Ballooning for Biologists:

Mission Essentials for Flying Experiments on Large NASA Balloons

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Review Article

Ballooning for Biologists: Mission Essentials for Flying Life Science Experiments to Near Space on NASA Large Scientific Balloons

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ABSTRACT

Despite centuries of scientific balloon flights, only a handful of experiments have produced biologically relevant results. Yet unlike orbital spaceflight, it is much faster and cheaper to conduct biology research with balloons, sending specimens to the near space environment of Earth's stratosphere. Samples can be loaded the morning of a launch and sometimes returned to the laboratory within one day after flying. The National Aeronautics and Space Administration (NASA) flies large unmanned scientific balloons from all over the globe, with missions ranging from hours to weeks in duration. A payload in the middle portion of the stratosphere (~35 km above sea level) will be exposed to an environment similar to the surface of Mars—temperatures generally around -36°C, atmospheric pressure at a thin 1 kPa, relative humidity levels <1%, and harsh illumination of ultraviolet (UV) and cosmic radiation levels (about 100 W/m^2 and 0.1 mGy/d, respectively)—that can be obtained nowhere else on the surface of the Earth, including environmental chambers and particle accelerator facilities attempting to simulate space radiation effects. Considering the operational advantages of ballooning and the fidelity of space-like stressors in the stratosphere, researchers in aerobiology, astrobiology, and space biology can benefit from balloon flight experiments as an intermediary step on the extraterrestrial continuum (i.e., ground, low Earth orbit, and deep space studies). Our review targets biologists with no background or experience in scientific ballooning. We will provide an overview of large balloon operations, biology topics that can be uniquely addressed in the stratosphere, and a roadmap for developing payloads to fly with NASA.

INTRODUCTION

In 1783, a hydrogen balloon lifted off from Paris, France, starting the era of scientific

Summary

Unlike orbital spaceflight, it is much **faster and cheaper** to conduct biology research with balloons, sending specimens to the near space environment of Earth's stratosphere. Samples can be loaded the morning of a launch and sometimes returned to the laboratory within one day after flying. The National Aeronautics and Space Administration (NASA) flies large, unmanned scientific balloons from all over the globe, with missions ranging from **hours to months** in duration.

A payload in the middle portion of the stratosphere (~35 km above sea level) will be exposed to an environment similar to the surface of Mars: temperatures generally around -36 °C, atmospheric pressure at a thin 1 kPa, relative humidity levels < 1%, and a harsh illumination of ultraviolet (UV) and cosmic radiation levels (about 100 W/m^2 and 0.1 mGy/d, respectively) that **can be obtained nowhere else on the surface of the Earth, including environmental chambers and particle accelerator facilities attempting to simulate space radiation effects**.

Considering the operational advantages of ballooning and the fidelity of space-like stressors in the stratosphere, researchers in the NASA Human Research Program can benefit from balloon flight experiments as **an intermediary step on the extraterrestrial radiation continuum** that includes low Earth orbit and deep space studies.

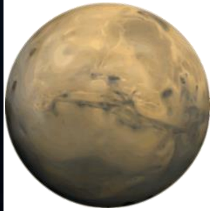
Big picture: NASA wants to understand how life responds to space radiation. The stratosphere is *Near Space*. It is part of a radiation continuum (Ground < Near Space < Low Earth Orbit < Deep Space)

Near Space is on the Radiation Continuum

Ground radiation simulations

This is where balloons fly (Near Space radiation)

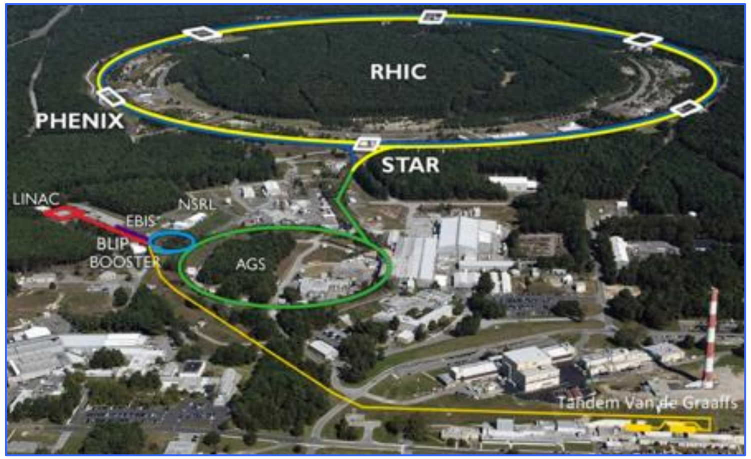
This is where most NASA radiation research occurs (low Earth orbit)



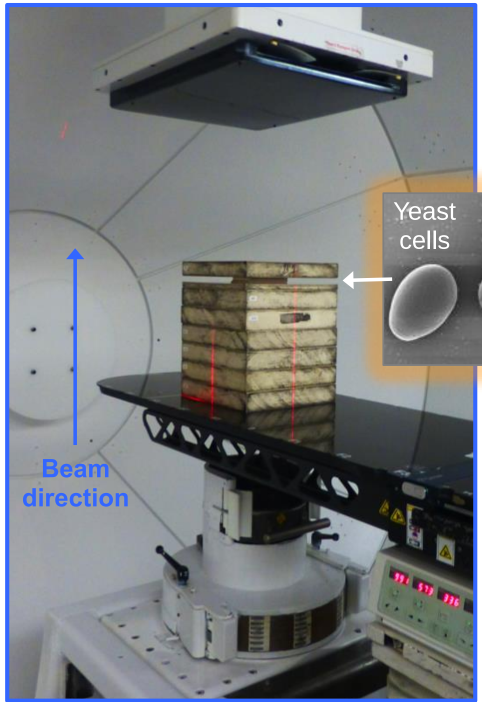
This is where we want to go (deep space radiation)

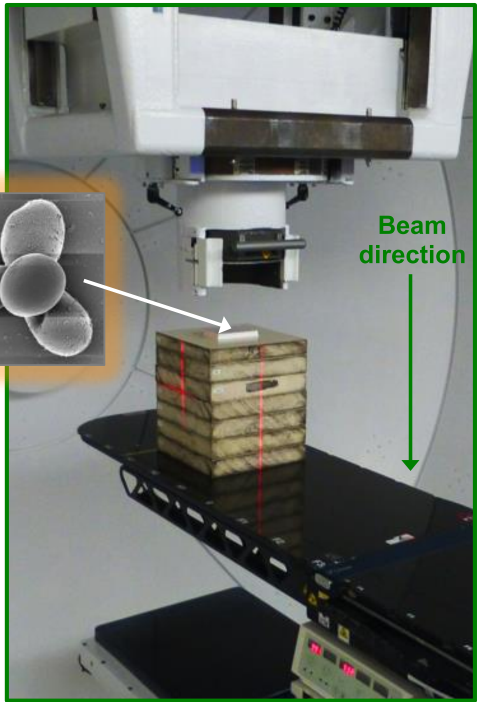
Limitation of ground based facilities

- While hypobaric chambers and particle accelerating facilities may also be used to measure the effects of space-like environments on biology, ground simulations are often (1) expensive to perform, (2) volume limited, and (3) unable to accurately mimic dynamic sunlight levels
- Consequently, ground-based experiments tend to be short-lasting, small in size, and limited by artificial doses of radiation. In contrast, the stratosphere naturally produces a fuller suite of biological stressors expected in space – including real high energy particles (and secondary scattering difficult to simulated in ground facilities).
- In order to study the effects of GCR and solar particle events on both biology and physics, NASA has developed a specialized radiation exposure facility at Brookhaven National Laboratory (https://www.bnl.gov/nsrl/). The NASA Space Radiation Laboratory (NSRL) is capable of generating a range of ions from protons to uranium at relevant energies observed beyond LEO (from 50 MeV to 1000 MeV, depending on the ion). Beam target size is limited to about 20 x 20 cm^2 which can be a limitation for experiments requiring large hardware for biological samples. Current beamline developments should permit more complex mixed ion exposures in the future; but **the need to perform studies at very low dose rates to replicate the space environment is not always practical at NSRL due to access limitations and cost**.

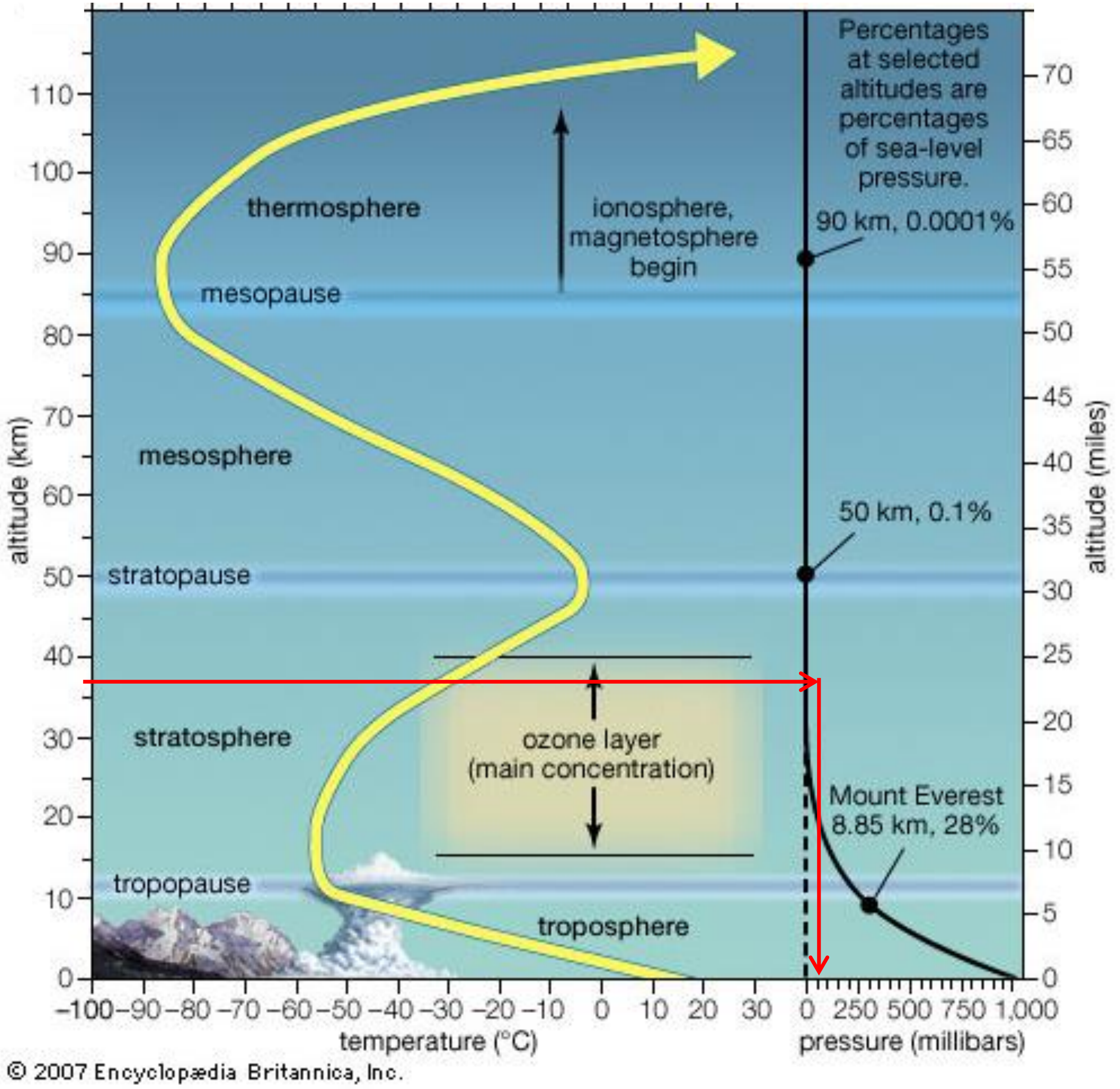


Figures courtesy of BioSentinel science team

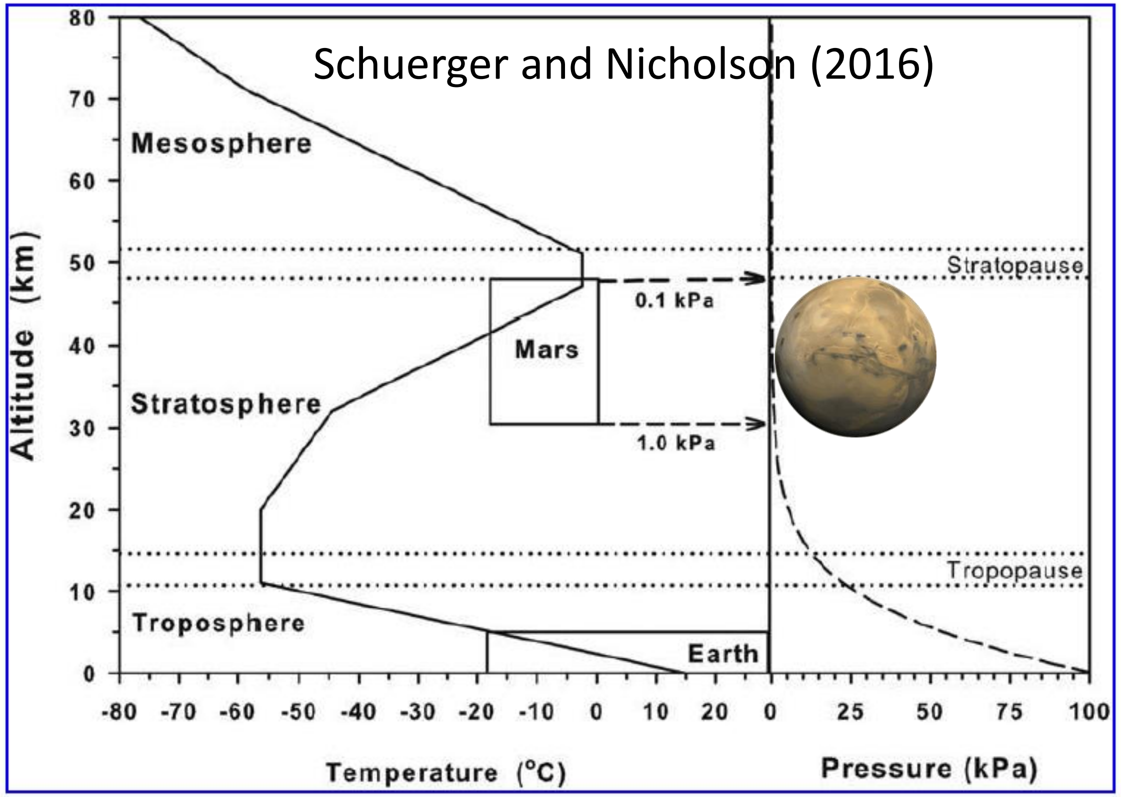




Earth's Atmosphere

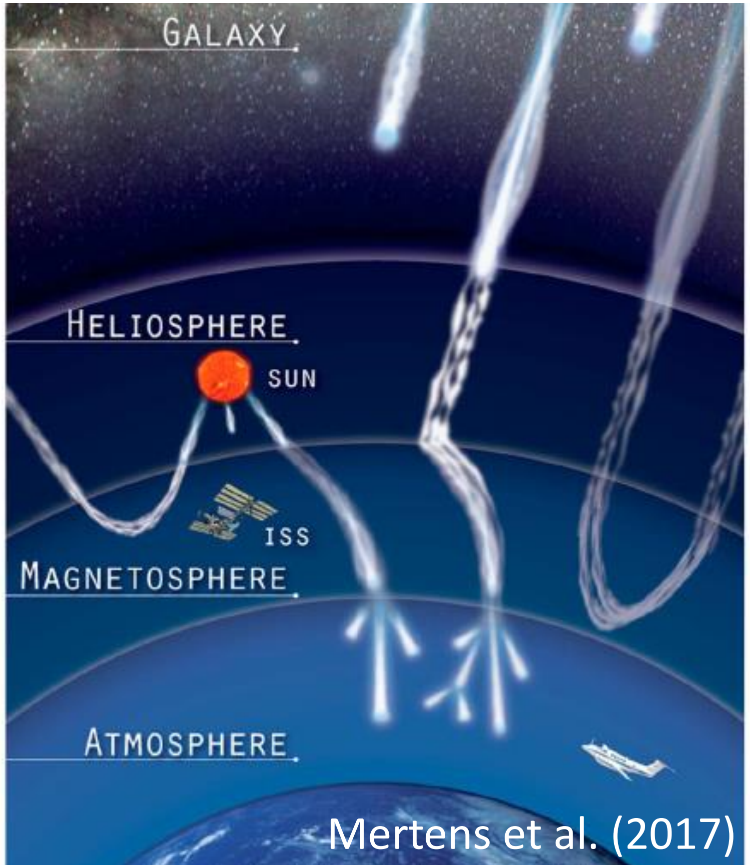


Using the stratosphere as a Mars analog environment



Overview of Near Space Conditions

There are two sources of cosmic rays: (1) the ever-present galactic cosmic rays (**GCR**), with origins outside the solar system and (2) the transient solar energetic particles (**SEP**) (or solar cosmic rays)



Location	UVB Total (W m^{-2}) 280-315 nm	UVC Total (W m^{-2}) 100-280 nm	Ionizing Radiation (mGy/d)	Pressure (kPa)	Temp (°C)	RH (%)
New Mexico (35 km ASL)	10.6	2.60	0.066	2.84	-30	< 2
Mars (surface)	8.38	3.18	0.200	0.700	-53	<< 1

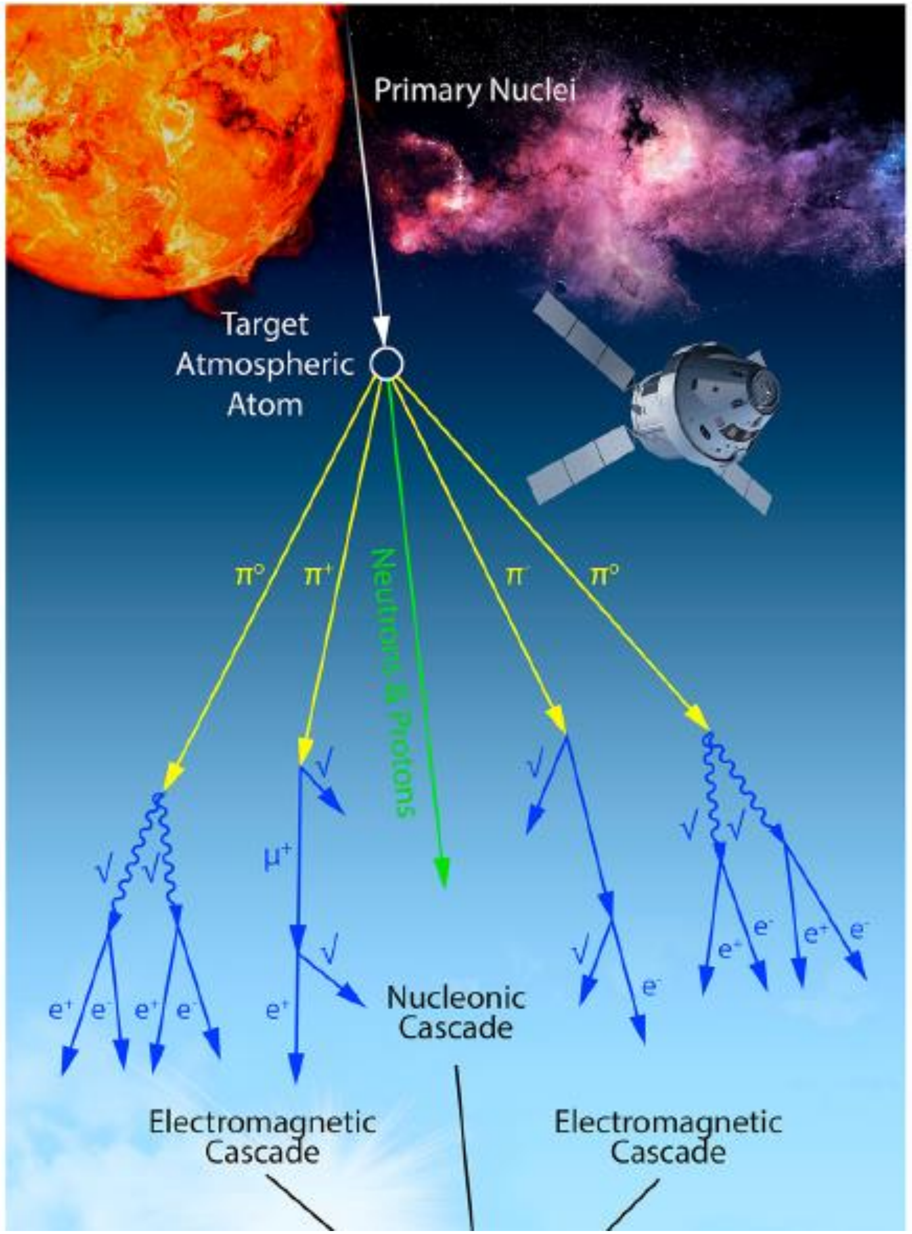
*Values averaged from Nicholson et al. (2002), Hassler et al. (2014), Mertens et al. (2017), Khodadad et al. (2017)

Energetic particle radiation from space continuously bombards the Earth's atmosphere. Cosmic radiation has sufficient energy to penetrate deep within the atmosphere and adversely affect biology.

Background

- Another way of looking at Near Space radiation
- Note: at the altitudes where balloons fly (35-40 km ASL) collisions between cosmic radiation and the atmospheric aerosols/gases can generate **secondary radiation through nuclear fragmentation processes**
- Some spacecraft shielding materials may give rise to secondary fragmentation products that could be more damaging than the primary radiation field (NCRP, 2006).

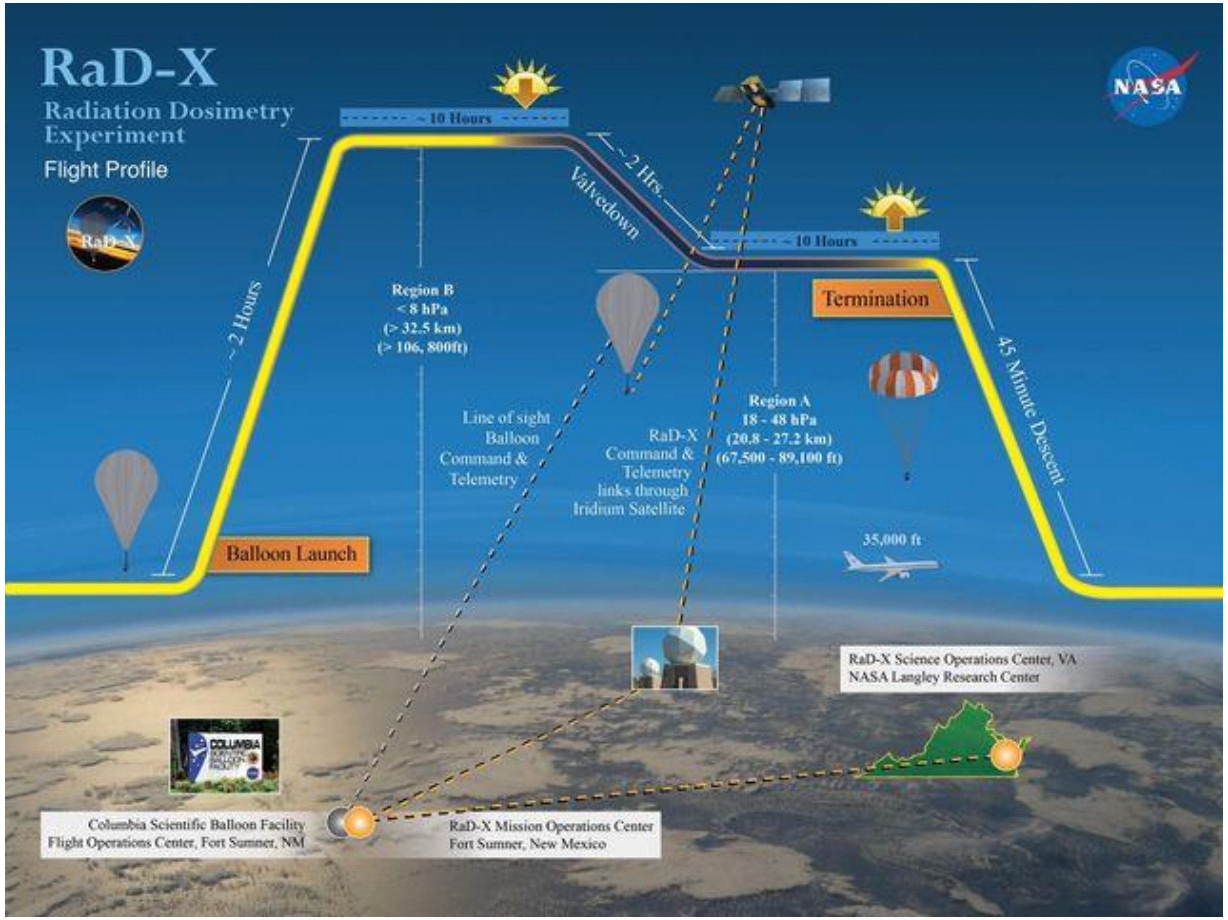
Figure adapted from Mertens et al. (2017)



This is where balloons fly (Near Space radiation)

Overview of Near Space/Stratosphere Conditions (more on ionizing radiation dose)

- In a recent NASA balloon flight experiment launched September 2015 (Flight #666N from Ft. Sumner, NM), the Radiation Dosimetry Experiment (**RaD-X**) was sent to 36.6 km ASL to test an ionizing radiation instrument suite. Average dose rates in the stratosphere were approximately 0.064 mGy/d (Mertens et al., 2016); slightly lower than recent measurement by the MSL rover on the surface of Mars, 0.18 to 0.225 mGy/d (Hassler et al., 2014). The average linear energy transfer (density of ionizations per unit length) was found to increase as altitude increased from 24.3 to 36.7 km (Mertens et al., 2017) probably due to heavy ions (Z = 6-28) (NCRP, 1995)
- Neutrons are the most hazardous radiation for multicellular biological studies in the stratosphere (Schimmerling, 2011).



Overview of Near Space/Stratosphere Conditions
(more on ionizing radiation dose – recently measured by RaD-X mission)

Table 2. Comparison of the Dose Rate in Tissue Calculated Using the Three GCR Models to RaD-X TEPC Dose Rate Measurements

Altitude (km)	Pressure (hPa)	TEPC Dose Rate (μGy/h)	BO2014 Dose Rate (μGy/h)	DLR Dose Rate (μGy/h)	ISO Dose Rate (μGy/h)
24.3	27.3	3.05 ± 0.48	2.63	2.86	2.44
36.7	4.5	2.58 ± 0.41	2.28	2.46	2.05

Table and figures from Norman et al. (2017)

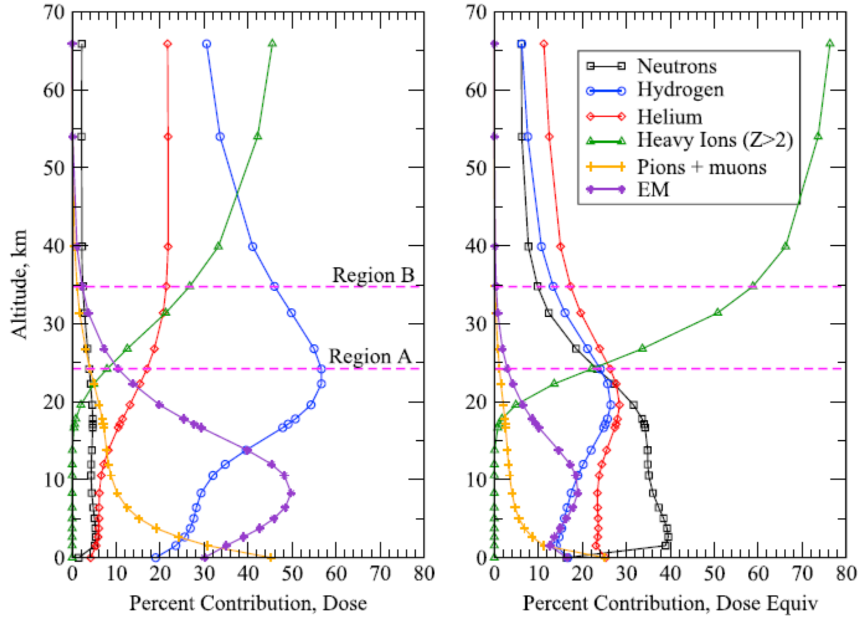


Figure 7. The percent contribution to (left) dose and (right) dose equivalent by different particle groups as a function of altitude for the RaD-X flight (25–26 September 2015) from the three GCR models. Horizontal dashed lines correspond to average altitude for Regions B and A for reference.

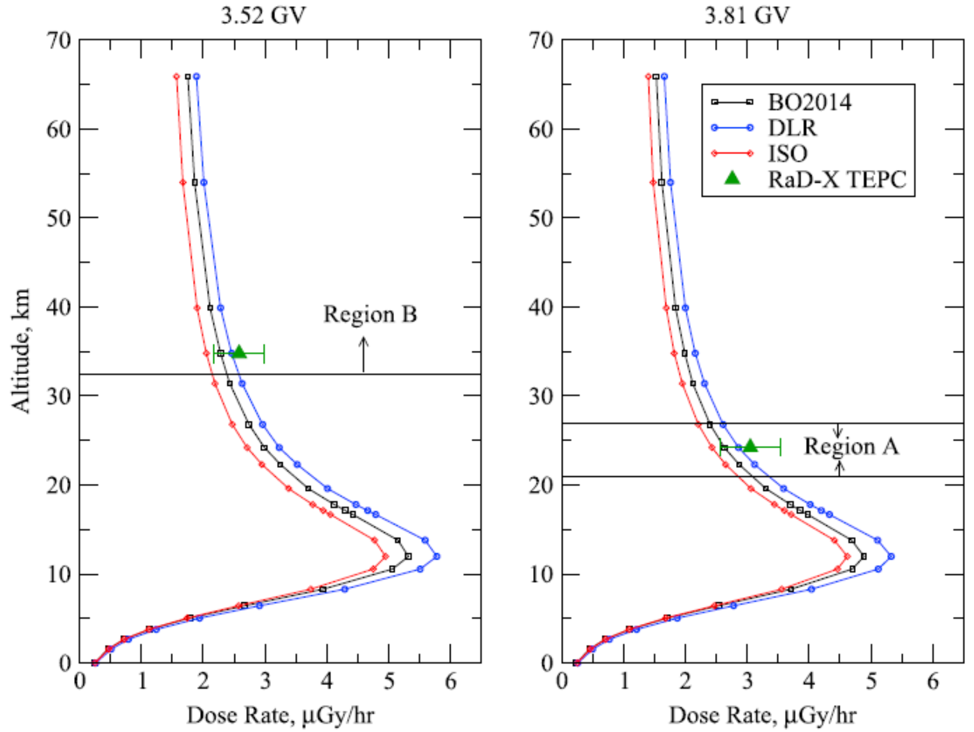
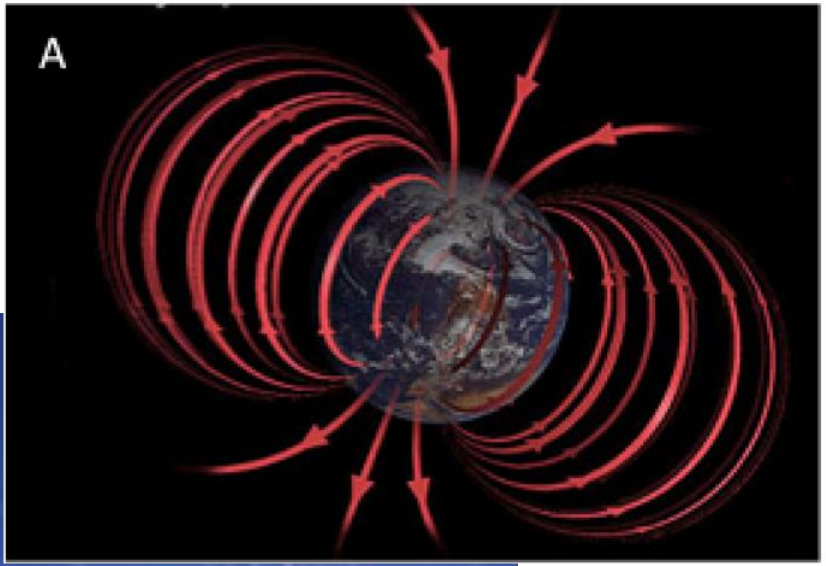


Figure 4. Dose rate in tissue as a function of altitude for the RaD-X flight (25–26 September 2015) from the three GCR models compared to RaD-X TEPC dose rate measurements. (left) Calculated with a vertical cutoff rigidity of 3.52 GV, which corresponds to the average value, while RaD-X was in Region B (> 32.5 km). (right) Calculated with a vertical cutoff rigidity of 3.81 GV, which is the average value during Region A (21–27 km).

Dose rate is largest at high magnetic latitudes (polar regions)

- Bottom line: recent RaD-X measurements show dynamic low dose of radiation in Near Space; demonstrates potential for **long duration, low dose rate ionizing radiation experiments**
- Important point: RaD-X was a mid-latitude flight. **Polar balloon flights** (NASA launches 1-2 per year) would provide more high particle radiation to due to the magnetic field window at latitudes above 70°.
- Most cosmic radiation particles are deflected around the Earth by its magnetic field. However, solar and deep space particles do penetrate through the magnetic north and south poles

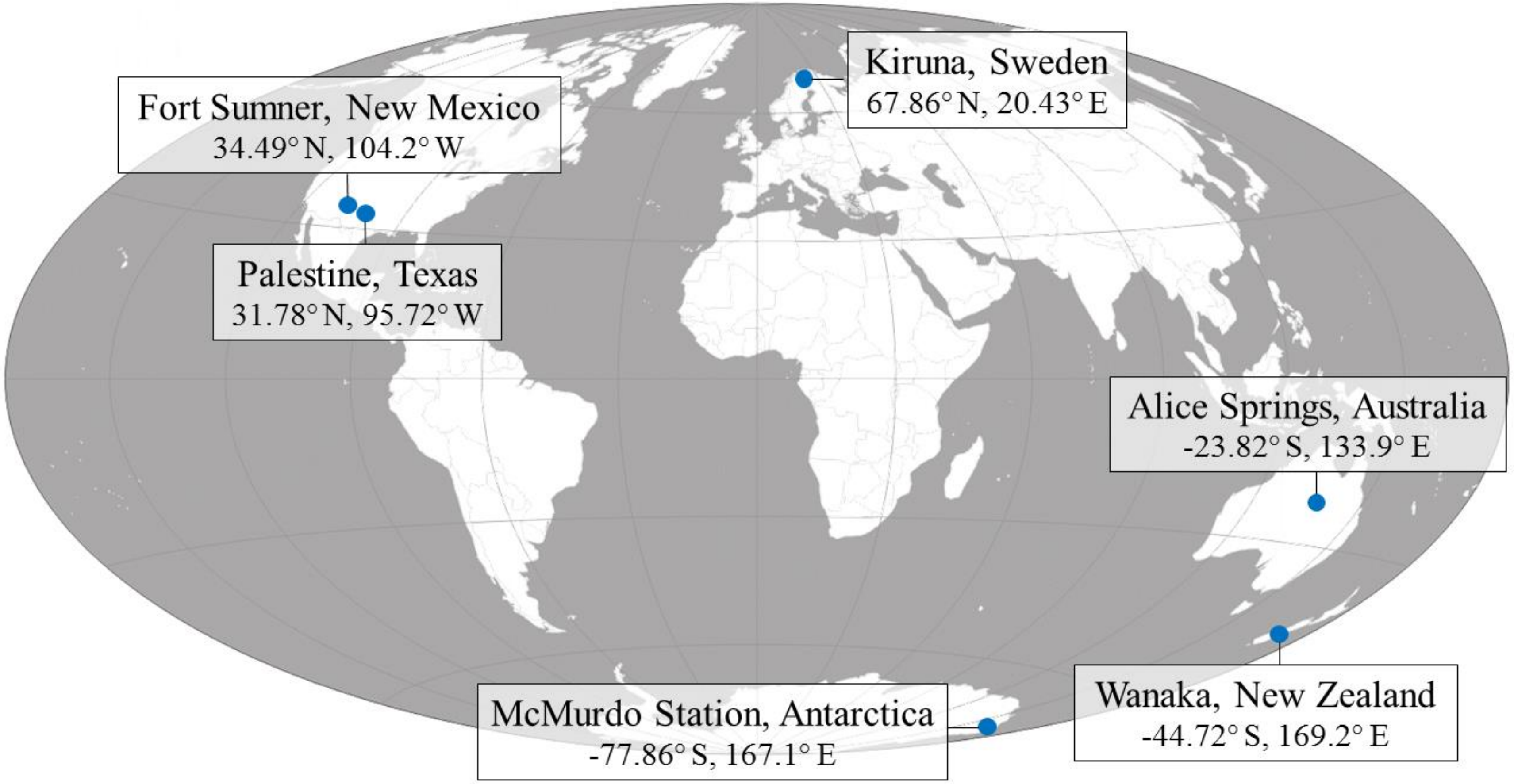


Figures courtesy of NASA

Examples of existing ISS or ground-based biology hardware that could easily be flown on balloons

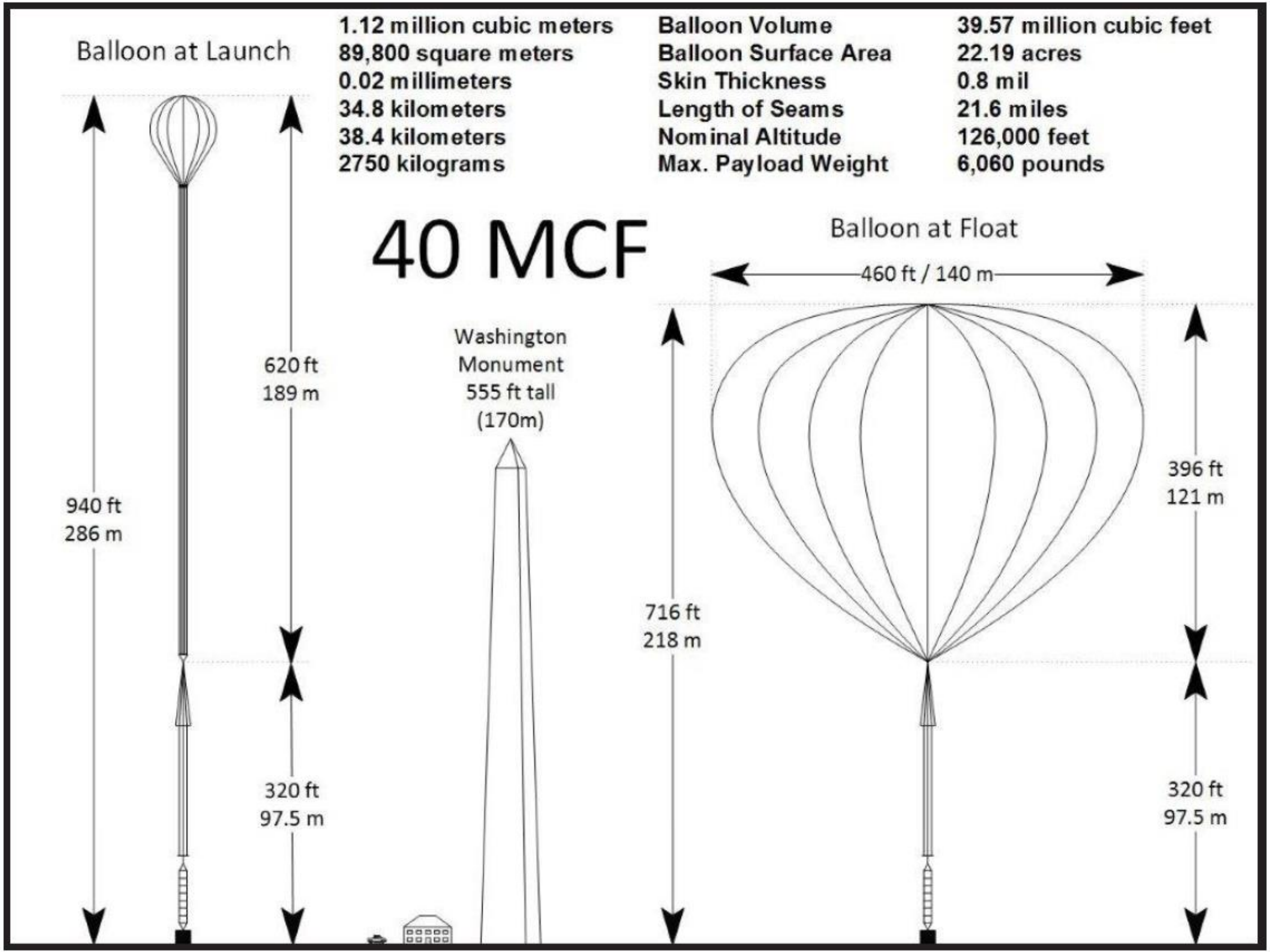
Overview of NASA Balloon Program

The NASA Balloon Program Office (BPO) is located at Goddard Space Flight Center's Wallops Flight Facility (WFF) at Wallops Island, Virginia (https://sites.wff.nasa.gov/code820/). It oversees operations for a portfolio of 10 to 16 annual missions sponsored and approved by NASA's Science Mission Directorate (SMD)



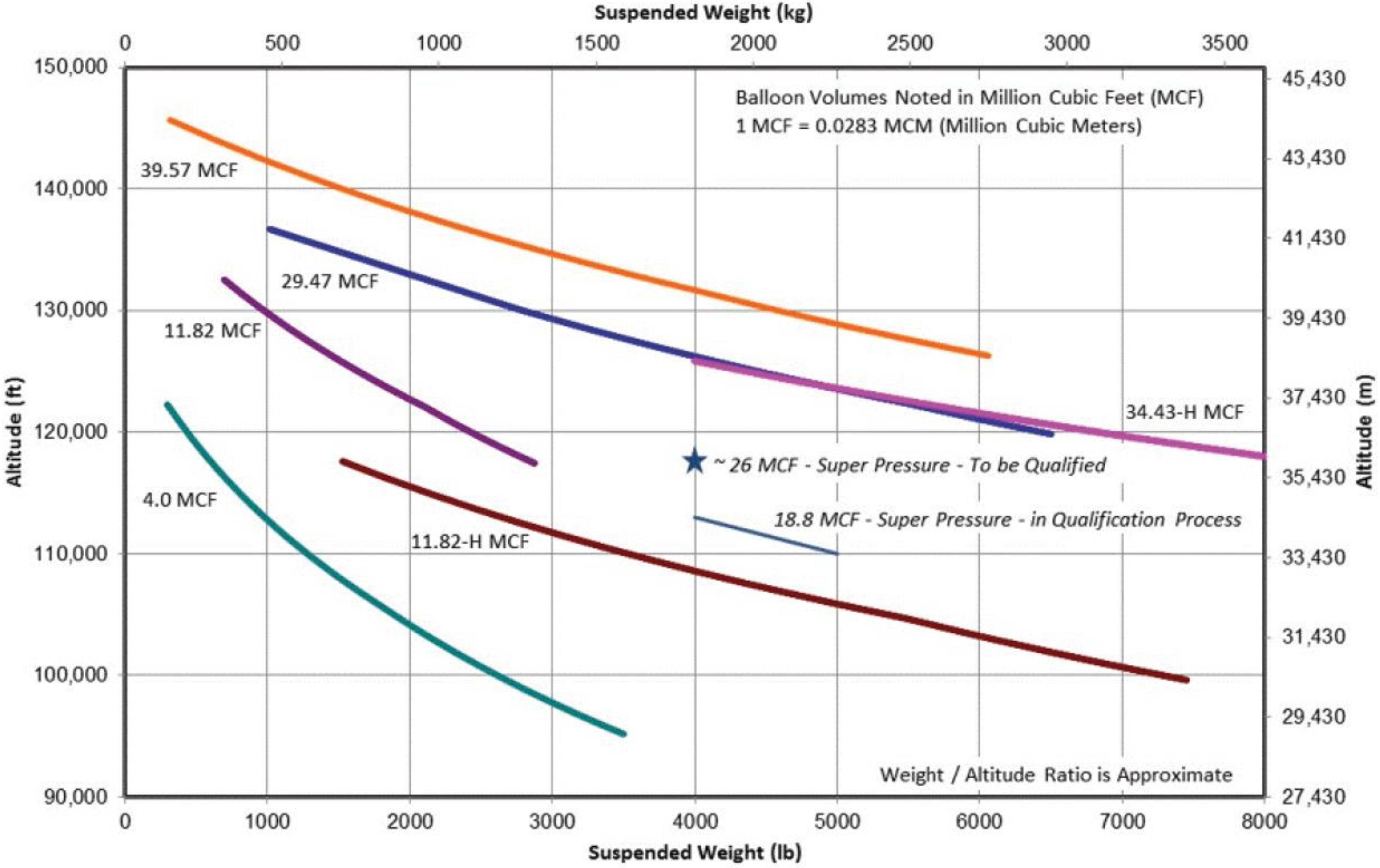
At launch

At float

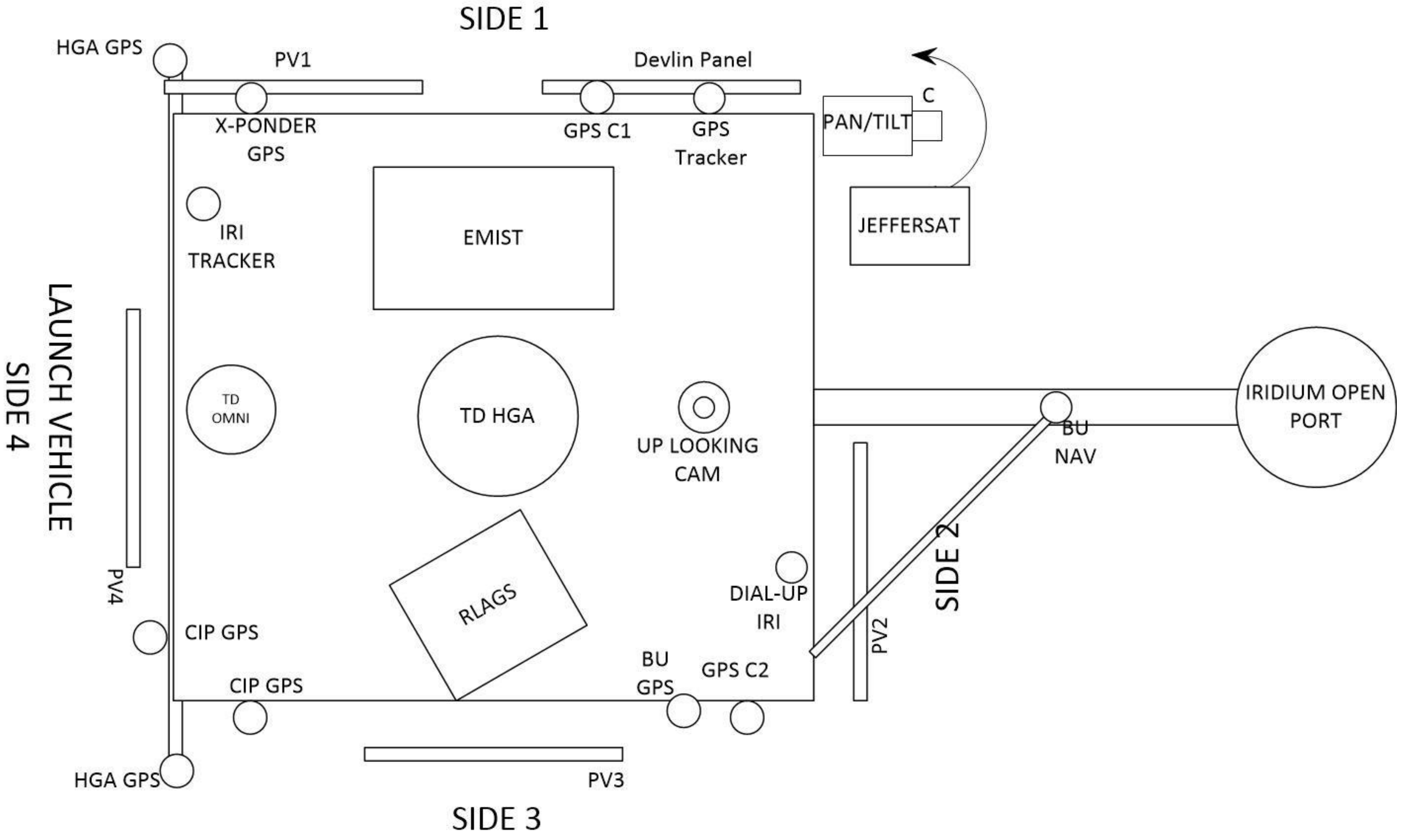


1.12 million cubic meters
Balloon Volume
39.57 million cubic feet
89,800 square meters
Balloon Surface Area
22.19 acres
0.02 millimeters
Skin Thickness
0.8 mil
34.8 kilometers
Length of Seams
21.6 miles
38.4 kilometers
Nominal Altitude
126,000 feet
2750 kilograms
Max. Payload Weight
6,060 pounds
Balloon at Launch
40 MCF
Balloon at Float
460 ft / 140 m
620 ft
189 m
940 ft
286 m
320 ft
97.5 m
Washington
Monument
555 ft tall
(170m)
716 ft
218 m
396 ft
121 m
320 ft
97.5 m

NASA Balloon Program Office: Capabilities



EXAMPLE GONDOLA CONFIGURATION

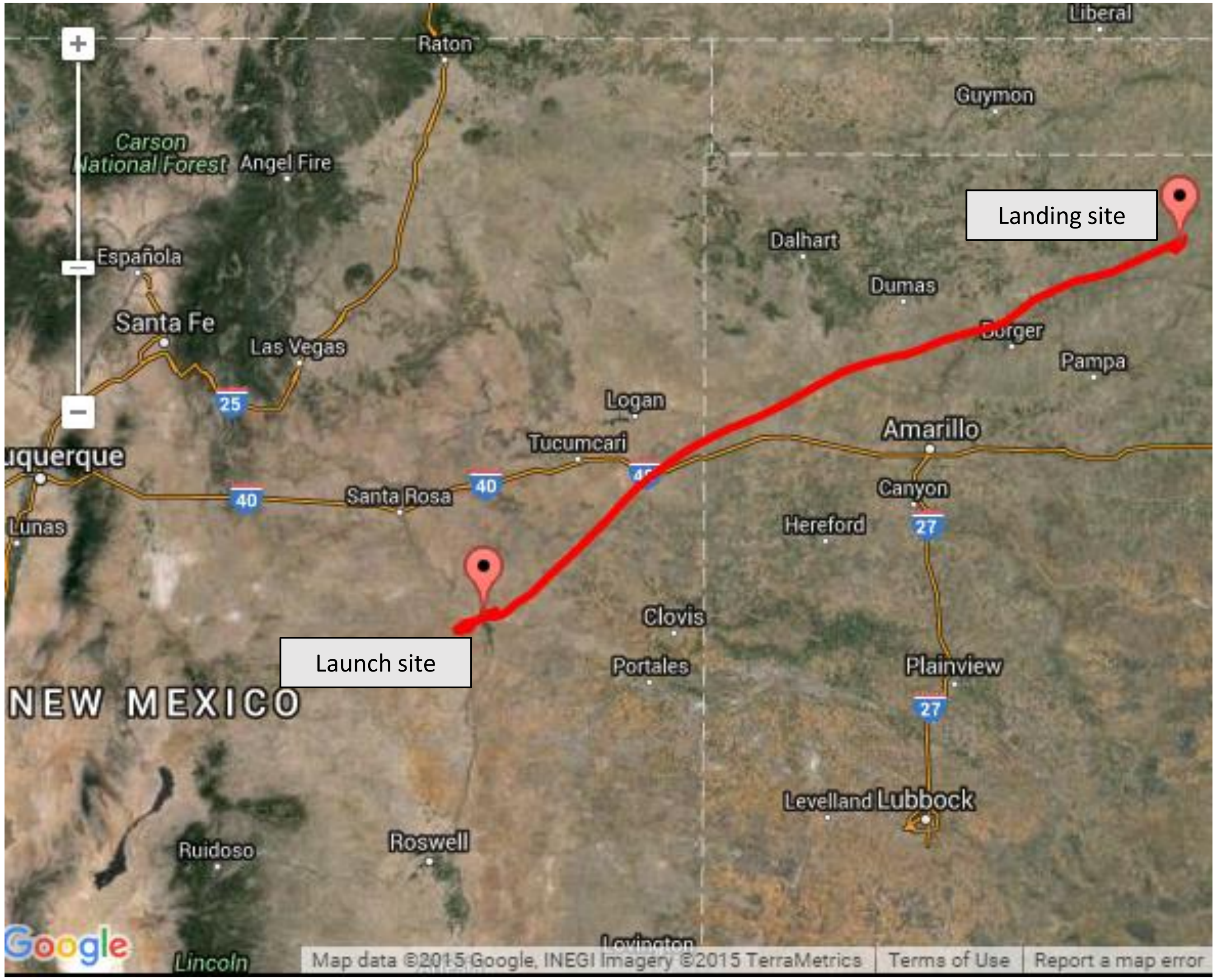


Launch Vehicle

Rollout to Launch / Late Load

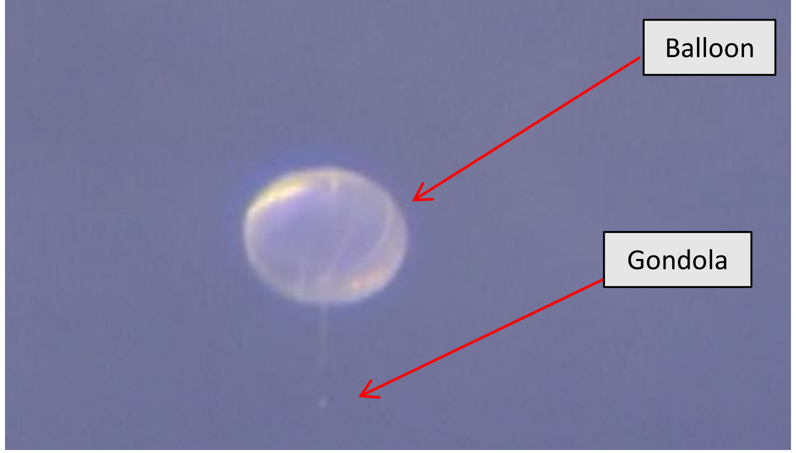
INFLATION

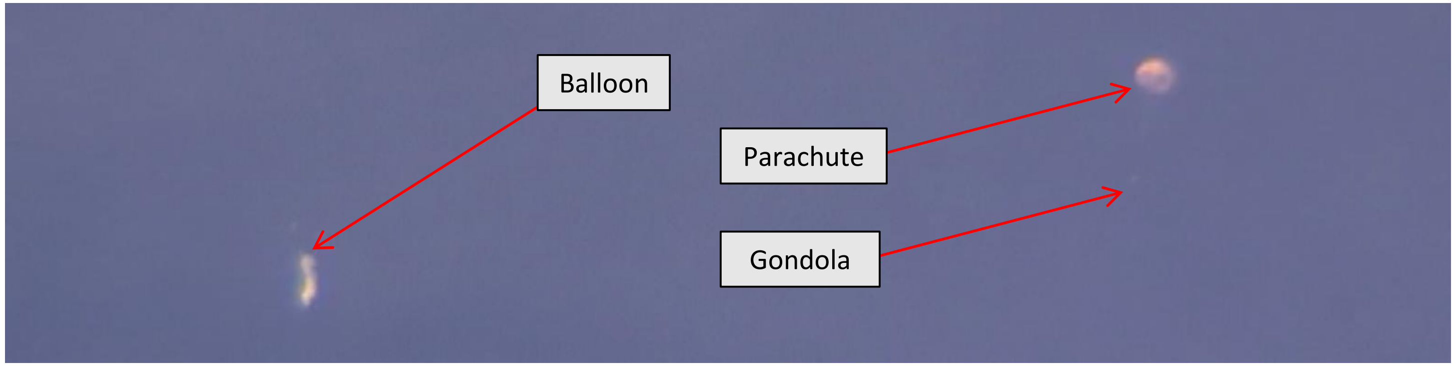
Example Flight Path from Ft. Sumner Launch Site




NASA

Payload Recovery





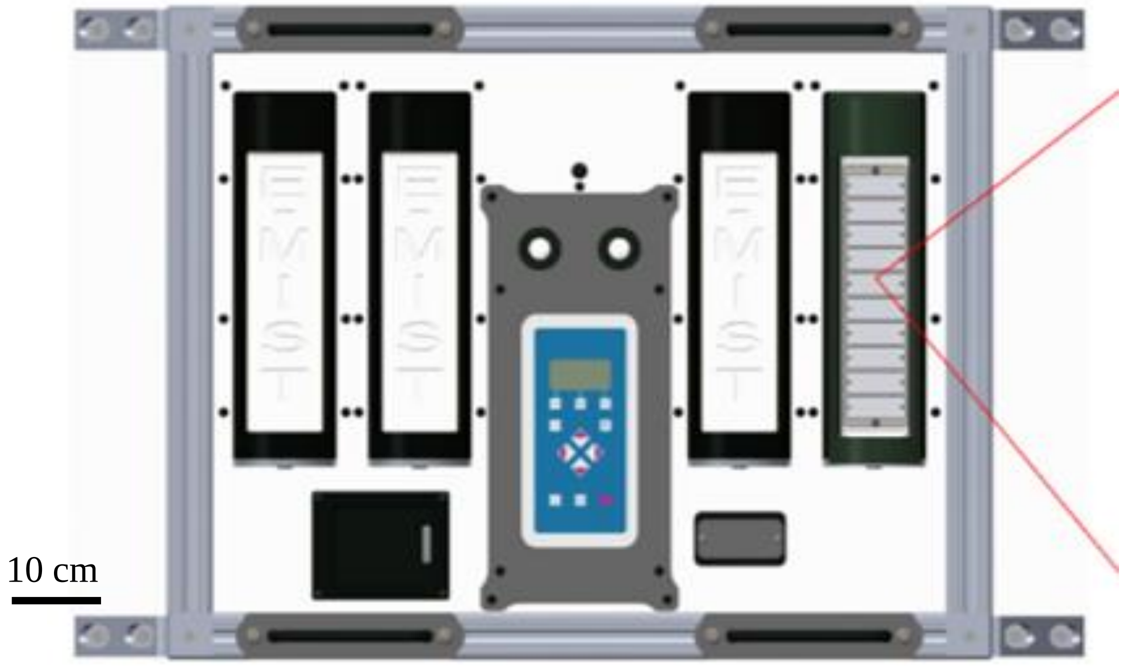
Exposing Microorganisms in the Stratosphere (E-MIST)

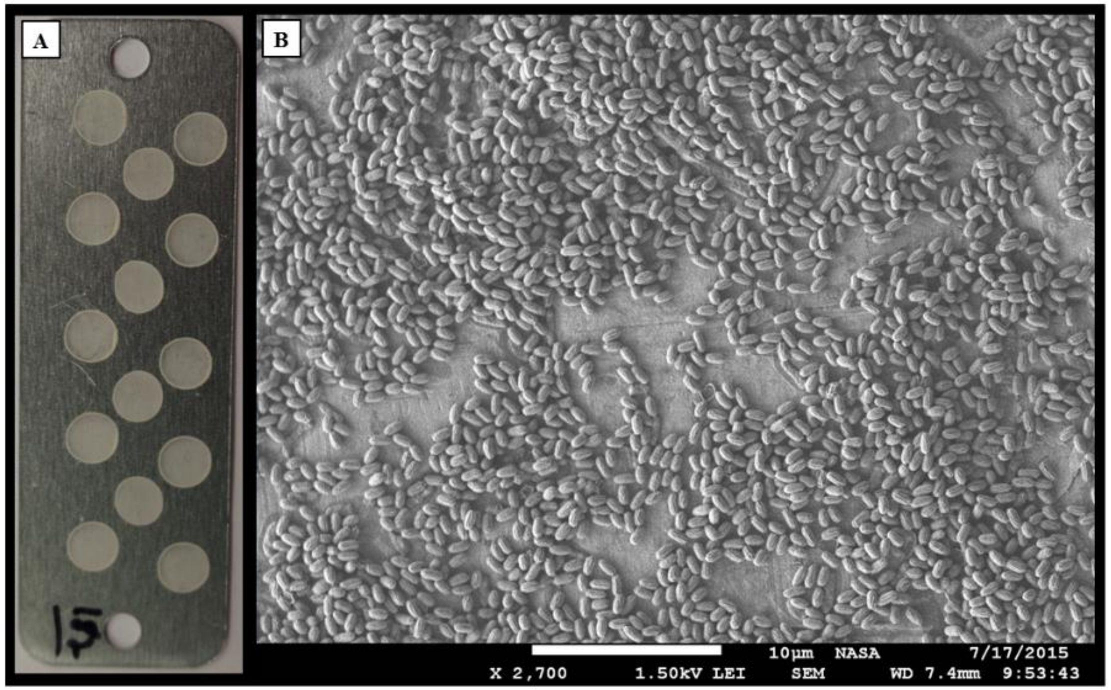
Flown August 2014, October 2015

We know microbes are traveling to Mars on NASA spacecraft.
Will they survive once reaching the Red Planet?

Ground simulations suggested…

- *Bacillus pumilus* SAFR-032, would **not** be able to withstand the combined effects of Mars-like temperature, pressure, desiccation, and irradiation after direct exposure to such conditions for up to 8 hours.
- Our hypothesis was testable by sending known quantities of monolayered bacteria into the Earth's stratosphere on a long duration balloon flight while collecting pertinent environmental data





http://www.nasa.gov/ames/research/space-biosciences/e-mist-2015

E-MIST: Recent Publication

An 8-hour stratospheric flight on the NASA E-MIST balloon killed off even the hardiest microbes.

David J. Smith/NASA

UV light could easily kill microbial stowaways to Mars

By Joshua Sokol
Mar. 28, 2017, 2:15 PM

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Mary Ann Liebert, Inc.
DOI: 10.1089/ast.2016.1549

Stratosphere Conditions Inactivate Bacterial Endospores from a Mars Spacecraft Assembly Facility

Christina L. Khodadad,[1] Gregory M. Wong,[2] Leandro M. James,[3] Prital J. Thakrar,[3] Michael A. Lane,[3] John A. Catechis,[1] and David J. Smith[4]

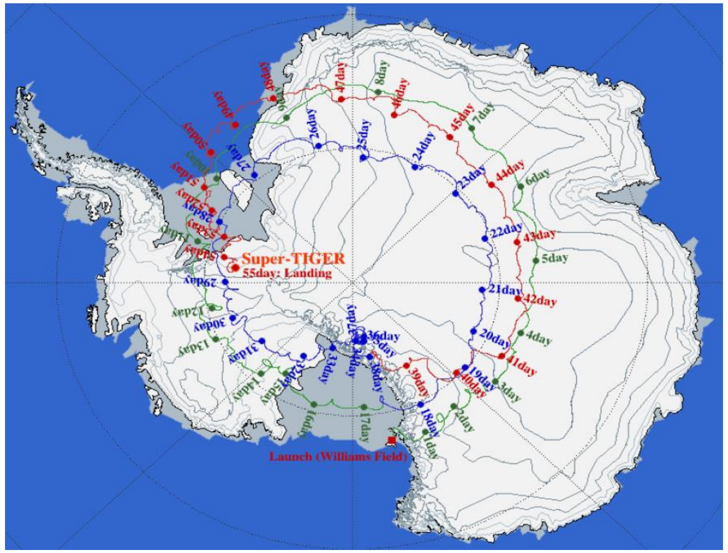
Abstract

Every spacecraft sent to Mars is allowed to land viable microbial bioburden, including hardy endospore-forming bacteria resistant to environmental extremes. Earth's stratosphere is severely cold, dry, irradiated, and oligotrophic; it can be used as a stand-in location for predicting how stowaway microbes might respond to the martian surface. We launched E-MIST, a high-altitude NASA balloon payload on 10 October 2015 carrying known quantities of viable *Bacillus pumilus* SAFR-032 (4.07×10^7 spores per sample), a radiation-tolerant strain collected from a spacecraft assembly facility. The payload spent 8 h at ~31 km above sea level, exposing bacterial spores to the stratosphere. We found that within 120 and 240 min, spore viability was significantly reduced by 2 and 4 orders of magnitude, respectively. By 480 min, <0.001% of spores carried to the stratosphere remained viable. Our balloon flight results predict that most terrestrial bacteria would be inactivated within the first sol on Mars if contaminated spacecraft surfaces receive direct sunlight. Unfortunately, an instrument malfunction prevented the acquisition of UV light measurements during our balloon mission. To make up for the absence of radiometer data, we calculated a stratosphere UV model and conducted ground tests with a 271.1 nm UVC light source (0.5 W/m^2), observing a similarly rapid inactivation rate when using a lower number of contaminants (640 spores per sample). The starting concentration of spores and microconfiguration on hardware surfaces appeared to influence survivability outcomes in both experiments. With the relatively few spores that survived the stratosphere, we performed a resequencing analysis and identified three single nucleotide polymorphisms compared to unexposed controls. It is therefore plausible that bacteria enduring radiation-rich environments (*e.g.,* Earth's upper atmosphere, interplanetary space, or the surface of Mars) may be pushed in evolutionarily consequential directions. Key Words: Planetary protection—Stratosphere—Balloon—Mars analog environment—E-MIST payload—*Bacillus pumilus* SAFR-032. Astrobiology 17, 337–350.

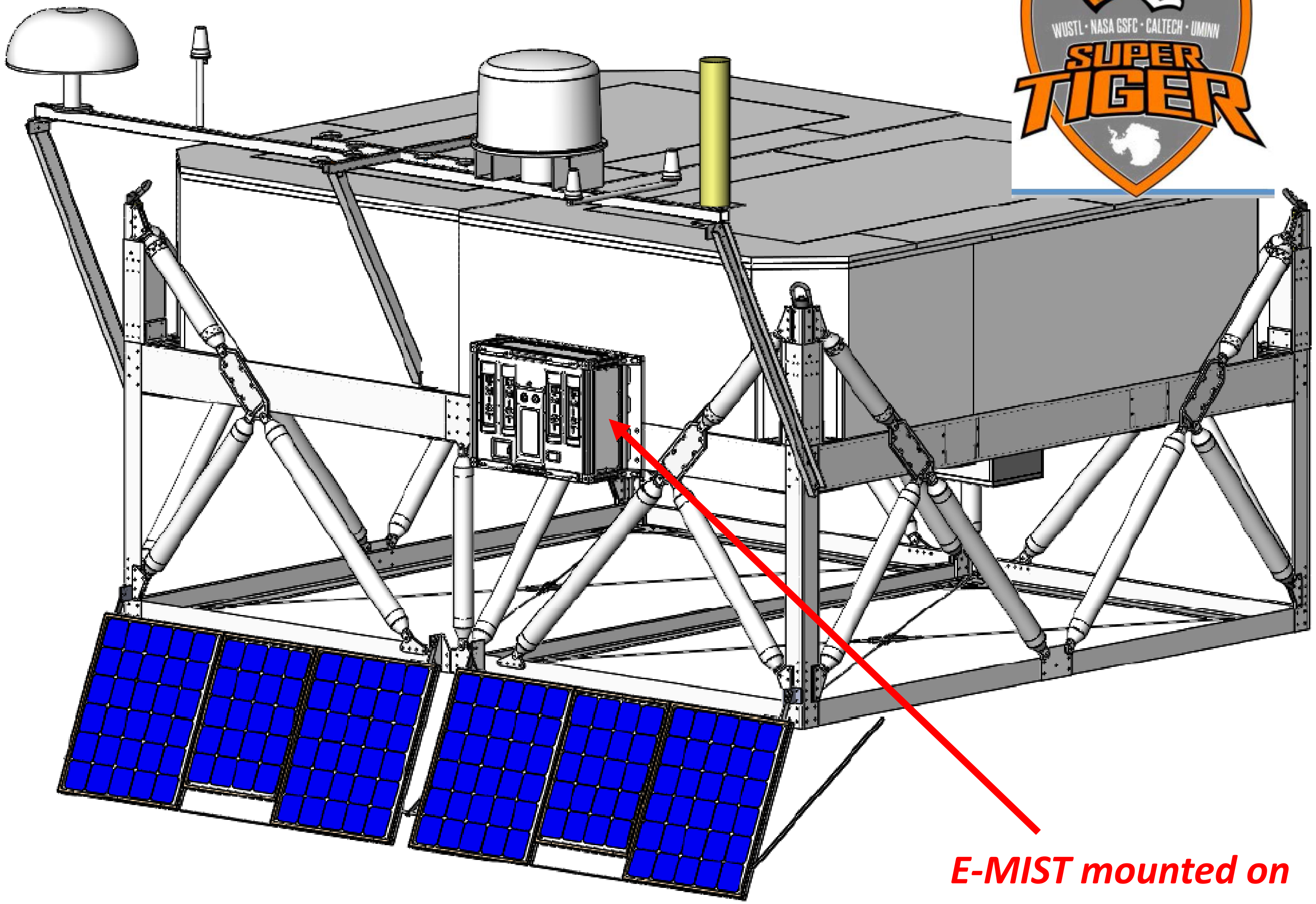
http://online.liebertpub.com/doi/full/10.1089/ast.2016.1549

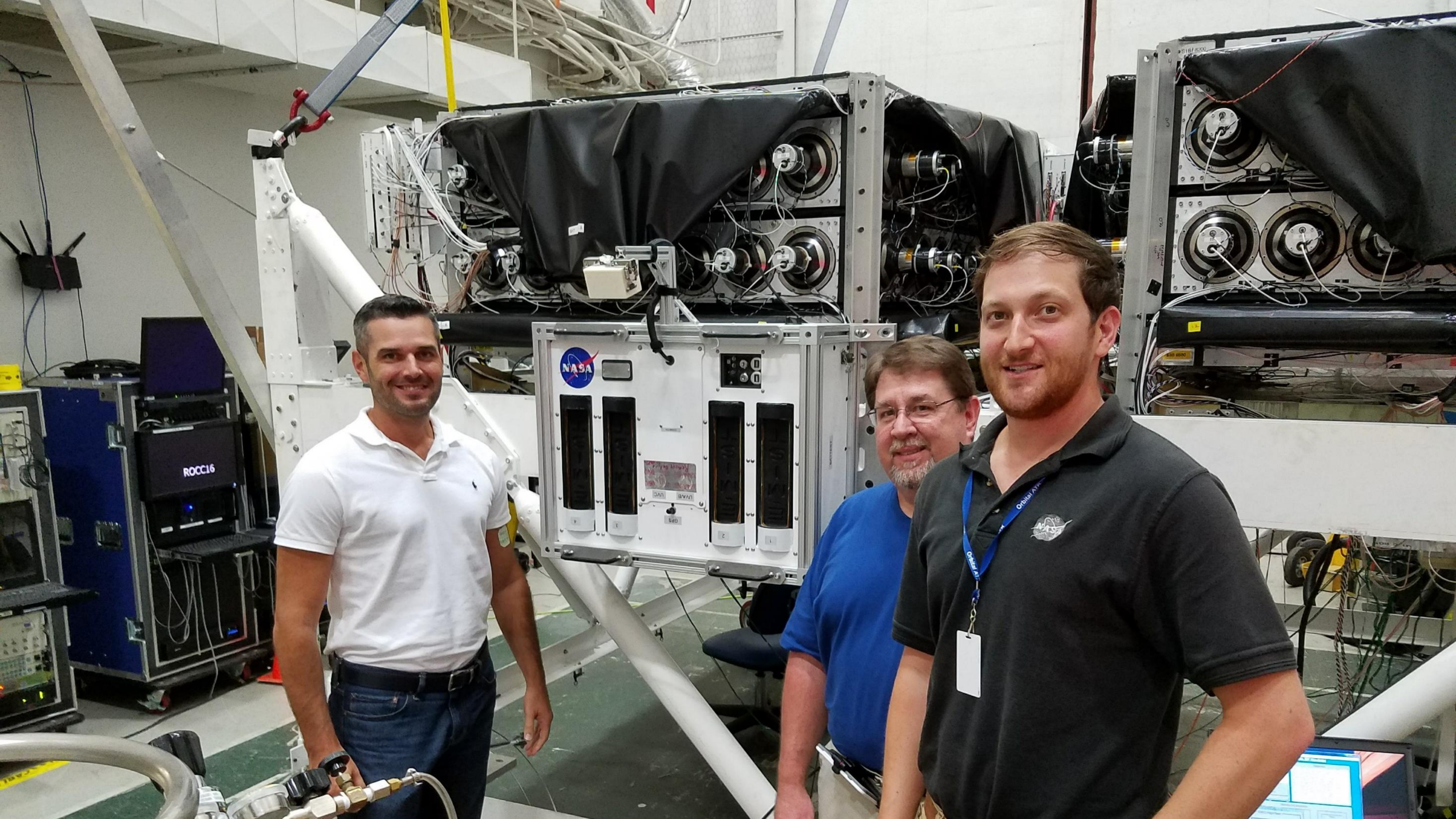
Next E-MIST Launch: South Pole, December 2017

- Piggyback payload on SuperTIGER II LDB (PI Bob Binns, Washington University)
- SuperTIGER I mission floated for 55 days in 2013



- 5 NASA-relevant microbes will be flown: shaded and unshaded treatments




NASA
ROCC16

New Commercial Carriers on the Horizon

(in addition to what NASA BPO already offers)

http://www.worldview.space/

Crewed flights (*planned*) could offer more HRP opportunities and hands-on experiment time

http://nsc.aero/

General Comparison of Flying Micro experiments to ISS vs. Near Space on Balloons

Factor	ISS	Balloons
Planning time req'd before a flight	1+ year and often much longer	< 1 year
Cost to Fly	Multiple million$ per experiment	Tens of thousand$ per experiment
Frequency of Flights	Rare	Available
Payload weight capacity	Usually < 100 lbs per experiment	Payload usually has 3,000 lbs to spare
Payload power capacity	Power demands highly regulated	Unlimited power (solar cells)
Handover lead time	Up to 6 months	< 1 hr prior to launch
Recovery lag time	Days to weeks	< 24 hrs samples back in laboratory
Available space-relevant exposures	• + ionizing rad • – UV rad • + microgravity	• + ionizing rad • + UV rad • – microgravity
Crew available for manual ops	Yes	No (experiments must be automated)

Take Home Messages

- *Why should you care/listen*: The near space environment can be used as a high fidelity research location for microbiological experiments examining responses to space radiation. Balloon experiments are cheap and fast to fly.
- *Why not just keep flying ISS experiments?* Pace is slow, costs a lot of money, and some questions can be examined (and with better statistical power) using balloon flights.
- *Why not just use ground-based radiation simulation facilities?* There's no substitute for real sunlight and high energy particles from space. Naturally available in the stratosphere using balloons. Low dose rate, long duration exposures unique to Near Space environment.

Acknowledgements

Space Biology Program (HEOMD/SLPSRA), Kennedy Space Center IR&D, Planetary Protection Office (SMD), Balloon Program Office (SMD) and Columbia Scientific Balloon Facility

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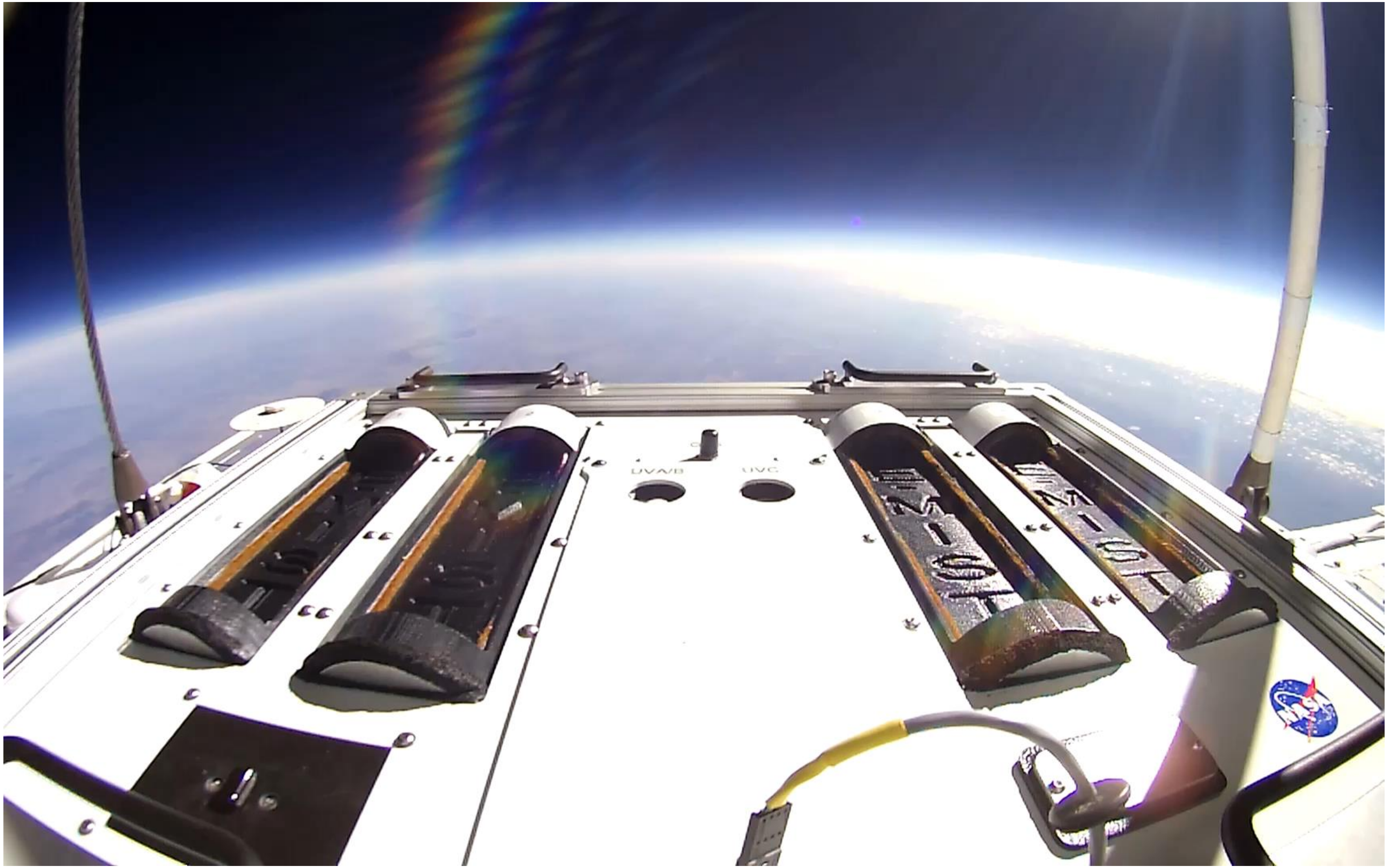
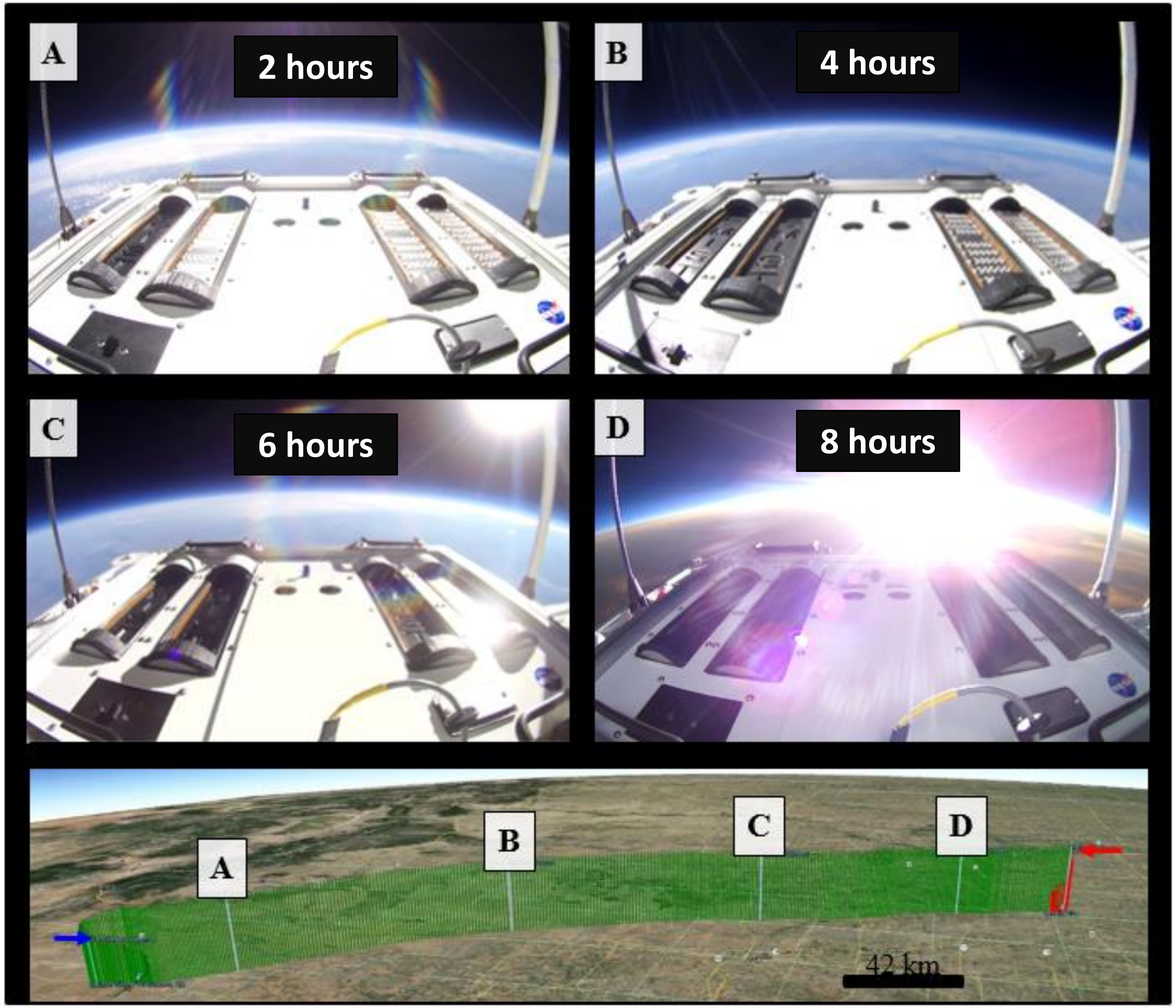
Backup

E-MIST Balloon Payload

E-MIST October 2015 Flight – Experiment Initiation

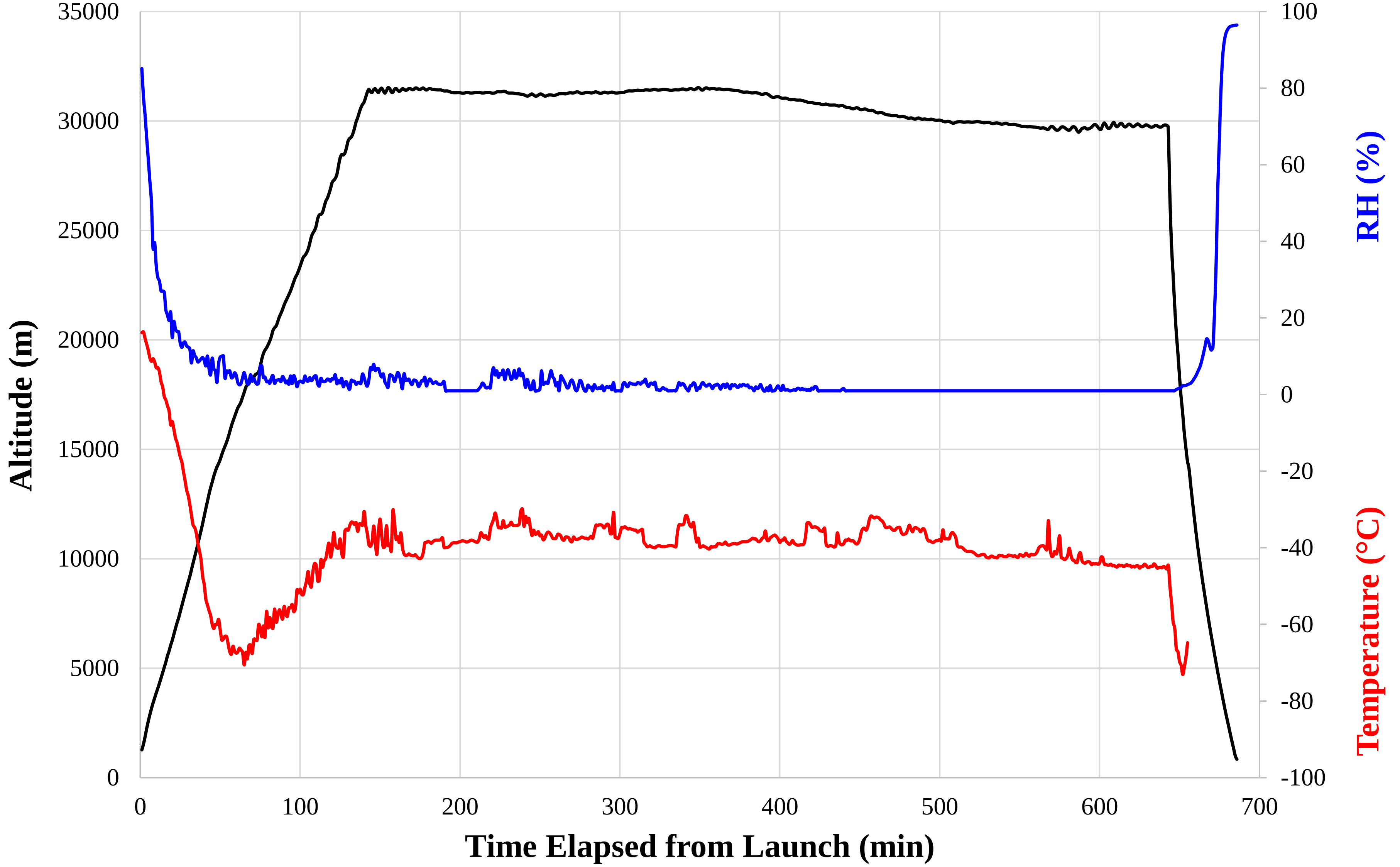


E-MIST October 2015 Flight – Experimental Time Series

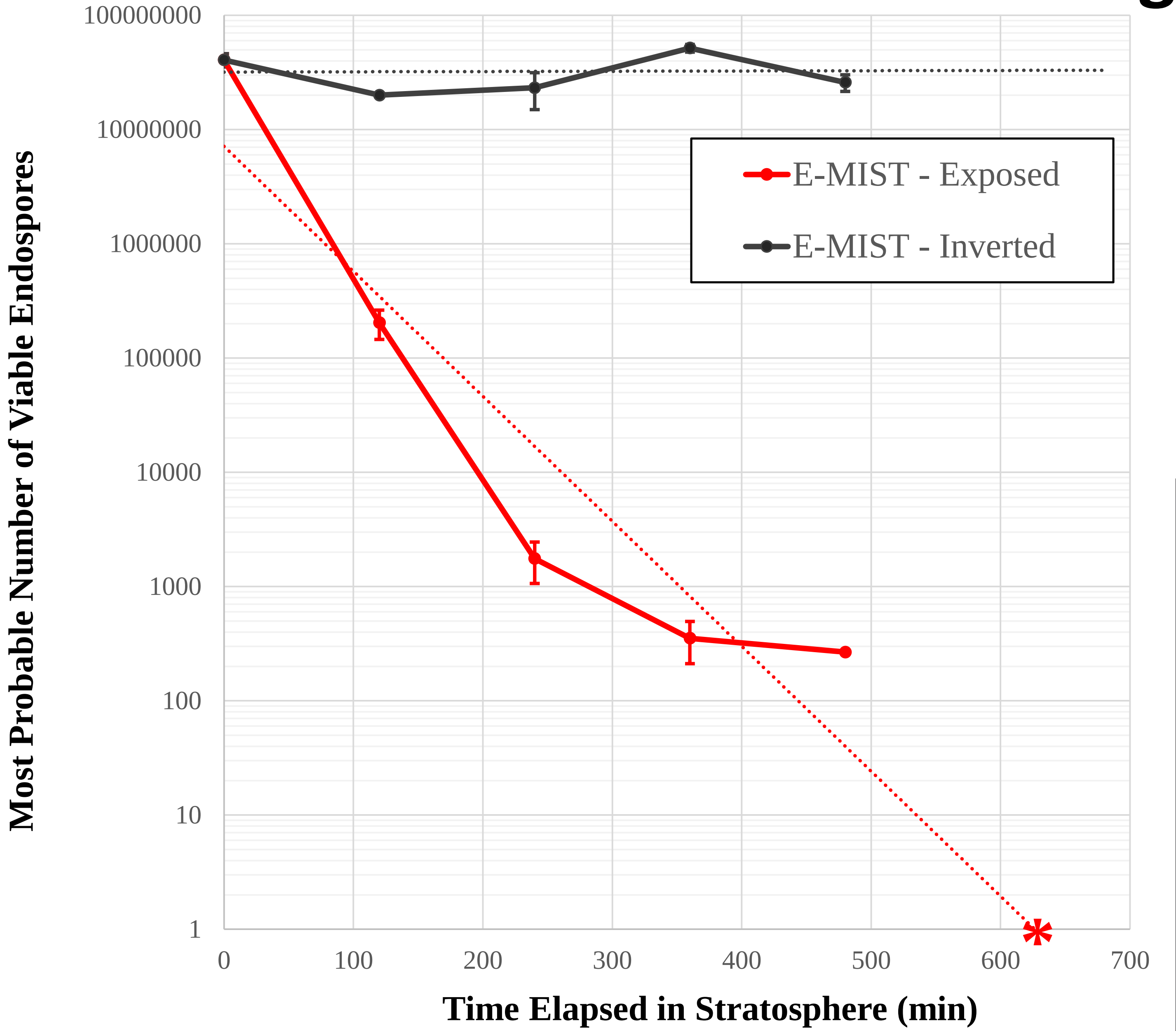


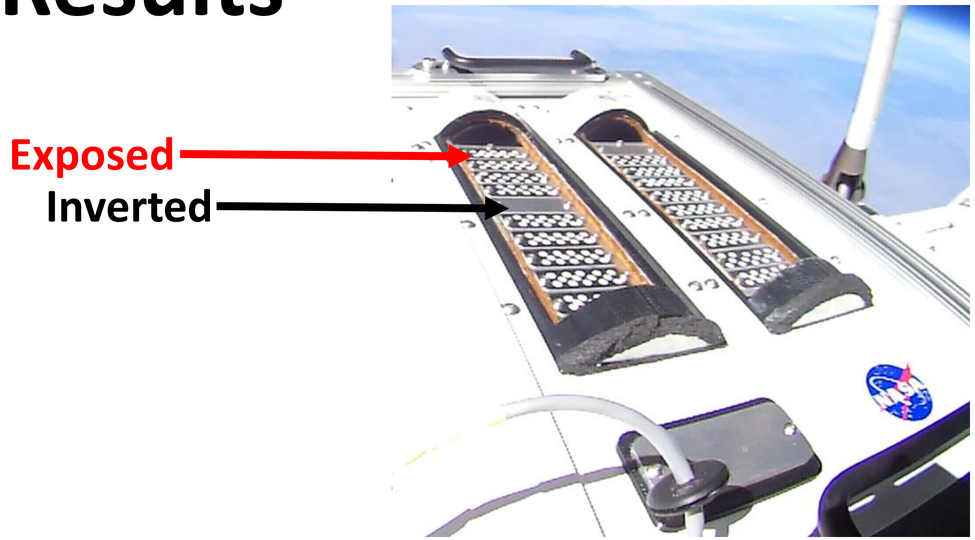
Khodadad et al. (2017)

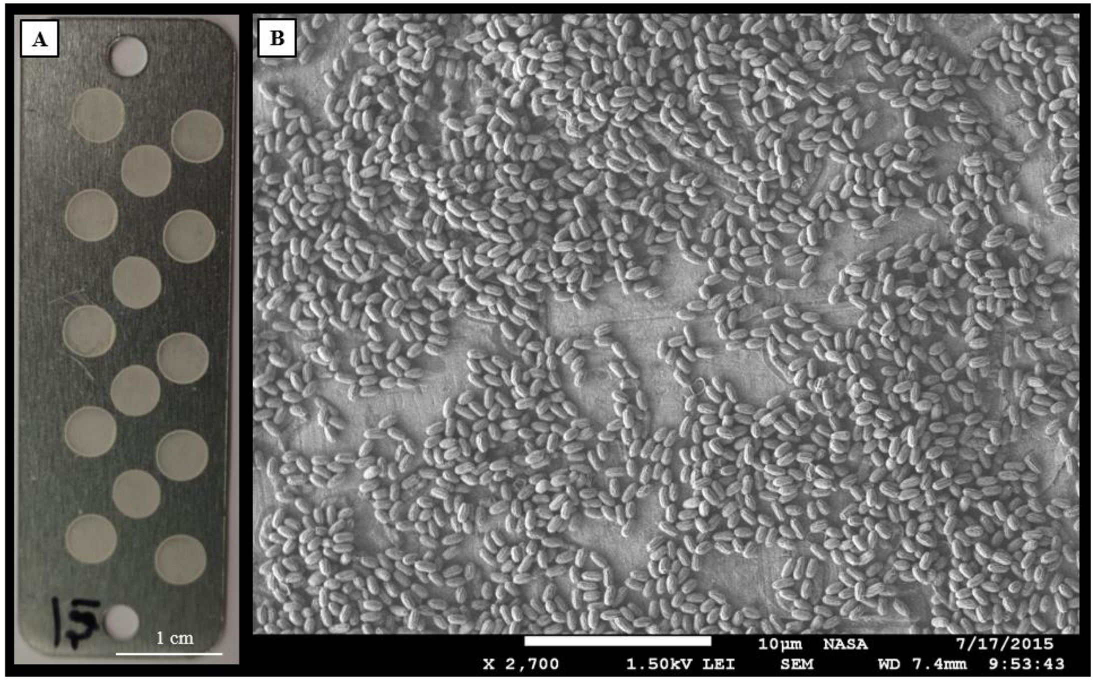
E-MIST 2015 Flight



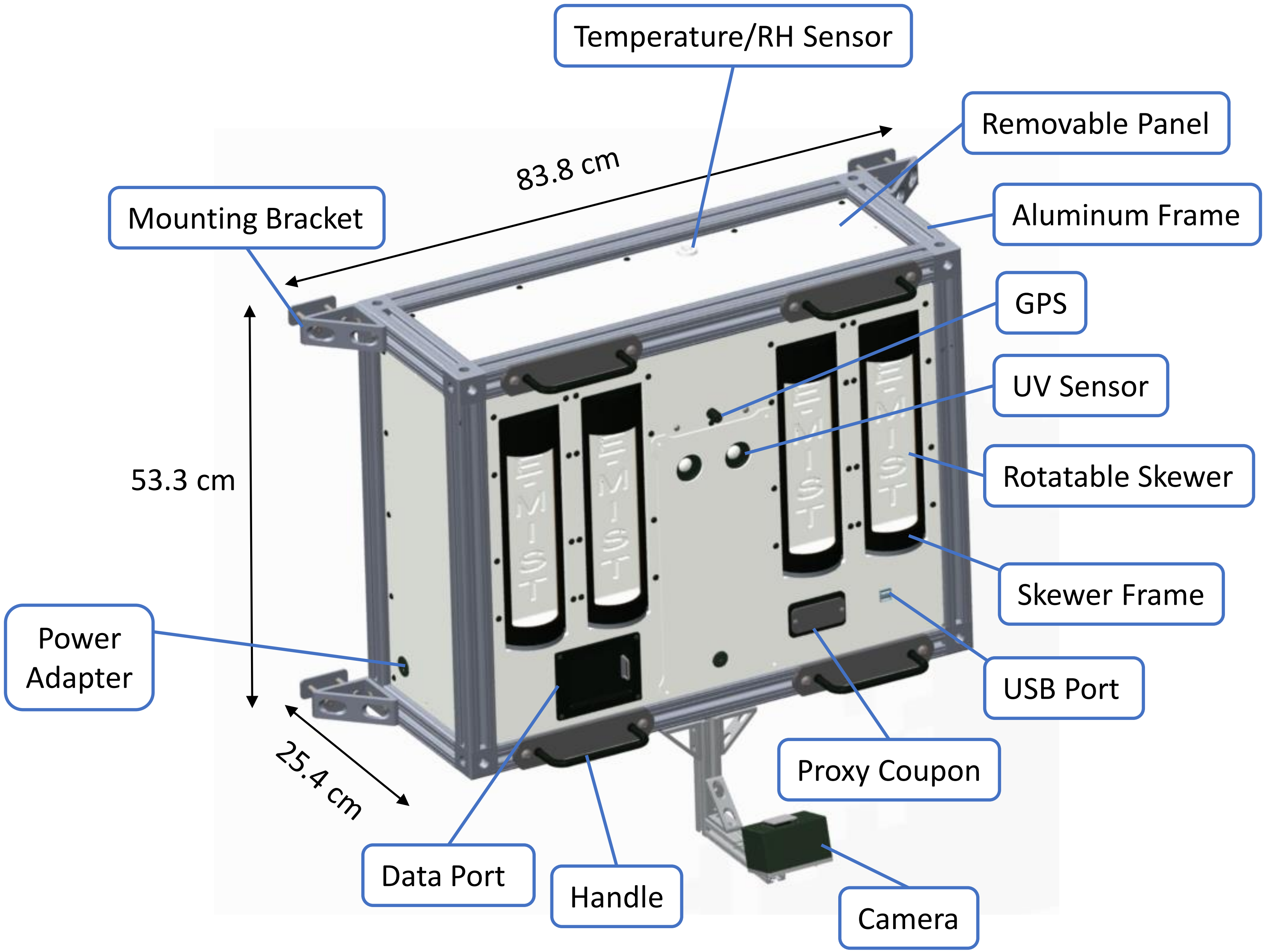
E-MIST 2015 Flight Results

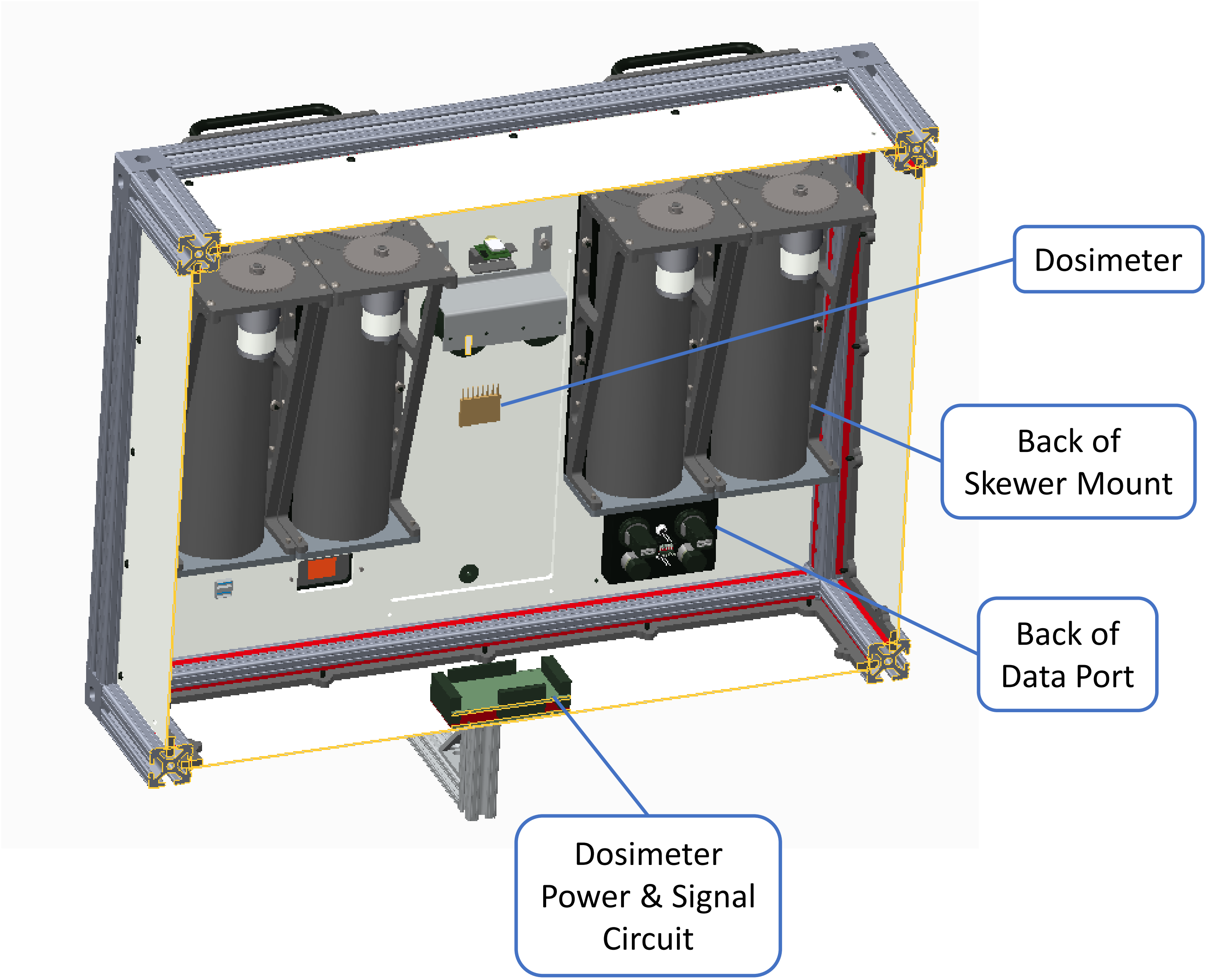






Khodadad et al. (2017)


Temperature/RH Sensor
Removable Panel
Aluminum Frame
83.8 cm
Mounting Bracket
GPS
UV Sensor
Rotatable Skewer
53.3 cm
Skewer Frame
Power
Adapter
USB Port
Proxy Coupon
25.4 cm
Data Port
Handle
Camera


Dosimeter
Back of Skewer Mount
Back of Data Port
Dosimeter Power & Signal Circuit