The Deep Space Radiation Probe: Development and Results from a First Lunar Science Payload for Space Environment Studies and Capacity Building

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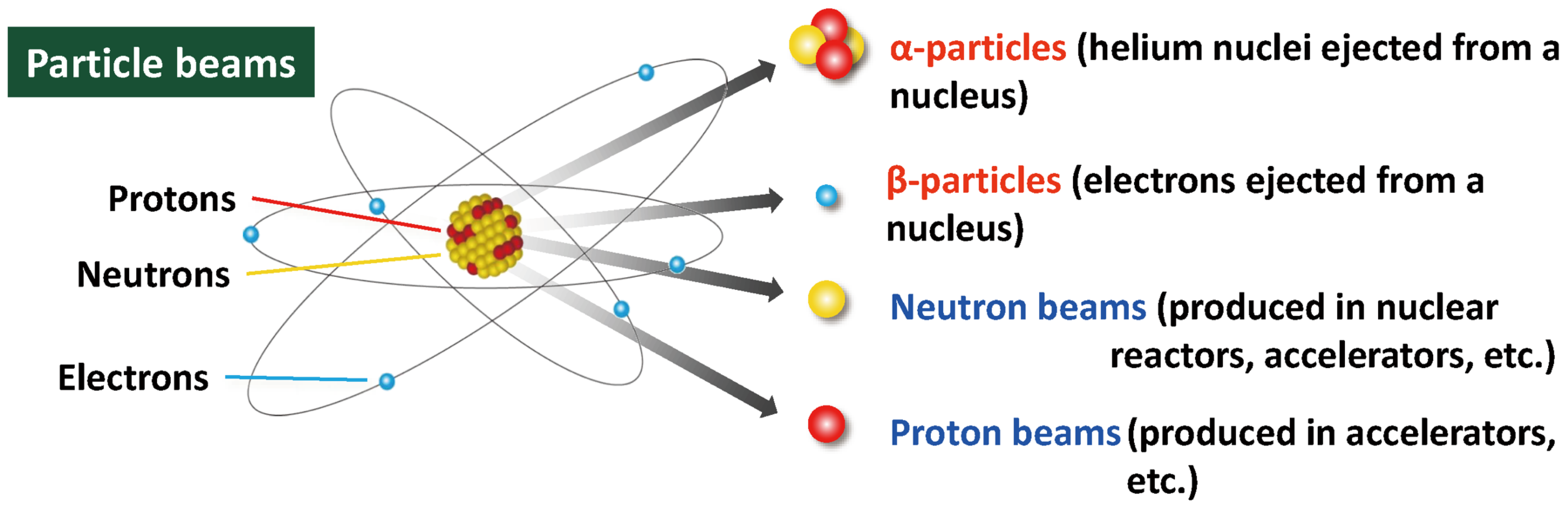
2025/09/02
114年第三十九屆天氣分析與預報研討會

Types of Ionizing Radiation

Image: Japan Ministry of Environment



α-particles (helium nuclei ejected from a nucleus)

β-particles (electrons ejected from a nucleus)

Neutron beams (produced in nuclear reactors, accelerators, etc.)

Proton beams (produced in accelerators, etc.)

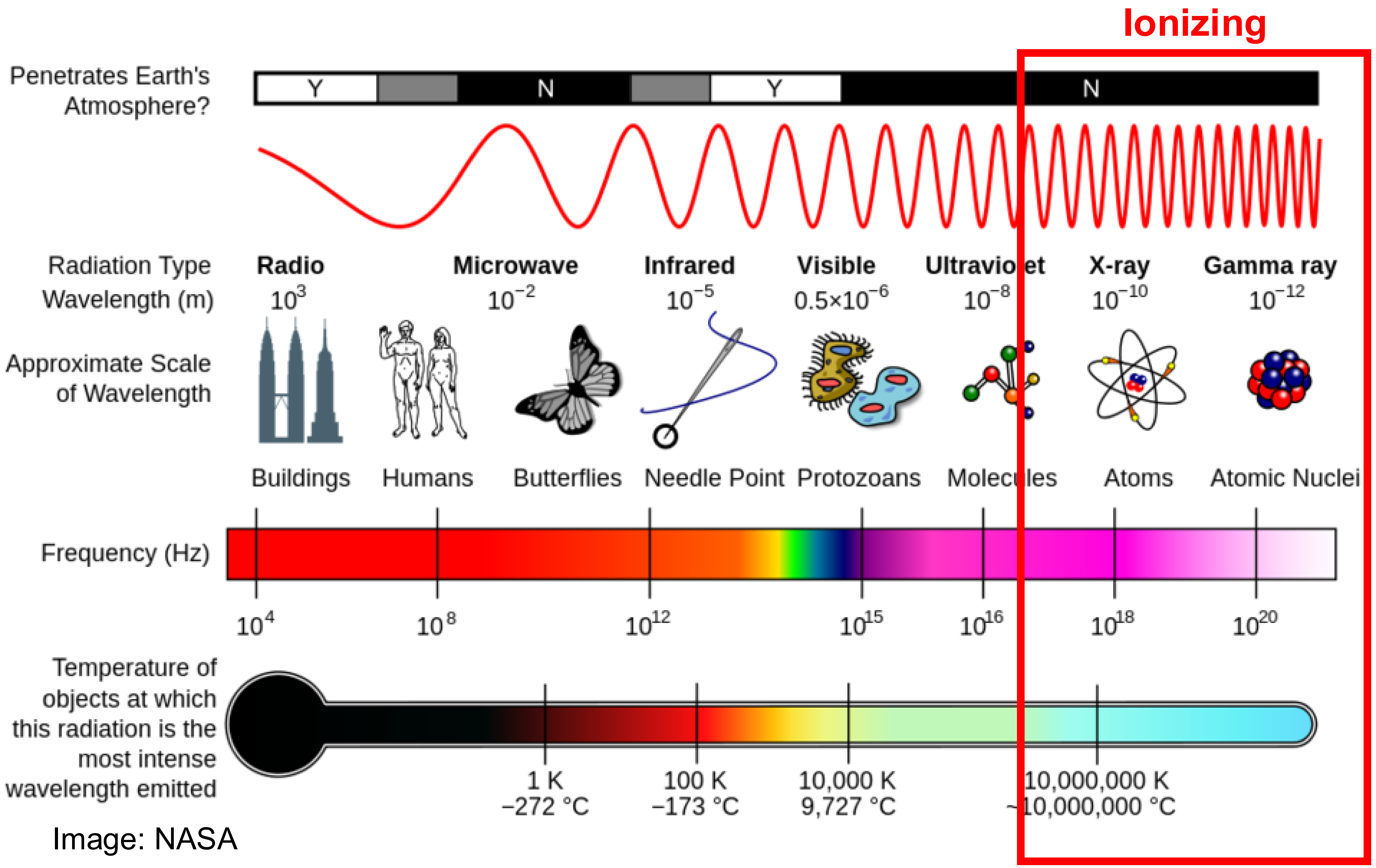
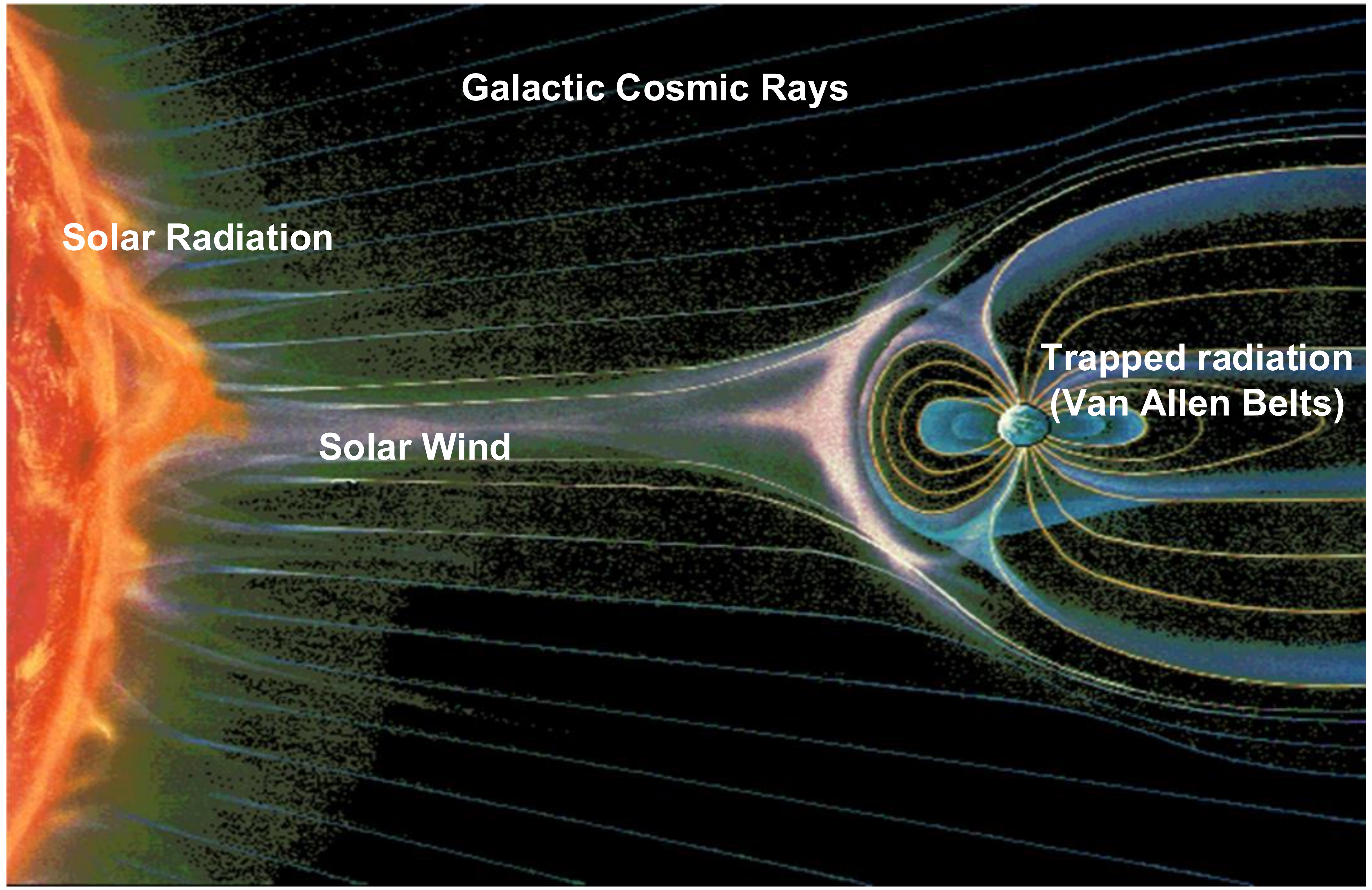


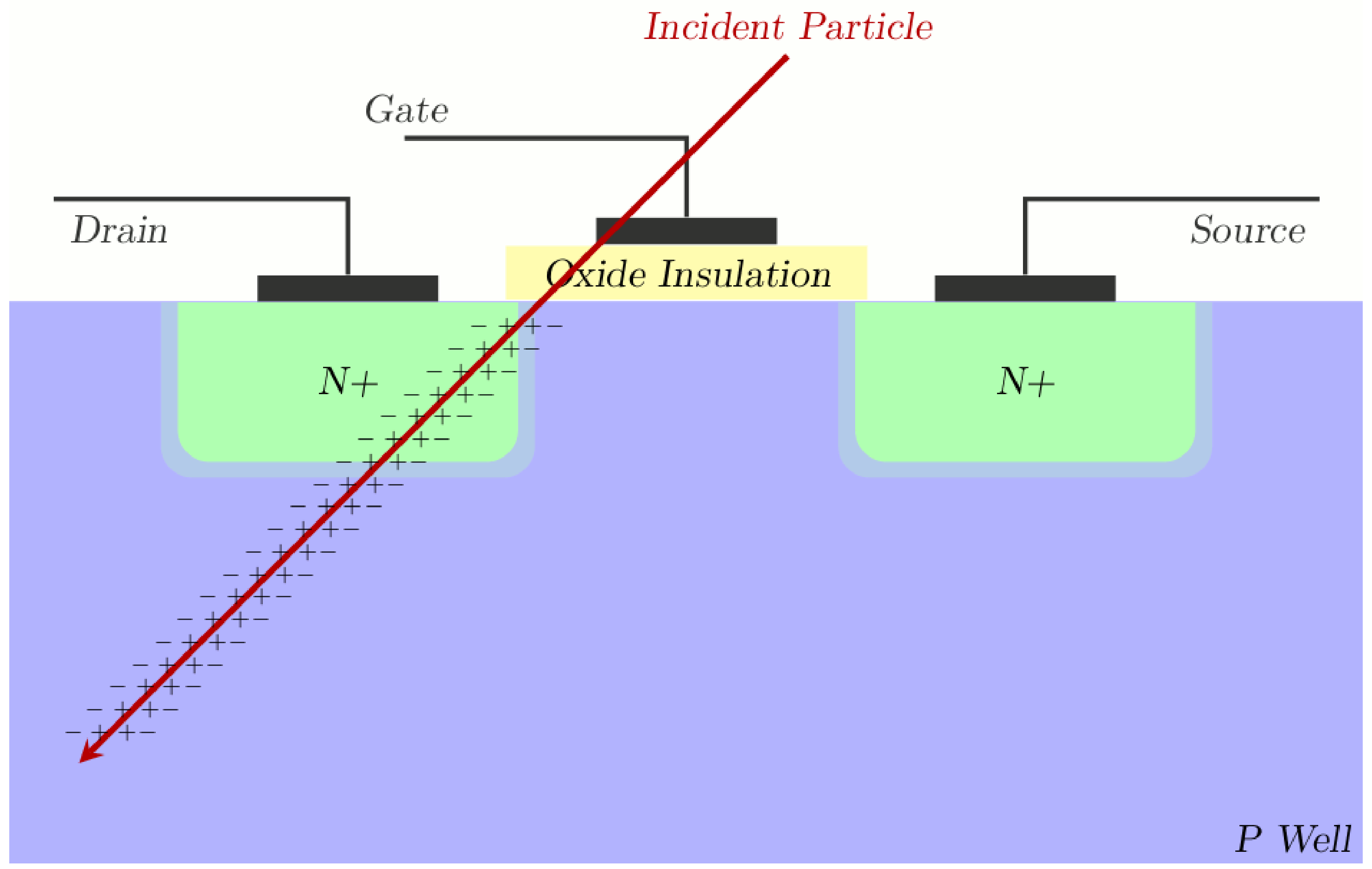
Image: NASA

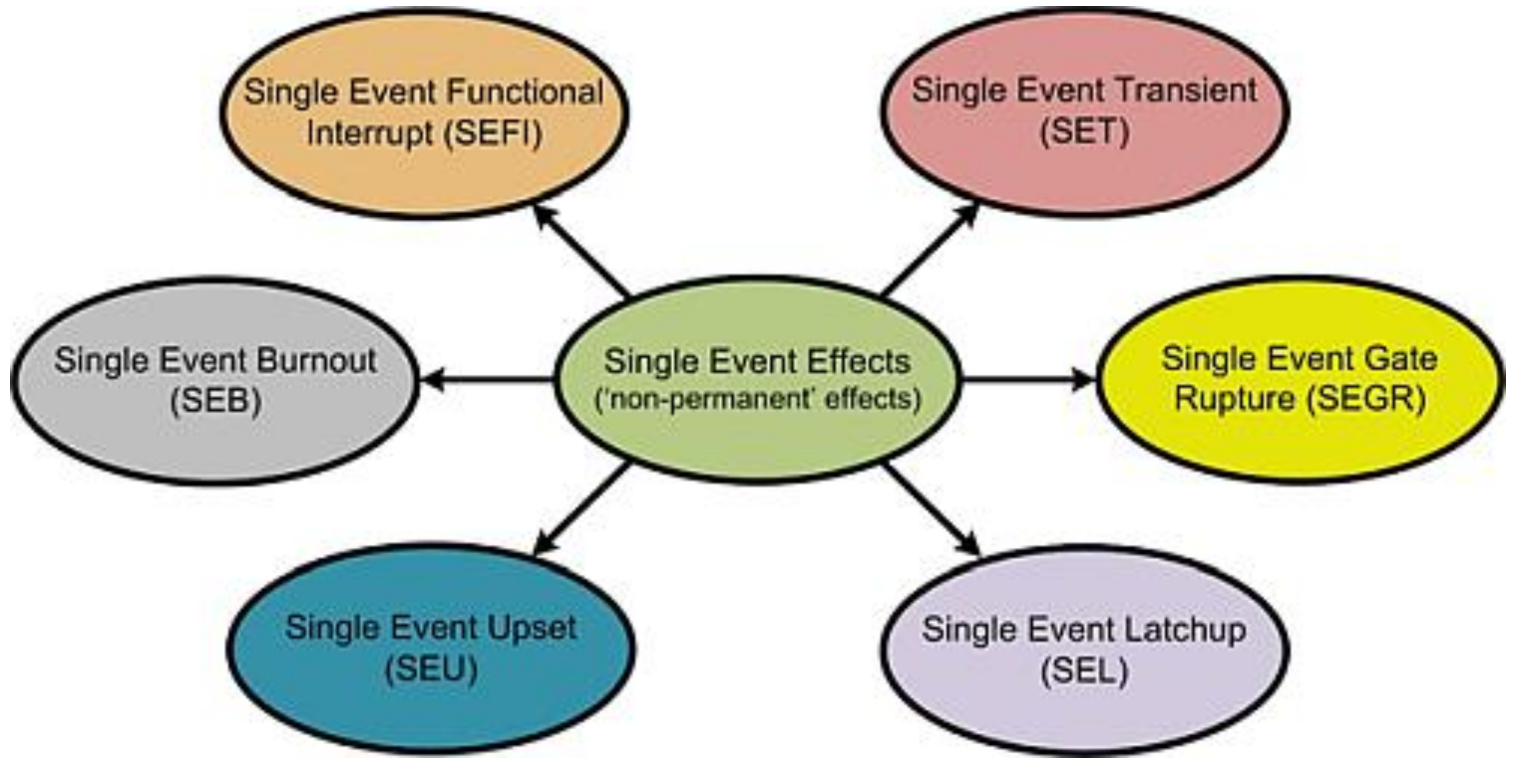
Particulate Radiation
Electrons, Protons, Neutrons, Ions

Electromagnetic Radiation
Extreme Ultraviolet, X-rays, Gamma Rays

Space Radiation Environment






Single Event Effects ('non-permanent' effects)

Single Event Functional Interrupt (SEFI)

Single Event Transient (SET)

Single Event Burnout (SEB)

Single Event Gate Rupture (SEGR)

Single Event Upset (SEU)

Single Event Latchup (SEL)

TOTAL IONIZING DOSE
Degradation in electronics lifespan. Risk of radiation poisoning.

SINGLE EVENT UPSET (SEU)
Bit errors and data/ control sequence corruption.

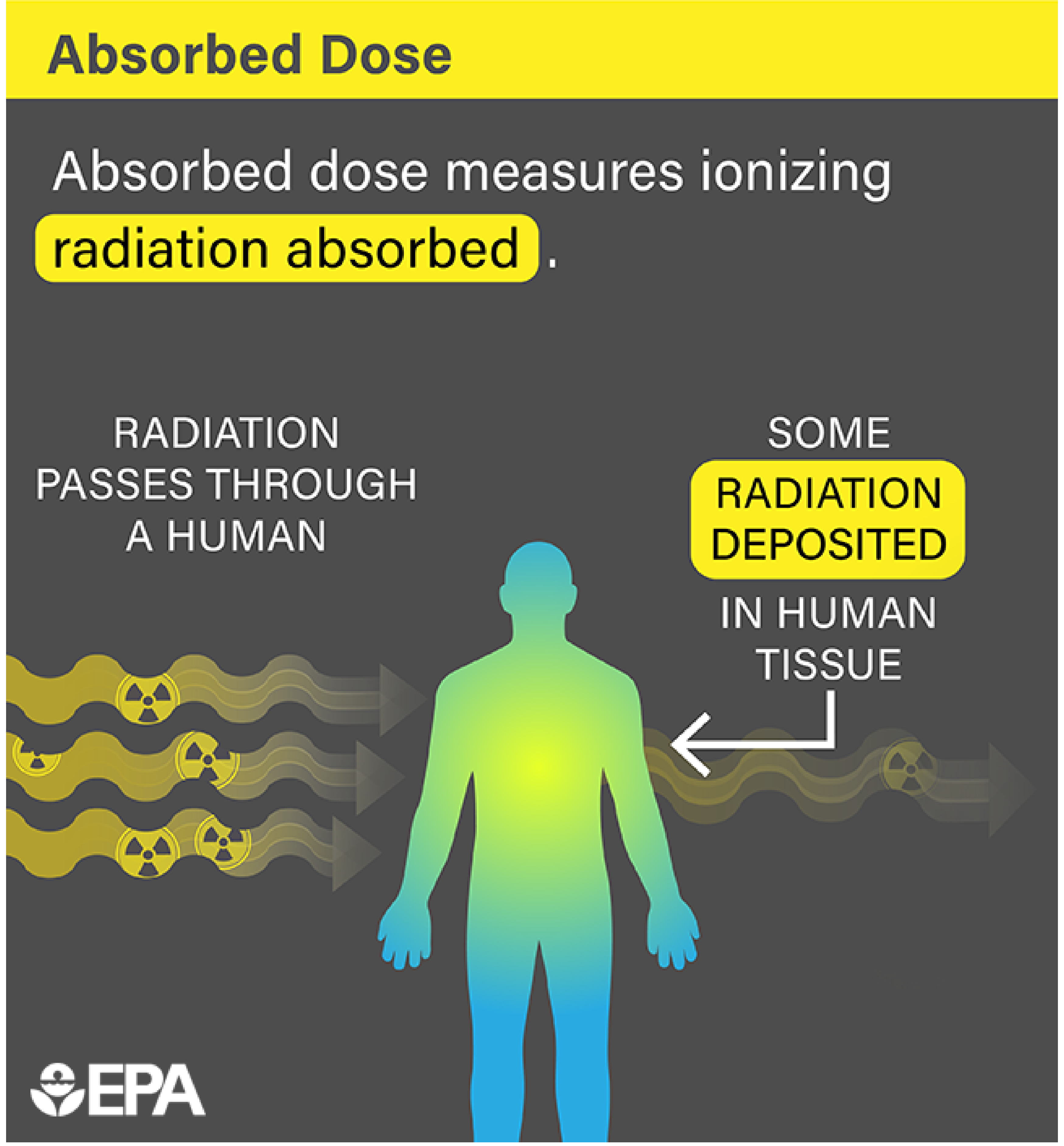
SINGLE EVENT LATCHUP (SEL)
Disable CMOS ICs till power cycle. Risk of burnout from overcurrent.

SINGLE EVENT BURNOUT (SEB)
Irreversible destructive event.

Ionizing radiation environment significant challenge for space exploration, including total ionizing dose (TID) for electronics and biological organisms and single event effects (SEEs) for electronics.

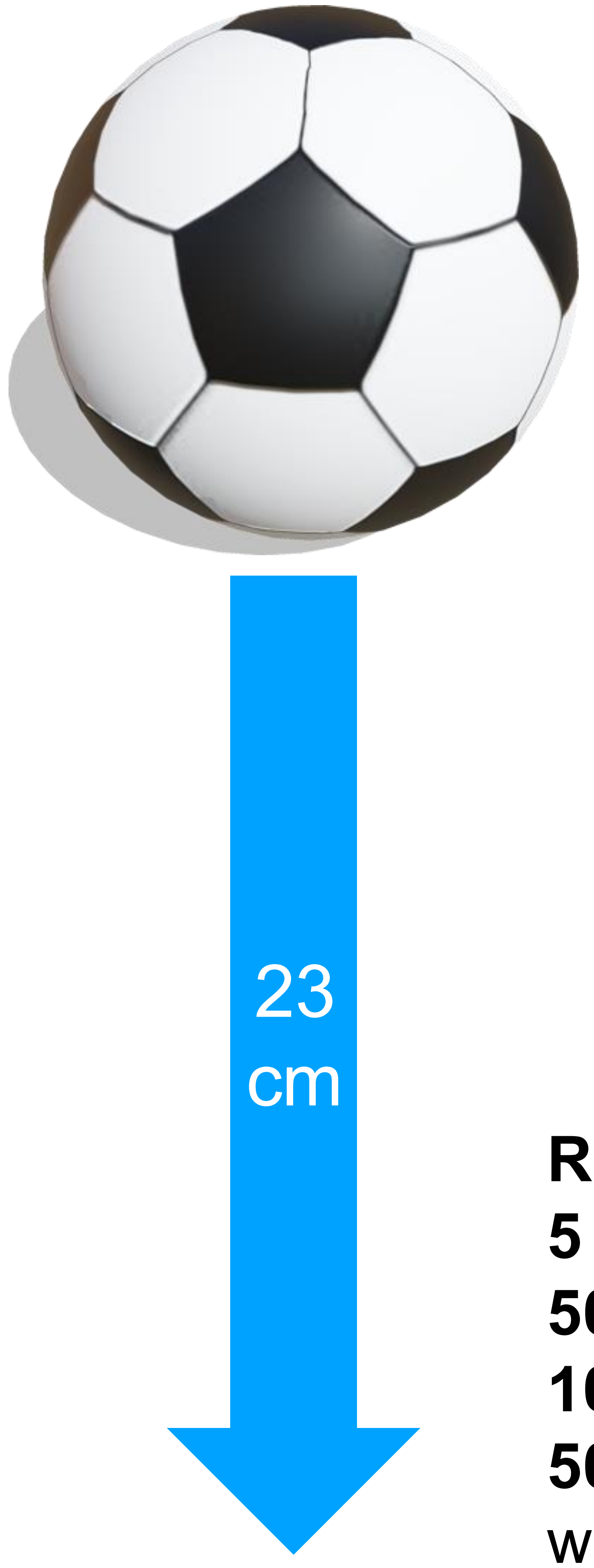
Environment must be characterized to facilitate spacecraft avionics design and mission planning.

Ionizing Radiation Dose



Absorbed Dose

Absorbed dose measures ionizing radiation absorbed.



Dose 劑量:
Absorbed radiation energy per unit mass

- 1 J/kg = 1 Gray
  1 rad = 0.01 J/kg

1 Joule:
Approximately the energy of a soccer ball falling 23 cm.

1 Grey (100 rads):
Multiply the number of falling soccer balls by your mass in kg.

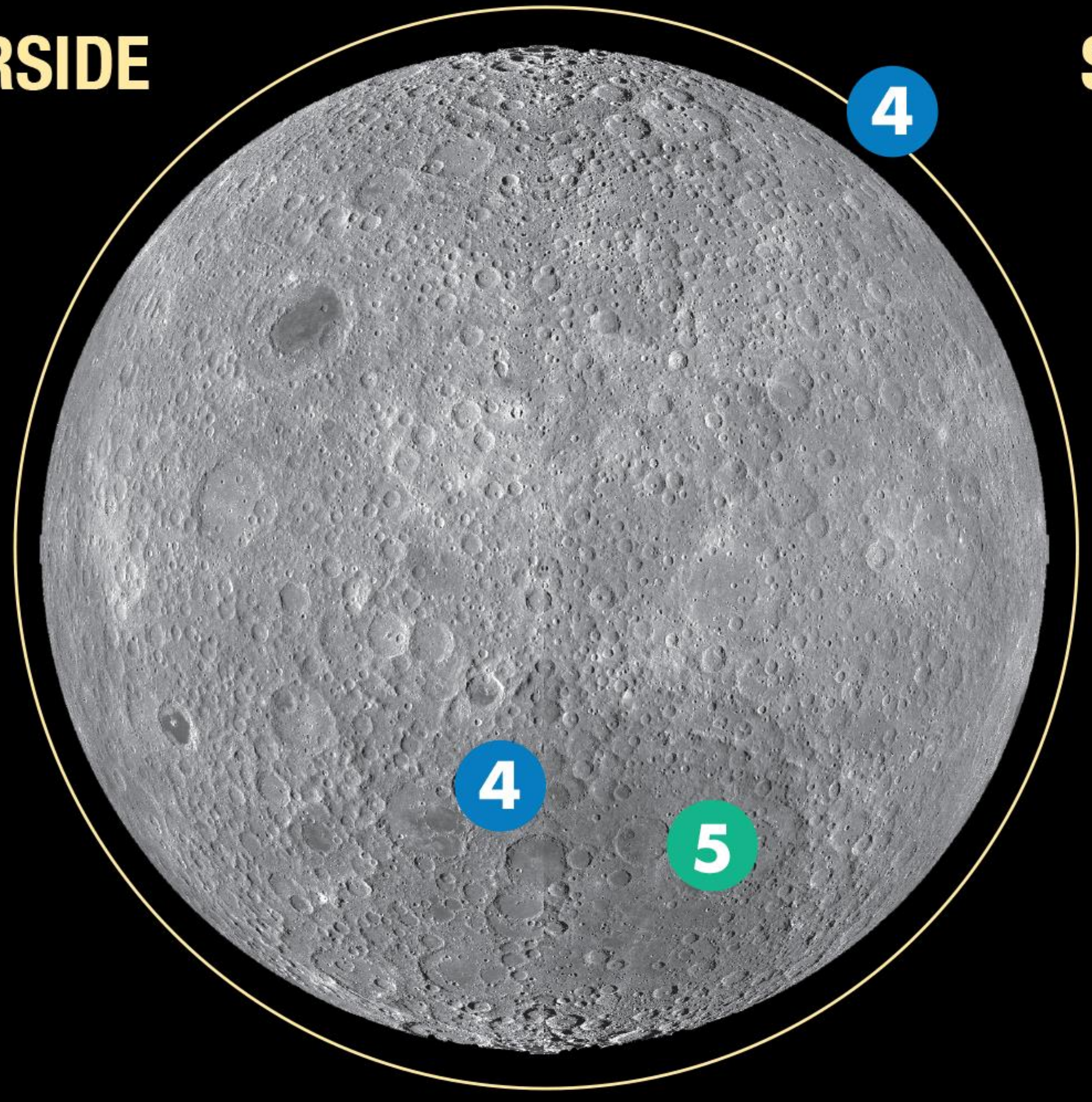
Reference (1 rad = 0.01 Grey):
5 rads (0.05 Grey): Increase in long term cancer risk.
50 rads (0.5 Grey): Disruption in blood cell count.
100 rads (1 Grey): Mild radiation sickness.
500 rads (5 Grey): Radiation sickness. 50% chance of death in 60 days with no treatment.
1000 rads (10 Grey): Acute radiation sickness. Fatal.

COMMERCIAL LUNAR PAYLOAD SERVICES LANDING SITES

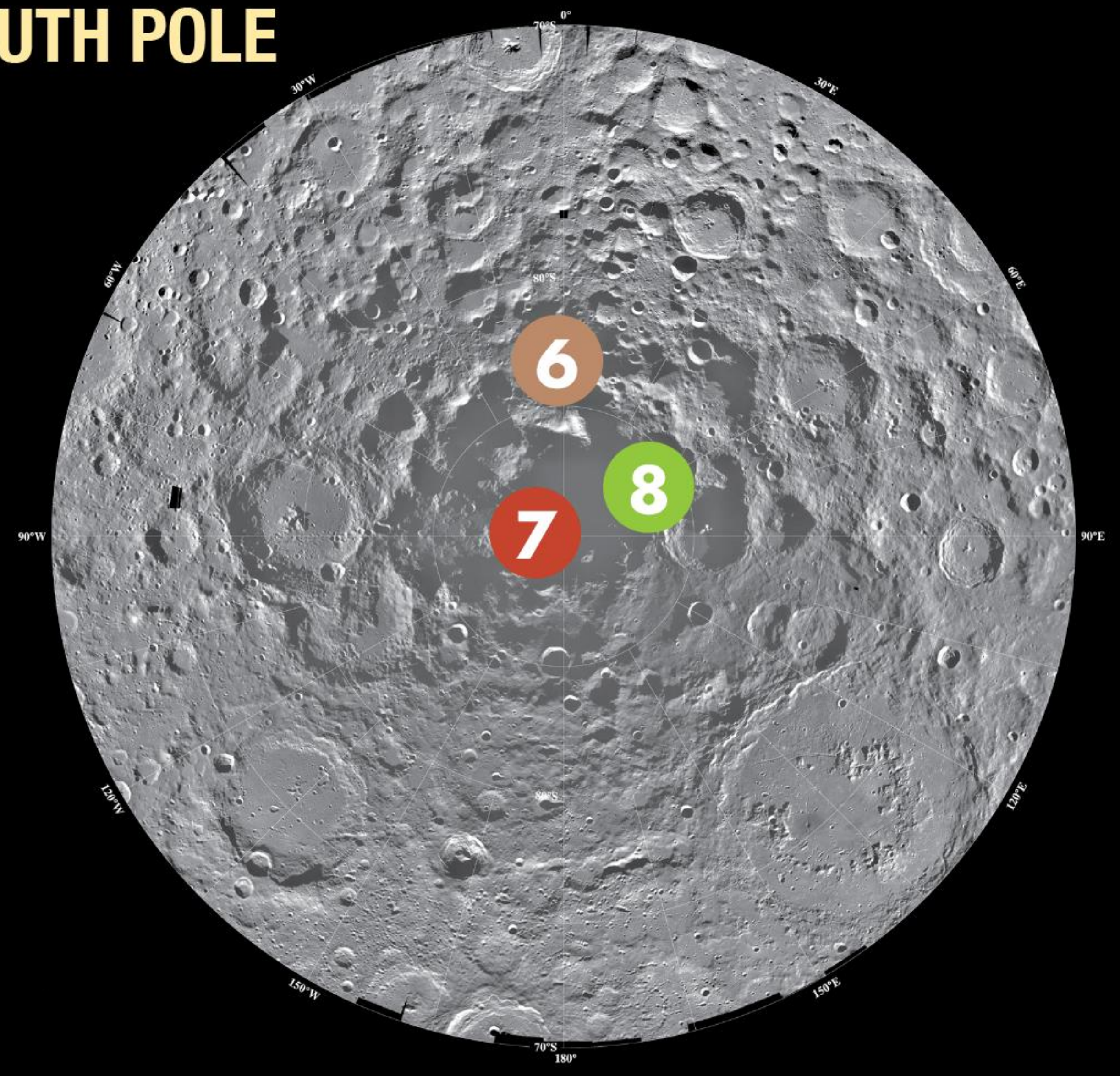
National Aeronautics and
Space Administration

NEARSIDE

FARSIDE



SOUTH POLE



① **Astrobotic Peregrine Mission-1**
LANDING SITE: Sinus Viscositatis
LANDER NAME: Peregrine
CLPS CONTRACT AWARD: TO 2-AB

② **Intuitive Machines IM-3**
LANDING SITE: Reiner Gamma
LANDER NAME: NOVA-C
CLPS CONTRACT AWARD: TO CP-11

③ **Firefly Blue Ghost Mission 1**
LANDING SITE: Mare Crisium
LANDER NAME: Blue Ghost
CLPS CONTRACT AWARD: TO 19D

④ **Firefly Blue Ghost Mission 2**
LANDING SITE: Lunar Farside and Orbit
LANDER NAME: Blue Ghost
CLPS CONTRACT AWARD: TO CS-3 and CS-4

⑤ **Team Draper**
LANDING SITE: Schrödinger Basin
LANDER NAME: SERIES-2
CLPS CONTRACT AWARD: TO CP-12

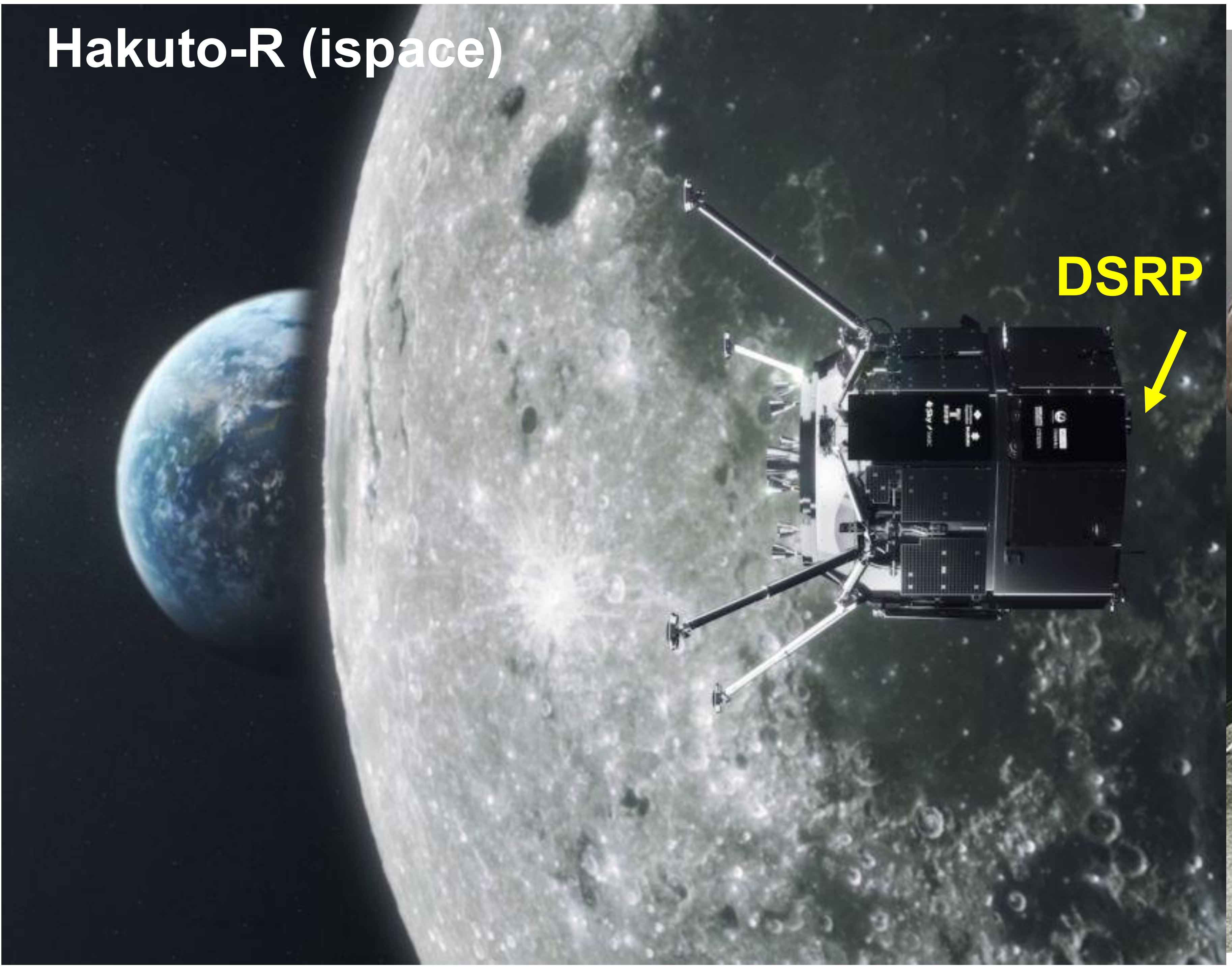
⑥ **Intuitive Machines IM-1**
LANDING SITE: Malapert A
LANDER NAME: NOVA-C
CLPS CONTRACT AWARD: TO 2-IM

⑦ **Intuitive Machines IM-2**
LANDING SITE: Shackleton Connecting Ridge
LANDER NAME: NOVA-C
CLPS CONTRACT AWARD: TO PRIME-1

⑧ **Astrobotic Griffin Mission-1**
LANDING SITE: Mons Mouton
LANDER NAME: Griffin
CLPS CONTRACT AWARD: TO 20A (VIPER)

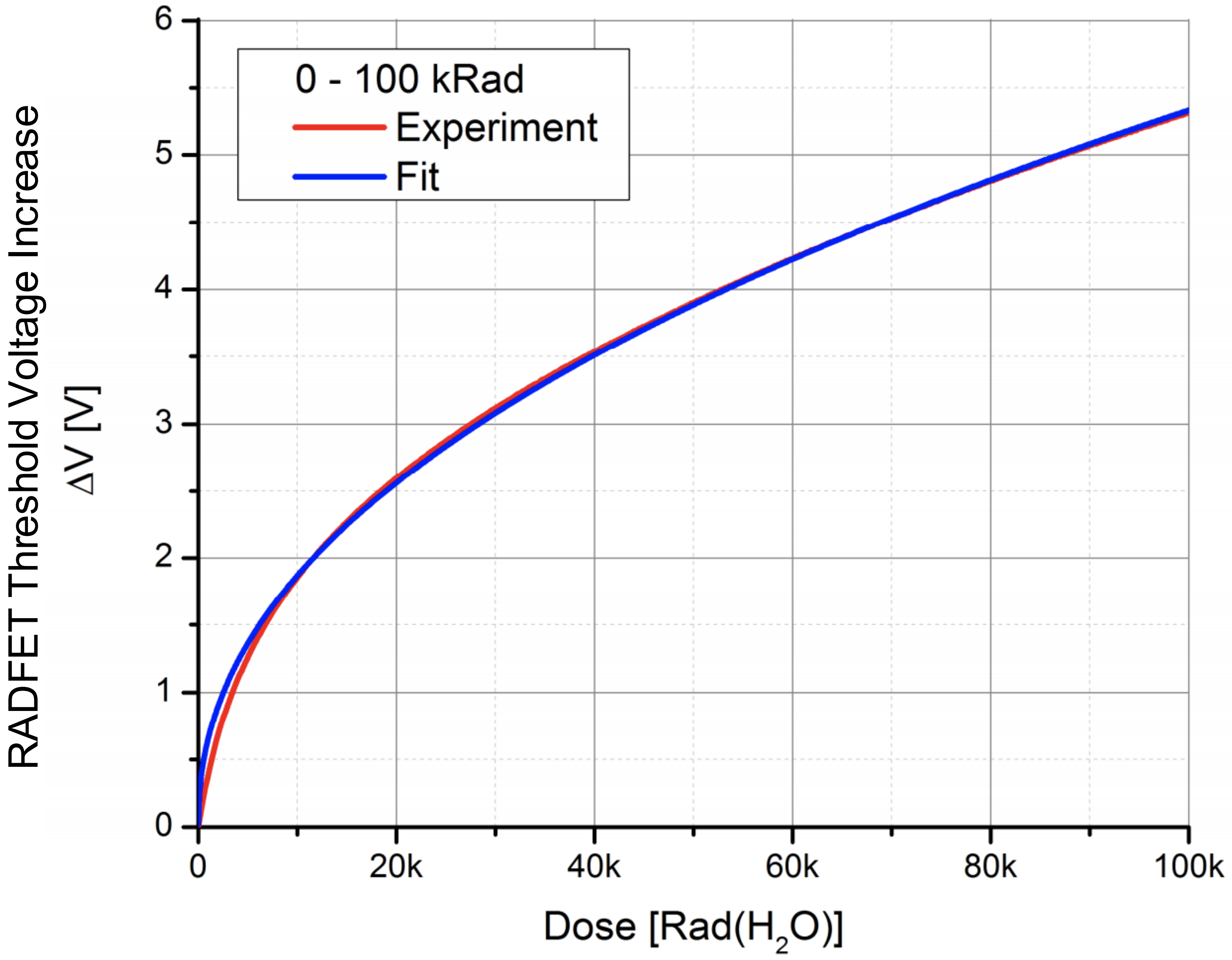
Significant increase in government and private lunar missions expected over next decade.
Expected growth in rideshare opportunities beyond Low Earth Orbit (LEO).
Develop capacity to design and implement payloads for deep space.

Project Origins



- Opportunity to participate in ispace Hakuto-R Mission 2 lunar orbiter and landing mission with 400 gram rideshare payload via HelioX Cosmos and SpaceBD. First lunar payload mission from Taiwan.
- Developed Deep Space Radiation Probe payload to measure deep space radiation environment and provide hands-on learning opportunity to students, leveraging past small satellite avionics development and operation experience.
  - Project kickoff in March 2022 with student team. Flight Model delivery and handover in January 2024.
- Launch: 2025/1/15. 5 month mission via low energy trans lunar orbit (4 months for Earth-Moon transfer, 1 month in lunar orbit).

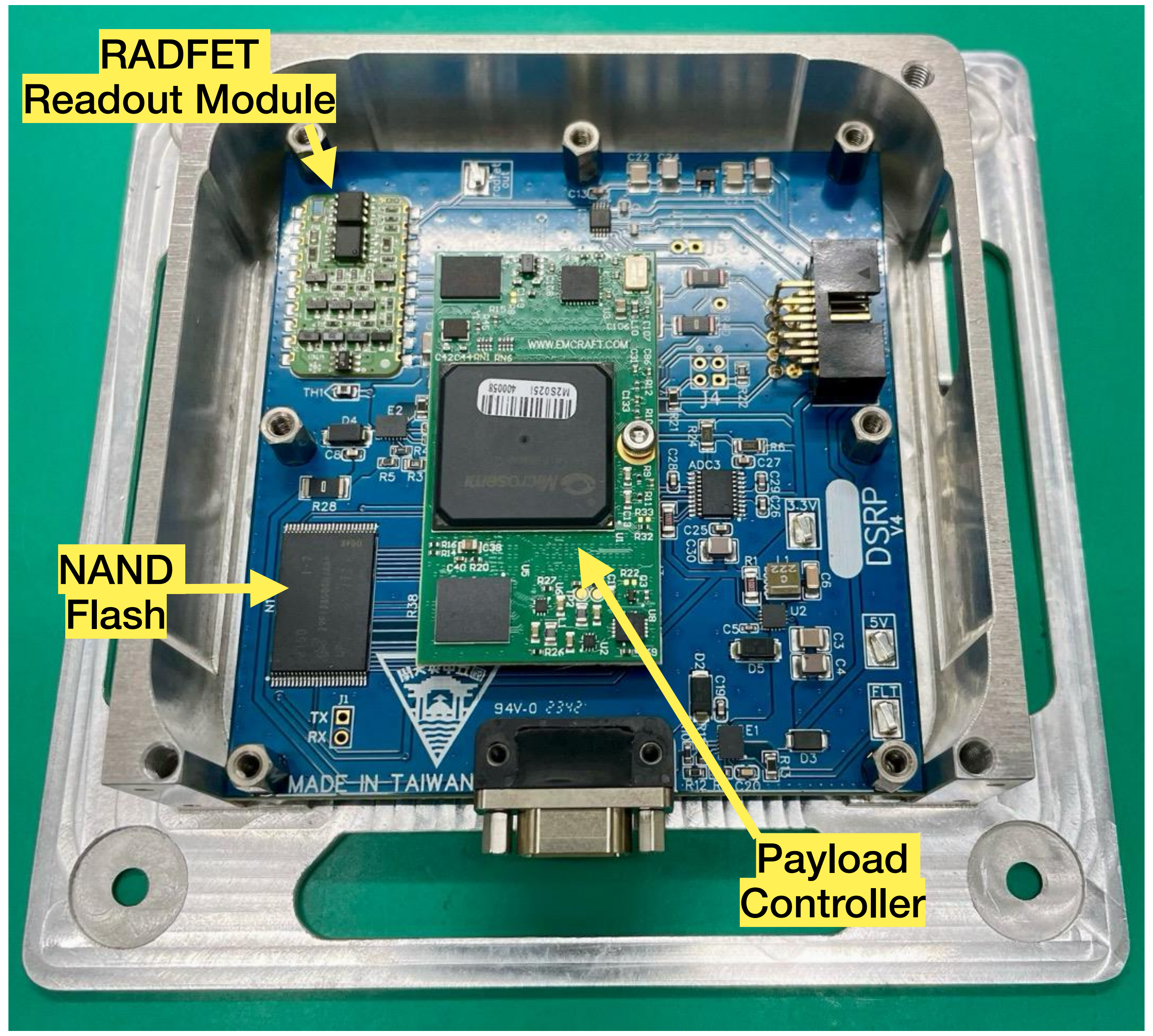
NCU Deep Space Radiation Probe (DSRP)



1	1	0	0	1	0	1	1	Memory before SE

Bit-flip after Soft Error

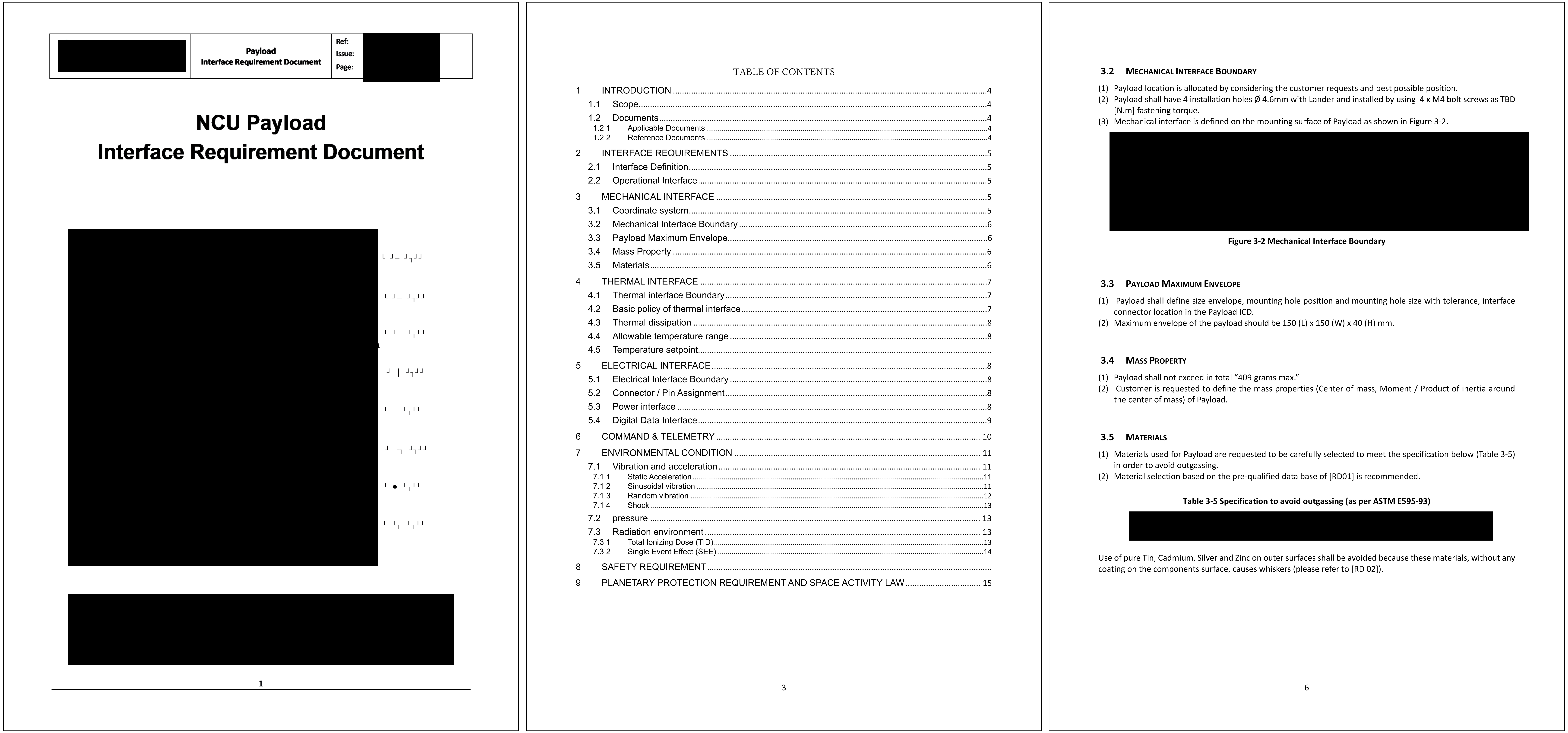
1	1	0	0	1	1	1		Memory after SE



- 2 RADFET dosimeters: Radiation dose inferred from increase in threshold voltage of radiation sensitive field effect transistor. Dose rate can be calculated by regular sampling. Sensitive to X-rays, gamma rays, and particle radiation. Low power consumption.

- SEU counter: NAND flash memory periodically scanned for bit errors, which are corrected and counted.

- Development constraints:
  Mass: 399 grams, Max. Power < 900 mW, Max. Load: 33 *g*.



[redacted]	**Payload** **Interface Requirement Document**	**Ref:** **Issue:** **Page:**	[redacted]

NCU Payload
Interface Requirement Document

[redacted]

[redacted]

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3.2 MECHANICAL INTERFACE BOUNDARY

(1) Payload location is allocated by considering the customer requests and best possible position.
(2) Payload shall have 4 installation holes Ø 4.6mm with Lander and installed by using 4 x M4 bolt screws as TBD [N.m] fastening torque.
(3) Mechanical interface is defined on the mounting surface of Payload as shown in Figure 3-2.

[redacted]

Figure 3-2 Mechanical Interface Boundary

3.3 PAYLOAD MAXIMUM ENVELOPE

(1) Payload shall define size envelope, mounting hole position and mounting hole size with tolerance, interface connector location in the Payload ICD.
(2) Maximum envelope of the payload should be 150 (L) x 150 (W) x 40 (H) mm.

3.4 MASS PROPERTY

(1) Payload shall not exceed in total "409 grams max."
(2) Customer is requested to define the mass properties (Center of mass, Moment / Product of inertia around the center of mass) of Payload.

3.5 MATERIALS

(1) Materials used for Payload are requested to be carefully selected to meet the specification below (Table 3-5) in order to avoid outgassing.
(2) Material selection based on the pre-qualified data base of [RD01] is recommended.

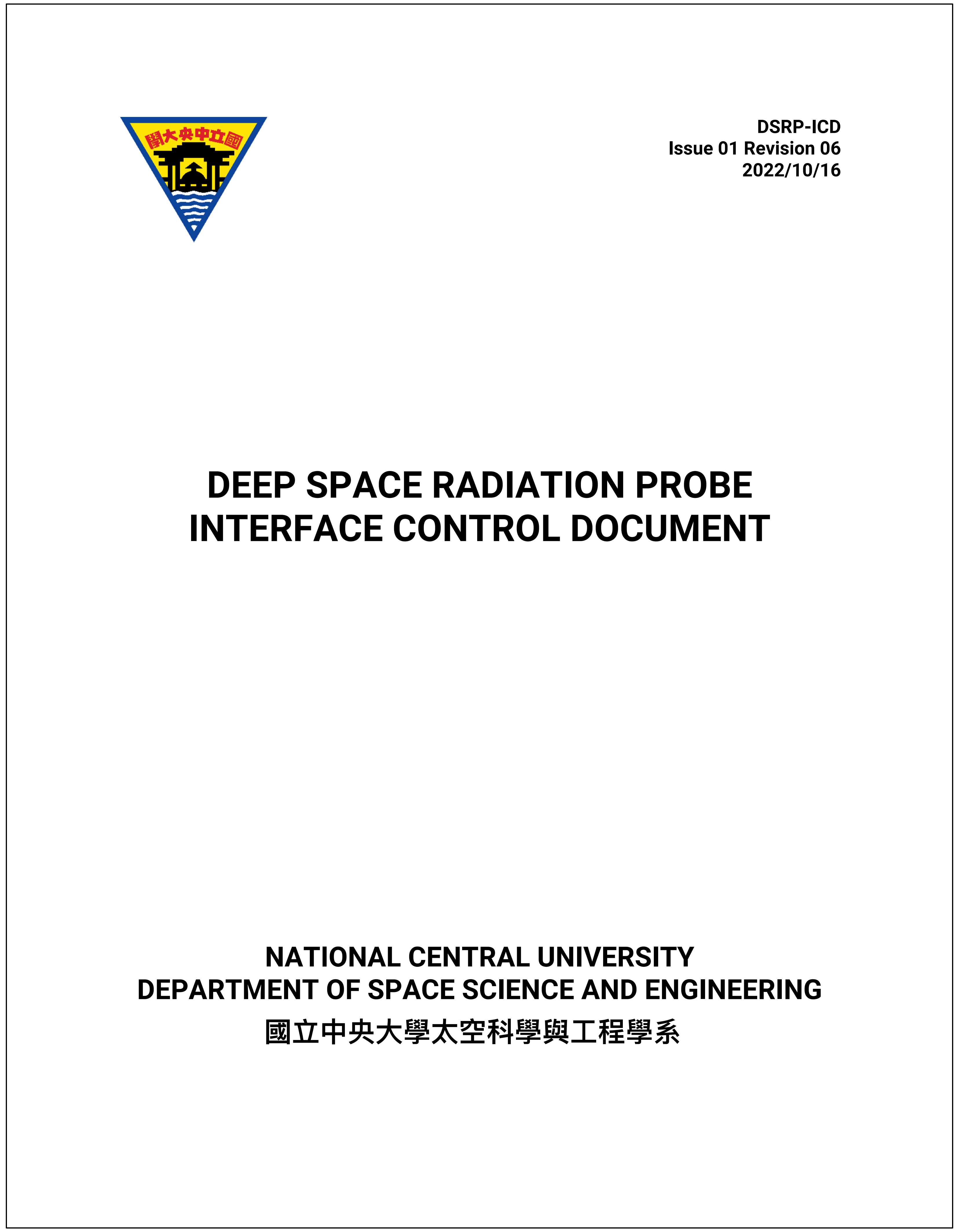
Table 3-5 Specification to avoid outgassing (as per ASTM E595-93)

[redacted]

Use of pure Tin, Cadmium, Silver and Zinc on outer surfaces shall be avoided because these materials, without any coating on the components surface, causes whiskers (please refer to [RD 02]).

Interface Requirement Document

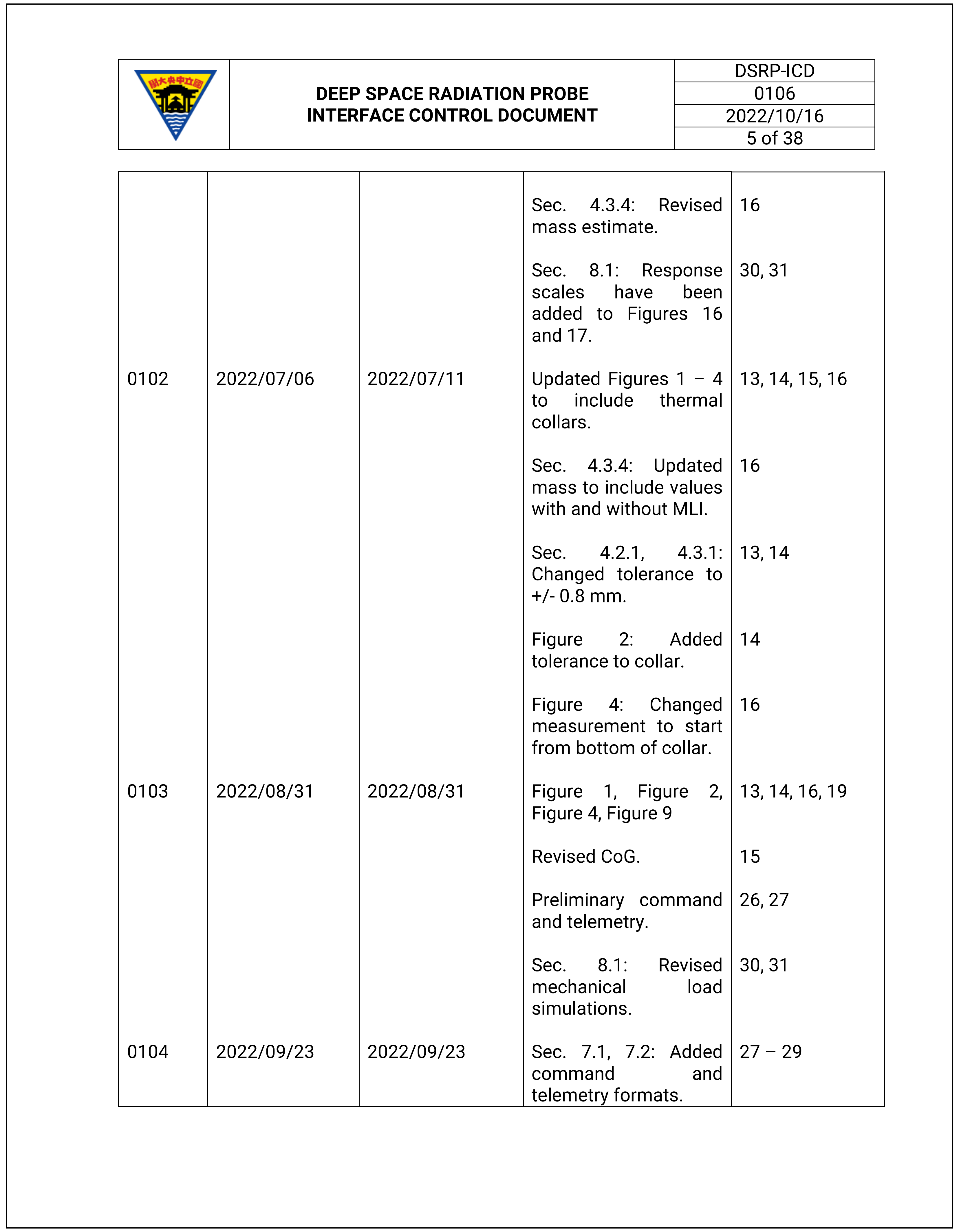
Provided by ispace to DSRP team at project kickoff in 2022/02 to specify interface requirements for system in development.
Facilitates parallel development of lander and payload by two different teams.



DSRP-ICD
Issue 01 Revision 06
2022/10/16

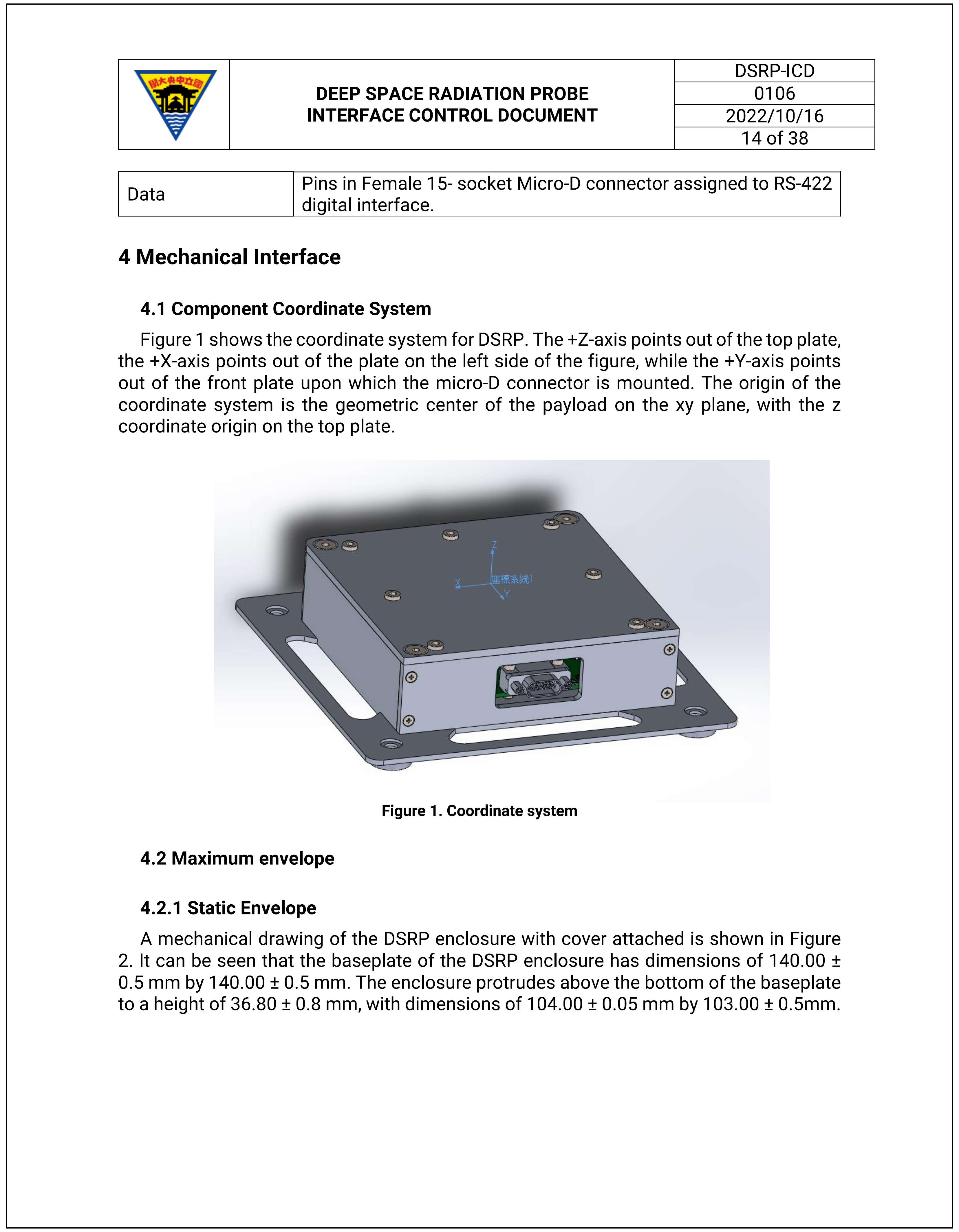
DEEP SPACE RADIATION PROBE
INTERFACE CONTROL DOCUMENT

NATIONAL CENTRAL UNIVERSITY
DEPARTMENT OF SPACE SCIENCE AND ENGINEERING
國立中央大學太空科學與工程學系



DEEP SPACE RADIATION PROBE INTERFACE CONTROL DOCUMENT	DSRP-ICD 0106 2022/10/16 5 of 38

			Sec. 4.3.4: Revised mass estimate.	16
			Sec. 8.1: Response scales have been added to Figures 16 and 17.	30, 31
0102	2022/07/06	2022/07/11	Updated Figures 1 – 4 to include thermal collars.	13, 14, 15, 16
			Sec. 4.3.4: Updated mass to include values with and without MLI.	16
			Sec. 4.2.1, 4.3.1: Changed tolerance to +/- 0.8 mm.	13, 14
			Figure 2: Added tolerance to collar.	14
			Figure 4: Changed measurement to start from bottom of collar.	16
0103	2022/08/31	2022/08/31	Figure 1, Figure 2, Figure 4, Figure 9	13, 14, 16, 19
			Revised CoG.	15
			Preliminary command and telemetry.	26, 27
			Sec. 8.1: Revised mechanical load simulations.	30, 31
0104	2022/09/23	2022/09/23	Sec. 7.1, 7.2: Added command and telemetry formats.	27 – 29



DEEP SPACE RADIATION PROBE INTERFACE CONTROL DOCUMENT	DSRP-ICD 0106 2022/10/16 14 of 38

Data	Pins in Female 15- socket Micro-D connector assigned to RS-422 digital interface.

4 Mechanical Interface

4.1 Component Coordinate System

Figure 1 shows the coordinate system for DSRP. The +Z-axis points out of the top plate, the +X-axis points out of the plate on the left side of the figure, while the +Y-axis points out of the front plate upon which the micro-D connector is mounted. The origin of the coordinate system is the geometric center of the payload on the xy plane, with the z coordinate origin on the top plate.

Figure 1. Coordinate system

4.2 Maximum envelope

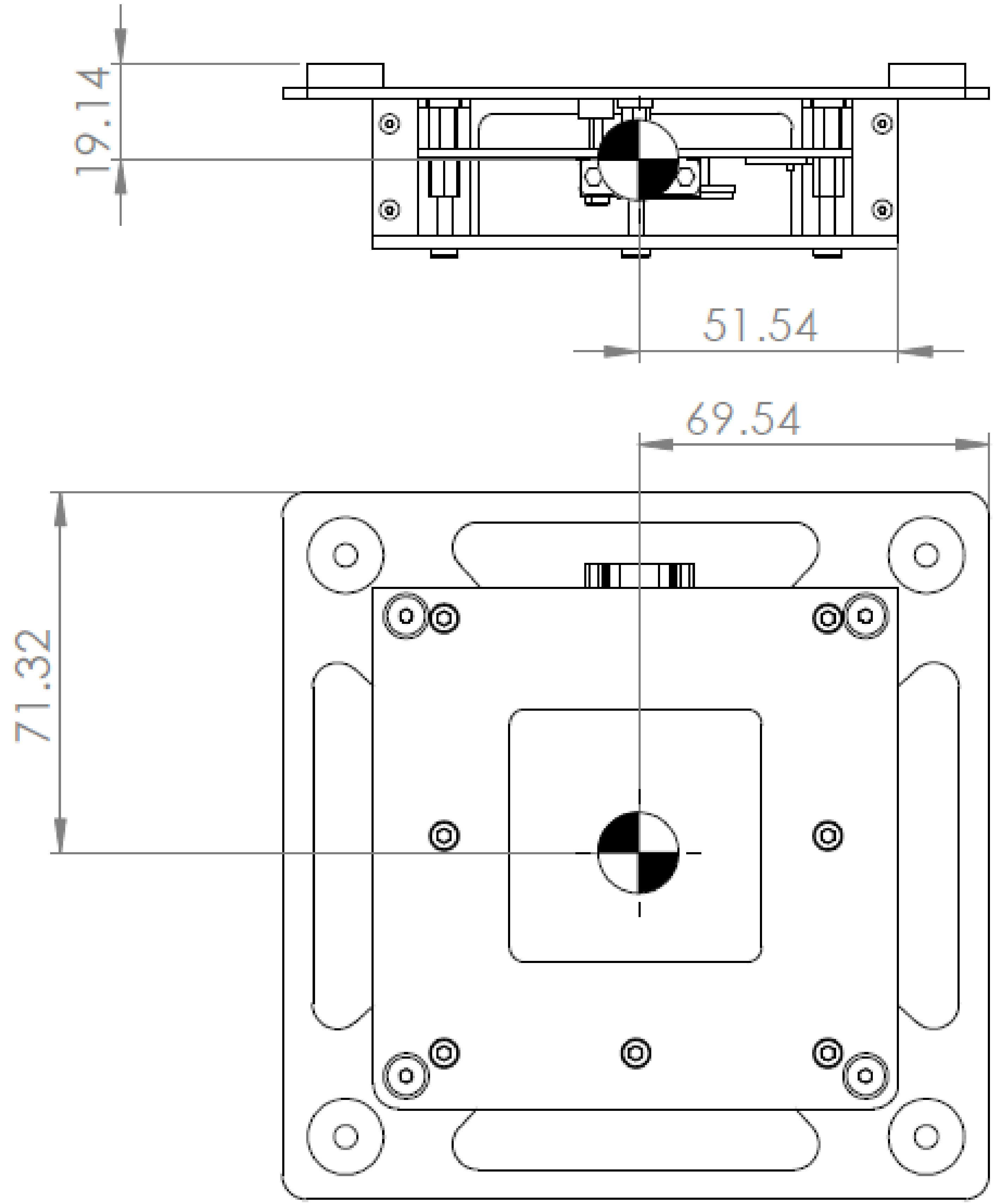
4.2.1 Static Envelope

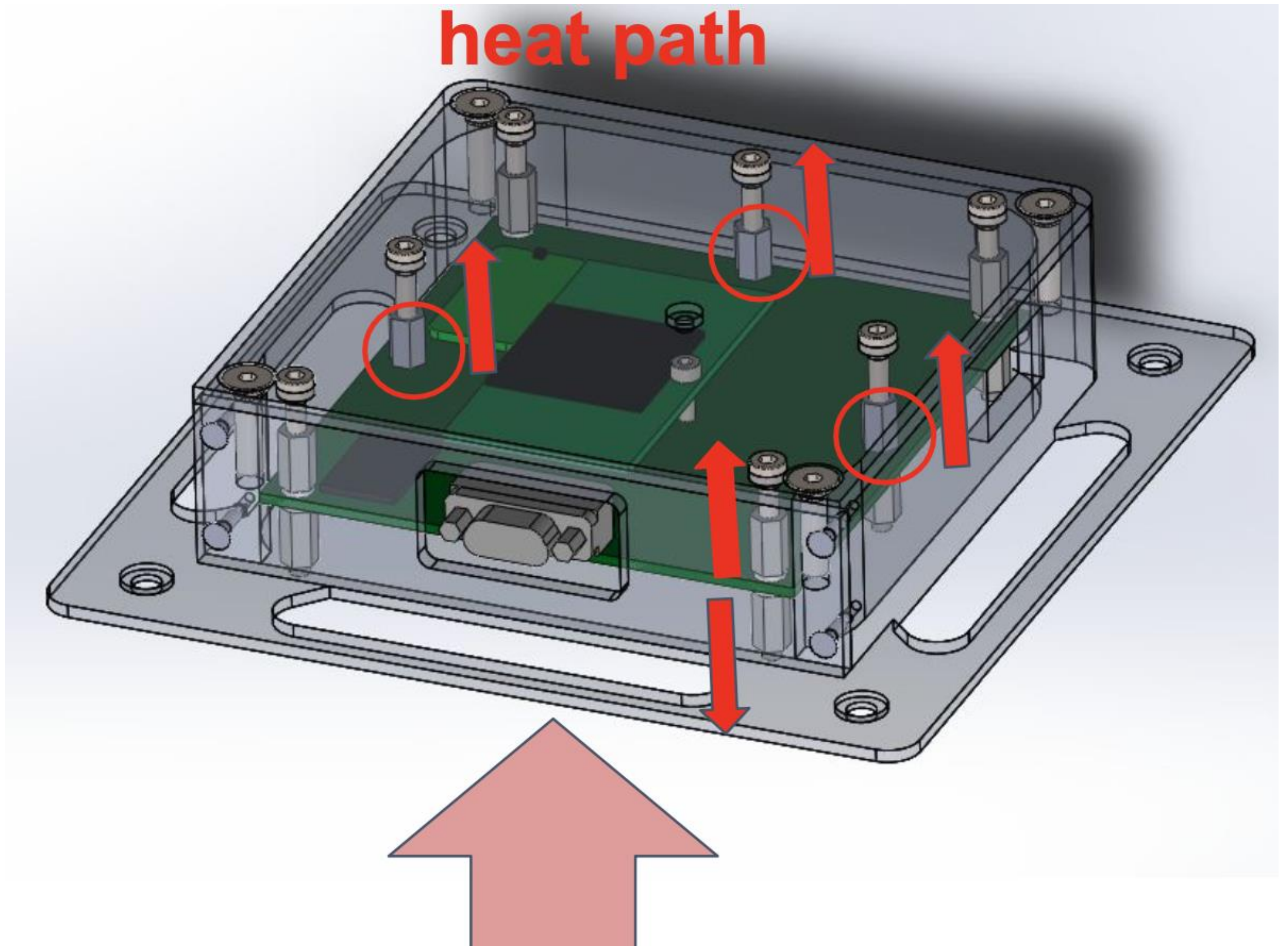
A mechanical drawing of the DSRP enclosure with cover attached is shown in Figure 2. It can be seen that the baseplate of the DSRP enclosure has dimensions of 140.00 ± 0.5 mm by 140.00 ± 0.5 mm. The enclosure protrudes above the bottom of the baseplate to a height of 36.80 ± 0.8 mm, with dimensions of 104.00 ± 0.05 mm by 103.00 ± 0.5mm.

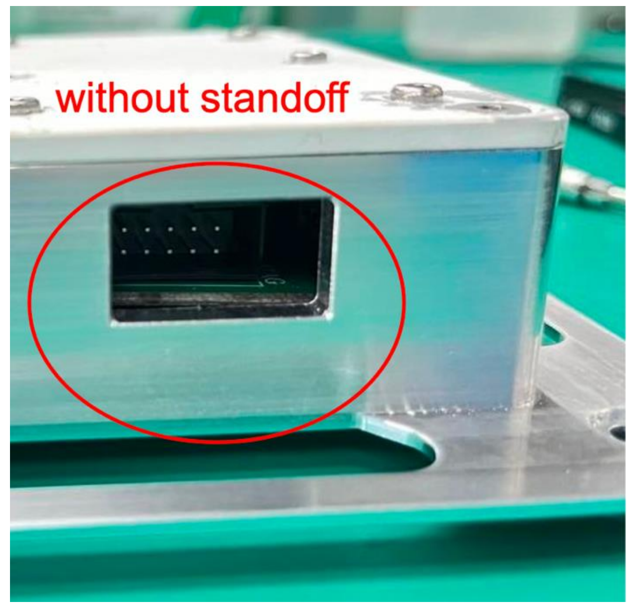
DSRP Interface Control Document

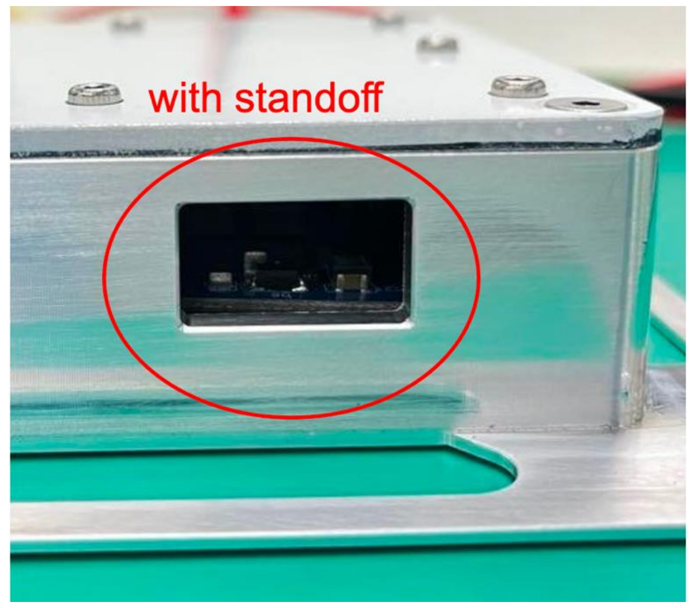
Provided by DSRP team to ispace team to facilitate integration of payload with spacecraft.
Complies with spacecraft Interface Requirements Document.
Continuously updated during payload development in consultation with spacecraft team.

Design and Constraints



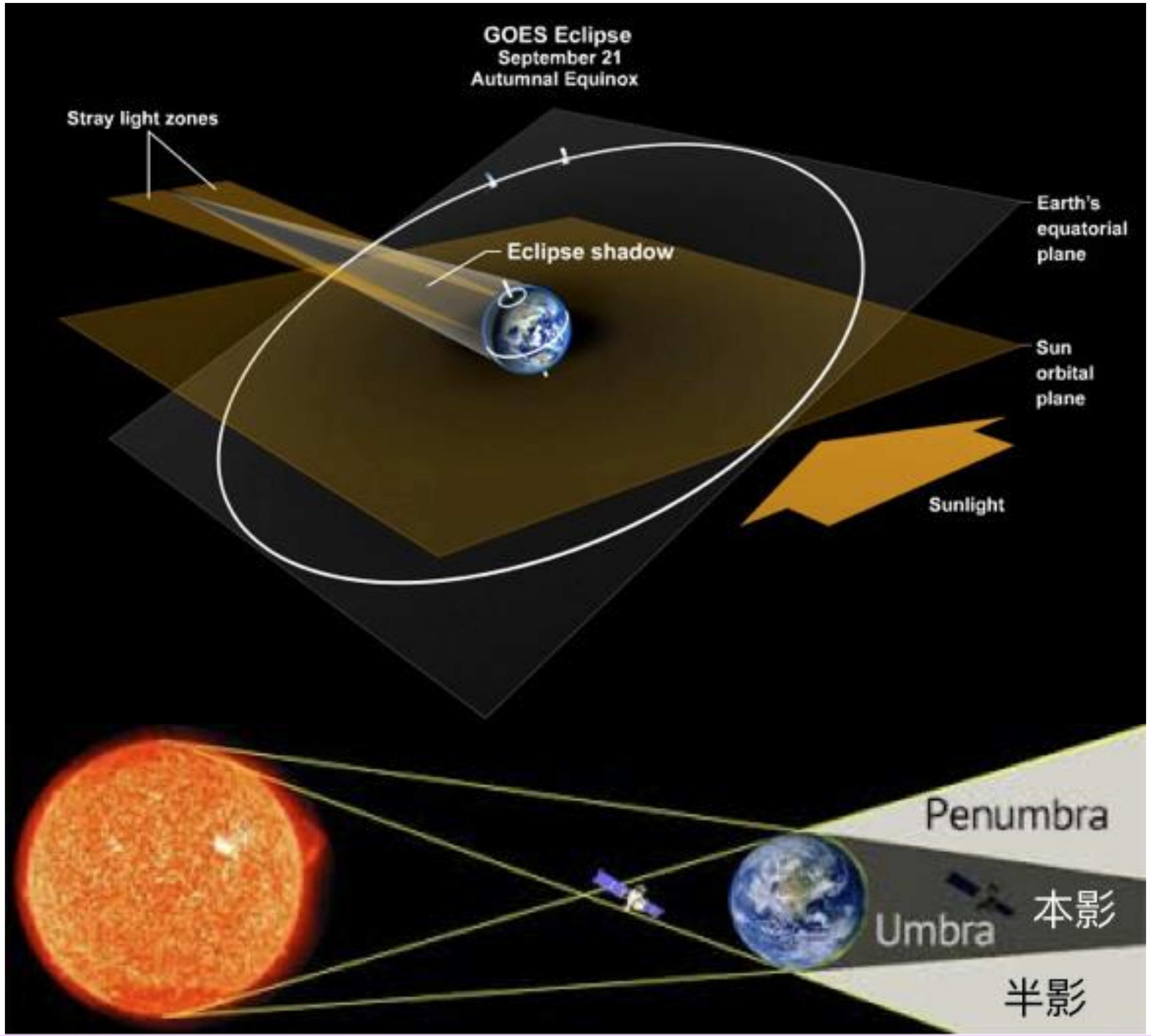


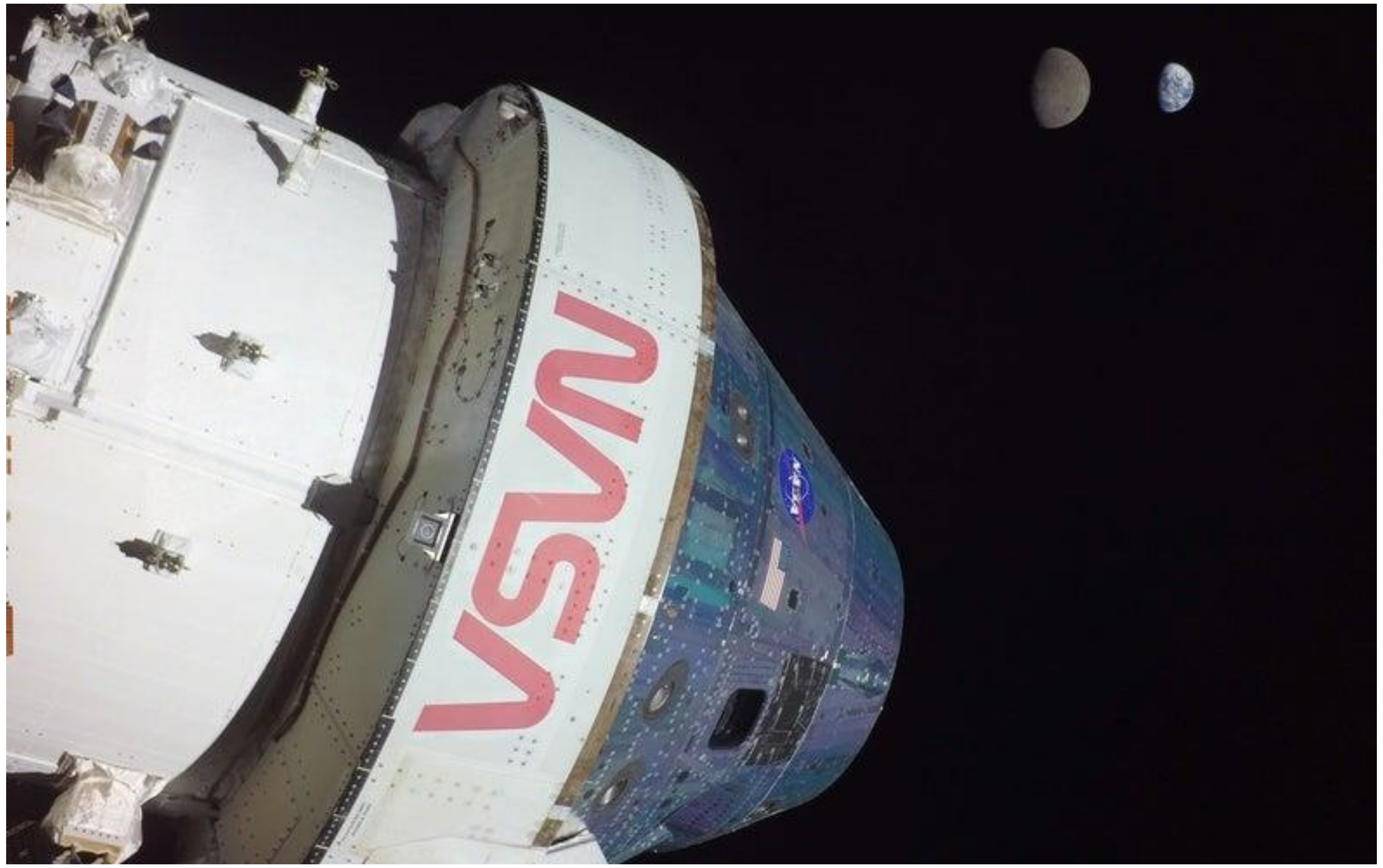




- Stringent qualification standards for vibration and shock environment: 33 g load (compare to 15 g for Falcon 9 rideshare payload).
- PCB warping due to variable thermal conductivity observed during curing of epoxy in oven during EM fabrication required additional fixtures.
- Mass limit of 400 grams required light weighting of chassis.
- Maximum power limit: 900 mW.

Thermal Challenges:
Solar heating and radiative cooling



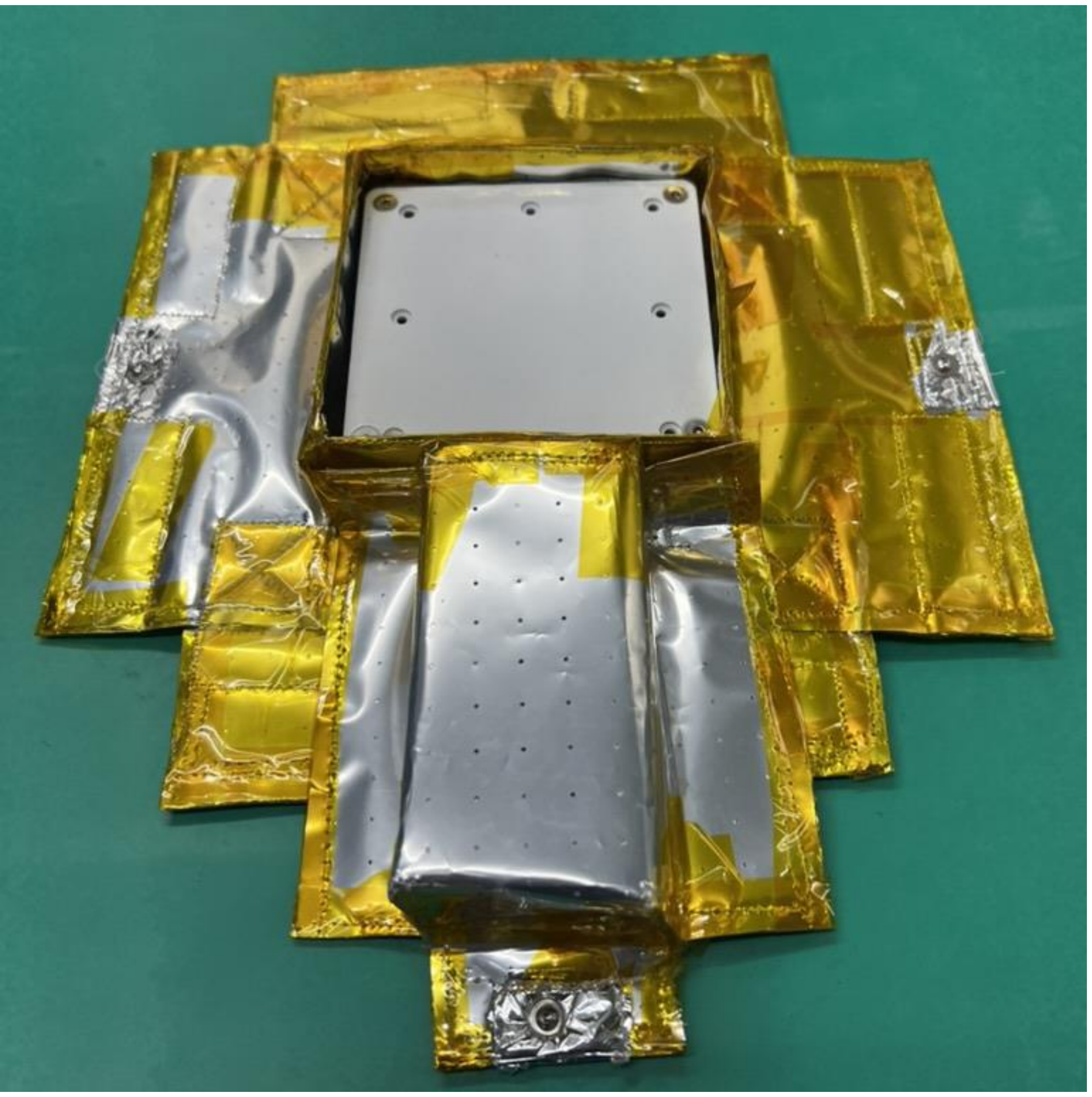


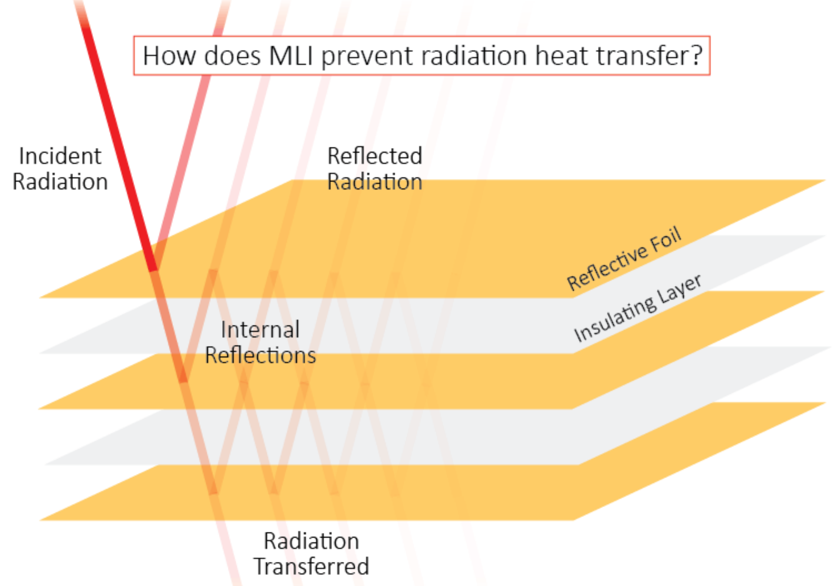
Eclipse refers to periods where the Sun is blocked by the Earth (not always the same as nighttime).

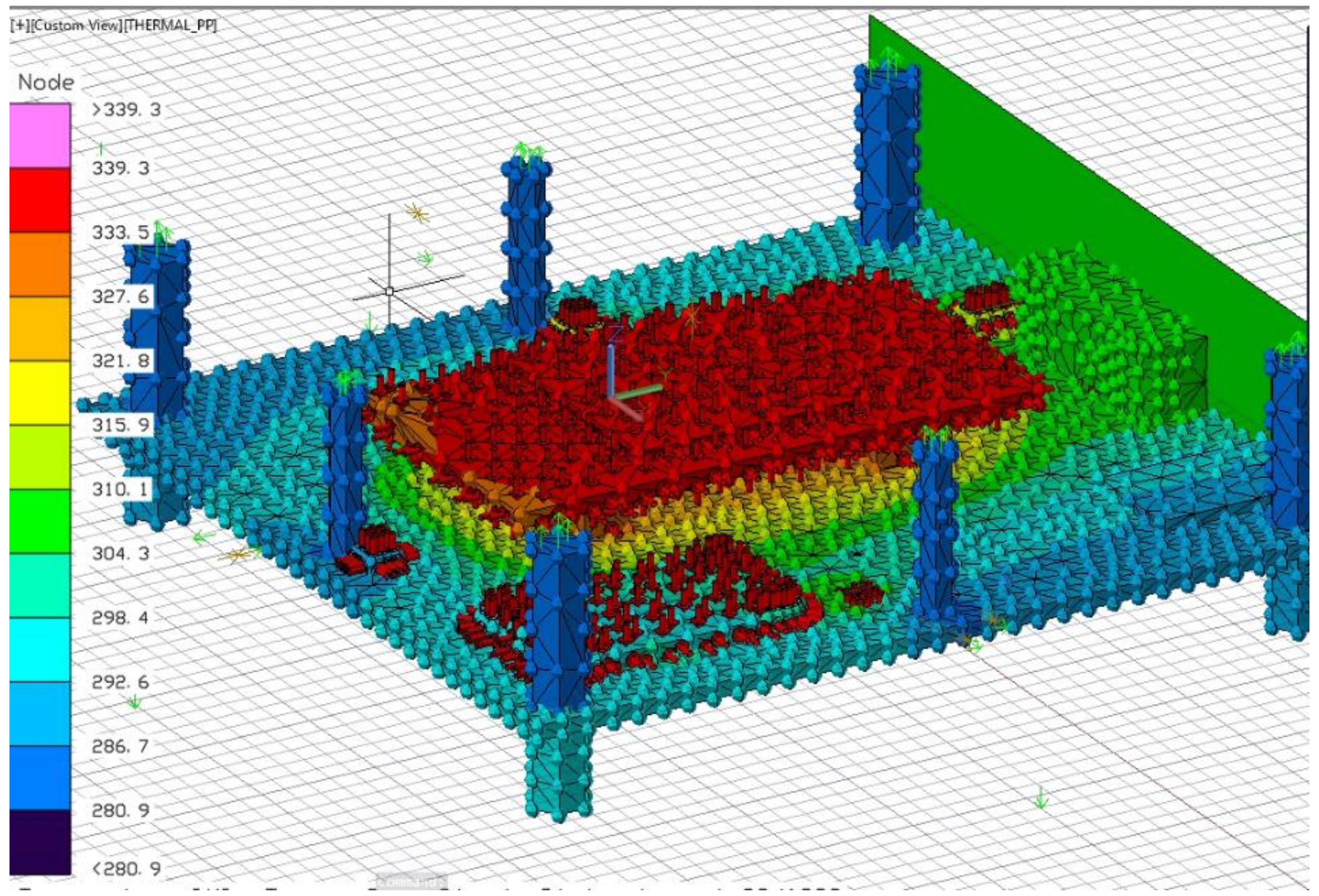
The Sun is blocked by the Earth less in higher orbits.

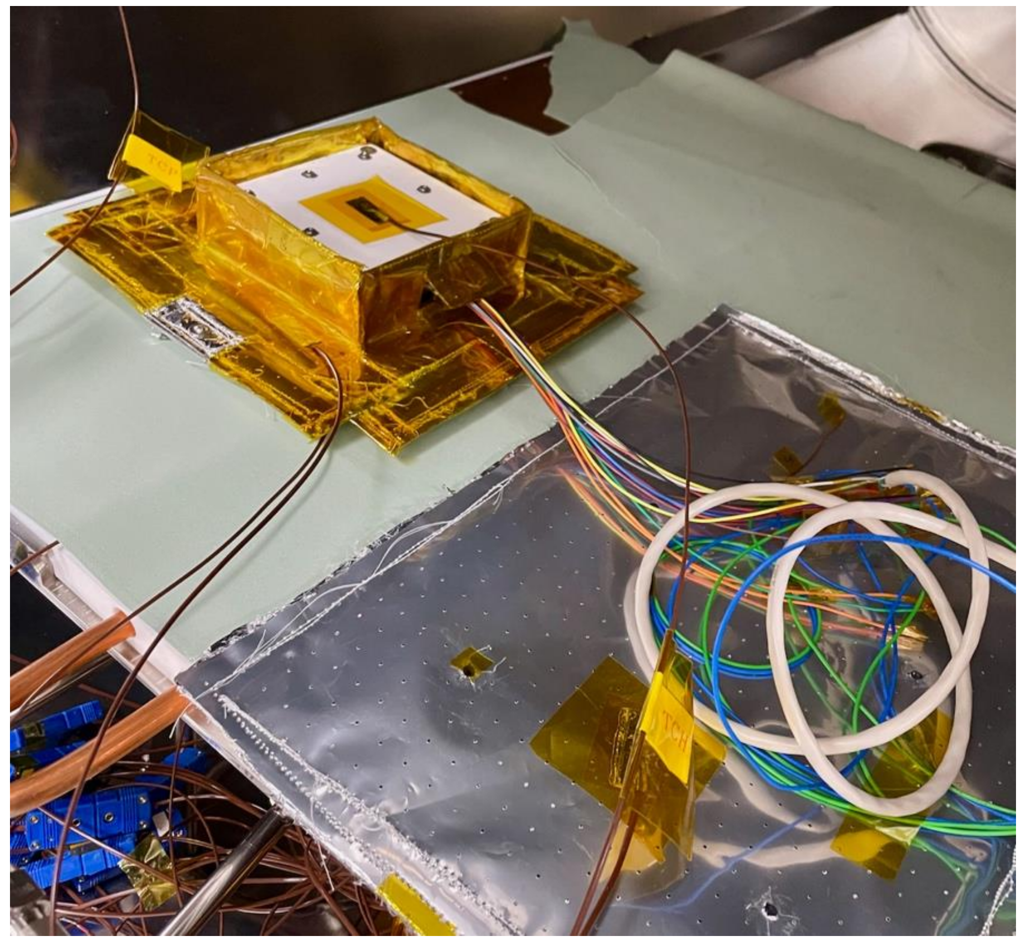
The side of spacecraft facing the Sun can experience long periods of heating, while the side of the spacecraft facing cold space can rapidly lose heat through radiation.

DSRP Thermal Control









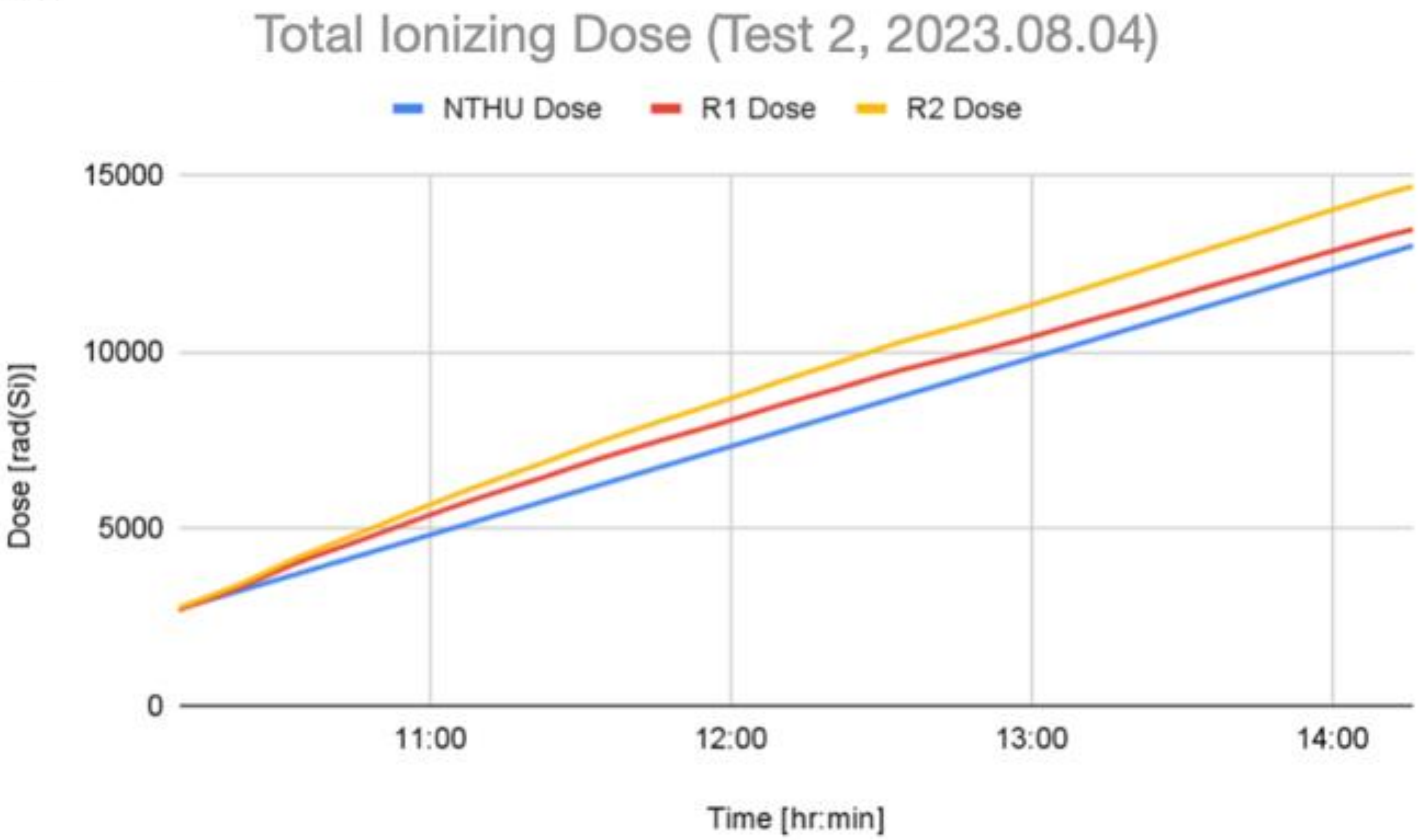
Extreme temperatures require the use of heaters, conductors, multi-layer insulation and radiators. Development of thermal simulation capability for environments beyond LEO.

Worst cold conditions required installation of heater on lander side.

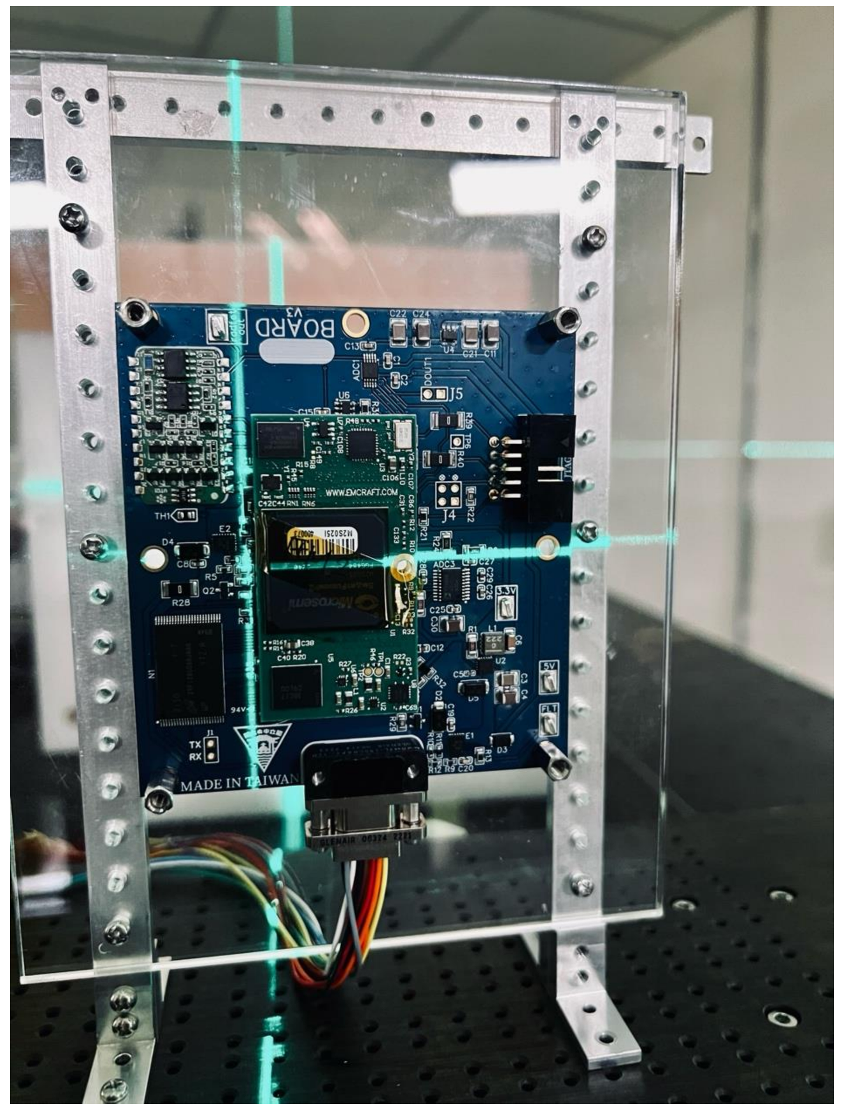
Temperature coefficients also characterized during TVAC tests.

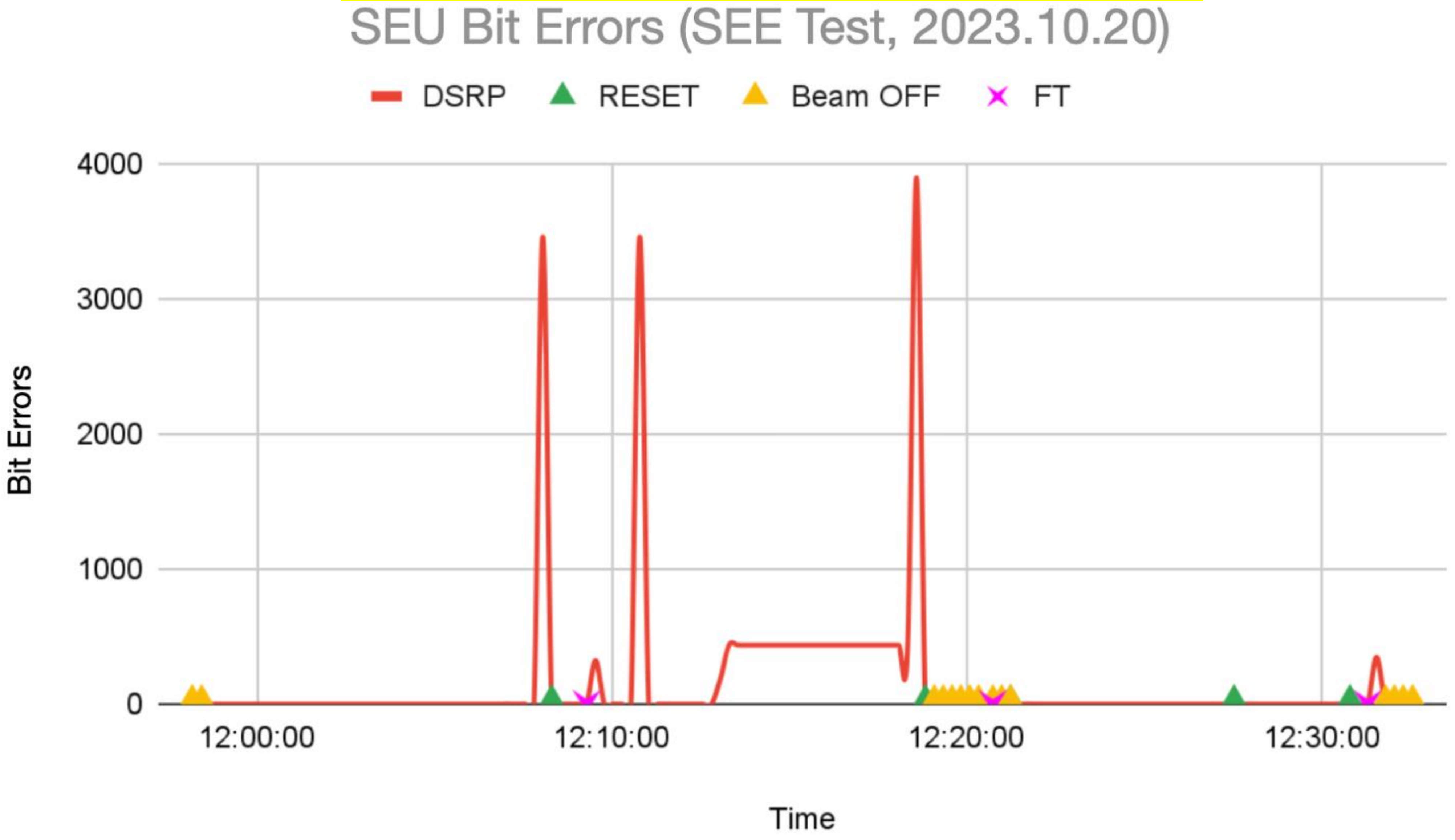
Component (Operating Temp., ℃)	Orbit (℃)		Lunar Surface (℃)	
	Worst Hot No TC	Worst Hot With TC	Worst Hot No TC	Worst Hot With TC
PCB (-40 ~ 85)	56 ~ 101	45 ~ 60	78 ~ 89	65 ~ 71
RS-422 Transceiver IC (-40 ~ 80)	101	51	108	65
RADFET Module (-40 ~ 85)	65	51	78	66
NAND Flash IC (-40 ~ 85)	67	52	82	70
Controller (-40 ~ 100)	68	54	82	70

NTHU Radioisotope Lab
Co-60 TID Test



CGMH Proton and Radiation Therapy Center
Proton Beam Single Event Test

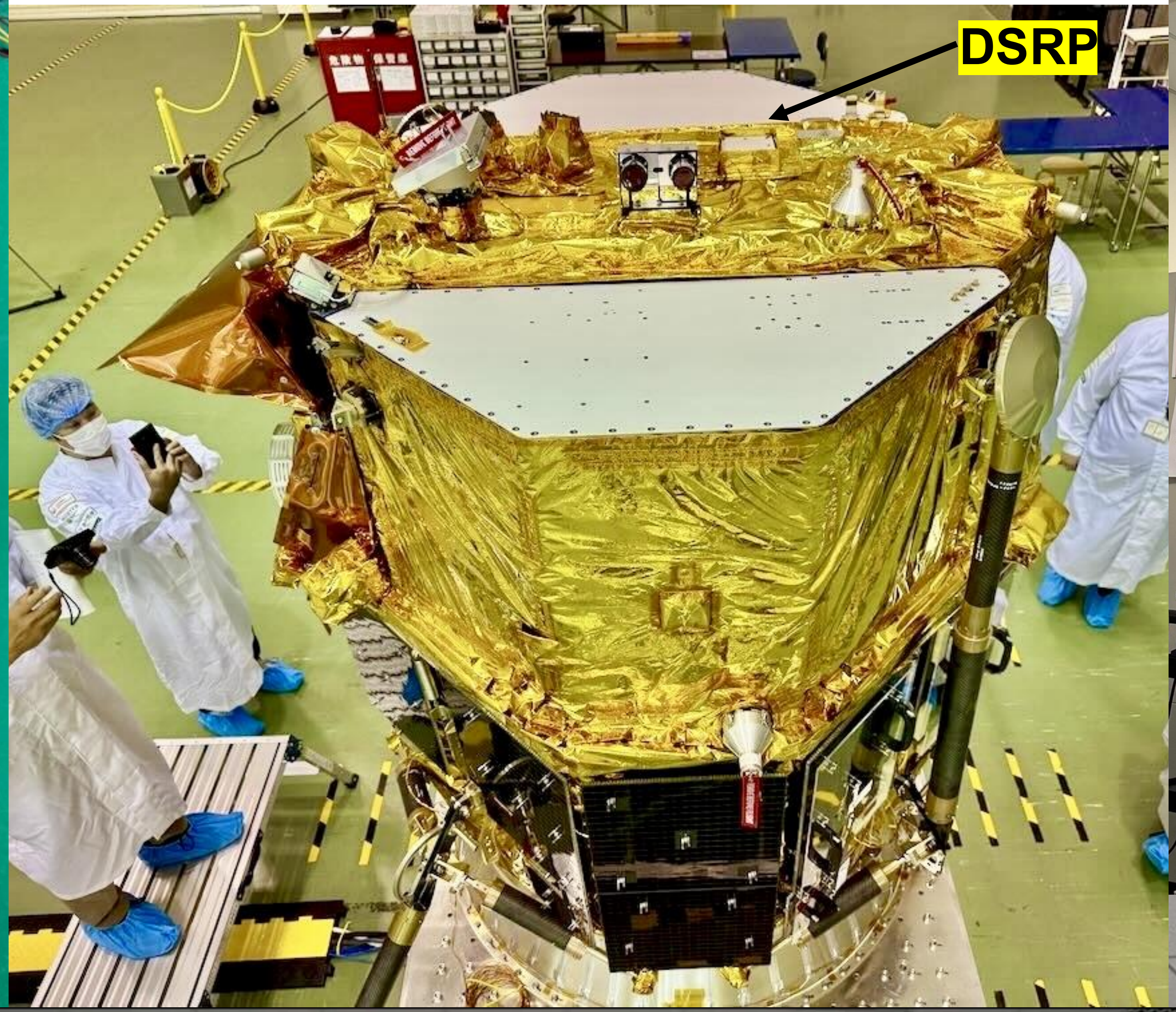


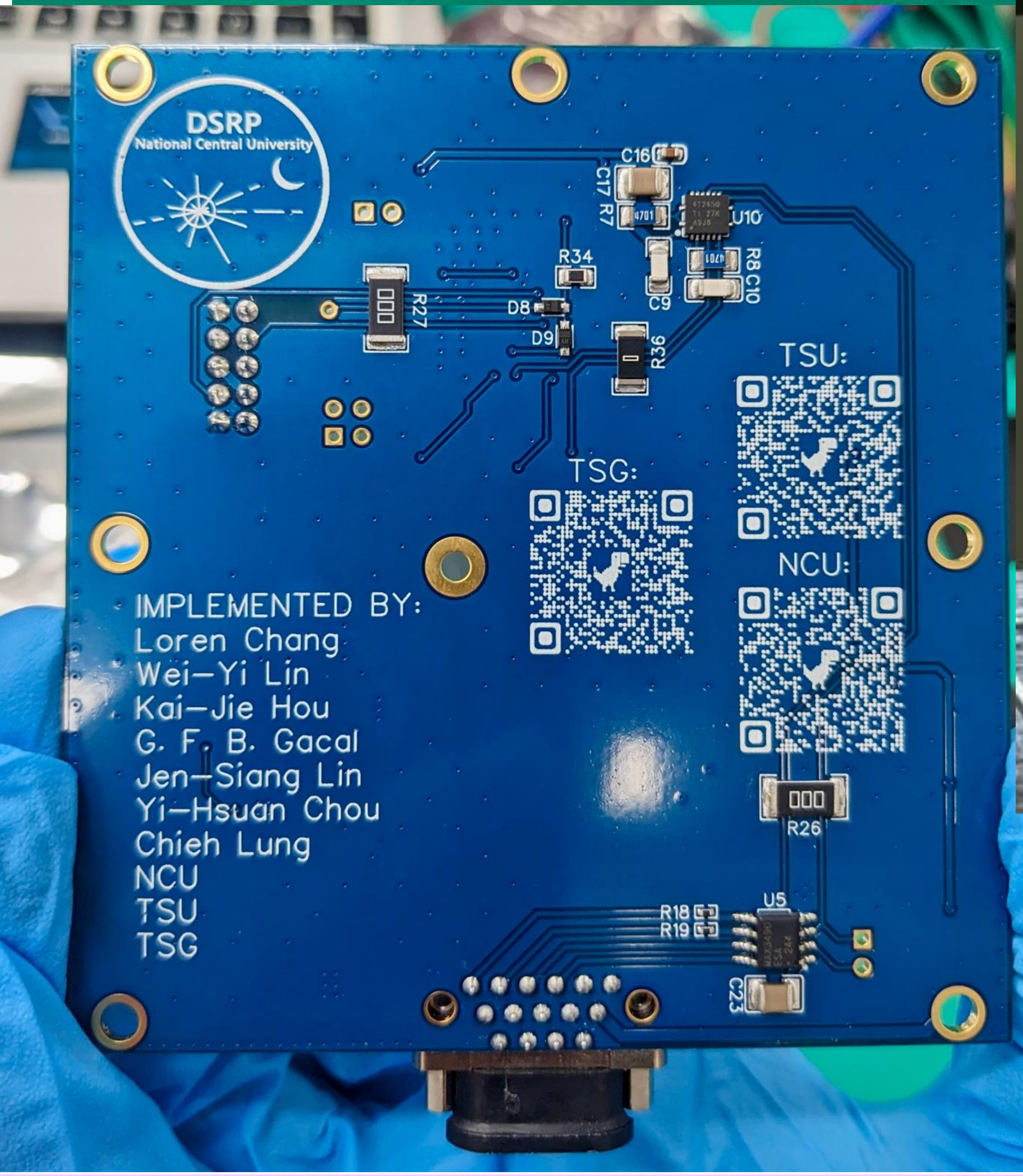


- Total Ionizing Dose qualification requirement for Lunar Payload over 4 months: 10 krad (100 Gy) with 2 mm aluminum shielding, based on SPENVIS predictions.

- TID tests using Cobalt 60 gamma ray source verified survival up to 20 krad before irreversible damage (DC-DC converter). Maximum dose errors of 8% and 17% for qualification unit.

- Single Event Effect tests using 221.2 MeV proton beam verified SEU counting ability with no anomalous un-commanded resets or power cycles. Anomalous persistence of bits in error for 5 minutes may be due to software bug or charge pump failure but can be corrected through post processing.






高砂熱学 Takasago Thermal Engineering
月面用水電解装置
Water-splitting experiment

ispace
月面探査車
ispace Micro Rover

ユーグレナ
藻類培養実験モジュール
LunaGlena

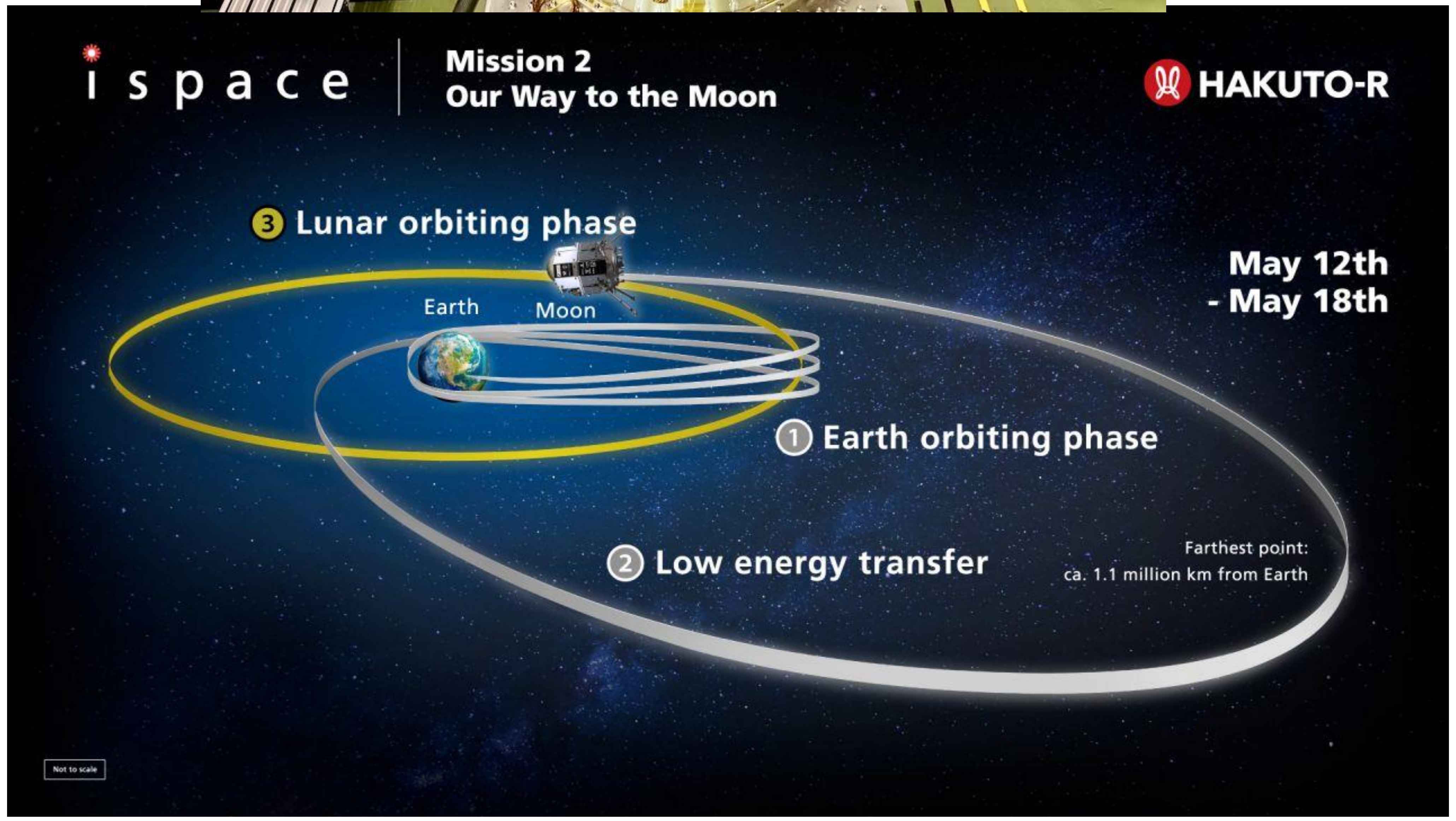
深宇宙放射線プローブ
Deep Space Radiation Probe

BANDAI NAMCO
「GOI 宇宙世紀憲章」プレート
"Space Century Charter" plate

隨奔向深太空科學酬載 寫下我史上首次

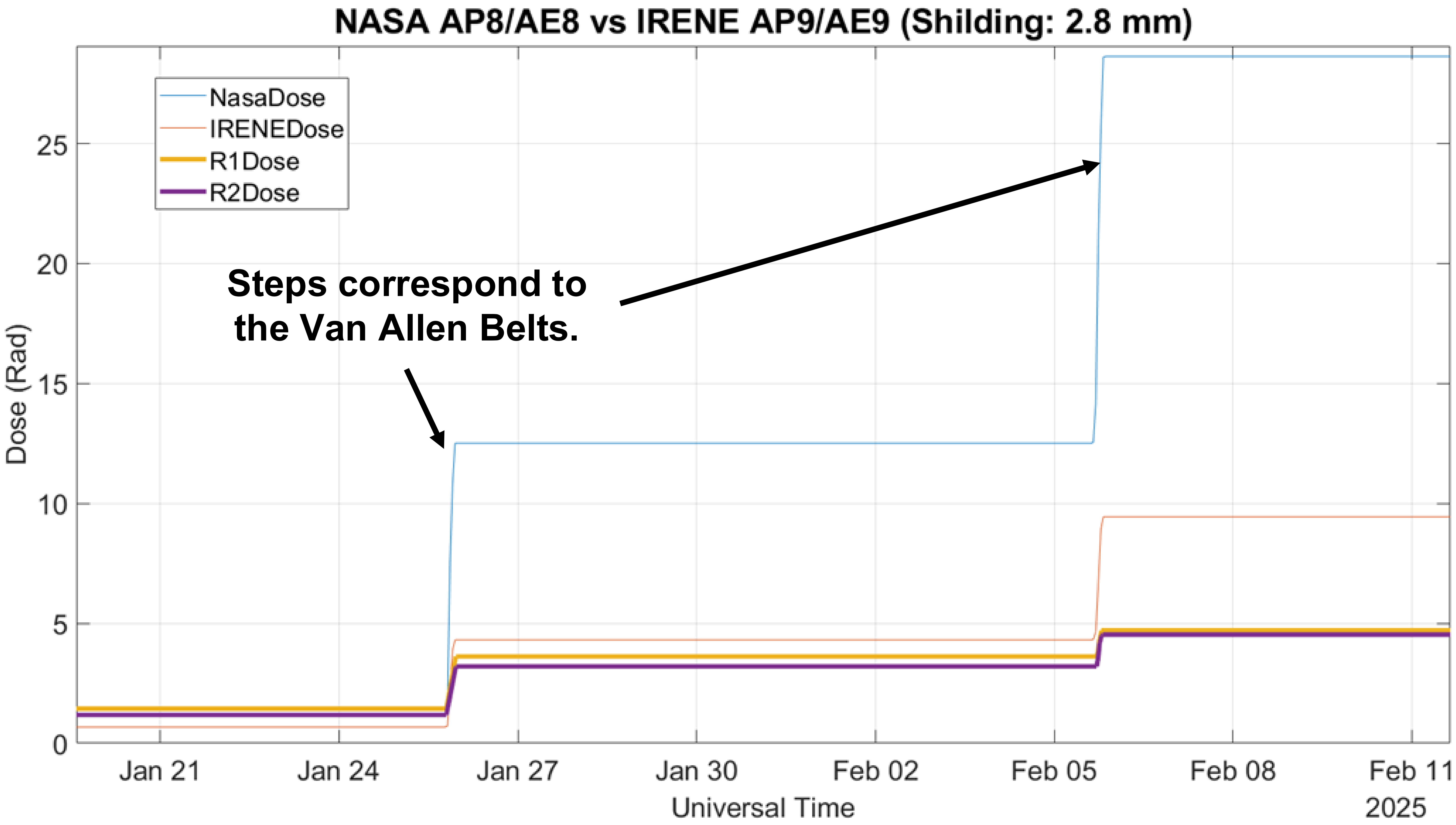
2022/03/01: Project kickoff.
2024/01/15: Unpackaging, final update, and formal transfer to ispace.
2024/09/12: Integration complete.
2025/1/15: Launch and start of operations!

ispace Hakuto-R M2 Profile



- DSRP mounted on top face of ispace *Resilience* lander. Direct exposure to space.
- DSRP powered on after post launch checkout on 2025/1/15. Entered lunar orbit on 5/6. Hard landing on 6/6. DSRP active on all mission segments except lunar descent.
- Initial lunar swing by orbit: 2.5 revolutions on 394,458 x 13,548 km radius lunar swing by orbit.
- Transition to low energy lunar transfer orbit following apogee of third swing by orbit.
- 5 passes mostly through outer Van Allen Belt (13,000 - 60,000 km altitude, mainly electrons).

Comparison to Models



- Predicted TID of 28 Rads using AP8/AE8 NASA, 10 Rads using AP9/AE9 IRENE. Settings: Detector: Silicon; Solar Activity: High; Shielding: 2.8 mm.

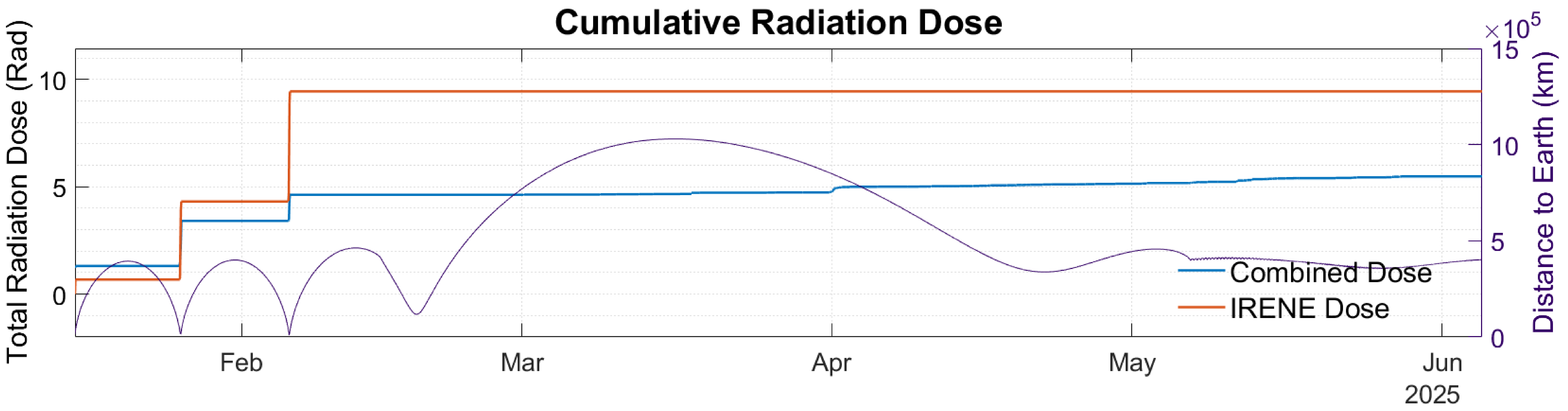
- Limitations: Models used consider only particle radiation from the radiation belts, not electromagnetic radiation, solar radiation storms, galactic cosmic rays, or regions outside L = 11.5 (~ 66969 km altitude). Dose outside radiation belts may be underestimated, although the highest doses will still be from the radiation belts.

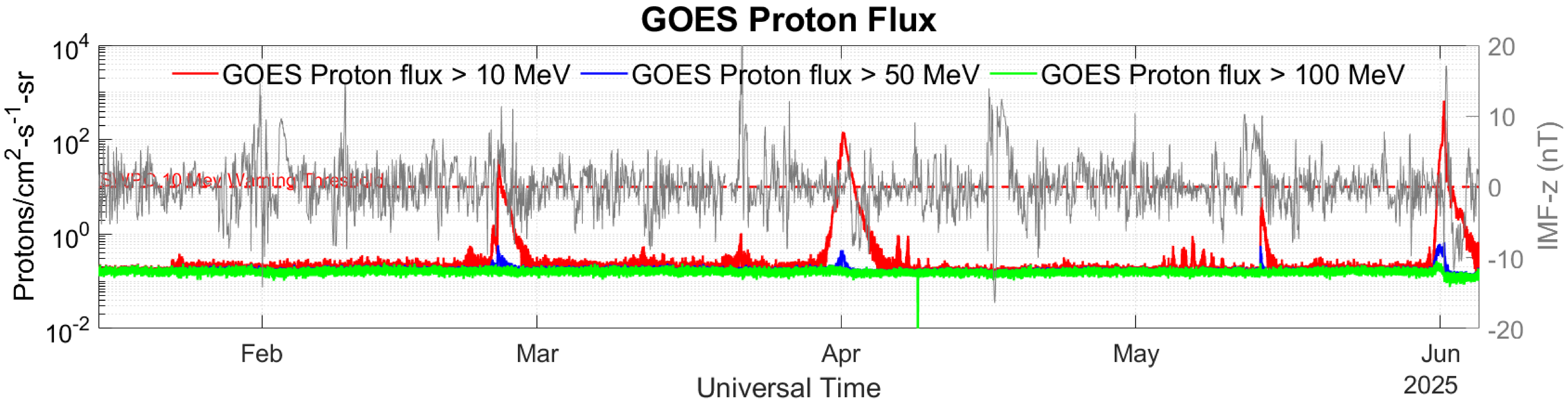
  - IRENE dose estimates with minimal shielding are ~2000 x larger than using 2.8 mm DSRP shielding.

- Similar trend for DSRP R1 and R2 as model predictions, but smaller by a factor of 2 compared to AP9/AE9 using similar levels of shielding. Both RADFETs show similar trends but differences in magnitude.

  - Measured flux influenced by shielding from lander on one face.

DSRP Dose Observations





Increases in dose (silicon) correspond to transit through the radiation belts.

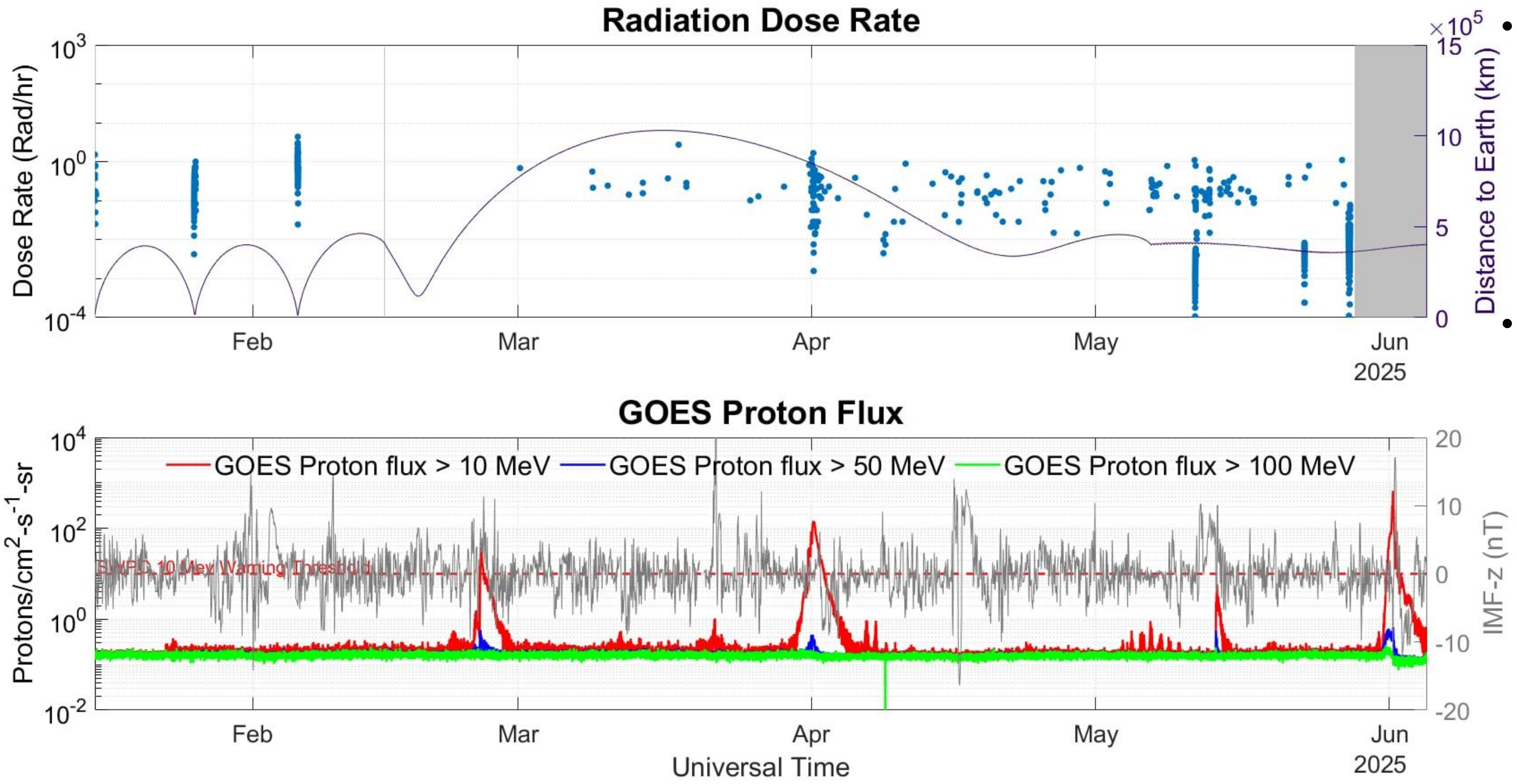
- Measured flux influenced by shielding from lander on one face.

3 solar particle events (SPEs) reaching NOAA SWPC 10 MeV warning threshold observed on 2/25, 4/1, 6/1.

- Dose rate of 4/1 SPE larger than 2/25, potentially due to interplanetary magnetic field (IMF) being negative on 4/1 event allowing for magnetic reconnection to occur.

- 6/1 event may be underestimated. Checking noise filtering process.

DSRP Dose Rate Observations



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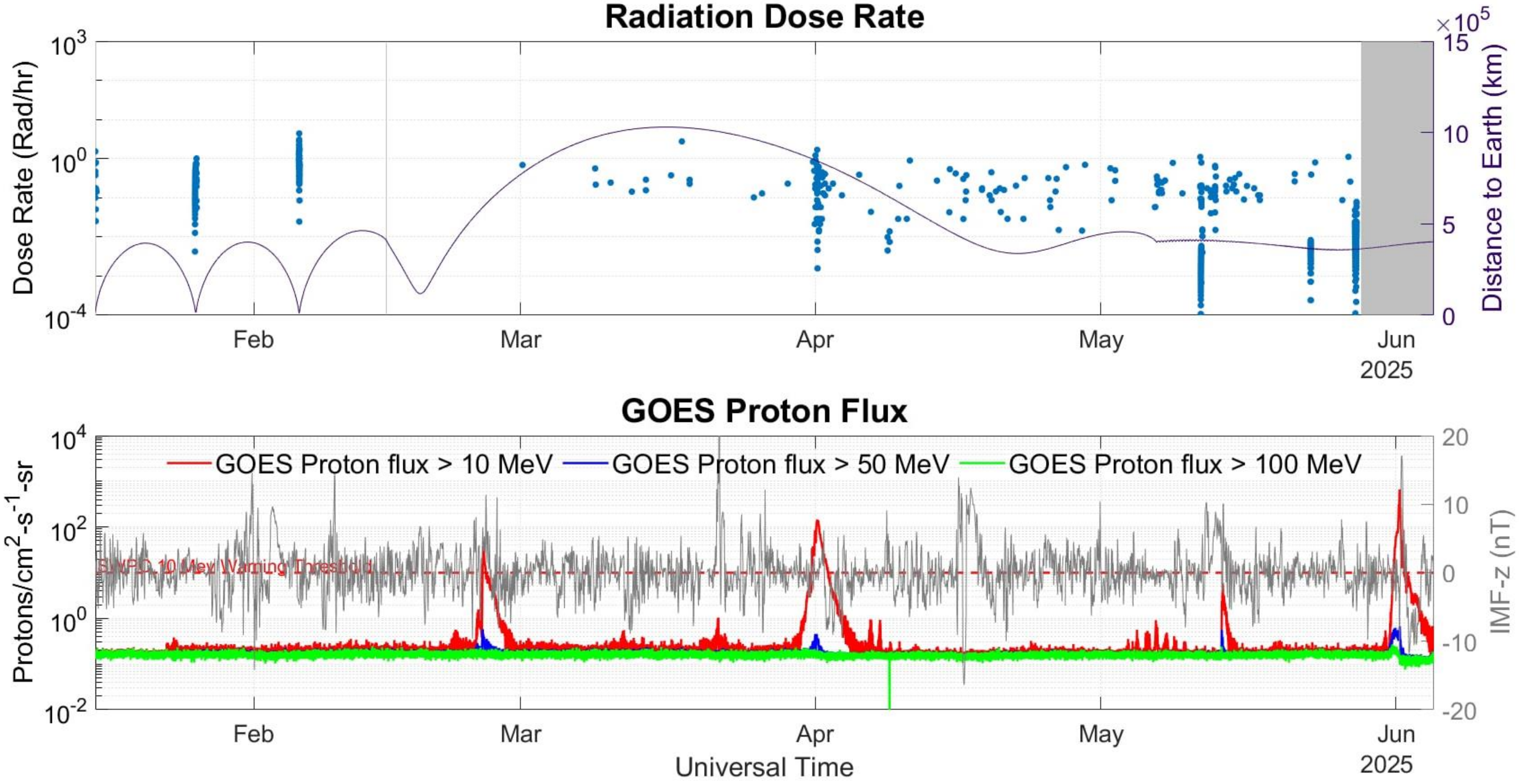
[1] Zhang et al. (*Science Advances*, 2020); [2] George et al. (*Nature*, 2024)

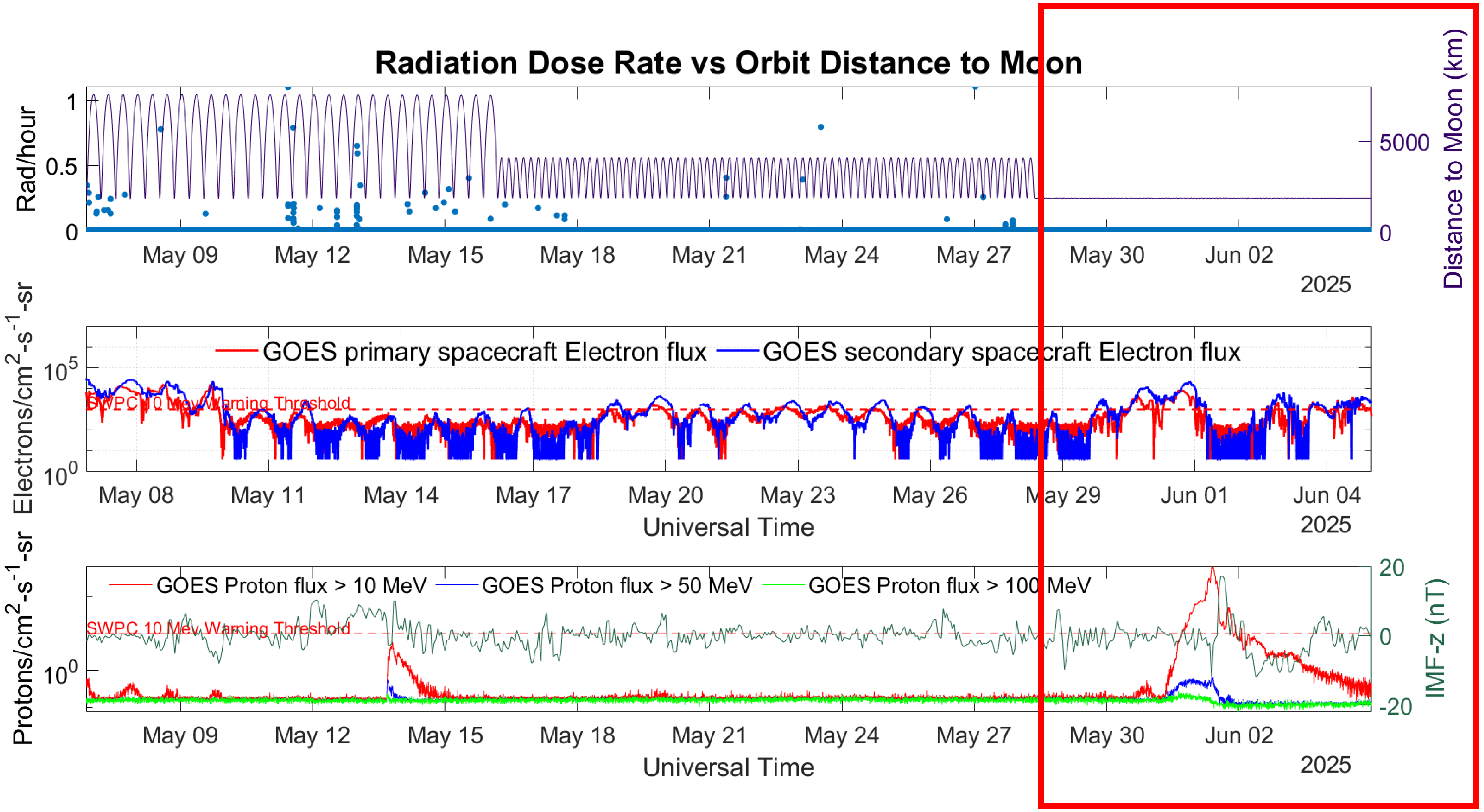
DSRP Dose Rate Observations

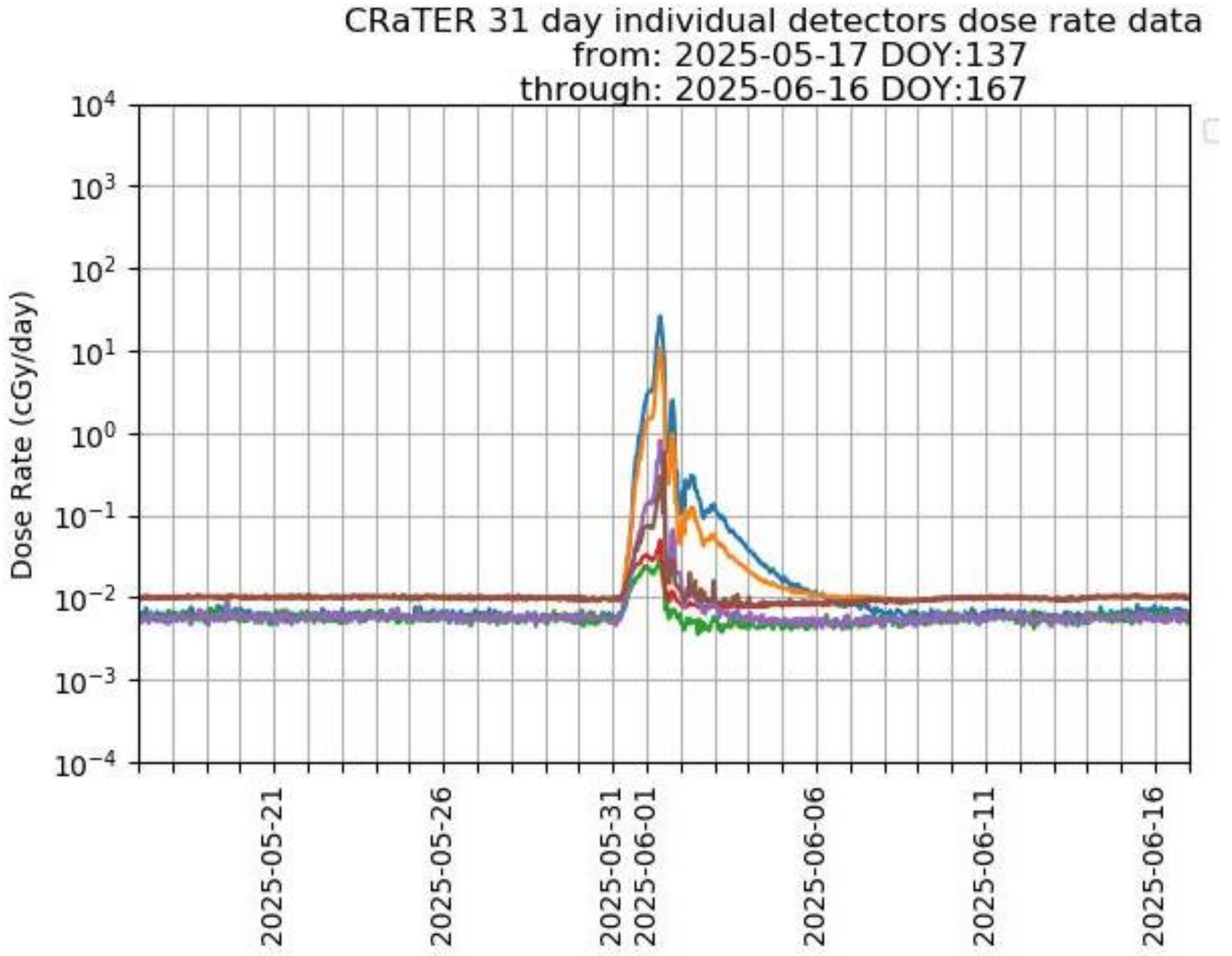


- Increases in dose rate correlated with transit through the radiation belts, as well as solar particle events and some geomagnetic storms.
- Comparison (solar min):
  - Chang’E 4 (2019), lunar surface: 1.32 x 10^{-3} rad/hour [1]
  - Artemis 1 capsule internal (2022), inner radiation belts: 1.435 rad/hour lunar orbit: 1.5 x 10^{-3} rad/hour [2]

[1] Zhang et al. (*Science Advances*, 2020); [2] George et al. (*Nature*, 2024)

Lunar Orbit Dose Anomaly

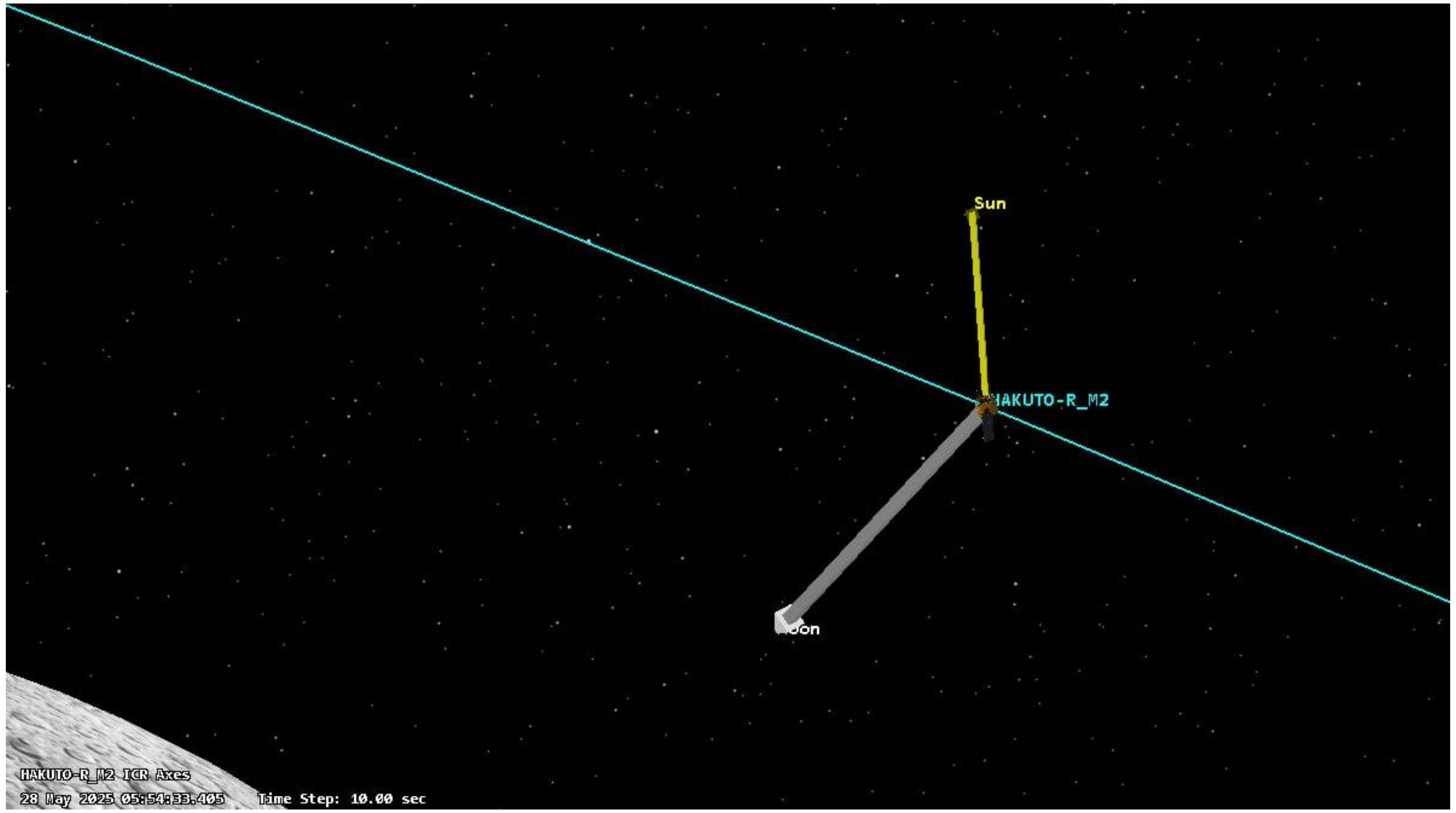




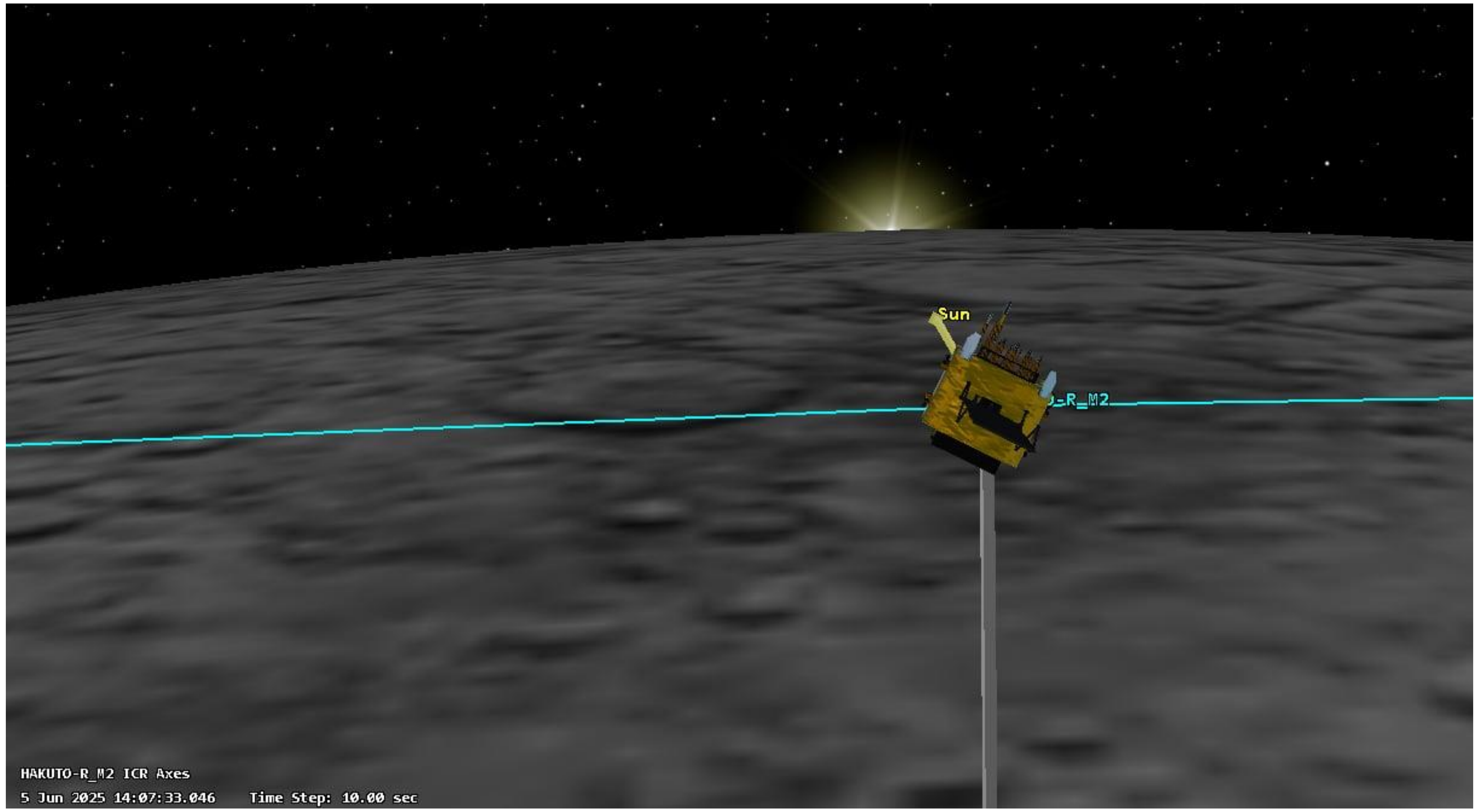
- 6/1 SPE dose oddly small. Spacecraft was not in Earth’s magnetotail at the time. Checking spacecraft orientation.
  - Was detected by Cosmic Ray Telescope for the Effects of Radiation (CRaTER) aboard Lunar Reconnaissance Orbiter (LRO), ~ 0.41 rad/hour peak.

Lunar Orbit Dose Anomaly

May 28, 2025

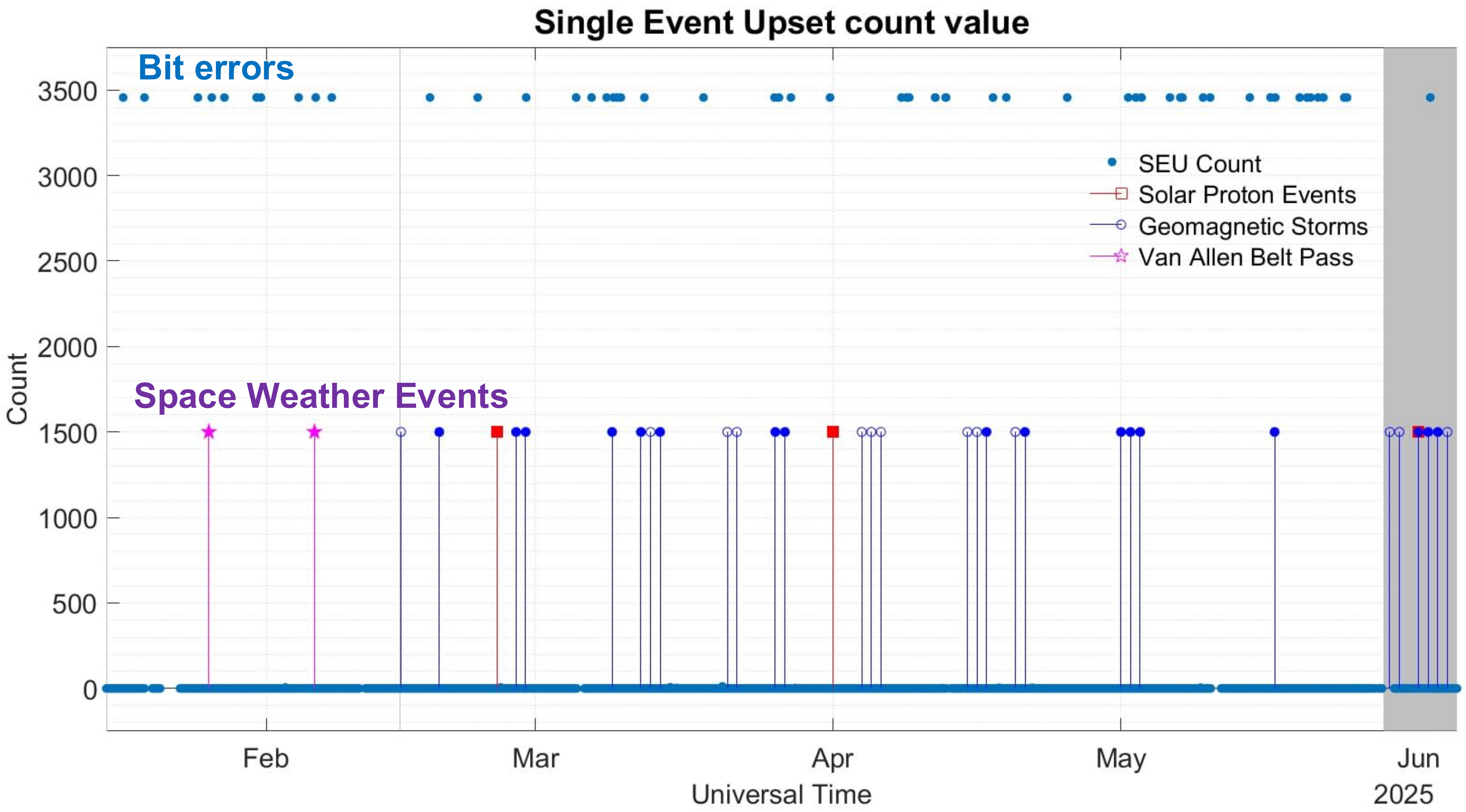


June 5, 2025



- STK analysis shows multiple eclipses with 100% obscuration of Sun by Moon from 5/28 – 6/6. No such eclipses prior to 5/28 due to higher orbit.
  - Shielding from Moon?

SEU Hakuto-R M2 On Orbit (+/- 12 hours)



Solar Particle Event: 100% (3/3)
02/25, 04/01, 06/01

Geomagnetic Storms Event: 56.7% (17/30)
02/15, 02/19, 02/27, 02/28, 03/09, 03/12, 03/13, 03/14, 03/21, 03/22, 03/26, 03/27, 04/04, 04/05, 04/06, 04/15, 04/16, 04/17, 04/20, 04/21, 05/01, 05/02, 05/03, 05/17, 05/29, 05/30, 06/01, 06/02, 06/03, 06/04

Van-Allen Belt Pass: 100% (2/2)
01/26, 02/06

Multiple SEUs encountered. Bit errors ~3.4 kb consistent with proton beam tests on ground.
Solar proton events and Van Allen Belt crossings have 100% occurrence rate.
Other possible sources: Geomagnetic storms, galactic cosmic rays.

Conclusions and Future Work

- The NCU Deep Space Radiation Probe (DSRP) is Taiwan's first deep space payload, intended to better understand the deep space radiation environment and its effects on electronics and biological organisms, as well as develop the capacity to design and fabricate deep space payloads and spacecraft subsystems.

- Parallel development of DSRP with ispace Hakuto-R M2 *Resilience* lander. Fit check with prototype (version 2) to verify interface in 2023/02. EM (version 3) passed qualification testing by 2023/09. FM (version 4B) completed acceptance testing in 2023/11 and handed over to ispace in 2024/1. Hard landing on 2025/6/6.

- Challenges included limited mass, power, and data volume, as well as the more severe deep space radiation and thermal environment.

- Flight results are mostly in agreement with ground testing, as well as the the time variation predicted by the AFRL AP-9 / AE-9 models. However, measured dose is smaller than predicted values by a factor of 2. Additionally, DSRP measures increases in dose rate outside lunar orbit not attributable to radiation belts. Some overlap with solar particle events and geomagnetic storms, but not exclusively so.

- DSRP has been modified for CubeSat form factor as the Compact Radiation Probe (CRP). Flight is expected on at least two LEO CubeSat missions:

    - COSPAR-1 CubeSat mission (2026 Q2). Handover to Peru National Engineering University (UNI) team performed on 2025/3/31.

    - Kyushu Institute of Technology Cuket Mission 3 (2027).