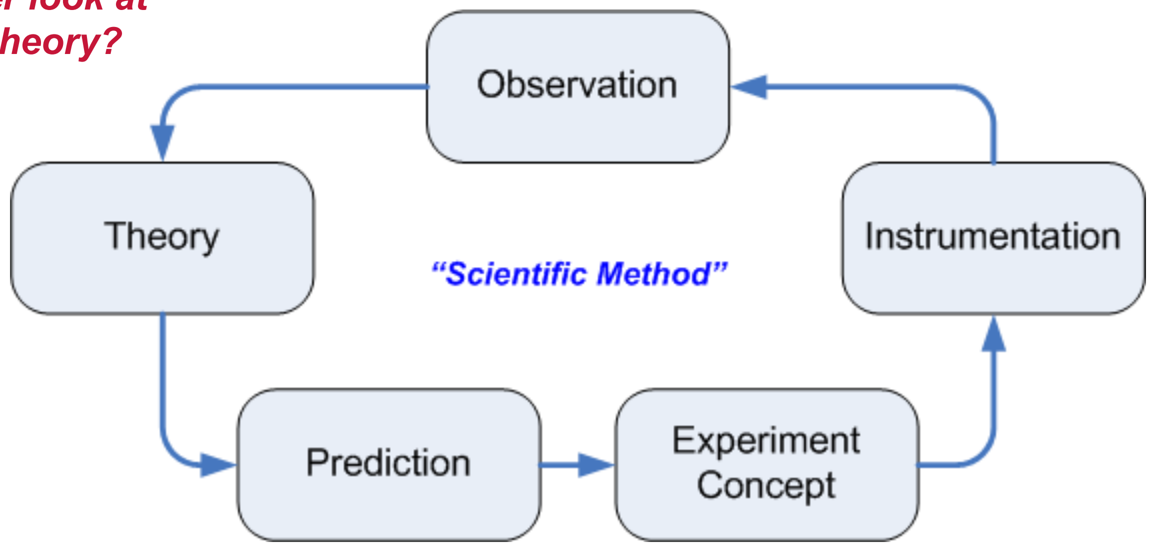
Instrumentation in Space and Planetary Physics

5. Mercury does have a magnetic field

6. Maybe we should take another look at that theory?

1. Planet Mercury has a solid interior



4. Magnetometer

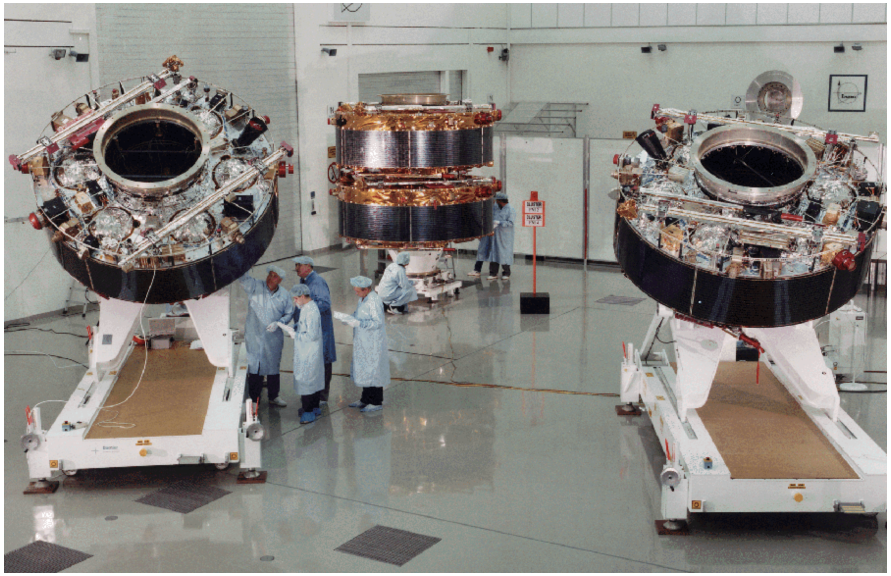
2. Mercury should have no magnetic field

3. The Mariner 10 mission

In space and planetary physics, time from theory to observation is typically decades

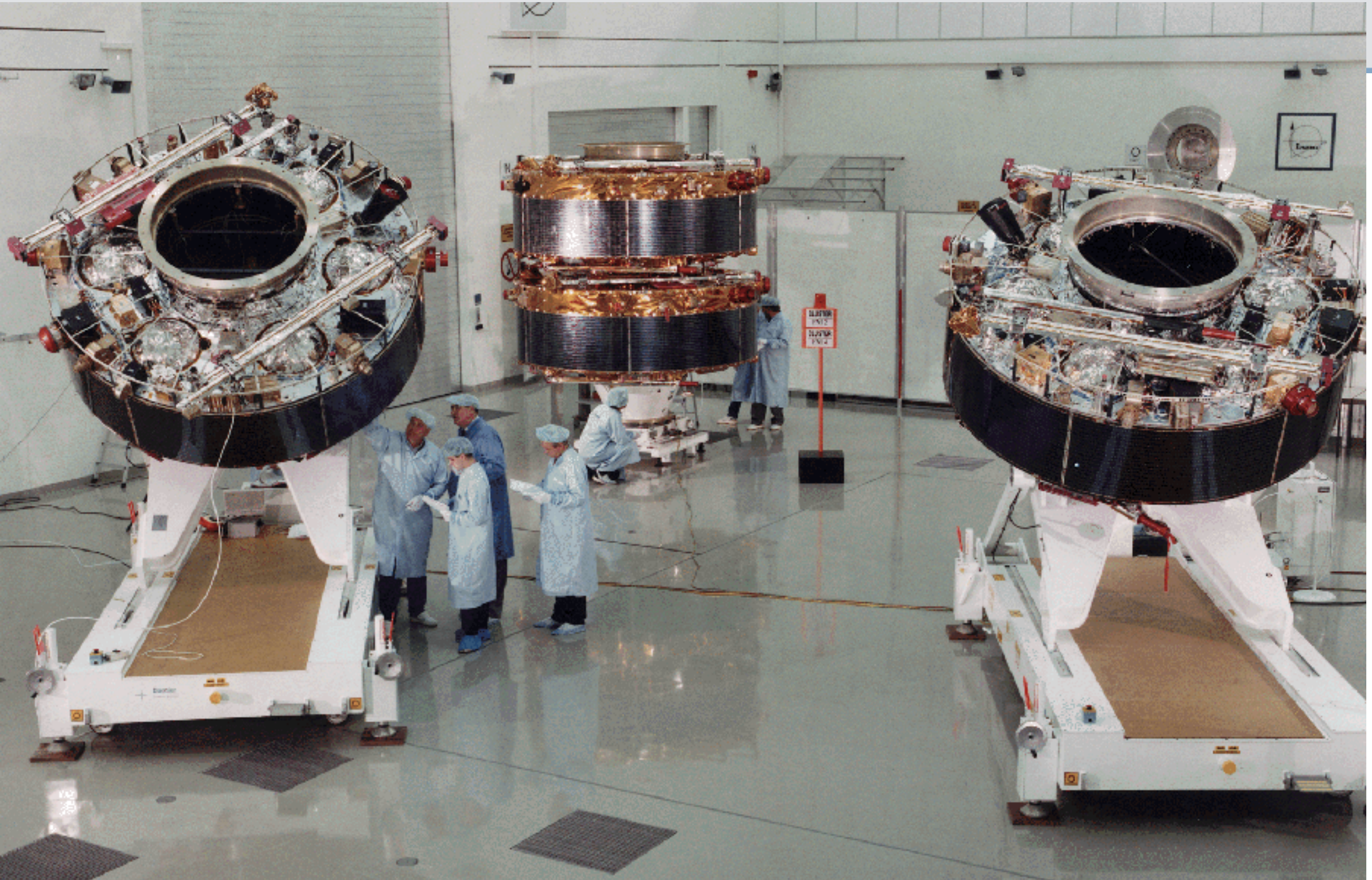
2. Techniques for Fields

- We want to measure
  - Electric Field
  - Magnetic Field
  - DC to typically 10’s kHz
- Additionally we might like to get other plasma properties
  - Density
  - Temperature
- In this section
  - Double-probe E-field sensors
  - Langumuir and Impedance probes
  - Search-coil magnetometers
  - Fluxgate magnetometers

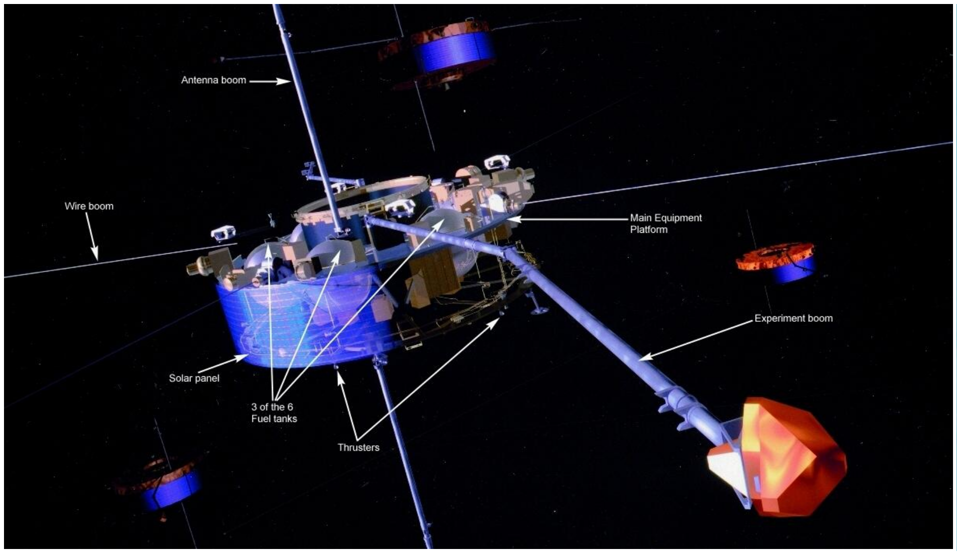


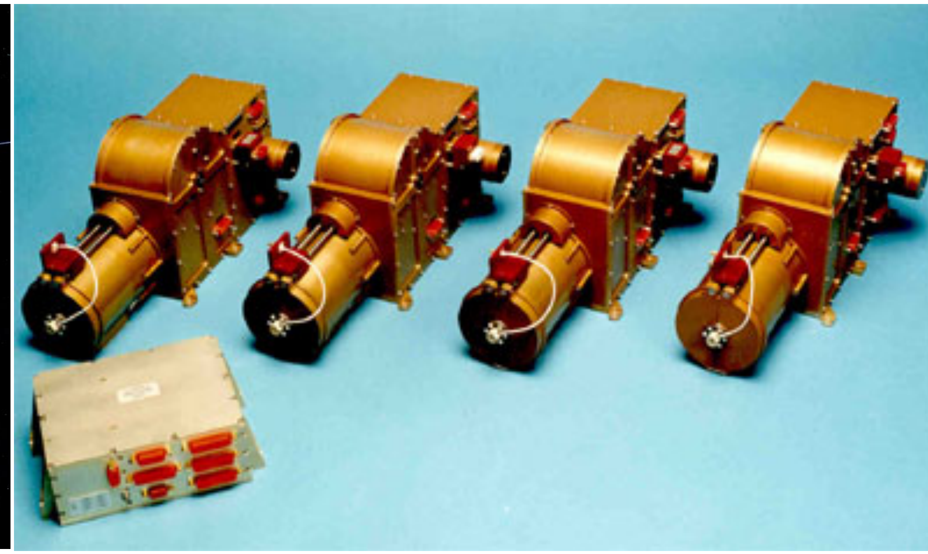
Context: 4 Cluster spacecraft during testing at IABG Munich

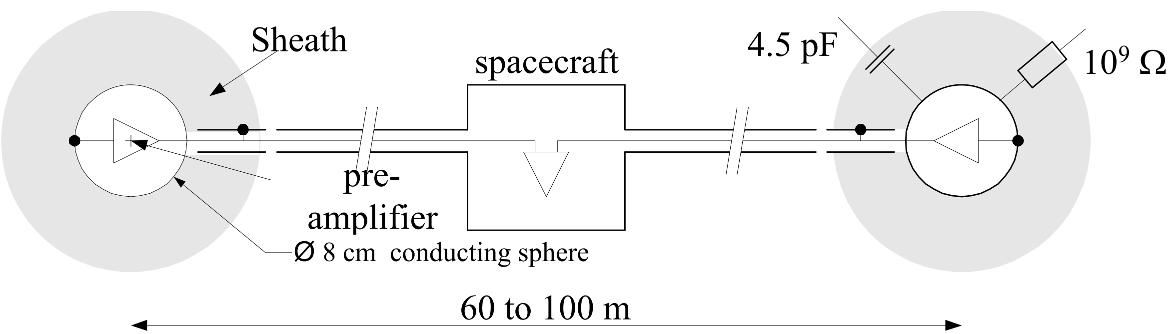
Cluster: Multi-point Plasma Physics in Polar Earth Orbit

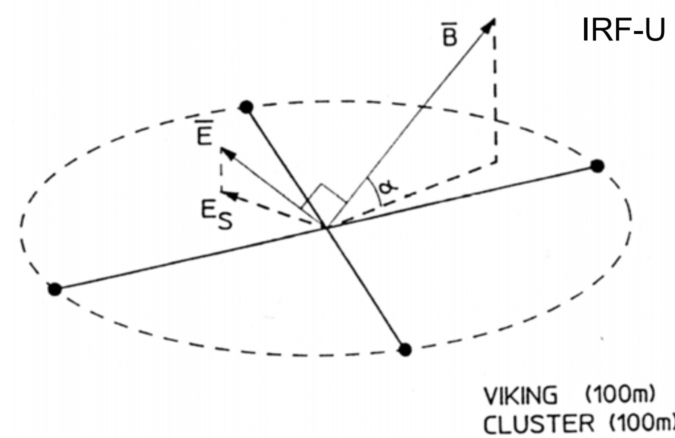


Dual Probe Electric Field Technique
Example: Cluster EFW (Electric Fields and Waves)



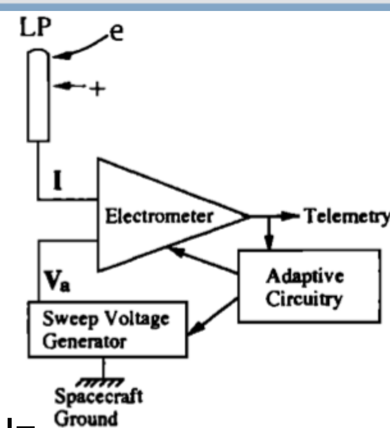


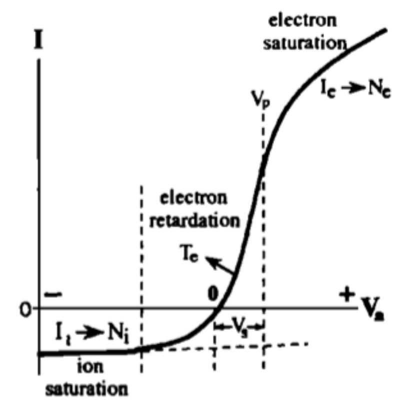


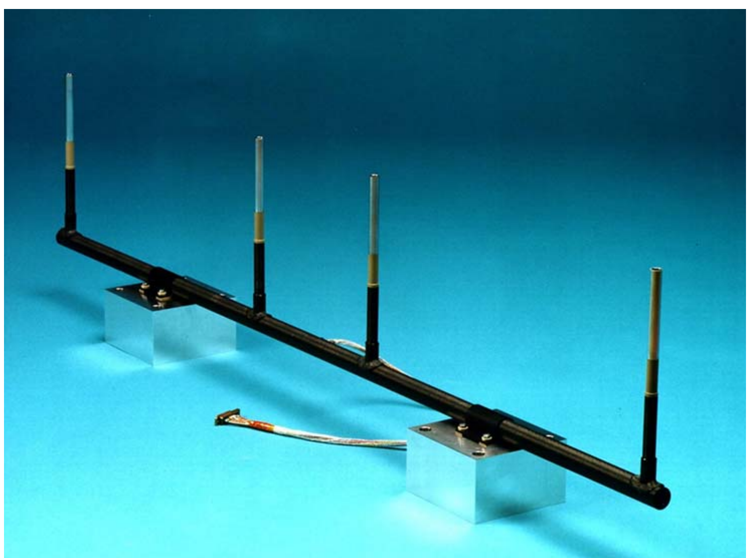


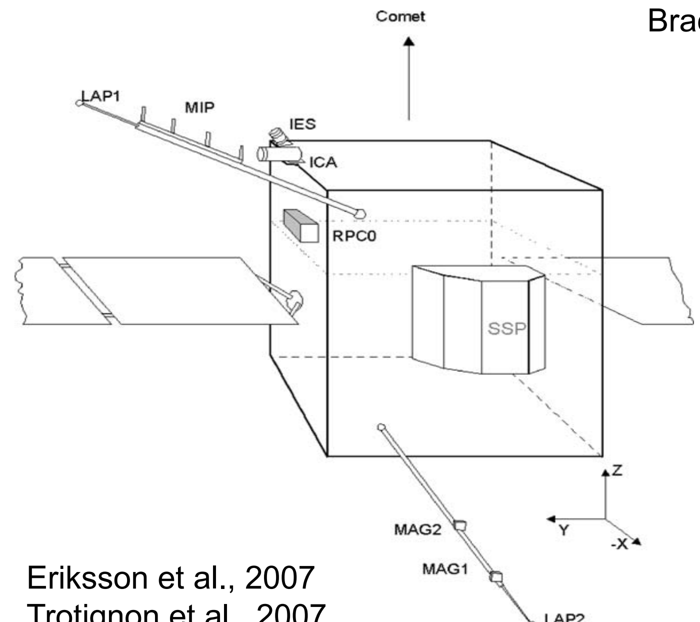
Active Measurements
Example: Rosetta LAP and MIP

- Langmuir probes
  - Measure V vs. I characteristic of plasma by sweeping a voltage in the range ±20V
- Mutual Impedance probes
  - Pair of Tx/Rx antennae
  - Measure capacitive impedance of plasma
- Yields:
  - Plasma density, temperature, waves to few MHz









Brace

Eriksson et al., 2007
Trotignon et al., 2007

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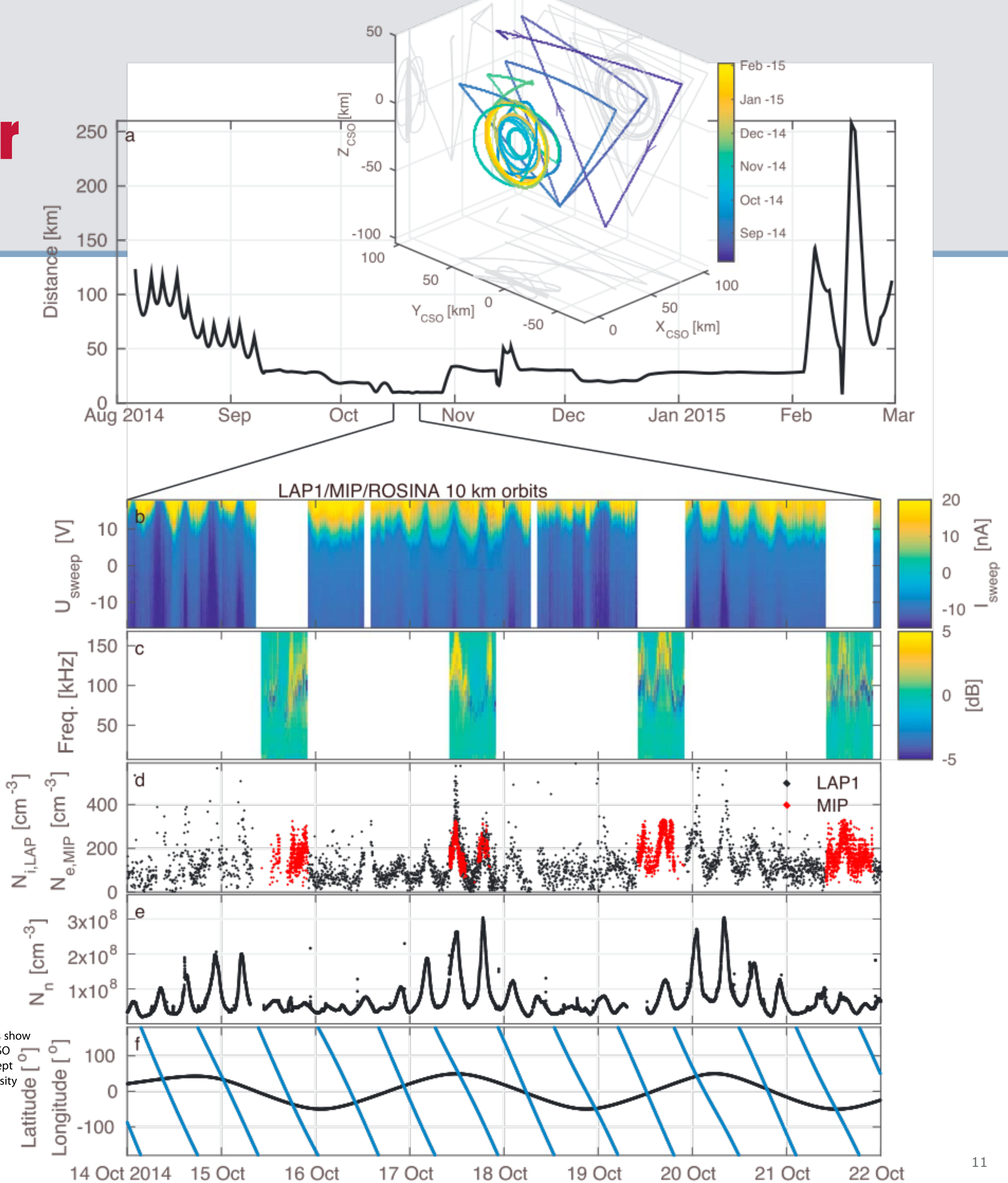
LAP/MIP Results for 10km Orbits

- 6.2 hour periodicity in electron, ion and neutral density
- Comet has 12.4 hour rotation period

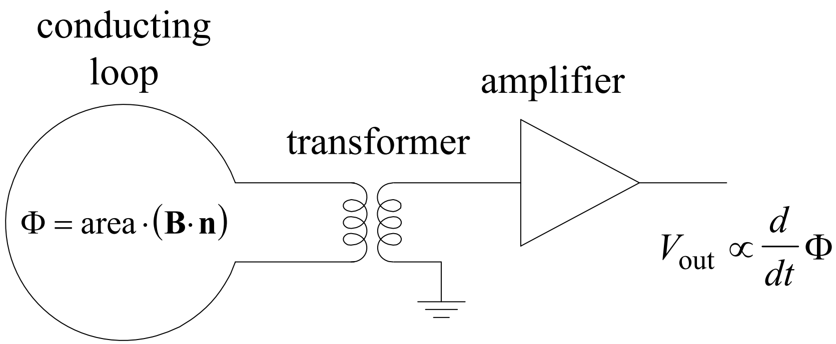


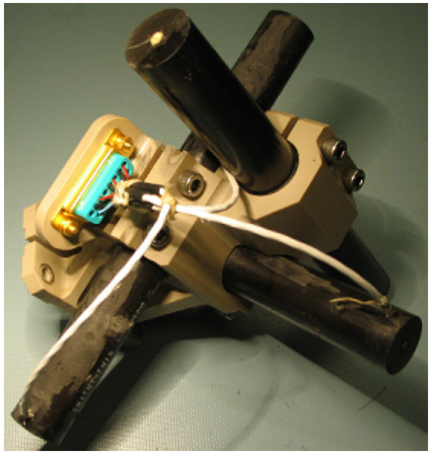
Edberg et al., 2015

Figure 1. Time series of Rosetta RPC-LAP/MIP data from the bound orbits at 10 km distance. The individual panels show (a) the cometocentric distance of Rosetta, with the inset showing the trajectory of Rosetta around the comet in CSO coordinates with time color coded along the track, (b) sweep data from LAP1 where the bias voltage is shown swept from −18 V to +18 V and the collected current is color coded, (c) active spectrogram from MIP, (d) derived ion density from the LAP1 sweeps (black) and electron density measured by MIP (red), (e) ROSINA/COPS neutral density, and (f) latitude (black) and longitude (blue).

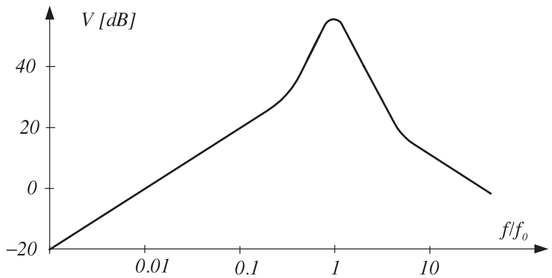
Magnetic Field: AC 'Search Coil' Magnetometers

- Simple loop antenna will measure time-varying magnetic field
- Use of a coil (1000's turns) greatly improves sensitivity
- High permeability core concentrates magnetic flux and further enhances performance
- Three perpendicular coils for the three components of the AC field vector
- Sensitivity poor at very low and high frequencies
- Use of flux-feedback can flatten the response curve





Themis Search-Coil Magnetometer



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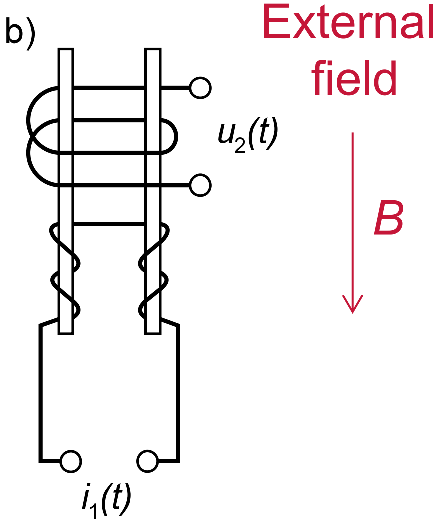
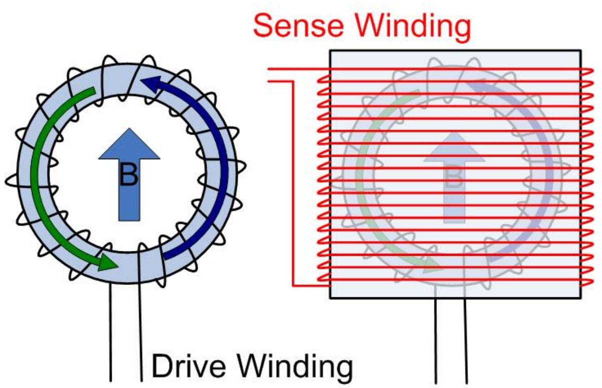
Magnetic Field: DC 'Fluxgate' Magnetometers

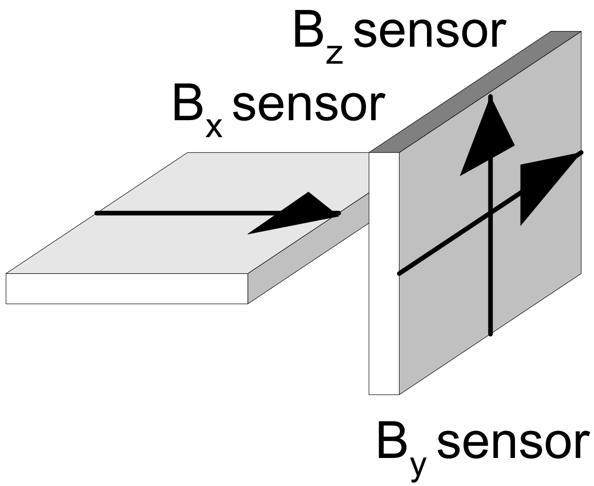
- Principle:
  - Time varying current $i_1(t)$ modulates the magnetic permeability of two Permalloy rods
  - This modulates the flux due to the external DC field *B*
  - Hence we get a time varying voltage $u_2(t)$ which is proportional to *B*
- Interpretation:
  - The flux due to *B* is 'gated'
  - External field is modulated from DC (hard to measure) to AC (easy to measure)
- Ring-core geometry brings symmetry and closed drive flux

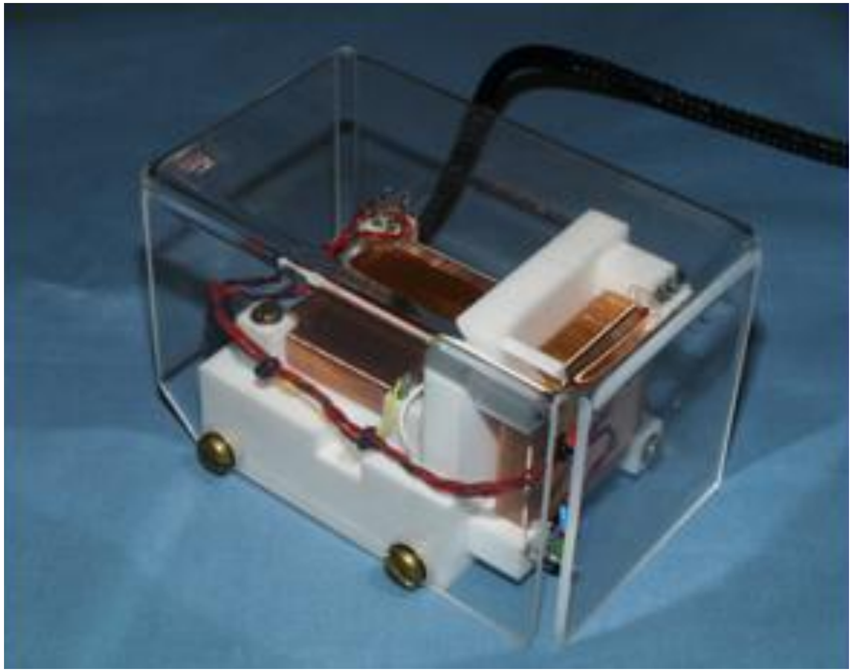




Tri-axial Fluxgate

- Two orthogonal ring-core sensors
  - Each can measure the field in 2 orthogonal directions in the plane of the ring-core
  - Ceramic mounting for stability

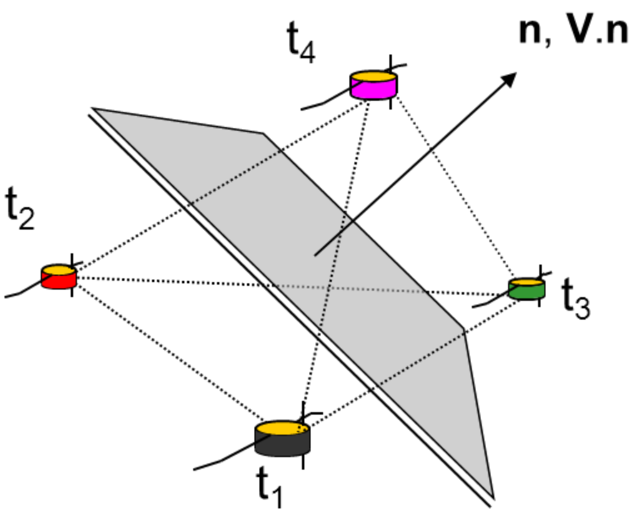


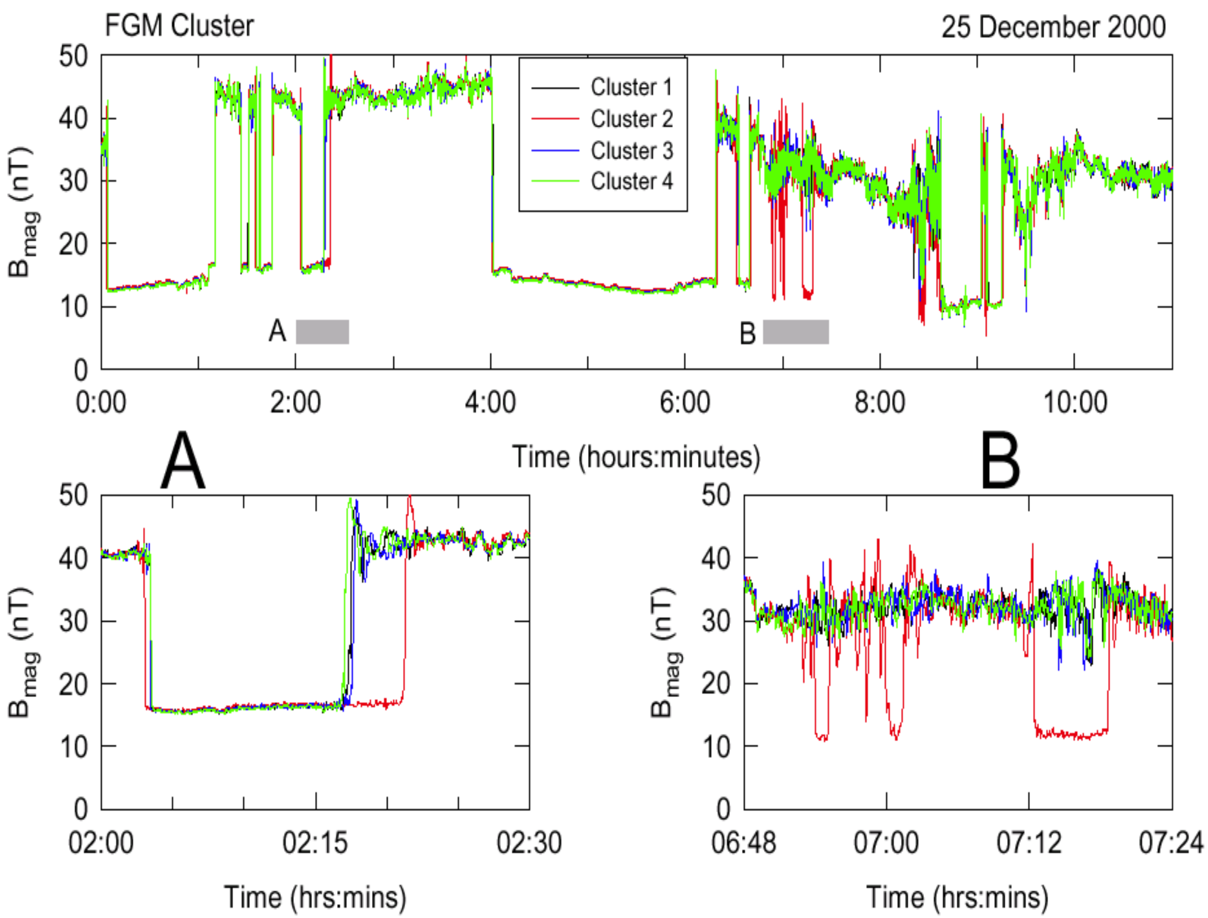


DoubleStar Fluxgate Magnetometer prototype
Ultra Electronics / Imperial College London

Cluster Fluxgate Magnetometers

- Unique ‘3D’ capability from four point measurements
  e.g. speed and orientation of the bow-shock





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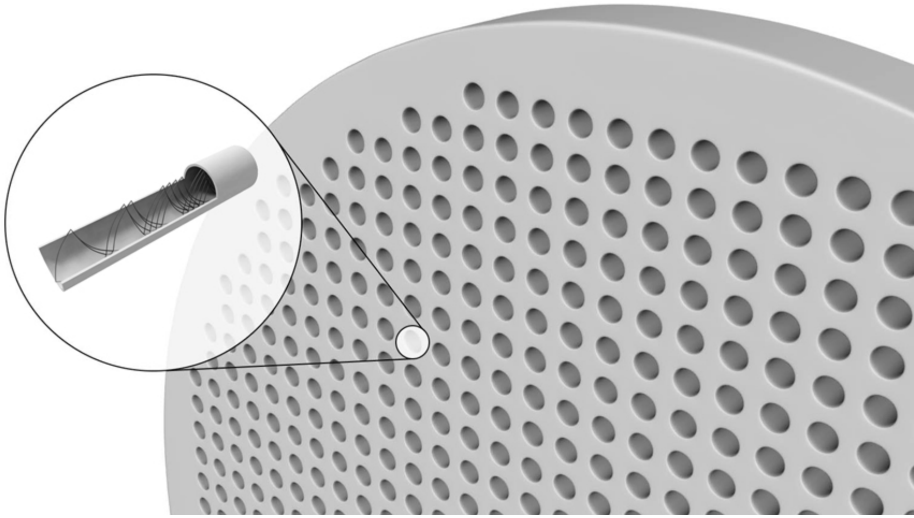
3. Charged Particle Measurements

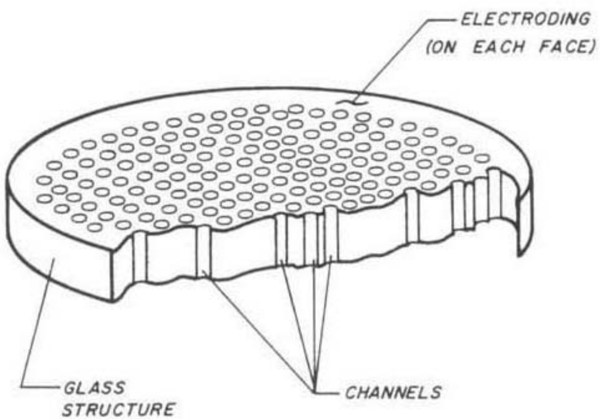
- We want to measure:
  - Ions and electrons
  - Their energy distribution
  - Their directional distribution
    - Ideally over all directions (4π sr)
  - All as a function of time
- Additionally for ions we would like to know
  - Their mass
  - Their charge state
  - E.g. to distinguish O^+ from O^{++}

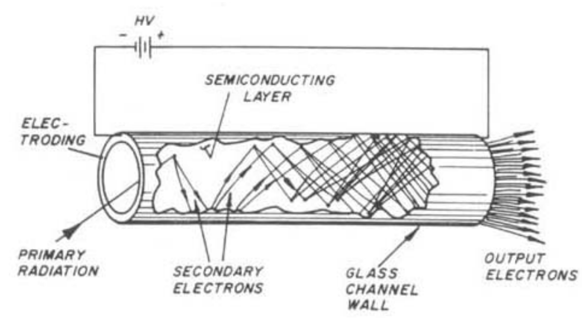
- In this section:
  - Particle detectors
  - Electrostatic Analysers
  - Composition Analysers
  - Example instruments [Rosetta]

Charged particle detectors: The Micro-channel Plate (MCP)

- Need to count individual ions / electrons
- To make a charge big enough to read with electronics, we need charge amplification
- Technique similar to photomultiplier tube
- 10^5 charge gain
- Charge collected at an anode plates
- Pinpoints location of incident particle



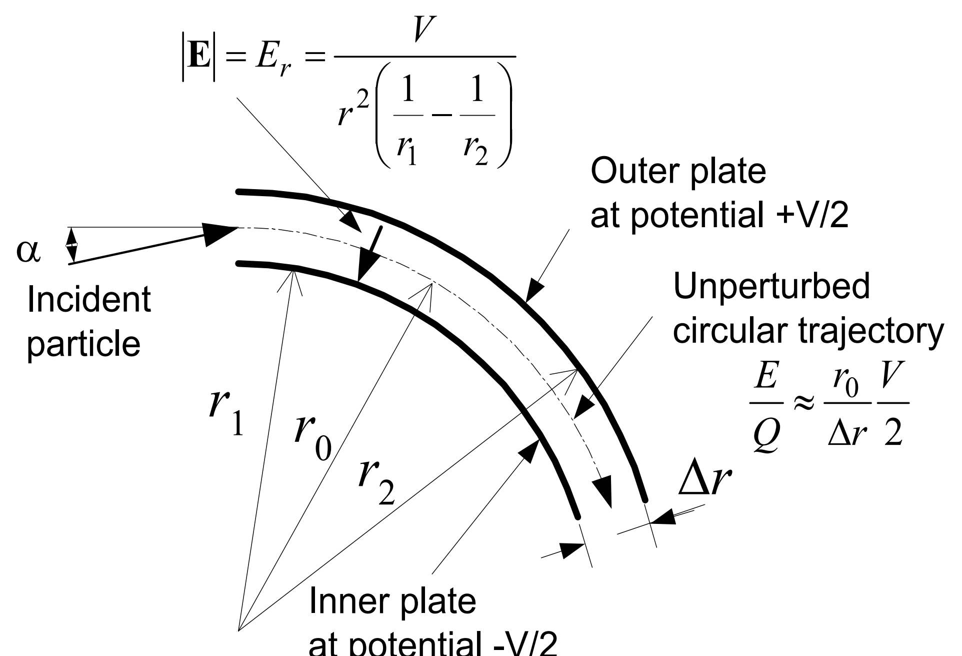




www.photonis.com

The Electrostatic Analyser (ESA)

- Voltage *V* applied across circular conducting plates
- Principle:
  - Normally incident ions (or electrons) with a precise *E/Q* ratio follow a circular path
  - Other ions (electrons) will hit the plates
  - *V* can be varied to select for *E/Q*
- Practice:
  - For a given *V* the analyser passes ions with a small range of *E/Q* and entrance angle α



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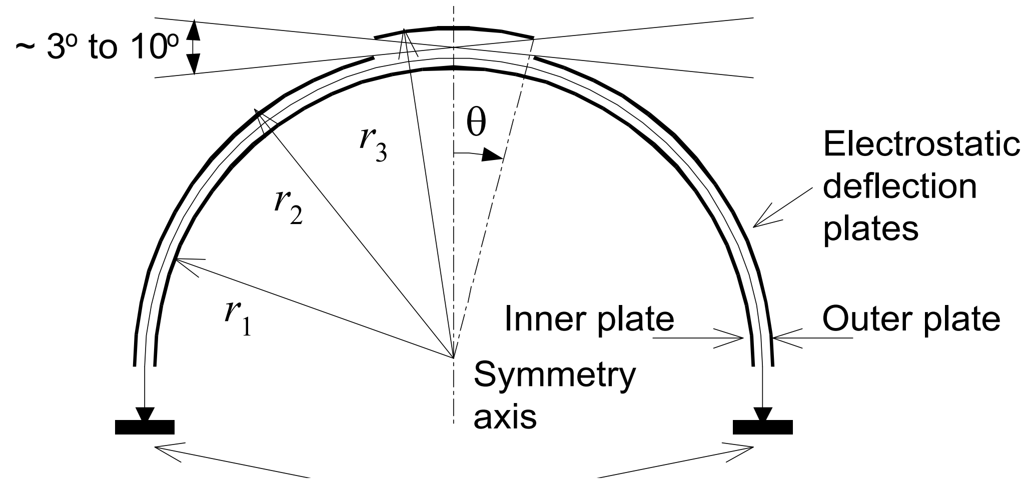
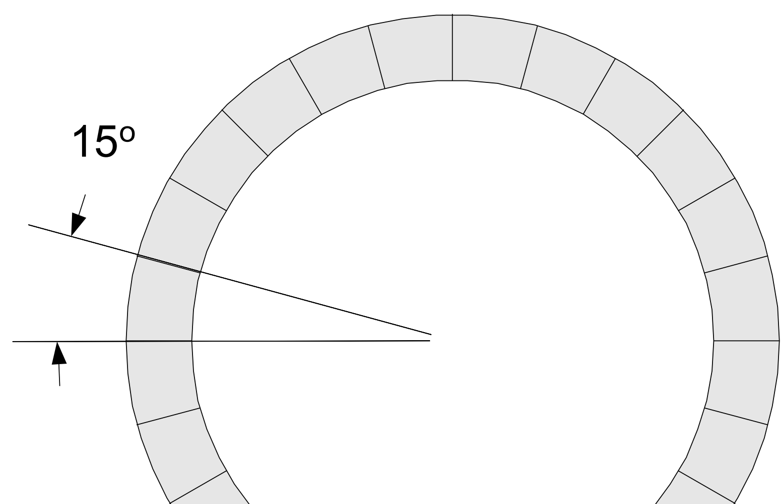
'Top-hat' Electrostatic Analyser

- Hemispherical geometry
  - Rotationally symmetric about dashed line
- Field of view typically 5° × 360°
- Ring-shaped detector for azimuth angle
  - Typically 5 to 15° resolution
- Problem:
  - Fixed elevation angle
- Solutions:
  - Spin the spacecraft
  - Additional electrostatic deflection plates

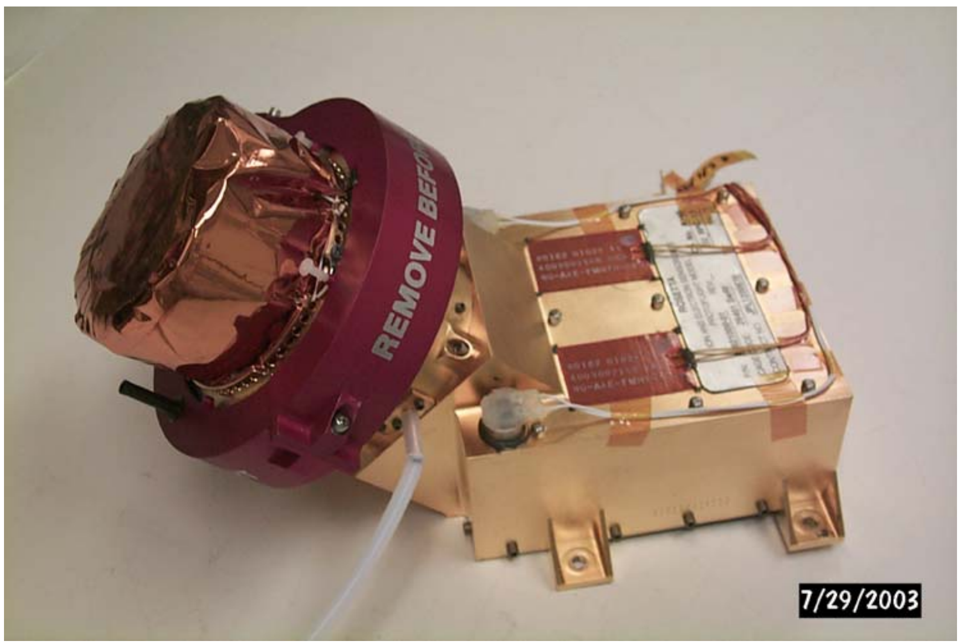


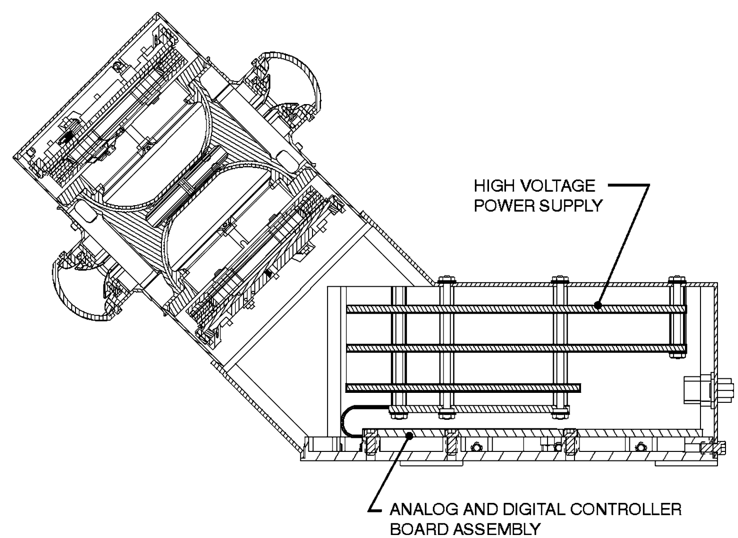
Schematic sectored position sensing detector



Example: Rosetta Ion/Electron Sensor (IES)

- Dual 'top hat' analysers for ions and electrons
- External electrostatic deflectors extends FoV to 90° × 360°
- Ion energies from 4eV up to 22keV





J. Burch / SwRI

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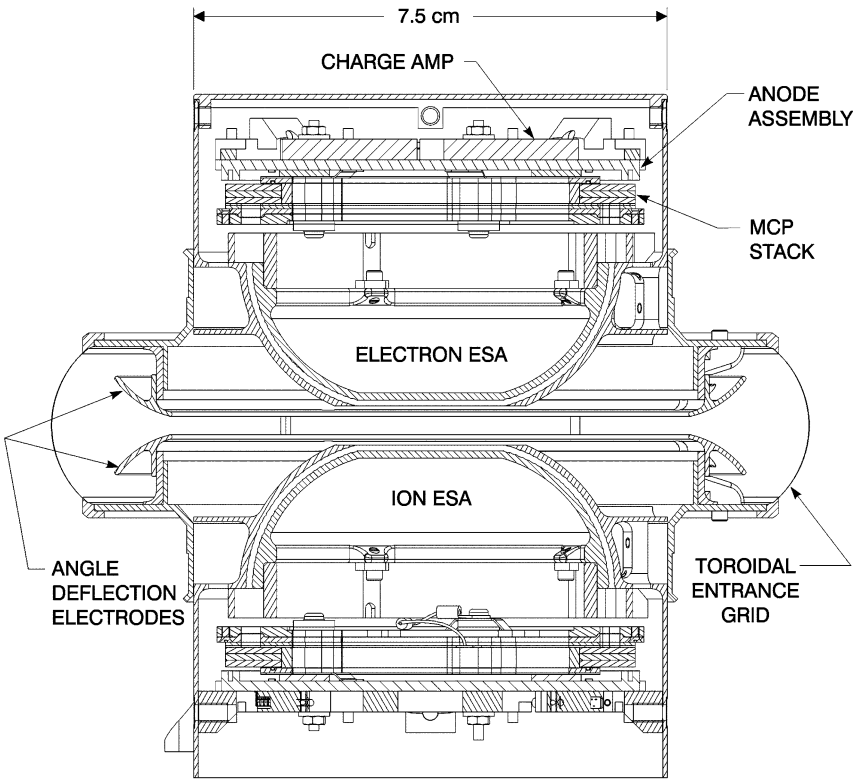
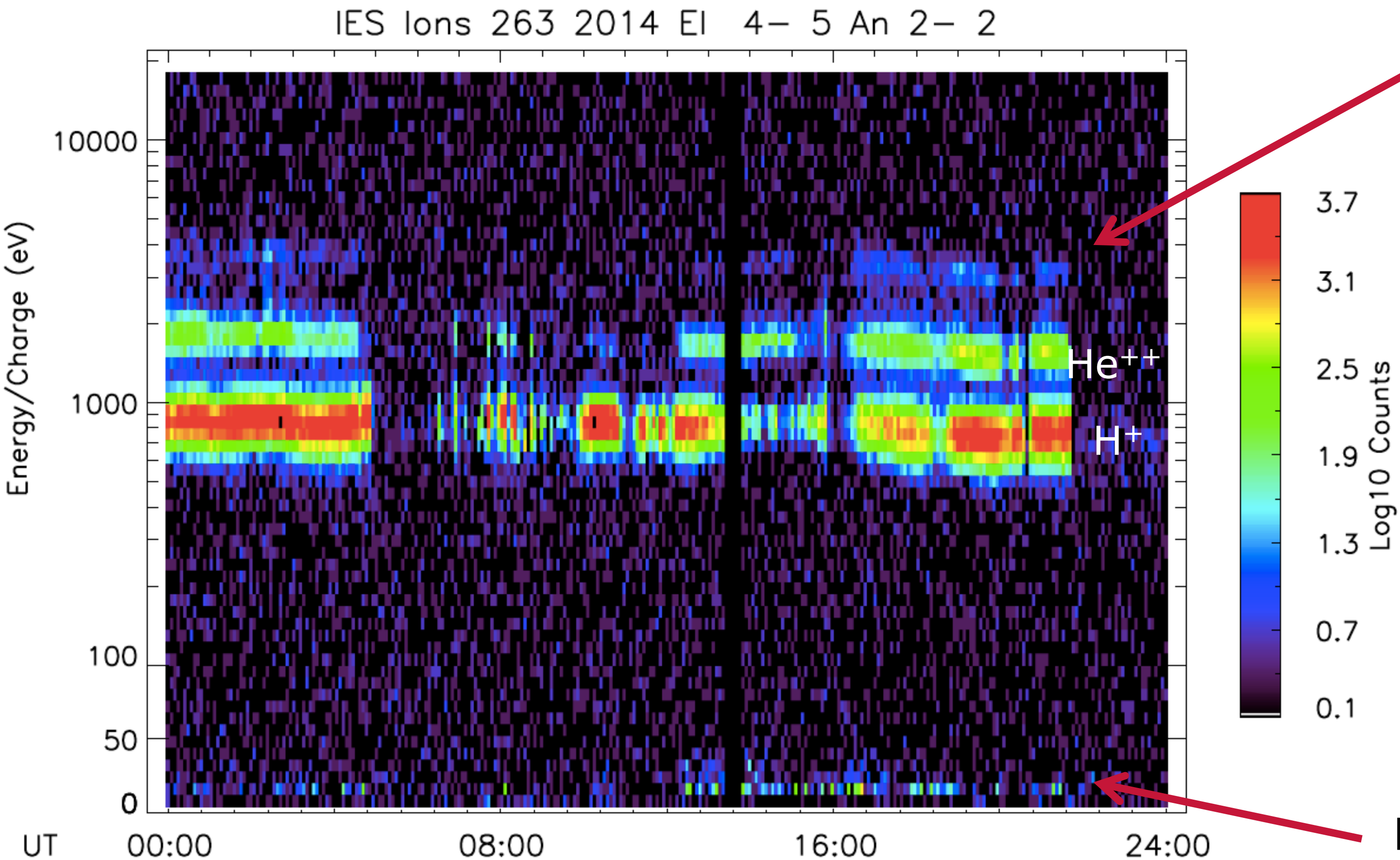
IES Sensor

- Voltage set on deflection plates selects elevation angle
- Ions (or electrons) striking MCPs generate electron bursts which are collected at anodes
- Charge amplifiers and pulse-counting electronics
- Sweeping the voltages on the deflection plates and the ESAs delivers ion and electron counts as a function of energy and direction



J. Burch / SwRI

Rosetta IES Ion Measurements approaching the comet



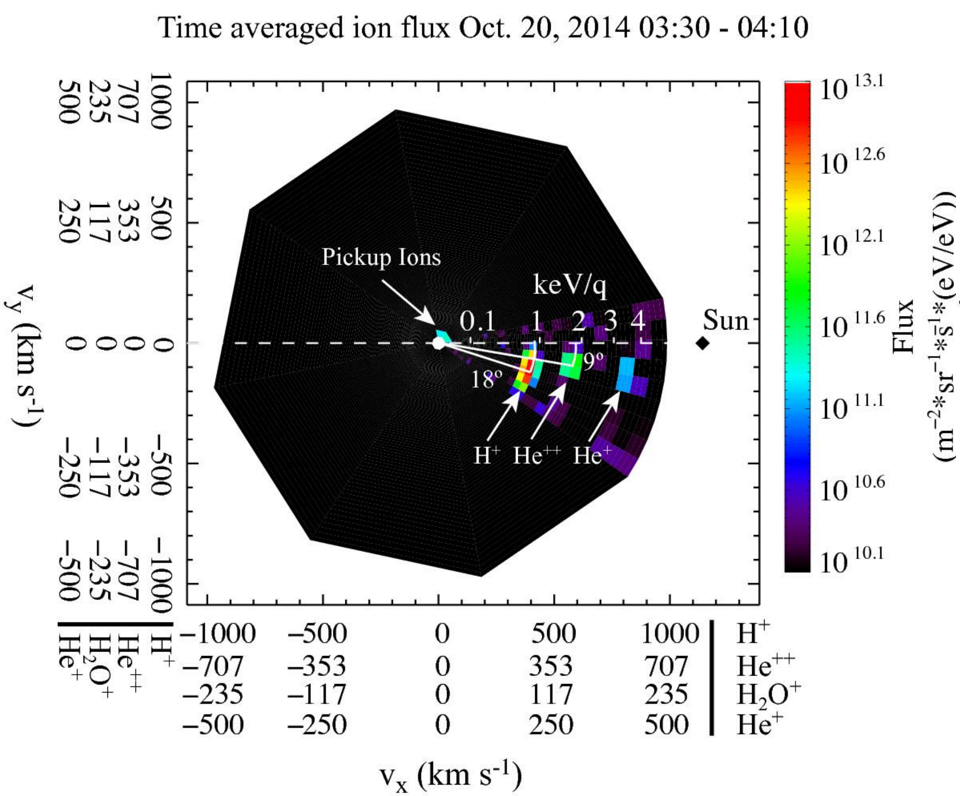
20th September 2014

Identification of He+ (by charge exchange)

Pick-up ions at low energy

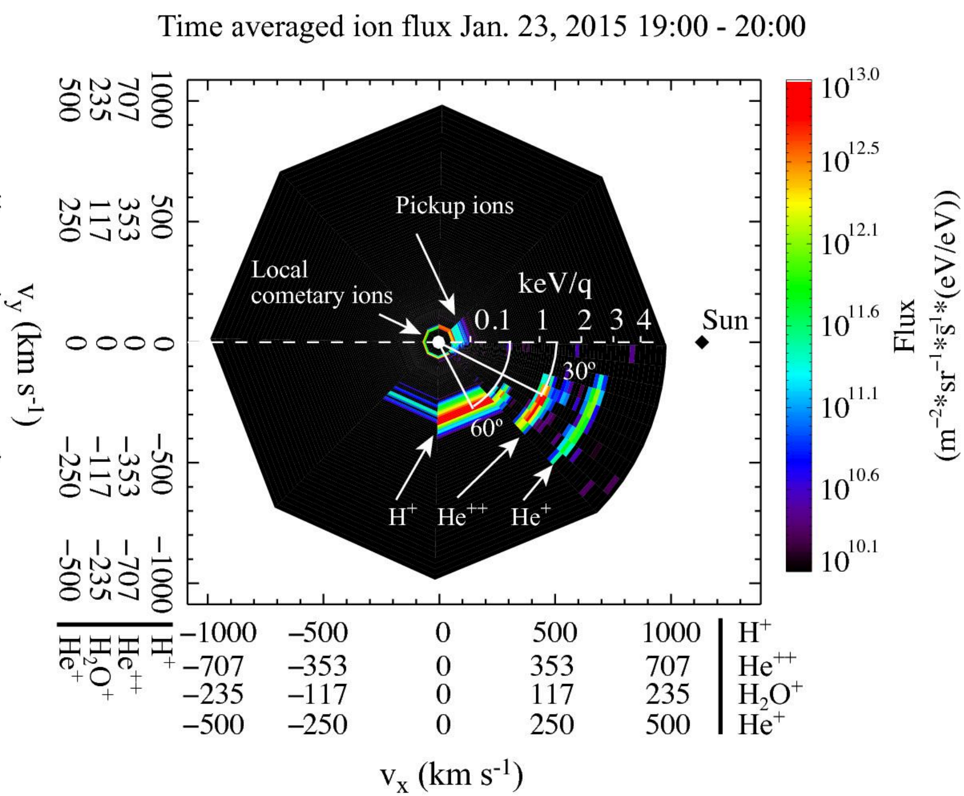
Figure: J. Burch / R. Goldstein

Solar wind deflection



October 2014

(~3AU)



January 2015

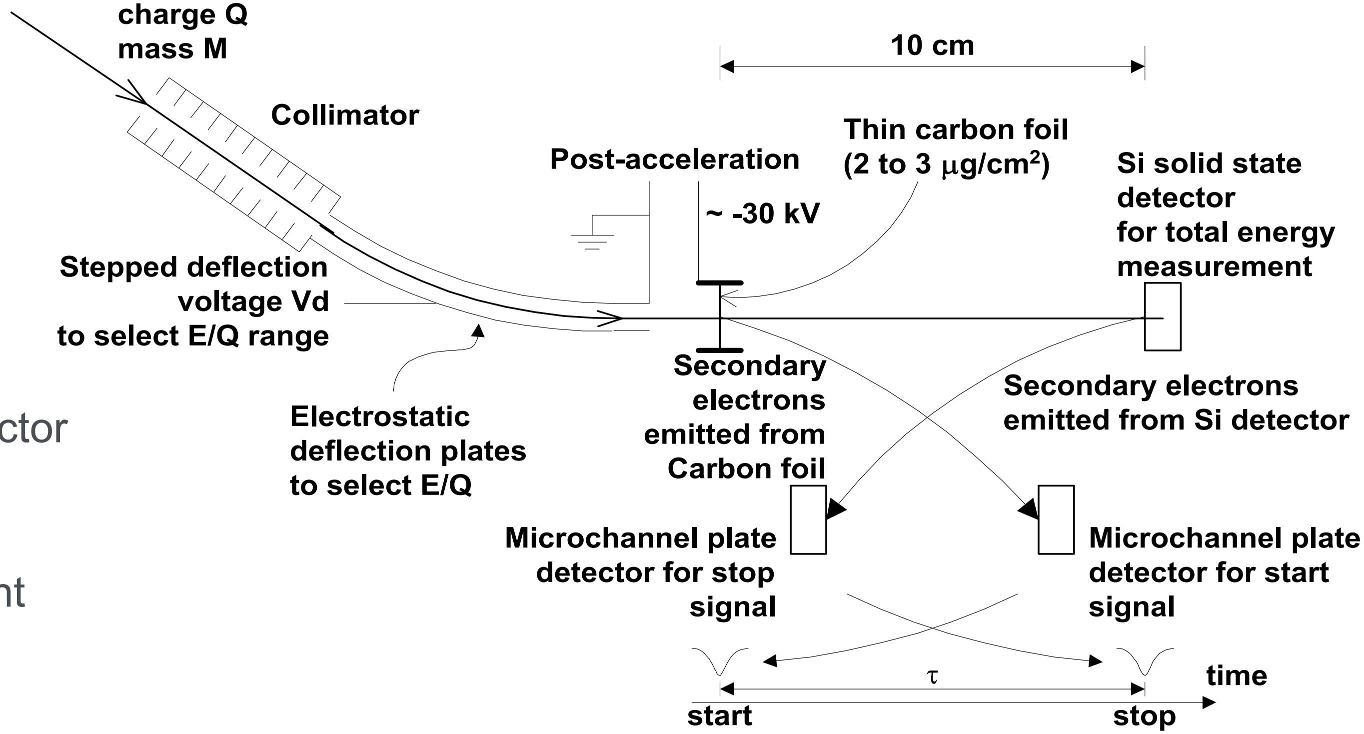
(~2.5AU)

IES measurements of solar-wind and cometary ions in the sensor azimuthal plane (averaged over elevation). Broiles et al. A&A 2015.

Ion Composition:
The Time-of-Flight Technique

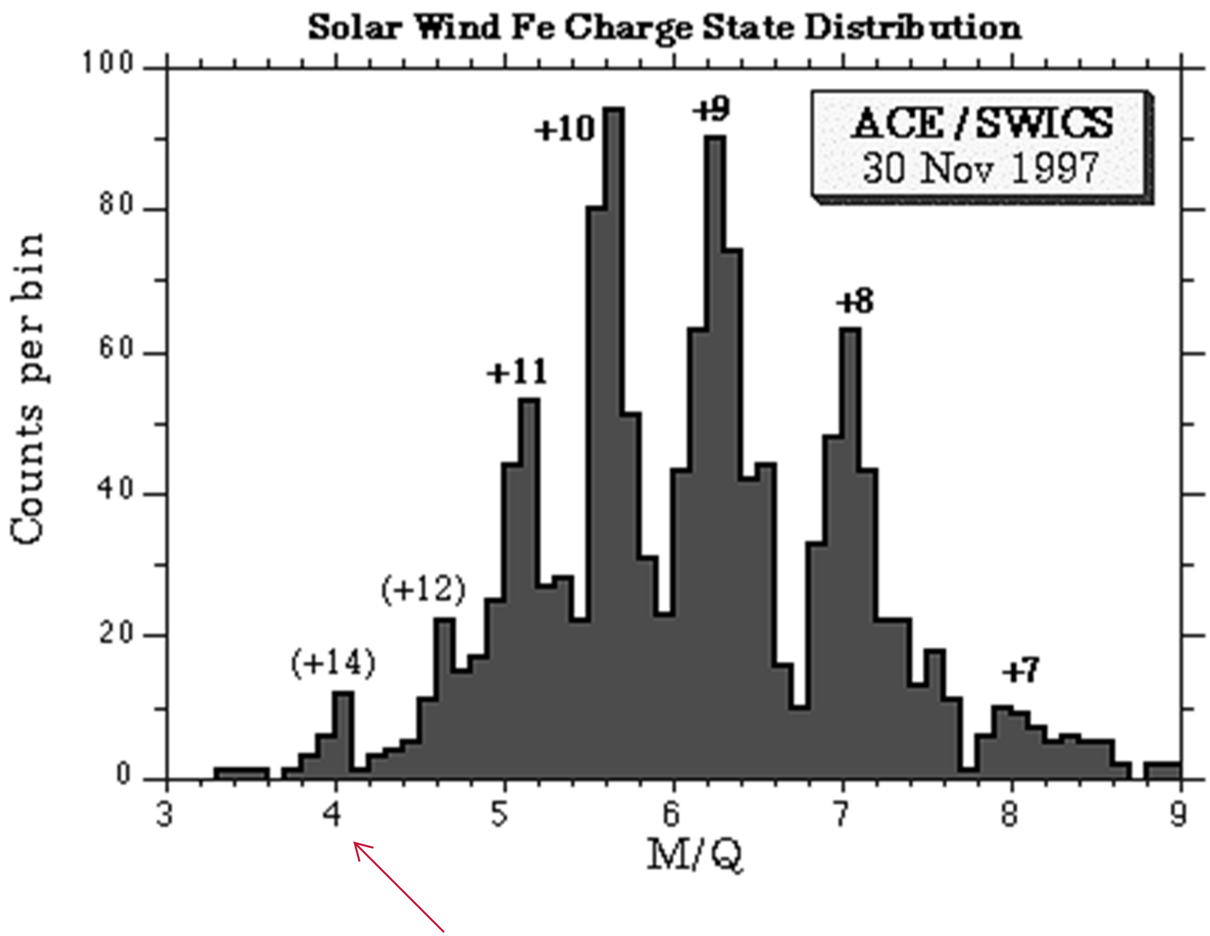
e.g. Ulysses, ACE SWICS

- Principle:
  - Incident ion has known *E/Q*
  - Silicon detector measures $E=\frac{1}{2}Mv^2$
  - Time-of-flight gives *v*



- Technique measures *E*, *M* and *Q*

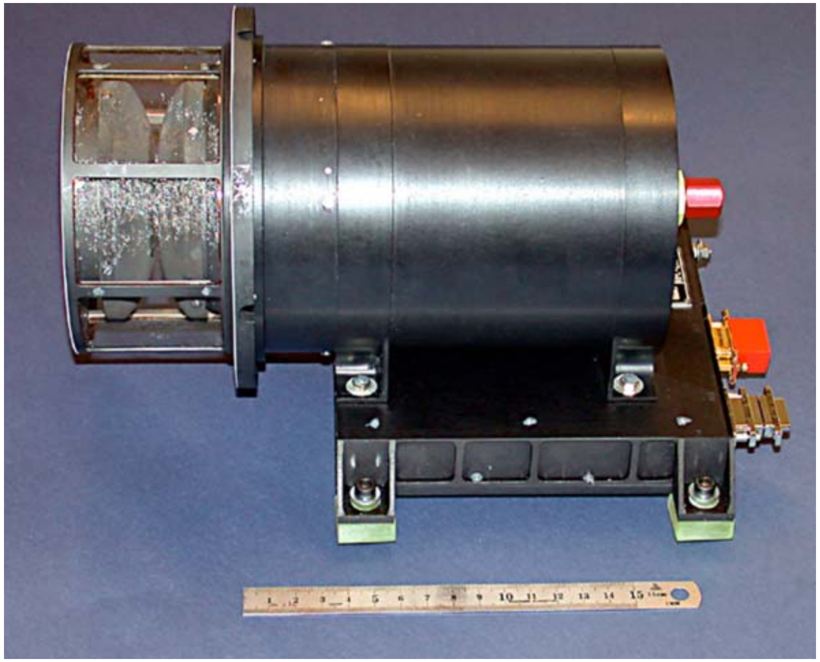
Distribution of Charge States for Iron in the Solar Wind

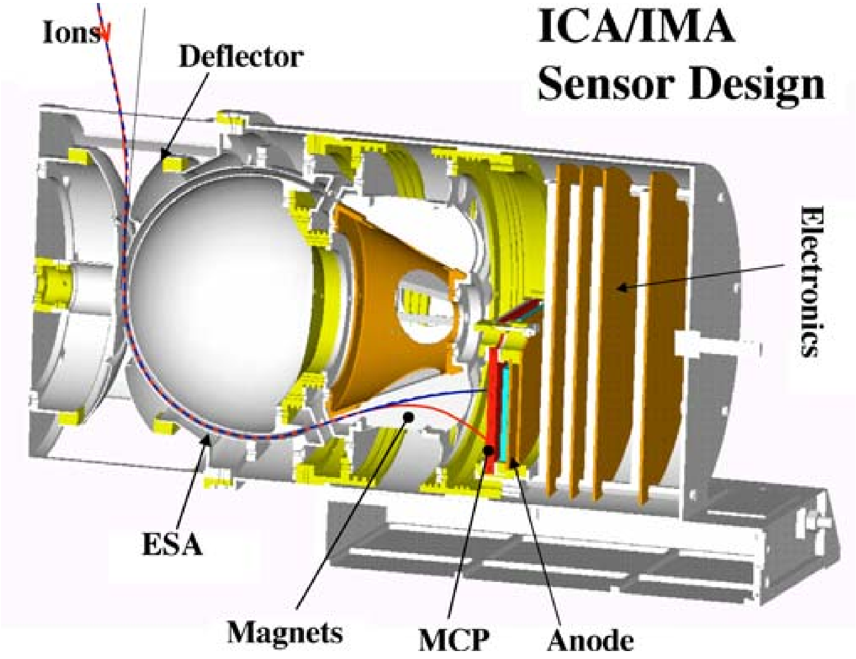


e.g. M/Q=4 corresponds to Fe^{14+}

Alternative (smaller) Technique: Rosetta Ion Composition Analyser (ICA)

- Ion electrostatic analyser followed by **magnetic** deflection
- Deflection distance measured by MCP



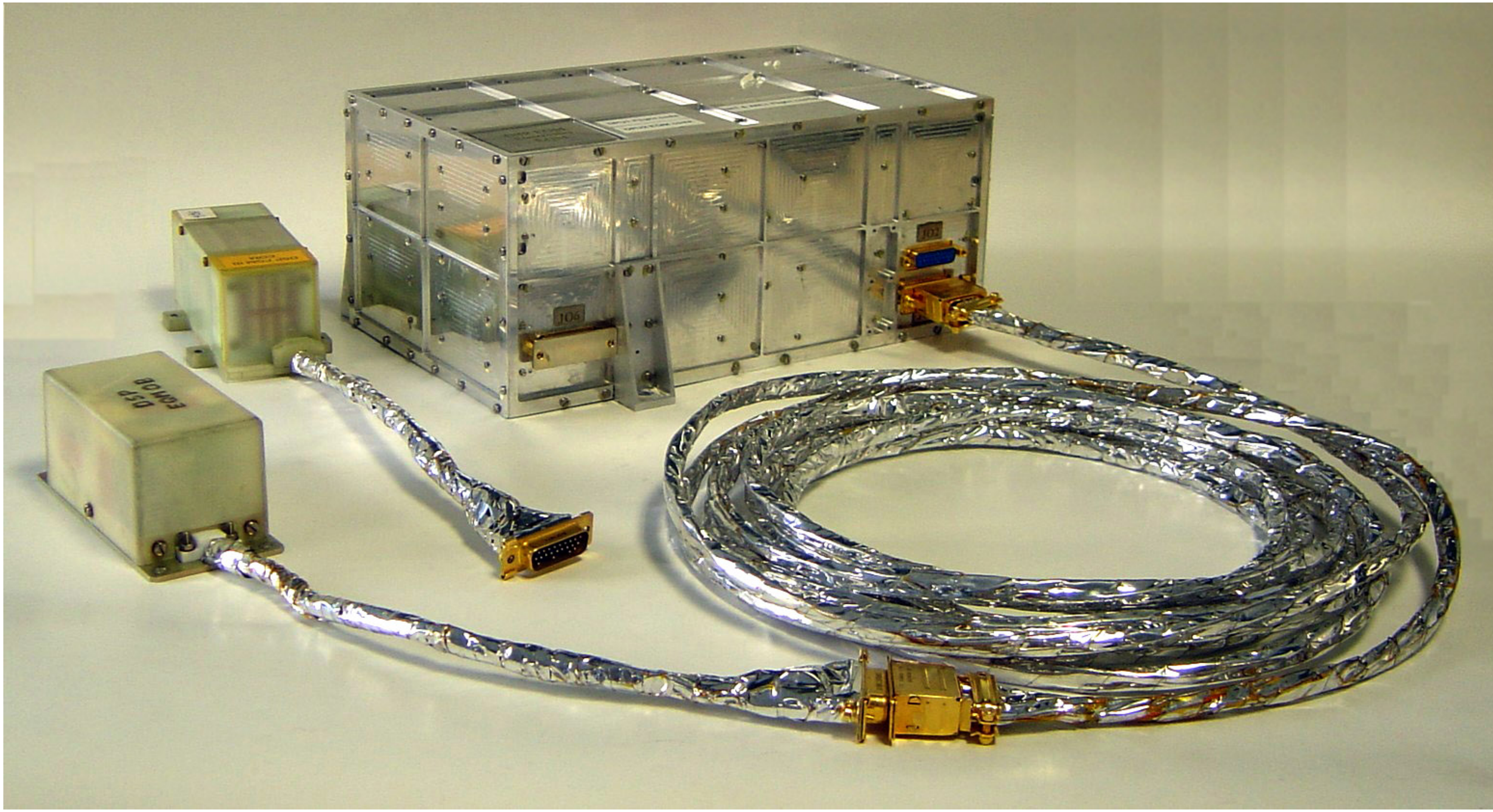


Performance, Characterisation and Calibration

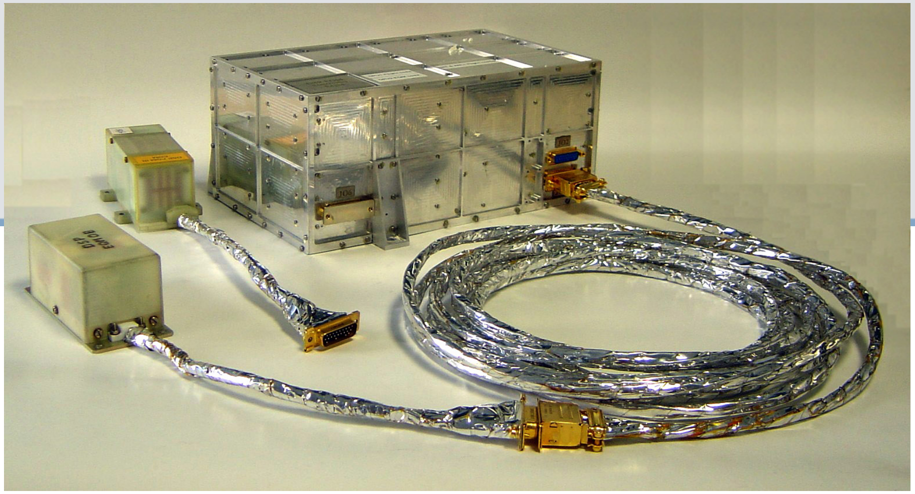
- Motivation:
  - Validation of instrument performance
  - Calibration against some traceable standard

- In this section
  - Design Considerations
  - Three ways to characterise an instrument
  - Calibration

Fluxgate Magnetometer Instrument for the ESA/CNSA 'Double Star' Mission



Design Considerations



- Performance
  - Measurement Range
  - Resolution
  - Frequency Response
  - Noise
  - Calibrated accuracy
  - Stability (over time and temperature)
- Environment
  - Reliability
  - Thermal and mechanical stresses
  - Radiation
- Resources
  - Mass, power, telemetry
  - Cost
  - Schedule

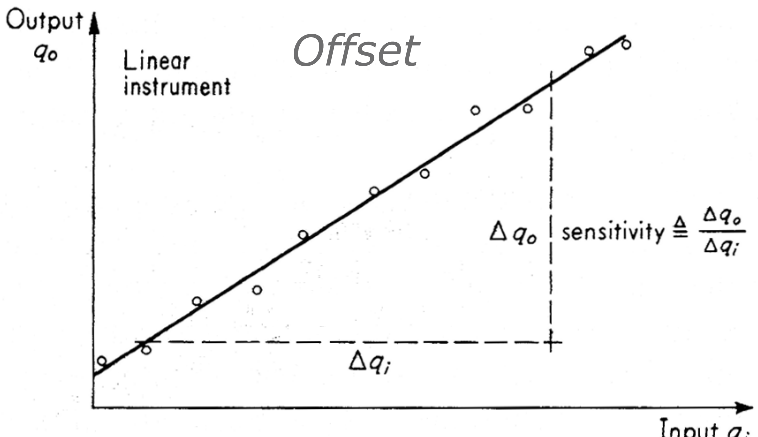
System Characterisation

We may fully characterise a system by measuring its

1. **Transient Response**
   (typically step-input $y(t)=u(t)$)
2. **Static Response**
   (after transients decayed)
3. **Frequency Response**
   (response to sinusoidal input swept over some range of input frequencies)

Static Response: Deviation from the ideal

Offset



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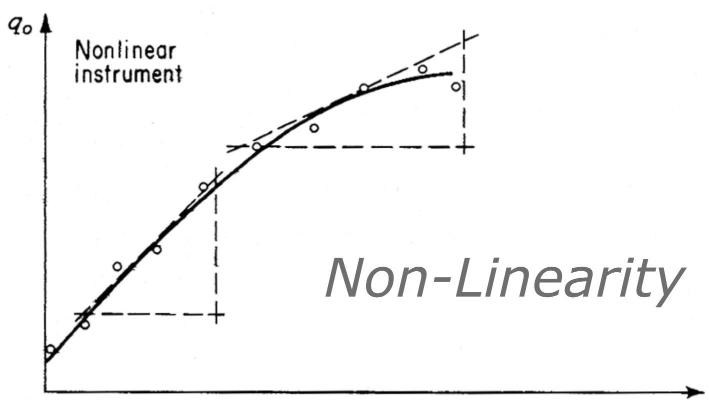


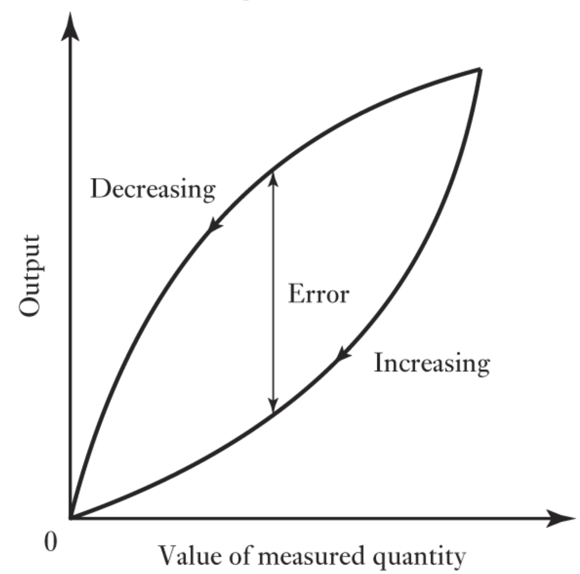
(b)

Non-Linearity

All may introduce non-linear effects resulting in artefacts in the data especially harmonic distortion

- *Offset may be subtracted*
- *Non-linearity and hysteresis more pernicious*

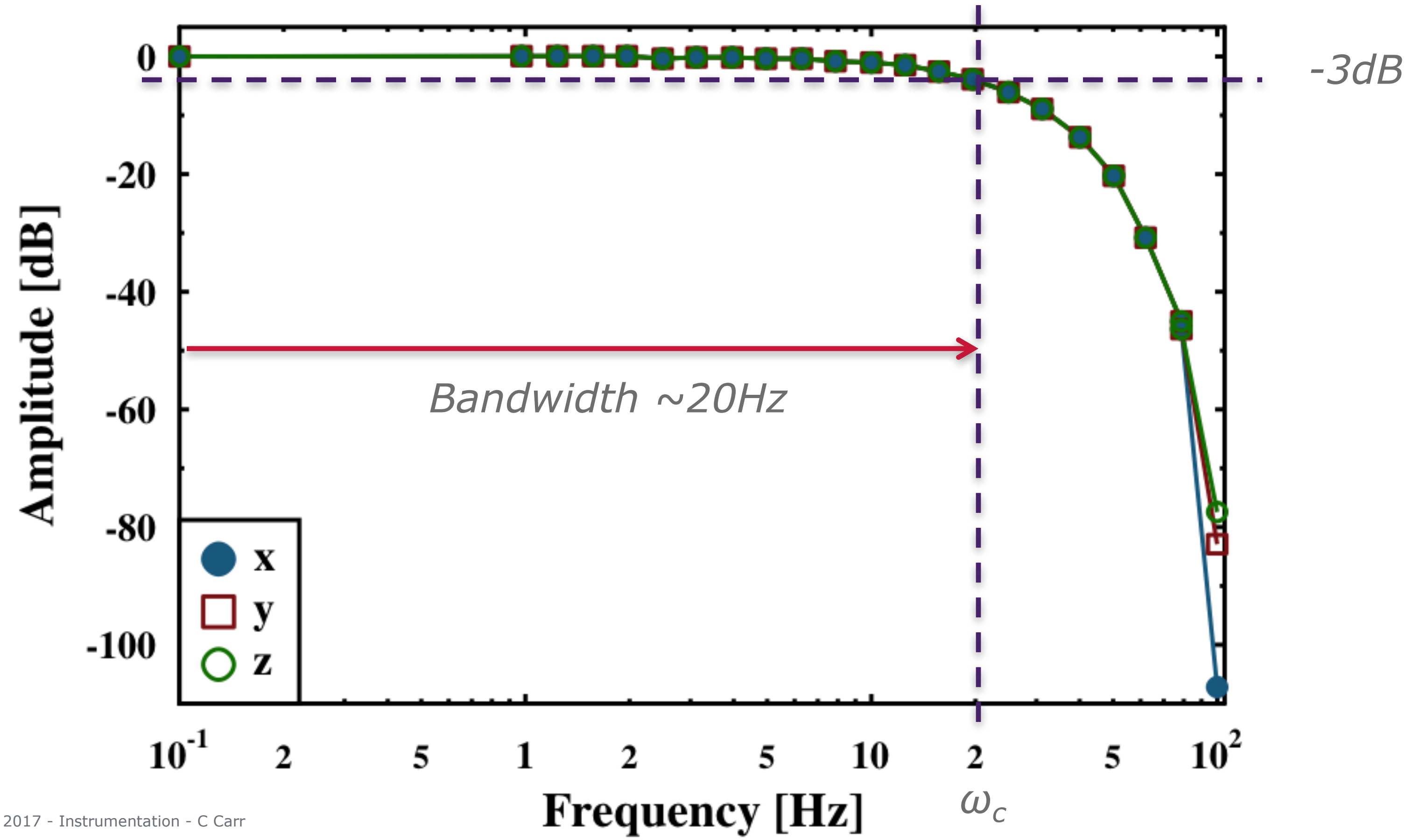
Hysteresis



Cluster Magnetometer Frequency Response

Bode Plot (Magnitude part only)

Bandwidth is defined as response from DC to ω_c

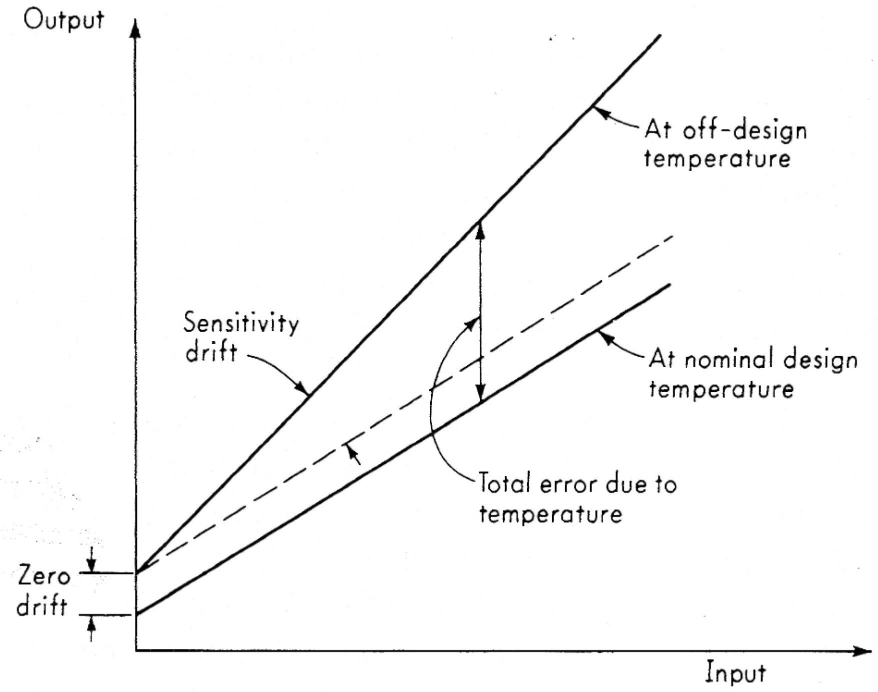


Uncontrolled External Input

Temperature-dependent static-sensitivity and offset

Other environmental considerations

- Pressure, vibration,
- Drift, ageing (electronic systems)
- Wear (mechanical systems)



Calibration Principle

Compare against reference measurement with other input factors controlled / constant

- Cover parameter space
- Control external factors such as temperature

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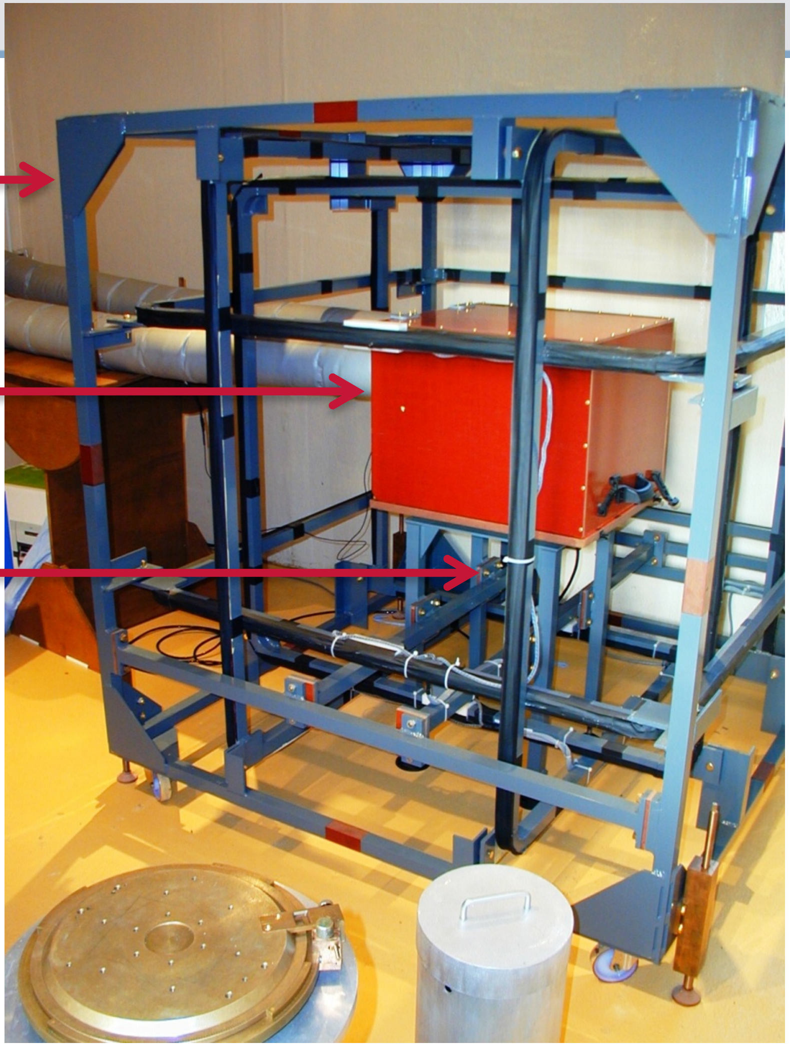
Calibration Principle

Helmholtz coils null Earth's field and apply test <u>B</u>

Temperature-controlled Box houses Magnetometer under test

Reference magnetometer mounted **outside** box



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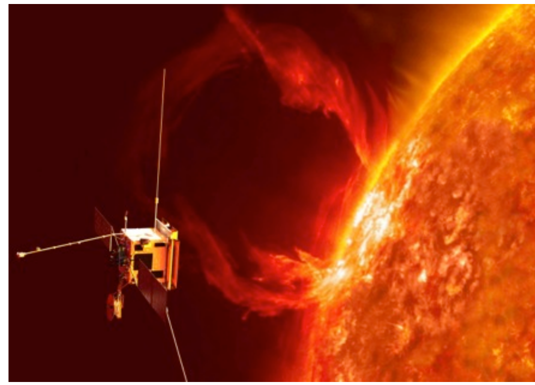
Designing for the Space Environment

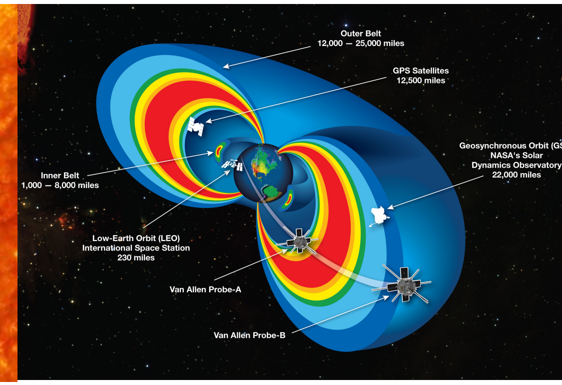
- Challenges
  - Launch stresses
  - Radiation
  - Thermal extremes
  - Vacuum
  - Interference from other instruments or the spacecraft
  - Reliability

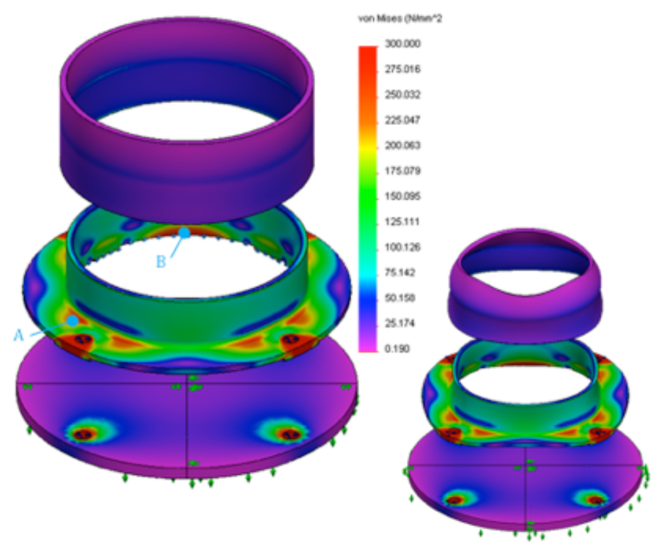
- In this section
  - The space environment
  - Launch
  - Interference and Contamination
  - Use of Redundancy to enhance relaibility

Space Environment

- Radiation
  - Radiation belts
  - Solar events
  - Cosmic rays
  - ➢ Shielding and specialised electronics
- Thermal
  - Extreme hot/cold
  - Cycling between extremes, e.g. eclipses
  - ➢ Design and prediction by modelling
- Solar UV (on exposed surfaces)
- Vacuum





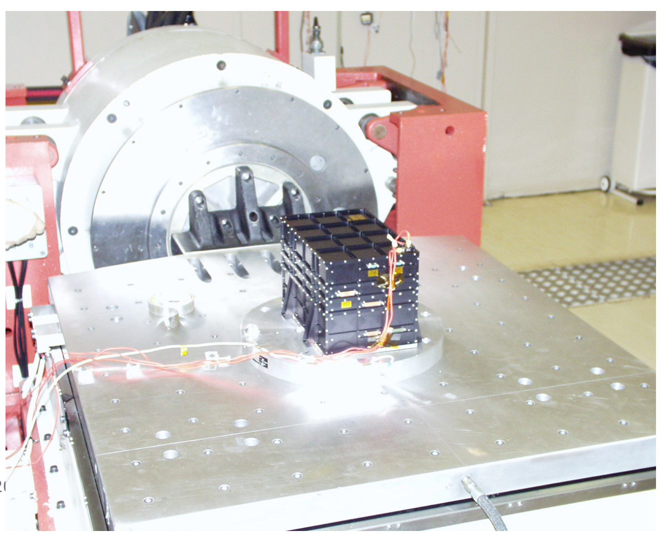


Thermal stress analysis for Solar Orbiter magnetometer bracket

Launch

- Severe vibration during ascent
- Static acceleration
- Also transient shocks due to explosive deployments
  - Fairing jettison
  - Separation of spacecraft from launcher

➢ Mechanical design analysis and extensive testing



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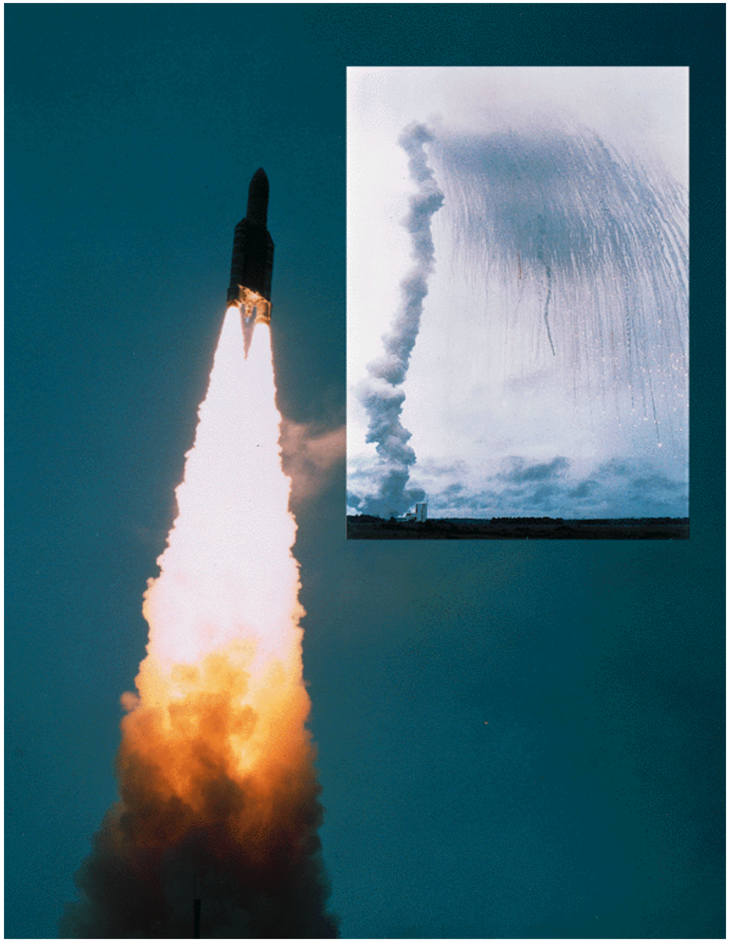
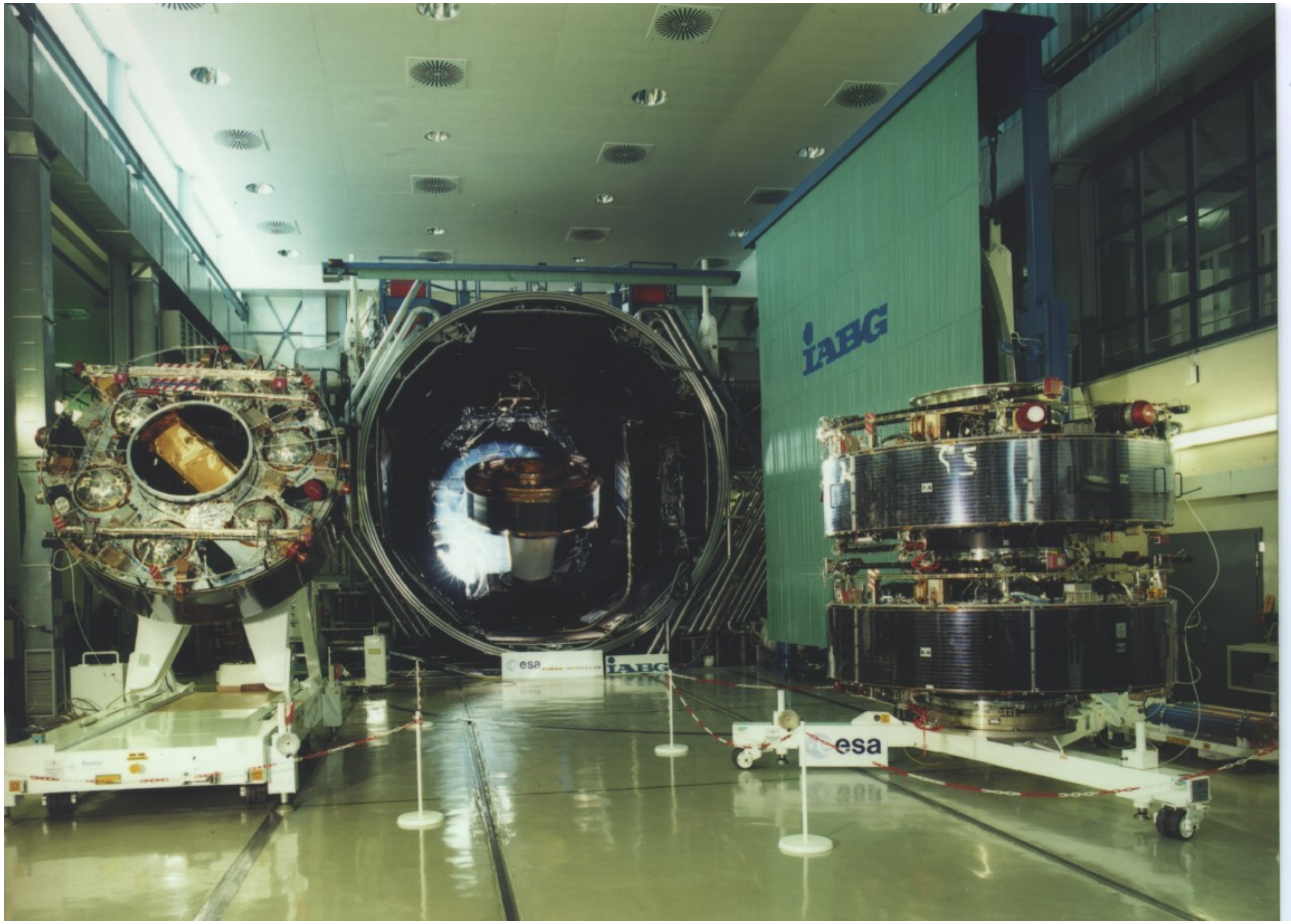
Cluster: first launch attempt, 4th June 1996 Kororou, French Guyana



Cluster Rebuilt: 1998-1999



Cluster spacecraft in preparation for thermal-vacuum testing in the IABG Space Environment test facility, Munich

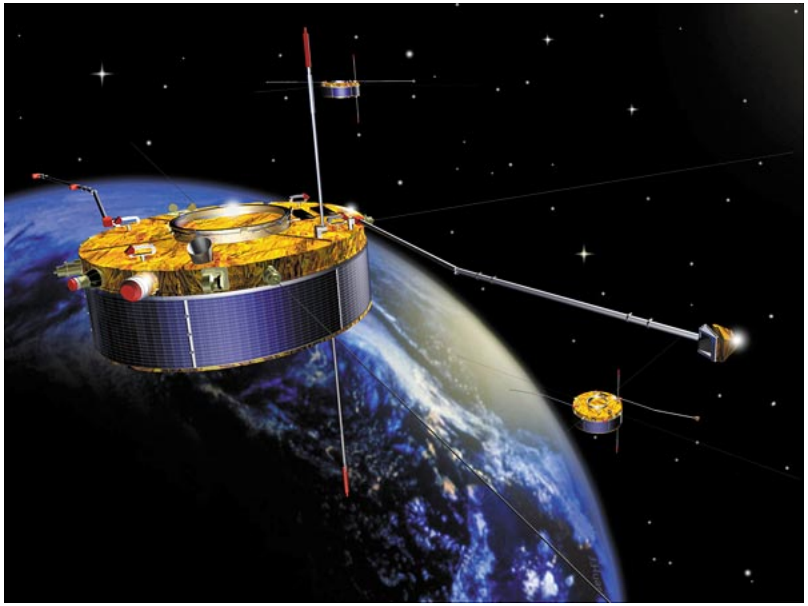
Cluster: second launch attempt, 16th July 2000 Baikonur, Kazakhstan

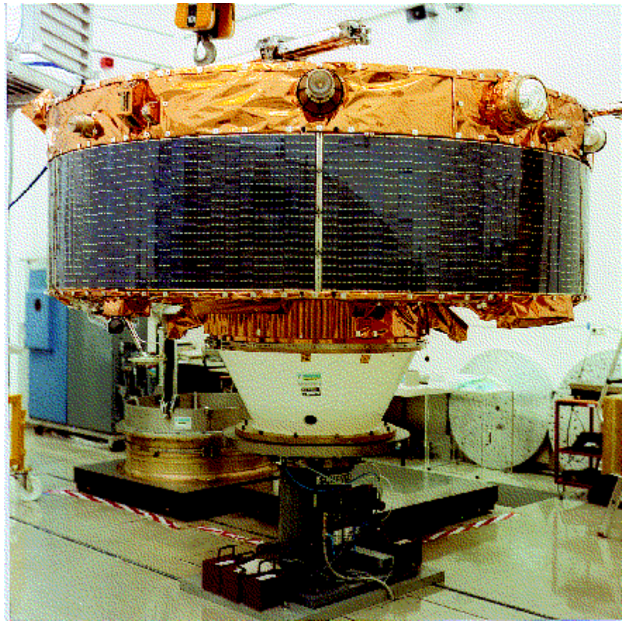
Two Cluster spacecraft stacked on top of Fregat upper stage

Launch 16th July 2000
and subsequently 9th August 2000

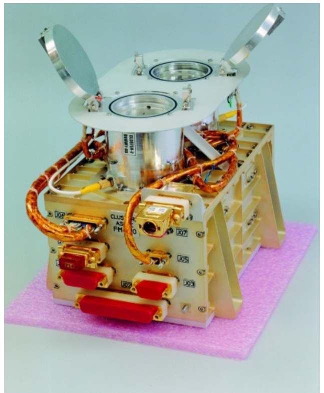
Spacecraft Charging

- Electrostatic contamination due to charging of the spacecraft distorts low-energy particle trajectories
  - ➢ Conducting surfaces
  - ➢ Active potential control





Cluster:
Active spacecraft potential controller



Cluster:
Conducting 'blankets'
Conducting solar panels

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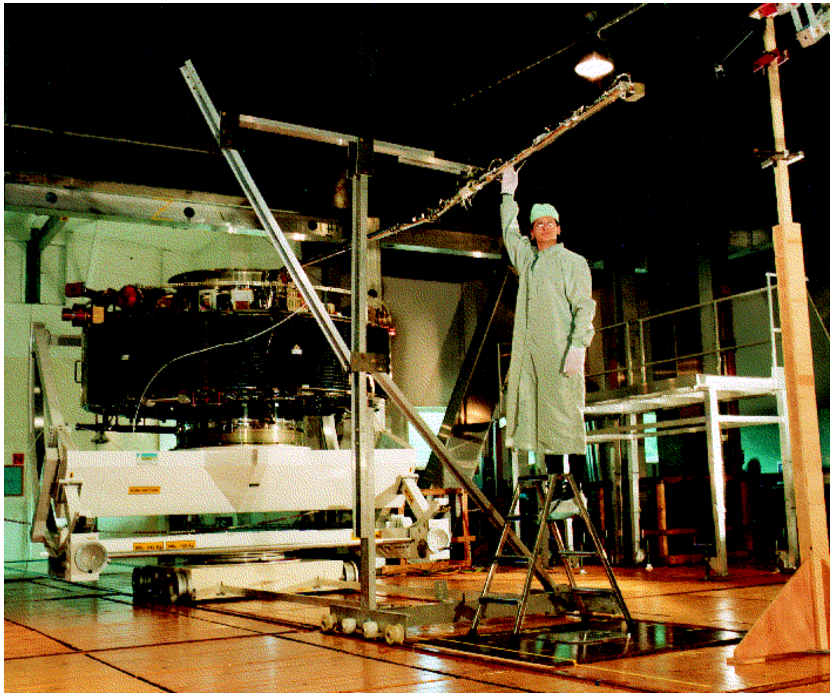
Magnetic Cleanliness

- Magnetic contamination due to currents and magnets used on the spacecraft
  - Boom-mounted sensors
  - Minimise sources by design

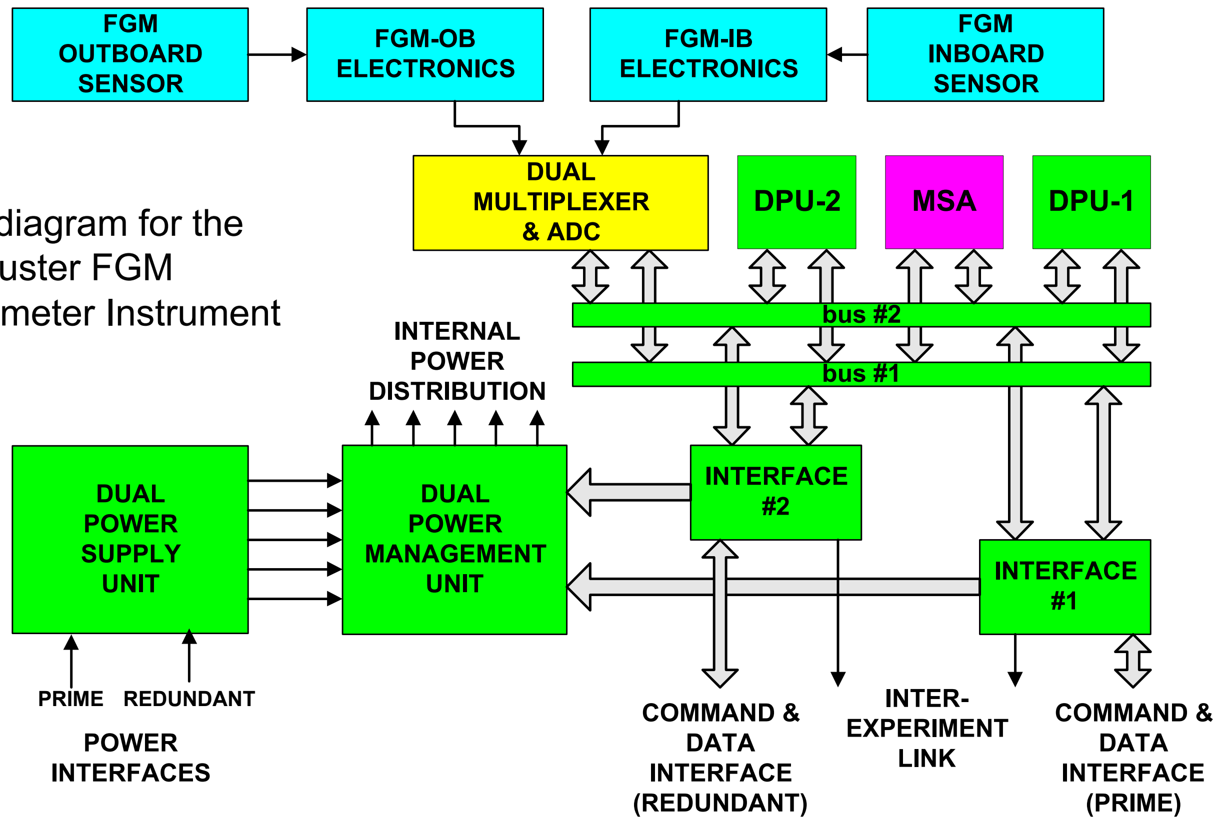


Magnetic Testing at the MFSA facility (Munich)

Reliability and Redundancy

- Duplication of all instrument functions
- Design goal: avoid the possibility of ‘single-point failures’

Block diagram for the Cluster FGM Magnetometer Instrument



Digital Signals

- Motivation:
  - All modern instrumentation delivers a digital data output
  - The trend is towards digitisation as close as possible to the sensor
  - This eliminates signal processing in analogue electronics
  - Moves processing to the digital domain
- In this section
  - Basic principles of sampling and digitisation
  - Quantisation Noise
  - Aliasing and the Nyquist theorem

Sampling and Digitisation

Is a 2-stage process

Is not just a phenomenon of the digital age

All laboratory data is

1. Sampled (measurement taken every minute)
2. Digitised (number written in a lab-book)

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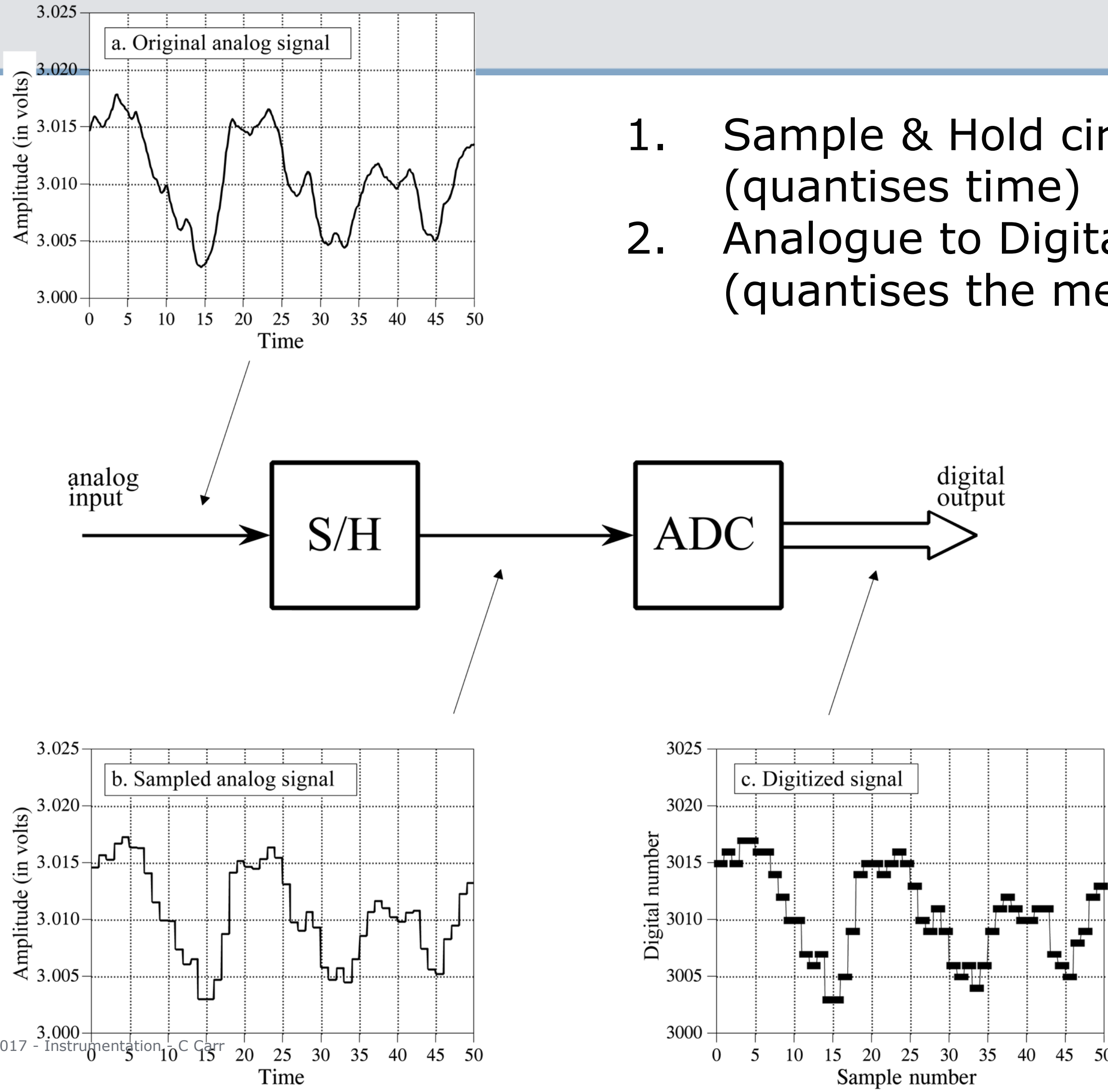
Electronic Digitiser

1. Sample & Hold circuit (quantises time)
2. Analogue to Digital Converter (quantises the measaurable)



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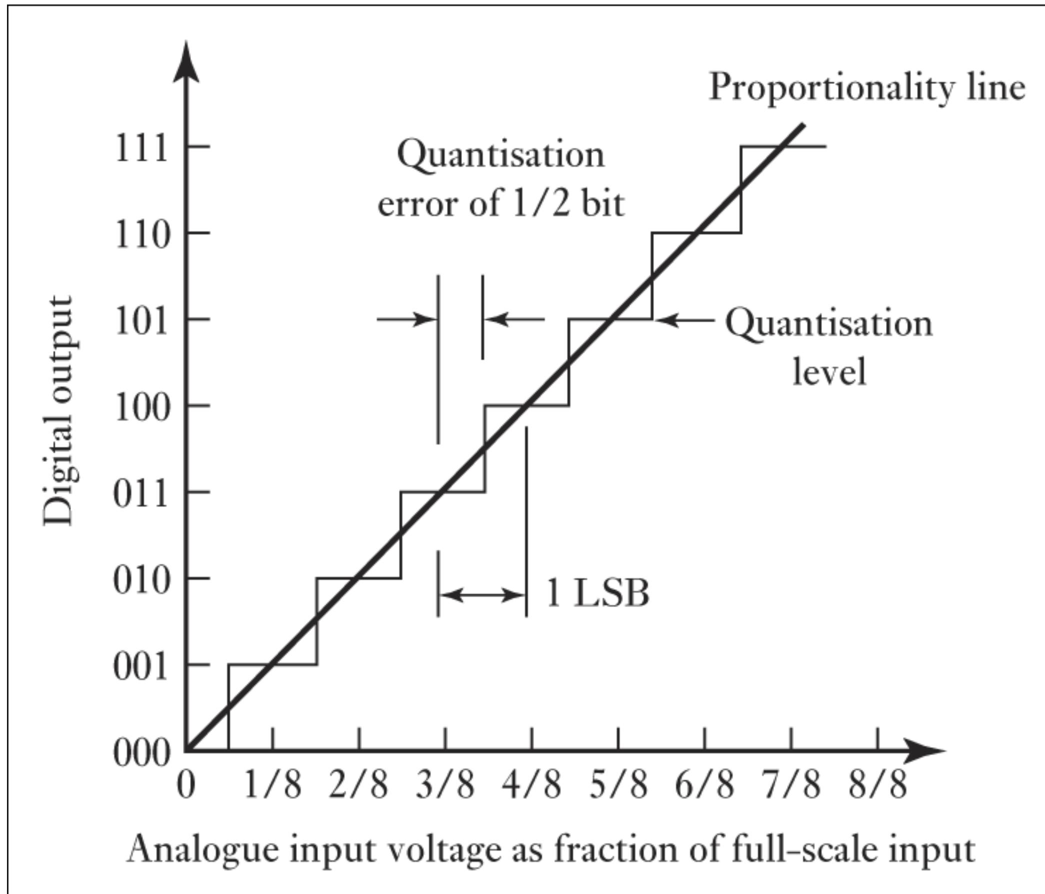
Quantisation

Sampling quantises time into a set of discrete values

- Want regularly spaced samples (sampling time T_s)
- Variability or 'noise' on T_s is known as **jitter**
- Stable **clock signal** (e.g. square-wave) will ensure regular, low-jitter sampling

Digitisation quantises the continuous analogue quantity (usually a voltage) as a discrete number

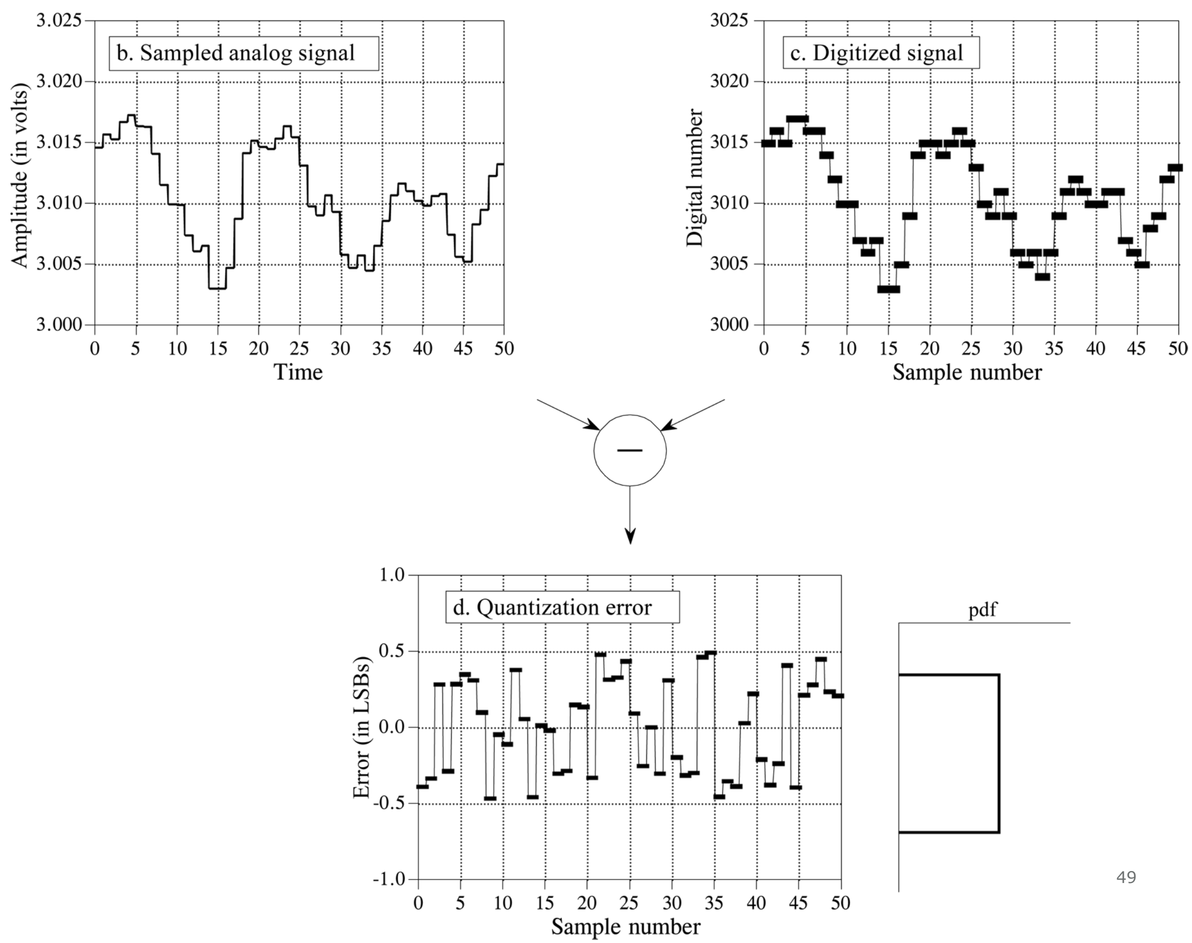
- Introduces an error to the digitised signal
- **Quantisation Error**



Quantisation error

- Quantisation error will be – over a long series of input values – **uniformly** distributed between ±½ the resolution of the digitiser
- Quantisation adds **noise**
- RMS noise added is

$$N_{RMS} = \frac{q}{\sqrt{12}}$$

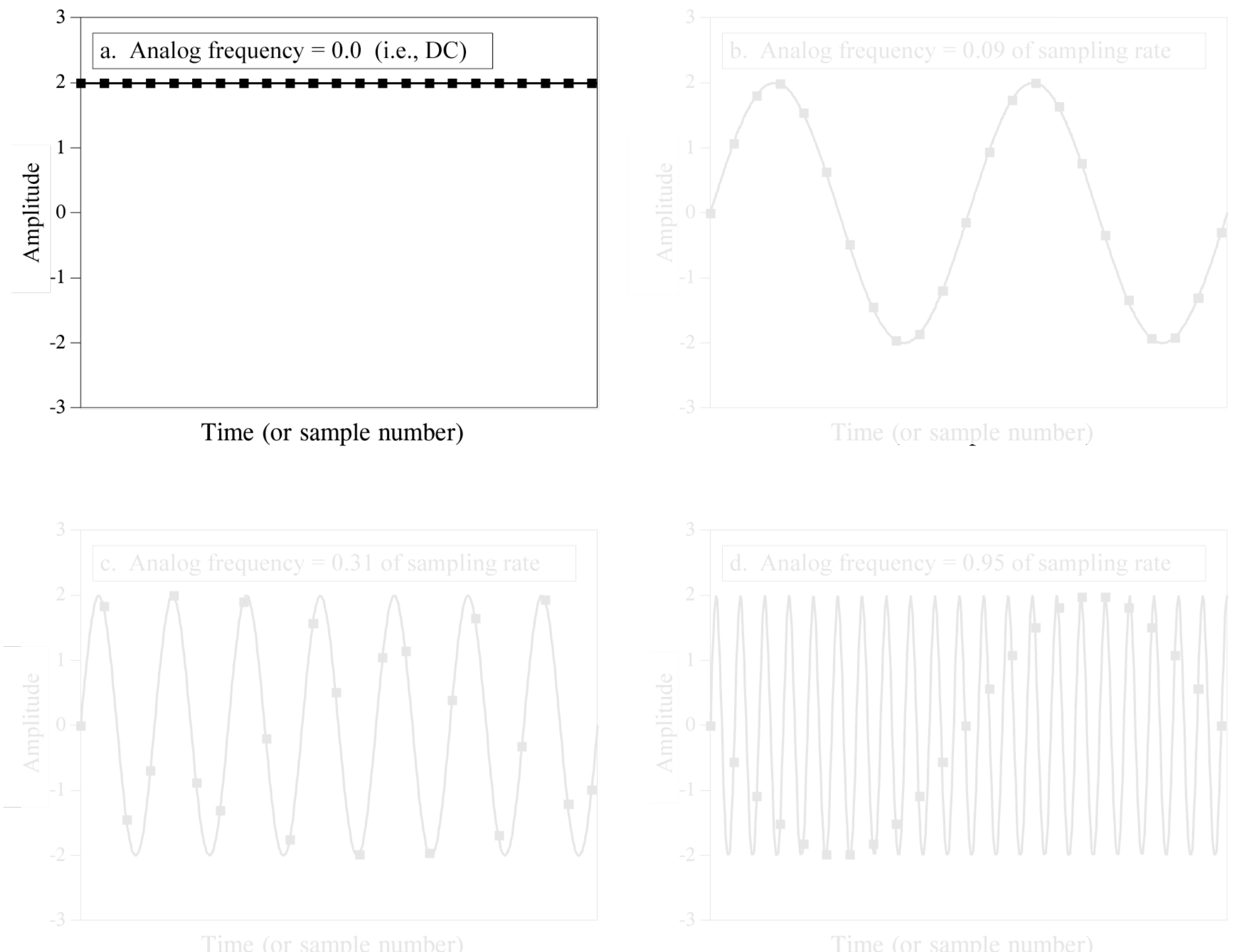


Nyquist Theorem

A signal can only be properly sampled if it has frequency components **below** half the sample rate

- Wagon-Wheel Effect
- This is **Aliasing**

Aliasing


a. Analog frequency = 0.0 (i.e., DC)
b. Analog frequency = 0.09 of sampling rate
c. Analog frequency = 0.31 of sampling rate
d. Analog frequency = 0.95 of sampling rate
Amplitude
Time (or sample number)
3
2
1
0
-1
-2
-3

Frequency-domain Characteristics of the Digitised Signal

$$F_s(\omega) = \frac{1}{T_s}\sum_{n=-\infty}^{\infty} F(\omega + n\omega_s)$$

$$\omega_s = \frac{2\pi}{T_s} = 2\pi f_s$$

Proper Sampling (obeys Nyquist)

Improper Sampling (aliasing)

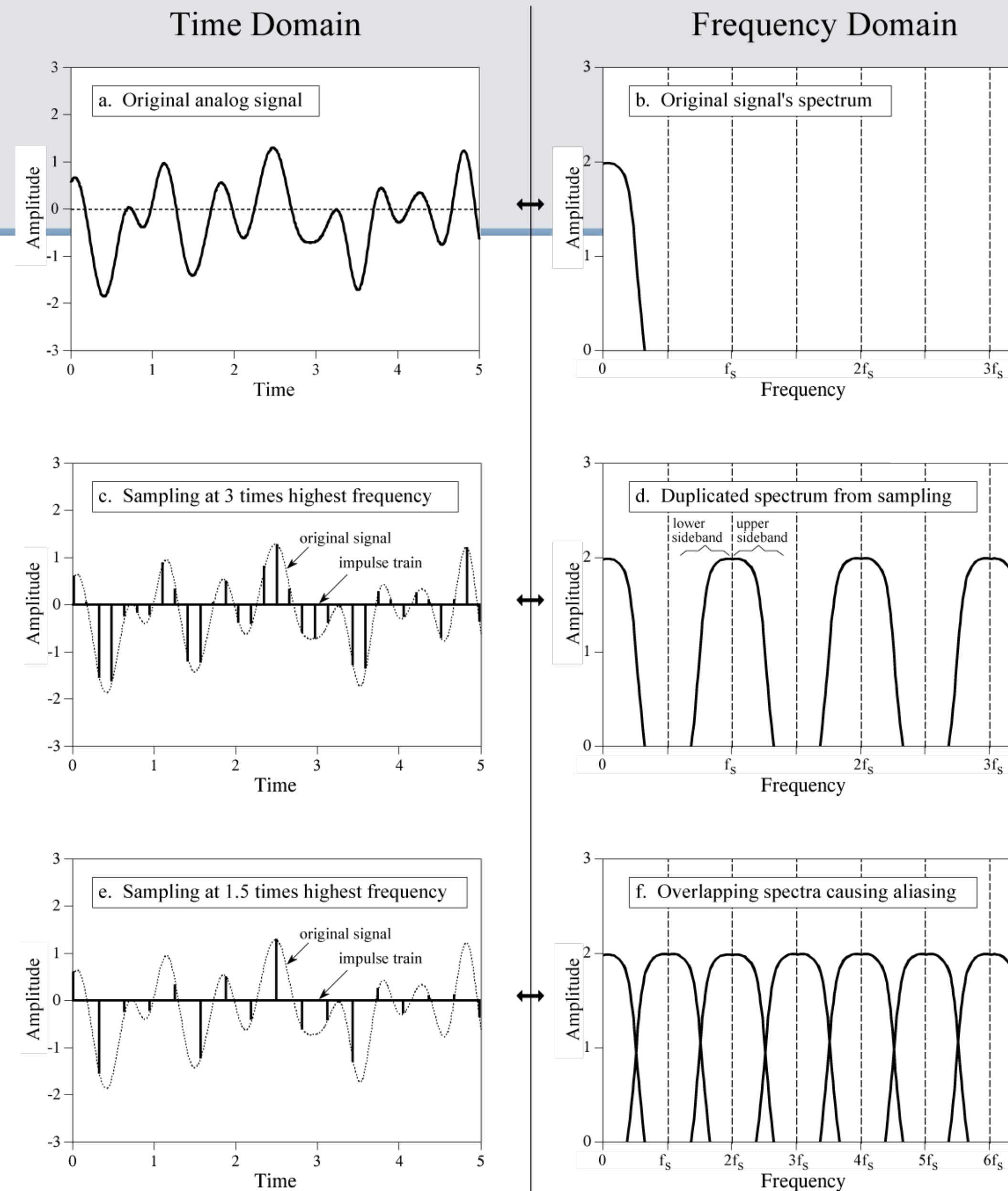


Figure 5.3: Sampled Signals in the Frequency Domain (from Smith, www.dspguide.com)

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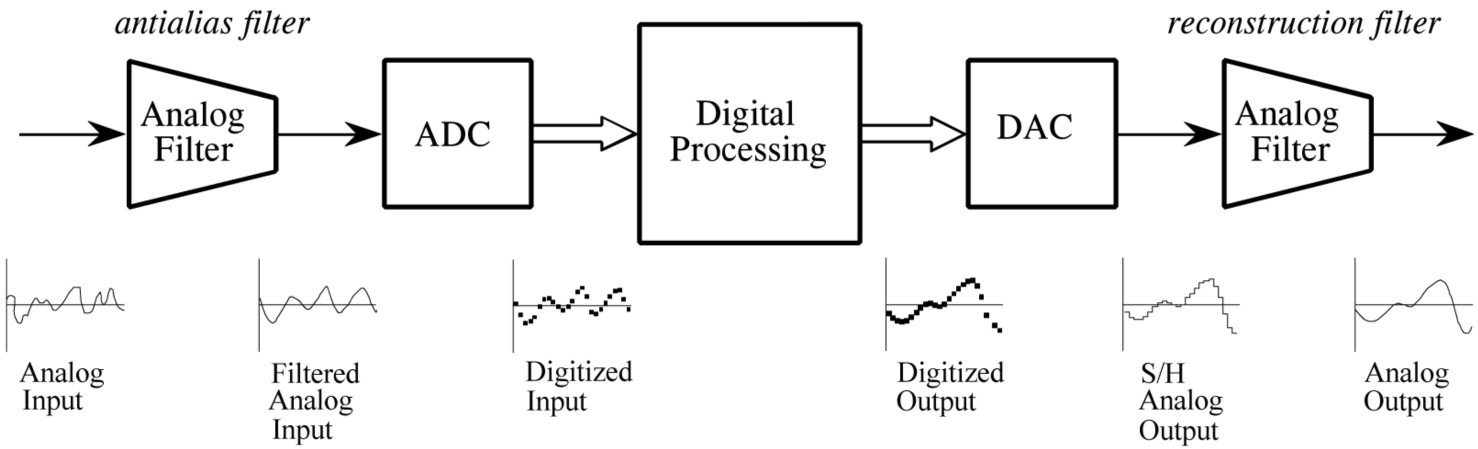
Avoid Aliasing: High design priority



- Anti-alias filter
  - » Filters the **analogue** signal
  - » **Removes** frequencies higher than the Nyquist limit

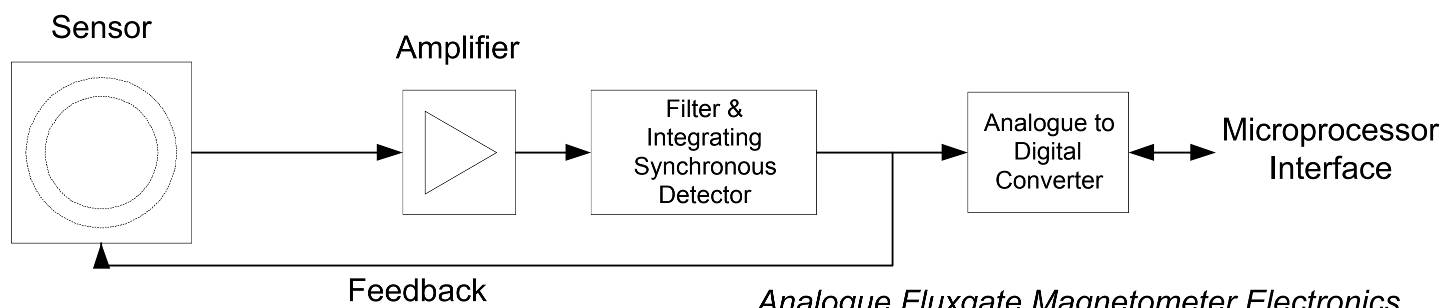
Future Developments

- Challenges
  - Reducing mass
  - Reducing power
  - Smaller spacecraft
  - Increasing the cadence for plasma distributions

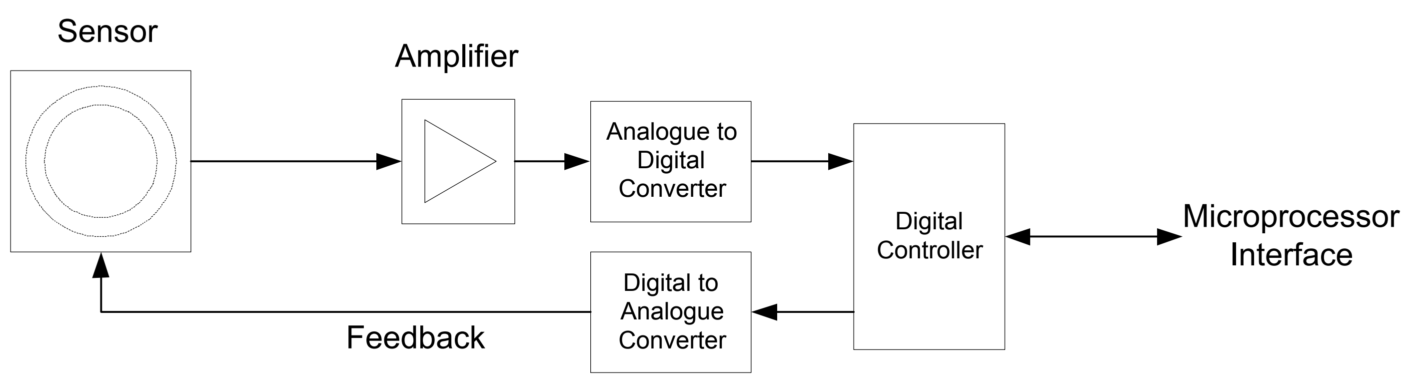
- In this section
  - Digital replaces analogue
  - New sensor technologies
  - MMS

Digital Replaces Analogue circuitry

- Decrease the number of components
- Increase the reliability



Analogue Fluxgate Magnetometer Electronics



Digital Fluxgate Magnetometer Electronics

e.g. O'Brien et al., 2007

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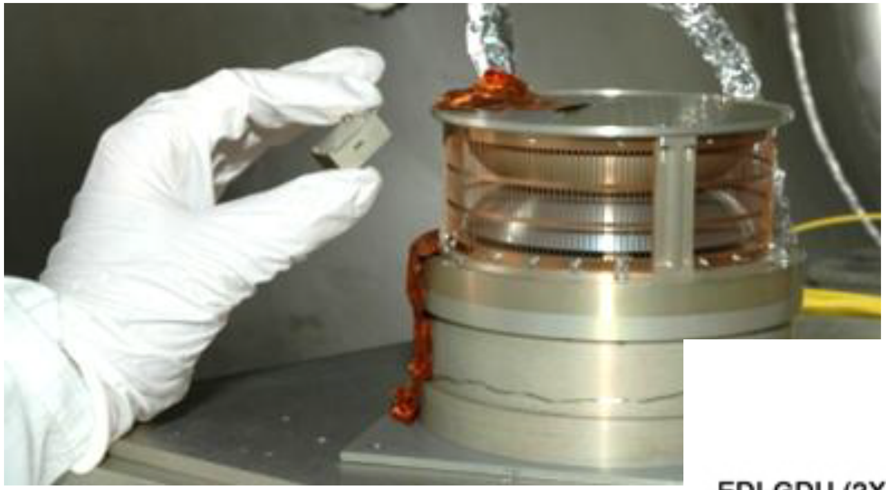
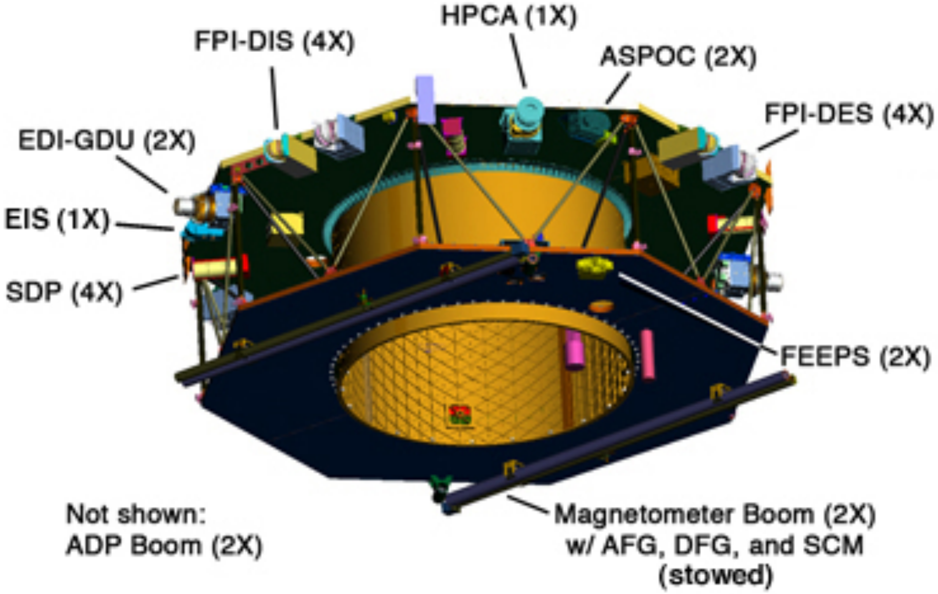
Particle Detectors

- Micro-machined Electrostatic Analyser



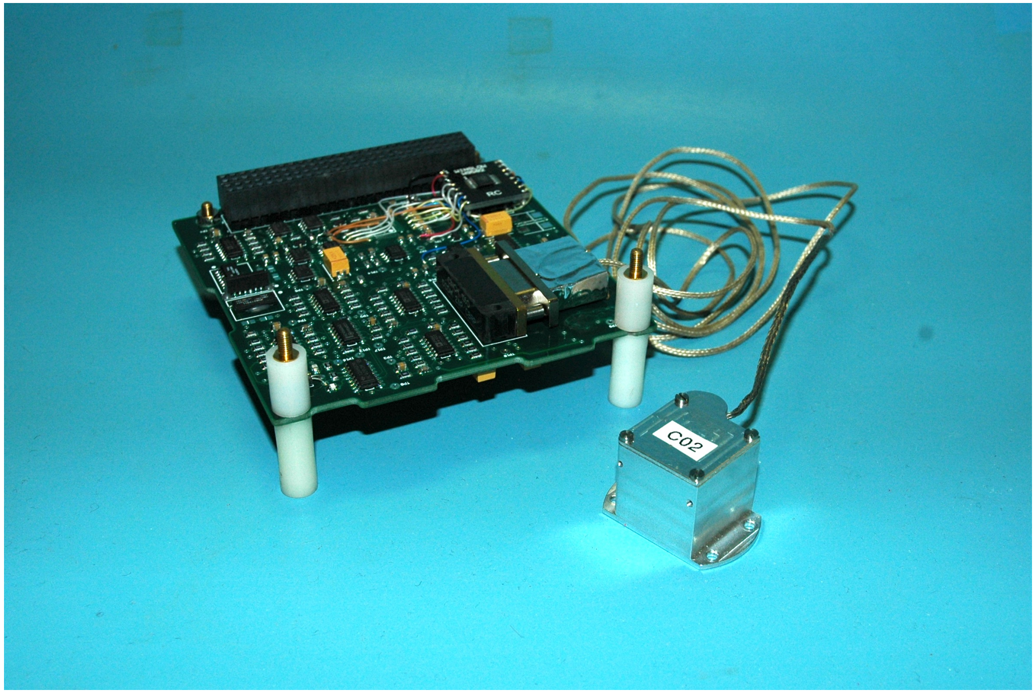
MEMS Analyser head compared to conventional electrostatic analyser (Bedington et al.)

- Fast plasma distribution measurement
  e.g. MMS Fast Plasma Exp.
  - 3D ion and electron distributions in 150ms and 30ms respectively
  - 8 ion and 8 electron analysers!



'Solid-State' sensors
e.g. magnetoresistive magnetometer

- Anisotropic magnetoresistive sensor replaces fluxgate
- Small / light / low-power



MAGIC
Magnetometer
e.g. Brown et al., 2012

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