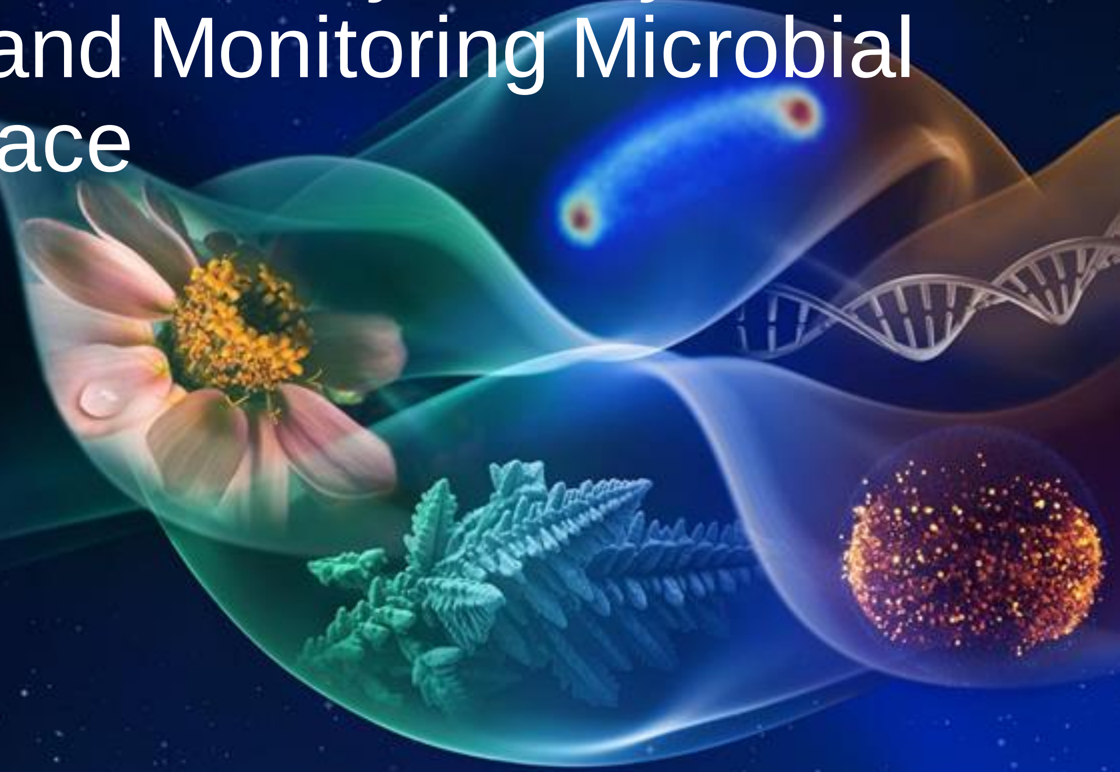
Integrated Microfluidic Bioanalytical Systems for CubeSats: Growing and Monitoring Microbial Cultures in Outer Space



Presentation by:

Diana Ly

Macarena Parra

Tony Ricco

NASA Ames Research Center


SPHEREX
IXPE
SPRITE
PANDORA
ASPERA
NUSTAR
BURSTCUBE
STARBURST
BLACKCAT
TESS
CUTE
NEASCOUT
JANUS
CPOD*
PATCOOL
CRYOCUBE
SPORESAT+
ACS3
STARLING
STF-1
IPEX+
PREFIRE
PHONESAT+
ALBUS+
GPX2
CYGNSS
TSIS-2
HYTI
NANOSAIL-D+
MINI-CARB*
RADSAT-G
OCSD-A*+
OCSD-B/C*+
ISARA+
TECHEDSAT-8*
EDSN+
CSUNSAT-1+
ASTERIA*+
HALOSAT
TECHEDSAT-12
PETITSAT
SPORT
MINXSS+
SORTIE
DELLINGR*+
R5-S1
RAINCUBE+
NACHOS 2
CSIM-FD
NACHOS
CIRIS-BATC
CTIM-FD
ICECUBE+
HARP
CUBERRT+
TEMPEST-D+
EcAMSat+
July 2021
PTD-1 HYDROS*
PTD-2 HYPER XACT*
PTD-3 T-BIRD*
PTD-4 LISA-T*
LUNAR ICECUBE
CAPSTONE
LUNAR TRAILBLAZER
LUNIR
LUNAR FLASHLIGHT
LUNAH-MAP
CU-E3
TEAM MILES
CISLUNAR EXPLORERS
BIOSENTINEL
SWFO-L1
PHARMASAT*+
TECHEDSAT-7*
GENESAT*+
COURIER SEP DEMO*
O/OREOS+
TILE DEMO*
RAVAN+
X-NAV*
ACMES
TROPICS
DUPLEX*
TROPICS PATHFINDER
CLICK-A*
ARCSTONE
CLICK-B/C*
NODES+
MC/COVE-2+
V-R3X
SNOOPI
PACE1
ATHENA
GRIFEX+
MIRATA
PACE2
PACE3
CHOMPTT*
SEEKER-1+
PACE4
EZIE
CERES
MINXSS-2+
ICON
SOLAR CRUISER
CURIE
AERO
REAL
CUPID
LLITED
PUNCH
CIRBE
ITC
CUSP
AEPEX
DAILI
VISTA
Q-PACE
ELFIN (A/B)
TRACERS
LMRST-SAT*+
GTOSAT
SUNRISE
SHIELDS-1*
DIONE
TBEX+
GLIDE
LAICE
HEOMD
JASD
EARTH SCIENCE
HELIOPHYSICS
PLANETARY SCIENCE
ASTROPHYSICS
BIOLOGICAL & PHYSICAL
STMD
ON-ORBIT ANOMALY
ESCAPADE
MARS HELICOPTER INGENUITY
MARCO (A/B)+
FUTURE MISSIONS IN BOLD
PARTNER-LED MISSIONS*
COMPLETED MISSIONS+
OPERATING, PAST, & FUTURE
SMALLSAT/CUBESAT FLEET
For questions, please contact Florence Tan.

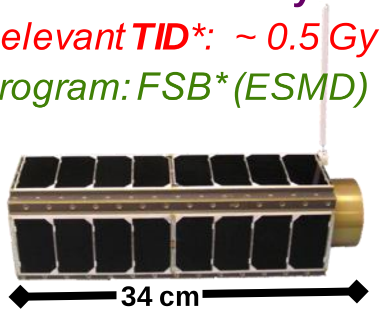
Ames Biological Small Satellite Payloads & Missions

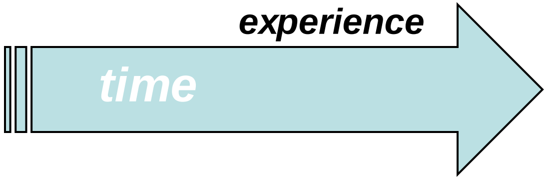
Mission* (format)	Description	Launch Date	Outcome
GeneSat-1 (3U)	• 2U payload measured expression of GFP in *E. coli* and tracked microbe population via light scattering • 1st NASA nanosatellite mission; 1st biological payload to fly in space in cubesat platform	2006	Full mission success
PharmaSat (3U)	• 2U payload measured antifungal drug dose response for *S. cerevisiae* using colorimetry to measure metabolic activity and population vs. time • 1st NASA PI-led nanosatellite mission	2009	Full mission success
O/OREOS (3U)	• Two independent 1U astrobiology payloads measured (a) survival of *B. subtilis* to 6 months and (b) photo-degradation of biomarkers and bio-building blocks for > 1.5 years via UV-visible spectroscopy • High-radiation high-inclination orbit; de-orbit mechanism; cells rehydrated in space	2010	Full mission success, both payloads Spacecraft operable ~ 5 years in orbit
SporeSat-1 SporeSat-2 (3U)	• 2U payload measures gravitational response of *C. richardii* fern spores via Ca^{2+} ion channel response • Variable **g** in microgravity ambient using 50-mm µcentrifuges with 32 ion-specific [Ca^{2+}] electrode pairs	SporeSat-1: 2014 SporeSat-2: dhyb	SporeSat-1: Successful spaceflight demo. of µcentrifuges & integral ion-specific electrodes
EcAMSat (6U)	• 2U payload measured antibiotic resistance in microgravity vs. dose for uropathogenic *E. coli* • 1st biological nanosat deployed from ISS; 1st Ames 6U biological nanosat	2017	Full mission success
BioSentinel (6U)	• 4U payload to measure radiation-induced DNA damage in radiation-sensitive S. cerevisiae strain and correlate with physical radiation dosimetry and spectroscopy • NASA Ames' 1st deep space nanosat.; 1st biology experiment beyond low Earth orbit since Apollo era	2021(?)	TBD

Ames Biological Small Satellite Payloads & Missions

GeneSat (2004-2006-2010)

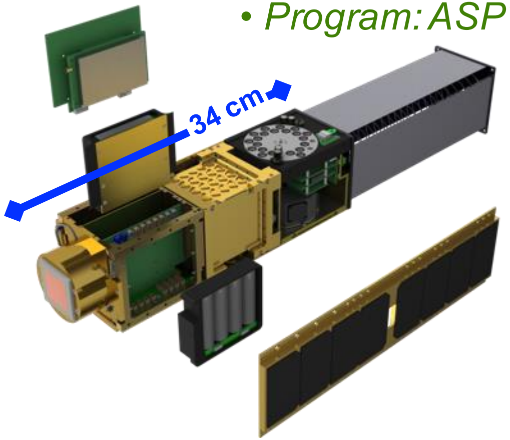
- *Orbit:* **Low Earth Orbit, 440 km**
- *Mission duration:* **1 month**
- *Orbital lifetime:* **3.7 years**
- *Relevant **TID***: ~ 0.5 Gy*
- *Program: FSB* (ESMD)*

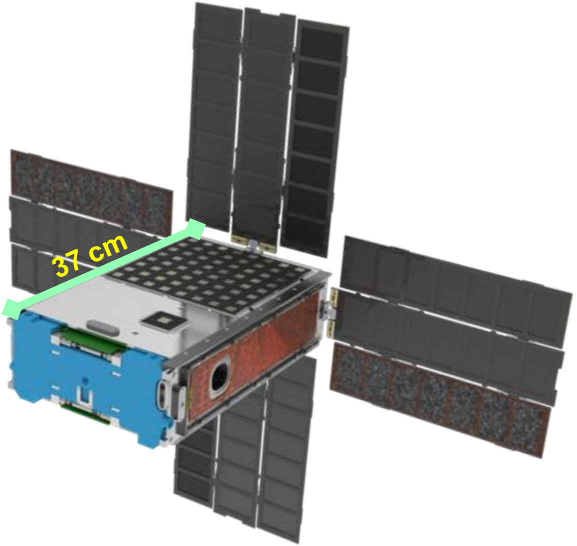




O/OREOS (2008-2010-2032)

- *Orbit:* **High-inclination LEO, 650 km**
- *Mission duration:* **6 – 18 months**
- *Orbital lifetime:* **~22 years**
- *Relevant **TID***: 1 – 50 Gy*
- *Program: ASP* (SMD)*





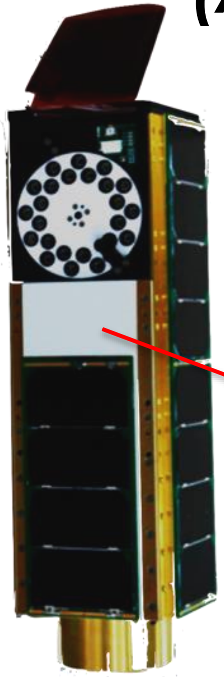
BioSentinel (2013-2021-7500000000)

- *Orbit:* **Interplanetary** (heliocentric), **100 k – 60 M km**
- *Mission duration:* **3 – 9 months**
- *Orbital lifetime:* ***~ 7.5 x 10^9 years***
- *Relevant **TID***: ~ 3 Gy*
- *Program: AES* (HEOMD)*

****TID** = total ionizing dose*

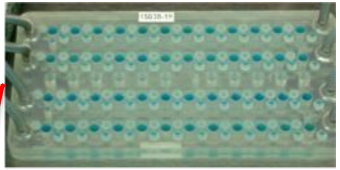
**FSB = Fundamental Space Biology *ASP = Astrobiology Small Payloads *AES = Advanced Exploration Systems*

Summary of NASA Ames' Nanosatellite (Astro)Biological Space Missions

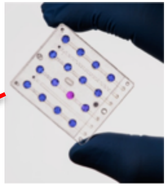


O/OREOS

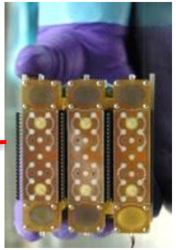
E. coli *GeneSat-1* (**2006**/3U): ***gene expression***
EcAMSat (**2017**/6U): ***antibiotic resistance***

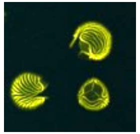


S. cerevisiae *PharmaSat* (**2009**/3U): ***drug dose response***
BioSentinel (**2021**/6U): ***DNA break/repair***



B. subtilis *O/OREOS** (**2010**/3U): ***survival, metabolism***





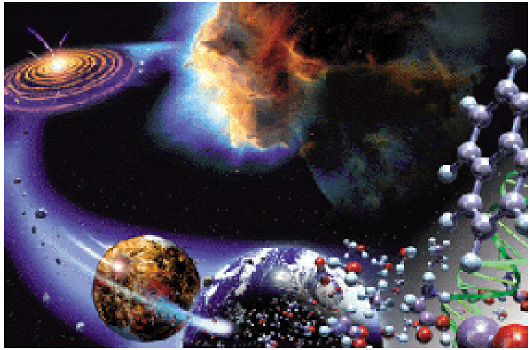
C. richardii *SporeSat-1* (**2014**/3U): **ion channel sensors, μ-centrifuges**
SporeSat-2 (3U): ***plant gravity sensing threshold***

**Organism/Organic Exposure to Orbital Stresses*

Astrobiology & Space Biology

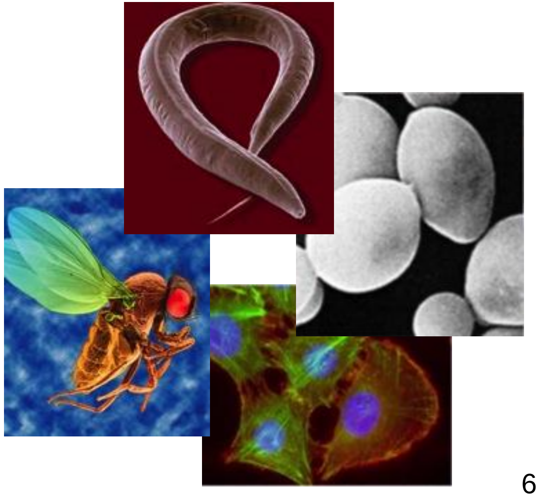
Astrobiology: origin, evolution, distribution, & future of life in the universe

- ***Why: fundamental understanding of life***
- Prebiotic chemistry – chemical building blocks of life – details, distribution
- Potential for life to adapt/survive in non-terrestrial environments
- Search for indicators of extant or extinct non-terrestrial life
- Find habitable environments in our solar system & beyond



Fundamental Space Biology: space environment effects on terrestrial life

- Reduced gravity effects
  - ***Mammals***: fluid distribution, musculoskeletal loading ⇒ immune stress, decreased bone density, muscle atrophy, slowed wound healing
  - ***Cells***, ***microbes*** in culture: nutrient and waste transport
- Radiation effects: damage from (high-energy) ionizing radiation
  - Greater outside Earth's magnetosphere, ~70,000 km
  - DNA damage: strand breaks, mutations
  - Cell membrane, protein, oxidative damage; cell death
- Bio/chemical effects of extraterrestrial environments: dust etc.
- Synergies of combined effects possible
- ***Why: human space travel, moon/planetary habitation; insights & therapies for human disease, aging, radiation effects***



Biology Beyond LEO is integral to NASA's goals

Conditions Beyond Low Earth Orbit cannot accurately be simulated closer to home

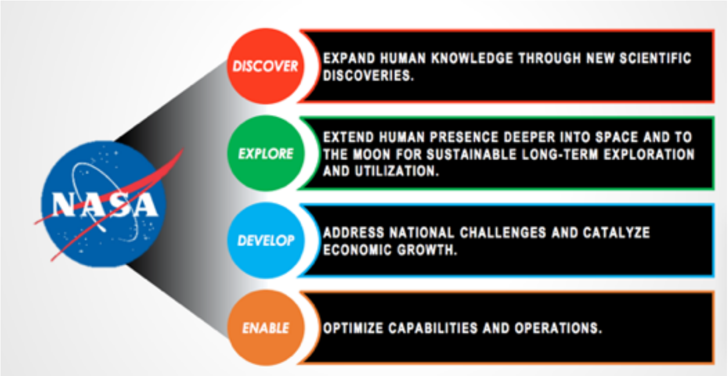
- Unique radiation environment
- Combined radiation + partial gravity

BLEO research addresses multiple recommendations of the 2010 Decadal Survey in Biological & Physical Sciences

- P2: robust spaceflight program to understand biological responses to multiple spaceflight stimuli
- CC8, CC9: Use of model organisms to assess radiation risk to humans in space – in a way that cannot be simulated on the ground

Engineering challenges still limit life support/ experiment support systems

- Radiation shielding
- Biocompatibility
- Thermal environment
- Data transmission
- Autonomy
- Duration/Late Load

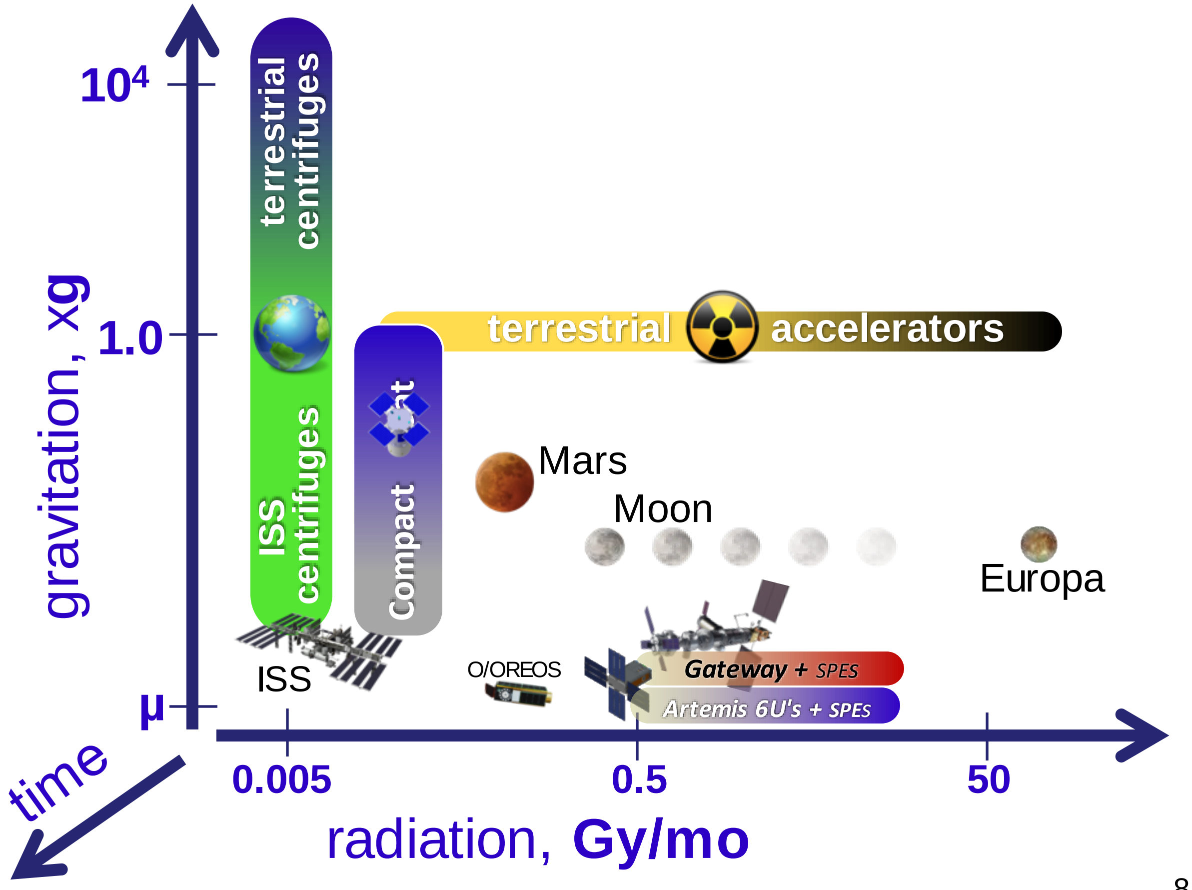


Theme	Strategic Goal	Strategic Objective
DISCOVER	EXPAND HUMAN KNOWLEDGE THROUGH NEW SCIENTIFIC DISCOVERIES.	1.1: Understand the Sun, Earth, Solar System, and Universe.
		1.2: Understand Responses of Physical and Biological Systems to Spaceflight.
EXPLORE	EXTEND HUMAN PRESENCE DEEPER INTO SPACE AND TO THE MOON FOR SUSTAINABLE LONG-TERM EXPLORATION AND UTILIZATION.	2.1: Lay the Foundation for America to Maintain a Constant Human Presence in Low Earth Orbit Enabled by a Commercial Market.
		2.2: Conduct Exploration in Deep Space, Including to the Surface of the Moon.

In NASA's Strategic Plan 2018, the Discover and Explore themes prompt Astrobiology and Space Biology BLEO research

BioMapping the gravity-radiation-time "landscape"

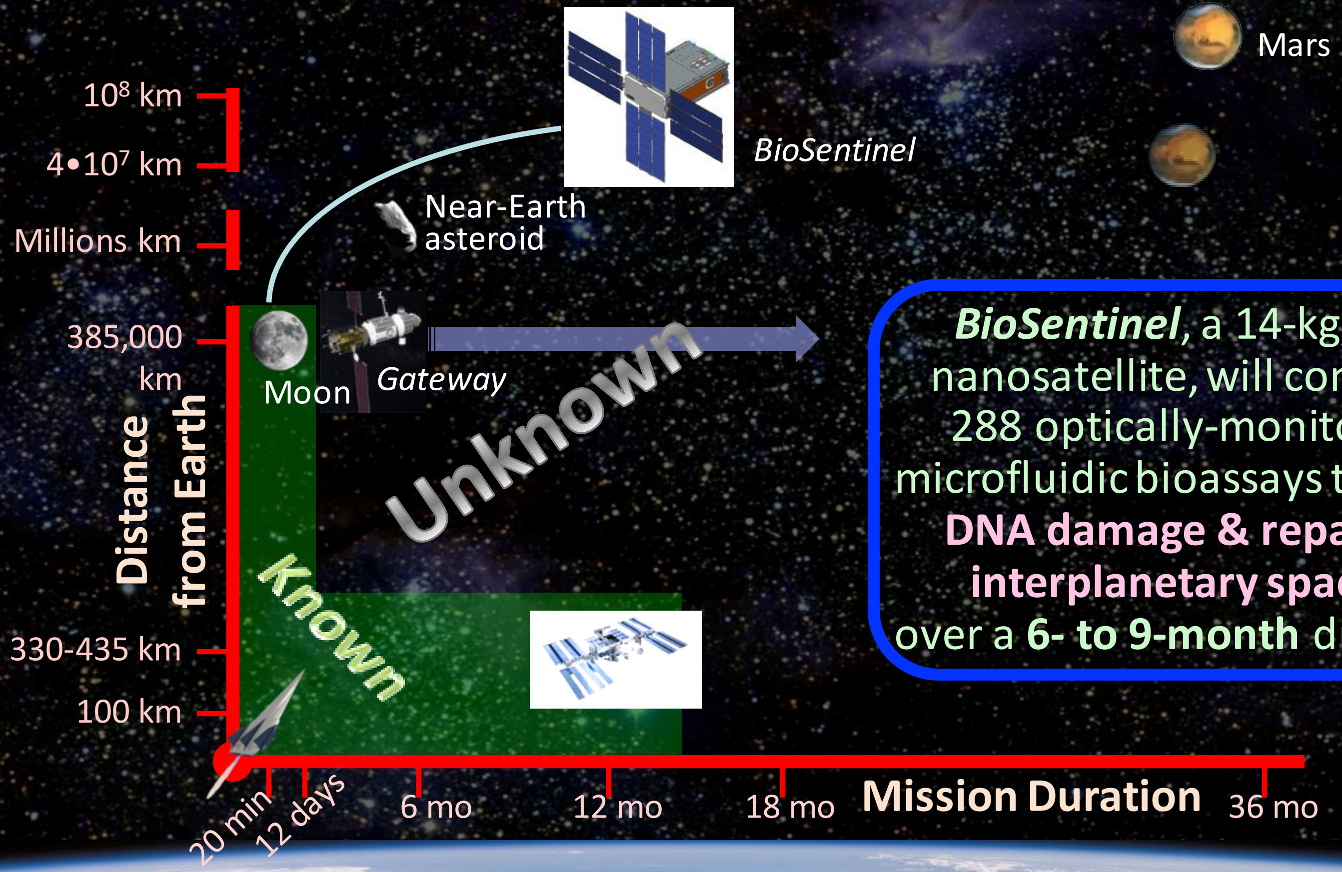
New options for orbits / destinations, rotation rates, and mission duration are ***expanding parametric coverage***



"Biomapping" our solar system: going beyond the known low-altitude / short-duration mission parameter space...

<u>BioMapping:</u>

Looking for **Life Signatures** *and* testing **Terrestrial Life** in many locations

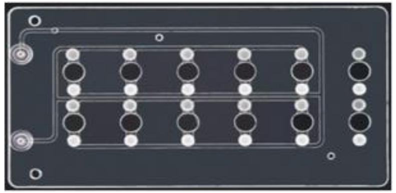


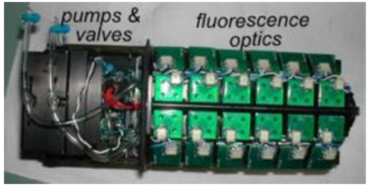
BioSentinel, a 14-kg, 6U nanosatellite, will conduct 288 optically-monitored microfluidic bioassays to track **DNA damage & repair** in **interplanetary space*** over a **6- to 9-month** duration

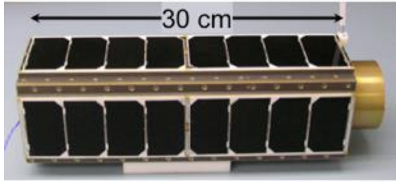
**9 time points; 32 microwells/timepoint*

GeneSat-1: 1st biological nanosatellite in LEO, 1st real-time, gene expression measurement in space

model organism:
0.5 x 2 µm
bacteria
E. coli

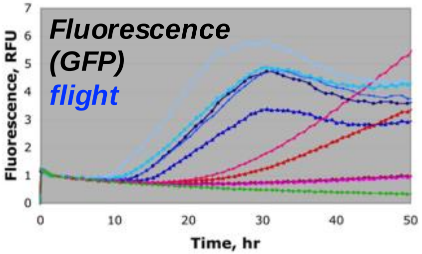




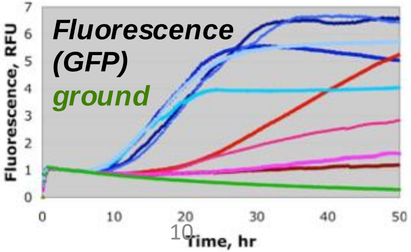


- nutrient deprivation in dormant state (6 weeks)
- launch: December 16, 2006 to low Earth orbit (440 km)
- nutrient solution feed upon orbit stabilization, grow *E. coli* in µgravity
- monitor green fluorescent protein (***GFP***): gene expression
- monitor optical density: cell population

Telemeter data to Earth

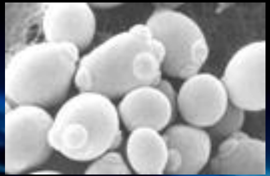


Compare to ground data



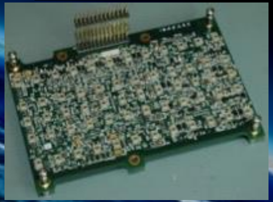
PharmaSat: *Effect of Microgravity on Yeast Susceptibility to Antifungal Drugs*

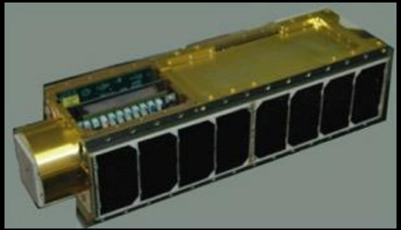
- Grow yeast in multiwell fluidics card in µ-gravity
  - Measure inhibition of growth by antifungal
  - Optical absorbance (turbidity: cell density)
  - Metabolism indicator dye: Alamar Blue
  - Control + 3 concentrations of antifungal



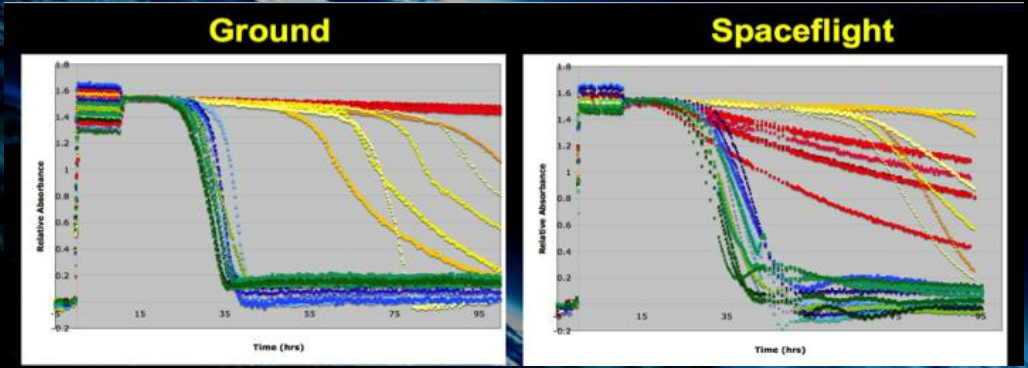
S. cerevisiae

+





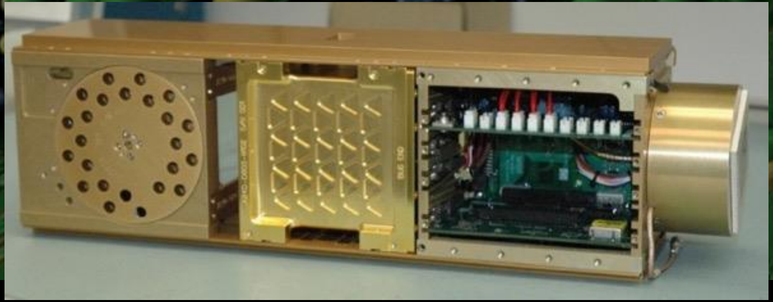
19 May 2009



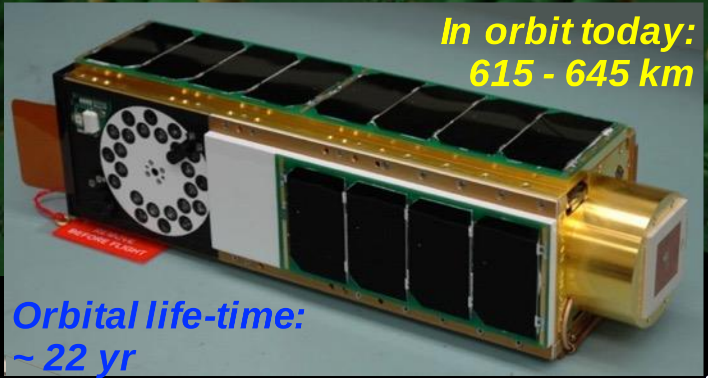
O/OREOS Astrobiology Mission

Effects of space exposure on biological organisms (6 mos.) & organic molecules (18 mos.)

- Monitor survival, growth, and metabolism of *Bacillus subtilis*:
  in-situ optical density / colorimetry
- Track changes in organic building blocks and biomarkers:
  UV / visible / NIR spectroscopy



Flight prototype

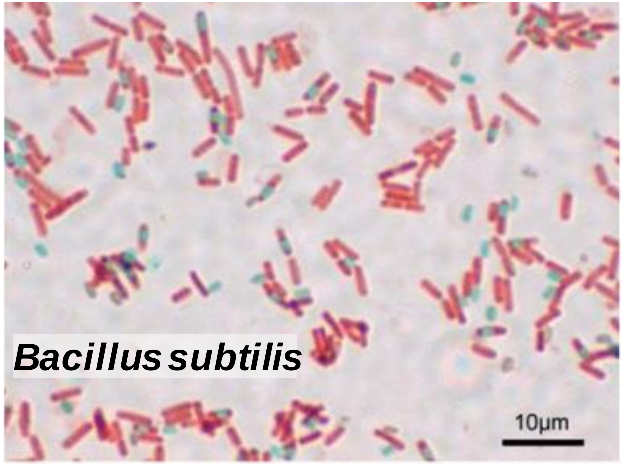


Ehrenfreund *et al*, *Acta Astro* 93, 501 (2014)

Payload 1: Space Environment Survivability of Live Organisms (SESLO)

Organisms, wildtype & mutant, exposed to μgravity & space radiation

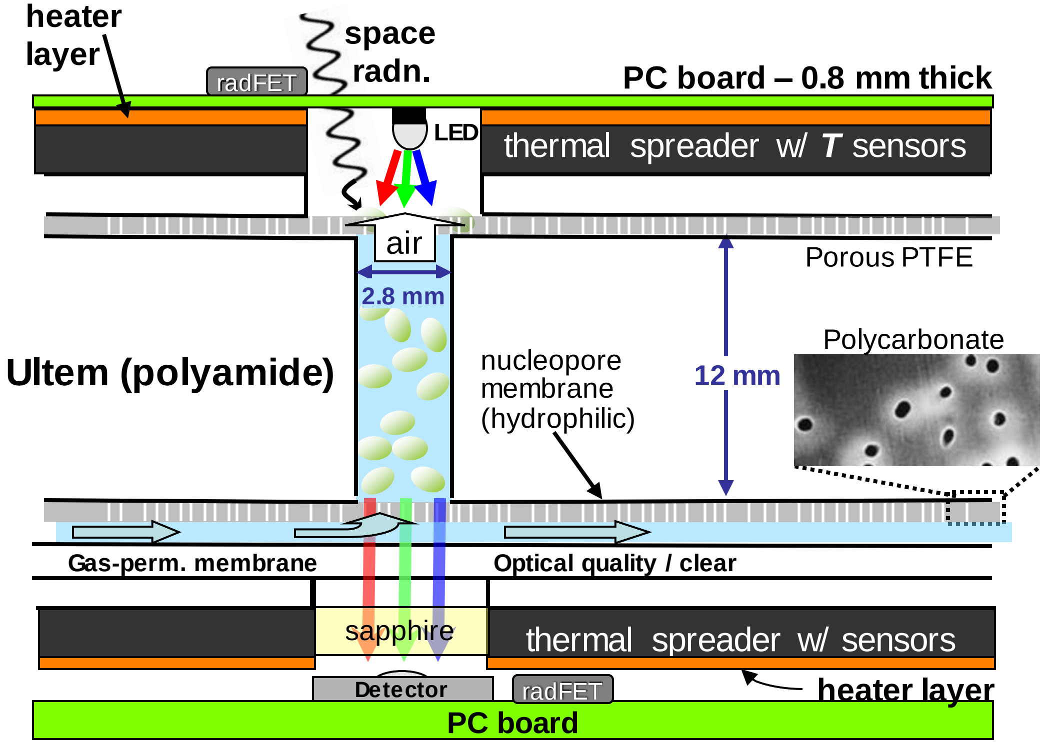
- On Earth: dry organisms on microwell walls
- In space: Rehydrate & feed 6 μwells / organism:
  t = 2 wk, 3 mo, 6 mo **(requires perfect sterility)**
- Grow @ **37 °C for ~3 days**
- Measure RGB absorbance@ **615**, **525**, **470** nm
  - track culture population via optical density
  - track metabolic activity via [**Alamar Blue]**
- Sensors: ***T***, ***p***, ***RH***, ***rad*** (integrated dose), **μgrav**
  - » temperature (6 sensors per 12-well bioblock)
  - » pressure, relative humidity (1 sensor each)
  - » radiation total dose @ both ends of wells (2 radFETs)
  - » microgravity levels calc'd. from solar panel currents

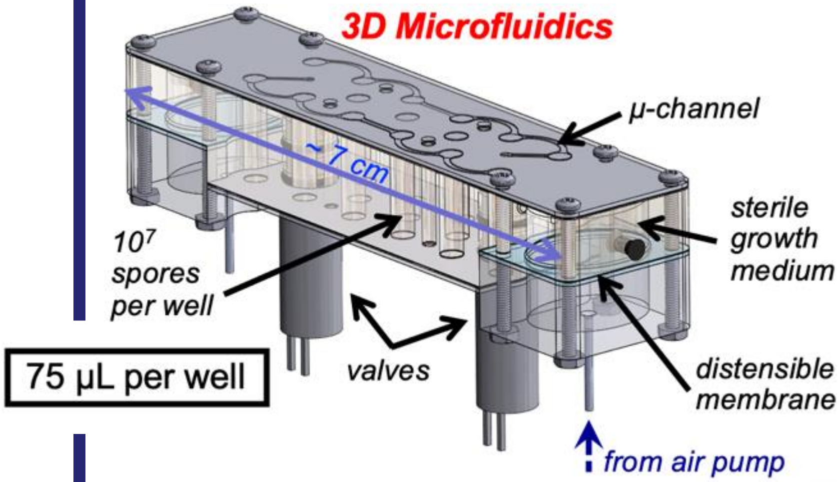


Nicholson *et al.*, *Astrobio 11*, 951 (2011); Nicholson & Ricco, *Life 10*, 1 (2020).

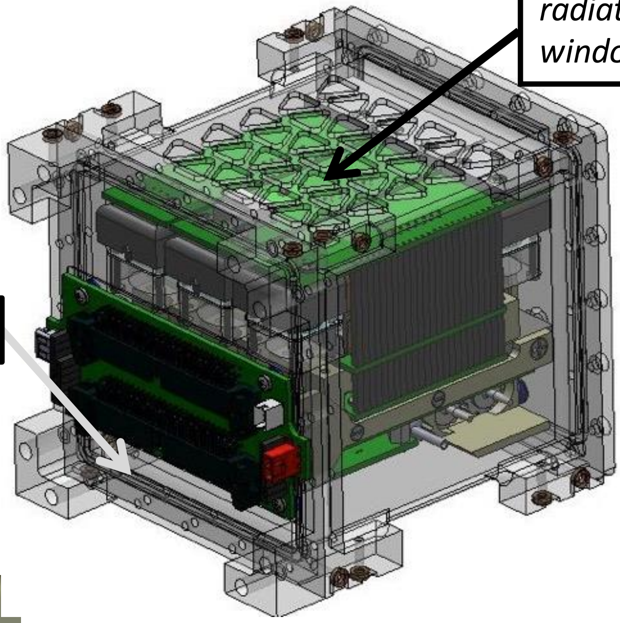
SESLO payload on O/OREOS

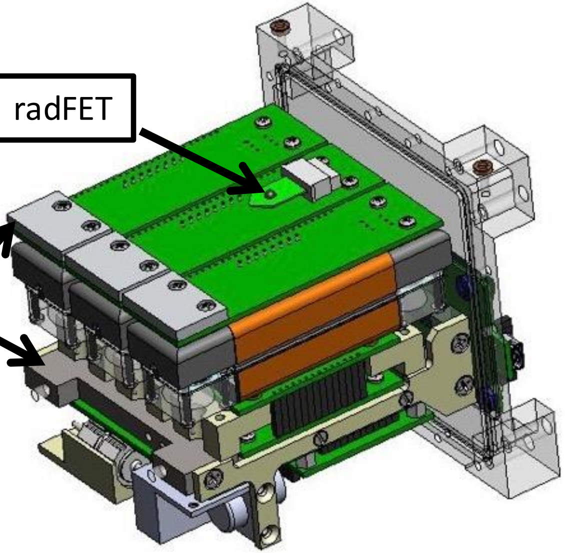
Biological / fluidic / optical / thermal cross-section





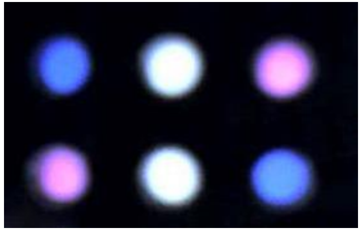
SESLO Integration Summary



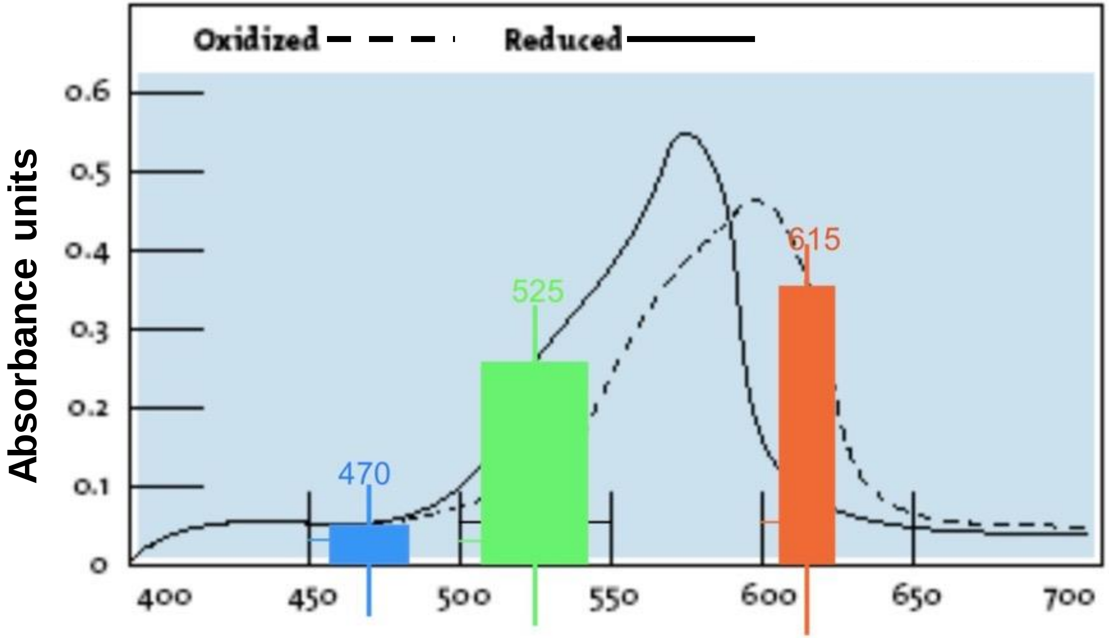


AlamarBlue:
"viability dye" changes color & becomes fluorescent in response to metabolic activity of almost any cell type

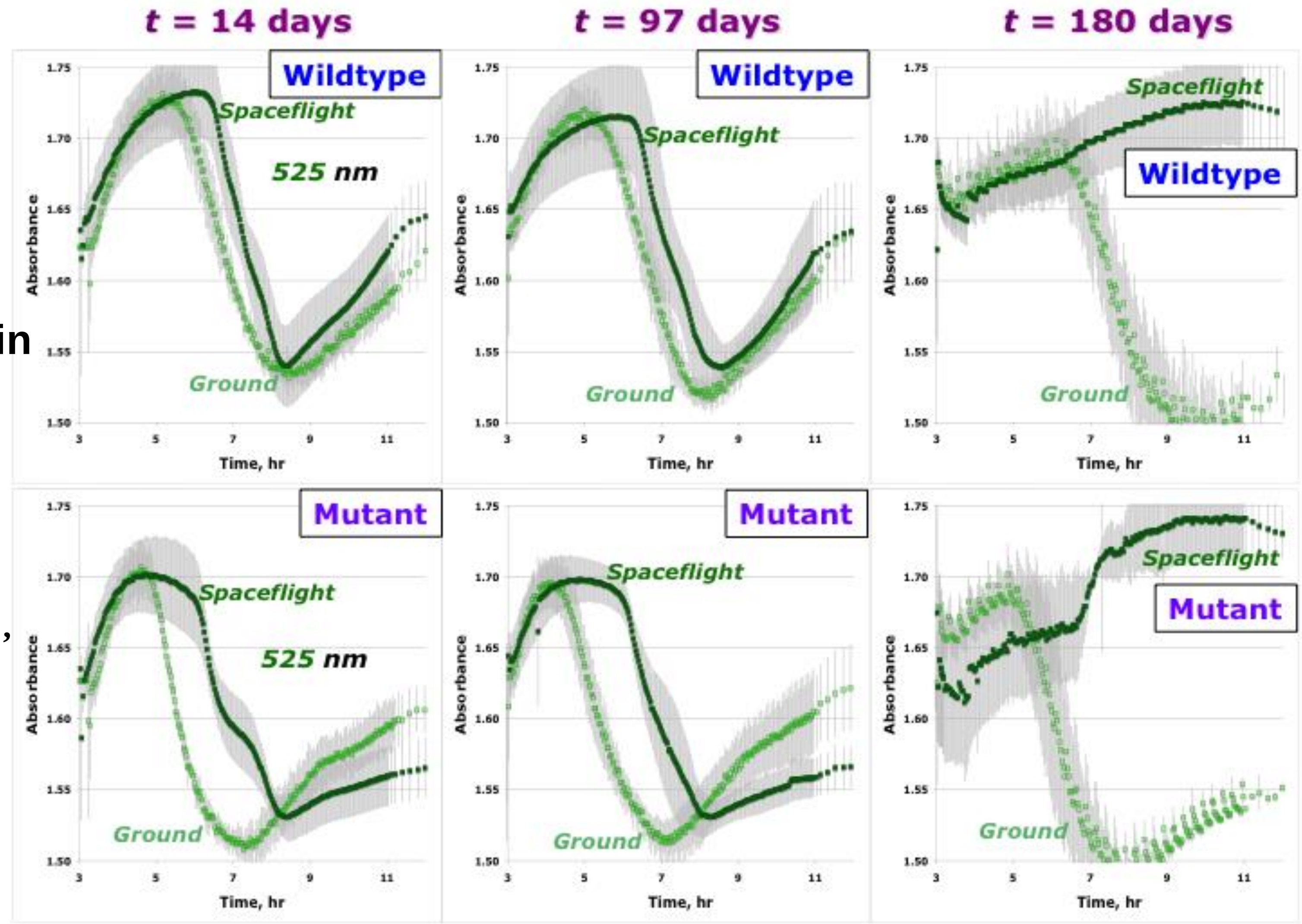
–– some cells under some conditions subsequently convert pink form to colorless



Alamar Blue spectra in both forms with LED wavelengths & bandwidths



SESLO Spaceflight Results: **Growth of *B. subtilis* in space vs. ground**



WL Nicholson, AJ Ricco, *et al*, *Astrobiology*, *11*, 951-958 (2011)

WL Nicholson and AJ Ricco, *Life*, *10*, 1-14 (2020)

SporeSat

- PI team: J. Rickus, A. Salim, Purdue University;
  S. Roux, University of Texas, Austin
- Objective: Investigate gravity dependence of fern-spore single-cell calcium ion fluxes during germination

- System: *Ceratopteris richardii*
- Variables: Gravitation: micro-***g*** to 2x ***g***
- Measurement: Differential calcium ion concentration between gravitational "top" and "bottom" of each spore

- 3 U, 5.5 kg (SporeSat-1)
- 18 Ap 2014 Launch, SpaceX Dragon Cargo Capsule, CRS3
- 18 Ap 2014, deployed at 400 km altitude prior to ISS arrival
- ~100 kB payload data

- Findings:
  - Long pre-launch duration (> 100 days) + illumination source failure prevented spore germination
  - Ion-selective electrode pairs, mini-centrifuges, thermal-control functioned nominally: provided baseline response
  - Ground experiments demonstrated variable-gravity response to net acceleration (rotation plus gravitation)
  - SporeSat-2 developed to address SS-1 hardware issues

DOI: 10.1039/C6LC01370H

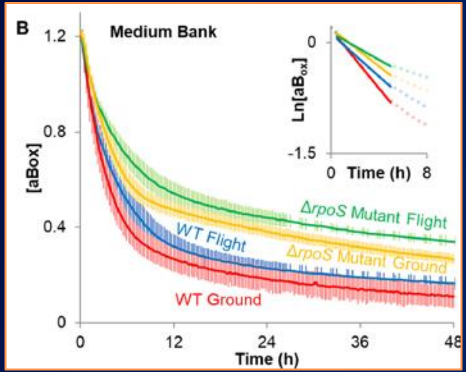
E. coli AntiMicrobial Satellite (EcAMSaT)

- PI: AC Matin, Stanford University
- Objective: Determine how microgravity alters the antibiotic resistance of *E. coli* and the role of the gene *rpoS* in antibiotic resistance

- System: *E. coli* wild-type and Δ*rpoS*
- Variables: zero, low, medium, high dose of gentamicin
- Measurement: Alamar Blue absorbance

- 6 U, 11 kg
- 12 Nov 2017 Launch
- 20 Nov 2017 ISS Deployment (NanoRacks)
- ~100 kB payload data

- Findings:
  - Microgravity reduced resistance in both strains
  - Multi-week storage made Δ*rpoS* less metabolically active
  - Loss of *rpoS* makes *E. coli* more susceptible to stressors



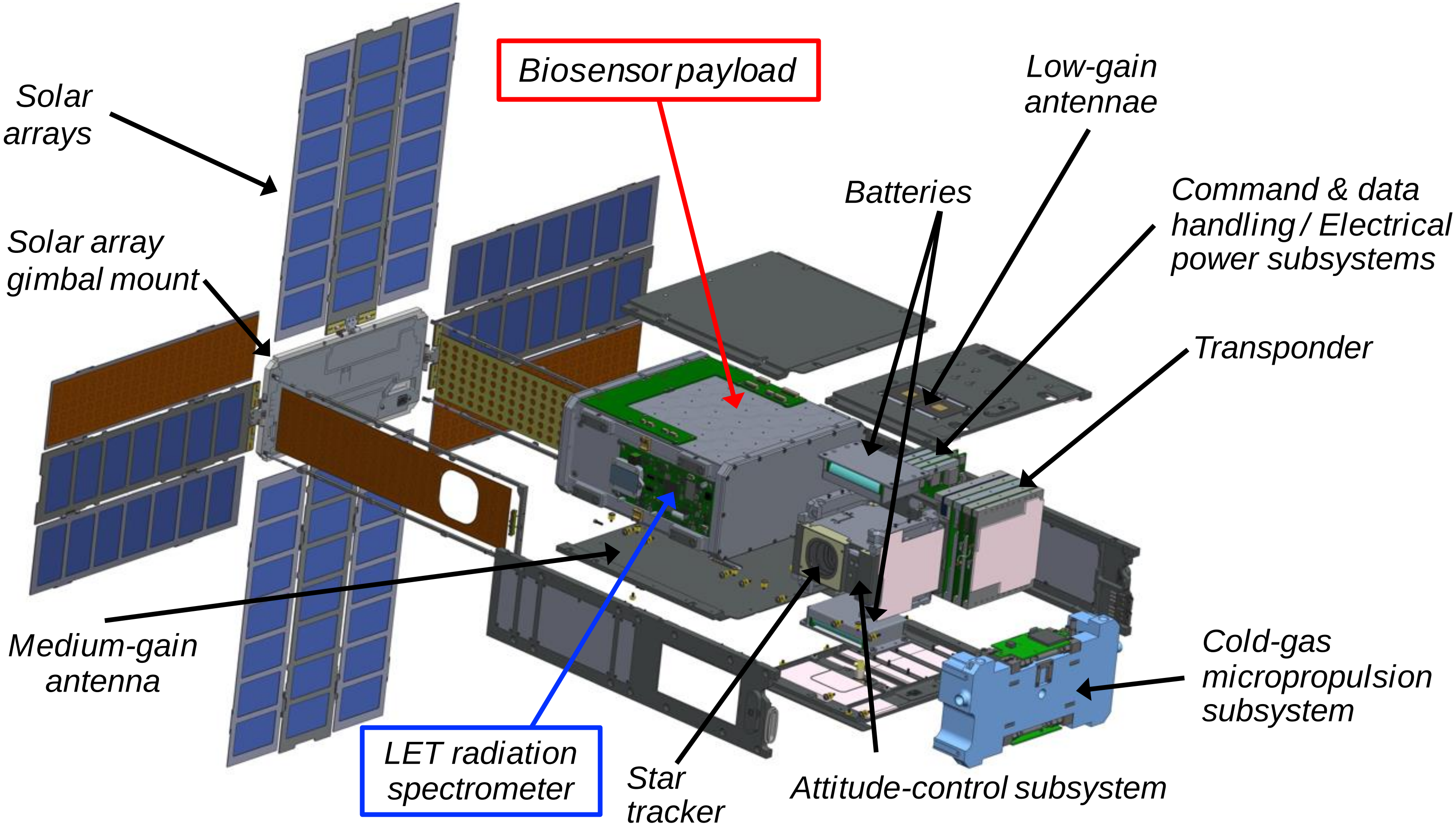
DOI: 10.1016/j.lssr.2019.10.007

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

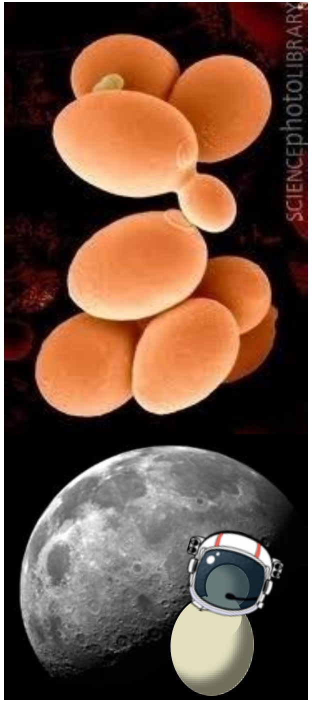
B. Klamm & A. J. Ricco, NASA Ames Research Center in Cottin et al. **2017** *Space Sci Rev, 209*, 83–181

BioSentinel Subsystem Overview



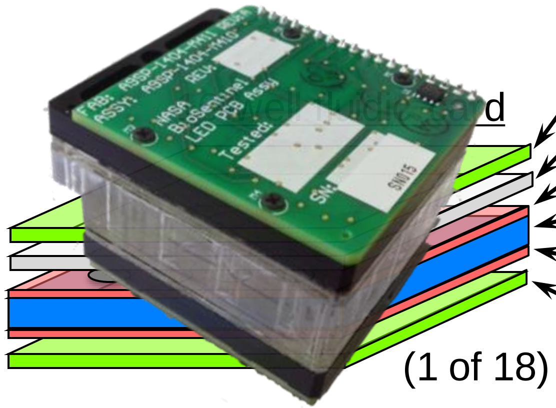
BioSentinel Science Mission: *"Canary in a Coal Mine"*

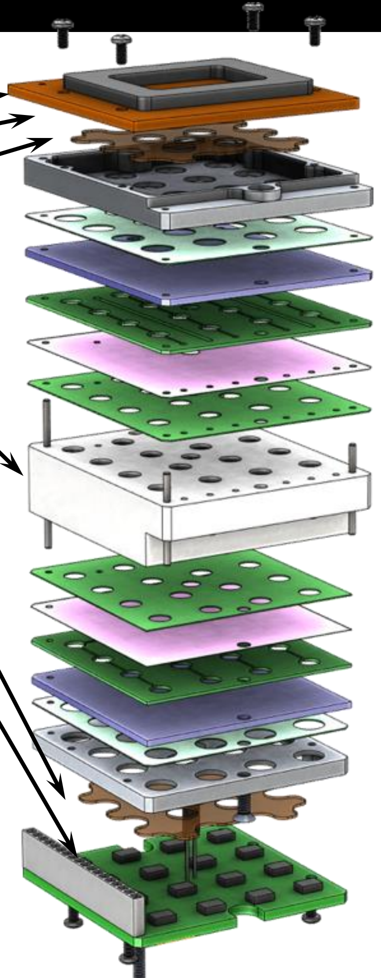
- ***Quantify DNA damage from space radiation environment***
  - Deep space environment cannot be reproduced on Earth: *omnidirectional, continuous, low flux, variety of particle types*
  - Health risk for humans spending long durations beyond LEO
  - Radiation flux can spike 1000x during a solar particle event (SPE)
- **Yeast assay: microfluidic arrays monitor DNA damage**
  - Two strains of *S. cerevisae*: 1 control (wild-type), 1 mutant
    - *engineered strain is sensitive to DNA damage, esp. double-strand breaks (DSBs)*
  - Wet and activate multiple banks of yeast in µwells over mission duration
  - DNA damage impairs cell growth & division, esp. for *rad51*Δ mutant
- **Correlate biological response with physical radiation measurements**
  - ***Linear Energy Transfer*** (LET) spectrometer bins and counts particle events by their LET
  - Total Ionizing Dose (TID): calculation of integrated deposited energy by LET system



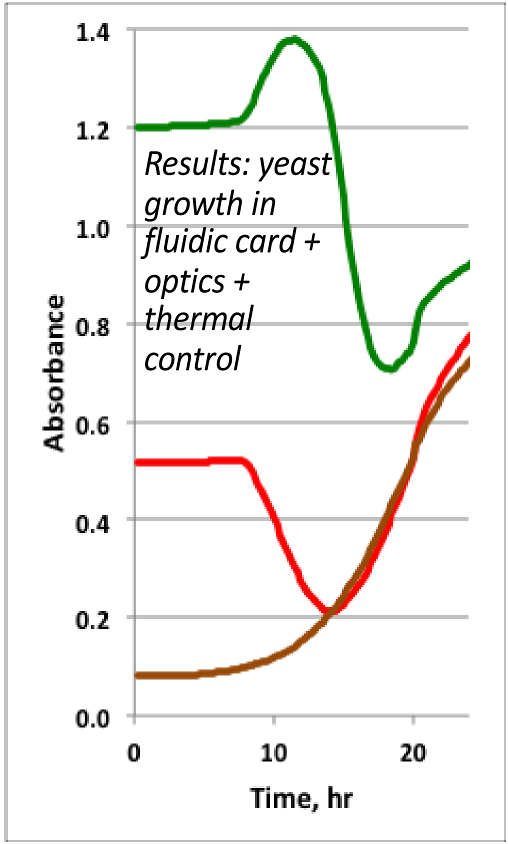
AJ Ricco, SR Santa Maria, RP Hanel, S Bhattacharya, *et al.* **2020** *IEEE Aerospace Elect Sys Mag*, *35*, 6-18.

BioSensor Payload Configuration





- **Optical absorbance measurement per well**
  - ➢ Dedicated 3-color optical system at each well
  - ➢ Measure dye absorbance & optical density (cell population) with stray light correction
  - ➢ Ground pre-calibration + in-flight "active" cal.
- **Pressure & humidity sensors** in P/L volume
- **Dedicated thermal control system per card**
  - ➢ 16 – 23°C; 1 °C uniformity, accuracy, stability
  - ➢ 1 RTD sensor per card: closed-loop control



Biofluidic Subsystem

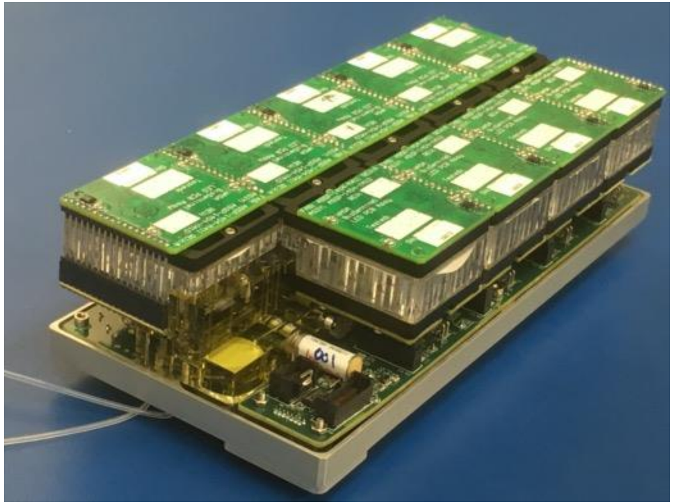
9-fluidic-card manifold (144 wells) [1 of 2]

Manifold-integrated components:
- *active & check valves*
- *bubble traps*
- *desiccant traps*
- *optical calibration cells*

Reagent-and-pump manifold [1 of 2]

Tally of components:
- *2 pumps, 2 main bubble traps*
- *24 active valves, 38 check valves*
- *16 fluidic cards with 16 small bubble traps, 16 desiccant traps, 288 wells total*

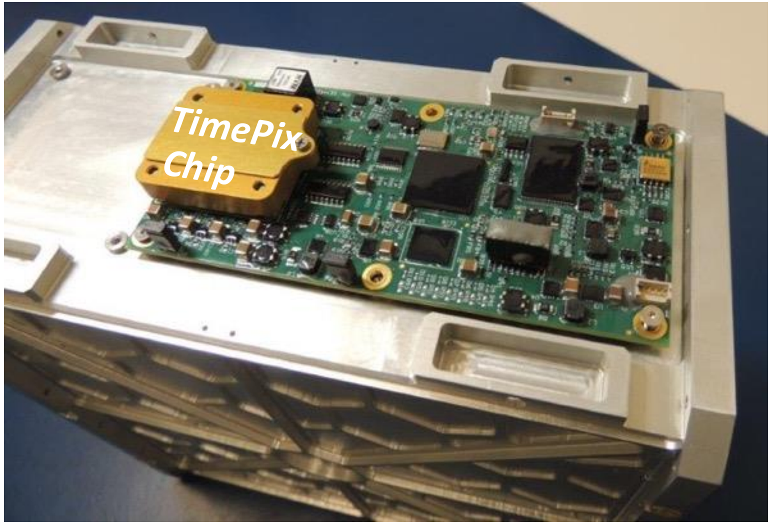
9 fluidic cards integrated with measurement optics, thermal control, and fluidic manifold [1 of 2]



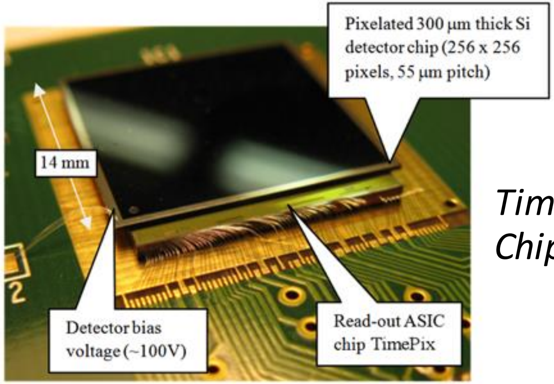
BioSentinel

Monitoring Radiation: Single-PCB Linear Energy Transfer Spectrometer

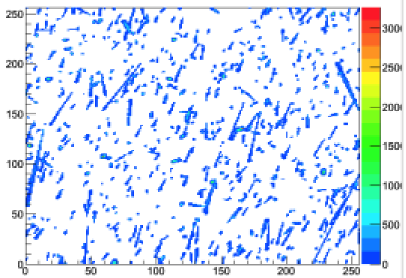
- LET “spectrometer”: TimePix solid-state device
  - measures **linear energy transfer** spectra
  - time-over-threshold (TOT) mode. Wilkinson-type ADC
    - *direct energy measurement per pixel*
  - LET 0.2 – 300 keV/µm into 256 bins, each 3% width; store hourly bin totals
  - Download “local space weather” periodic snapshots
  - Also reports **TID** (total ionizing dose)
- SPE Trigger: TID rate increase causes wet-out of a pair of fluidic cards



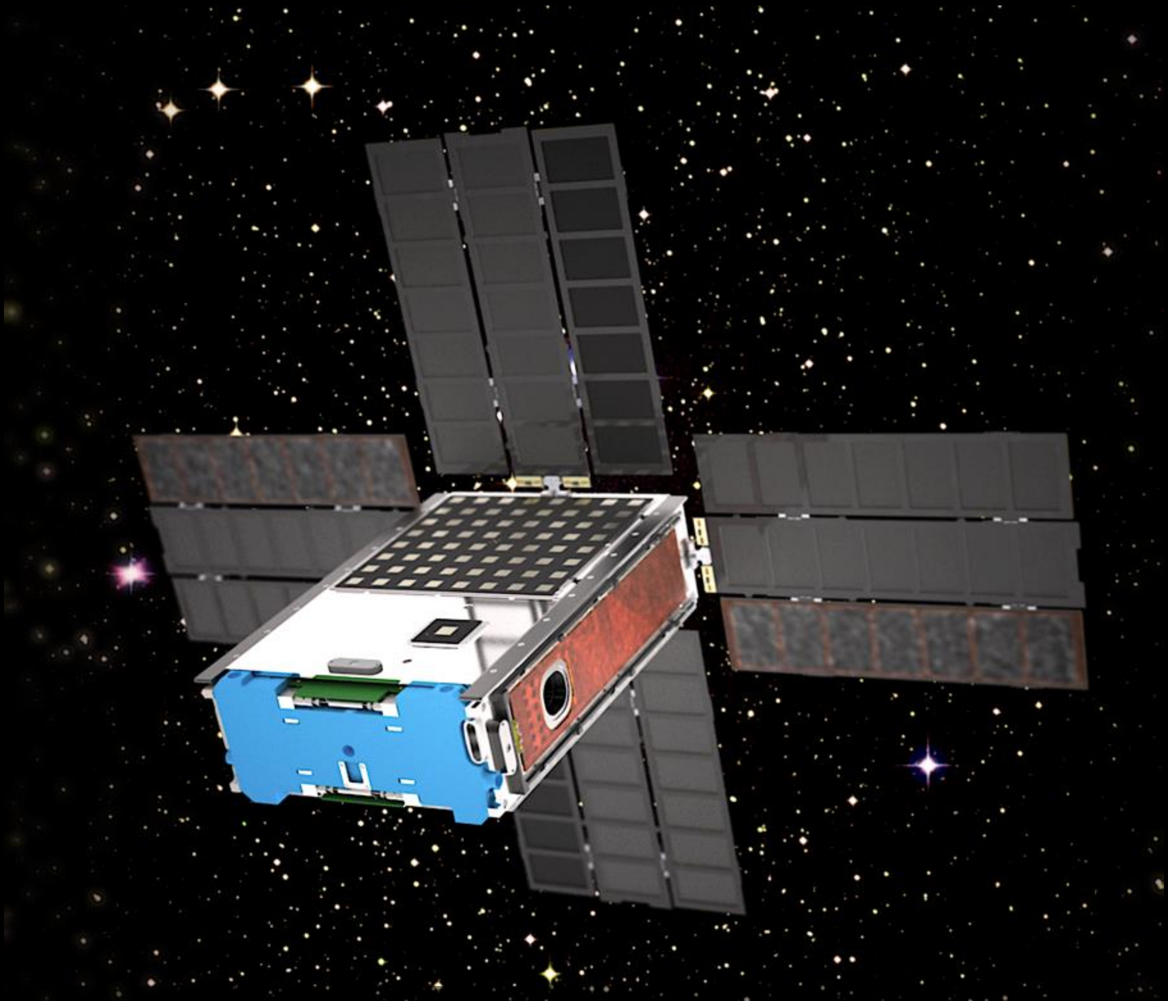
Single-board LET spectrometer mounted on *BioSentinel* biosensor payload enclosure



TimePix Chip



Typical TimePix frame:
256 x 256 x 14 bits

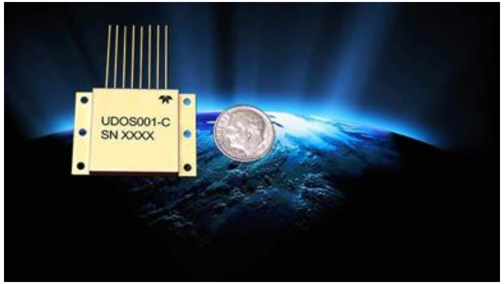


AJ Ricco, SR Santa Maria, RP Hanel, S Bhattacharya, *The Radworks Group*, and the *BioSentinel Team*, *IEEE Aerospace Elect Sys Mag*, *35*, 18-24 (2020).

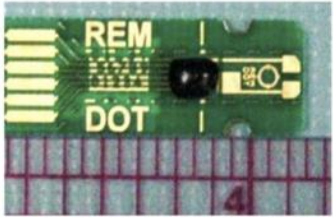
Radiation Dosimeters

Critical adjunct to biology experiments

- Correlate radiation dose, dose rate, or time-varying spectrum with biological effects
- Radiation details can vary locally: embed sensors with bio payloads even if host platform includes integral radiation measurements
- Tissue-equivalent sensors (proportional counter or plastic scintillator) measure biologically-relevant exposure
- Science objectives drive dosimeter selection – more than one dosimeter technology may be needed



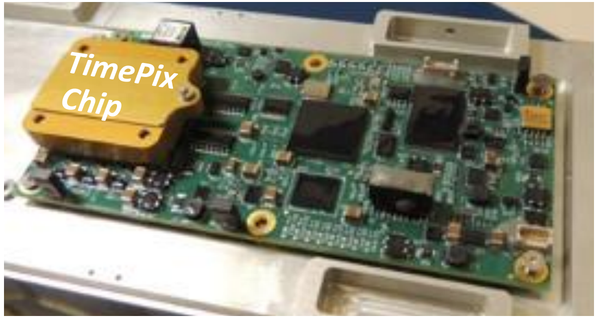
Total Ionizing Dose (TID) – Teledyne µDOS



RadFET: Total Ionizing Dose (TID), records TID with power off or on

PIN diode: Real-time dose rate, low cost for multi-location applications

Plastic scintillator: radiation dose response similar to tissue, including neutron and proton responses



Single-Board Linear Energy Transfer (LET) Radiation Spectrometer

Lessons Learned

- No such thing as a ‘simple’ modification
- Be sure to test biocompatibility of all parts that come in contact with the science, including the treatment of the materials before integration with the biology (e.g., autoclave, EtO, etc.)
- Be sure to offgas all materials in the cubesats since the long turnover period may be detrimental to the science before activation
- Negotiate a late turnover to minimize the offgassing effects
- Perform end-to-end tests, including long-duration stasis period
- Murphy’s law of bubbles in microgravity
- Science and engineering teams need to work side-by-side for biological experiments

Lunar Explorer Instrument for space biology Applications (LEIA)

- Anticipated landing site for potential LEIA mission is lunar south pole (84-90 deg S)
- BioSensor payload must be adapted for operation during lunar daytime environment (south pole) and interface with Commercial Lunar Payload Services (CLPS) vehicle
  - Lunar south pole environment is cold and LEIA may be in shade of CLPS lander; LEIA BioSensor may require additional insulation and increased heater power
  - LEIA enclosure must shield electronics but not biology from radiation
  - LEIA must protect against interference from adjacent payloads (e.g. EMI, thermal)
  - BioSentinel mission (6-12 months) substantially longer than LEIA mission (<14 days). LEIA BioSensor fluidics “cards” will all need to run in parallel, affecting thermal profile and power draw.
- Short LEIA mission timeframe drives selection of biology that is more sensitive to radiation, but may be less robust to long-term stasis. LEIA’s BioSensor payload will incorporate a “late load” capability to substantially reduce time the biology is in stasis.
- LEIA to include charged particle radiation detector to correlate radiation data with biological data. A high energy neutron detector is also under consideration.

Future Plans for BLEO Science

- Annual Space Biology call for BLEO science
  - CLPS
  - Gateway
  - SmallSat/CubeSats
- Need both scientists and engineers to be successful!

Thanks!

GeneSat & PharmaSat: John Hines, Macarena Parra, Charlie Friedericks, Chris Kitts, Bob Ricks, Dave Squires, Mike McGinnis, Dave Niesel, Matthew Piccini, Linda Timucin, Elwood Agasid, Chris Beasley, Lori Brooks, Li Chang, Roland Coelho, Greg Defouw, Orlando Diaz, Millan Diaz-Aguado, Tammy Doukas, Laurent Giovangrandi, Mike Henschke, Denver Hinds, David Husmann, Andrew Kudlicki, Wenschel Lan, Simon Lee, Ricky Leung, Ed Luzzi, Diana Ly, Dana Lynch, Nghia Mai, Rocco Mancinelli, Ignacio Mas, Mike McIntyre, Mike Miller, Carsten Mundt, David Oswell, Mike Rasay, Karolyn Ronzano, Jason Samson, Stevan Spremo, Chris Storment, George Swaiss, John Tucker, Usen Udoh, Roy Vogler, Phelps Williams, Bruce Yost, Ken Zander

NASA/Ames, Santa Clara U., UTMB, Stanford U.

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LEIA: Jennifer Lee, Matthew Lera, Brandon Maryatt

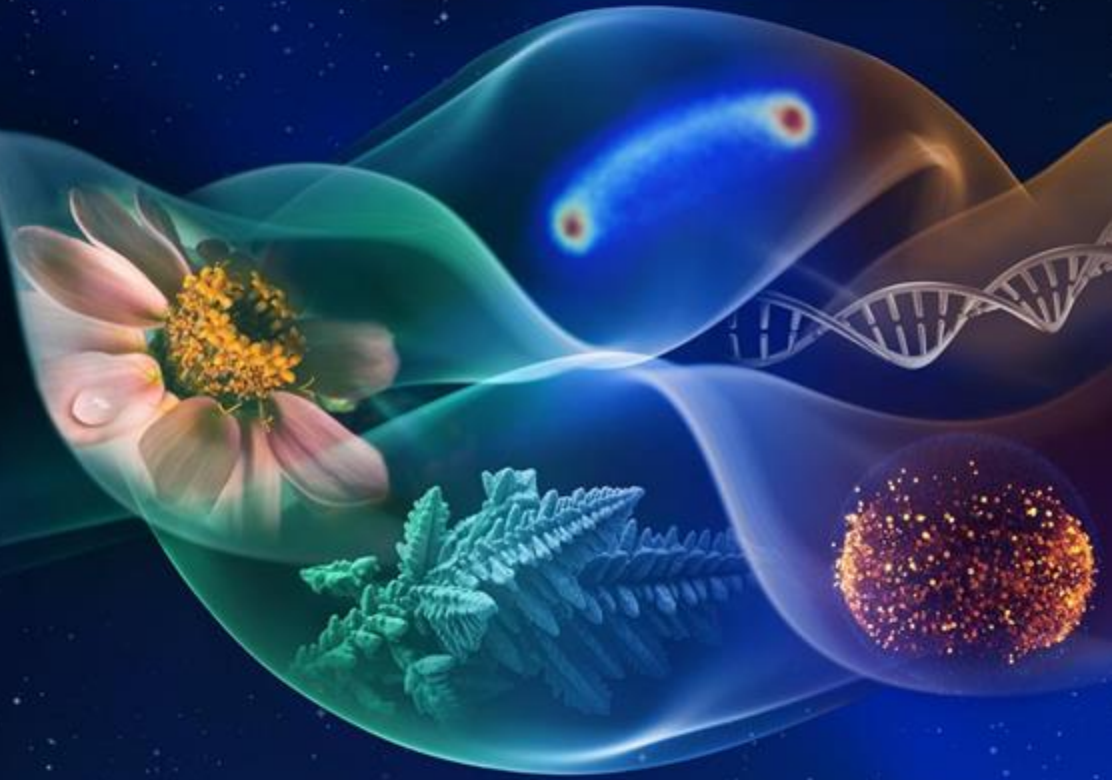
NASA/Ames

$ GeneSat/PharmaSat: NASA Fundamental Space Biology, ESMD (now BPS/SMD)

$ O/OREOS: NASA Astrobiology Small Payloads Program, SMD

$ BioSentinel: NASA Advanced Exploration Systems, HEOMD

Backup Slides



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