Electric Field Measurements

- Types of electric field measurements
- Double Probe Measurements
  - Theory
  - Measurements in the ionosphere
  - Measurements in the magnetosphere
  - The THEMIS electric field experiment
- Further Reading:
  - Bonnell et al., The THEMIS EFI instrument, Space Science Reviews, 2008.
  - Maynard, N. C., 1998 Electric field measurements in moderate to high density space plasmas with passive double probes, in Measurement Techniques in Space Plasmas, AGU Geophys. Monogr. 103, p., 13, 1998.
  - Paschmann, G., et al., The electron drift technique for measuring electric and magnetic fields, in Space Plasmas, AGU Geophys. Monogr. 103, p., 39, 1998.
  - Pedersen et al., Electric field measurements in a tenuous plasma with spherical double probes, in Measurement Techniques in Space Plasmas, AGU Geophys. Monogr. 103, p. 1, 1998.
  - Harvey, P. R., et al., The electric field instrument on the POLAR satellite, Space Sci. Rev., 71, 583, 1995.
  - Gustafsson, G., et al., The electric field and wave experiment for the Cluster mission, Space Sci. Rev., 79, 137, 2008.
  - Whipple, E. C., Potentials of surfaces in space, Rep. Prog. Phys., 44, 1197, 1981.
  - Laakso H., and A. Pedersen, Satellite photoemission characteristics, in Materials in a space environment, edited by H. T. D. Guyenne, pp 361-365, ESA SP-368, ESTEC, Noordwijk, 1994.
  - Grard, R. J. L., Properties of the satellite photoelectron sheath derived from photoemission laboratory measurements, J. Geophys. Res., 78, 2885, 1973.

Electric Fields, Overview

Type of E-field Instr.	**Basic Principle**	**Output quantity / limits**
Double Probe	direct potential measurement	wave form up to 10Hz ***0.5mV/m (10Hz ... DC)*** compressed data up to 100kHz ***50nV/m/Hz***
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)***
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)***

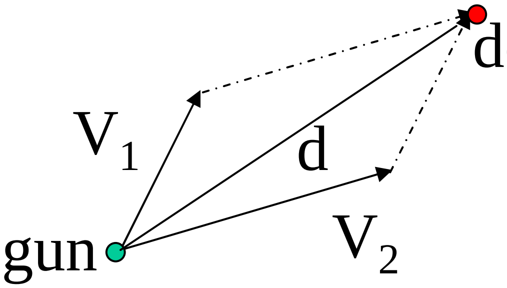
Electron Drift Instrument

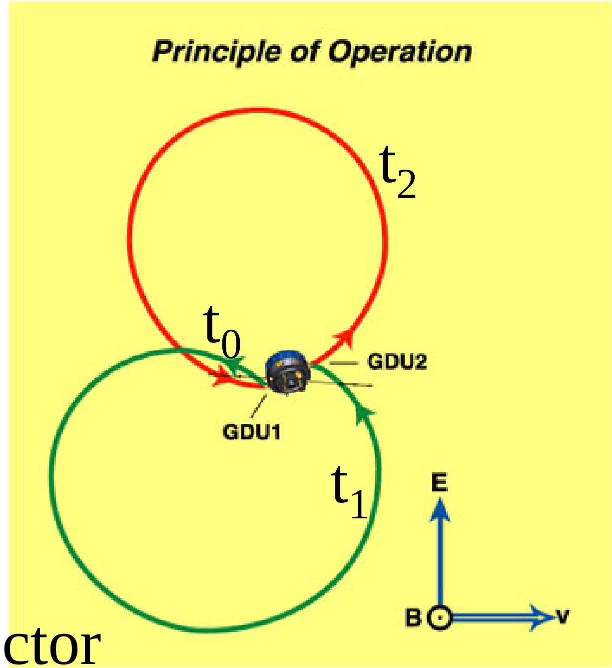
Measurement of displacement

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

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

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





Measurement of time of flight

$t_1 = t_0 + T_g(1 + \mathbf{v}_D/\mathbf{v}_e)$
$t_2 = t_0 + T_g(1 - \mathbf{v}_D/\mathbf{v}_e)$

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

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

$T_g = ((t_1 - t_0) + (t_2 - t_0))/2$

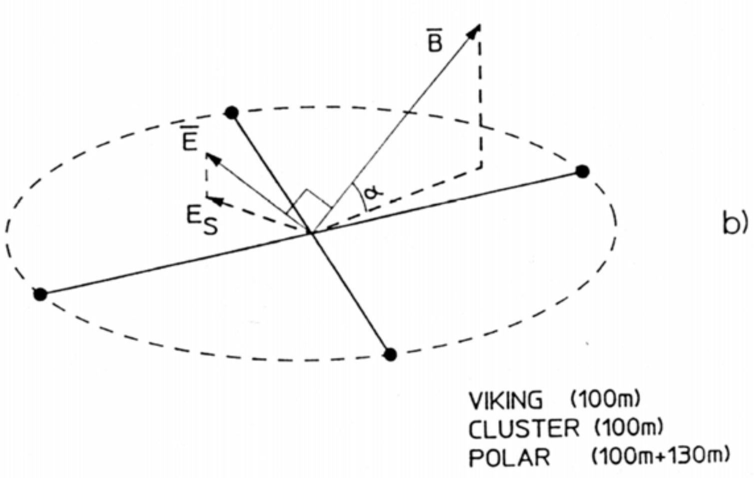
Electron Drift Instrument

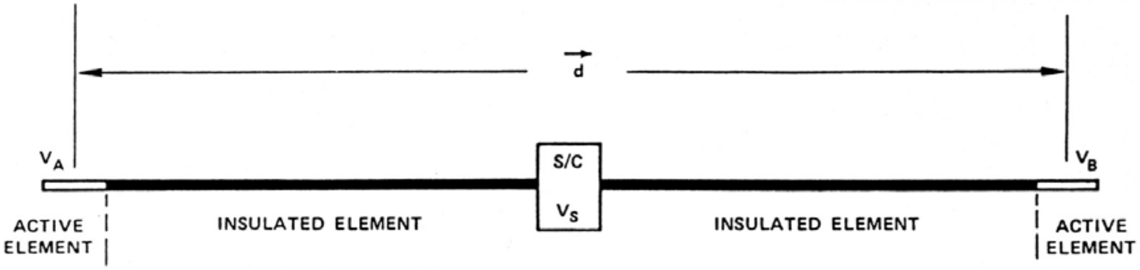
- Principle of Operation
  - E-field normal to **B** derived by measurement of **E**x**B** drift of emitted electrons
  - Two modes: (1) measurement of displacement for high fields, (2) time of flight measurement for moderate fields.
  - In mode (2) magnitude of B can be derived by gyration period
  - 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, proof of principle
    Equator-S, Cluster fully operational

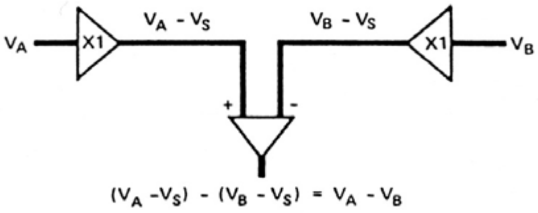
E-field measurement - EDI (2)

Double Probe

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







[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/sqrt(Hz)
  - Noise at 100 kHz: 10^{-9} V/m/sqrt(Hz)

- Application
  - Ground application:
    EM-sounding
  - Space application:
    sounding rockets and
    all magnetosphere missions
    since late 60s

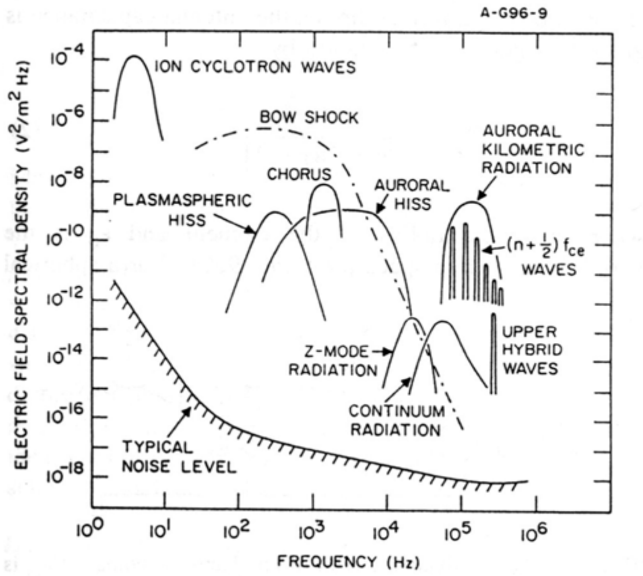


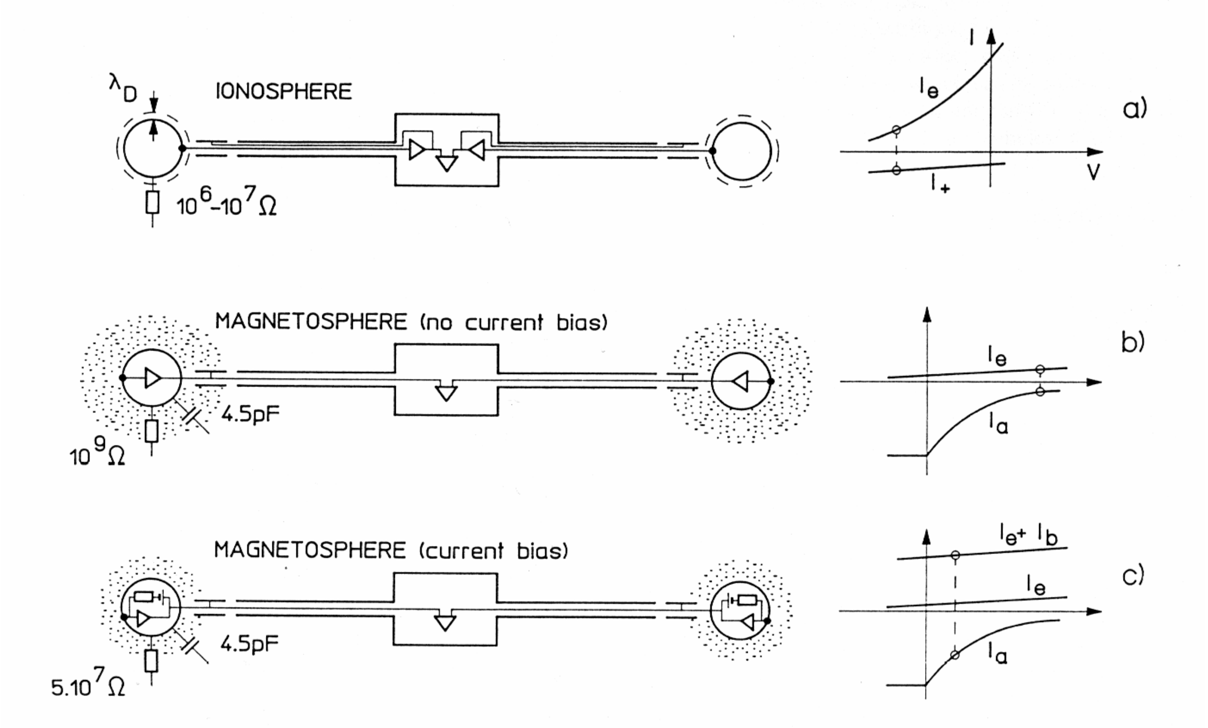
Figure 1. Representative electric field spectrums for various plasma wave phenomena observed in the Earth's magnetosphere.

[D.A.Gurnett, 1998]

Double Probe

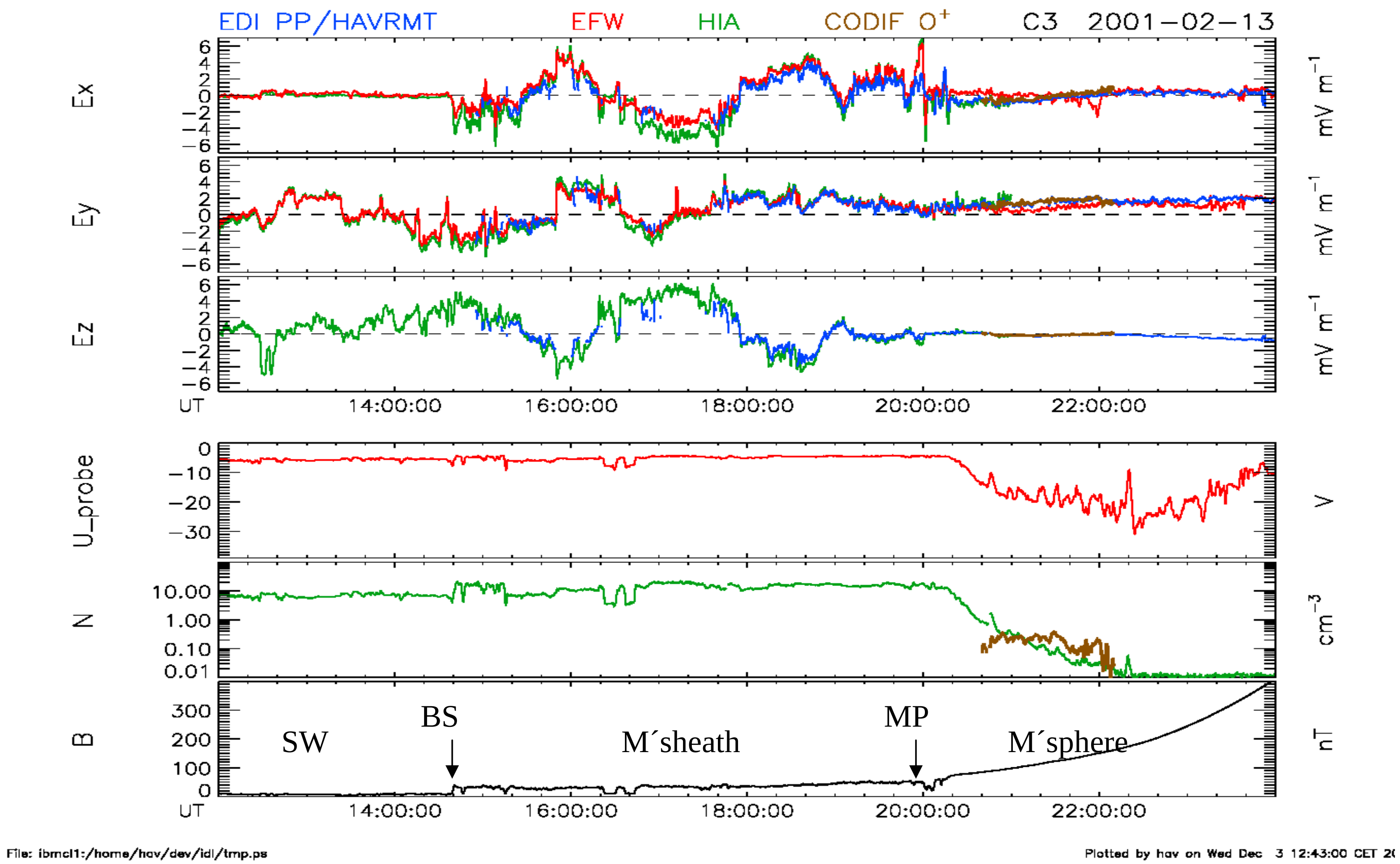
- Problem areas
  - Large probe separation necessary to increase signal, wire booms are used normal to spin axis, boom for spin axis component difficult

$$I_{plasma-e} + I_{ph-e-ret} + I_{ph-e-sc} + I_{measur} = I_i + I_{ph-e}$$



[Pedersen et al., 1998]

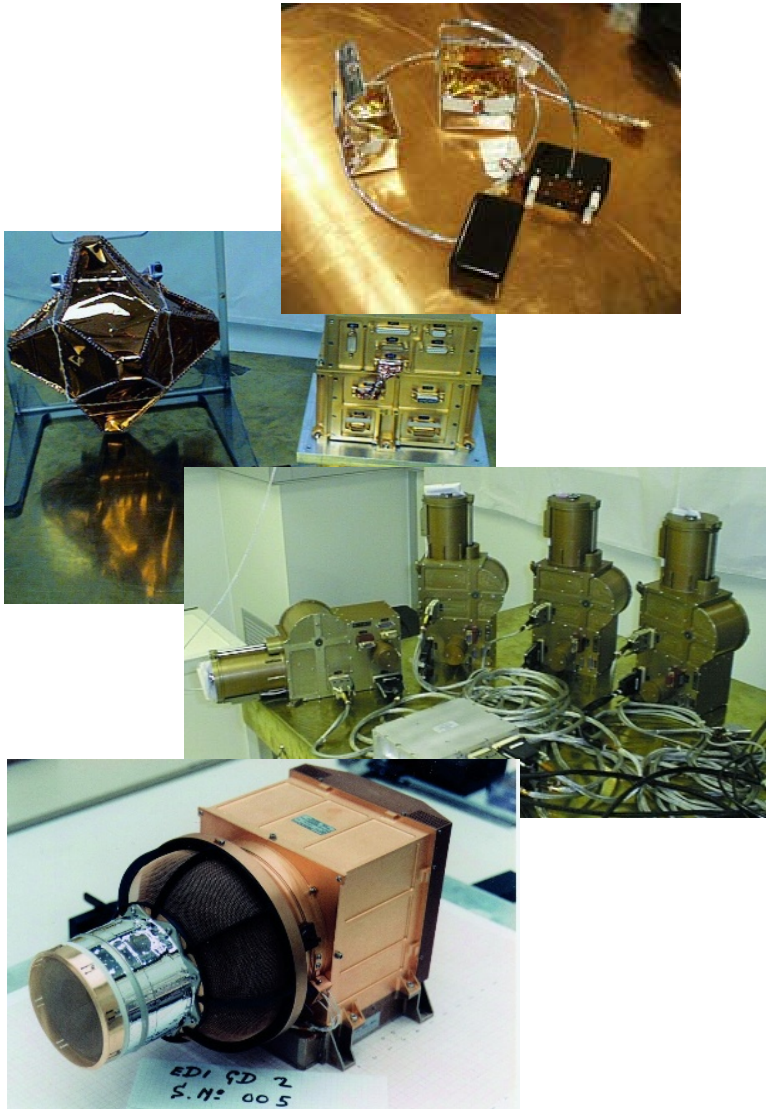
E-Field Examples



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

E&M Instrumentation on Cluster

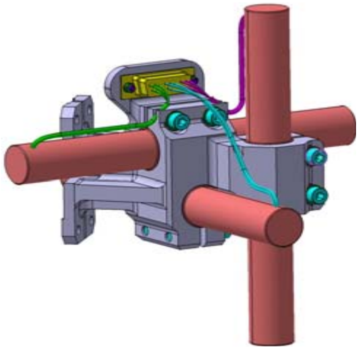
- Fluxgate Magnetometer, FGM
  - PI: Andre Balogh IC London
  - Dual Sensor (3.1m & 5.1m distance) analogue FG
- Search Coil Magnetometer, STAFF
  - PI: Nicole Cornilleau-Wehrlin,
  - Three component boom mounted sensor
- Double Probe, EFW
  - PI: Mats Andre, IRFU Uppsala
  - Two sets of wire booms in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



E&M Instrumentation on Themis

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

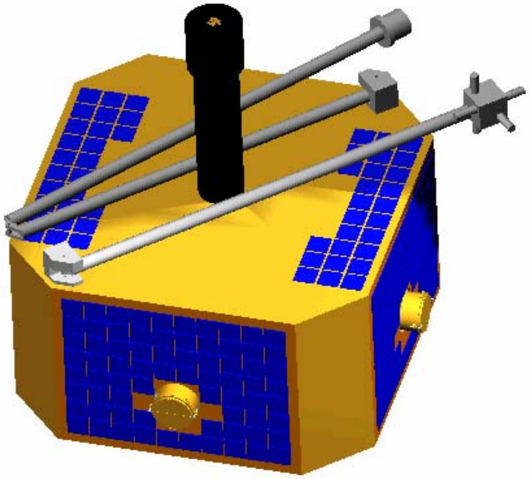
- Search Coil Magnetometer, SCM
  - A.Roux, CEPT
  - The SCM 3-axis antennas are located at the end of 1 meter SCM boom



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

E&M Sensor Accommodation

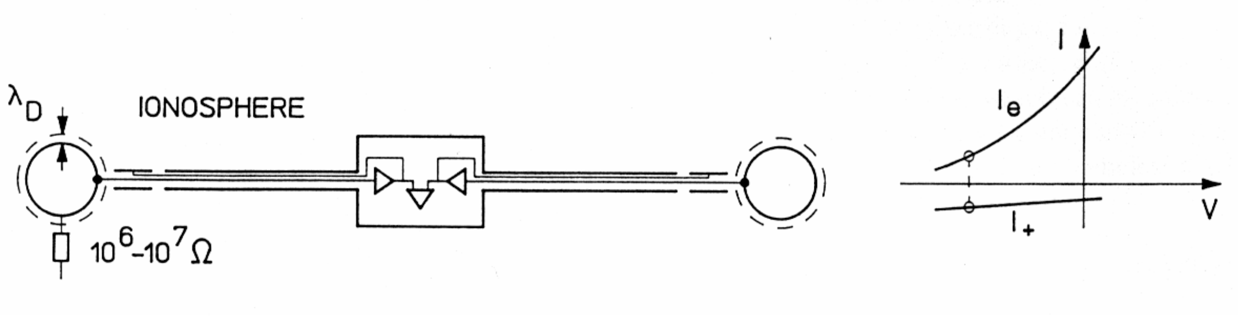
- Boom Geometry
  - 1-3 segment boom (Cluster Double Star, Themis ...)
  - Boom made by spring elements (MMO)
  - Wire Booms (Cluster, Themis ...)
- Release & launch lock mechanism
  - Doors:
    - Pyro (Cluster)
    - Shaped Memory Alloy (Themis)
  - Wires: motor driven
  - Axials: Stacers
- Deployment force
  - Centrifugal force
  - Motor driven



Double Probe Theory

- Debye shielding, $\lambda_D=(kT_e/Ne^2)^{1/2}$
  - Homework#1: Derive potential at 1-D grid is $\phi=\phi_o \exp(-|x|/\lambda_D)$
- Ambient electron current collected by probe
  - $I_e=I_{e0}\exp(V/V_e)$, $V<0$ where: $V_e=kT_e/e$
  - $I_e= I_{e0}(1+V/V_e)$, $V>0$ where: $I_{e0}=-A\ e\ n_e\ \mathrm{sqrt}(kT_e/2\pi m_e)$
  - Homework #2: Prove this
- Ambient ion current collected by probe
  - $I_i= I_{i0}(1-V/V_e)$, $V<0$
  - $I_i=I_{i0}\exp(-V/V_e)$, $V>0$ where: $I_{i0}= I_{e0} / \mathrm{sqrt}(m_i/m_e)$
  - Homework #3: assuming $I_i+I_e=0$, show that
    - Floating potential = $kT_e\ \mathrm{sqrt}(m_i/m_e)$
    - Ion saturation current, when $V<<0$, is: $I_{sat}=I_{i0}= A\ e\ n_e\ \mathrm{sqrt}(kT_e/2\pi m_i)$
- Once I_{sat} is found, slope gives kT_e, and A gives n_e
  - This is operational principle of Langmuir probes

Ionospheric measurements



- λ_D~ 1cm; $R=(\delta I/\delta V)^{-1}$~$10^7\Omega$; C ~ 10pF (sphere + stray)
- Probe charges negative due to $V_e>V_i$
- Voltage set by:
  - Balance of ambient electron (I_e) and ion (I_+) currents
  - Note: other currents are smaller: $I_{plasma-e} \cancel{+I_{ph-e-ret}} \cancel{+I_{ph-e-sc}} \cancel{+I_{measur}} = I_i \cancel{+I_{ph-e}}$
- High impedance (>10MΩ) measurement easy
- Large fields => Short booms => Preamp on board
- Cylindrical are as just good as spherical sensors

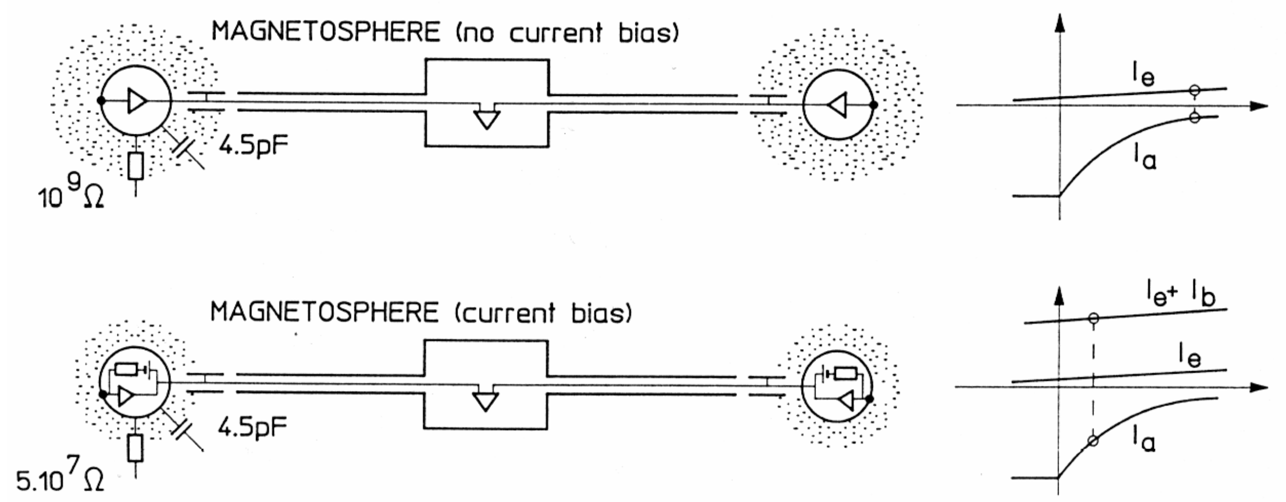
Ionospheric measurements: problems

1st order problem	**Mitigation**
• Velocity wake	Avoid: 3axis stabilized spacecraft

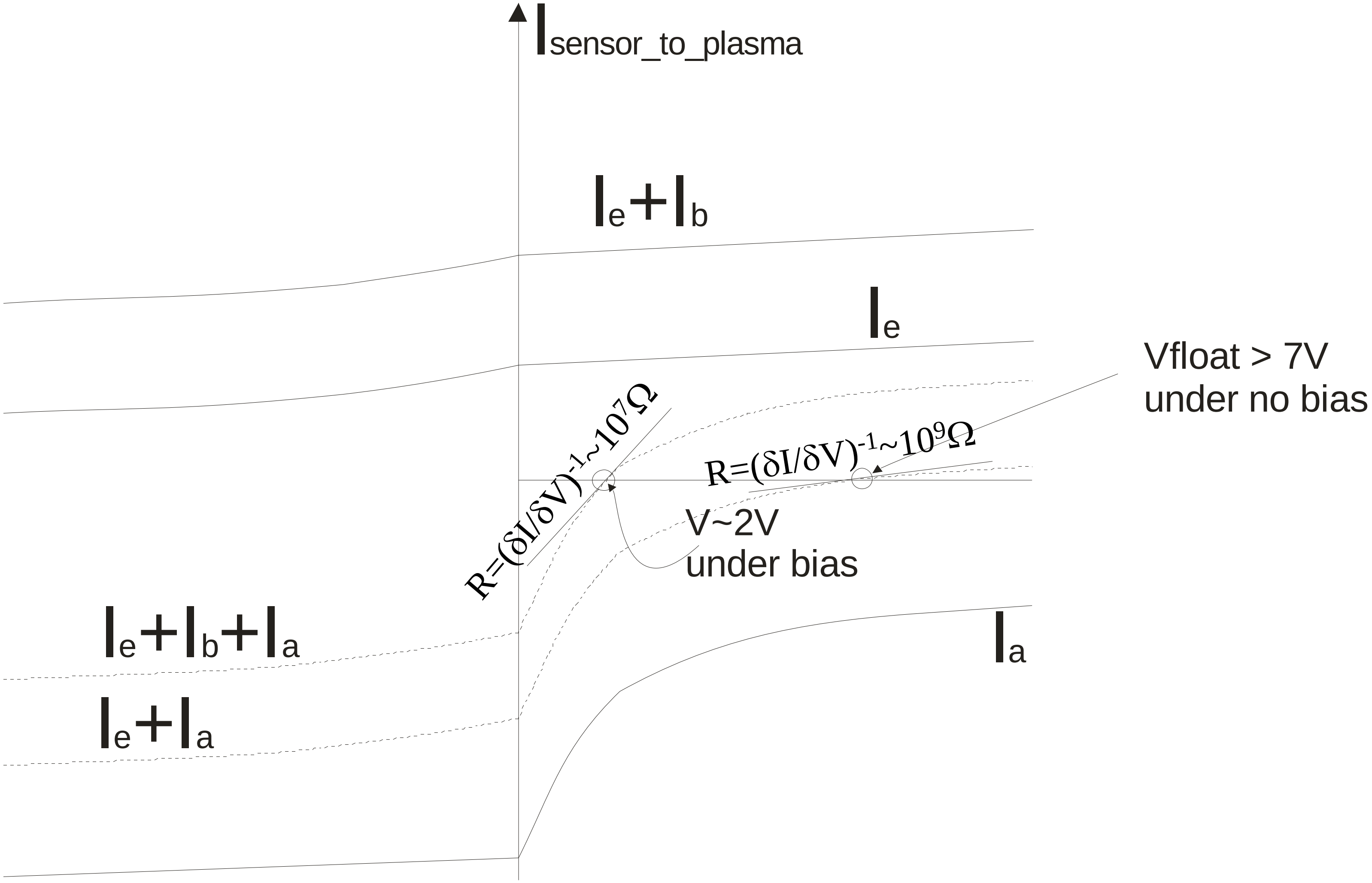
2nd order problems	**Mitigation**
• Photoemission	Use spherical sensors
• Body photoelectrons	Repel with guards

Others (see Maynard, N. Table 1).

Magnetospheric measurements



- λ_D~ 500m; R=$(\delta I/\delta V)^{-1}$ ~$10^9\Omega$; C ~ 4.5pF (sphere)
- Probe positive due to photoemission (I_a). I_e is from plasma.
  - Other currents are (or made) negligible: $I_{plasma-e} + \cancel{I_{ph-e-ret}} + \cancel{I_{ph-e-sc}} + \cancel{I_{measur}} = \cancel{I_i} + I_{ph-e}$
  - In practice 1st order error (and correction) comes from $I_{ph\text{-}e\text{-}sc}$ and $I_{ph\text{-}e\text{-}ret}$
- Resistive coupling to plasma through photoemission
  - Bias current
    - reduces dynamic resistance
    - reduces potential w/r/t plasma
    - makes measurement feasible unless bias



$I_{sensor\_to\_plasma}$
I_e+I_b
I_e
Vfloat > 7V under no bias
$R=(\delta I/\delta V)^{-1}\sim 10^7\Omega$
$R=(\delta I/\delta V)^{-1}\sim 10^9\Omega$
V~2V under bias
$I_e+I_b+I_a$
I_e+I_a
I_a

Magnetospheric measurements

- Photoelectron current: analytical
  - $I_a = I_{ao}, V<0,\ I_{a0} = (S/4)\ j_{a0}$; where:
    - S=sphere surface area
    - j_{a0} depends on materials and ambient plasma
  - $I_a = I_{ao}(1+V/V_{ph})\exp(-V/V_e),\ V_{ph} = kT_{ph}/e,\ V>0$
  - Further reading: Grard, 1973
- Photoelectron current: empirical (x4)
  - $j_a = 80(\mu Am^{-2})\exp(-V/2) + 3(\mu Am^{-2})\exp(-V/7.5)$; V in Volts
  - Further reading: Laakso and Pedersen, 1994
- Objective:
  - Bias current such that potential only 1-2Volts above plasma
- Coupling:
  - Resistive below $1/R_sC_s \sim 100$Hz; capacitive above it

Magnetospheric measurements: problems

1st order problems	**Mitigation**
Sensor asymmetric photoemission	Constrain s/c pot with guards
Body photoelectrons	Repel with guards
Ion wake	Longer booms
Axial: no DC	Make symmetric spacecraft Electrostatically clean Obtain E_{axial} from $\mathbf{E}*\mathbf{B}=0$

2nd order problems	**Mitigation**
Shielding of external field by sc	Use negative guards, or …live with it
Magnetic wake	Live with it