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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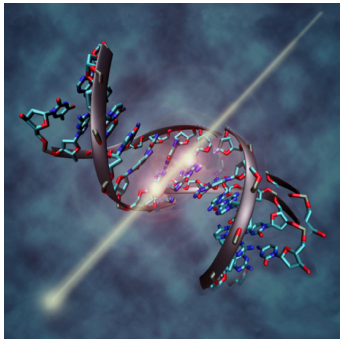
BioSentinel Project Objectives

- Advanced Exploration Systems (AES) Program Office selected BioSentinel to fly on the Space Launch System (SLS) Exploration Mission (EM-1) as a secondary payload
  - 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

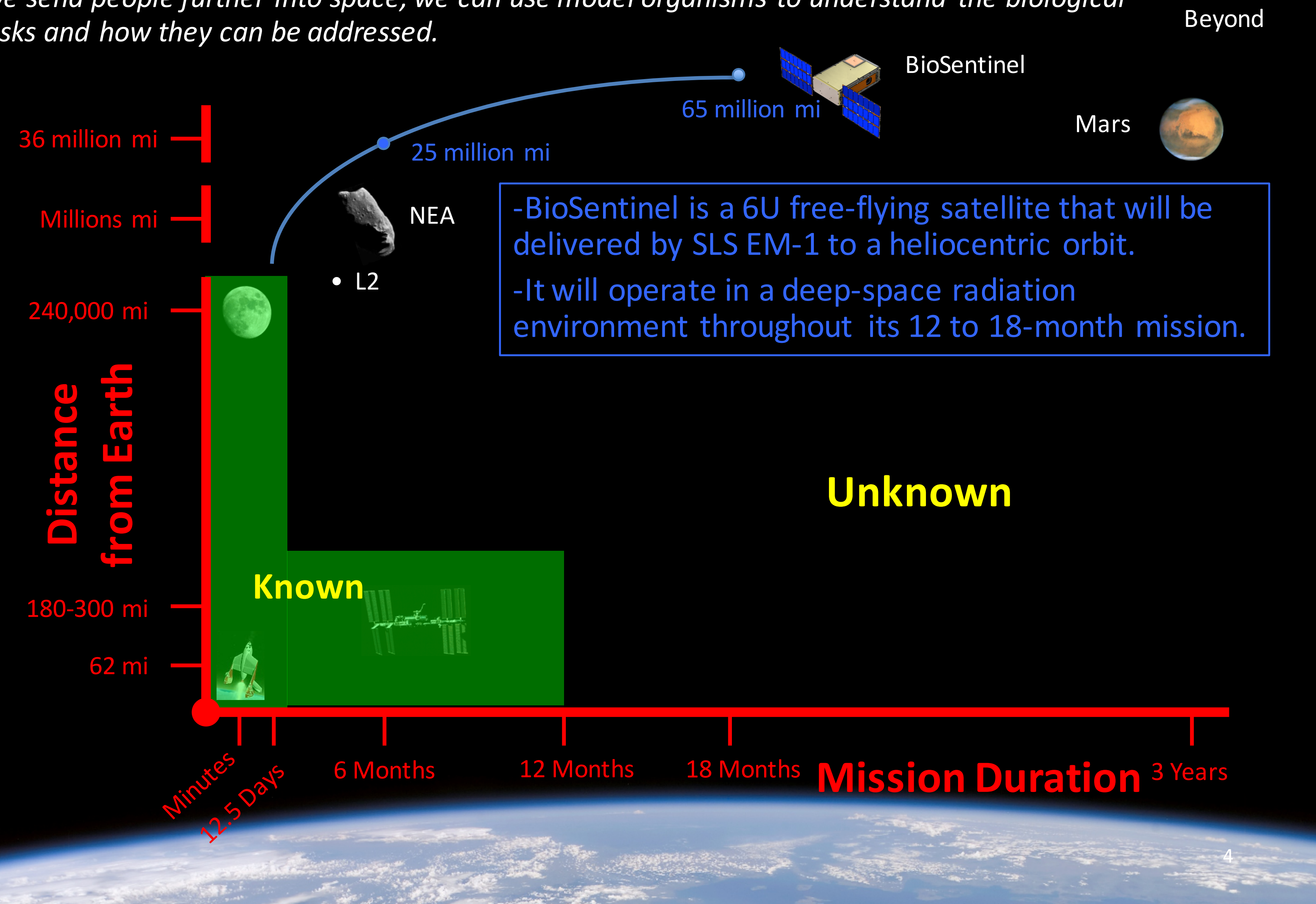
Goals:

- 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

Filling Strategic Knowledge Gaps (SKGs)	
SKG documents	**Gaps**
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

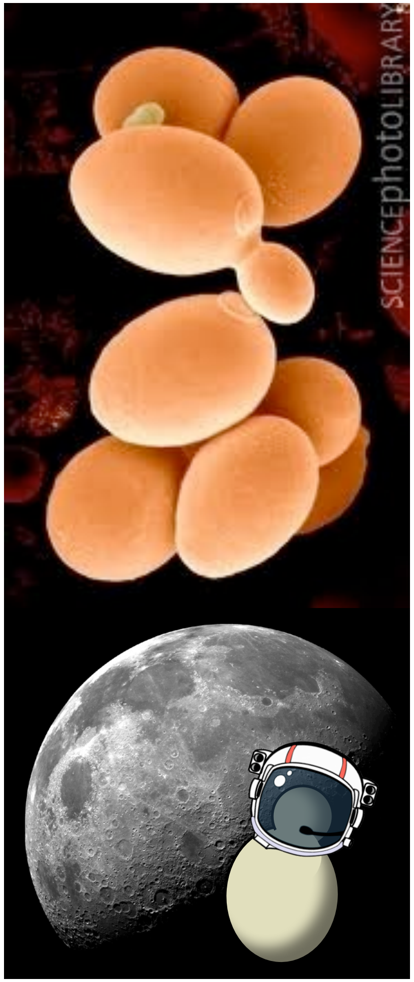
The 1st Biology Experiment beyond LEO since Apollo

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 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)

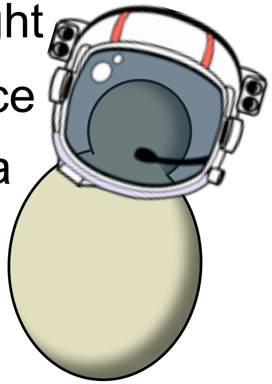


BioSentinel: A BioSensor in Space

- 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

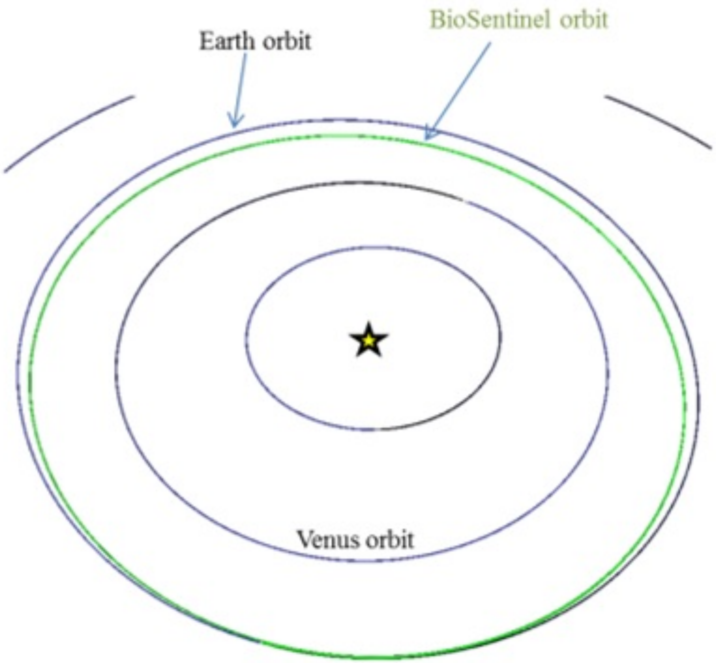
BioSentinel EM-1 Mission

Launch

Artist's rendering of the Space Launch System

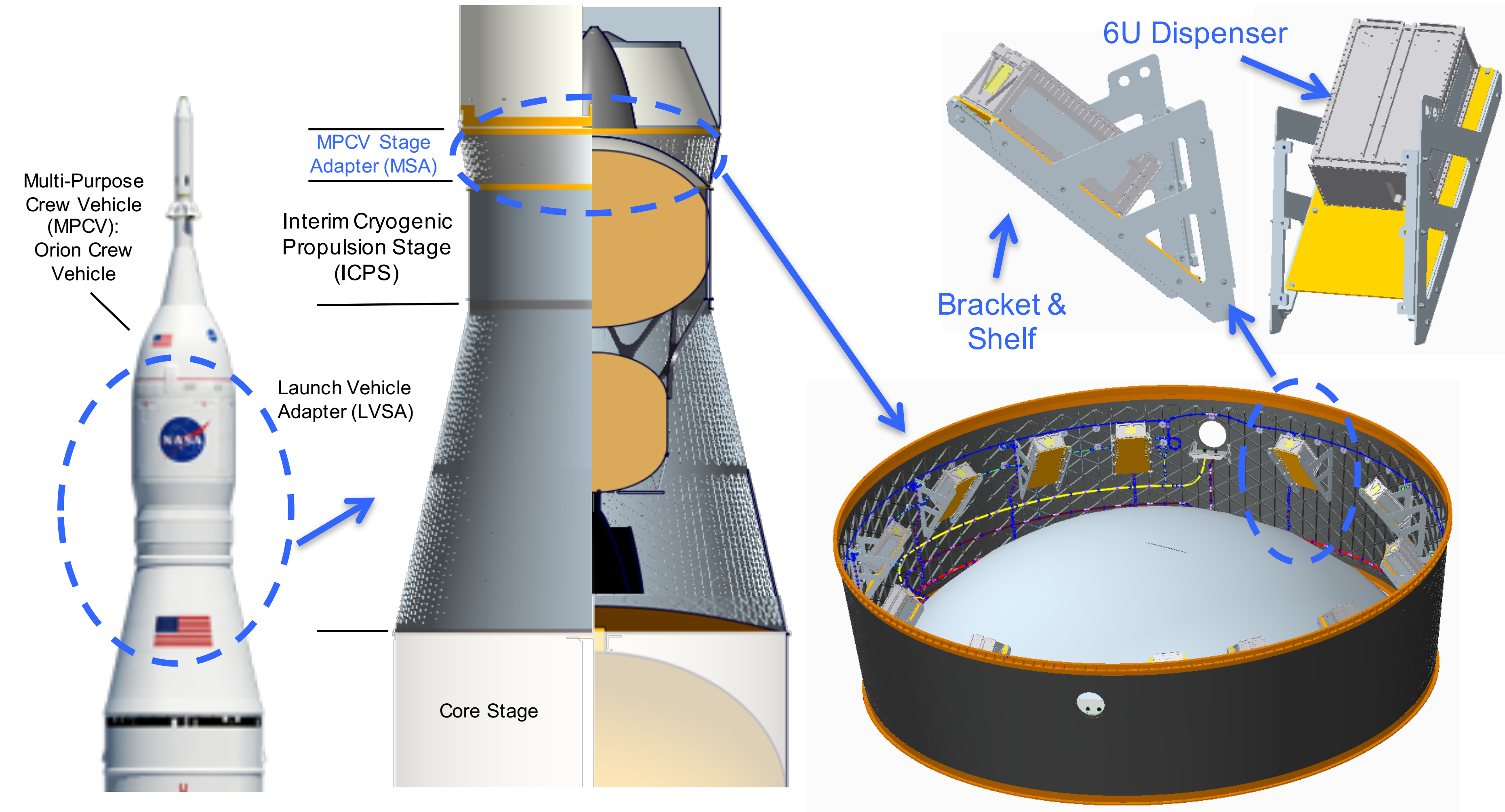
- Launched as a secondary payload on SLS **EM**-1
  - **E**xploration **M**ission 1: 1st flight of NASA's Space Launch System
  - Pre-launch starts with loading of biology at L-6 months
- Final orbit of secondary's to be determined
- Will likely be Earth-interior, heliocentric orbit
- Far outside the 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



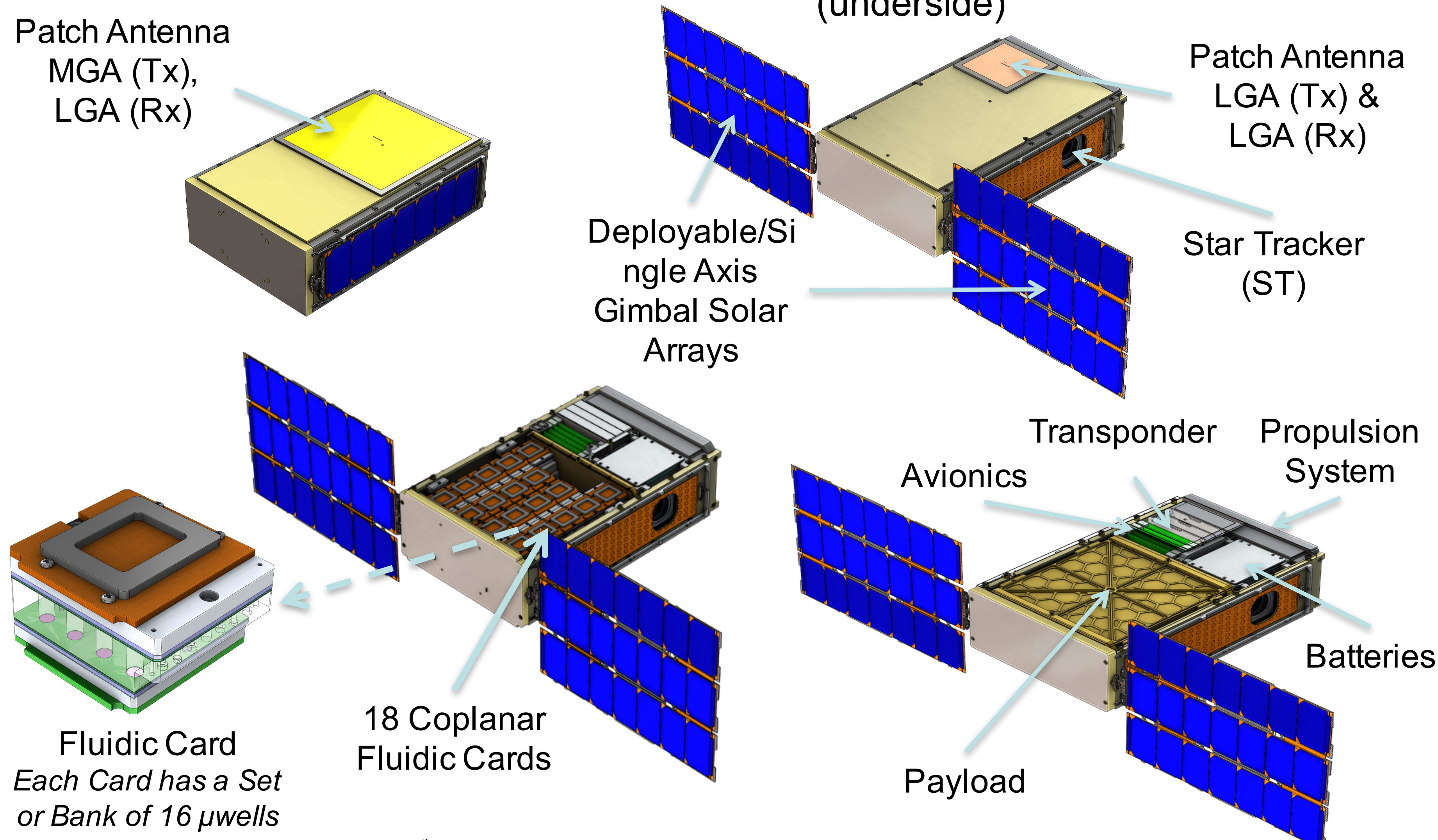
A representative orbit that BioSentinel might occupy

Secondary Payload Location on SLS EM-1



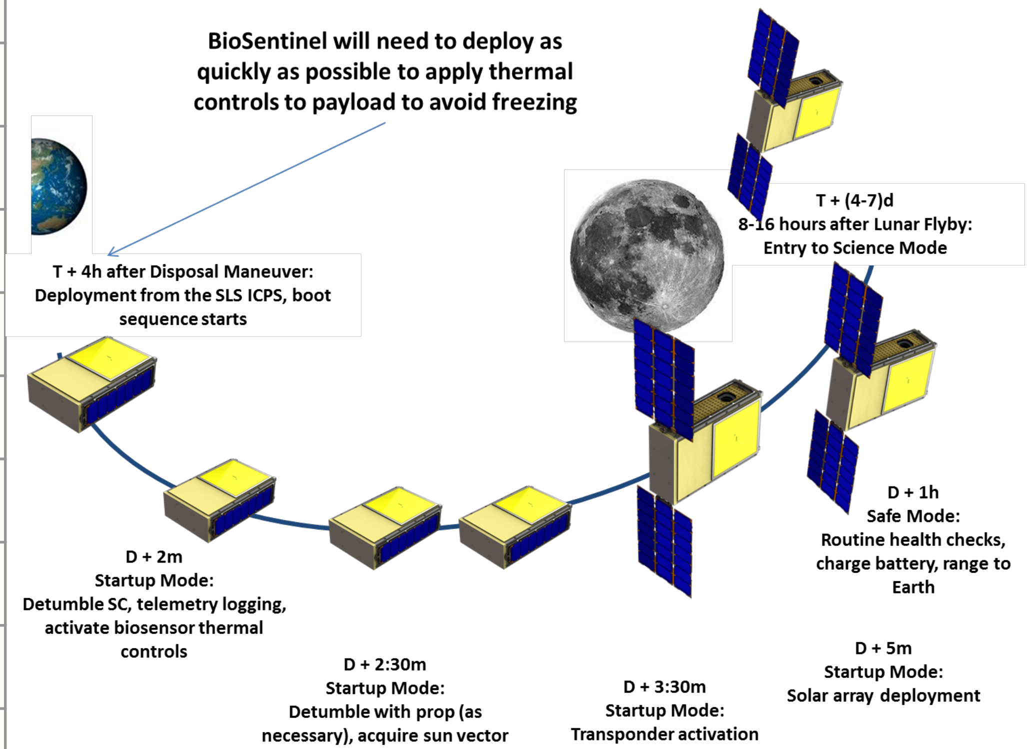
- 11 - dispenser locations that each support a 6U (14 kg) secondary payload
- 1 - bracket location allocated to a sequencer
- EM-1 only accommodates 6U; EM-2 may accommodate 12U payloads

BioSentinel EM-1 Spacecraft



BioSentinel Launch and Deployment ConOps

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



BioSentinel Month-in-the-Life ConOps

Monitor Bus Functions

1. Wet new card (1x per month, ATS)
2. Collect science data (Continuous, RTS)
1. Refresh card (1x per month, ATS)
3. Transmit to DSN (2 to 4X per week, 2 – 4 hours per contact, ATS)

1

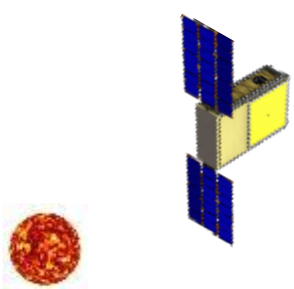
Major Functions	Subfunctions
Select card	• Determine fluidic card • Select µ-controller • Select pump and valve set
Apply Fluids	• Open inlet valve • Open plate valve • Open nutrient valves • Activate Pump
Configure Thermal Control	• Apply warm set points • Apply cold set points to other cards
Close System	• Close inlet valve • Close plate valve • Close nutrient valves • De-activate pump

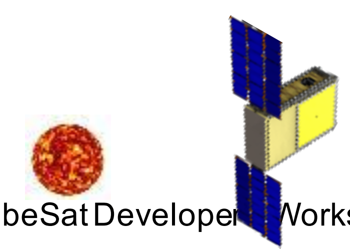
2

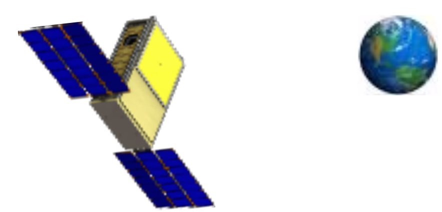
Major Functions	Subfunctions
Readout BioSensor (15 min cadence)	• Determine fluidic card • Select u-controller • Select and power well LEDs • Select and readout sensor • Iterate all wells
Readout TID sensor (5 min cadence)	• Apply power to sensor • Wait for stabilization • Sample analog readouts
Readout LET Spectrometer sensor (1 hour cadence)	• Acquire binned data • Store data in file system
Monitor for SPE	• Sample TID readout • Sample LET shutter info • Wet new card if SPE detected

3

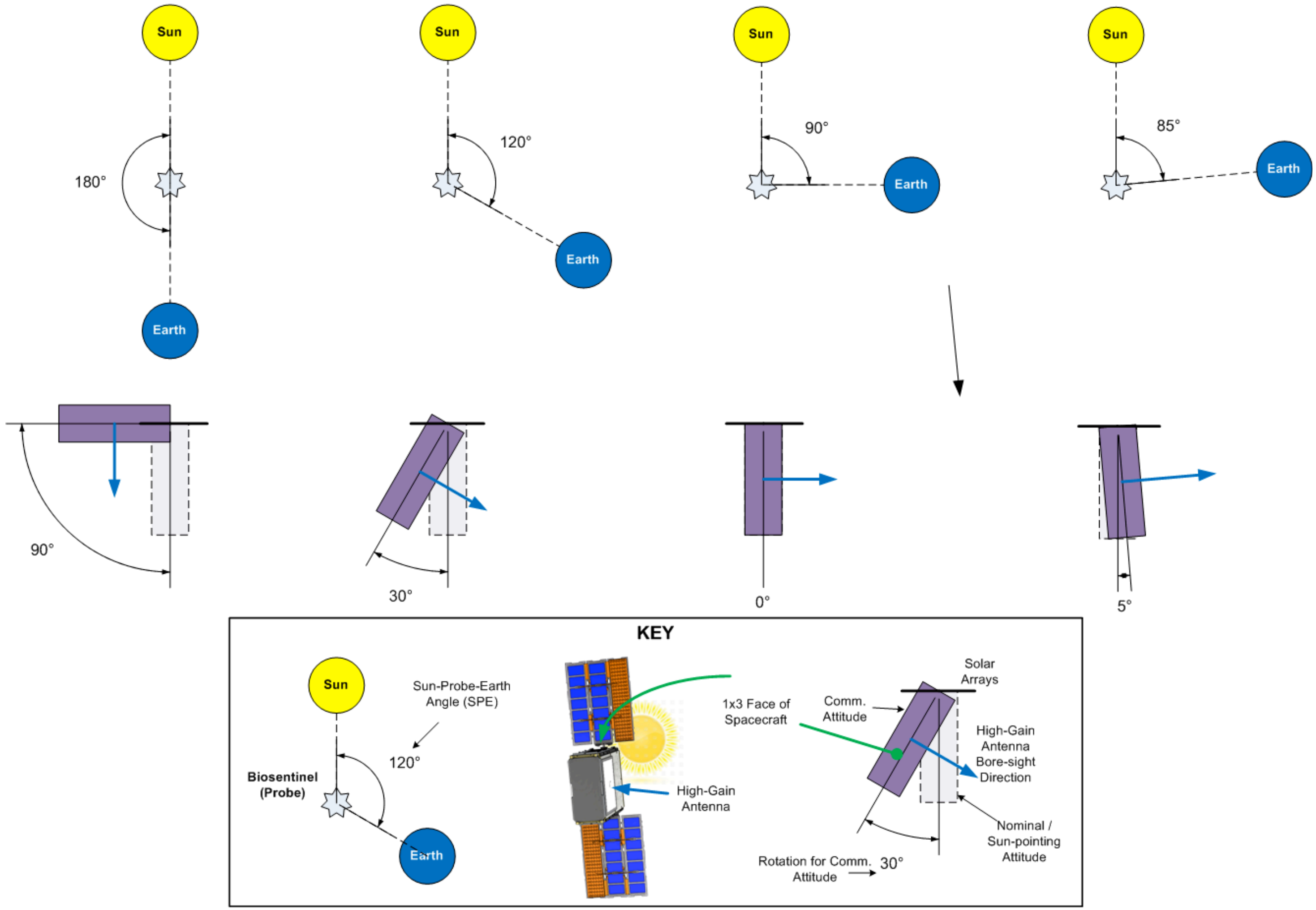
Major Functions	Subfunctions
Align spacecraft	• Determine vector to Earth • Slew to Earth vector
Power Tx	• Power transmitter
Broadcast data	• Broadcast SOH • On CFDP command, transmit BioSensor, LET, TID data
Deactivate Tx	• Power off transmitter
Realign spacecraft	• Slew back to sun vector



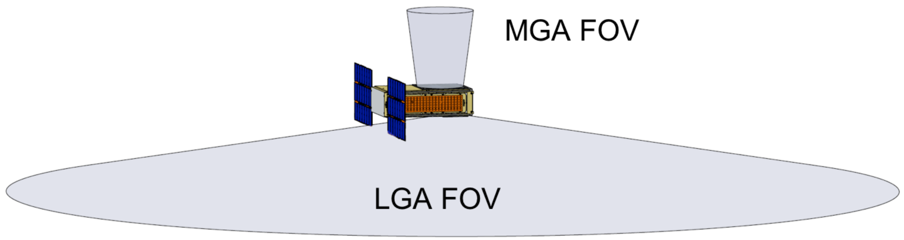


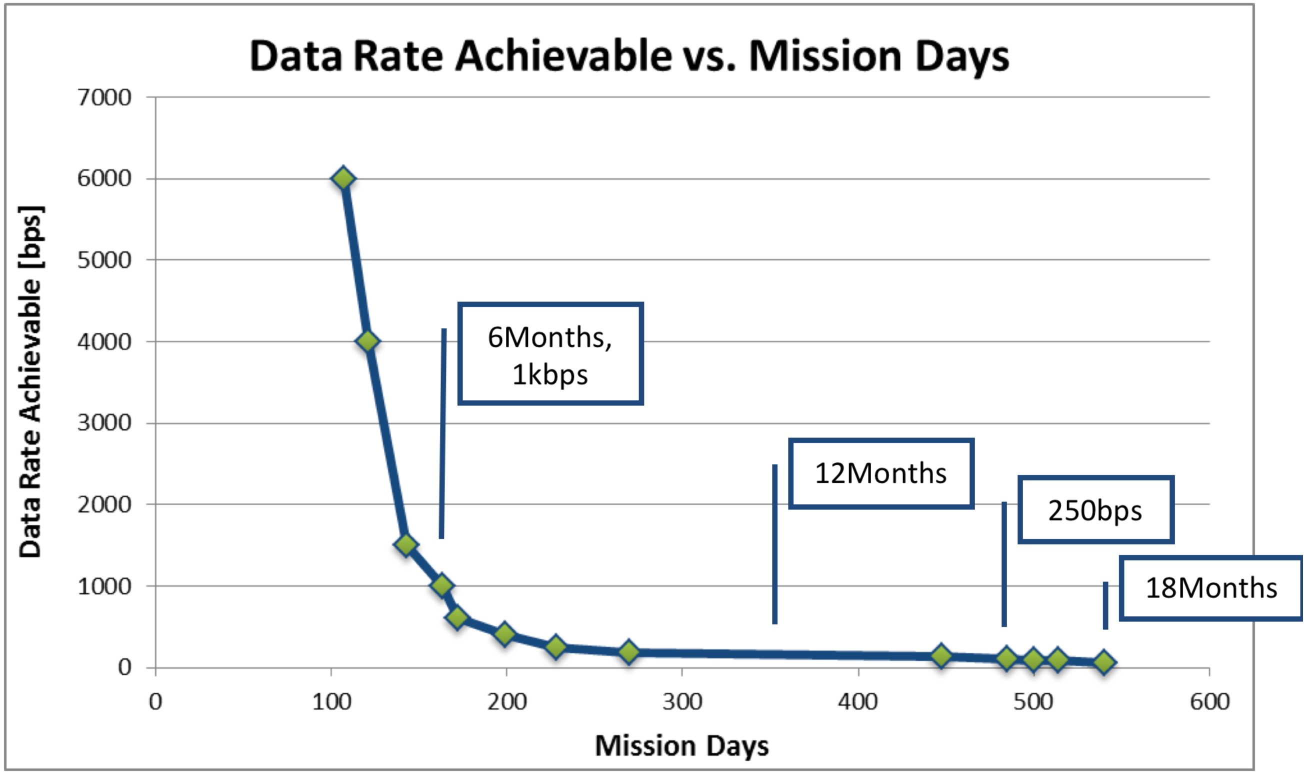


Attitude Pointing During Communication

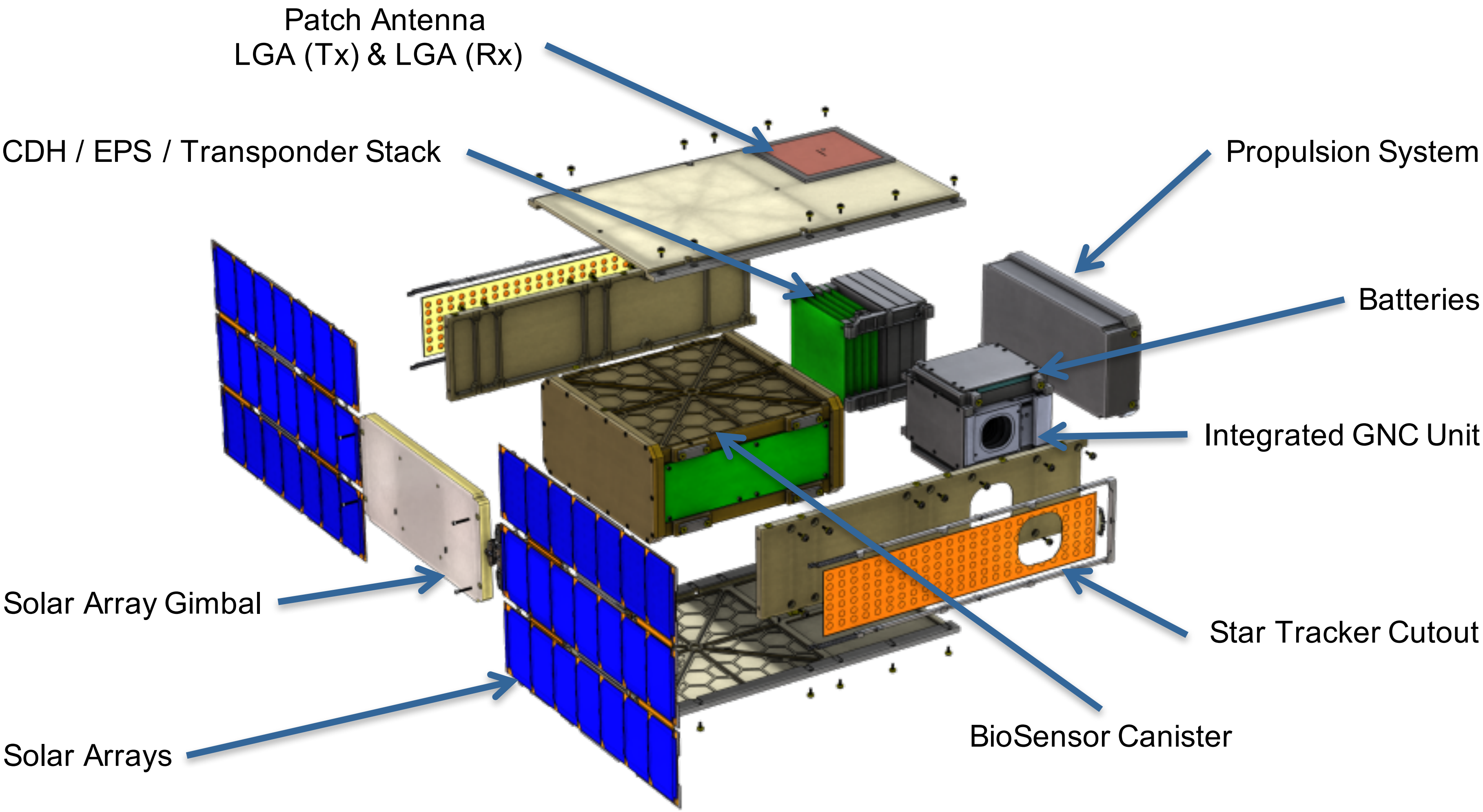


Antenna FOV & Achievable Data Rate

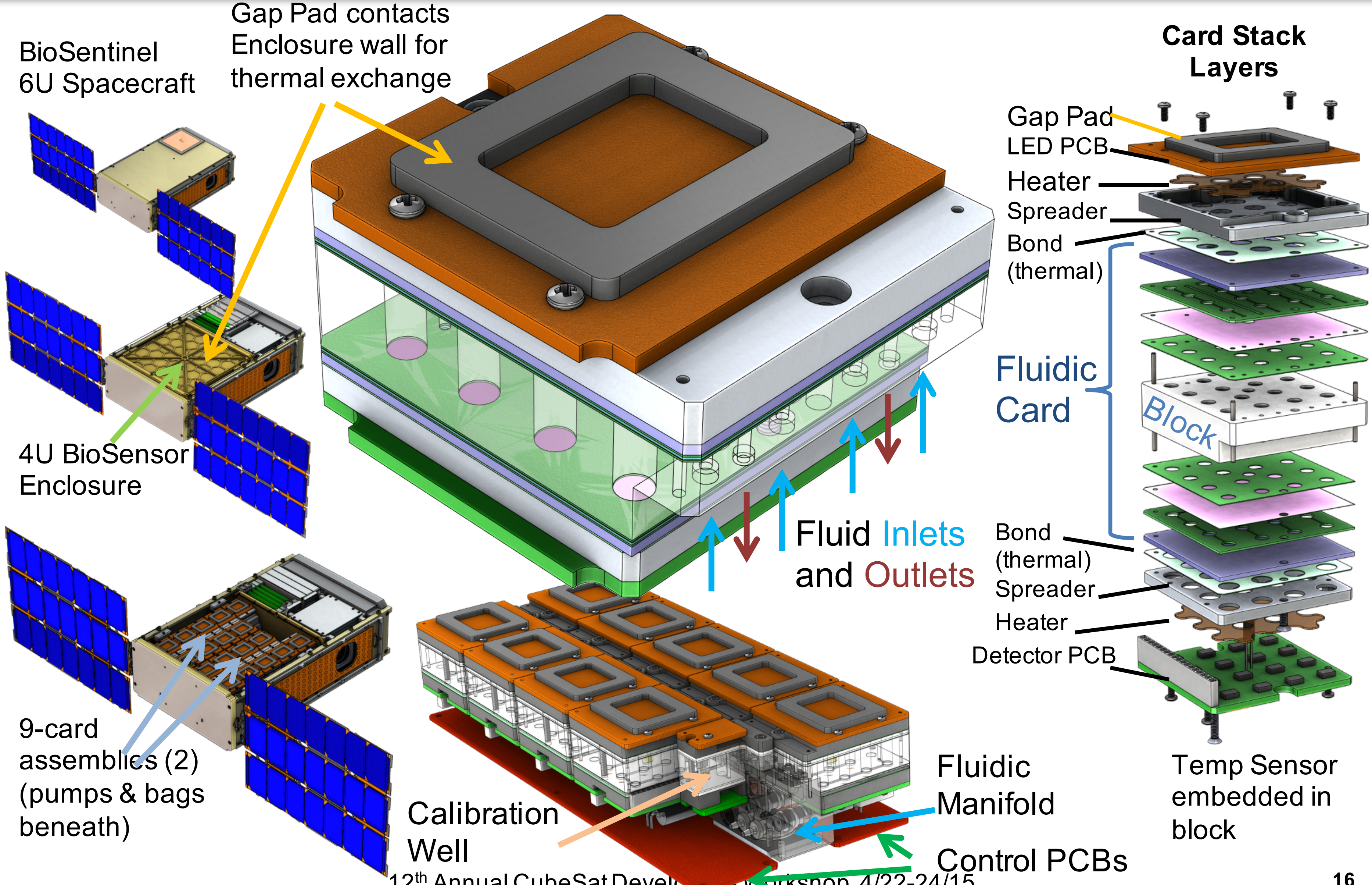




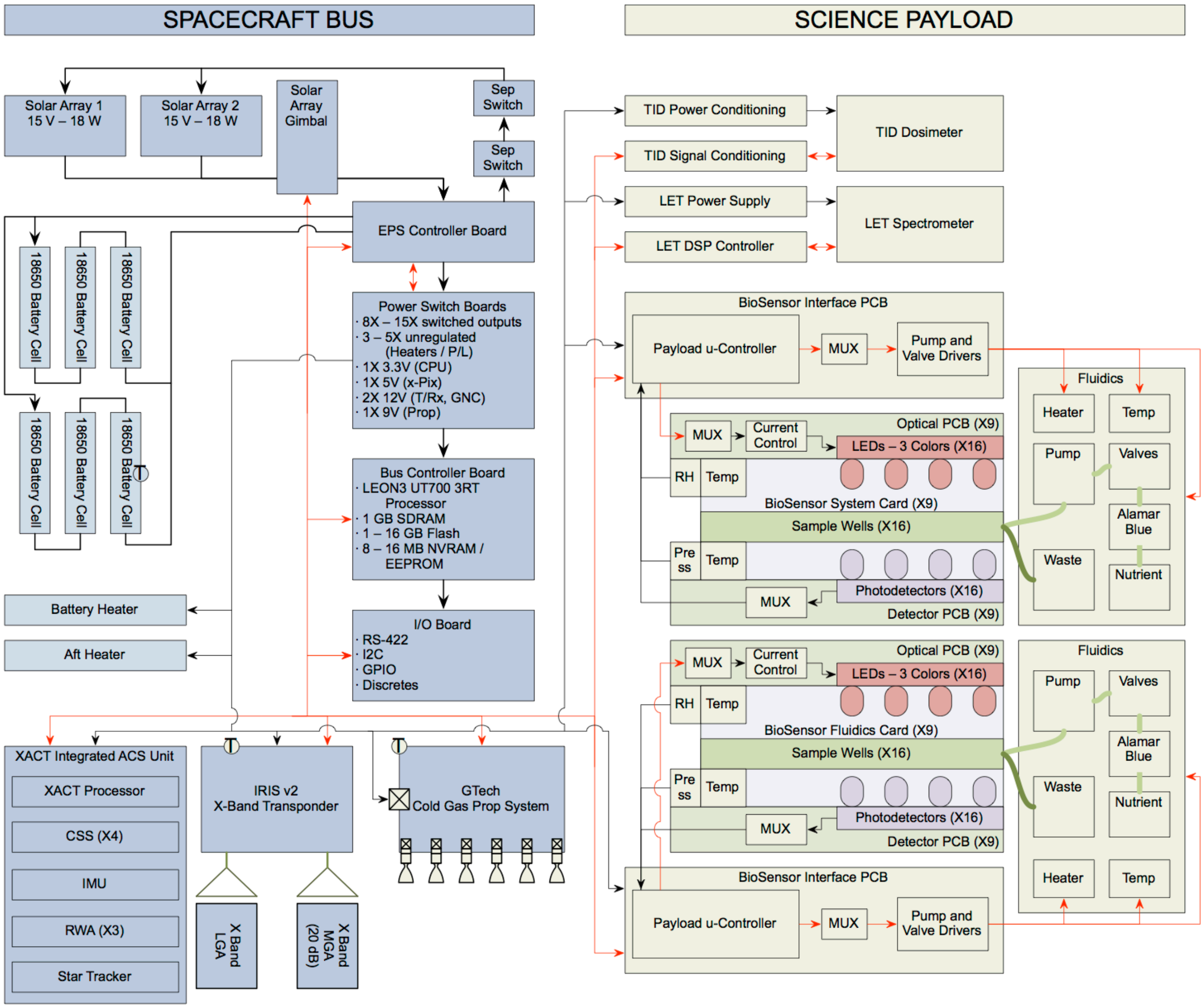
BioSentinel Spacecraft Internal Configuration



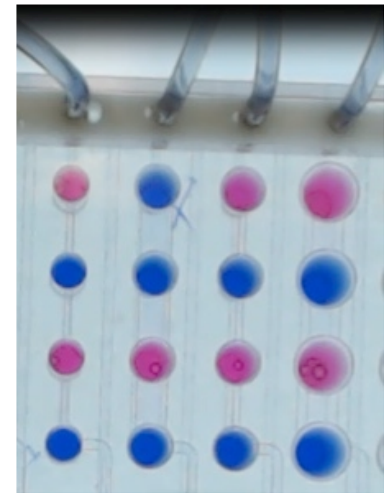
16-Well (4x4) Fluidic Card Stack



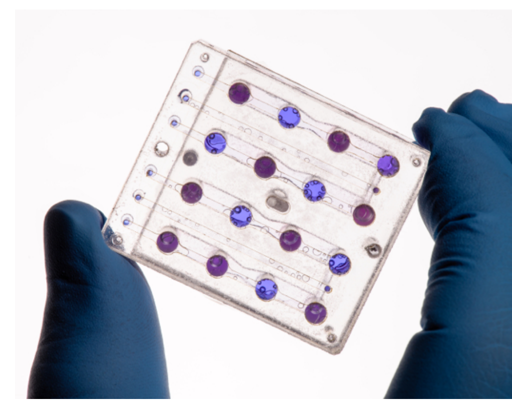
BioSentinel Spacecraft Functional Block Diagram



Biological Support & Measurement Systems

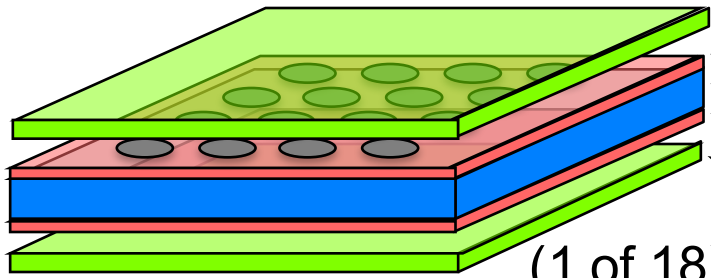


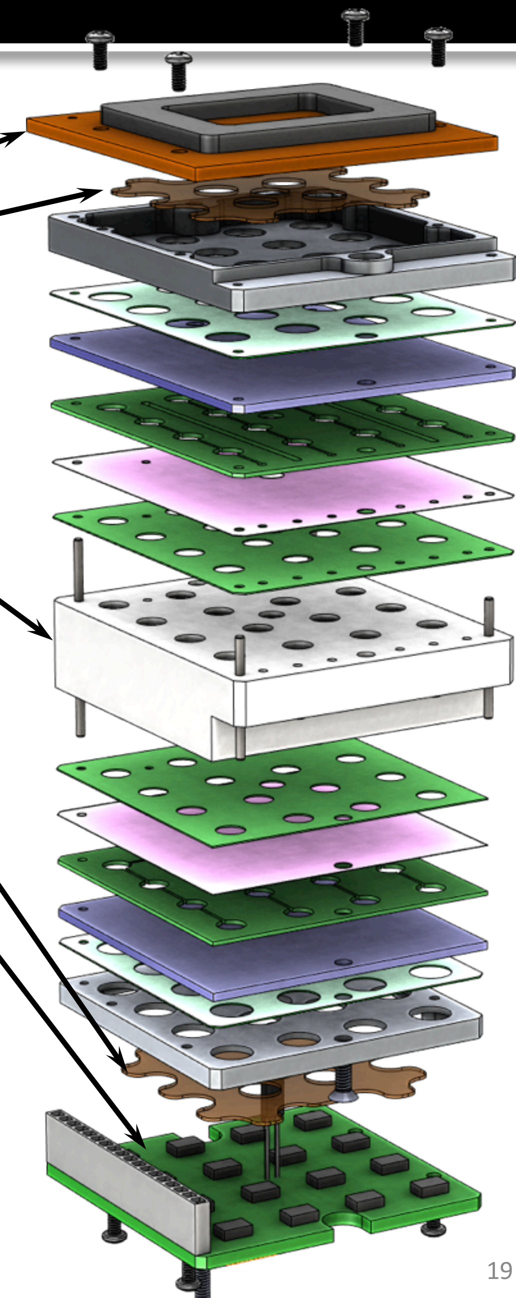
- support biology in stasis & growth
- enable & perform measurements
- compatible with multiple platforms
  - free flyer (EM-1), ISS, ground experiments
  - robust, standard data & power interfaces
- Configuration: 4U hermetic containment vessel
  - 1 atm internal pressure, low RH
  - **Fluidics**: 18 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

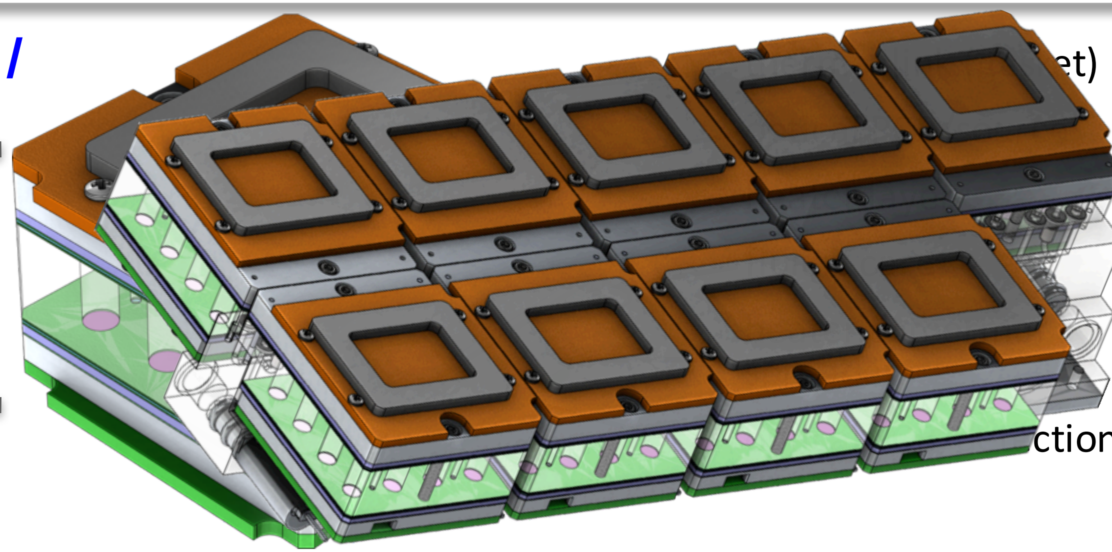


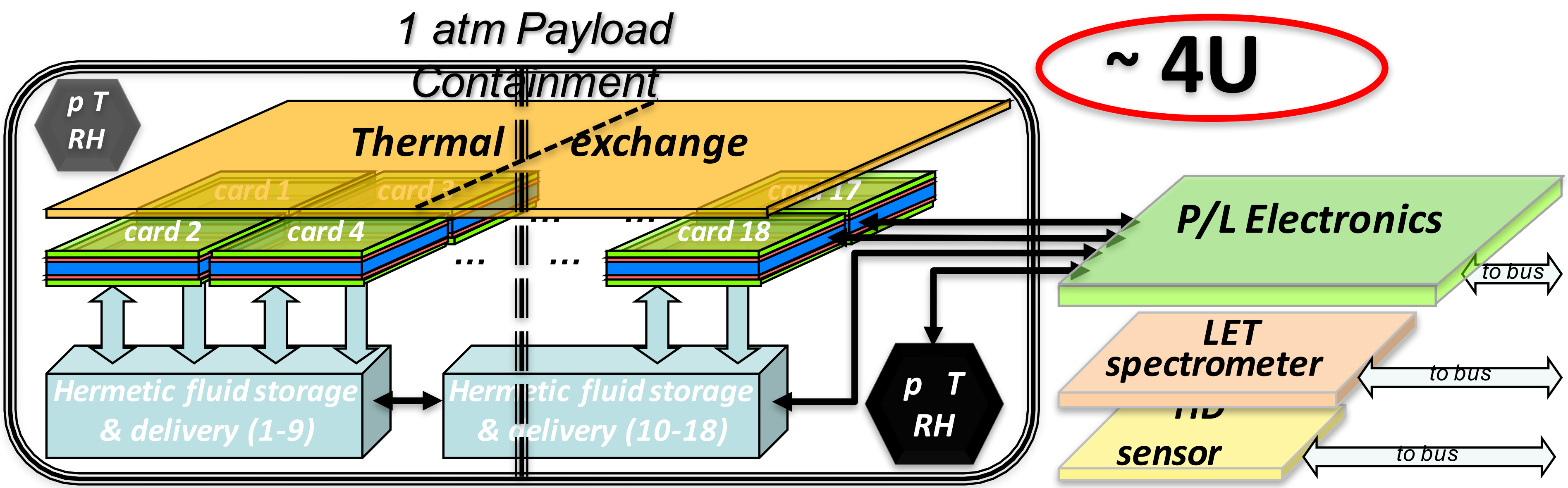


- **Optical absorbance measurement per well**
  - ➢ Dedicated 3-color optical system at each well
  - ➢ Measure dye absorbance & optical density (cell population)
  - ➢ Ground pre-calibration + in-flight "active" cal.
- **Pressure & humidity sensors** in P/L volume
- **Dedicated thermal control system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

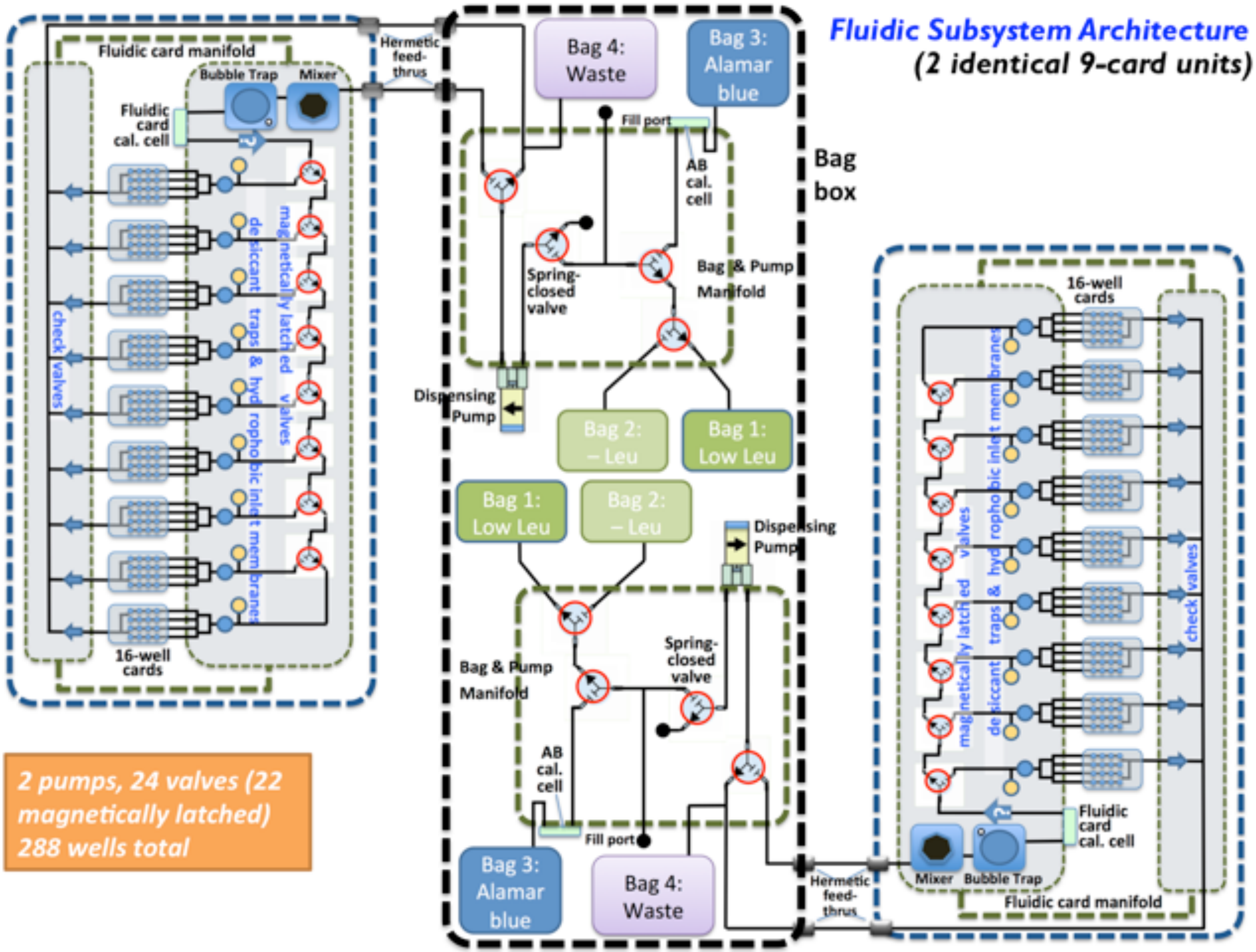
Biology / fluidics / optical / thermal configuration

16-well card
= 1 "set"
(18 sets total)





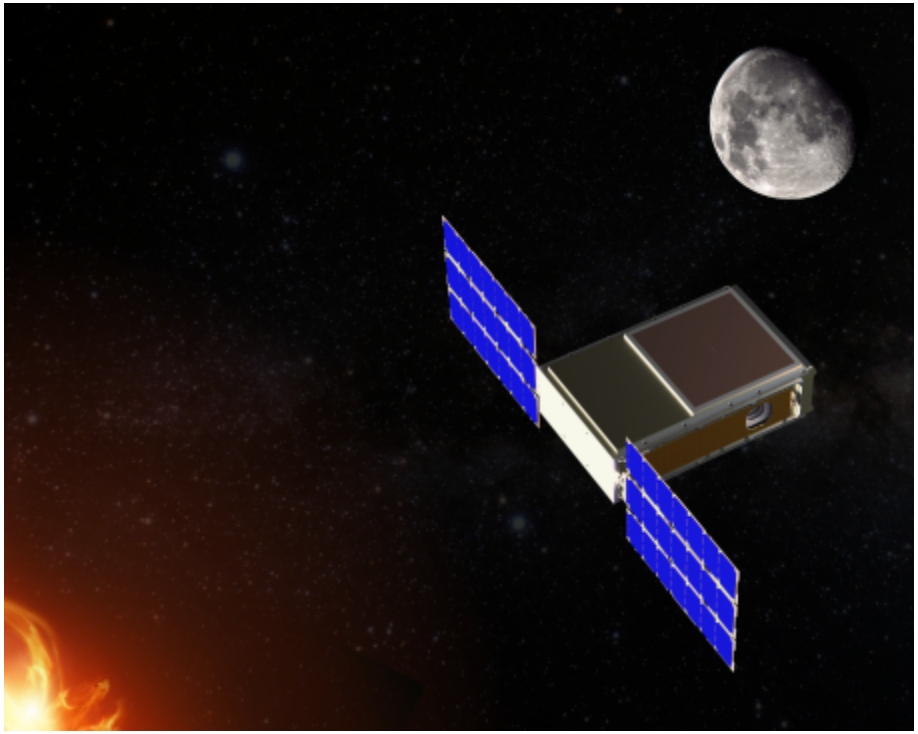
Fluidic Delivery System Block Diagram



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

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

***Support* :** NASA Human Exploration and Operations Mission Directorate (HEOMD) Advanced Exploration Systems Division – Jitendra Joshi, Jason Crusan Program Execs.

BACK-UP

BioSentinel Teaming

The Project Team

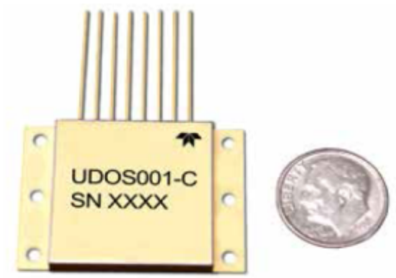
- Management
  - Bob Hanel, Elwood Agasid, Andres Martinez, Debra Reiss-Bubenheim
- Science
  - Sharmila Bhattacharya, Macarena Parra, Tore Straume, Sergio Santa Maria, Diana Marina, C. Mark Ott, Sarah Castro, Greg Nelson, Troy Harkness
- Payload
  - Tony Ricco, Travis Boone, Ming Tan, Charlie Friedericks, 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

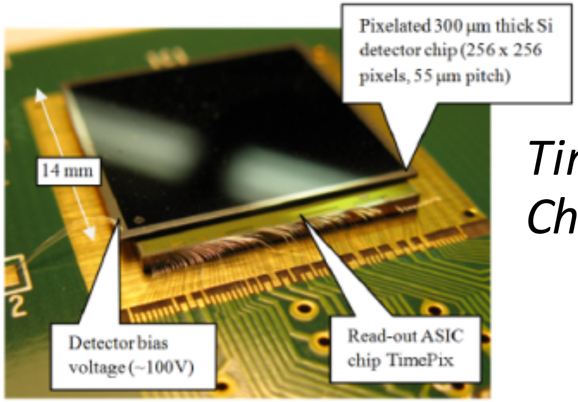
Support NASA Human Exploration and Operations Mission Directorate (HEOMD); Advanced Exploration Systems Division – Jitendra Joshi, Jason Crusan Program Execs.

- **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

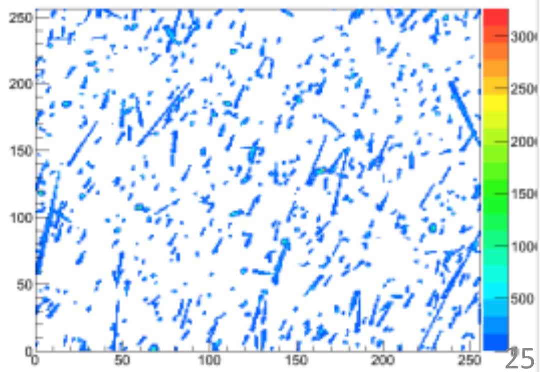
Typical TimePix frame:
256 x 256 x 14 bits
0.25 – 150 keV/µm LET range



Teledyne dosimeter



TimePix Chip



BioSentinel Payload

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