BioSentinel: Mission Development of a Radiation Biosensor to Gauge DNA Damage and Repair Beyond Low Earth Orbit on a 6U Nanosatellite

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BioSentinel Project Objectives

  - Payload selected to help fill HEOMD Strategic Knowledge Gaps in Radiation effects on Biology
  - Current EM-1 Launch Readiness Date: July 2018

- Key BioSentinel Project Objectives
  - Develop a deep space nanosat capability
  - Develop a radiation biosensor useful for other missions
  - Define & validate SLS secondary payload interfaces and accommodations for a biological payload

- AES also selected two other (non-biological) missions for EM-1
  - Near Earth Asteroid (NEA) Scout (MSFC)
  - Lunar Flashlight (JPL)
BioSentinel Relevance to SKGs

Goals:
• Life science studies beyond Low Earth Orbit (LEO) relevant to human exploration
• Use simple organisms to inform us of greatest risks to humans beyond LEO, so that appropriate protection can be developed, dangers can be mitigated
• Provide critical advances to autonomous life support technologies for small organisms

<table>
<thead>
<tr>
<th>SKG documents</th>
<th>Gaps</th>
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</table>
| Mars Precursor Strategic Analysis Group (P-SAG) SKGs, May 2012 | II-D Effects of radiation and effectively low g on biology and physiology  
III-G Radiation shielding, specifically for subsystems |
| P-SAG & MEPAG (Mars Exploration Program Analysis Group) | B3-2, Crew Health and Performance: place detector in orbit to measure energy spectra during Solar Energetic Particle Events (SPEs) |
| SBAG SKGs, Nov 2012                                 | III-B: Ionizing Radiation Environment at Small Body Surfaces         |
| LEAG-SAT SKGs, March 2012                           | A4-4: Auto systems tech demo                                        
A4-6: Life support tech demo                        
A4-7: Mechanisms tech demo                          
B3-6: Radiation shielding                           
B5-3: Microbial survival, Mars conditions          |
The 1st Biology Experiment beyond LEO since Apollo

The limits of life in space, as we know it, is 12.5 days on a lunar round trip or 1 year in LEO. As we send people further into space, we can use model organisms to understand the biological risks and how they can be addressed.

- BioSentinel is a 6U free-flying satellite that will be delivered by SLS EM-1 to a heliocentric orbit.
- It will operate in a deep-space radiation environment throughout its 12 to 18-month mission.
BioSentinel Science Concept

• Quantify DNA damage from space radiation environment
  – Space environment cannot be reproduced on earth
  – Omnidirectional, continuous, low flux with varying particle types
  – Health risk for humans spending long durations beyond LEO
  – Radiation flux can spike 1000x during a solar particle event (SPE)

• Correlate biologic response with LET and TID data
  – BioSensor payload uses engineered *S. cerevisiae* yeast
  – Measures rate of Double Strand Breaks (DSB) in DNA
  – Linear Energy Transfer (LET) spectrometer measures particle energy and count
  – Total Ionizing Dose (TID) dosimeter measures integrated deposited energy

• Yeast assay uses microfluidic arrays to monitor for DSBs
  – Three strains of *S. cerevisae*, two controls and engineered strain
  – Wet and activate multiple banks of micro-wells over mission lifetime
  – DSB and associated repair enable cell growth and division
  – Activate reserve wells in event of a Solar Particle Event (SPE)
BioSentinel: A BioSensor in Space

• **What**: BioSentinel is a yeast radiation biosensor that will measure the DNA damage caused by space radiation, specifically double-strand breaks (DSBs).

• **Why**: Deep space radiation environment cannot be duplicated on Earth.

• **How**: Engineered *S. cerevisiae* will sense and repair DNA DSBs.

• **Why yeast**: Eukaryotic organism; easy genetic / physical manipulation; DNA repair mechanism in common with humans; availability of assays; extensive flight heritage; can be stored in long-duration stasis

**Key Goals**

1) Characterize rates of DNA DSB-and-repair events during spaceflight
2) Use radiation-sensitive yeast strains to obtain survival data in space
3) Characterize DNA damage repair and cell survival in response to a solar particle event (SPE)
4) Correlate data of exposures using terrestrial radiation facilities to ambient space radiation
BioSentinel EM-1 Mission Overview

- SLS EM-1 Pre-launch Integration flow starts ~L-6 months (biology in stasis)
- Launch on SLS EM-1 in July 2018 as a secondary payload
- Deployment from the SLS 2nd Stage will achieve a lunar flyby and place BioSentinel into an Earth-Interior Heliocentric orbit
  - The BioSentinel-to-Earth Distance will increase over time
- By being outside the Van Allen Belts, BioSentinel will be in a radiation deep space environment at a nominal 1-AU from the sun
- Science Mission Duration (post launch) is 12-mo baseline, 18-mo extended, & 3-mo minimum
  - Consistent with a typical 10-mo outbound flight to Mars or 6-mo Near Earth Asteroid (NEA) manned rendezvous mission
  - The longer the mission, the greater the chance to observe a Solar Particle Event (SPE)
- Spacecraft bus provides deep space capability
- BioSentinel payload consists of:
  - BioSensor
  - Linear Energy Transfer (LET) Spectrometer (provided by JSC RadWorks)
  - Total Integrating Dose (TID) Dosimeter
BioSentinel EM-1 Mission

Launch

- Launched as a secondary payload on SLS \textbf{EM-1}
  - Exploration \textbf{Mission 1: 1st flight of NASA’s Space Launch System}
  - Pre-launch starts with loading of biology at L-6 months
- Final orbit of secondary's to be determined
- Will likely be Earth-interior, heliocentric orbit
- Far outside the LEOs typically occupied by CubeSats
  - Range to Earth of 0.73 AU at 18 months
  - Far outside the protective shield of Earth’s magnetosphere

Mission Orbit

A representative orbit that \textit{BioSentinel} might occupy
Secondary Payload Location on SLS EM-1

- 11 - dispenser locations that each support a 6U (14 kg) secondary payload
- 1 - bracket location allocated to a sequencer
- EM-1 only accommodates 6U; EM-2 may accommodate 12U payloads
BioSentinel EM-1 Spacecraft

Stowed Configuration

- Patch Antenna
  - MGA (Tx), LGA (Rx)

- Fluidic Card
  - Each Card has a Set or Bank of 16 µwells

- 18 Coplanar Fluidic Cards

Deployed Configuration (underside)

- Deployable/Single Axis Gimbal Solar Arrays
- Star Tracker (ST)
- Patch Antenna
  - LGA (Tx) & LGA (Rx)

- Transponder

- Propulsion System
- Batteries

- Avionics
- Payload
BioSentinel Launch and Deployment ConOps

<table>
<thead>
<tr>
<th>Time</th>
<th>Events</th>
<th>BioSentinel State</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-0</td>
<td>Launch</td>
<td>Powered off, 2X inhibits</td>
</tr>
<tr>
<td>T+90s</td>
<td>Ascent</td>
<td>Powered off, 2X inhibits</td>
</tr>
<tr>
<td>T+4h</td>
<td>Deployment window</td>
<td>Powered off, 2X inhibits</td>
</tr>
<tr>
<td>T+4h (TBD s)</td>
<td>BioSentinel Deployment</td>
<td>2X Switches close, power applied</td>
</tr>
<tr>
<td>D+90s</td>
<td>FSW Boot</td>
<td>FSW boot sequence complete</td>
</tr>
<tr>
<td>D+1:45m</td>
<td>Interface App Initialization</td>
<td>Interface applications loaded on FSW framework</td>
</tr>
<tr>
<td>D+2m</td>
<td>BioSensor Activated</td>
<td>Thermal control applied to biologic payload</td>
</tr>
<tr>
<td>D+2:15m</td>
<td>ADCS Unit Activated</td>
<td>ADCS booted</td>
</tr>
<tr>
<td>D+2:30m</td>
<td>Rate Reduction</td>
<td>Prop system commanded to Rate Reduction (as required)</td>
</tr>
<tr>
<td>D+3m</td>
<td>Acquire sun vector</td>
<td>ADCS commanded to acquire sun vector</td>
</tr>
<tr>
<td>D+3:30m</td>
<td>Transponder activated</td>
<td>Transponder powered on, broadcasting telemetry, state-of-health</td>
</tr>
<tr>
<td>D+5m</td>
<td>Solar arrays deployed</td>
<td>Solar arrays commanded to deploy, reacquire sun vector</td>
</tr>
<tr>
<td>D+1h (TBC)</td>
<td>Ranging, Checkout</td>
<td>Initial checkout and ranging to system to establish ephemeris</td>
</tr>
<tr>
<td>D+(4-7)d</td>
<td>Lunar flyby</td>
<td>Lunar flyby and entry to science mode</td>
</tr>
</tbody>
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BioSentinel will need to deploy as quickly as possible to apply thermal controls to payload to avoid freezing.

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## BioSentinel Month-in-the-Life ConOps

### Monitor Bus Functions

1. **Wet new card**
   - **1x per month, ATS**

2. **Collect science data**
   - **Continuous, RTS**

3. **Refresh card**
   - **1x per month, ATS**

4. **Transmit to DSN**
   - **2 to 4X per week, 2 – 4 hours per contact, ATS**

### Major Functions

#### Select card
- Determine fluidic card
- Select \( \mu \)-controller
- Select pump and valve set

#### Apply Fluids
- Open inlet valve
- Open plate valve
- Open nutrient valves
- Activate Pump

#### Configure Thermal Control
- Apply warm set points
- Apply cold set points to other cards

#### Close System
- Close inlet valve
- Close plate valve
- Close nutrient valves
- De-activate pump

#### Readout BioSensor
- Determine fluidic card
- Select \( \mu \)-controller
- Select and power well LEDs
- Select and readout sensor
- Iterate all wells

#### Readout TID sensor
- Apply power to sensor
- Wait for stabilization
- Sample analog readouts

#### Readout LET Spectrometer sensor
- Acquire binned data
- Store data in file system

#### Monitor for SPE
- Sample TID readout
- Sample LET shutter info
- Wet new card if SPE detected

#### Align spacecraft
- Determine vector to Earth
- Slew to Earth vector

#### Power Tx
- Power transmitter

#### Broadcast data
- Broadcast SOH
- On CFDP command, transmit BioSensor, LET, TID data

#### Deactivate Tx
- Power off transmitter

#### Realign spacecraft
- Slew back to sun vector

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Attitude Pointing During Communication

180°
120°
90°
85°
90°
30°
0°
5°

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BioSentinel Spacecraft Internal Configuration

- CDH / EPS / Transponder Stack
- Solar Arrays
- Solar Array Gimbal
- Patch Antenna
- LGA (Tx) & LGA (Rx)
- Propulsion System
- Batteries
- Integrated GNC Unit
- Star Tracker Cutout
- BioSensor Canister
16-Well (4x4) Fluidic Card Stack

Gap Pad contacts Enclosure wall for thermal exchange.

BioSentinel 6U Spacecraft

4U BioSensor Enclosure

9-card assemblies (2) (pumps & bags beneath)

Fluid Inlets and Outlets

Fluidic Card

Gap Pad LED PCB
Heater Spreader Bond (thermal)

Block

Bond (thermal) Spreader Heater
Detector PCB

Temp Sensor embedded in block

Calibration Well

Control PCBs

Fluidic Manifold
**Biological Support & Measurement Systems**

- support biology in stasis & growth
- enable & perform measurements
- compatible with multiple platforms
  - free flyer (EM-1), ISS, ground experiments
  - robust, standard data & power interfaces
- Configuration: 4U hermetic containment vessel
  - 1 atm internal pressure, low RH
  - **Fluidics**: 18 sets (cards) of 16 µwells each
    - 2 cards / month; 1 – 2 sets on “SPE standby”
  - **Pumps, Valves, Tubing, Media** external to cards
    - low-permeability materials to keep dry yeast dry
Payload Configuration (cont’d.)

16-well fluidic card

- Optical absorbance measurement per well
  - Dedicated 3-color optical system at each well
  - Measure dye absorbance & optical density (cell population)
  - Ground pre-calibration + in-flight “active” cal.

- Pressure & humidity sensors in P/L volume

- Dedicated thermal control system per card
  - 23°C with 1°C uniformity, accuracy, stability
  - 1 temp. sensor per card: closed-loop control
**Biology / fluidics / optical / thermal configuration**

16-well card = 1 “set”  
(18 sets total)
Fluidic Delivery System Block Diagram

Fluidic Subsystem Architecture
(2 identical 9-card units)

Bag 1: Low Leu
Bag 2: – Leu
Bag 3: Alamar blue
Bag 4: Waste

Dispensing Pump

Bag & Pump Manifold
Spring-closed valve

2 pumps, 24 valves (22 magnetically latched)
288 wells total

Version - 3/10/15
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BioSentinel (Potential) Firsts & Challenges

• 1st NASA biology studies beyond LEO in 4 decades
  – Enabling comparison across multiple radiation & gravitation environments
• 1st Complement of 6U CubeSats to fly beyond LEO (on SLS EM-1)
  – Challenges for communications and attitude control
• 1st CubeSat to combine a biology science payload with capable C&DH and FSW
  – Payload includes autonomous measurement response to SPEs

Affiliations: NASA ARC, NASA JSC, NASA GRC, LLUMC, Univ. Saskatchewan

BACK-UP
BioSentinel Teaming

The Project Team

• Management
  – Bob Hanel, Elwood Agasid, Andres Martinez, Debra Reiss-Bubenheim

• Science
  – Sharmila Bhattacharya, Macarena Parra, Tore Straume, Sergio Santa Maria, Diana Marina, C. Mark Ott, Sarah Castro, Greg Nelson, Troy Harkness

• Payload
  – Tony Ricco, Travis Boone, Ming Tan, Charlie Friedericks, Aaron Schooley, Charlie Ricco, Terry Lusby, Bobbie Gail Swan, Scott Wheeler, Susan Gavalas, Edward Semones

• Spacecraft and Bus
  – Brian Lewis, Matthew Sorgenfrei, Matthew Nehrenz, Vanessa Kuroda, Ben Klamm, Craig Pires, Shang Wu, Abe Rademacher, Josh Benton, Doug Forman, Hugo Sanchez, Brittany Wickizer

Affiliations

NASA Ames, NASA JSC - RadWorks, LLUMC, Univ. Saskatchewan

Support

NASA Human Exploration and Operations Mission Directorate (HEOMD); Advanced Exploration Systems Division – Jitendra Joshi, Jason Crusan Program Execs.
• **Radiation sensors**
  - LET spectrometer device: TimePix family solid-state device
    - energy (LET) measured
    - direction (crudely) determined
    - frequent measurement & caching of results; selective downlink
    - *technology demonstration is underway on ISS (JSC)*
  - Total integrating dosimeter: Teledyne µDOS001
    - 15 µrad resolution; ranged analog outputs
    - highly successful on LRO

**Typical TimePix frame:**
256 x 256 x 14 bits
0.25 – 150 keV/µm LET range
BioSentinel Payload currently in development for EM-1

- 18-fluidic card BioSensor Payload; each card has 16 micro-fluidic wells
- Volume: ~4U (10 cm x 20 cm x 20 cm)
- Mass: 6 – 8 kg
- Power: 5 – 8 W
- Data Volume: 0.2-1 MB/week
- Linear energy transfer (LET) Spectrometer
- Total ionizing dose (TID) Sensor

- Wet 1 card every ~ 3-4 weeks over the 12-month baseline mission
- Record consequences of cosmic radiation including solar particle event(s) if they occur