Low Cost Environmental Sensors for Spaceflight: NMP Space Environmental Monitor (SEM) Requirements

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California Institute of Technology,
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Space Environmental Monitor (SEM) for the New Millenium Program (NMP)

AGENDA:
-Representative New Millenium Program Technologies/Missions
-Why a SEM for these missions?
-What Environments/Interactions are of concern?
-What will a SEM look like?
NMP Candidate Technologies

Deployment Booms

Solar Array

Advanced Photovoltaic Cells

Lightweight Array/Panel Technology

Thermal Management

Box in Powered Down Mode

Normal ops

Radiator deactivated allowing heat to keep powered down box above lower limit

no heat flow (low emittance surface)

heat flow (high emittance surface)

High-performance COTs Computing

Fault Tolerant General Purpose Computing Nodes

Fault Tolerant Embeddable Microcontrollers

Fault Tolerant Interconnect

Why Include SEM with NMP Validation Flights?

SEM measures local, instantaneous space environment.

SEM replaces/supplements NMP environmental monitors.

SEM data in conjunction with environmental models improve design of future missions.

Space Environment Knowledge Critical to Understanding NMP Test Results

It is technically feasible and affordable

Space weather is complex and variable

SEM provides instant weather data not obtainable from other sources.
**Value of a SEM to NMP Technology Experiments**

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<th>Critical Effects Measured by SEM</th>
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<td>SEU computer performance degradation, TID computer speed reduction</td>
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*Space environments can affect items in red.*

**NMP Environments/Interactions Concerns**

- Contamination Environment
- Atomic Oxygen Erosion
- Radiation Dose
- Radiation SEU
- Magnetic Field
- Thermal Environment
Contamination Environments

- Environment:
  - Particulate
    - Particle Size: 0.1 to 500 µm
    - Evolution: At time of deployment
  - Molecular
    - Particle Size: < 0.1 µm
    - Evolution: Continuous Particle

- New Technology Problem:
  - Deployable structures carry particulate contamination from assembly facility.
  - Large area film materials are new sources of molecular contamination.

- Testing Problem:
  - New materials can not be adequately tested in the laboratory due to many compounding factors (e.g., UV, particle radiation, etc.)

Modeling/Testing Contamination

- Models:
  - There are no models to predict the outgassing behavior of new materials.
  - New materials are characterized empirically using:
    - TML (total mass loss)
    - VCM (volatile condensable material)

- Tests:
  - Laboratory tests are not complete because of the compounding effects of various environmental factors.

- Different materials have very different outgassing rates.
**Example: ST8 Contamination Predictions**

- **SEM:** will measure in-situ contamination from:
- **Contamination sources:**
  - Deployable Solar Arrays
  - Deployable Booms
- **Contamination sinks:**
  - Thermal Radiator: Emissivity degradation
  - Solar Arrays: Power output degradation.
  - Optical Components: Image blurring

### ST8 Particle Contamination Estimates

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**Scaling:** ST8 results will be scaled to future missions using particulate transport models.

Contamination impacts system performance and longevity.

### SEM QCM Specification

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<tr>
<td>Diameter</td>
<td>mm</td>
<td>3.6</td>
</tr>
<tr>
<td>Sensor range</td>
<td>g/cm²</td>
<td>&gt; 10⁴</td>
</tr>
<tr>
<td>Temp. Sensitivity</td>
<td>Hz/K°C</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>Temp. Range</td>
<td>°C</td>
<td>-43 to +80</td>
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<td>Sensor Output</td>
<td>bps</td>
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<tr>
<td>Sensitivity</td>
<td>ng/cm²</td>
<td>&gt; 4.4</td>
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**Atomic Oxygen Effects**

- **Environmental Problem:**
  - Atomic oxygen is formed in low earth orbit by the UV photolysis of molecular oxygen.

- **New Technology Problem:**
  - AO causes:
    - Oxidation of polymers
    - Degradation of metal surfaces
    - Erosion of insulators

**Kapton Erosion Example**

2.54 cm diameter Kapton substrate

High AO fluence (> 1E22 /cm²) levels cause micro-cracking and detachment of the protecting layer of DC99-500 on Kapton.

Atomic Oxygen erodes Polymers and Composite Materials
Atomic Oxygen Models and Lab Tests

• **Modeling:**  
  • AO effects are highly variable and hard to model because AO depends on:  
    • Altitude  
    • Solar cycle  
    • Direction of test article relative to ram direction.

• **Tests:**  
  • Lab tests are effective in identifying global material response to AO. AO tests are complex for they depend on other environments such as UV.

Example: ST8 AO Predictions

**SEM:** will carry an AO monitor to characterize the instantaneous AO environment and to interpret results from

**Boom:** Degradation in mechanical properties.

**Solar Array:** Solar cell output power.

**Thermal:** AO changes emissivity of thermal surfaces.

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</tr>
<tr>
<td>Temperature: Accuracy</td>
</tr>
<tr>
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• **Scaling:** ST8 results will be scaled to future missions using AO models.
Particle Radiation Dose Effects

- **Environment Problem:**
  - Extremely high fluxes of low energy electrons and protons will cause damage to polymers exposed to free space.

- **New Technology Problem:**
  - Previous missions were less concerned with low energy radiation. New technologies with unshielded sensitive thin polymer film surfaces are severely affected by low energy radiation.

- **Testing Problem:**
  - Laboratory testing well understood except for combined effects such as UV and particle radiation.

  Coloration of commonly used white paint samples due to radiation exposure for 10-years in space environment.
Total Dose Model and Lab Test Problems

- Models:
  - NASA standard orbit dose is below currently proposed dose levels.
  - Electron fluxes show 20x discrepancy.
  - Can’t rely on currently available radiation models to predict dose in space because of:
    - Uncertainty in model predictions.
    - Instantaneous variations.

- Tests:
  - Limited to mono-energetic particle sources.
  - Tests are highly accelerated using much higher dose rate than found in space.

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<th>STS Total Dose Radiation Specifications</th>
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</tr>
<tr>
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</tr>
<tr>
<td>Sensitivity</td>
</tr>
<tr>
<td>Temp. Sensitivity</td>
</tr>
<tr>
<td>Sensor Output</td>
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SEUs (Single-Event-Upsets) Effects

- Environment Problem:
  - SEU’s cause errors in digital components such as memories, microprocessors, and FPGA which upset affect system performance.

- Technology Problem:
  - COTS technologies are SEU sensitive and depend on:
    - Component LET sensitivity
    - Particle type and flux
    - Shielding
    - Orbit
    - Sun cycle.

- Testing Problem:
  - Lab tests cannot replicate the operational space environment at the system level.
Example: ST8 SEU Predictions

- **ST8 Orbit**: SEUs in the ST8 orbit will be mostly caused by proton interactions inside semiconductor devices and heavy ions in GCR.

- **SEM**: will carry an SEU monitor to characterize the in-situ SEU environment and to interpret results from:
  - **COTS Computer**: Upset rate versus orbit location.

- **Scaling ST8 results**: ST8 results will be scaled to interplanetary space environments which have particles with different LET spectrum than protons.

High LET particles cause upsets even for well shielded electronics.

Integral LET spectra of the charged particle radiations in space under different Al thickness, 50, 200 and 800 mils. Solid line is CREES mission measurements. From "Radiation Hazards in Space", by L. Miroshnichenko, 2003, pp. 30 Kluwer Academic Publishers

The Earth's Magnetic Field

- Earth's magnetic field is both spatially and temporally variable
- Field can cause torques, affect attitude, induce currents

**MAGNETIC INTENSITY AT THE EARTH'S SURFACE**

**THE SOUTH ATLANTIC ANOMALY**
**Magnetic Field Range**

Variations in B Field with Altitude and Latitude

Variations imply the following Magnetometer Requirements:

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<thead>
<tr>
<th>PARAMETER</th>
<th>UNIT</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field Range</td>
<td>μT*</td>
<td>±50</td>
</tr>
<tr>
<td>Resolution</td>
<td>nT</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Sensor Output</td>
<td>bps</td>
<td>0.1</td>
</tr>
<tr>
<td>Attitude Accuracy</td>
<td>deg.</td>
<td>&lt;3</td>
</tr>
</tbody>
</table>

*below 6000 km

**Thermal Sensors**

Characteristics:

- Temperature measurements are ubiquitous—often needed by other sensors to remove temperature sensitivities
- Temperature sensors need to be included as health check on data logging electronics
- Potentially important to understanding contamination rates/effects

**Temp Sensor Specification**

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<td>&lt;±0.2</td>
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<tr>
<td>Sensor Output</td>
<td>bps</td>
<td>1</td>
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Space Environmental Monitor (SEM) Requirements

1. Questions:
   - What space environments effects on NMP technologies are addressed by SEM?
   - What are the limitations of lab tests and models for predicting space effects?
   - How will SEM help predict environmental effects on future missions?

2. Environmental effects on representative NMP technologies:

<table>
<thead>
<tr>
<th>ENVIRONMENT</th>
<th>ST8-1</th>
<th>ST8-2</th>
<th>ST8-3</th>
<th>ST8-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>Boom</td>
<td>Solar Array</td>
<td>Thermal</td>
<td>Computer</td>
</tr>
<tr>
<td>1. Electron/Proton Radiation Dose</td>
<td>Moderate</td>
<td>HIGH</td>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td>2. Cosmic Rays: Single-Event Upsets</td>
<td></td>
<td></td>
<td>Moderate</td>
<td>HIGH</td>
</tr>
<tr>
<td>3. Atomic Oxygen</td>
<td>HIGH</td>
<td>Moderate</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>4. UV Radiation</td>
<td>Moderate</td>
<td>HIGH</td>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td>5. Contamination: Particulate &amp; Molecular</td>
<td>Moderate</td>
<td>Moderate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Conclusions:
   - Space environment is uncertain* and highly variable.
   - Simulations/laboratory measurements notoriously poor in predicting space results.
   - SEM provides instantaneous in situ measurements to explain experimental results.
   * Total dose uncertainty: +100%, -50%.

SEM Characteristics

SEM Conceptual Schematic

SEM System-Level Specifications

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<thead>
<tr>
<th>PARAMETER</th>
<th>UNIT</th>
<th>VALUE</th>
</tr>
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<tbody>
<tr>
<td>Mass</td>
<td>g</td>
<td>250</td>
</tr>
<tr>
<td>Volume</td>
<td>cm³</td>
<td>250</td>
</tr>
<tr>
<td>Power Operating</td>
<td>W</td>
<td>5</td>
</tr>
<tr>
<td>Power Quiescent</td>
<td>W</td>
<td>0.1</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>°C</td>
<td>20</td>
</tr>
<tr>
<td>Thermal Heat Sink</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Output</td>
<td>bps</td>
<td>1000</td>
</tr>
<tr>
<td>Data Storage</td>
<td>Mbits</td>
<td>1</td>
</tr>
<tr>
<td>Fault Protection</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Time Tag</td>
<td>s</td>
<td>0.1</td>
</tr>
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Key Characteristics:

- Environments—Contamination, Atomic Oxygen, Ionizing Radiation, Cosmic Radiation, EMI, and Temperature
- Small, hockey-puck sensors.
- Additional sensors added in future in a plug-and-play manner to allow tailoring to specific mission
Space Environmental Monitor (SEM): A monitor-grade instrument for measuring critical environmental parameters during NMP flights

SEM characterizes general space environment needed to analyze results from NMP flight validation experiments.

Conclusions-Why SEM?

a. Space Environmental Effects:
Problem: Space environment is uncertain and highly variable.
Solution: SEM provides instantaneous in situ measurements to explain ST8 results.

b. Lab Tests and Models:
Problem: Simulations/laboratory measurements notoriously poor in predicting space results because of combined effects.
Solution: SEM separately measures individual environmental effects.

c. Predictions for Future Missions:
Problem: Current predictions depend on average models.
Solution: SEM data, in conjunction with environmental models, will reduce the risk in the use of new technology to future missions.
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Inclination of Orbit Plane (Degrees)

Perigee: 300 km
Apogee: 1400 km
Inclination: 70°
Duration: Six months

Daily total ionizing radiation dose behind a 2.5-mm (100-mil) thick aluminum shield.

Particle Radiation Dose Effects

- Environment Problem:
  - Extremely high fluxes of low energy electrons and protons will cause damage to polymers exposed to free space.

- New Technology Problem:
  - Previous missions were less concerned with low energy radiation. New technologies with unshielded sensitive thin polymer film surfaces are severely affected by low energy radiation.

- Testing Problem:
  - Laboratory testing well understood except for combined effects such as UV and particle radiation.

Coloration of commonly used white paint samples due to radiation exposure for 10-years in space environment.
**Total Dose Model and Lab Test Problems**

- **Models:**
  - NASA standard orbit dose is below currently proposed dose levels.
  - Electron fluxes show 20x discrepancy.
  - Can't rely on currently available radiation models to predict dose in space because of:
    - Uncertainty in model predictions.
    - Instantaneous variations.

- **Tests:**
  - Limited to mono-energetic particle sources.
  - Tests are highly accelerated using much higher dose rate than found in space.

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**SEUs (Single-Event-Upsets) Effects**

- **Environment Problem:**
  - SEU's cause errors in digital components such as memories, microprocessors, and FPGA which upset affect system performance.

- **Technology Problem:**
  - COTS technologies are SEU sensitive and depend on:
    - Component LET sensitivity
    - Particle type and flux
    - Shielding
    - Orbit
    - Sun cycle.

- **Testing Problem:**
  - Lab tests cannot replicate the operational space environment at the system level.
Example: ST8 SEU Predictions

- **ST8 Orbit**: SEUs in the ST8 orbit will be mostly caused by proton interactions inside semiconductor devices and heavy ions in GCR.

- **SEM**: will carry an SEU monitor to characterize the in-situ SEU environment and to interpret results from:
  - **COTS Computer**: Upset rate versus orbit location.

- **Scaling ST8 results**: ST8 results will be scaled to interplanetary space environments which have particles with different LET spectrum than protons.

High LET particles cause upsets even for well shielded electronics.

Integral LET spectra of the charged particle radiations in space under different Al thickness, 50, 200 and 800 mils. Solid line is CREES mission measurements. From "Radiation Hazards in Space", by L. Miroshnichenko, 2003, pp. 30 Kluwer Academic Publishers

The Earth’s Magnetic Field

-Earth’s magnetic field is both spatially and temporally variable
-Field can cause torques, affect attitude, induce currents

**MAGNETIC INTENSITY AT THE EARTH’S SURFACE**

**THE SOUTH ATLANTIC ANOMALY**

- Earth’s magnetic field is both spatially and temporally variable
- Field can cause torques, affect attitude, induce currents
Magnetic Field Range

Variations in B Field with Altitude and Latitude

Variations imply the following Magnetometer Requirements:

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNIT</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field Range</td>
<td>μT</td>
<td>±50</td>
</tr>
<tr>
<td>Resolution</td>
<td>nT</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Sensor Output</td>
<td>bps</td>
<td>0.1</td>
</tr>
<tr>
<td>Attitude Accuracy</td>
<td>deg.</td>
<td>&lt;3</td>
</tr>
</tbody>
</table>

*below 6000 km

Thermal Sensors

Characteristics:

- Temperature measurements are ubiquitous--often needed by other sensors to remove temperature sensitivities
- Temperature sensors need to be included as health check on data logging electronics
- Potentially important to understanding contamination rates/effects

Temp Sensor Specification

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNIT</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. Range</td>
<td>°C</td>
<td>-43 to +80</td>
</tr>
<tr>
<td>Temp. Accuracy</td>
<td>°C</td>
<td>&lt;±1</td>
</tr>
<tr>
<td>Temp. Precision</td>
<td>°C</td>
<td>&lt;±0.2</td>
</tr>
<tr>
<td>Sensor Output</td>
<td>bps</td>
<td>1</td>
</tr>
</tbody>
</table>
Space Environmental Monitor (SEM) Requirements

1. Questions:
   - What space environments effects on NMP technologies are addressed by SEM?
   - What are the limitations of lab tests and models for predicting space effects?
   - How will SEM help predict environmental effects on future missions?

2. Environmental effects on representative NMP technologies:

<table>
<thead>
<tr>
<th>ENVIRONMENT</th>
<th>ST8-1</th>
<th>ST8-2</th>
<th>ST8-3</th>
<th>ST8-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Electron/Proton Radiation Dose</td>
<td>Moderate</td>
<td>HIGH</td>
<td>Thermal</td>
<td>Moderate</td>
</tr>
<tr>
<td>2. Cosmic Rays: Single-Event Upsets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Atomic Oxygen</td>
<td>HIGH</td>
<td>Moderate</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>4. UV Radiation</td>
<td>Moderate</td>
<td>HIGH</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>5. Contamination: Particulate &amp; Molecular</td>
<td>Moderate</td>
<td>Moderate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Conclusions:
   - Space environment is uncertain* and highly variable.
   - Simulations/laboratory measurements notoriously poor in predicting space results.
   - SEM provides instantaneous in situ measurements to explain experimental results.

* Total dose uncertainty: +100%, -50%.

SEM Characteristics

SEM Conceptual Schematic

Key Characteristics:
- Environments—Contamination, Atomic Oxygen, Ionizing Radiation, Cosmic Radiation, EMI, and Temperature
- Small, hockey-puck sensors.
- Additional sensors added in future in a plug-and-play manner to allow tailoring to specific mission
Space Environmental Monitor (SEM):
A monitor-grade instrument for measuring critical environmental parameters during NMP flights

SEM characterizes general space environment needed to analyze results from NMP flight validation experiments.

Conclusions-Why SEM?

a. Space Environmental Effects:
Problem: Space environment is uncertain and highly variable.
Solution: SEM provides instantaneous in situ measurements to explain ST8 results.

b. Lab Tests and Models:
Problem: Simulations/laboratory measurements notoriously poor in predicting space results because of combined effects.
Solution: SEM separately measures individual environmental effects.

c. Predictions for Future Missions:
Problem: Current predictions depend on average models.
Solution: SEM data, in conjunction with environmental models, will reduce the risk in the use of new technology to future missions.