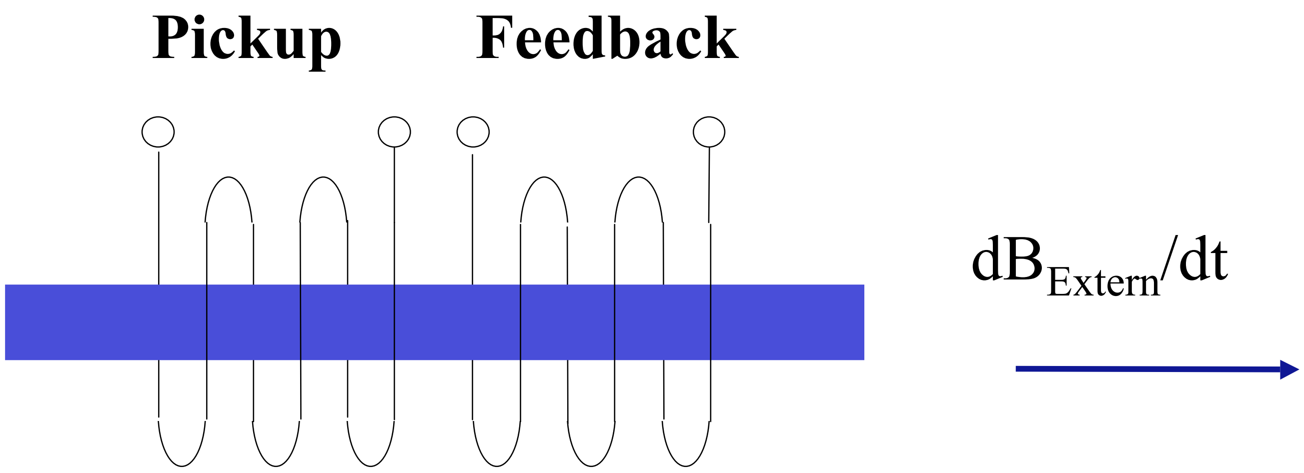
Overview Field Measurement

- Magnetic Field measurement
  - Measurement methods
  - Overview about instruments applied in space
- Electric Field Measurement
  - Measurement methods
  - Overview about instruments applied in space
- Requirements on Spacecraft
  - Sensor accommodation
  - Auxiliary information
  - Typical mass power telemetry budgets
  - EMC compatibility
- Examples
  - Field payload on Cluster and Themis
  - Typical Data

Types of Magnetometers

Type of magnetometer	**Basic Principle**	**Output quantity / limits**	**Space application?**
Classical Instruments	manipulation with magnets	field direction (compass) field variation (e.g. QHM) horizontal force (Theodolites) ***100pT / (minutes ... DC)***	No
Search Coil	Faraday's law of induction	field vector (dB/dt) ***0.01..10pT / (50kHz ... 1Hz)***	Yes
Fluxgate	saturated transformer	field vector ***10pT / (100Hz ... DC)***	Yes
Optical Pumped	Zeeman splitting, Lamour frequency	scalar magnetometer with coil system vector ***1pT (1kHz ... DC)***	Rubidium in 60th He onboard Cassini
Proton /Overhauser	proton precession, gyro magnetic ratio	scalar magnetometer with coil system vector ***10pT (1Hz ... DC absolute)***	Yes
SQUID	Josephson effect	field vector (dB/dt) ***0.1pT / (100kHz ... 0.001Hz)***	No
Magneto resistive	Anisotropic Magnetoresistive Effect	field vector ***10nT / (100Hz ... DC)***	(attitude control)
Hall	Lorentz Force	field vector ***1mT / (30kHz ... DC)***	No

Search Coil Magnetometer



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

Search Coil Magnetometer

- Principle of Operation
  - Application of Faraday's law
  - Output signal depends on μ_r (long core to keep the demagnetisation factor low), N (weight of copper) and A (weight of softmagnetic material)
  - Sensitivity depends on frequency due to (dB/dt) behaviour and resonance of coil-electronics system.

- Parameter
  - Noise at 1Hz: 10pT/√Hz
  - Noise at 10 kHz: 0.01pT/√Hz

- Application
  - Ground application:
    Audio EMT-sounding
  - Space application:
    all magnetosphere missions
    partly on planetary missions

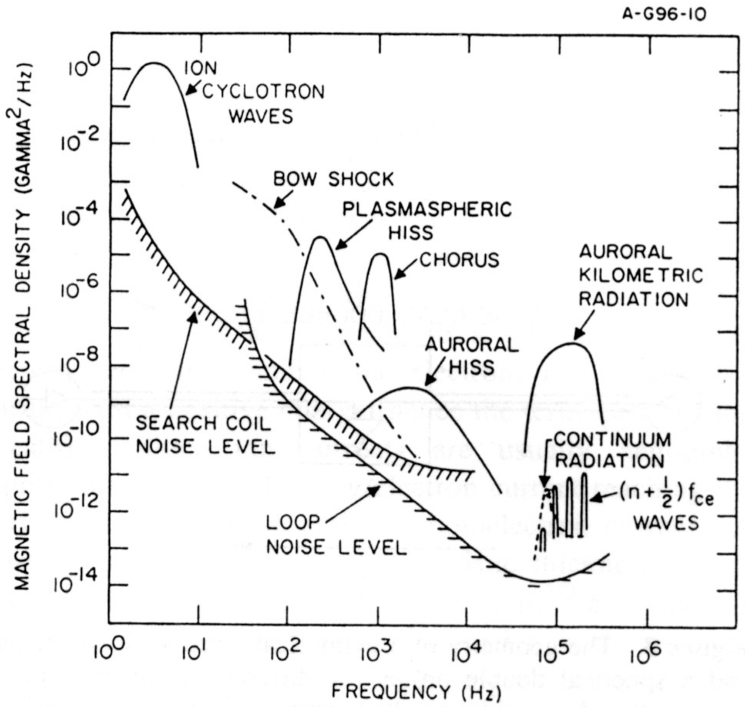
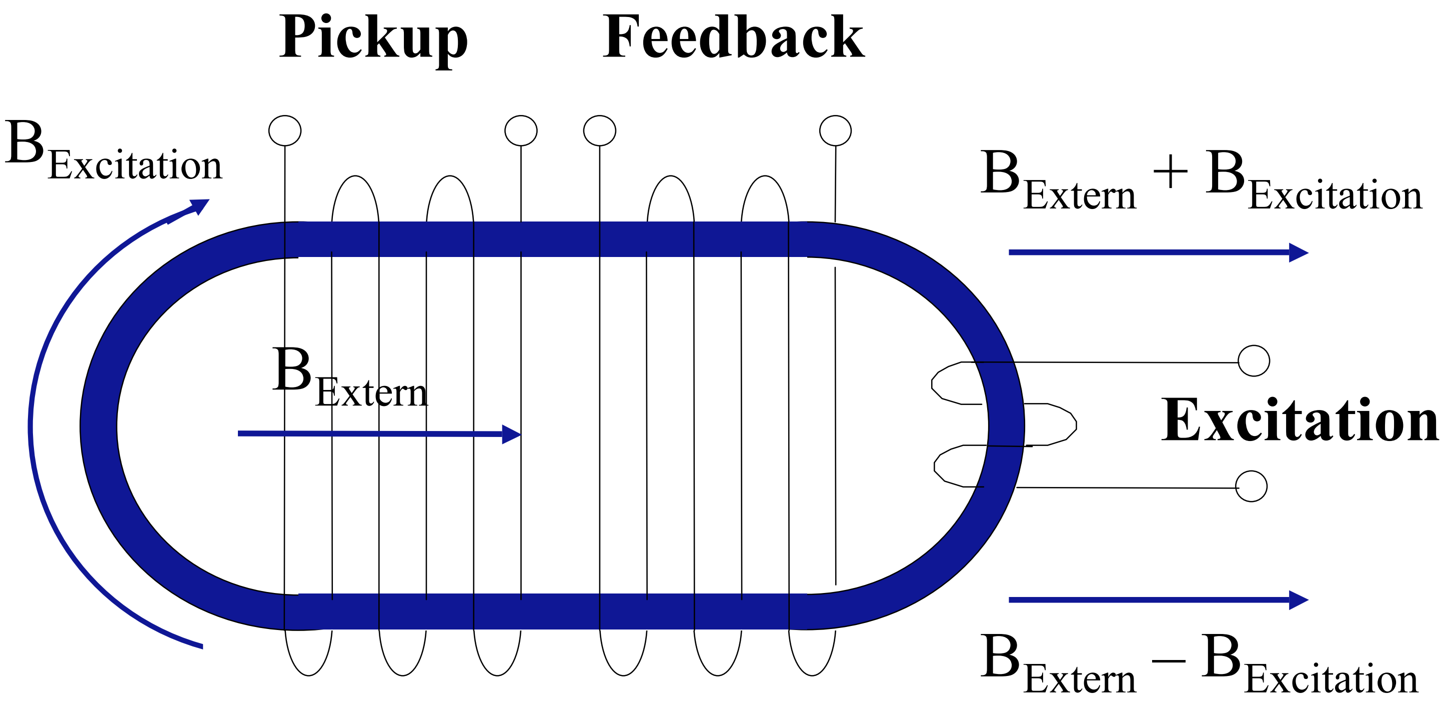


Figure 2. Representative magnetic field spectrums for various plasma wave phenomena observed in the Earth's magnetosphere.

[D.A.Gurnett, 1998]

Fluxgate Magnetometer



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

Fluxgate Magnetometer

- Principle of Operation
  - Magnetic material saturated by symmetric AC (f0) drive current
  - Secondary signal becomes asymmetric if external field disturbs the symmetry by shifting the zero point on the hysteresis
  - Second harmonics of drive frequency is quantity for asymmetry = magnitude of external field
  - Field feedback holds working point close to zero
- Parameter
  - Measurement range: Solar Wind (10th of nT) - Earth field 60.000nT
  - Frequency range: 100Hz ... DC
  - Stability: 1nT...10nT/year
  - Noise: 10pT/√Hz at 1Hz
- Application
  - Ground application: e.g. observatories, EMT-sounding, applied physics
  - Space application: all magnetosphere, nearly all planetary missions, attitude control for low Earth missions

Proton Magnetometer (NMR)

Fundamental properties of a proton:

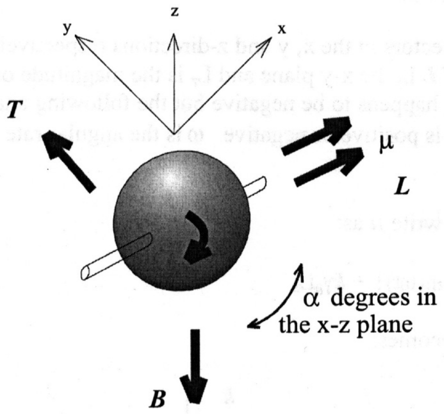
Angular momentum: $\mathbf{L} = 5.27 \;\, 10^{-35} \; kg\, m^2\, s^{-1}$

Magnetic moment: ì $= 1.41 \;\, 10^{-26} \; A\, m^2$

Relation between both: $\boldsymbol{\mu} = \gamma_P \; \mathbf{L}$

gyro magnetic ratio $\gamma_P \; = \; 267515528 \; s^{-1} \; T^{-1}$

Properties of a proton in a B-field



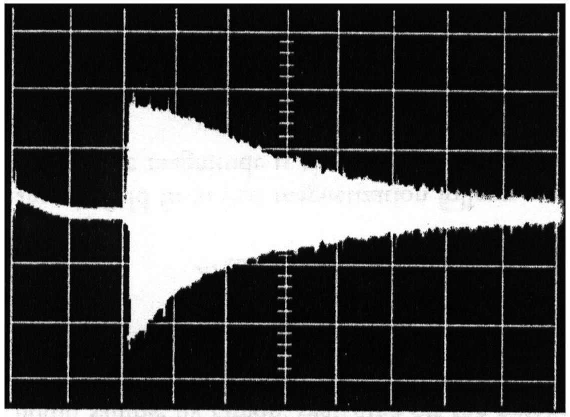
Torque: $\mathbf{T} = $ ì $\times \mathbf{B}$

Relation between **L** and **T**: $\mathbf{T} = {d\mathbf{L}}/{dt}$

Precession: $\omega_\gamma = \gamma \; B_0$

Proton Magnetometer

- Principle of Operation
  - Sensor is a bottle of water (alcohol) + coil for polarisation and pick up
  - Polarisation aligns all proton,
  - Fast change from polarisation to pick up provides a in phase precession
  - Frequency is measured, signal amplitude depends on time (relaxation)
  - Polarisation can be done continuously via electrons (Overhauser)
- Parameter
  - Measurement range: 20.000nT ... 100.000nT
  - Frequency range: 1Hz ... DC
  - Relaxation time: 1sec
  - Accuracy: 0.1nT absolute



- Application
  - Ground application: observatories, applied physics
  - Space application: missions investigating the Earth field

Vector measurement by scalar sensors

- Measurement of field components using a scalar magnetometer
  - Sensor has to be equipped with a coil system for bias fields
  - Applying fields in + and - direction, field components can be derived by a set of three scalar measurements

$$F^2 = H^2 + Z^2$$

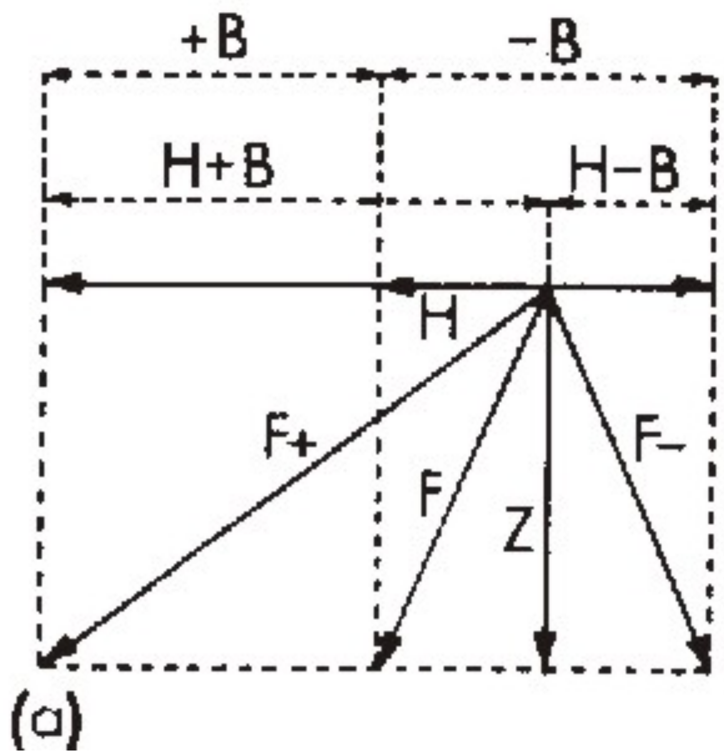
$$F_+^2 = (H+B)^2 + Z^2 = F^2 + B^2 + 2HB$$

$$F_-^2 = (H-B)^2 + Z^2 = F^2 + B^2 - 2HB$$

$$F_+^2 + F_-^2 = 2\left(F^2 + B^2\right)$$

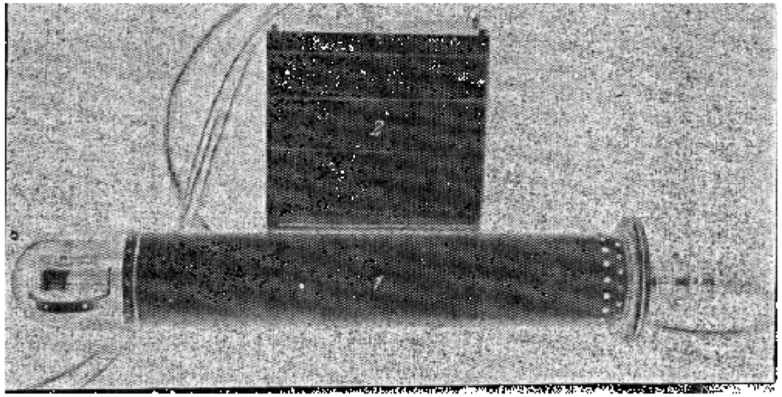
$$F_+^2 - F_-^2 = 4HB$$

$$H = \frac{F_+^2 - F_-^2}{2\sqrt{2\left(F_+^2 + F_-^2 - 2F^2\right)}}$$

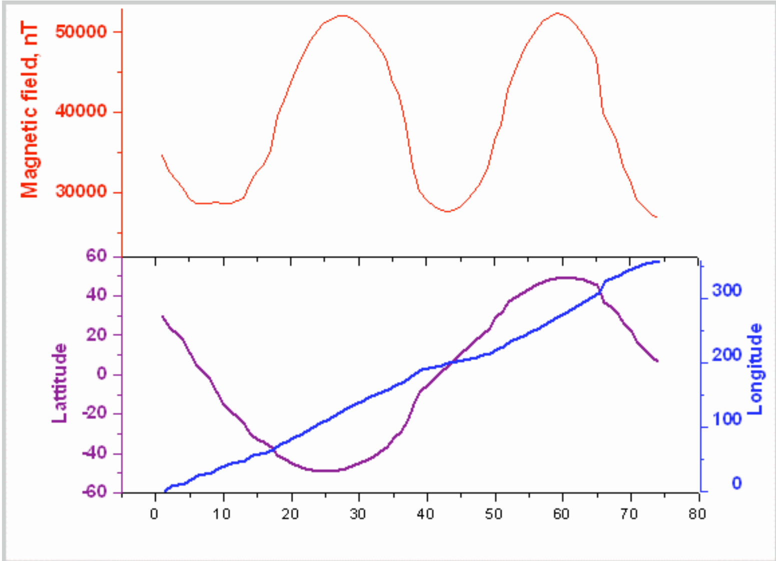


First Measurement in Space

In situ studies by spacecraft of the magnetic field of Earth and all the planets except for Pluto began with the USSR's launch of Sputnik 3 in 1958. The study of the geomagnetic field by the USA followed with Vanguard 3 in 1959. Since then the US Explorer, Mariner, Pioneer, Voyager, Ulysses and Galileo missions have surveyed all the planets from Mercury to Neptune as well as the Earth's Moon.
The USSR repeatedly studied Earth's Moon, Venus and Mars with their Luna, Venera, Mars and Phobos missions.
N.F.Ness „Planetary and Lunar Magnetism", 2004



- 15. 05. 1958, Sputnik 3
  - Three component fluxgate magnetometer
  - PI: Dolginov / Zhuzgov
  - No attitude data: Scalar field only
- 18. 09. 1959,Vanguard 3
  - Proton magnetometer
  - PI: Heppner



Results of Sputnik 3 Magnetometer

Interplanetary Missions

- Earth Moon
  - 1959 Luna 1 & 2
  - 1968 Lunachod
  - 1969-71 Apollo 12,14,16

  „No“ magnetic field

- Mercury
  - 1974: Mariner 10

  Weak dipole

- Venus
  - 1962-67: Mariner 2,4,5
  - 1967: Venus 4
  - 1978: PVO
  - 2005: Venus Express

  Induced magnetosphere

- Mars
  - 1964 Mariner IV
  - 1974 Mars 4
  - 1988 Phobos 2
  - 1997 MGS

  Induced magnetosphere
  Surface magnetisation

- Outer Planets
  - Jupiter: 1973 Pioneer 10
  - Saturn: 1979 Pioneer 11
  - Uranus: 1986 Voyager 2
  - Neptune: 1989 Voyager 2

  Large dipoles with various orientations

History of Instrumentation

Status 1965:

TABLE 12-1. LIST OF SPACE-PROBE INSTRUMENTS

Instruments for Studying the Interplanetary Medium (Chap. 13)

Phenomenon	*Instruments and Experiments**	*Page*
Magnetic field (temporal and spatial variations of flux)	Search-coil magnetometer	298
	Fluxgate magnetometer	301
	Proton-precession magnetometer	305
	Rb-vapor magnetometer	306
	Helium magnetometer	309
Space radiation (corpuscular and gamma radiation)	Geiger-Mueller counter	316
	Proportional counter	317
	Ionization chamber	318
Basic detectors	Channel multiplier	319
	Scintillators	320
	Cerenkov detector	322
	Cadmium-sulfide cell	323
	Solid-state detector	325
Detector combinations	Telescopes (various types)	328
	Magnetic spectrometers	335
	Ionization chamber and Geiger-Mueller counter	337
Track imagers	Spark chamber	345
	Scintillation chamber	347
	Emulsions, cloud and bubble chambers	348
Interplanetary plasma (flux, species, and velocity distributions)	Curved-surface electrostatic analyzers	351
	Faraday-cup probes	356
	Spherical ion traps	361
	Radio-propagation experiments	378

* It is important to distinguish between the experiments and the instruments used in the experiments. See text.

- Magnetic Field Instruments
  - Status 1965 = Status 2007
- Electric Field Instruments
  - Not available in 1965

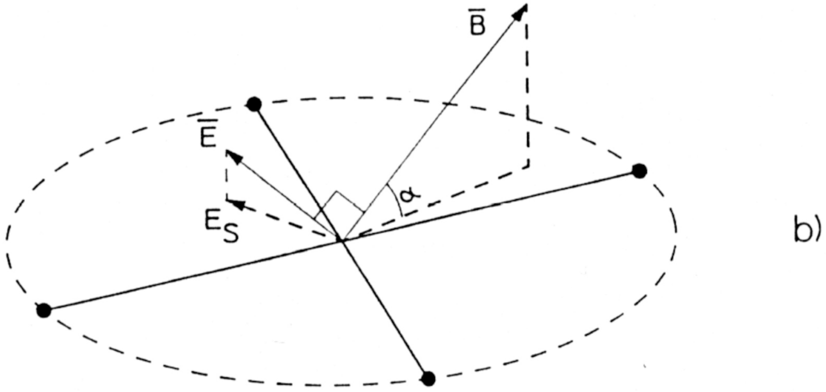
[Van Nostrand, (1965), Space Probes and Planetary Exploration]

E-Field Measurement

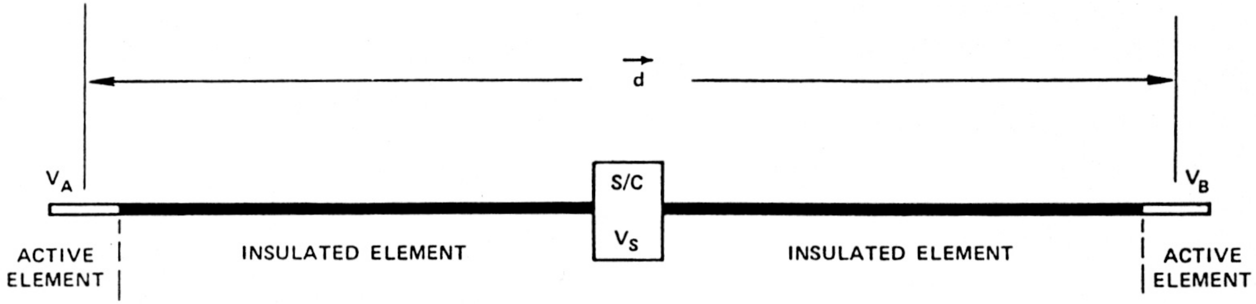
Type of E-field Instr.	Basic Principle	Output quantity / limits	Space application?
Double Probe	direct potential measurement	wave form up to 10Hz ***0.5mV/m (10Hz ... DC)*** compressed data up to 100kHz ***50nV/m/Hz***	Yes
Electron Drift Instrument	**E**x**B** drift of emitted electrons (displacement or time of flight measurement)	E field normal to B ***0.05mV/m (10Hz ... DC)***	only
All particle Instruments	E-field derived from measured velocity distribution and B-field	E field normal to B ***0.1..1mV/m depends on plasma (spin period... DC)***	only

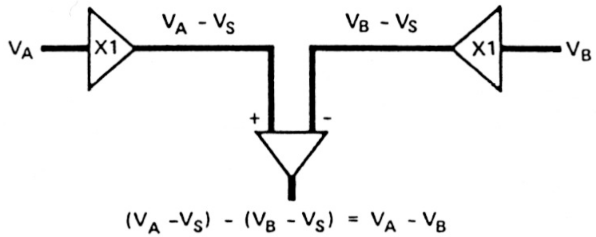
Double Probe

$$\left(\Phi_1 - \Phi_2\right)/\left|d\right| = \left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) \bullet \mathbf{d}$$



VIKING (100m)
CLUSTER (100m)
POLAR (100m+130m)





[Pedersen et al., 1998]

[N.C.Maynard, 1998]

E-field measurement - Double Probe (1)

Double probe

- Principle of Operation
  - Direct measurement
  - Only method which can be used to measure $E_{||}$

- Parameter
  - Noise at 1Hz: 10-5 V/m/√Hz
  - Noise at 100 kHz: 10-9 V/m/√Hz

- Application
  - Ground application: EMT-sounding
  - Space application: sounding rockets and all magnetosphere missions since late 60th

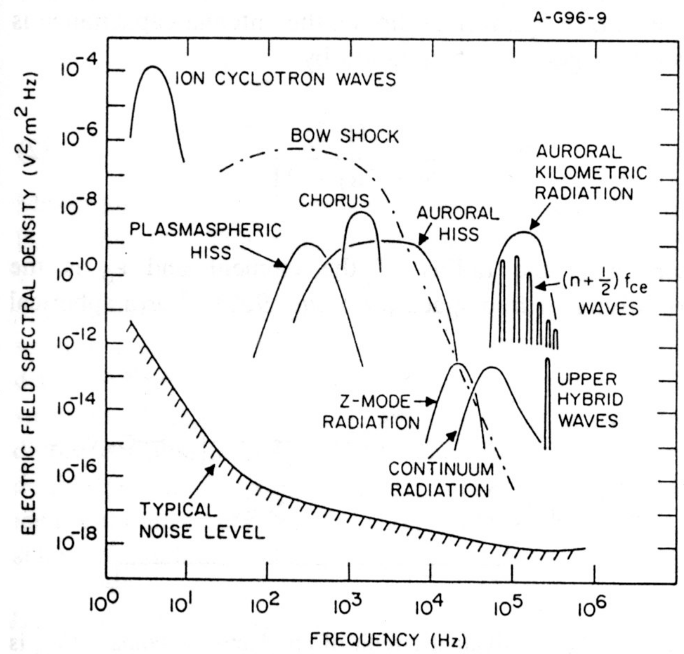


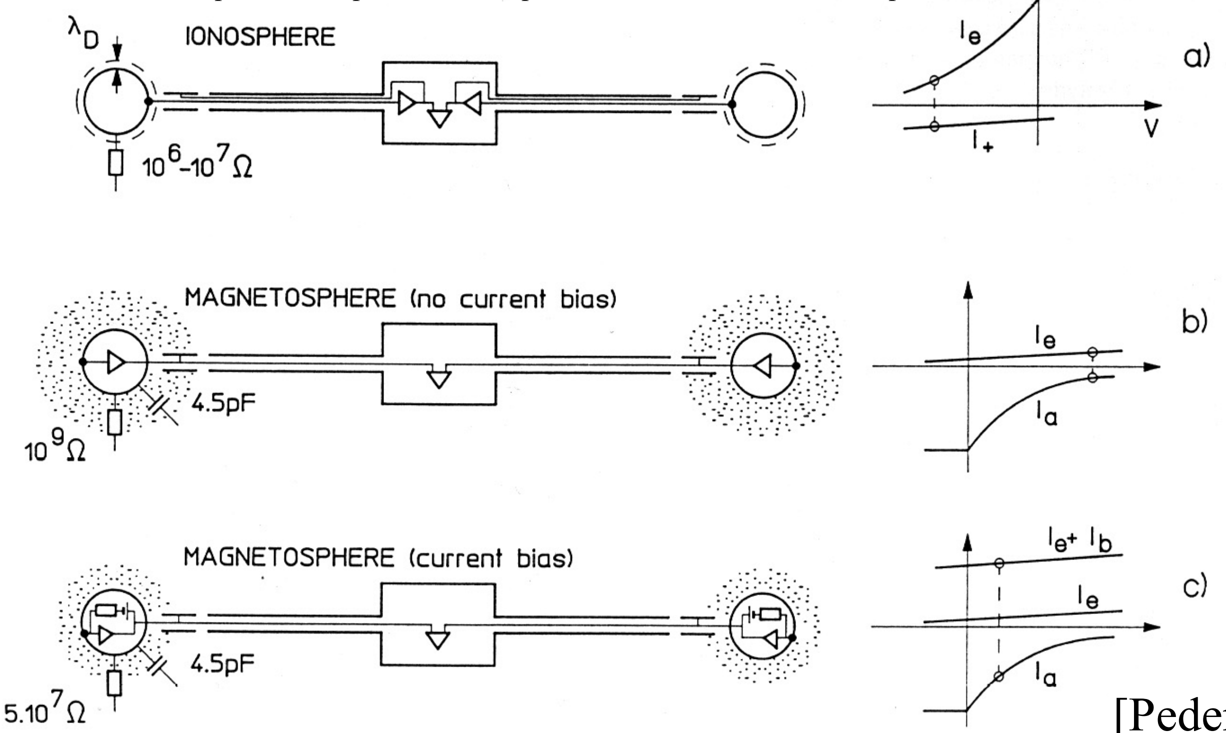
Figure 1. Representative electric field spectrums for various plasma wave phenomena observed in the Earth's magnetosphere.

[D.A.Gurnett, 1998]

Double Probe

- Problem areas
  - Large probe separation necessary to increase signal, wire booms are used normal to spin axis, boom for spin axis component more difficult
  - Resistance between probes is not infinite (S/C & measurement current), effective distance is smaller, has to be calibrated
  - Potential of plasma is not potential of probes - coupling to plasma by bias current

$$I_{ph-e} + I_{ph-e-r} + I_{ph-e-sc} + I_m = I_e + I_p$$



[Pedersen et al., 1998]

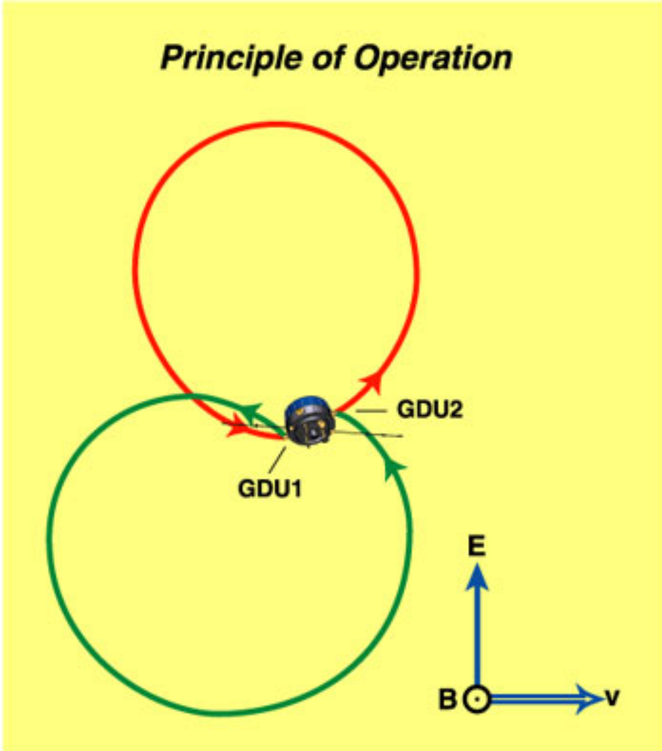
Electron Drift Instrument

Measurement of displacement

$$\mathbf{v}_D = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$$

$$\mathbf{d} = \mathbf{v}_D T_g = \frac{\mathbf{E}\times\mathbf{B}}{B^2} T_g$$

$$\mathrm{d}[m] = 3.57\ 10^4 \frac{E_\perp[mV/m]}{B^2[nT]}$$



Measurement of time of flight

$$\mathbf{v}_D = \frac{\Delta T}{2T_g}\mathbf{v}_e$$

$$|\mathbf{B}| = \frac{2\pi m}{eT_g}$$

[Paschmann et al., 2001]

Electron Drift Instrument

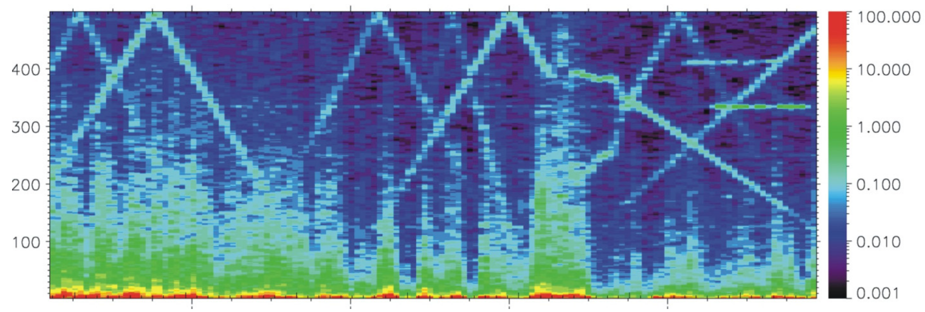
- Principle of Operation
  - E-field normal to **B** derived by measurement of **E**x**B** drift of emitted electrons
  - Two modes: (1) measurement of displacement for high fields, (2) time of flight measurement for moderate fields.
  - In mode (2) magnitude of B can be derived by gyration period
  - Gradient **B** drift can be separated by different energies of test electrons
- Parameter
  - Mode and Applicability depends on **B**-field magnitude and variability
  - Accuracy: 0.05 mV/m (absolute)
- Application
  - Ground application: not applicable
  - Space application: GEOS, Geotail, prove of principle
    Equator-S, Cluster fully operational

Auxiliary Information

- Attitude information
  - Sun sensors, attitude lost during eclipse
  - Star sensors
  - Required accuracy about 0.1°
  - Spin rate must be known much better for despinning the data (averaging necessary)
- Synchronisation between Experiments
  - Master clock (used for small spacecrafts like Equator-S, Themis) for all instruments
  - Low frequency synchronisation (spin pulse or second pulse available)
  - Inter experiment links
  - Capabilities of SpaceWire Interface
- Housekeeping (offline)
  - Temperature
  - Power
  - S/C status

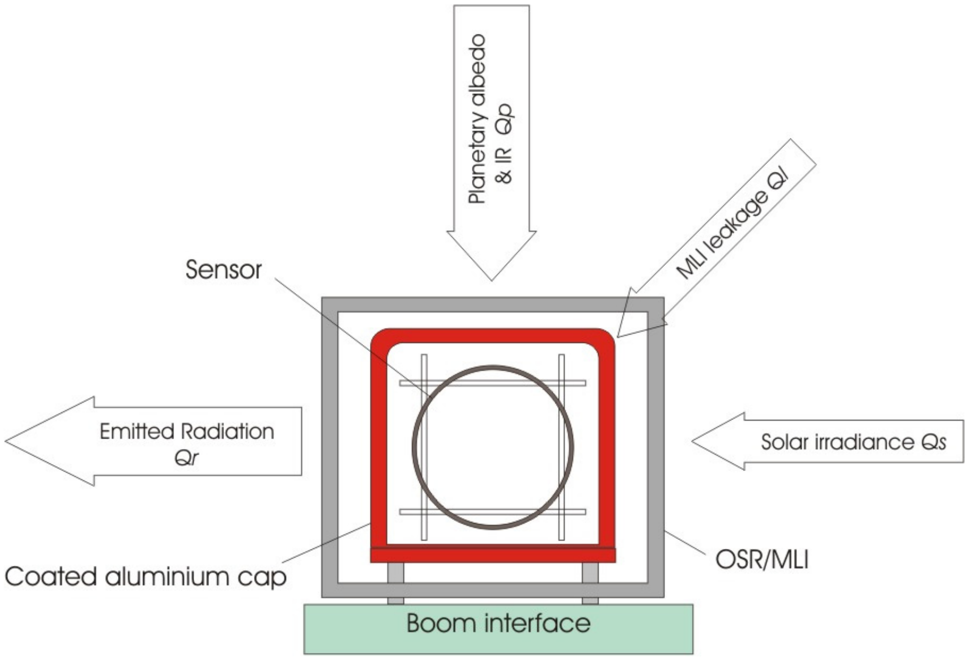
EM-Compatibility

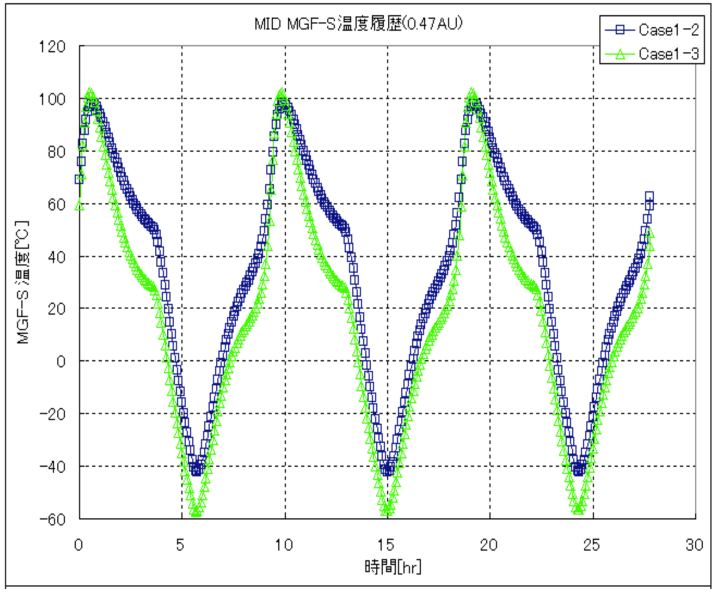
- Classical EMC
  - 300Hz ... MHz
  - Specs well defined, Facilities exist, Tests mandatory
- Special requirements of field experiments
  - Remanent (DC) magnetic field
  - Time variable (AC) interferences
  - Electrostatic requirements



- Disturbance Sources
  - Thrusters, Reaction Wheels, SADM, Solar Panels, Batteries, Ground loops, Torquer ...
- Practicable solution
  - Working groups established by Agencies (ESA), S/C provider and field experimenters to find the balance between
    - S/C design based on proved elements, funding, boom length, acceptable magnetic interference

Thermal Environment

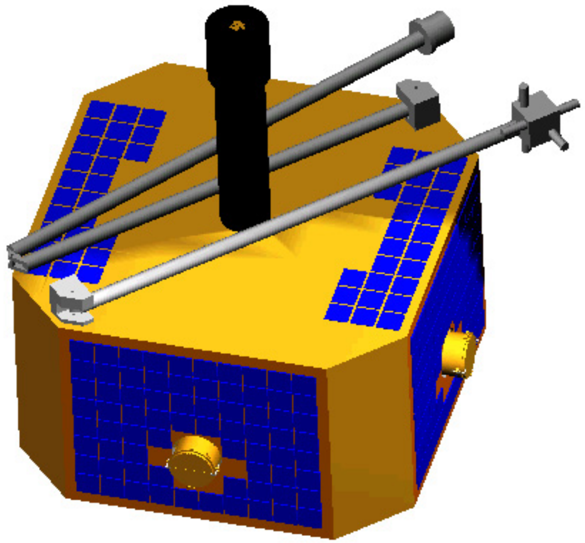




- Thermal requirements
  - Sensors have wide temperature range, but sensible for temperature changes
  - Eclipse crossings must be buffered by high thermal capacity & low epsilon
  - Averaged temperature depends on alpha/epsilon ratio of MLI/OSR

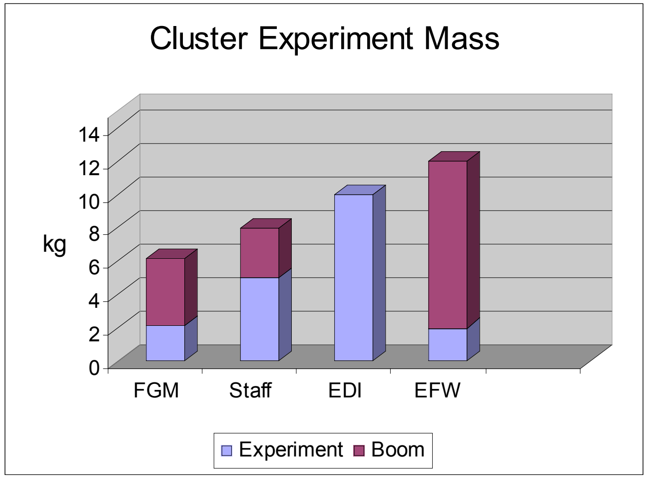
Sensor Accommodation

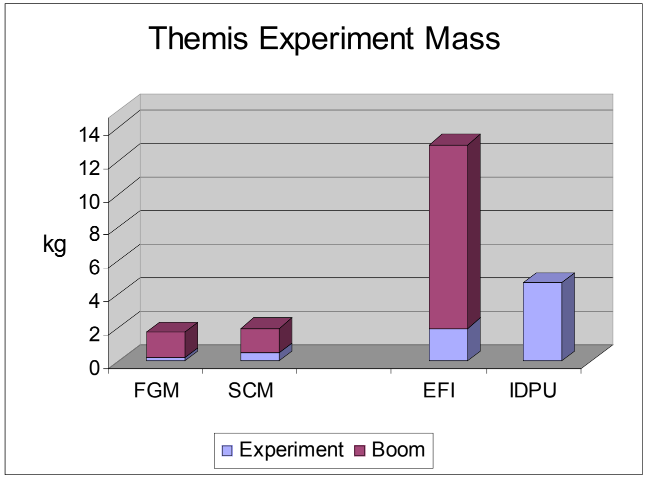
- Boom Geometry
  - 1-3 segment boom (Cluster Double Star, Themis ...)
  - Boom made by spring elements (MMO)
  - Wire Booms (Cluster, Themis ...)
- Release & launch lock mechanism
  - Pyro
  - Melting band,
  - Motor driven
- Deployment force
  - Centrifugal force
  - Spring driven
  - Motor driven



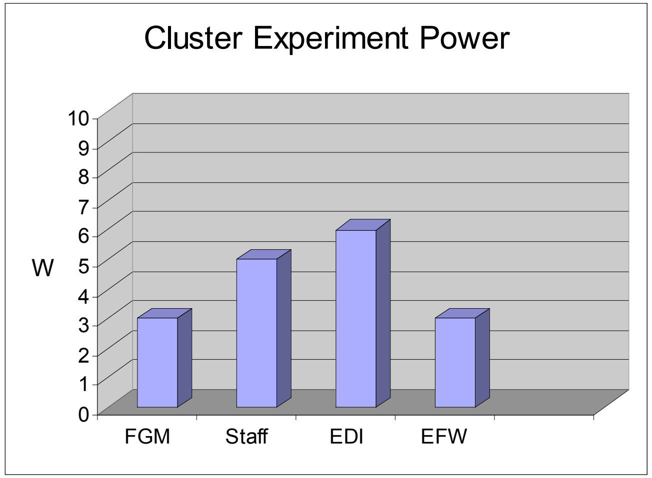
Required Resources

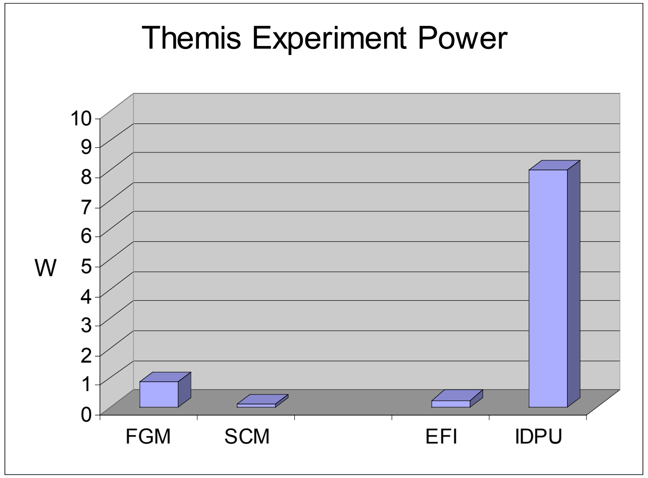
- Mass





- Power





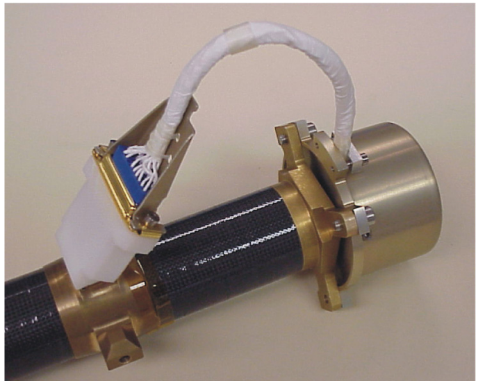
- Telemetry
  - Onboard data processing (spin fit, fft, filtering, compression, event control ...)

Instrumentation on Cluster

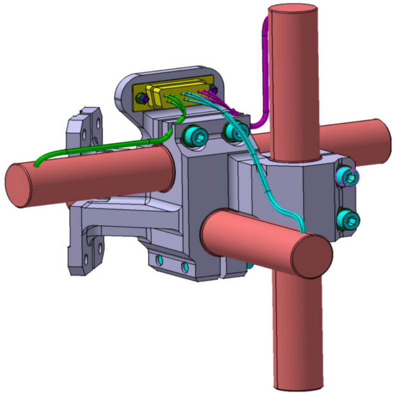
- Fluxgate Magnetometer, FGM
  - PI: Andre Balogh IC London
  - Dual Sensor (3.1m & 5.1m distance) analogue FG
- Search Coil Magnetometer, STAFF
  - PI: Nicole Cornilleau-Wehrlin,
  - Three component boom mounted sensor
- Double Probe, EFW
  - PI: Mats Andre, IRFU Uppsala
  - Two sets of wire booms in spin plane
- Electron Drift Experiment, EDI
  - PI: Götz Paschmann, MPE Garching
  - Two gun/sensor system

Instrumentation on Themis

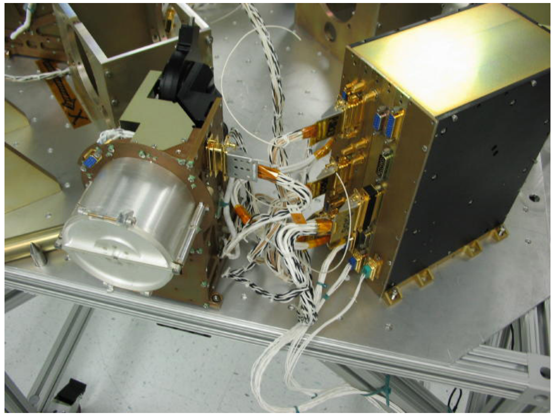
- Fluxgate Magnetometer, FGM
  - PI: K.H. Glassmeier, TU-Braunschweig
  - Single sensor (2m boom), digital electronics



- Search Coil Magnetometer, SCM
  - PI: A.Roux, CEPT
  - The SCM 3-axis antennas are located at the end of 1 meter SCM boom



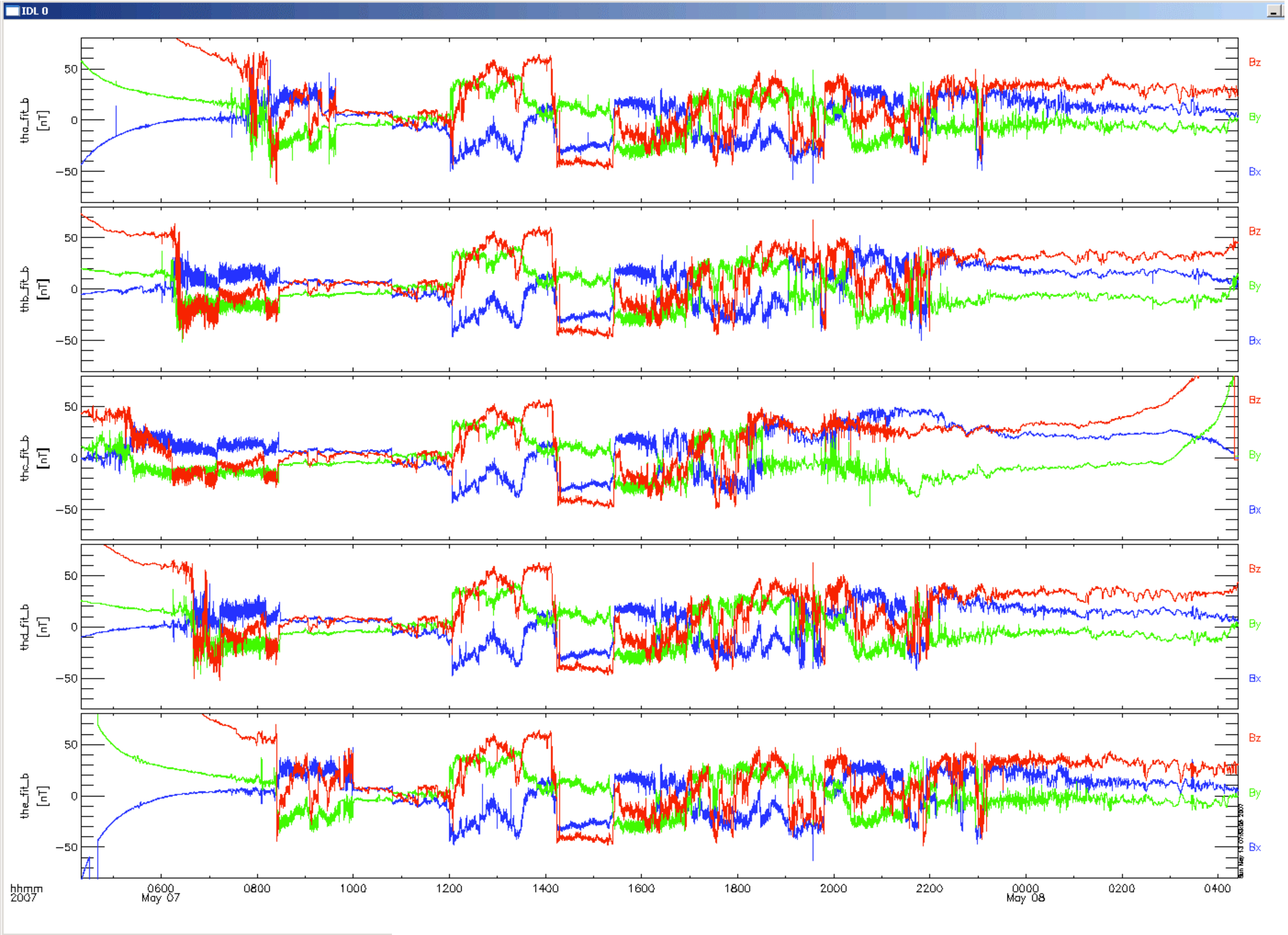
- Double Probe, EFI
  - PI: J.Bonell, UCB
  - Two sets of wire booms in spin plane
  - one set of axial booms



Regional Workshop for Space Physicists

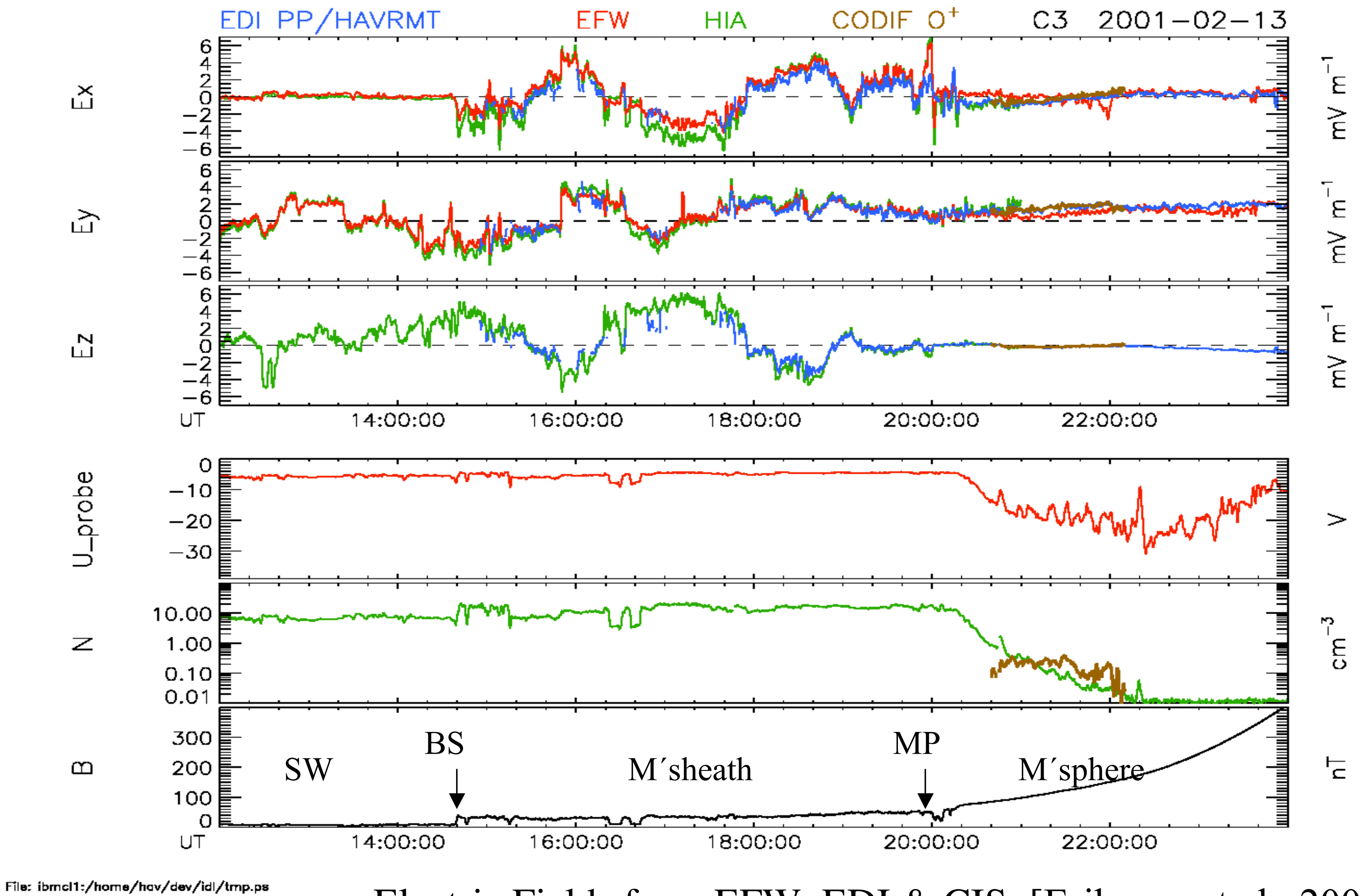
STIINTE

B-Field Example



Magnetic Fields from Themis A-E; [V. Angelopoulos]

E-Field Example



Electric Fields from EFW, EDI & CIS; [Eriksson et al., 2003]

Summary

- Magnetic Field measurement
  - Early satellites already equipped with magnetometers
  - Fluxgate / Search Coil magn. on magnetospheric missions
  - Fluxgate / Proton magnetometer on Earth field missions
- Electric Field Measurement
  - On the first view simple, but in practice much more difficult.
  - Double probes (one - three components) standard instrumentation
  - EDI complements E-field measurement and supports B-field measurement
- Measurement environment
  - 50% instrumentation, 50% environment
  - EMC, tests on ground, service on board, timing on board, event detection, data compression, navigation information, data processing, calibration, ... archiving