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

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Space Environmental Monitor (SEM) for the New Millenium Program (NMP)

AGENDA:

-Representative New Millenium Program Technologies/Missions

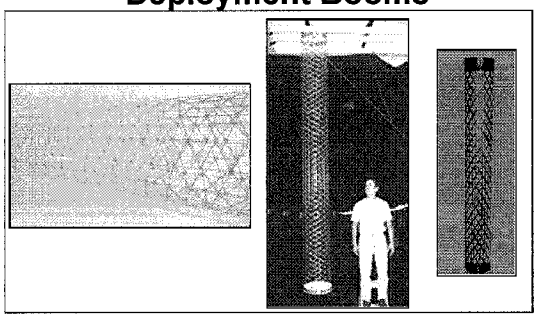
-Why a SEM for these missions?

-What Environments/Interactions are of concern?

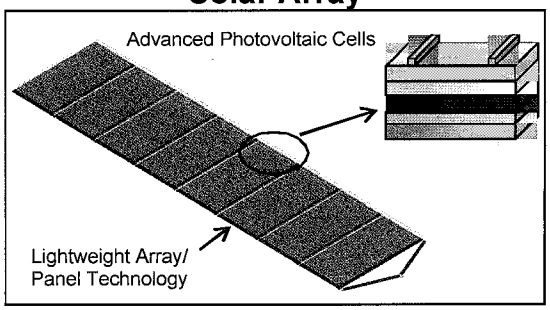
-What will a SEM look like?

NMP Candidate Technologies

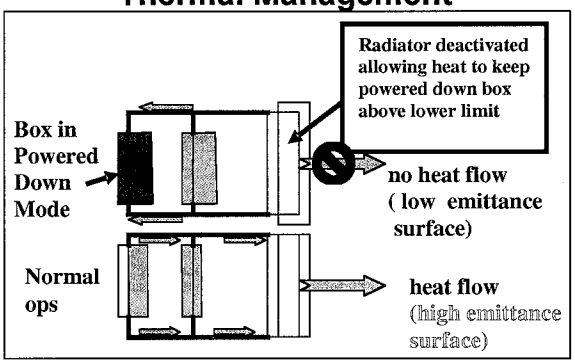
Deployment Booms



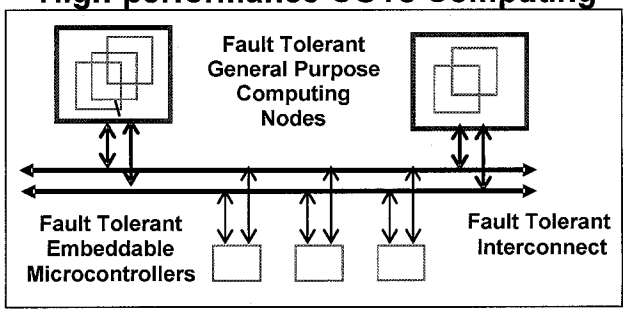
Solar Array



Thermal Management



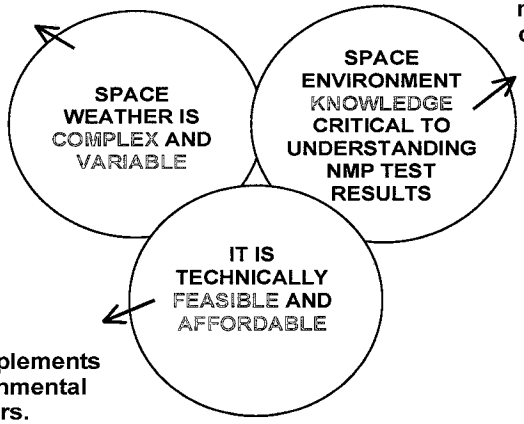
High-performance COTs Computing



Why Include SEM with NMP Validation Flights?

SEM measures local, instantaneous space environment.

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



SEM replaces/supplements NMP environmental monitors.

SEM provides instant weather data not obtainable from other sources.

Value of a SEM to NMP Technology Experiments

NMP Technologies	Required NRA Measurements	Critical Effects Measured by SEM
Deployment of Ultra Lightweight Booms	Mechanical Shape, Stability Deployment Dynamics Deployment Power	AO Induced stiffening UV/radiation induced bond scission/cracking
Deployment of Lightweight Solar Array	Deployment Dynamics Structural Dynamics Dimensional Stability Power Output with Time	Radiation dose cell damage AO polymer damage UV/radiation darkening Particulate/Molecular Contamination
Thermal Management Subsystem	Thermal Component Power Dissipation Thermal Component Temperature Electrical Power for Thermal Control	AO thermal radiator surface damage UV/radiation thermal radiator surface damage Contamination of radiator surface
COTS High Performance Computing	MIPS/Watt Performance Radiation TID and SEU Environment Fault Rates, Locations, & Recovery Time	SEU computer performance degradation TID computer speed reduction

Space environments can affect items in red.

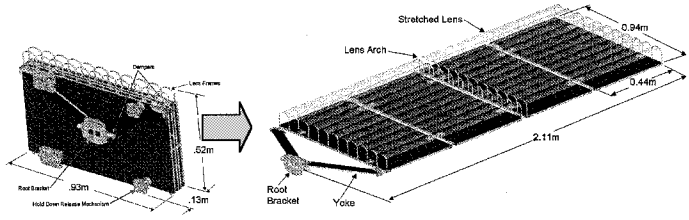
NMP Environments/Interactions Concerns

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

Contamination Environments

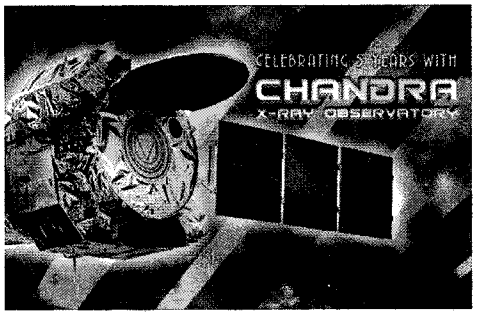
- **Environment:**
  - **Particulate**
    - Particle Size: 0.1 to 500 μm
    - Evolution: At time of deployment
  - **Molecular**
    - Particle Size: < 0.1 μm
    - Evolution: Continuous Particle

ST8 Solar Array Deployment



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

Chandra X-Ray Telescope: Molecular contamination caused fogging on filter



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

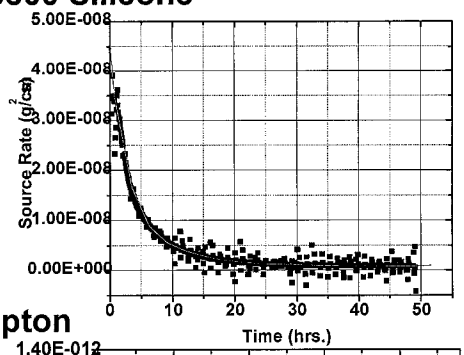
Modeling/Testing Contamination

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

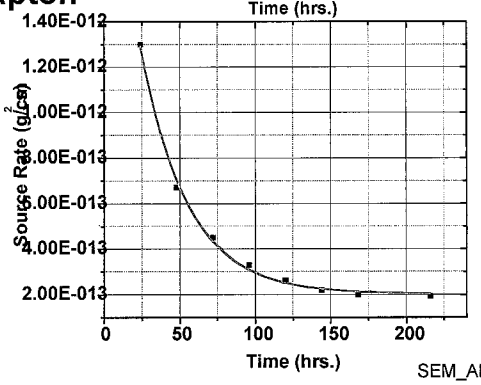
- **Tests:**
  - Laboratory tests are not complete because of the compounding effects of various environmental factors.

• Different materials have very different outgassing rates.

DC 93500 Silicone



Kapton



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

SEM QCM Specification

PARAMETER	UNIT	VALUE
Diameter	mm	3.6
Sensor range	g/cm^2	$> 10^{-4}$
Temp. Sensitivity	Hz/°C	<2.5
Temp. Range	°C	-43 to +80
Temp. Accuracy	°C	<±1
Temp. Precision	°C	<±0.2
Sensor Output	bps	1
Sensitivity	ng/cm^2	> 4.4

- **ST8 Particle Contamination Estimates**

ST8 Technology	Component	Particle mass (g)
ABEL Solar Array Class 100,000	Nusil CV-2568	3.0 x 10 -5
Isogrid Boom ILC Dover L.P. Class 100,000	Graphite fibers Resin Polymer	7.5 x 10-5
Lockheed Martin Collapsible Boom Class > 100	Graphite fibers CE3 Cyanate Ester	6.8 x 10-8
Sail mast boom ABEL Eng. Co. Class 100,000	Graphite Mast Epon Resin 9405	1.8 x 10-4

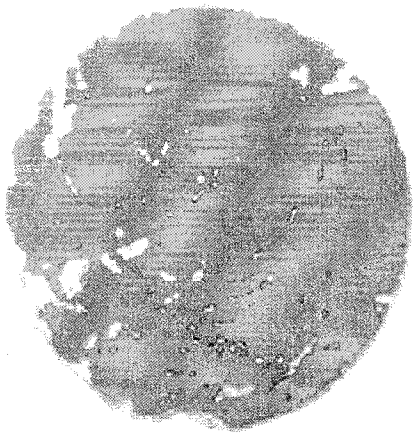
- **Scaling:** ST8 results will be scaled to future missions using particulate transport models

Contamination impacts system performance and longevity.

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



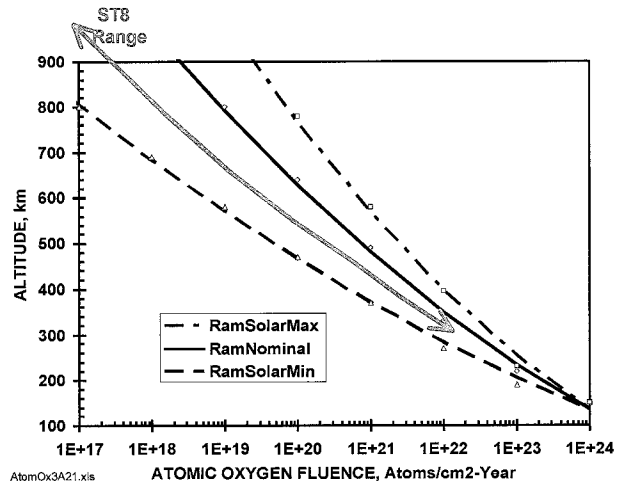
2.54 cm diameter Kapton substrate

High AO fluence (> 1E22 /cm2) levels cause micro-cracking and detachment of the protecting layer of DC93-500 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.

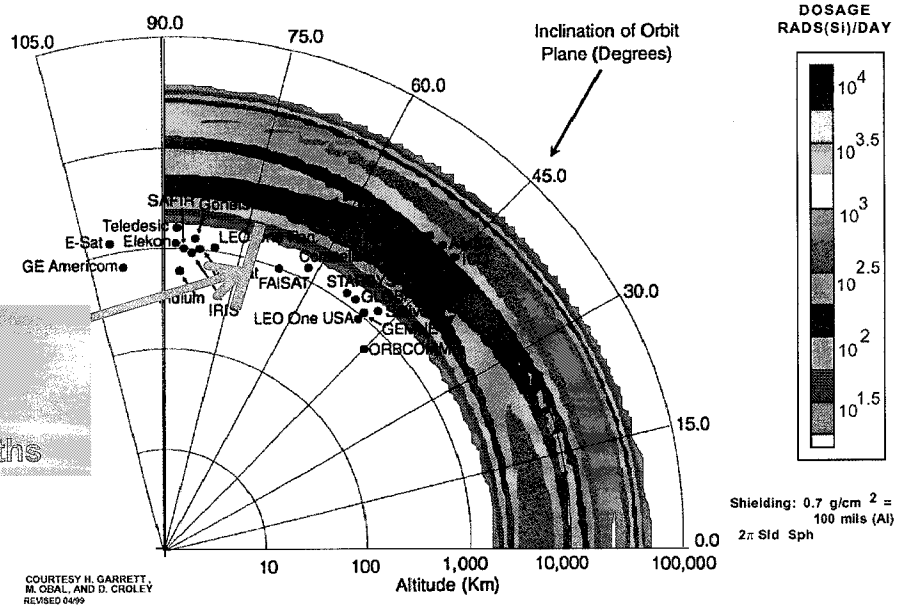
Thermal: AO changes emissivity of thermal surfaces.

ST8 Atomic Oxygen Specifications

PARAMETER	UNIT	VALUE
Range	Atoms/cm^2-year	10^{16} to 10^{22}
Test Coating	NA	TBD
Test 1 Resistor-Silver	Ohms	1 to 100
Test 2 Resistor-Carbon	Ohms	1k to 100k
Temperature: Range	°C	-50 to +80
Temperature: Accuracy	°C	±1
Sensor Output	bps	10

- **Scaling:** ST8 results will be scaled to future missions using AO models.

NMP ST8 Orbit in Earth's Trapped Radiation Belt



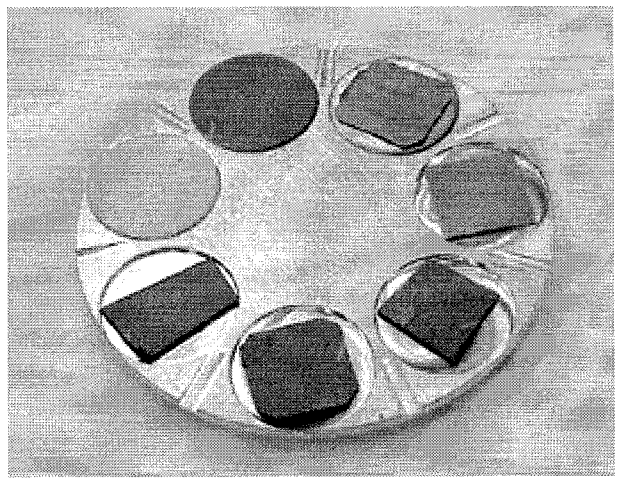
Perigee: 300 km
Apogee: 1400 km
Inclination: 70°
Duration: Six months

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.

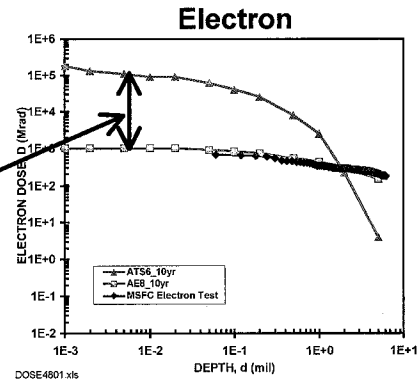
White Paint Degradation Example



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.

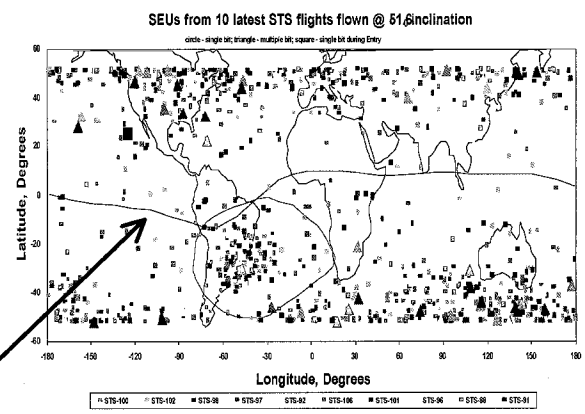
ST8 Total Dose Radiation Specifications

PARAMETER	UNIT	VALUE
Range	krad	0.1 to 50
Sensitivity	mV/rad	0.2
Temp. Sensitivity	krad/°C	0.001
Sensor Output	bps	1

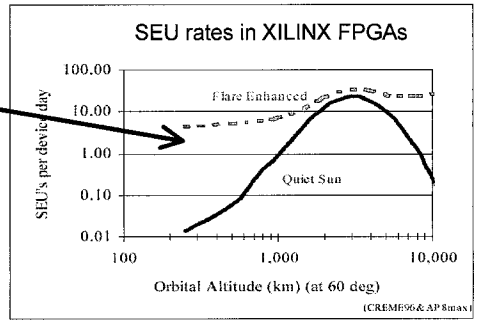
SEUs (Single-Event-Upsets) Effects

- **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.

SEU rates in Space Shuttle Computer



SEU rates in XILINX FPGAs



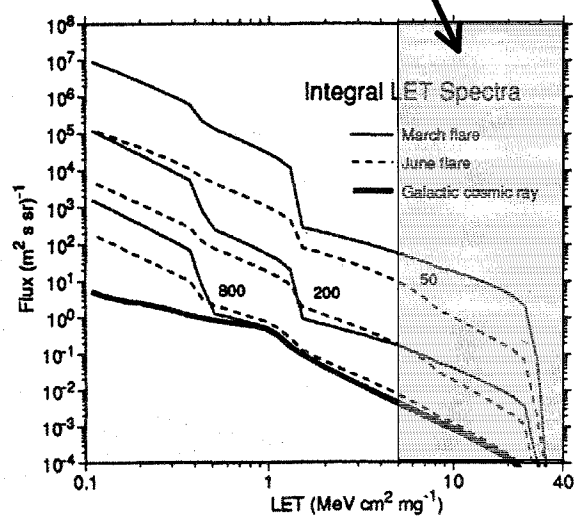
Example: ST8 SEU Predictions

High LET particles cause upsets even for well shielded electronics.

- **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.



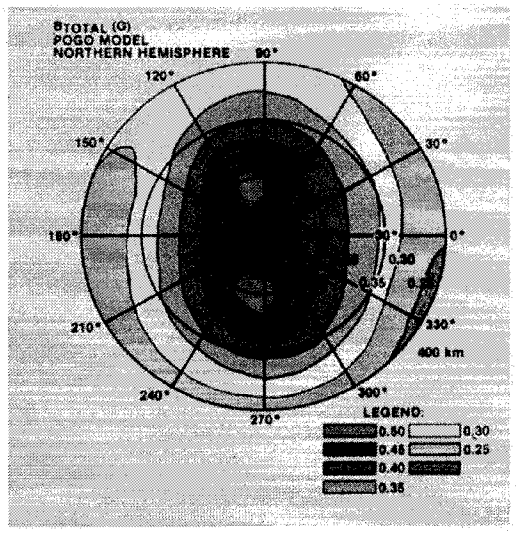
Integral LET spectra of the charged particle radiations in space under different Al thickness, 50, 200 and 800 mils. Solid line is CREES mission measurements. From "Radiation Hazards in Space", by L. Miroshnichenko , 2003, pp. 30 Kluwer Academic Publishers

The Earth's Magnetic Field

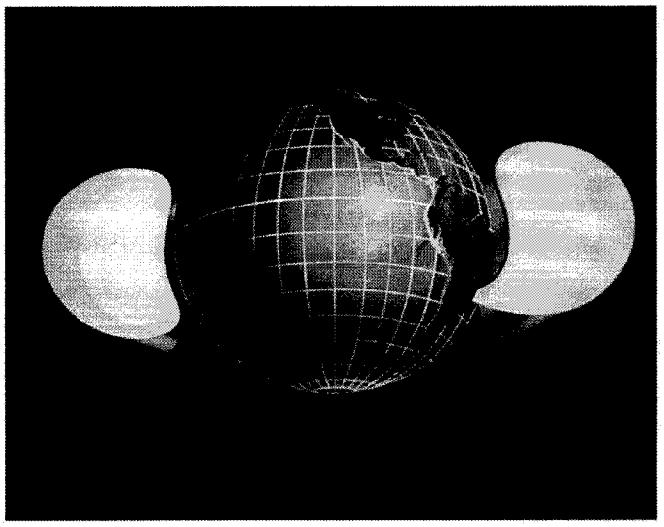
-Earth's magnetic field is both spatially and temporally variable

-Field can cause torques, affect attitude, induce currents

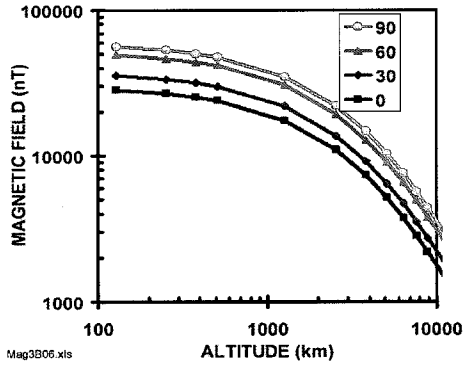
MAGNETIC INTENSITY AT THE EARTH'S SURFACE



THE SOUTH ATLANTIC ANOMALY



Magnetic Field Range



Variations in B Field with Altitude and Latitude

Variations imply the following Magnetometer Requirements:

Three-Axis Magnetometer

PARAMETER	UNIT	VALUE
Magnetic Field Range	μT*	±50
Resolution	nT	<10
Sensor Output	bps	0.1
Attitude Accuracy	deg.	<3
*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 loging electronics
- Potentially important to understanding contamination rates/effects

Temp Sensor Specification

PARAMETER	UNIT	VALUE
Temp. Range	°C	-43 to +80
Temp. Accuracy	°C	<±1
Temp. Precision	°C	<±0.2
Sensor Output	bps	1

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:**

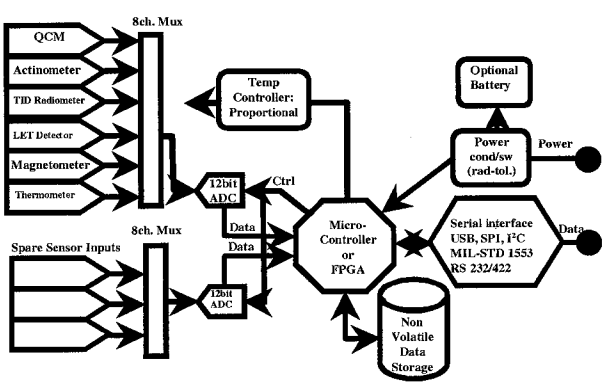
ENVIRONMENT	ST8-1 Boom	ST8-2 Solar Array	ST8-3 Thermal	ST8-4 Computer
1. Electron/Proton Radiation Dose	Moderate	HIGH		Moderate
2. Cosmic Rays: Single-Event Upsets				HIGH
3. Atomic Oxygen	HIGH	Moderate	Moderate	
4. UV Radiation	Moderate	HIGH	Moderate	
5. Contamination: Particulate & Molecular		Moderate	Moderate	

- **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

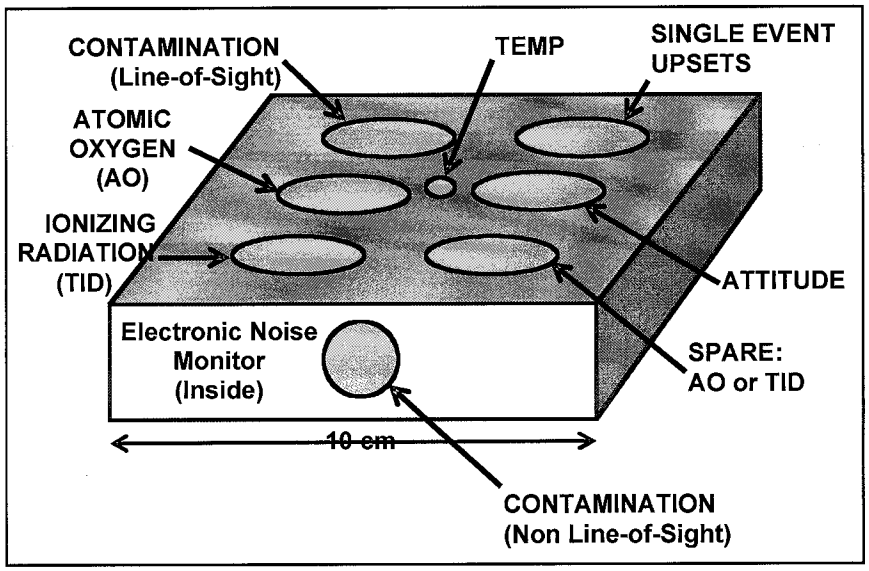
PARAMETER	UNIT	VALUE
Mass	g	250
Volume	cm^3	250
Power Operating	W	5
Power Quiescent	W	0.1
Temperature Rise	°C	20
Thermal Heat Sink	TBD	TBD
Output	bps	1000
Data Storage	Mbits	1
Fault Protection	TBD	TBD
Time Tag	s	0.1

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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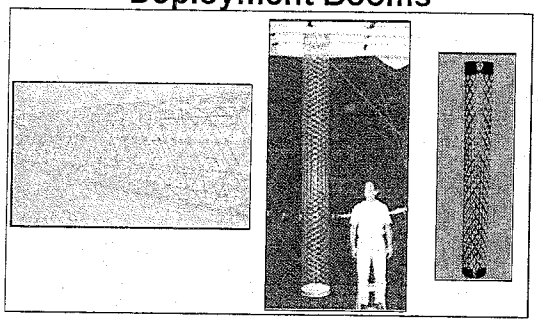

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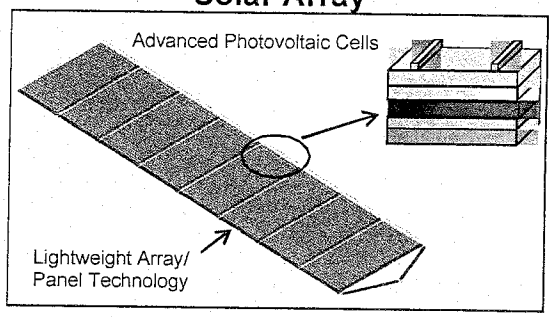

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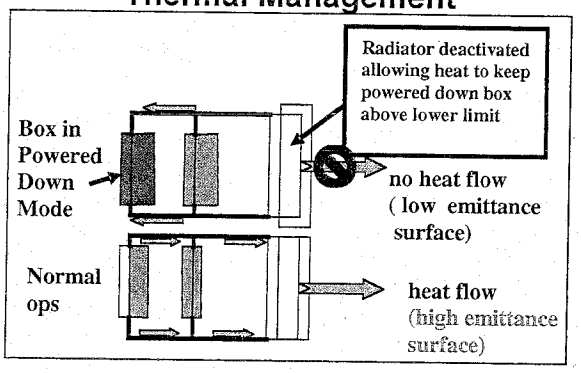

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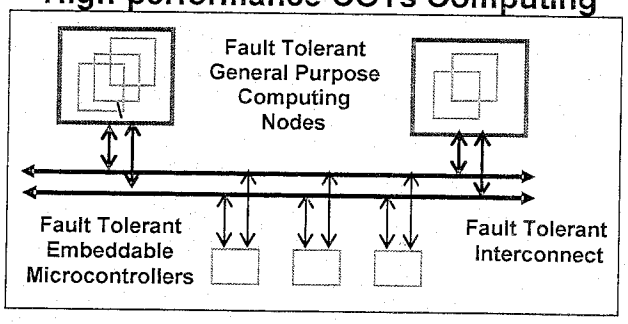

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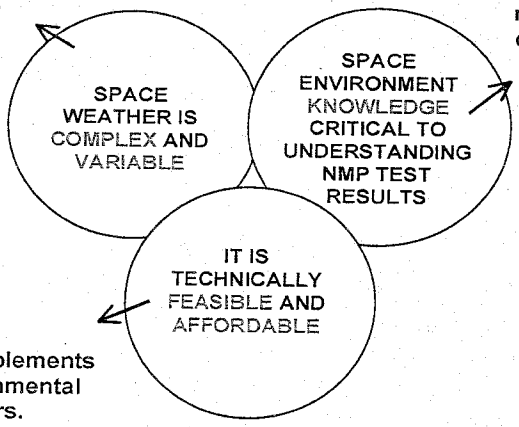

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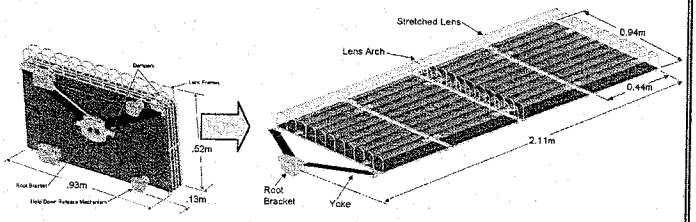
    - Particle Size: 0.1 to 500 μm
    - Evolution: At time of deployment
  - **Molecular**
    - Particle Size: < 0.1 μm
    - Evolution: Continuous Particle

ST8 Solar Array Deployment



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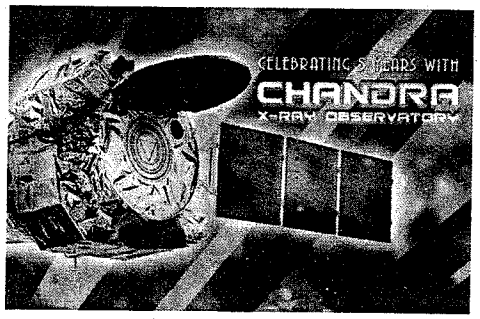

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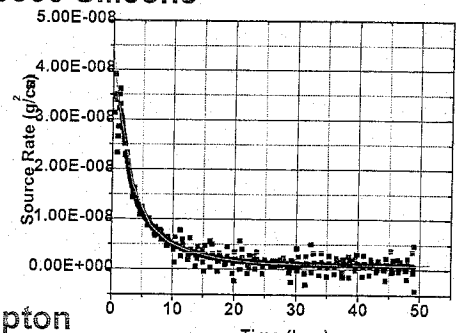
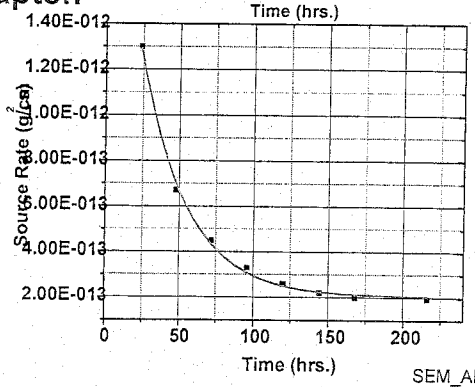


Kapton



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

SEM QCM Specification

PARAMETER	UNIT	VALUE
Diameter	mm	3.6
Sensor range	g/cm^2	$> 10^{-4}$
Temp. Sensitivity	Hz/°C	<2.5
Temp. Range	°C	-43 to +80
Temp. Accuracy	°C	<±1
Temp. Precision	°C	<±0.2
Sensor Output	bps	1
Sensitivity	ng/cm^2	> 4.4

- **ST8 Particle Contamination Estimates**

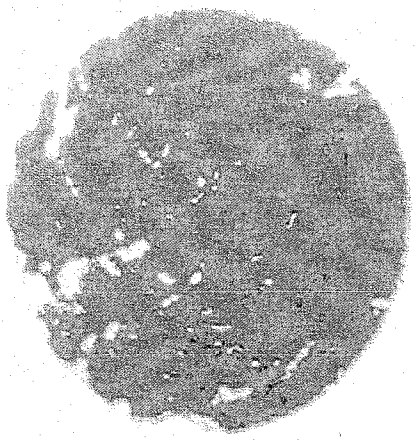
ST8 Technology	Component	Particle mass (g)
ABEL Solar Array Class 100,000	Nusil CV-2568	3.0 x 10 -5
Isogrid Boom ILC Dover L.P. Class 100,000	Graphite fibers Resin Polymer	7.5 x 10-5
Lockheed Martin Collapsible Boom Class > 100	Graphite fibers CE3 Cyanate Ester	6.8 x 10-8
Sail mast boom ABEL Eng. Co. Class 100,000	Graphite Mast Epon Resin 9405	1.8 x 10-4

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

Contamination impacts system performance and longevity.

Atomic Oxygen Effects

Kapton Erosion Example



2.54 cm diameter Kapton substrate

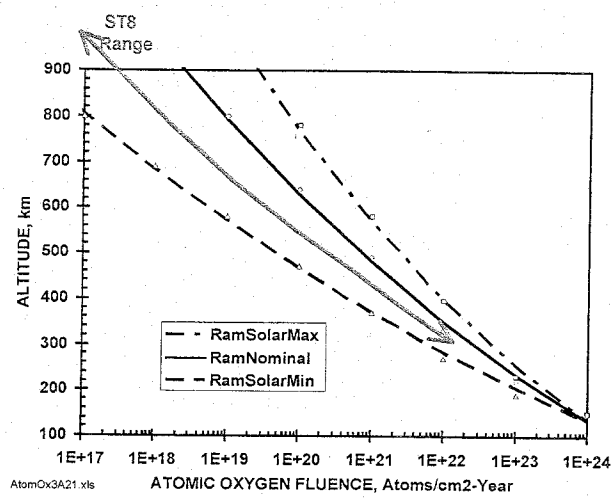
High AO fluence (> 1E22 /cm2) levels cause micro-cracking and detachment of the protecting layer of DC93-500 on Kapton.

- **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

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.

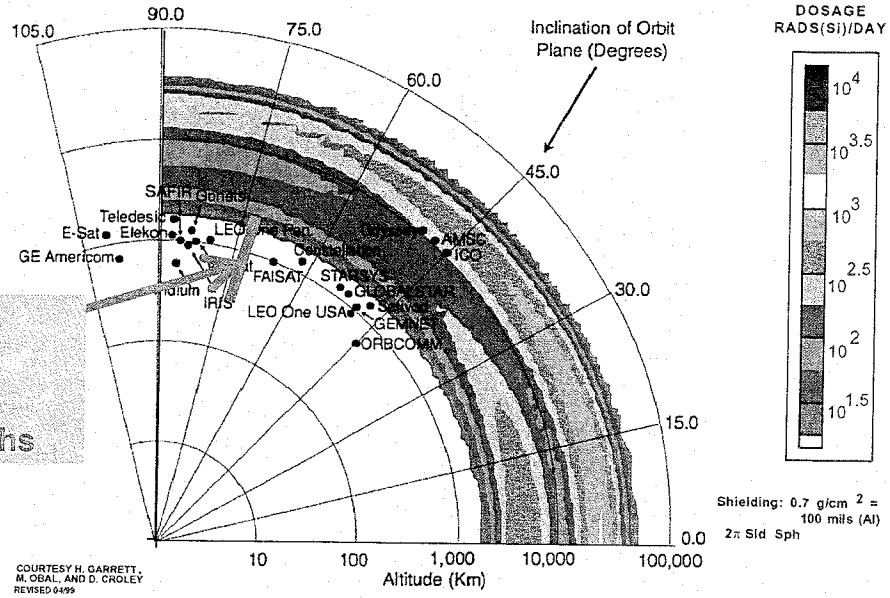
Thermal: AO changes emissivity of thermal surfaces.

ST8 Atomic Oxygen Specifications

PARAMETER	UNIT	VALUE
Range	Atoms/cm^2-year	10^{16} to 10^{22}
Test Coating	NA	TBD
Test 1 Resistor-Silver	Ohms	1 to 100
Test 2 Resistor-Carbon	Ohms	1k to 100k
Temperature: Range	°C	-50 to +80
Temperature: Accuracy	°C	±1
Sensor Output	bps	10

- **Scaling:** ST8 results will be scaled to future missions using AO models.

NMP ST8 Orbit in Earth's Trapped Radiation Belt



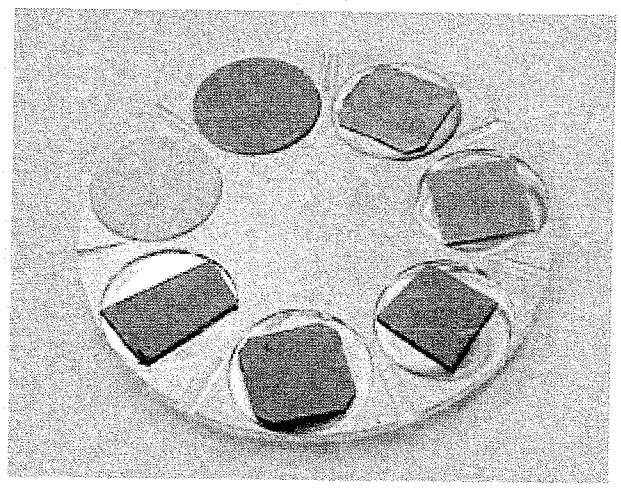
Perigee: 300 km
Apogee: 1400 km
Inclination: 70°
Duration: Six months

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.

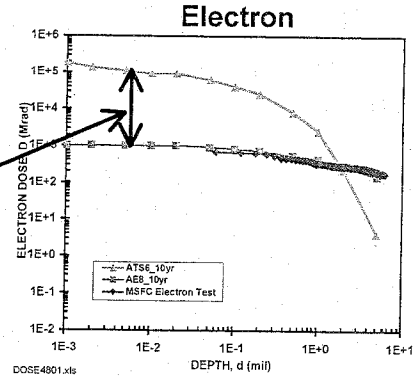
White Paint Degradation Example



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.

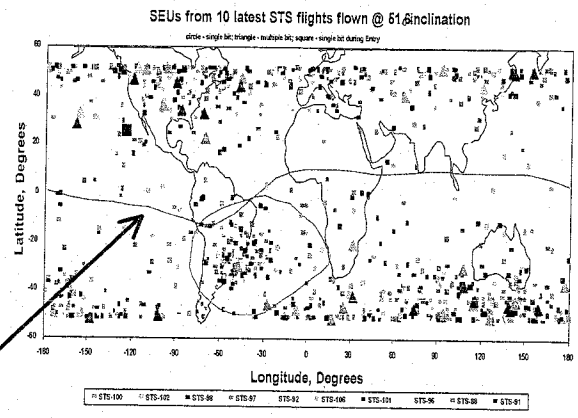
ST8 Total Dose Radiation Specifications

PARAMETER	UNIT	VALUE
Range	krad	0.1 to 50
Sensitivity	mV/rad	0.2
Temp. Sensitivity	krad/°C	0.001
Sensor Output	bps	1

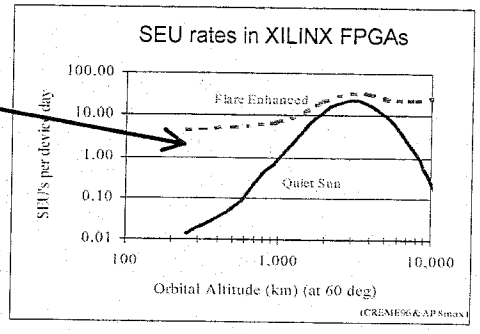
SEUs (Single-Event-Upsets) Effects

- **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.

SEU rates in Space Shuttle Computer



SEU rates in XILINX FPGAs



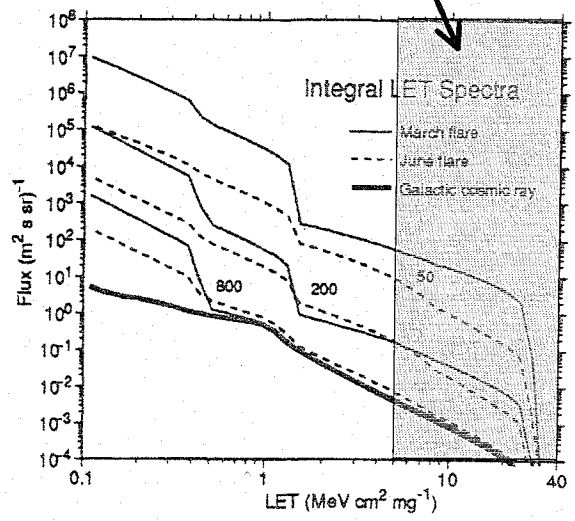
Example: ST8 SEU Predictions

- **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.



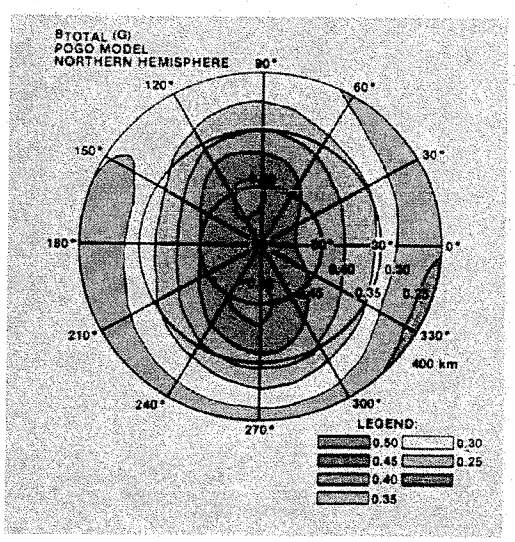
Integral LET spectra of the charged particle radiations in space under different Al thickness, 50, 200 and 800 mils. Solid line is CREES mission measurements. From "Radiation Hazards in Space", by L. Miroshnichenko , 2003, pp. 30 Kluwer Academic Publishers

The Earth's Magnetic Field

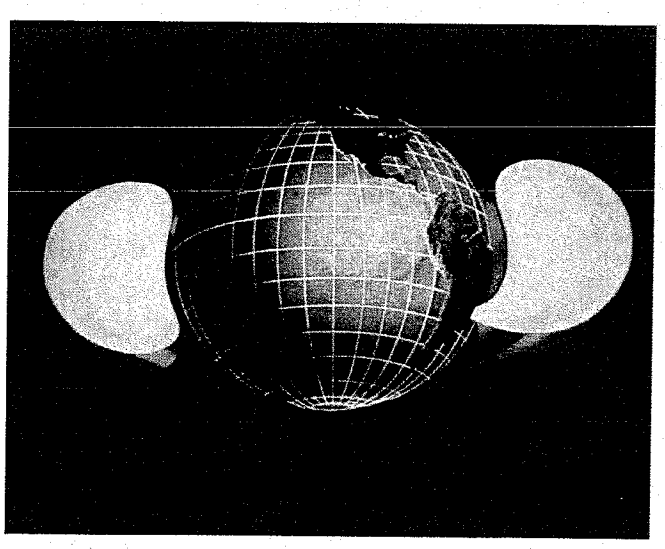
-Earth's magnetic field is both spatially and temporally variable

-Field can cause torques, affect attitude, induce currents

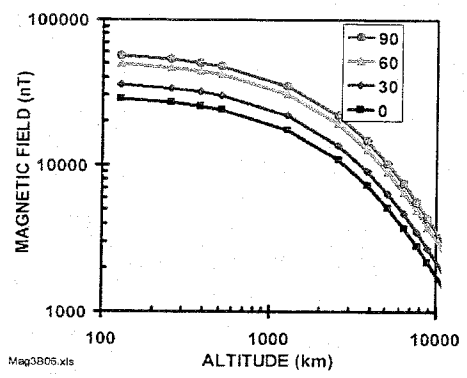
MAGNETIC INTENSITY AT THE EARTH'S SURFACE



THE SOUTH ATLANTIC ANOMALY



Magnetic Field Range



Variations in B Field with Altitude and Latitude

Variations imply the following Magnetometer Requirements:

Three-Axis Magnetometer

PARAMETER	UNIT	VALUE
Magnetic Field Range	μT*	±50
Resolution	nT	<10
Sensor Output	bps	0.1
Attitude Accuracy	deg.	<3
*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 loging electronics
- Potentially important to understanding contamination rates/effects

Temp Sensor Specification

PARAMETER	UNIT	VALUE
Temp. Range	°C	-43 to +80
Temp. Accuracy	°C	<±1
Temp. Precision	°C	<±0.2
Sensor Output	bps	1

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:**

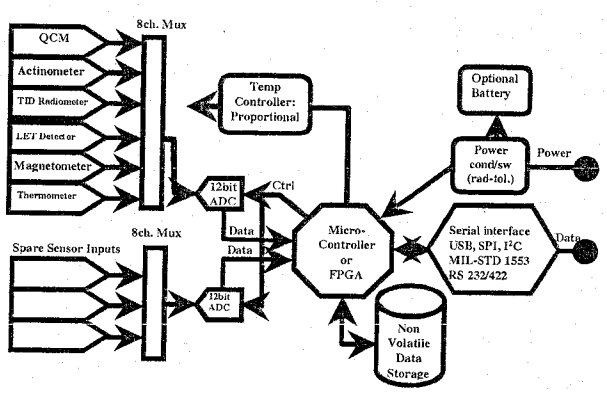
ENVIRONMENT	ST8-1 Boom	ST8-2 Solar Array	ST8-3 Thermal	ST8-4 Computer
1. Electron/Proton Radiation Dose	Moderate	HIGH		Moderate
2. Cosmic Rays: Single-Event Upsets				HIGH
3. Atomic Oxygen	HIGH	Moderate	Moderate	
4. UV Radiation	Moderate	HIGH	Moderate	
5. Contamination: Particulate & Molecular		Moderate	Moderate	

- **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

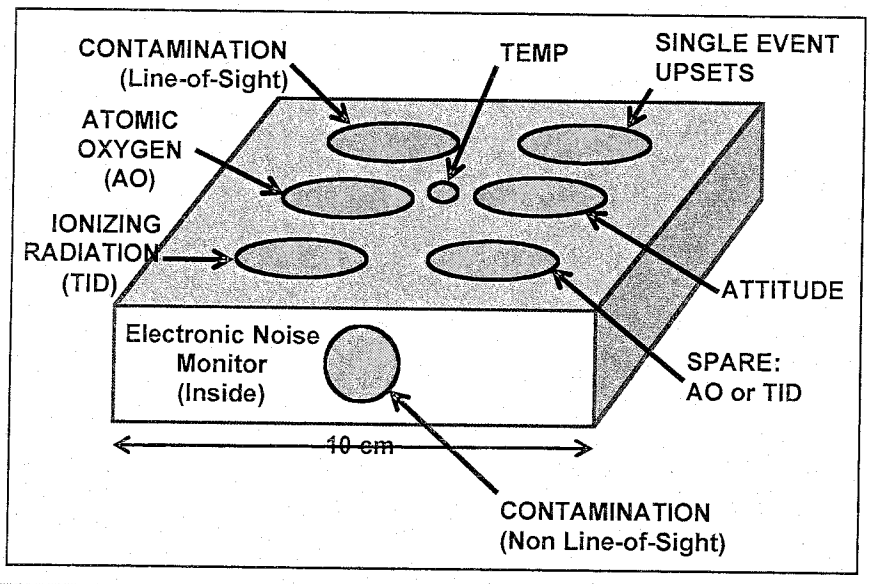
PARAMETER	UNIT	VALUE
Mass	g	250
Volume	cm^3	250
Power Operating	W	5
Power Quiescent	W	0.1
Temperature Rise	°C	20
Thermal Heat Sink	TBD	TBD
Output	bps	1000
Data Storage	Mbits	1
Fault Protection	TBD	TBD
Time Tag	s	0.1

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.