Plans for Microbial Biology Experiments on the Gateway

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NASA's Science and Exploration Directorates are Involved

- Science Mission Directorate (SMD)
  - **Planetary Science Division** supports "classical" astrobiology, i.e. studying the origin, evolution, distribution, & future of life in the universe
  - The basic plan: **offer Gateway as a platform** for doing science, as SMD does for ISS
  - **Up to individual researchers to decide** what SMD science they want to propose for Gateway within the framework of existing SMD funding channels; peer review determines what is considered

- Human Exploration and Operations Mission Directorate (HEOMD or HEO)
  - Division of **Space Life and Physical Sciences Research and Applications (SLPSRA)** supports life science research in the context of human space exploration
  - Their mission includes microbiological studies with links to human mission operations, health, and performance
  - HEO is developing a "crosscutting" plan / prioritization via their Life Science Research Capabilities Team (LSRCT) …

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Life Science Research Capabilities Team (LSRCT) at NASA

- Formed by SLPSRA/Space Biology Office at Ames
  - **Cross-cutting** team responds to interests of Space Biology (HEOMD) along with Astrobiology and Planetary Protection (Planetary Science/SMD)
- Consolidated **Space Biology/LSRCT** top level requirements submitted to NASA's Gateway Utilization Office:

Science Need	Science Goals / Objectives	Model Organisms: Main Processes Studied	Hardware (All components can be in a single BioBox for shared use)	
Understand the Deep-Space Radiation Environment	Understand acute and long-term effects on **biological organisms** of deep-space **radiation** **INSIDE** the habitation module	**Microbes --** *bacteria & yeast*: DNA damage/repair, evolutionary adaptation, microbiome, biofilms **Plants** -- *arabidopsis et al.*: Genetics -- microgreens: Micronutrient production, greens validation	1) Glovebox 2) Incubator 3) Cold Stowage 4) Microbiology Habitat	5) *In-situ* analyses (e.g. PCR, MinION, Spectrum) 6) Plant habitat
	Understand acute and long-term effects on **biological organisms** of deep-space **radiation** **OUTSIDE** the habitation module	**Microbes --** *bacteria & yeast*: DNA damage/repair, evolutionary adaptation, microbiome, biofilms **Plants:** Effects on seeds of exposure	1) Glovebox (pre/post exposure) 2) Incubator (pre/post exposure) 3) Cold Stowage (pre/post exposure) 4) Microbiology habitat	5) *In-situ* analyses (e.g. PCR, MinION, Spectrum) 6) Exposure Platform 7) Seed habitat
	Characterize the **physical radiation environment** & its effects, including shielding effects, **INSIDE** the habitation module	None	State-of-the-art sensor suite	
	Characterize the **physical radiation environment** & its effects, including shielding effects, **OUTSIDE** the habitation module	None	State-of-the-art sensor suite	

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NASA LSRCT Requirements (continued)

Science Need	Science Goals / Objectives	Model Organisms: Main Processes Studied	Hardware (All components can be in a single BioBox for shared	
Understand Deep-Space-Radiation + Altered-Gravity effects	Examine the **combined effects** of deep-space **radiation** and **reduced gravity** on **biological organisms**	**Microbes --** *bacteria & yeast*: DNA damage/repair, evolutionary adaptation, microbiome, biofilms **Plants** -- *arabidopsis et al.*: Genetics -- *microgreens*: Micronutrient production & greens validation	1) Glovebox 2) Incubator with centrifuge 3) Cold Stowage	4) Microbiology habitat 5) In-situ analyses (e.g. PCR, minion, Spectrum) 6) Plant habitat
Understand Absence-of-Magnetic-Field effects	Investigate acute & long-term effects on **biological organisms** of the absence of Earth's **geomagnetic field**	**Microbes** -- *bacteria & yeast*: General physiological & molecular effects **Plants** -- arabidopsis *et al.*: Genetics -- *microgreens*: Micronutrient production & greens validation	1) Glovebox 2) Incubator 3) Cold Stowage	4) Microbiology habitat 5) In-situ analyses (e.g. PCR, minion, Spectrum) 6) Plant habitat
Understand Absence-of-Magnetic-Field + Altered-Gravity effects	Examine the **combined effects** on **biological organisms** of absence of **magnetic field** and **reduced gravity**	**Microbes** -- *bacteria & yeast*: General physiological & molecular effects **Plants** -- *arabidopsis et al.*: Genetics -- *microgreens*: Micronutrient production & greens validation	1) Glovebox 2) Incubator with centrifuge 3) Cold Stowage	4) Microbiology habitat 5) In-situ analyses (e.g. PCR, minion, Spectrum) 6) Plant habitat

Assumptions:
All experiments utilize in situ analysis of only Priority 1 organisms: Microbiology & Plant (more complex organisms available if feasible for Gateway)
Sample return requested, but feasible Science even if unavailable
Compatible with broad temperature and gas mixture range
Compatible with Gateway ConOps & safety constraints
Compatible with TeleRobotics

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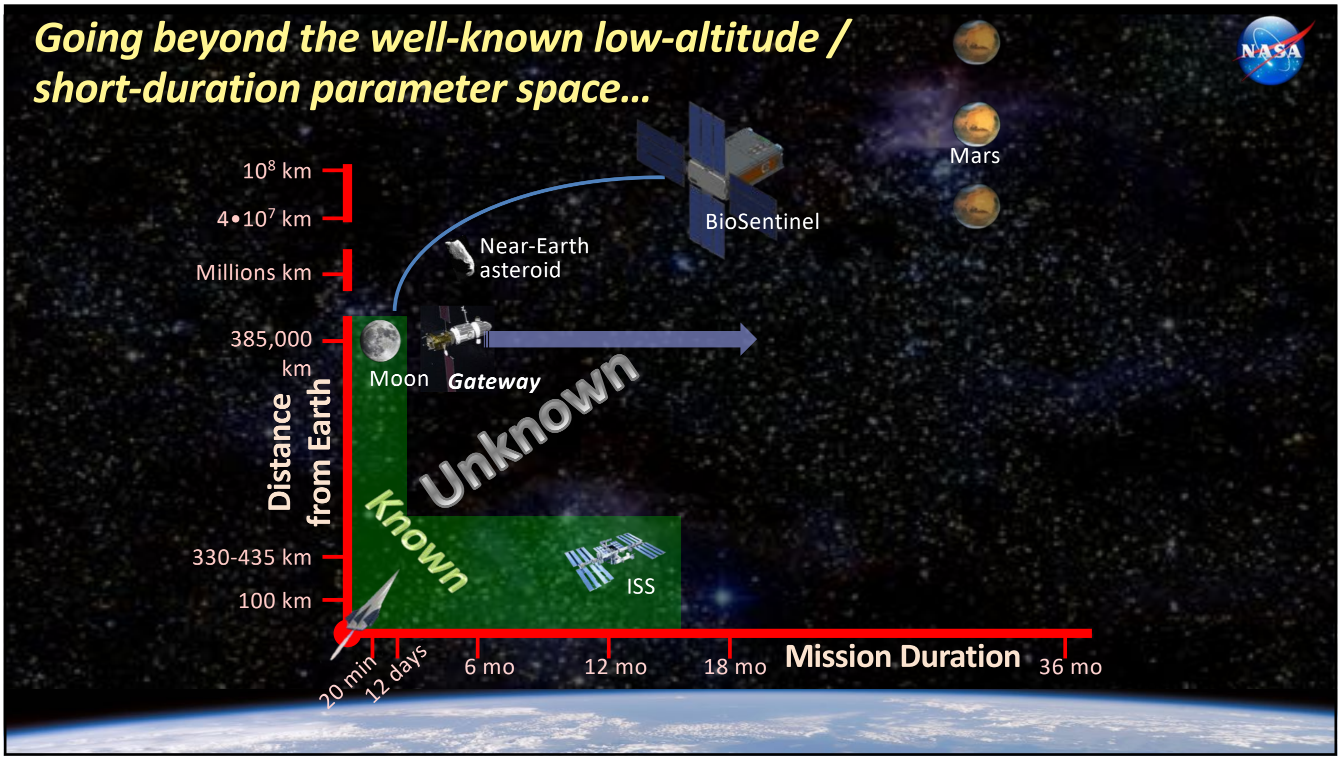
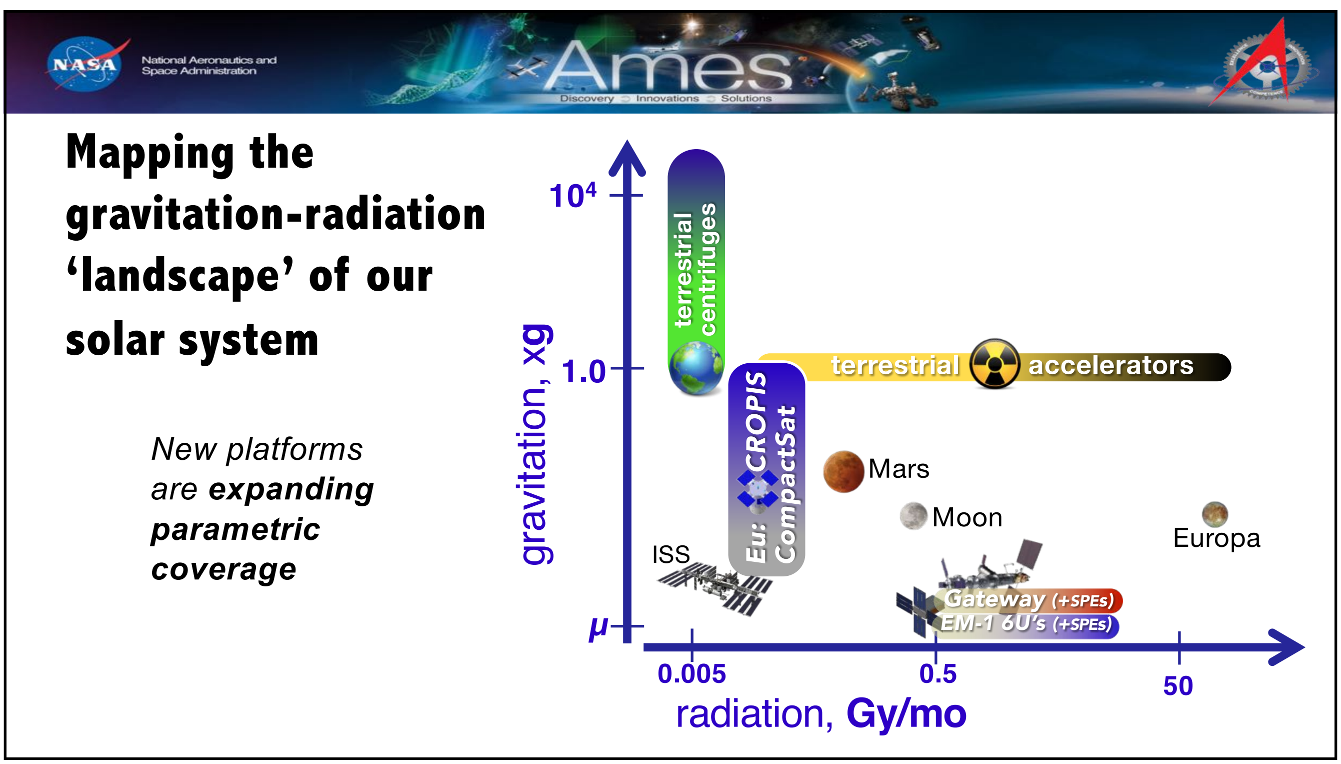

Going beyond the well-known low-altitude / short-duration parameter space…
10^8 km
4•10^7 km
Millions km
385,000 km
330-435 km
100 km
Distance from Earth
Mars
BioSentinel
Near-Earth asteroid
Moon
Gateway
Unknown
Known
ISS
20 min
12 days
6 mo
12 mo
18 mo
Mission Duration
36 mo


National Aeronautics and Space Administration
Ames
Discovery Innovations Solutions
Mapping the gravitation-radiation 'landscape' of our solar system
New platforms are expanding parametric coverage
gravitation, xg
10^4
1.0
μ
terrestrial centrifuges
terrestrial accelerators
Eu: CROPIS CompactSat
Mars
Moon
Europa
ISS
Gateway (+SPEs)
EM-1 6U's (+SPEs)
0.005
0.5
50
radiation, Gy/mo

NanoSat Technologies at NASA/Ames relevant to Astro/Biology at the *Gateway*

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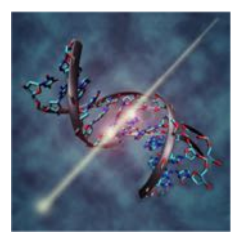
Why Study (Astro)Biology in Deep Space?

Low Earth Orbit provides perfectly adequate μ-gravity

***Answer*: Radiation.**

- Space beyond Earth's magnetosphere hosts a complex mixture of particle types
  - each particle type has its own energy spectrum
  - also: electromagnetic radiation extending into vacuum UV
- For some biological processes, **effects** of chronic low dosage of multiple particle types and energies ≠ acute dose of 1 - 2 particle types, 1 energy
  - Biology can self-repair. (Solid-state devices can too, but very differently)
  - Repair (and mutation) can profoundly impact long-term radiation effects in biological organisms that are not simulated by non-living materials
  - Cells communicate. Damage of a few cells may indirectly affect many others.
  - Cell lethality is typically not the main concern. The problem is those that survive a hit.
- High-radiation environments available in "special" cases of LEO
  - polar orbits, dense regions of Van Allen belts, So. Atlantic Anomaly
  - BUT these are not the same as deep space: GCR is shielded/modified by magnetosphere and SPEs are highly attenuated



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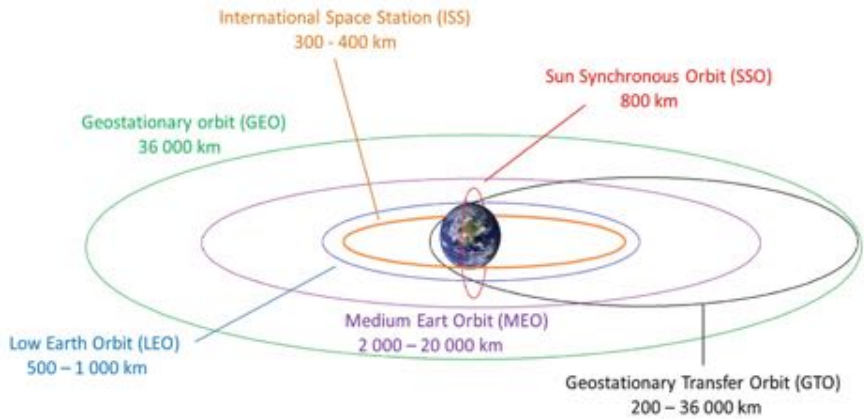
Earth Orbital Locations Near and Far



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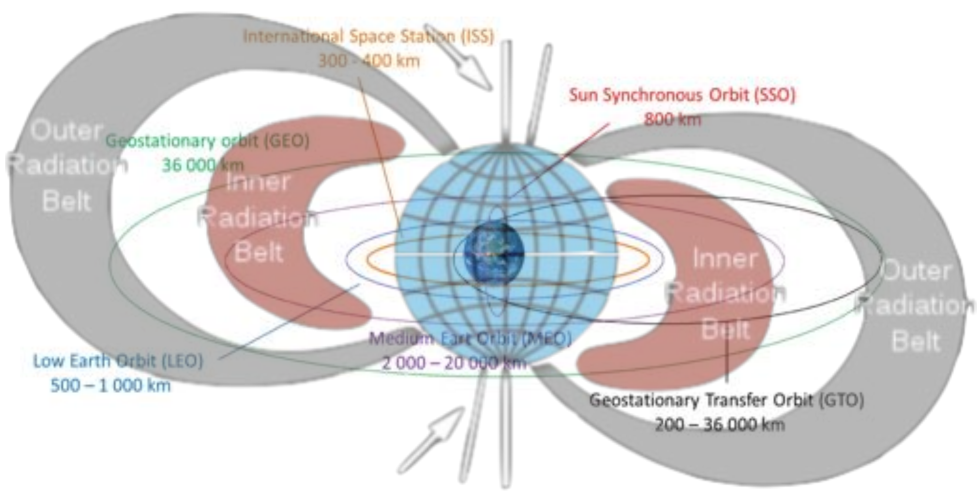
Earth Orbital Locations Near and Far



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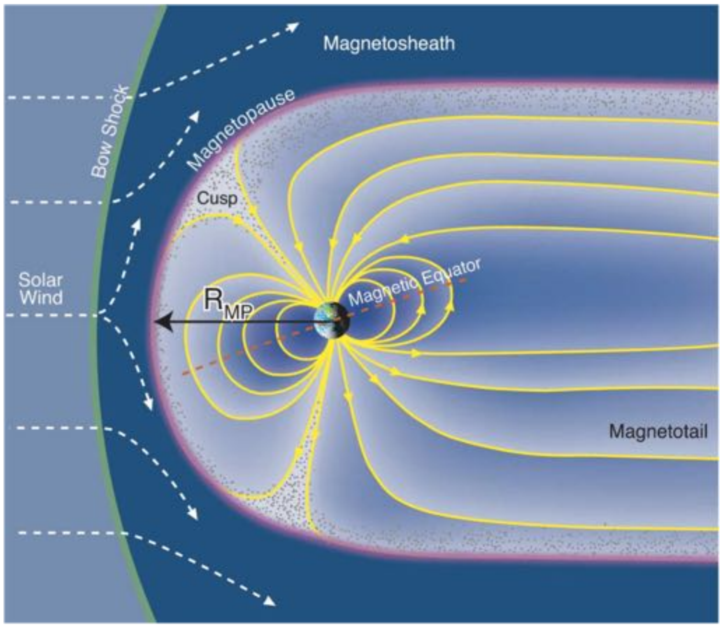
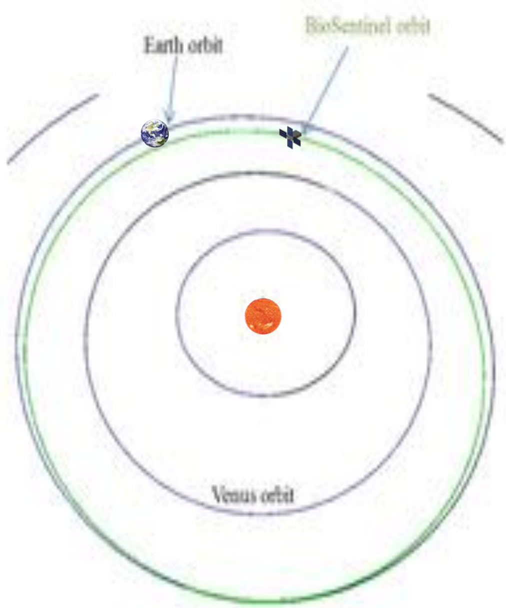
Solar Flux and the Radiation Environment in Earth's Vicinity



BioSentinel Orbits Sun, not Earth; Stays safely away from Earth, Moon

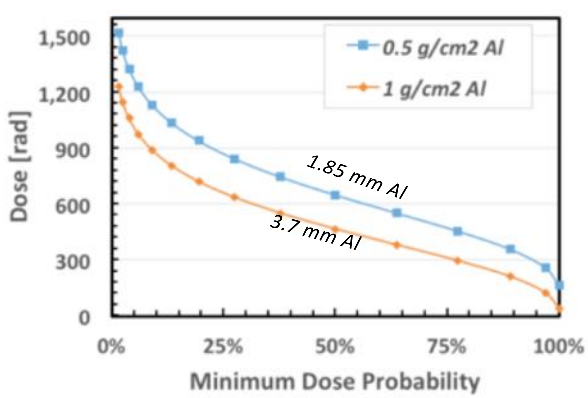


Earth Orbit & Beyond: Radiation Environments

Orbit	Altitude (from sea level, km)	Orbital Inclination[a]	Orbital Period around Earth	Predominant Particle Radiation Sources	Shielding-Dependent Monthly Radiation Dose[b] (Gy) 1 mm[c]	5 mm[c]
Low Earth Orbit (LEO)	300 – 2000	0 – 55°	90 – 127 min	electrons, protons	0.0061 – 660	0.0041 – 36
ISS in LEO	330 – 435	51.6°	91 – 93 min	electrons, protons	5 - 30	0.34 – 0.020
High-inclination LEO[d]	400 – 2000	65° – 115°	92 – 127 min	electrons, protons, GCRs, SEPs[h]	40 – 1500	0.69 – 140
Sun Synchronous LEO, including (near-) polar	400 – 1000 (typical)	~98° & others	92 – 105 min	electrons, protons, GCRs, SEPs	40 – 180	0.86 – 10
Medium Earth Orbit (MEO)	2000 – 35 750	Various	2 – 23.9 hr	electrons, protons (Van Allen Belts)	40 – 9700	0.69 – 190
Geosynchronous Equatorial Orbit (GEO)	35 786	0°	23.93 hr	electrons (Outer Van Allen Belt)	3300	32
Highly Elliptical Orbit (HEO)[e]	perigee < 1000 apogee > 35 800	Various	10.6 – 26 hr	electrons, protons (Van Allen Belt(s))	4.7 – 11000	1.3 – 190
Lunar libration points[f]	L1: 326 400 L2: 444 400	5°	27 – 29 d	GCRs, SEPs	11 – 140	0.55 – 21
Lunar orbit[j]	perigee: 363 104 apogee: 405 700	5°	27 d	GCRs, SEPs, neutrons	7.7 – 96	0.38 – 15
Interplanetary space[g]	> ~ 100 000		N/A	GCRs, SEPs	11 – 140	0.55 – 21

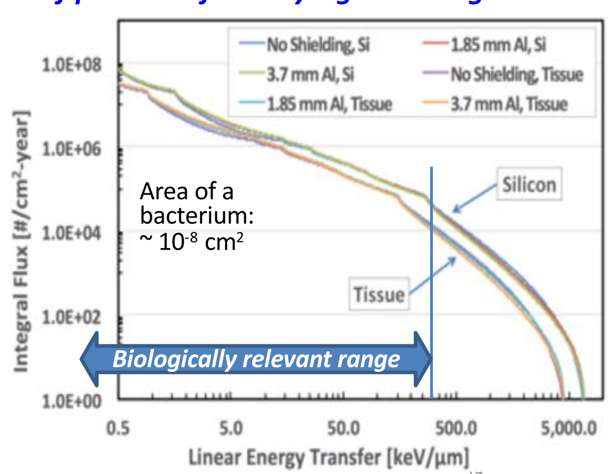
B. Klamm & A. J. Ricco, NASA Ames Research Center in Cottin et al. **2017** *Space Sci Rev, 209*, 83–181

BioSentinel *Interplanetary Radiation Environment*



Total Ionizing Dose (Si) in 1 year: Ambient Flux + possible SPE(s)

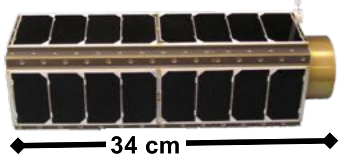
Flux (1 year) vs. linear energy transfer (LET) of particles for varying shielding thickness



Progression of NanoSat (Bio)Technologies at Ames

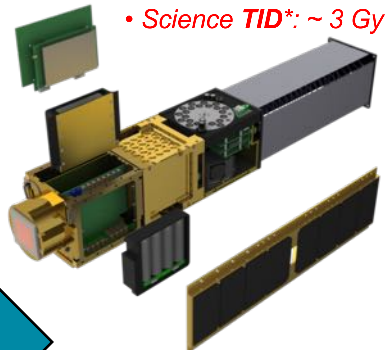
GeneSat (2004-2006-2010)

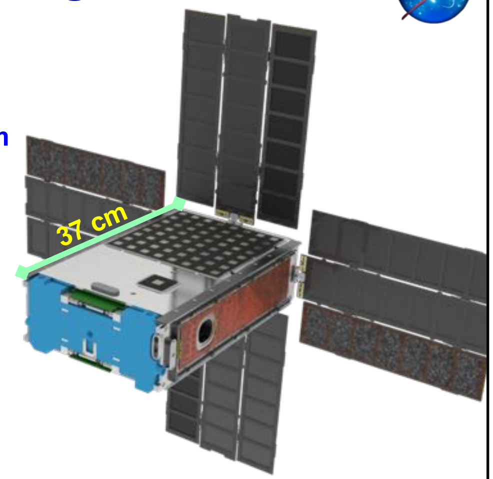
- *Orbit:* **Low Earth, 440 km**
- *Mission duration:* **1 month**
- *Orbital lifetime:* **3.7 years**
- *Science **TID***: ~ 0.5 Gy*



O/OREOS (2008-2010-2032)

- *Orbit:* **High-inclination LEO, 650 km**
- *Mission duration:* **6-17 months**
- *Orbital lifetime:* **~22 years**
- *Science **TID***: ~ 3 Gy*





BioSentinel (2013-2020-7.5 byf)

- *Orbit:* **Interplanetary** (heliocentric), **100 k – 1 M km**
- *Mission duration:* **9-18 months**
- *Orbital lifetime:* ***7.6 billion years***
- *Science **TID***: ~ 10 Gy*

***TID** = total ionizing dose in science phase
these estimates include minimal shielding
1 Gy = 100 rad

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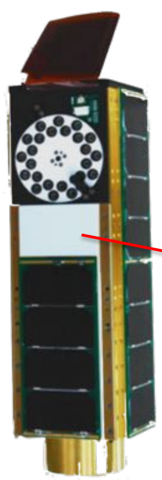
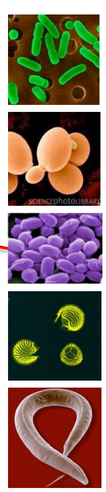
NASA Ames - NanoSatellite Biological Space Missions





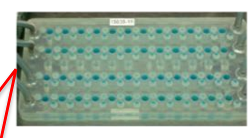
E. Coli *GeneSat-1* (2006/3U): ***gene expression***
EcAMSat (2017/6U): ***antibiotic resistance***

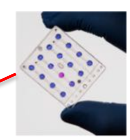
S. Cerevisiae *PharmaSat* (2009/3U): ***drug dose response***
BioSentinel (2029/6U): ***DNA break/repair***

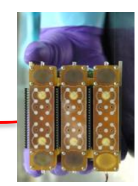
B. Subtilis *O/OREOS** (2010/3U): ***survival, metabolism***
*ADRoIT-M*** (20xx/6U): ***mutations / lithopanspermia***

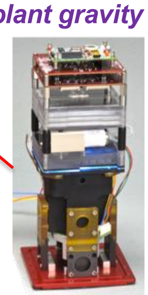
Ceratopteris Richardii *SporeSat-1* (2014/3U): **ion channel sensors, μ-centrifuges**
SporeSat-2 (20xx/3U): ***plant gravity sensing threshold***

C. Elegans *FLAIR* (20xx/3U):
dual-wavelength
fluorescence imager









*Organism/Organic Exposure to Orbital Stresses
**Active DNA Repair on Interplanetary Transport of Microbes

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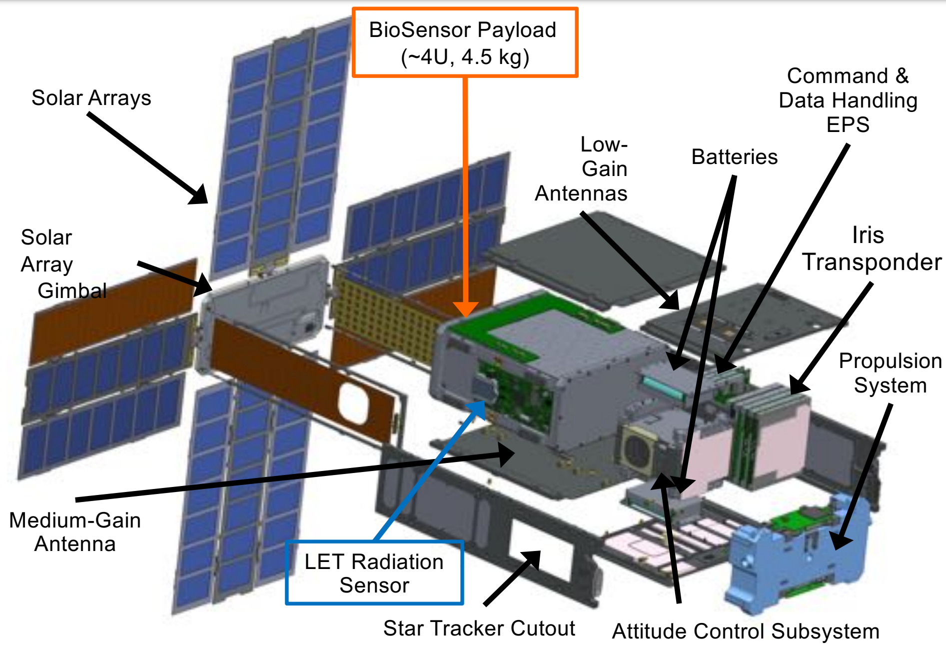
BioSentinel Subsystem Overview: moving from LEO to deep space



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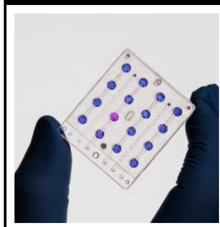
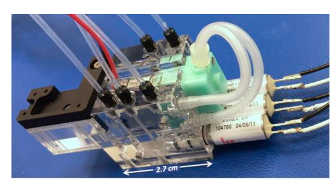
Biosentinel Advances in Biological & Radiation Science Capabilities-1



Integrated Microfluidics Advances:

Deep-space autonomous microbiology experiments enabled by new microfluidics capabilities

- **Large *n*:** Eighteen independently activated 16-microwell fluidic cards
- **Manifold Integration:** fluidic, optical, thermal components in monolithic manifolds
- **Long-duration biological specimen stabilization:**
  - Dormant fluidic cards "refrigerated" (only active cards held at growth temperature)
  - Low-moisture-permeability optical cover layers + desiccant improve dried cell longevity
  - Stasis tested to > 24 months for *S. cerevisiae*
- **All microbes measured:** optical paths include entire cell-containing volume
- **High-accuracy optical measurements:**
  - Integrated optical calibration cell per manifold enables *in-situ* calibration of 3-wavelength optical density/absorbance measurements at every microwell
  - Wavelengths custom selected for each experiment from 10's of LED options
- **Ease of sterilization:** Fluidic cards autoclavable; integrated manifolds rad. sterilized
- **Wide range of fluidic functions:** Active pumps, 3-way/2-way valves; passive check valves; bubble traps; moisture traps (desiccant); defined-pore-size membranes



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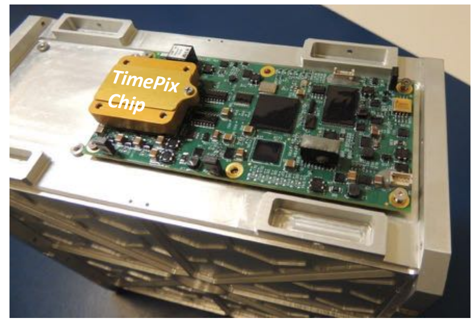
Biosentinel Advances in Biological & Radiation Science Capabilities-2

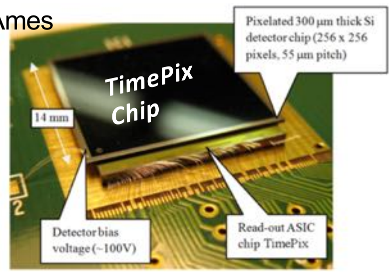
Radiation Sensing Advances

Low-power miniaturized linear energy transfer (LET) spectrometer:

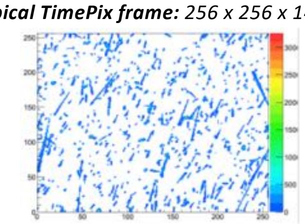
- **Hourly 256-bin LET spectrum:** 0.2 – 300 keV/μm
- Enables correlation of local “space weather” w/ biological effects
- Wilkinson-type ADC, direct energy measurement per pixel
- Categorizes each **event by particle type** / energy
- Calculates / reports **TID** (total ionizing dose)
- JSC Radworks **single-PC-board** implementation uses Timepix (*CERN*-developed) sensor
- Automatic integration time adjustment
- SPE “auto-trigger” designed by Ames



***Single-board LET spectrometer** mounted on BioSentinel payload enclosure*



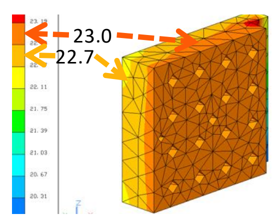
***Typical TimePix frame:** 256 x 256 x 14 bits*

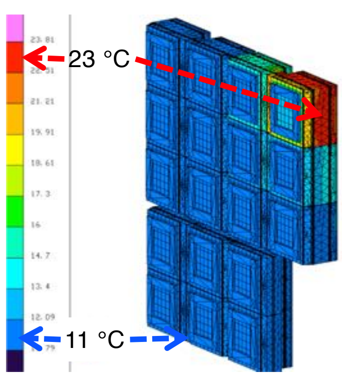


Biosentinel Advances in Biological & Radiation Science Capabilities-3

Thermal Management Advances

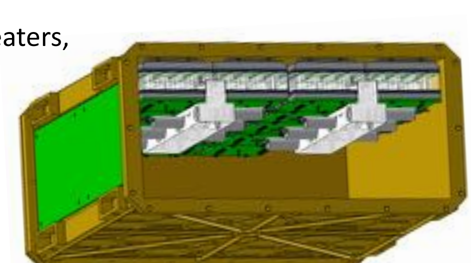
- **23 °C biology temp.** for “active growth” fluidic card
- **“Passive Refrigeration” ~ 8 °C for non-active cards** to maintain biological viability
  - “Keep-alive” 4 °C minimum at all times, cards & reagents





As-modeled, < 0.5 W to heat one card

- 46,000 Nodes, 6 heat loads, 18 heaters, 206 contactors; FD & FE objects
- Fluidics card components meshed separately (2200 nodes) at high resolution: capture thermal gradients, measure uniformity



"Adapting" Conventional Electronics to Space Flight

- Integrated circuits (ICs) are becoming inherently more radiation tolerant
  - Smaller feature sizes, thinner dielectrics: lower probability of trapped charge
- ICs for challenging environments – e.g. automobiles – are often quite radiation tolerant
  - E.g., TI MSP430 microcontroller (*BioSentinel*), available with F-RAM
- Use multiple "watchdog timers", both software and hardware to recover from latch-ups
  - Write "self-recovering" software
- Use redundant / error-checking storage of both data and experiment state
  - And keep humans out of the loop as much as possible
- Design circuits that include sensitive components be to dose-tolerant
  - MOSFET power switches

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Thanks!

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$ for *BioSentinel*: NASA Advanced Exploration Systems (HEOMD)

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