Electric Fields from Ion Distribution Images on Swarm

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1) Swarm  2) Thermal Ion Imaging  3) Sounding Rocket Examples
The Swarm Mission

- Precision $\mathbf{B}$ (vector and scalar)
- $\mathbf{E}$ from $-\mathbf{v}_i \times \mathbf{B}$ (2 & 16 Hz)
- $T_i, T_e, n_e$
- 3-axis stabilized
- $\sim 85$-$88^\circ$ inclination
- 2 satellites at $\sim 450$ km, laterally separated by 10’s km
- 1 satellite at $\sim 530$ km, displaced several hours in local time
- Nominal mission 2010-2014
**Why use** $E = -v \times B$?

- E-field booms difficult on a non-spinning platform
- Booms induce drag and affect stability in LEO
- Extensive orbital flight heritage (Heelis, Hanson et al.)
Magnetic Field Contributions as Seen on Orbit

$R_E = \text{Earth radius} \sim 6371\text{km}$

1) Swarm  2) Thermal Ion Imaging  3) Sounding Rocket Examples
“External” Magnetic Field Sources

500 km

\[ \mathbf{E}_\perp \approx 10^{1-2} \text{ mV/m} \]

\[ \delta \mathbf{B}_\perp \approx 10^{1-2} \text{ nT} \]

\[ \mathbf{j}_\parallel = \mathbf{\Delta} \cdot \mathbf{E}_\perp \]

Ionosphere

Thermosphere
"External" Magnetic Field Sources

\[ S_z = (\vec{E} \times \delta \vec{H}) \cdot \hat{z} = \int_z \sigma_P E^2 \]

- \( E_\perp \approx 10^{1-2} \text{ mV/m} \)
- \( B_\perp,\text{ext} \approx 10^{1-2} \text{ nT} \)

\[ \vec{j}_\parallel = \vec{\sigma} \cdot \vec{E}_\perp \]

- Ionosphere
- Thermosphere
# Measurement Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resolution</th>
<th>Accuracy (2(\sigma))</th>
<th>Rate (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_i)</td>
<td>6 m/s</td>
<td>50 m/s</td>
<td>2, 16</td>
</tr>
<tr>
<td>(E)</td>
<td>0.3 mV/m</td>
<td>3 mV/m</td>
<td>2, 16</td>
</tr>
<tr>
<td>(T_i, T_e)</td>
<td>10 K</td>
<td>50 K @ 0.1 eV</td>
<td>2, 16</td>
</tr>
<tr>
<td>(n_e)</td>
<td>10(^1) cm(^{-3})</td>
<td>1%</td>
<td>16</td>
</tr>
<tr>
<td>(B)</td>
<td>&lt; 1 nT</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>(S = ExH)</td>
<td>0.1 (\mu)W/m(^2)</td>
<td>3 (\mu)W/m(^2)</td>
<td>2, 16</td>
</tr>
</tbody>
</table>
Swarm Instruments

- Magnetic field magnitude (ASM) and vector components (VFM)
- Electric field vector components
  - Plasma density (in combination with GPS)
  - Ion drift velocity vector (EFI)
  - Ion and electron temperature (EFI)
- Air drag (ACC, GPS)
- Position, velocity, time, attitude (GPS, STR)

Courtesy: EADS, astrium
The Swarm CEFI

1) Swarm  2) Thermal Ion Imaging  3) Sounding Rocket Examples
Electrostatic Analyzer

Distribution Imager
[Whalen et al., 1994]

\[ E_{\text{max}}/q \sim \Delta V/3 \]

Compare: “Top-hat”
Carlson et al. [1983]

\[ E/q \sim 5\Delta V \]

- Sensitive to lower energies
- 2-D, energy/angle imaging
Ion Distribution Function Imaging

- velocity 2-D
- $E = -v_x B$
- temperature
- anisotropies

$v_z$ (km/s)

Ion distribution function $f(v)$

(simulation)
Development of the Thermal Particle Imager

- FREJA
- GEODESIC
- Cusp
- JOULE
- J-II
- ePOP
- Swarm

Ion Flows within an Alfvén Wave (GEODESIC Rocket)

1) Swarm  2)  Thermal Ion Imaging  3) Sounding Rocket Examples

IPELS    7 August 2007
Ion drift/ExB comparison (Sub-orbital platform)

Burchill [2003]

1) Swarm  2) Thermal Ion Imaging  3) Sounding Rocket Examples
Ion Temperature

JOULE Sounding rocket

Ion temperature enhancement within an auroral arc...

~0.1 eV increase inside arc

J. Clemmons

L. Sangalli
Conclusions

• 2-D thermal distributions up to 125 s$^{-1}$

Ion Heating Examples (Sub-orbital platform)

Sub-orbital examples

GEODESIC sounding rocket

Burchill et al. [2004]

TAI to 10 eV

JOULE Sounding rocket [L. Sangalli]

Heating ~0.1 eV

1) Swarm
2) Thermal Ion Imaging
3) Sounding Rocket Examples
IDM SENSOR CROSS-SECTION

GRID PLANES

X AXIS
(DIRECTION OF MOTION)

COLLECTOR PLATES

ELECTRONICS BDS.

INTERFACE CABLE

COMPONENT ENVELOPE

GRID DESIGNATORS

G1- INPUT
G2- RETARDING
G3- APERTURE
G4- SHIELD
G5- SHIELD
G6- SUPPRESSOR

(ALL 20 LINES/EM)

IDM DRIFT VELOCITY MEASUREMENTS

VECTOR REPRESENTATION

ENTRANCE PLANE

COLLECTOR SEGMENTS

A
B
C
D

FIGURE 2
**M-I Coupling: Thermospheric Driver**

- **ExH**
- **Knudsen [1990]**

1) Mission
2) CEFI Instrument
3) Science Themes
Sample CEFI image for 20% H⁺, 80% O⁺, $V_x = 7600$ m/s, $V_y = 3800$ m/s, $T_i = 0.1$ eV, $\Phi_{s/c} = -1$ V.

Telemetry:

16, 2-D moment estimates per second
2, 1-D profiles per second
1 full image each 128 s
Science Theme: Ion Heating and Outflow

Sub-orbital examples

GEODESIC sounding rocket [Burchill, 2004]

JOULE Sounding rocket [L. Sangalli]

TAI to 10 eV

Heating ~0.1 eV
Plasma instabilities at all latitudes (IV)

- Can relate $\delta n/n$, $v_i$ and $E$ to 1% at 16 s$^{-1}$ (500 m)
- $T_i$ at 2 s$^{-1}$
Ion heating and outflow (V)

- 3-D global ion circulation with 6 m/s resolution, 2 or 16 Hz
- Sources of ion heating - 5 meV (50 K) accuracy

Can telemeter one full distribution each ~5 minutes.

*Burchill et al. [2004]*
Sampling at Satellite Altitude (400km)
Swarm Mission Science Objectives

Primary

• Core Dynamics and Geodynamo Processes
• Lithospheric Magnetisation
• 3-D Electrical Conductivity of the Mantle
• Magnetospheric and Ionospheric Current Systems

Secondary

• Ocean Circulation and its Magnetic Signature
• Magnetic Forcing of the Upper Atmosphere