Ongoing Miniaturization Efforts for Ion and Neutral Vector Velocity Instruments

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Outline

• The changing face of space science missions
• Typical state of the art instrument specifications
• Focus on vector velocity instruments
  Neutral wind meter (NWM)
  Ion velocity meter (IVM)
  Functional descriptions
• Current approach & ongoing redesign efforts
• Comparative design estimates
• Conclusions
**Motivation - Future Mission Scenarios**

- Findings from previous single-spacecraft LEO space science missions
- Future missions must use fleets of small satellites to resolve spatial / temporal ambiguities – thus enabling new discoveries
  - Equatorial Spread-F
  - Auroral electrodynamics
- Geospace Electrodynamic Connections (GEC) mission is a good example

*Figure 4.2. The primary GEC orbital formation will be the pearls-on-a-string formation. Later in the mission the spacecraft will be maneuvered into a petal formation to permit sampling of the same latitude region at different altitudes.*
## GEC Mission – Design Estimates

<table>
<thead>
<tr>
<th>Measured Parameters</th>
<th>Mass estimate (kg)</th>
<th>Power estimate (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion temperature, density, and velocity</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Neutral composition, temperature, and velocity, plus ion composition</td>
<td>9</td>
<td>24</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Energetic particle distributions</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>B-field</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>E-field</td>
<td>31</td>
<td>14</td>
</tr>
</tbody>
</table>
Focus on Vector Velocity Instrumentation

- Sensors shown measure neutral and ion gas velocities in 3D from a satellite platform
- 6” ruler shown (bottom center)
- Total mass for both instruments is ~11 kg
- Filaments and solenoid in neutral wind instrument yield power requirements of almost 24 W - much too large for small satellite applications!
- Ion velocity instruments have no filaments, so much less power is consumed (~3.5 W)
Functional Description of the Ion Velocity Meter – Cross Track Component

- Instrument measures cross track (2D) component of the ion drift.
- Collector is divided into 4 equal segments – ratio of currents collected on various segments is proportional to the tangent of the arrival angle.
- Difference amplifiers generate signal related to the current ratio by taking the difference between logarithmic electrometer outputs
  \[ \log (A/B) = \log A - \log B \]
Functional Description of the Ion Velocity Meter – Ram Component

- Ions enter aperture through grounded grid
- Swept potential on retarding grid acts as a time varying energy barrier
- Resultant I-V curve represents ram energy of ions, which is dominated by satellite velocity but contains a smaller term related to the ion energy along the satellite track

\[
\frac{1}{2} m \left( V_{\text{RAM}} \right)^2 \sim \frac{1}{2} m \left( \frac{V}{S/C} \right)^2 + m \left( \frac{V}{S/C} V_{\text{ION}} \right)
\]
Functional Description of the Neutral Wind Meter

Cross-Track Wind Sensor

Measures neutral particle arrival angle by monitoring the pressure ratio in identical adjacent cavities.

Ram Wind Sensor

Measures the ram energy of AO via ionization and retarding potential analysis.
Measurement Environment

- Consider the range of currents to be encountered in LEO.
- Depending on the orbit, plasma densities (N) ranging from ~100 to a few times $10^6 \text{ cm}^{-3}$ are possible.
- Relative velocity (V) is ~ the orbital speed of 7-8 km/s.
- Collecting area (A) is at most a few cm$^2$.
- Net current $I_{\text{Net}} = N_e V A$, which ranges from 10 pA to about 1.0 µA.
Current Design - Circuit Board Details

- Discrete component design wastes space and uses power inefficiently, but has advantages in terms of radiation hardness.
- This board measures about 6 x 12 cm. It interfaces with a separate power conditioning board, a control board, and an output encoder board to comprise the complete instrument.
Electrometer Detail

- Mounting op-amps in a “dead bug” configuration eliminates leakage currents through the circuit board – major source of noise and cross-talk.
- Teflon insulators on leads and isolated stand-offs prevent shorting and leakage currents.
- Discrete op-amps are carefully tested to find closely matched pairs prior to fabrication.
- Ground plane surrounding sensitive portions of the instrument (electrometers) further reduce noise.
- System can measure 10 pA at 100 Hz.
On-chip Integrated Design Ideas for Cross Track IDM

- Digital portion of circuit offers no significant challenges to on-chip design efforts. Analog electrometer design is the critical path component.
$V_{\text{out}} \sim \log(I_{C1}/I_{C2})$ and is independent of device specific parameters.
MOSFET design provides good isolation from substrate at low frequencies (~100 Hz sampling). Design has high power efficiency and can drive large loads.
Results

Chip Layout

Simulation Result
Ion Drift Meter – Comparative Design Estimates

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Discrete Component Design on PCB</th>
<th>Integrated On-Chip Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power Consumed</td>
<td>2 W</td>
<td>80 mW</td>
</tr>
<tr>
<td>Size, including packaging</td>
<td>12 x 12 x 6 cm</td>
<td>3 x 3 x 1 cm</td>
</tr>
<tr>
<td>Radiation Tolerance</td>
<td>~ 10 krad</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Continuing Work and Schedule:
- Finalize IDM electrometer chip design for fabrication – complete in Fall 2003
- Test the on-chip version of the electrometer vs. the discrete component design. Iterate as necessary - complete in Spring and Summer of 2004
- Investigate radiation shielding approaches – built in redundancy?
Conclusions

• On-chip design approaches offer significant savings in terms of power and mass, and are capable of measuring the small currents required to determine plasma and neutral drift velocities in 3D with sub-kilometer spatial resolution.

• New designs can likely meet the needs of future space science LEO missions, in which fleets of small spacecraft will be deployed to resolve space/time ambiguities.

• Several on-chip electrometer design approaches are being fabricated for comparative testing, which will occur within 9 months.

• Radiation shielding is likely to be a major issue in fielding a flight instrument, and one that requires more intensive investigation.