Space Flight

Plasma Data Analysis

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Outline of Presentation

- FPMU Description and its implementation on ISS
- FPP analysis
- PIP analysis
- LP analysis
- ISS charging features
- Equatorial Ionospheric Features
- Extra: LP analysis of Laboratory Plasma Source
Floating Potential Measurement Unit (FPMU)

Role:
- Obtain floating potential and ionosphere plasma measurements for validation of the ISS charging model
- Assess Photo-Voltaic array variability
- Interpreting IRI predictions

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measured Parameter</th>
<th>Rate (Hz)</th>
<th>Effective Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPP</td>
<td>$V_F$</td>
<td>128</td>
<td>-180 V to +180 V</td>
</tr>
<tr>
<td>WLP</td>
<td>$N$, $T_e$, $V_F$</td>
<td>1</td>
<td>$10^9 \text{ m}^{-3}$ to $5 \times 10^{12} \text{ m}^{-3}$</td>
</tr>
<tr>
<td>NLP</td>
<td>$N$, $T_e$, $V_F$</td>
<td>1</td>
<td>$10^9 \text{ m}^{-3}$ to $5 \times 10^{12} \text{ m}^{-3}$</td>
</tr>
<tr>
<td>PIP</td>
<td>$N_e$</td>
<td>512</td>
<td>$1.1 \times 10^{10} \text{ m}^{-3}$ to $4 \times 10^{12} \text{ m}^{-3}$</td>
</tr>
</tbody>
</table>

Redundant measurements of each parameter!
FPMU Data Path (Simplified)

FPMU data passes through many “boxes” before capture by the ground station!

Perfect transmission: 100% checksum=0

Reality: telemetry noise

Some improvement in 2008:
FPP is effectively a high-impedance volt meter acquiring data at 128Hz.

Example of very noisy data:

What is the true signal?
FPP analysis method

Logic
- Band-pass filter: $-25 \leq fpv \leq 150$
- Apply median filters
- Iterative process to exclude values $> 2\sigma$

Acceptance Criteria
- $|fp_{sdev}/fpv| \leq 0.2$
- no. of surviving points $\geq 51$

Recovery rates
- > 98% (in general)
- > 90% (for the noisiest data)
FPP example with analysis result:
PIP measures the self impedance of a short, cylindrical antenna.

Antenna impedance $Z$ as function of applied voltage frequency: The real part is the resistance while the imaginary part is the reactance (or phase). Zero phase occurs at the electron cyclotron frequency ($f_c$) and the upper hybrid frequency ($f_{uh}$).

PIP frequency sweep: 0.1 to 20 MHz in 256 steps
**Upper hybrid resonance:**

\[ f_{uh}^2 = f_p^2 + f_c^2 \]

\[ N_e(m^{-3}) = 1.24 \times 10^{-2} [f_{uh}^2 - f_c^2] \]
Comparison of PIP and WLP derived density
The PIP-derived density is generally lower than the WLP-derived density from the ion ram current.

A modification to the PIP analysis has been introduced:

✓ During passage through the equatorial region at ~ 2007/355/02:45, a deep ionospheric hole was encountered. The density is $< 1 \times 10^9 \, \text{m}^{-3}$. The Magnitude -vs- frequency response in the middle of the hole has been extracted. The response has been curve-fit to the IDL GAUSSFIT function with nterms = 4.
PIP Analysis

2007/355/02:45

Sum of square of differences

![Graph showing MAG (ohms) vs. Freq (MHz)]
PIP fit w/residuals

2007/355/01:47:20

[Graphs showing PFP, PHS, MAG, and MAG_RES with annotations such as 'Baseline' and 'Red line is 5-pt smooth']
If a peak could not be determined from the residual curve, then the peak from the Magnitude-vs-frequency curve is used with a constant of 0.3 added. This 0.3 factor may change as more days are examined…. Not implemented yet!
LP analysis: Probe design

**WLP voltage sweep:**
1-sec for -20 to +80 V
1-sec +80 V to -20 V

**Voltage step size:**
250 mV from –20 V to 0
25 mV from 0 to 50 V
250 mV from 50 V to 80 V

**Implication for Te measurement:**

<table>
<thead>
<tr>
<th>(\Delta V_{\text{step}}) (V)</th>
<th>(T_e) (K)</th>
<th>No. of points/decade current change</th>
<th>No. of points/1 e-fold current change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>800</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>0.025</td>
<td>500</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

**NLP voltage sweep:**
1-sec for -4.85 to +4.85 V
1-sec +4.85 V to -4.85 V

**Voltage step size:**
constant 12 mV

**Implication for Te measurement:**

<table>
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<th>(\Delta V_{\text{step}}) (V)</th>
<th>(T_e) (K)</th>
<th>No. of points/decade current change</th>
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</tr>
<tr>
<td>0.012</td>
<td>500</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

**Probe radius/Debye length (≡ Debye ratio) ~ 2 – 22**

**Probe radius/electron gyroradius ~ 2.**

Not OML!
LP analysis

Typical Langmuir Probe I-V Curve

\[ I_e = I_{eo} \cdot \exp\left[e(V-V_{sp})/kT_e\right] \]

\[ T_e \sim 1/\text{slope} \]

Electron Saturation

OML-like expression:
\[ I_e = I_{eo} \left[ 1 + \frac{(V-V_{ref})}{kT_e} \right]^{\gamma} \]

Electron Retardation

Ion Saturation

\[ I_i = qN_i V_{ISS} A \left[ 1 + \alpha(V-V_{sp}) \right] \]

\[ N_i \sim I_i/A_{\text{cross-section}} \]

Typical Langmuir Probe I-V Curve

\[ I_{probe} = I_{ion} + I_{elec} = 0 \text{ @ } V_{fl} \]
LP analysis

- The “graphical method” has been employed – each section fit separately
- Much filtering and logic used to overcome noise in telemetry
- Fitting sequence:
  - Locate floating potential $V_{flt}$ [from $I_{total} = 0$]
  - If day, adjust for photoelectron current (not used at present)
  - Ion saturation region [fit to linear equation]
  - Determine electron current [$I_e = I_{total} - I_{ion}$]
  - Estimate space potential $V_{sp}$ [voltage at maximum of $dI_e / dV$]
  - Electron retarding region [linear fit for $\log_{10}(I_e)$] - Acceptance criteria: $(\Delta \text{slope/slope}) \leq 10.0$
  - Electron saturation region [fit to OML-like equation over a few volts $\geq$ initial guess for $V_{sp}$]
  - Determine $V_{sp}$ via intersection of curves from electron retarding and saturation regions
  - If $V_{sp}$ different from its initial guess by $> 0.5$ V, then iterate once on the electron retarding and saturation regions
  - Derive ionospheric properties using standard equations
**LP analysis: “good” data**

\[ \text{Ne} = 1.33 \times 10^{11} \text{ m}^{-3} \]

for \( A = \pi rL \)

\[ \text{Ne} = 0.82 \times 10^{11} \text{ m}^{-3} \]

for \( A = 2\pi r^2 \)
LP analysis: noisy data

Ground processing generates NLP sweep at +/- 5 V centered on FPP value. If FPP data word is corrupted, then sweep values are corrupted. However, Ni and Te values are OK because measured currents are passed in telemetry and Te depends only on slope (dl/dV where dV is known).
LP analysis: noisy data

NLP I-V Data

First Derivative of Current

Select Data + Ion Fit

Electron Current

\[ V_{fit} + 1 \]
LP analysis: relationship between Vsp and Vflt

Theory says that $V_{sp} - V_{flt} \sim \text{few} \cdot kT_e$
LP analysis: what to use for collecting area to derive Ne?

Answer is not straightforward.
LP analysis: Disagreement between NLP-Te and WLP-Te
LP analysis: Disagreement between NLP-Te and WLP-Te

![Diagrams showing data distributions for day and night with peak, fwhm, and npts values for each day and night sample.]

- **2008297 Day**
  - Peak = -9
  - FWHM = 30
  - NPTS = 26344

- **2008297 Night**
  - Peak = -5
  - FWHM = 47
  - NPTS = 17608

- **2008309 Day**
  - Peak = 7
  - FWHM = 28
  - NPTS = 17841

- **2008309 Night**
  - Peak = 12
  - FWHM = 63
  - NPTS = 15475
LP analysis: Time history of differences of WLP-Te with NLP-Te

Caution: Plot still under construction. All points do NOT have the same NLP analysis applied!

WLP Heating Lamp on for 64 hours!
General ISS Charging Features

1: magnetic induction, 2: eclipse exit, 3: plasma induced

- WLP
- NLP
- FPP

- Den (1x10^11 m^-3)
- Te (1000 K)
- GMT Hour

- Lat
- Lon/3 (deg)

- Day
- Alt (km)
ISS Charging at Sunset

FPMU: 2007355

β angle ~ -53°
ISS Charging at Sunset or Eclipse Entrance

\[ \beta \text{ angle } \sim -53^\circ \]
ISS Charging at Eclipse Exit: Normal Charging Event (NCE)

For NCEs in general: at a given density, the lower the Te the greater the charging amplitude.

Voltage behavior governed by # of active strings, PVA ram angle, and plasma conditions (primarily Te).

Rise time from magnetic induction baseline to peak ~ 10 – 30 seconds.
ISS Charging at Eclipse Exit: Rapid Charging Event (RCE)

Rapid because leading and trailing edge occurs much faster: rise times generally ≤ 5 secs and decay time ~ 10 – 30 secs.

RCE amplitude to first order is inversely related to density
Equatorial Ionosphere Observations from March 9, 2008
Ionospheric Physics Studies from ISS

Graph 1: Den (x10^11 m^-3)

Graph 2: Te (1000 K)

Graph 3: Lon & Alt (km)

From older analysis code
Extra:

LP analysis

of

LEO plasma simulation source
(a) Plasma Source CAD model: 1– Discharge chamber outer wall (anode), 2– hollow cathode, 3–inner part of the magnetic filter, 4- neutral density grids, 5– Sm-Co magnets, 6– outer part of the magnetic filter, 7- coaxial plasma expansion region. (b) Photograph of Plasma source during operation

Submitted to Plasma Sources, Science, and Technology
Spherical LP measurement

![Graphs showing various measurements and data points.]

- **080207085933_down_data.txt**
  - Log10 (Abs(I/A)) vs Voltage
  - Non-linear relationship observed

- **Electron Current**
  - Log10 Ie (10^-6 A) vs Voltage
  - Linear trend with voltage

- **Select Data + Ion Fit**
  - I (10^-6 A) vs Voltage
  - Non-linear trend with voltage

- **Values**:
  - \( N_i \times 10^{11} \text{ m}^{-3} \) = 15.7
  - \( T_e \text{ (eV)} \), %err = 0.167 1.6
  - \( V_f, V_{sp} \) = -0.46 0.32
Spherical LP measurement

080207085933_up_data.txt

Electron Current

Select Data + Ion Fit

\[
\begin{align*}
N_i \left(10^{11} \text{ m}^{-3}\right) &= 15.3 \\
T_e (\text{eV}), \% \text{err} &= 0.181 \quad 1.9 \\
V_f, V_{sp} &= -0.59 \quad 0.28
\end{align*}
\]
Concluding remarks:

- The thrust of this presentation was to highlight real world data and its complications.
- Noise is usually present.
- Theoretical probe response guides analysis logic, acceptance criteria, etc.
- Refinements to logic, acceptance criteria, etc. based on previous experience.
- Hopefully hardware operation and choice of downlinked data is robust in order to give options for analysis.
- Be wary of your software logic:
  - continually review it to make sure that all quirks in data are handled reasonably.
  - the computer logic is only as smart as you make it continually “eyeball” data with curve-fits.
- Reach out to colleagues

We at MSFC are very much in debt to C. Swenson, C. Fish, A. Barjatya, and D. Thompson for many discussions concerning the FPMU!