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.
## Electric Fields, Overview

<table>
<thead>
<tr>
<th>Type of E-field Instr.</th>
<th>Basic Principle</th>
<th>Output quantity / limits</th>
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</table>
| **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** | ExB 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) |
Measurement of displacement

\[ v_D = \frac{E \times B}{B^2} \]

\[ d = v_D T_g = \frac{E \times B}{B^2} T_g \]

\[ d[m] = 3.57 \times 10^4 \frac{E_1[\text{mV/m}]}{B^2[\text{nT}]} \]

Measurement of time of flight

\[ t_1 = t_0 + T_g(1 + \frac{V_D}{V_e}) \]

\[ t_2 = t_0 + T_g(1 - \frac{V_D}{V_e}) \]

\[ v_D = \frac{\Delta t}{2T_g} v_e \]

\[ |B| = \frac{2\pi m}{eT_g} \]

\[ T_g = (\frac{t_1 - t_0}{t_2 - t_0})/2 \]
**Electron Drift Instrument**

- **Principle of Operation**
  - E-field normal to $\mathbf{B}$ derived by measurement of $\mathbf{E} \times \mathbf{B}$ 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 $\mathbf{B}$ can be derived by gyration period
  - Gradient $\mathbf{B}$ drift can be separated by different energies of test electrons
- **Parameter**
  - Mode and Applicability depends on $\mathbf{B}$-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
\[
\frac{\Phi_1 - \Phi_2}{|d|} = (E + v \times B) \cdot d
\]

[Pedersen et al., 1998]
[N.C. Maynard, 1998]
Double probe

- Principle of Operation
  - Direct measurement
  - Only method which can be used to measure $E_\parallel$

- Parameter
  - Noise at 1Hz: $10^{-5}$ V/m/\(\text{sqrt}(\text{Hz})\)
  - Noise at 100 kHz: $10^{-9}$ V/m/\(\text{sqrt}(\text{Hz})\)

- 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

\[ I_{\text{plasma} - e} + I_{\text{ph} - e - ret} + I_{\text{ph} - e - sc} + I_{\text{meas}} = I_i + I_{\text{ph} - e} \]
E-Field Examples

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

Examples - E-field

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**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

Examples - Themis

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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 $\phi = \phi_0 \exp(-|x|/\lambda_D)$

- 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: $I_{e0} = -A_e n_e \sqrt{kT_e/2\pi m_e}$
  - 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: $I_{i0} = I_{e0} / \sqrt{m_i/m_e}$
  - Homework #3: assuming $I_i + I_e = 0$, show that
    - Floating potential = $kT_e \sqrt{m_i/m_e}$
    - Ion saturation current, when $V << 0$, is: $I_{sat} = I_{i0} = A_e n_e \sqrt{kT_e/2\pi m_i}$

- Once $I_{sat}$ is found, slope gives $kT_e$, and $A$ gives $n_e$
  - This is operational principle of Langmuir probes
Ionospheric measurements

- $\lambda_D \sim 1\text{cm}; R=(\delta I/\delta V)^{-1} \sim 10^7\Omega; C \sim 10\text{pF (sphere + stray)}$
- 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: $I_{\text{plasma-e}} + I_{\text{pk-e-ret}} + I_{\text{pk-e-sc}} + I_{\text{measur}} = I_i + I_{\text{pk-e}}$
- High impedance (>10M$\Omega$) measurement easy
- Large fields $\Rightarrow$ Short booms $\Rightarrow$ Preamp on board
- Cylindrical are as just good as spherical sensors
Ionospheric measurements: problems

1\textsuperscript{st} order problem
- Velocity wake

Mitigation
- Avoid: 3axis stabilized spacecraft

2\textsuperscript{nd} order problems
- Photoemission
- Body photoelectrons

Mitigation
- Use spherical sensors
- Repel with guards

Others (see Maynard, N. Table 1).
Magnetospheric measurements

• $\lambda_D \sim 500\text{m}; R = (\delta I / \delta V)^{-1} \sim 10^9\Omega; C \sim 4.5\text{pF (sphere)}$

• Probe positive due to photoemission ($I_a$). $I_e$ is from plasma.
  ‒ Other currents are (or made) negligible: $I_{\text{plasma-e}} + I_{\text{ph-e-ret}} + I_{\text{ph-e-sc}} \rightarrow \text{measur} = i + I_{\text{ph-e}}$
  ‒ In practice 1st order error (and correction) comes from $I_{\text{ph-e-sc}}$ and $I_{\text{ph-e-ret}}$

• Resistive coupling to plasma through photoemission
  ‒ Bias current
    • reduces dynamic resistance
    • reduces potential w/r/t plasma
    • makes measurement feasible unless bias
I_e + I_b

V \sim 2V 
under bias

R = (\frac{\delta I}{\delta V})^{-1} \sim 10^9 \Omega

V \text{float} > 7V
under no bias

I_e + I_a

I_a

I_{sensor\_to\_plasma}
Magnetospheric measurements

• Photoelectron current: analytical
  – \( I_a = I_{ao} V < 0, \quad I_{ao} = (S/4) j_{ao} \), where:
    • \( S \) = sphere surface area
    • \( j_{ao} \) depends on materials and ambient plasma
  – \( I_a = I_{ao} (1 + V/V_{ph}) \exp(-V/V_e), \quad V_{ph} = kT_{ph}/e, \quad V > 0 \)
  – Further reading: Grard, 1973

• Photoelectron current: empirical (x4)
  – \( j_a = 80(\mu\text{Am}^{-2}) \exp(-V/2) + 3(\mu\text{Am}^{-2}) \exp(-V/7.5); \quad V \text{ in Volts} \)
  – Further reading: Laakso and Pedersen, 1994

• Objective:
  – Bias current such that potential only 1-2Volts above plasma

• Coupling:
  – Resistive below \( 1/R_s C_s \sim 100\text{Hz} \); capacitive above it
# Magnetospheric measurements: problems

## 1st order problems
- Sensor asymmetric photoemission
- Body photoelectrons
- Ion wake
- Axial: no DC

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<tr>
<td>Constraining s/c pot with guards</td>
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<td>Repelling with guards</td>
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<td>Longer booms</td>
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<tr>
<td>Making symmetric spacecraft</td>
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<tr>
<td>Electrostatically clean</td>
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<tr>
<td>Obtaining $E_{\text{axial}}$ from $\mathbf{E}^*\mathbf{B}=0$</td>
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## 2nd order problems
- Shielding of external field by spacecraft
- Magnetic wake

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<tr>
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<tr>
<td>Using negative guards, or</td>
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<tr>
<td>…live with it</td>
</tr>
<tr>
<td>Live with it</td>
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