Space Environmental Damage Assessment on Sail/Deorbit Materials in Low Earth Orbit

Jin Ho Kang[1], Keith Gordon[1], Robert Bryant[2], W. Keats Wilkie[3], Kim de Groh[4], Olive Stohlman[3], Juan Fernandez[3], Jerry Warren[5], Gregory Dean[3], Nigel Schneider[6], Todd Denkins[7], Amanda Stark[5], Phillip Brown[6], and Matthew Chamberlain[3]

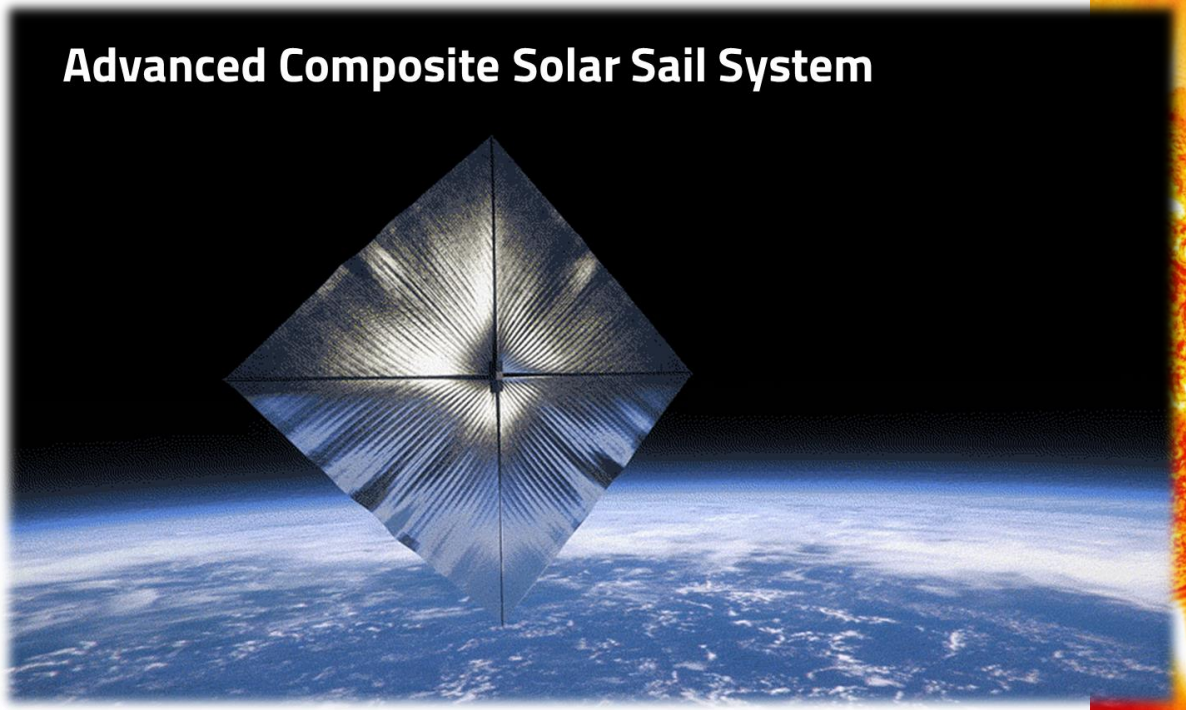
[1]*Advanced Materials and Processing Branch, NASA Langley Research Center, Hampton, VA, USA*
[2]*Durability, Damage Tolerance and Reliability Branch, NASA Langley Research Center, Hampton, VA, USA*
[3]*Structural Dynamics Branch, NASA Langley Research Center, Hampton, VA, USA*
[4]*Environmental Effects and Coatings Branch, NASA Glenn Research Center, Cleveland, OH, USA*
[5]*Structural and Thermal Systems Branch, NASA Langley Research Center, Hampton, VA, USA*
[6]*TEAM3 / NASA Langley Research Center, Hampton, VA, USA*
[7]*Chief Engineer Office, NASA Langley Research Center, Hampton, VA, USA*

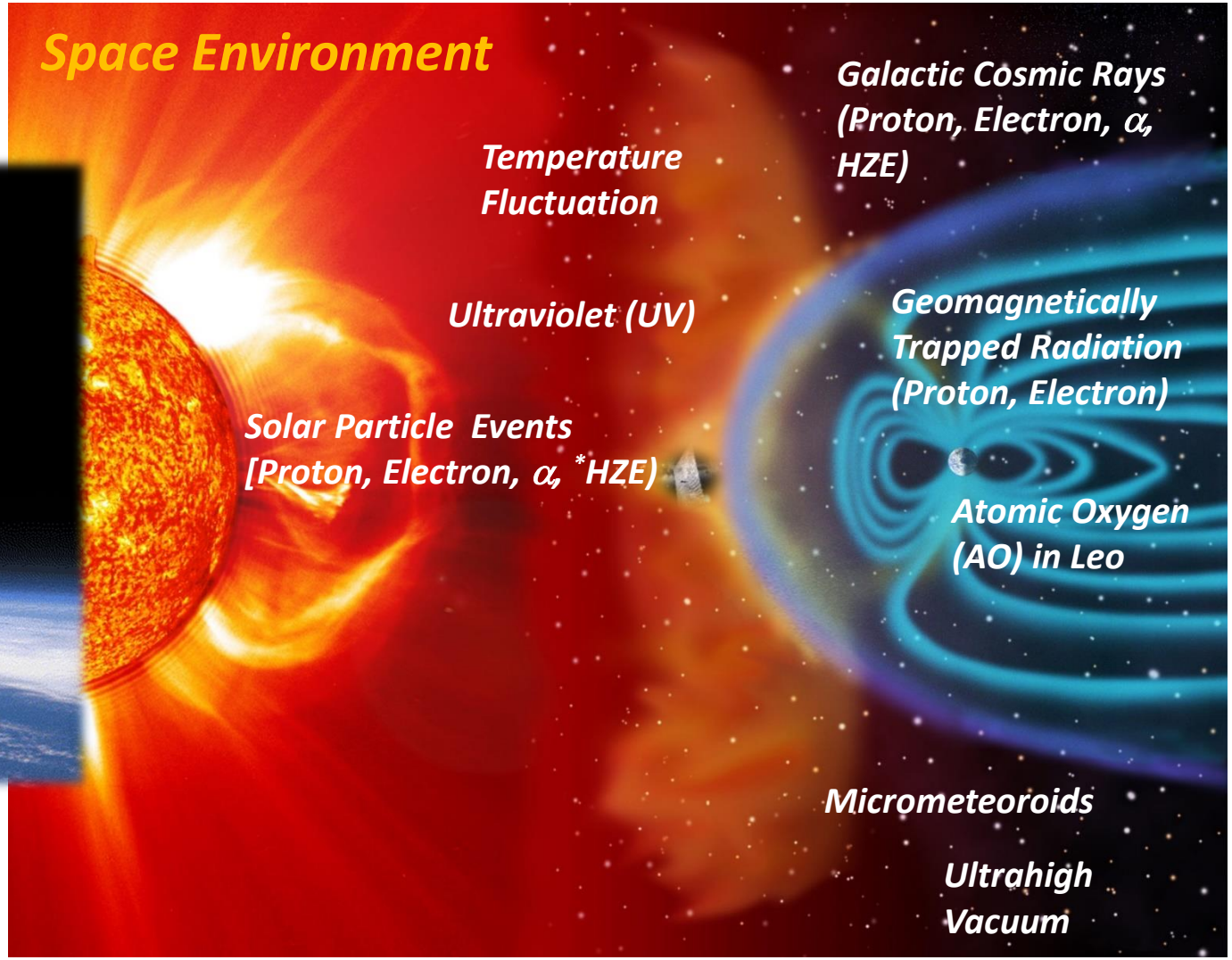
The 6th International Symposium on Space Sailing, June 8, 2023, New York, NY

Outlines

1. Introduction
2. Materials International Space Station Experiment (MISSE)
3. MISSE Test Condition
4. Sample List
5. Pre-, In- and Post-Flight Sample Images
6. Erosion Rate, Thermal Optical Property and Morphology Study
7. Summary and Future Works

Introduction

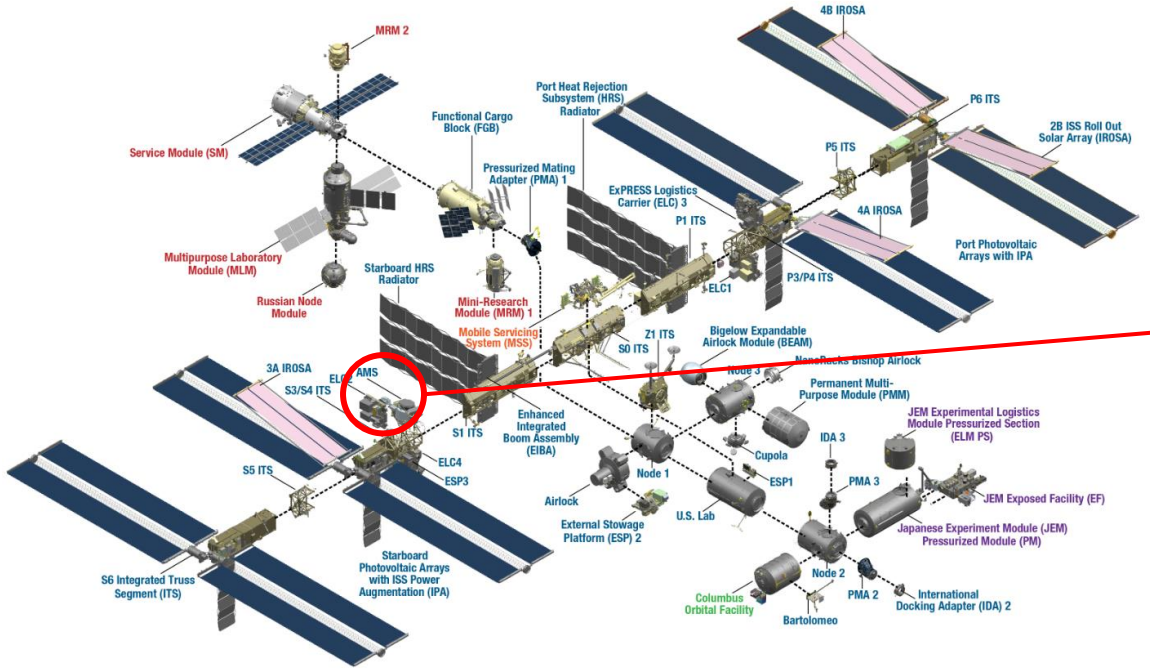


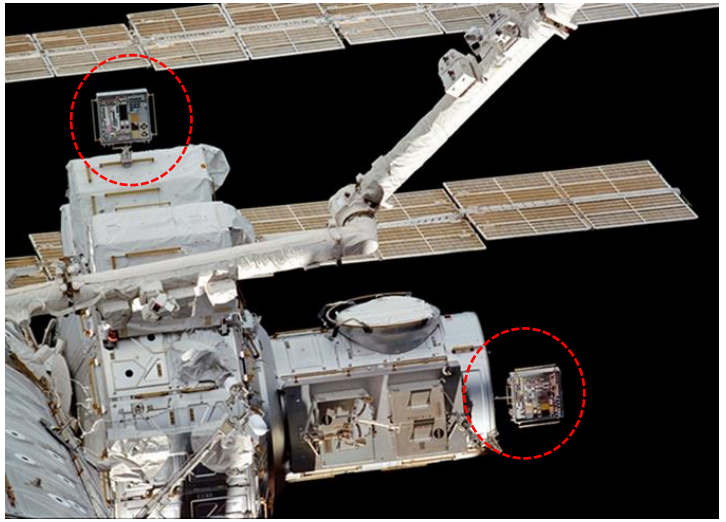


*High atomic number and energy particle (HZE)

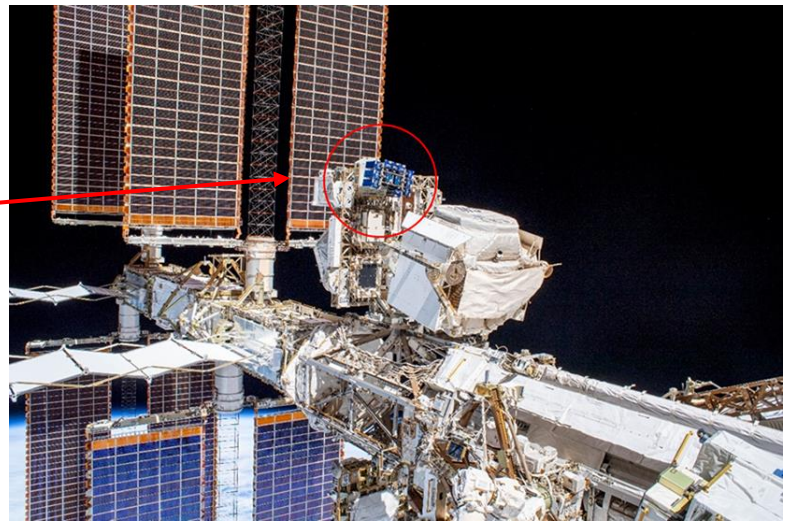
Materials International Space Station Experiment (MISSE)

A series of materials flown on the exterior of the International Space Station (ISS) to analyze the performance and durability of materials exposed to the low Earth orbit (LEO) space environment since 2001 (MISSE 1 and MISSE 2). The MISSE-Flight Facility (MISSE-FF) has been used as a test platform since 2018 (MISSE 9)





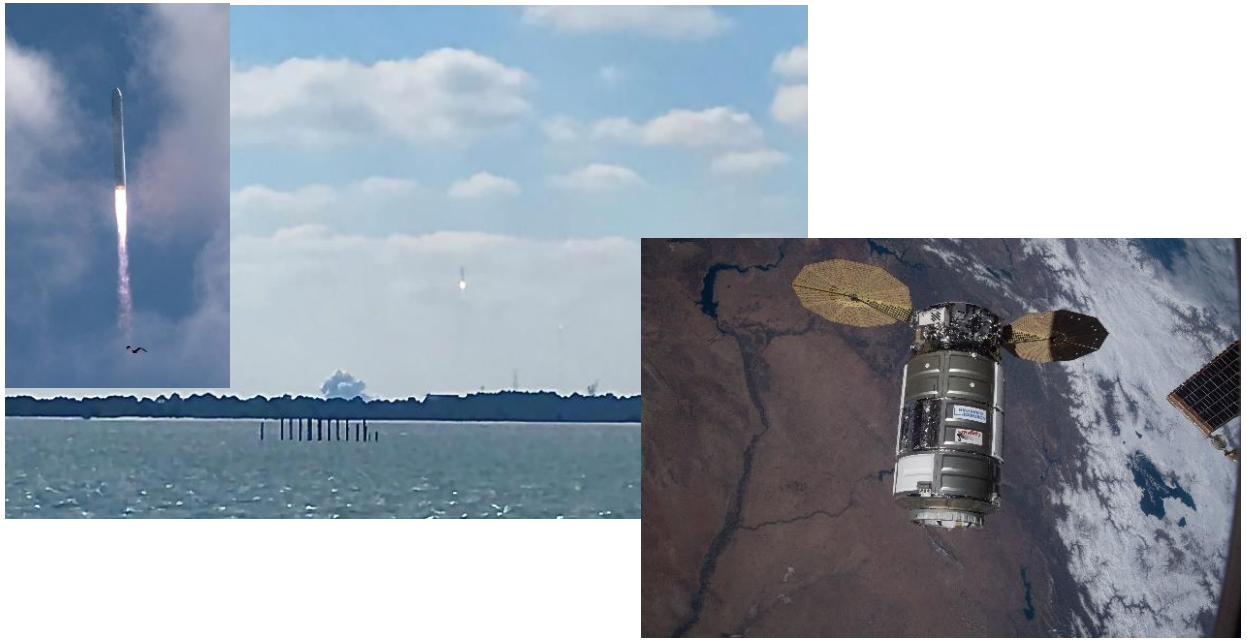
MISSE 1 (top left) and MISSE 2 (lower right) (December 7, 2001)



MISSE-FF on Express Logistics Carrier (ELC)-2 Site 3 (November 15, 2019)

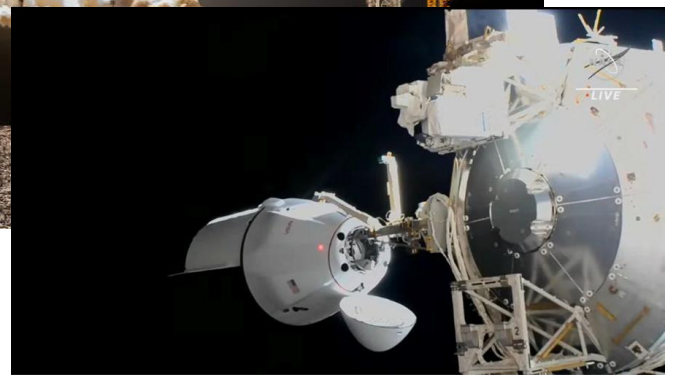
MISSE-FF Test Process

- Launch by Northrop Grumman Antares-Cygnus or SpaceX Falcon 9-Cargo Dragon



Northrop Grumman commercial resupply mission (GP 15) February 17, 2022 @ 17:36 UTC from MARS (Mid-Atlantic Regional Spaceport, Wallops Flight Facility), LP-0A by Antares 230+. Cygnus approaches ISS (MISSE 14)

SpaceX commercial resupply mission (CRS 27), March 15, 2023 @ 00:30 UTC from Kennedy Space Center on LC-39A (MISSE 17)



Cargo Dragon Docking to the Harmony module's space-facing port (Node 2 Forward)

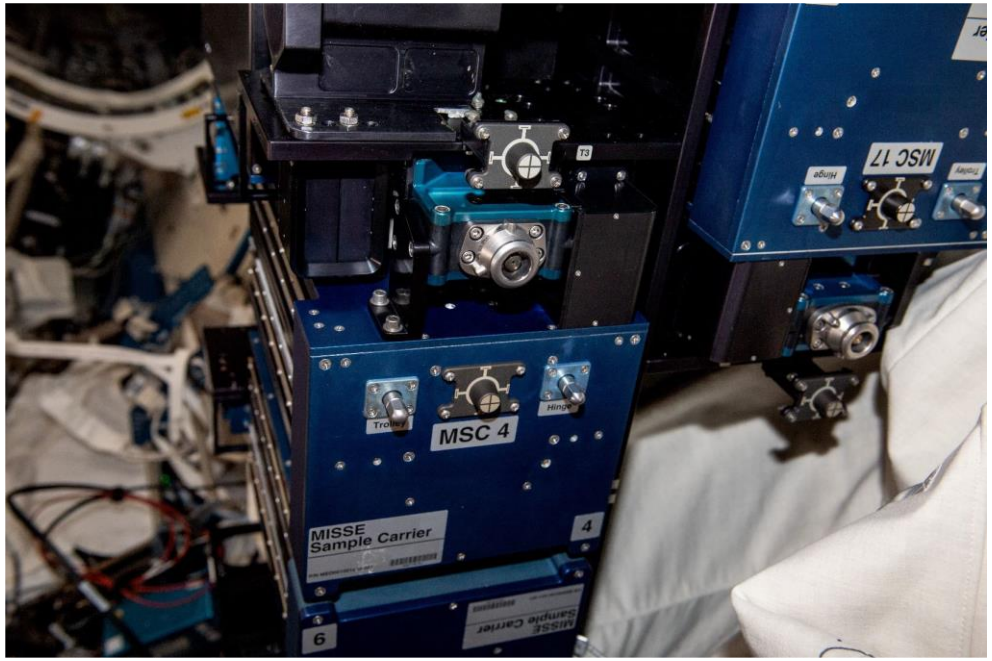
MISSE-FF Test Process

- Installation on MISSE Transport Tray (MTT): Astronauts installed MISSE Science Carriers (MSCs) and avionic boxes on the MTT. Then placed the MTT into the Japanese experiment module (JEM) airlock.

Installing MSCs on the MTT

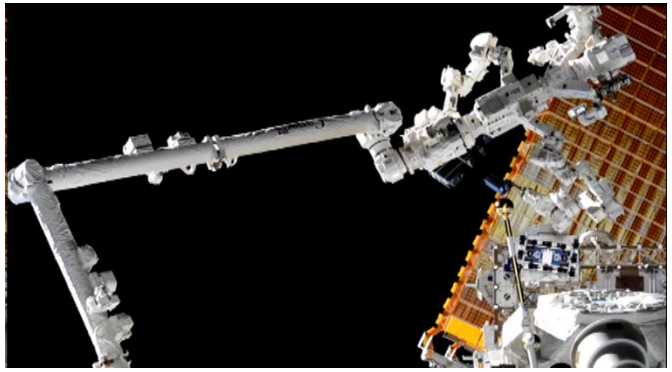
JAXA astronaut Soichi Noguchi installed the four MSCs, the MISSE Power and Data Box (MPD), and the MISSE Switch Box (MSB) on the MTT

Installing MSCs on the MTT

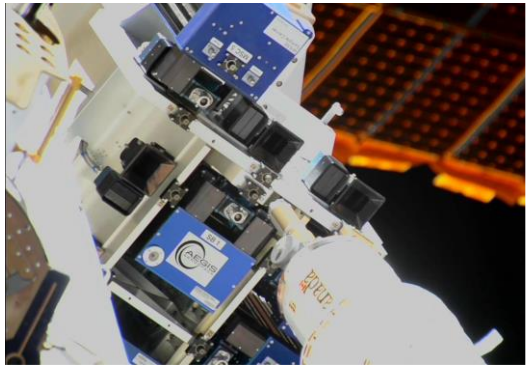


MISSE-FF Test Process

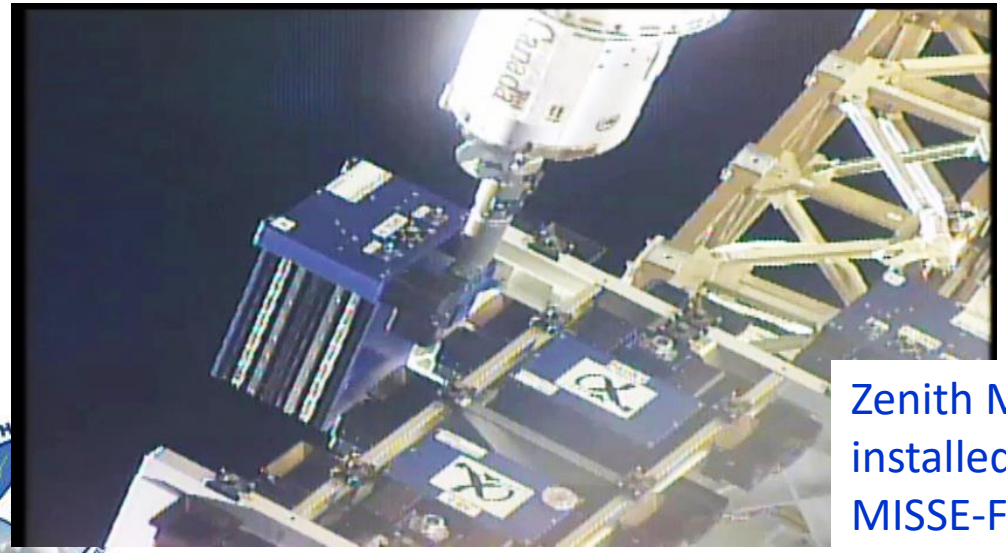
- MSCs installation on MISSE-FF: Start robotic arm operation, with support from the Canada Space Agency (CSA) ISS robotic systems team.



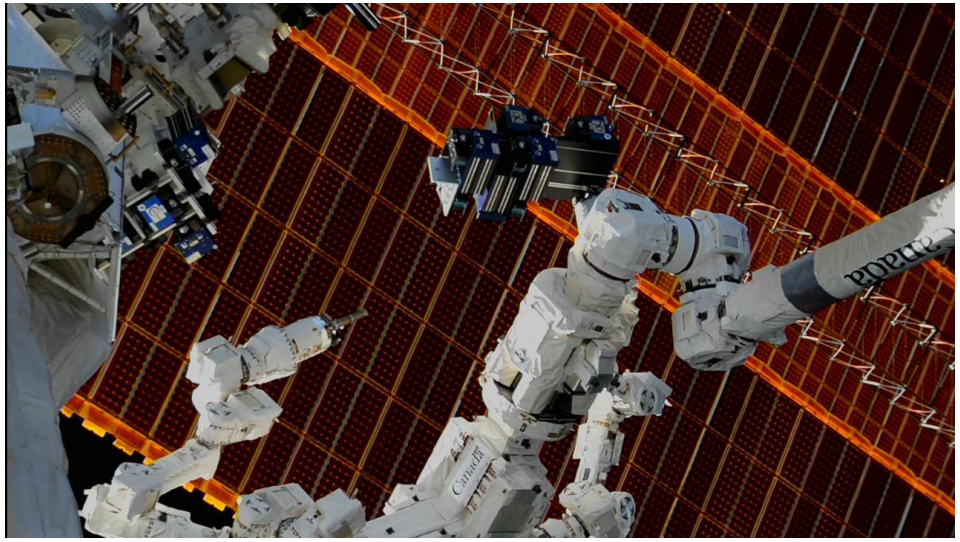
Wake MSC 12 getting installed on the MISSE-FF



Ram MSC getting installed on the MISSE-FF



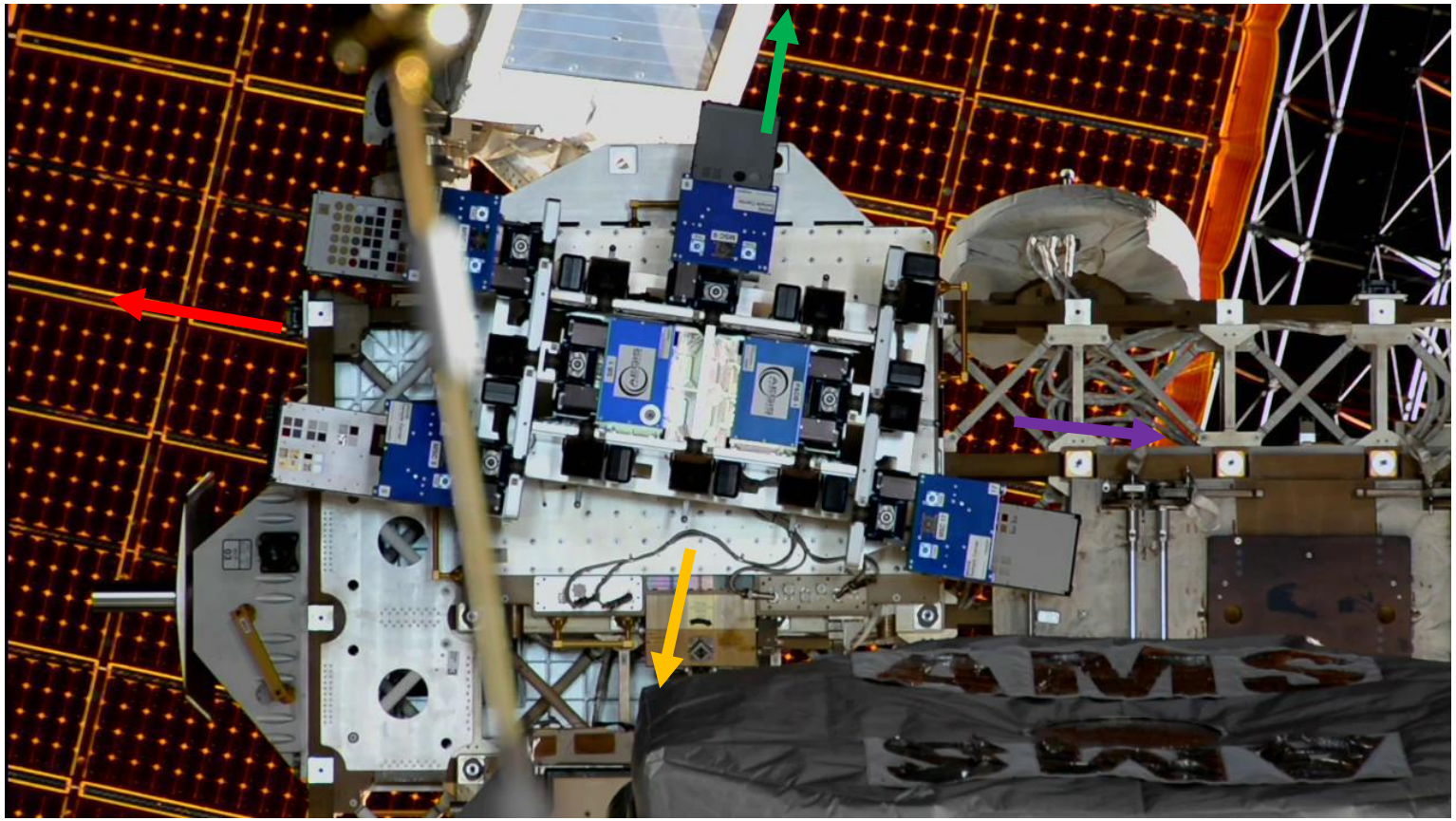
Zenith MSC 9 getting installed on the MISSE-FF



MSCs on the MTT and MISSE Flight Facility (the blue boxes, partially hidden)

MISSE-FF Test Process

- Turn on the MSCs and do a system check on the MSCs. Open the MSCs for flight test.

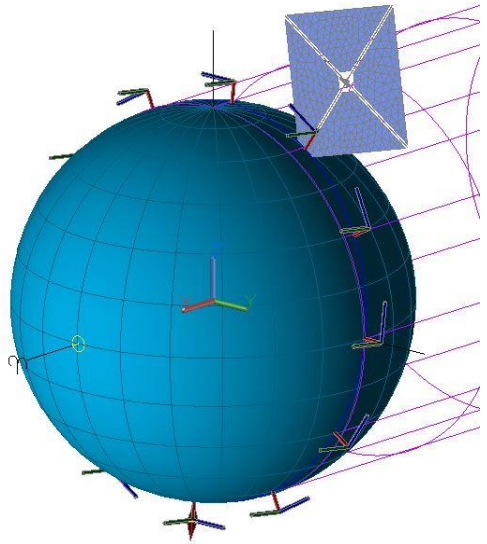


- **Ram** view unobstructed
- **Zenith** view unobstructed
- **Wake** view over ISS structure
- Nadir view into ISS structure

MISSE MSCs Opening

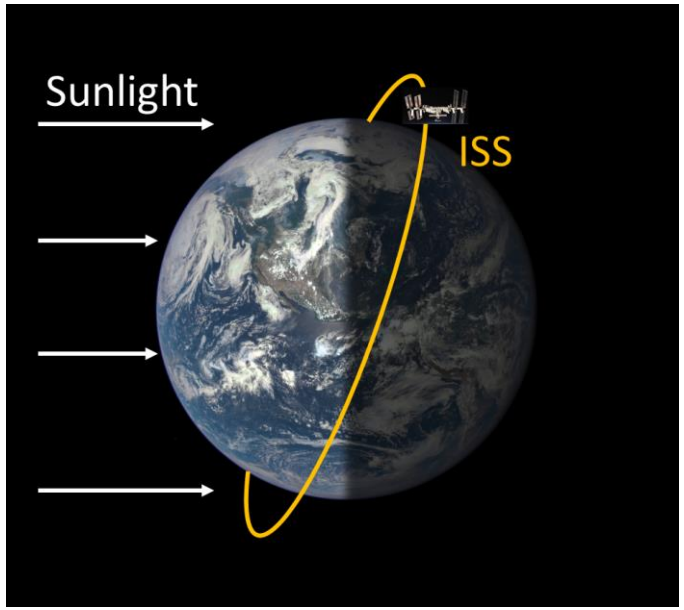
Orbit of the ACS3 and ISS

Advanced Composite Solar Sail System (ACS3)



Dawn-Dusk Sun-Synchronous Orbit: Reference 700 km, 98° inclination dawn-dusk sun-synchronous polar orbit for sail thermal equilibrium analyses. The sail surface normal is perpendicular to the orbit plane.

International Space Station (ISS)



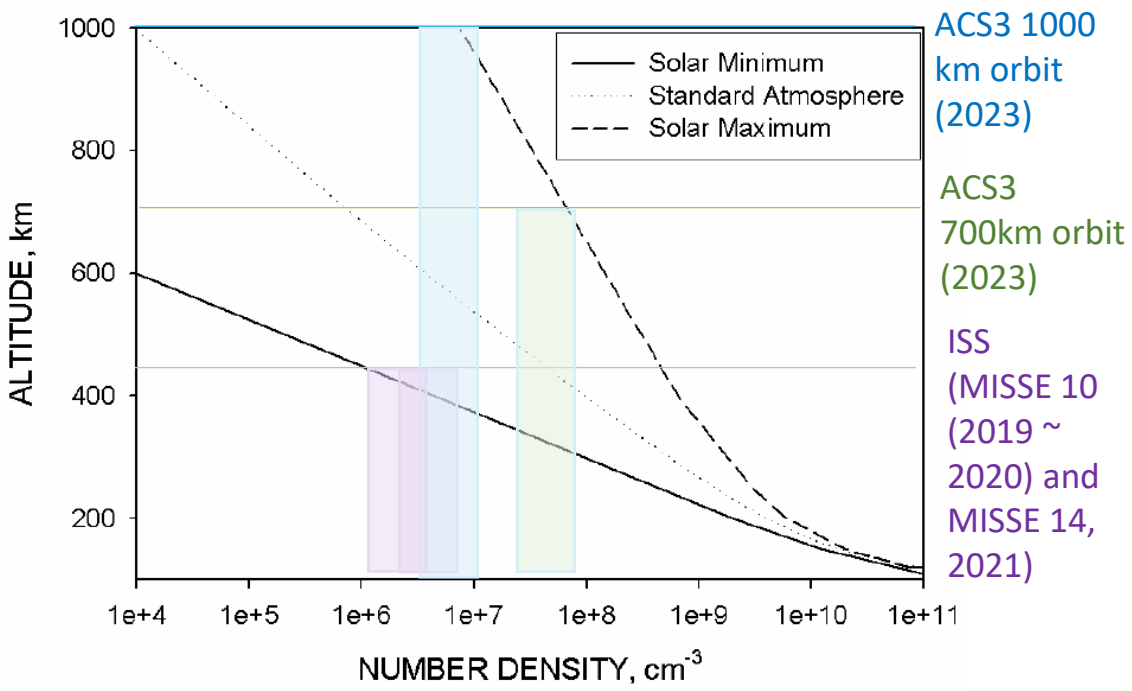
Perigee altitude	418 km (259.7 mi) above mean sea level (AMSL)
Apogee altitude	422 km (262.2 mi) AMSL
Orbital inclination	51.64°
Orbital speed	7.66 km/s (27,600 km/h; 17,100 mph)
Orbital period	92.68 minutes
Orbits per day	15.49

MISSE for Solar Sail Materials Test

MISSE 10 and 14

MISSE-FF Experiment	Flight Direction	MISSE Sample Carrier (MSC)	Launch Mission	Installed on MISSE-FF	Retrieved from MISSE-FF	Return Mission	Time on MISSE-FF (Years)	Direct Space Exposure Duration (Years)	Atomic Oxygen (AO) Fluence (atoms/cm^2)	Mission Equivalent Sun Hours (ESH)	Radiation (rads)
MISSE-10	Ram	R1 (MSC 11) MS	NG-10 November 17, 2018	Jan. 4, 2019	November 25, 2020	SpaceX-21 January 13, 2021	1.90	1.17	3.93E+20	1445.4	-
	Zenith	Z2 (MSC 10) MS			March 18, 2020	SpaceX-20 April 7, 2020	1.20	0.69	5.75E+18	702.0	-
MISSE 14	Ram	R2 (MSC 3)	NG-15 February 20, 2022	Apr. 21, 2022	December 26, 2022	SpaceX-24 January 23, 2022	0.68	0.36	2.54E+20	-	-
	Zenith	Z2 (MSC 9)						0.41	3.07E+19	-	11.995
	Wake	W1 (MSC 12)						0.36	3.96E+19	-	-
MISSE 20?				Future							

Space Environment of ISS: *Atomic Oxygen (AO)*



ACS3 1000 km orbit (2023)

ACS3 700km orbit (2023)

ISS (MISSE 10 (2019 ~ 2020) and MISSE 14, 2021)

Fig. Atomic oxygen flux versus altitude for solar minimum, nominal (standard atmosphere), and solar maximum conditions

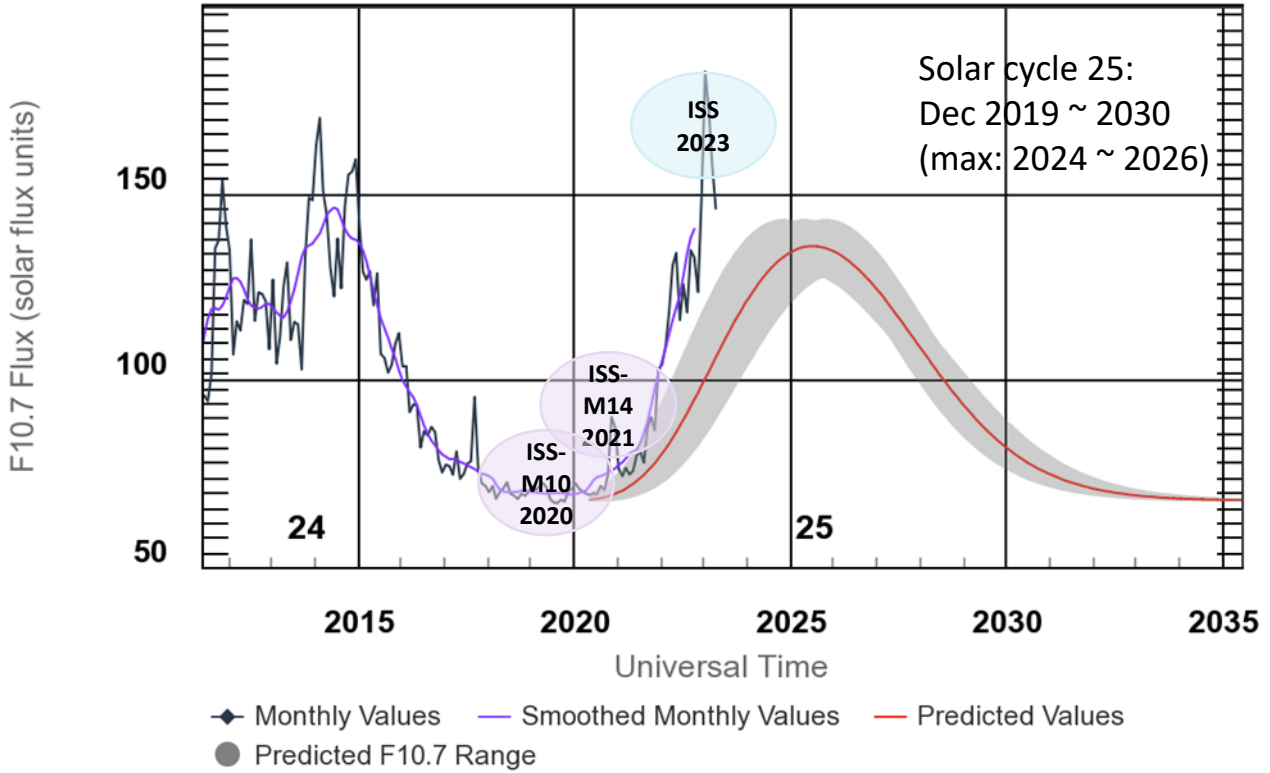


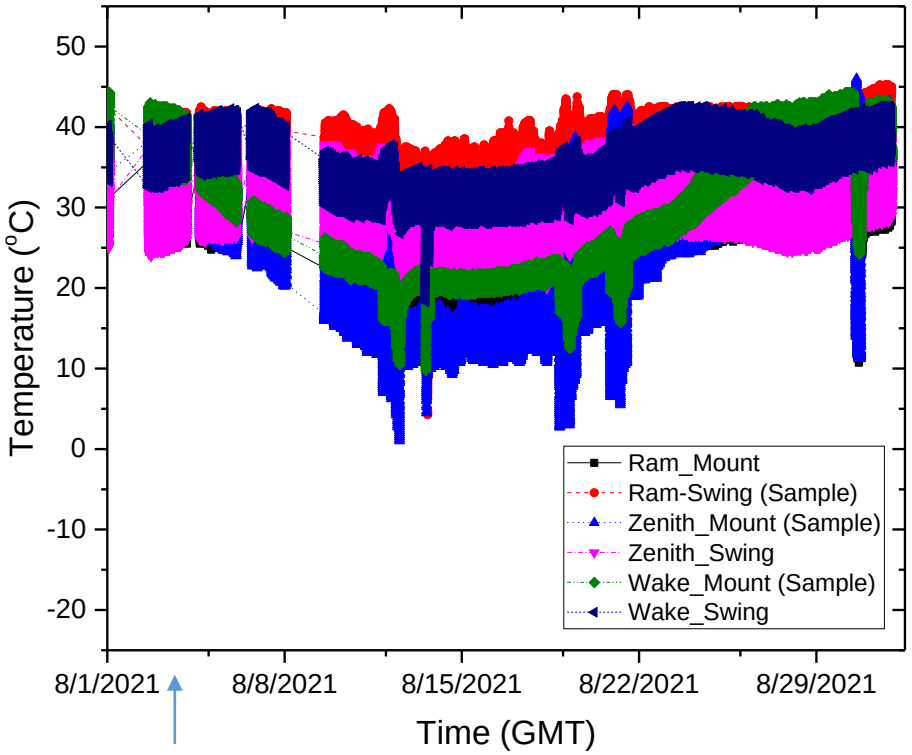
Fig. F10.7 Flux vs solar cycles

AO flux at 1000km in 2023 might be similar to that at 400km in 2021 (MISSE 14).
Estimated AO flux at~1000 km is 8.5E19 ~ 7.9E20 atoms/cm^2 yr, or 1.4E19 ~ 1.3E20 atoms/cm^2 2months
Estimated AO flux at ~715 km is 8.5E20 ~ 7.9E21 atoms/cm^2 yr, or 1.4E20 ~ 1.3E21 atoms/cm^2 2months
** AO flux for MISSE14 (400 km, 2021) was 1.3E19 (Zenith), 1.8E19 (Wake) ~ 1.2E20 (Ram) atoms/cm^2 2month*

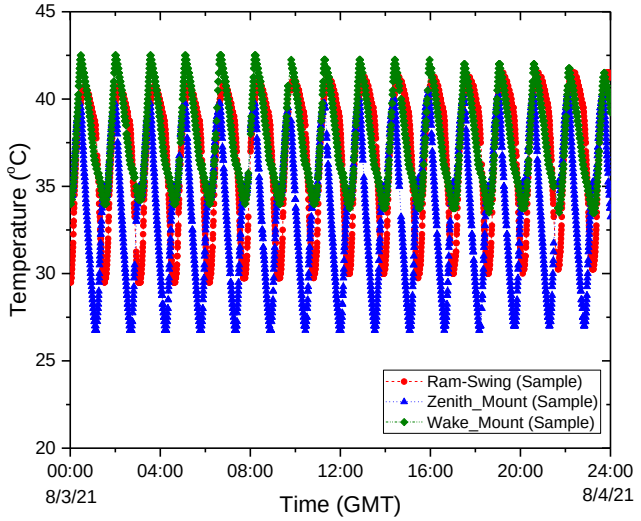
Ref. B.A. Banks, NASA/TM – 2004-213223; Solar Cycle Progression | NOAA / NWS Space Weather Prediction Center

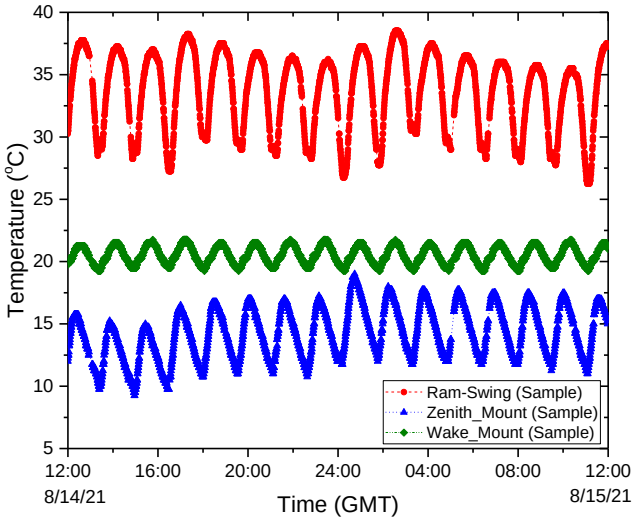
Space Environment of ISS: *Temperature (August 2021)*

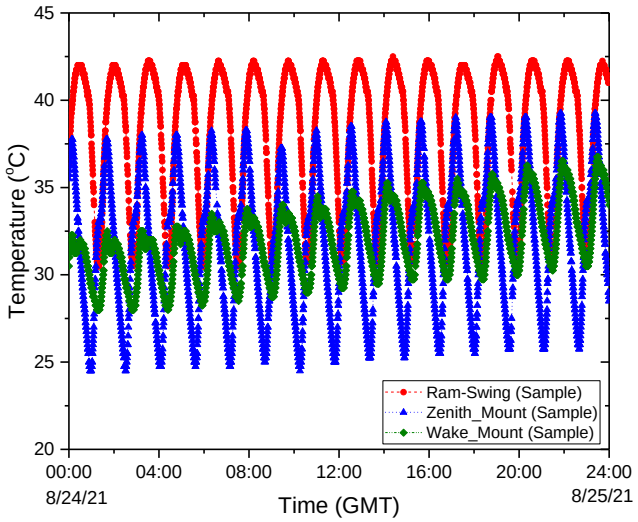
MISSE 14

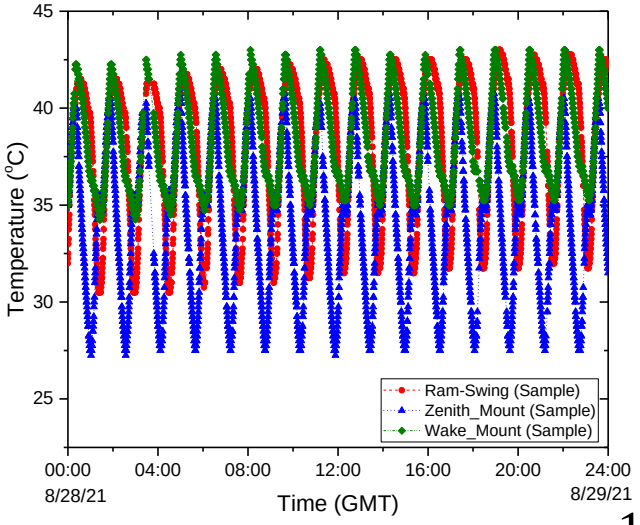


2nd Photo (Ram, Zenith, Wake, August 3, 2021)





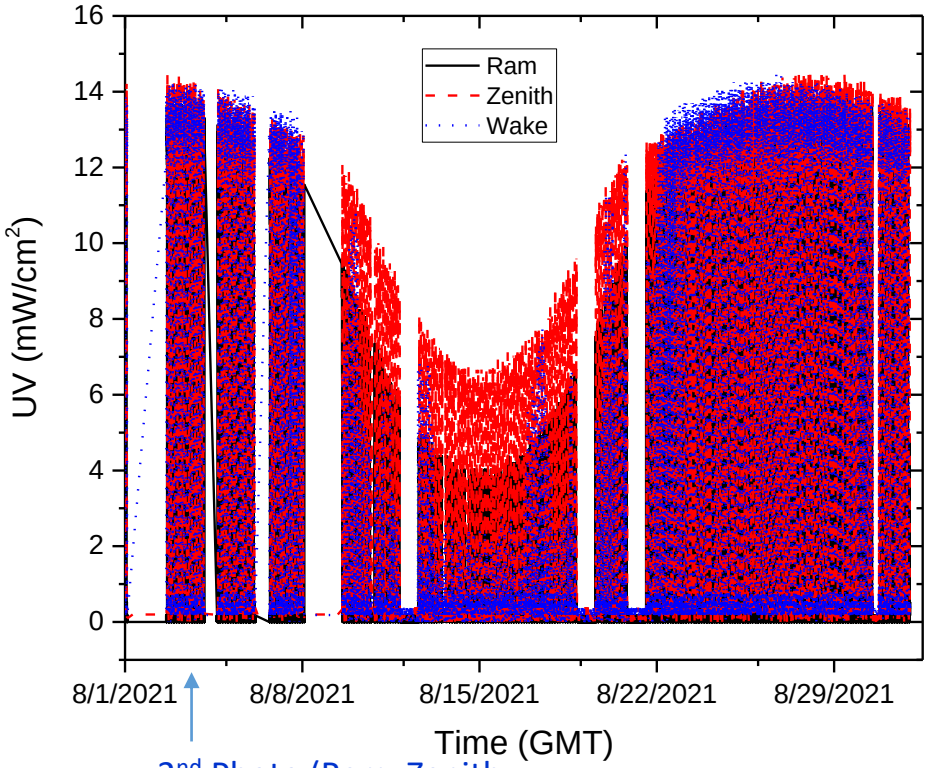




The temperature of MSC varied from about -17°C to 54°C during test

Space Environment of ISS: *UV (August 2021)*

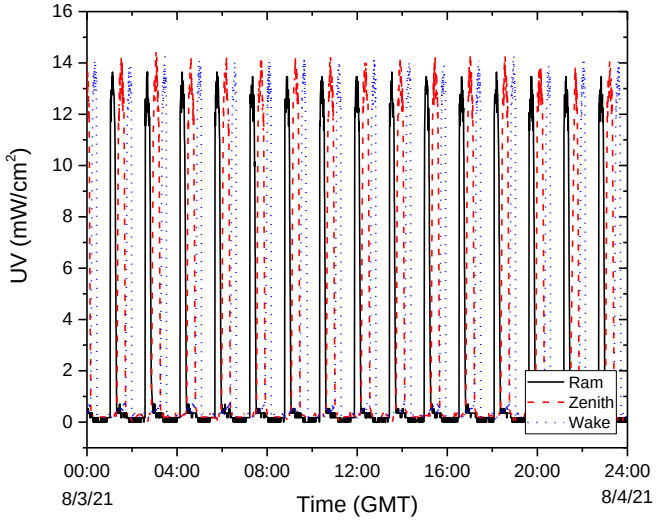
MISSE 14

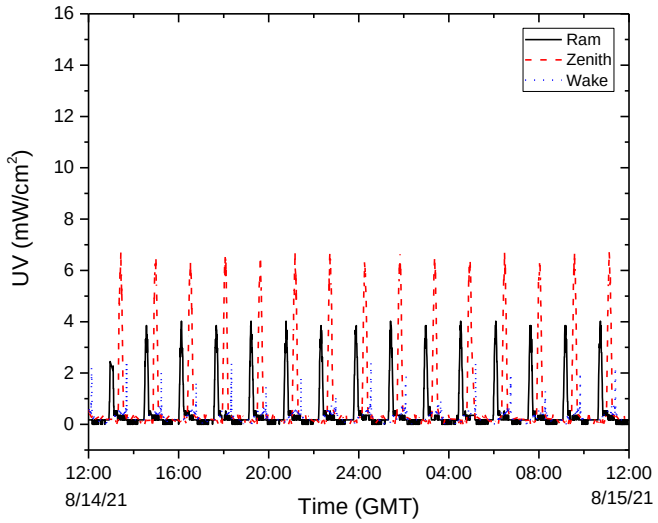


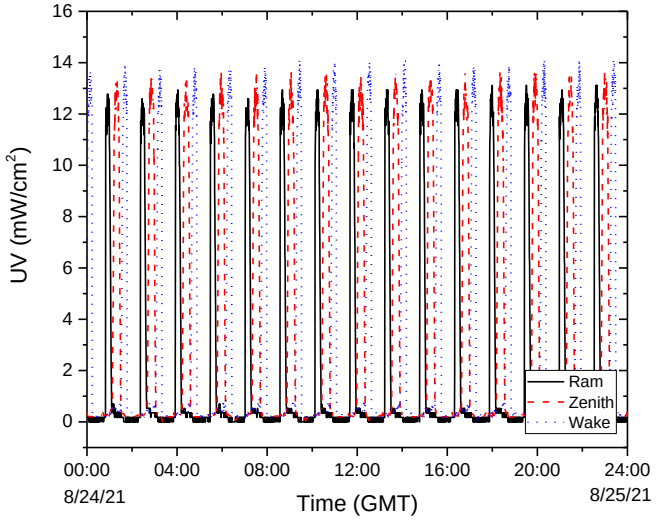
2nd Photo (Ram, Zenith, Wake, August 3, 2021)

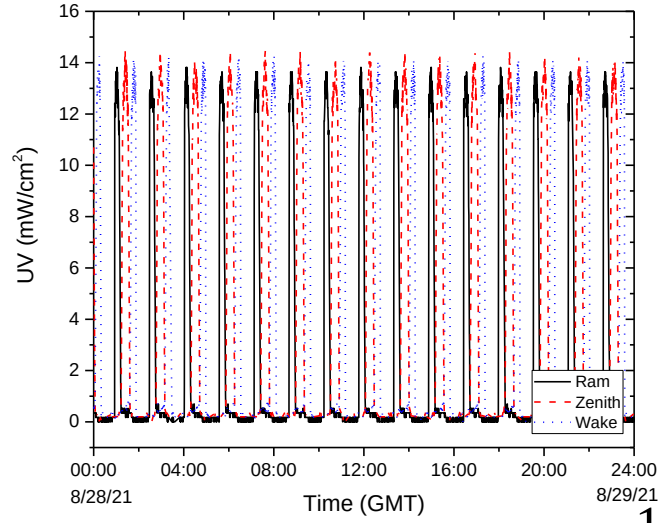
UV dosage in August :

Ram: 3.52 kJ/cm^2
Zenith: 4.95 kJ/cm^2
Wake: 3.24 kJ/cm^2









List of Materials

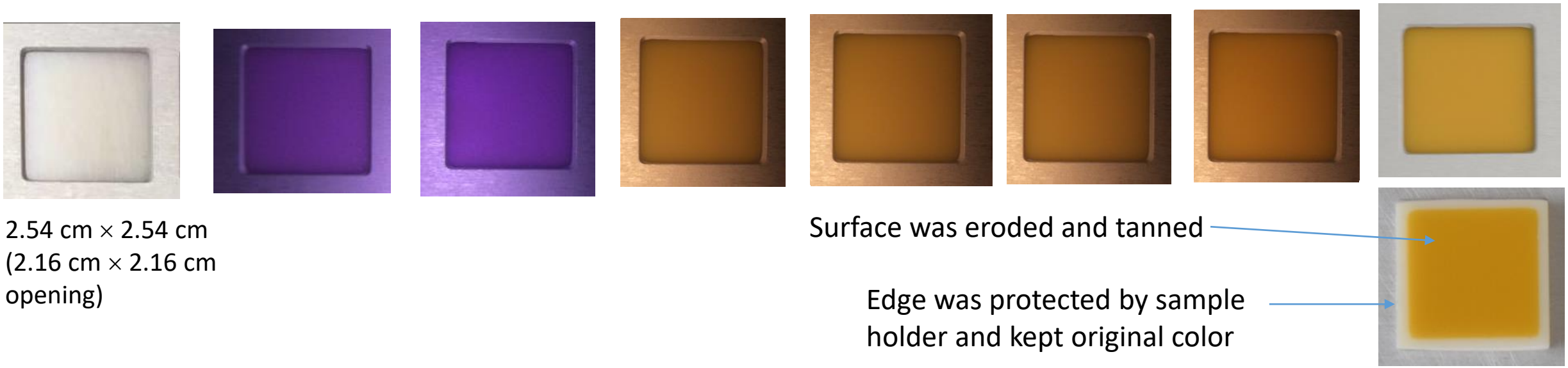
Material Abbreviation	*Materials	Specification	MISSE Mission	MISSE Sample ID	Flight Direction	Number of Layers
Kapton H	Kapton® H Polyimide	-	MISSE 10	M10R-C1~C3	Ram	2 each
			MISSE 14	M14-BK-R1	Ram	5
				M14-BK-Z1	Zenith	5
PMT F7	PMT F7 (novolac epoxy, Patz Materials and Technology)	-	MISSE 14	M14-BK-R2	Ram	1
				M14-BK-Z2	Zenith	1
EA 9696	Hysol® EA 9696 film adhesive	-	MISSE 14	M14-BK-W2	Wake	2
PEN	Polyethylene Naphthalate (PEN, Biaxially oriented, Teonex®)	-	MISSE 10	M10R-C11	Ram	2
Al-Met PEN	Metalized film (Aluminum 100nm / PEN 2µm / Chromium 15nm), Aluminum Side Exposure	-	MISSE 10	M10R-C12	Ram	2
				M10Z-C9	Zenith	2
			MISSE 14	M14-BK-R7	Ram	2
				M14-BK-Z3	Zenith	2
				M14-BK-W3	Wake	2
Seamed Met PEN	Seamed Met PEN. Chromium side up strip laminated on the seamed area	-	MISSE 14	M14-BK-R9	Ram	2
				M14-BK-Z5	Zenith	2
				M14-BK-W5	Wake	2
Epoxy PMT F7/M30S-1	Epoxy PMT F7 epoxy / carbon fiber fabric (plain weave, Toray M30S) composite	ACS3-like laminate [45PW_2 /0-90PW_2]	MISSE 14	M14-BK-R10	Ram	2
				M14-BK-Z7	Zenith	2
				M14-BK-W6	Wake	2
Epoxy PMT F7/M30S-3	Epoxy PMT F7 epoxy / carbon fiber fabric (plain weave, Toray M30S) composite	[45PW_4]	MISSE 14	M14-BK-R12	Ram	2
				M14-BK-Z9	Zenith	2
				M14-BK-W9	Wake	2

This is not an endorsement by the National Aeronautics and Space Administration (NASA)

Pre-, In- and Post-Flight Sample Images

In-Flight Image [Epoxy PMT F7 (M14-BK-R2), Ram]

MISSE 14



Significant color change (yellowing) was found after total 133 days exposure in Ram direction.

In-Flight Image [Epoxy PMT F7/M30S-1 (M14-BK-R10), Ram]

MISSE 14

ACS3-like laminate (LAM3) - [45PW$_2$ /0-90PW$_2$]

Before Flight

2.54 cm × 5.08 cm
(2.16 cm × 4.70 cm opening)

Total 5 days exposure (7/19/2021)

Total 8 days exposure (8/3/2021)

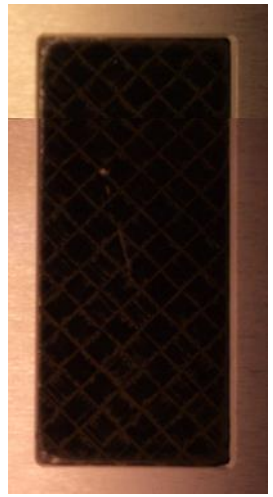
MMOD impact?

Total 57 days exposure (9/23/2021)

Total 58 days exposure (10/1/2021)

Total 84 days exposure (11/1/2021)

Total 111 days exposure (12/1/2021)



Post Flight (133 days exposure)

Surface started to change from shiny to dull

Significant erosion on the sample surface was found after total 133 days exposure in Ram direction. Micrometeoroids and orbital debris (MMOD) suspected impact damage was found.

Post-Flight Image [Epoxy PMT F7/M30S-1 (M14-BK-R10), Ram]

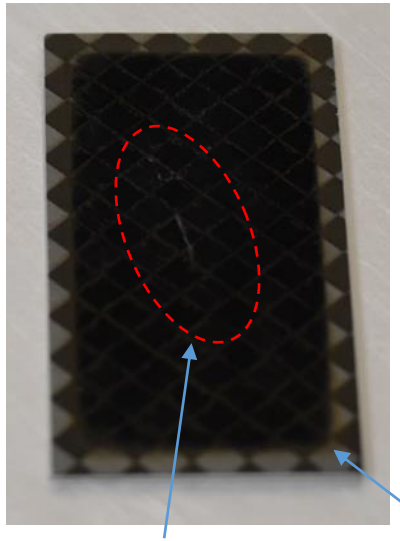
MISSE 14

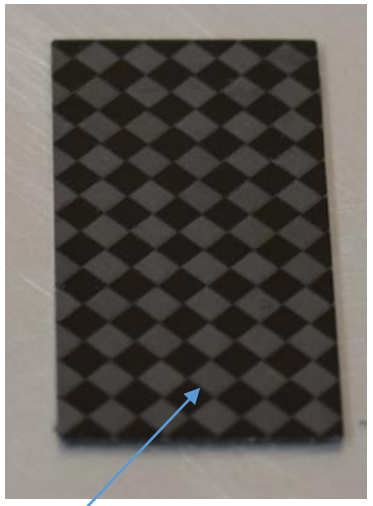
ACS3-like laminate (LAM3) - [45PW_2 /0-90PW_2]

Post Flight (133 days exposure)

1st Layer

2nd Layer

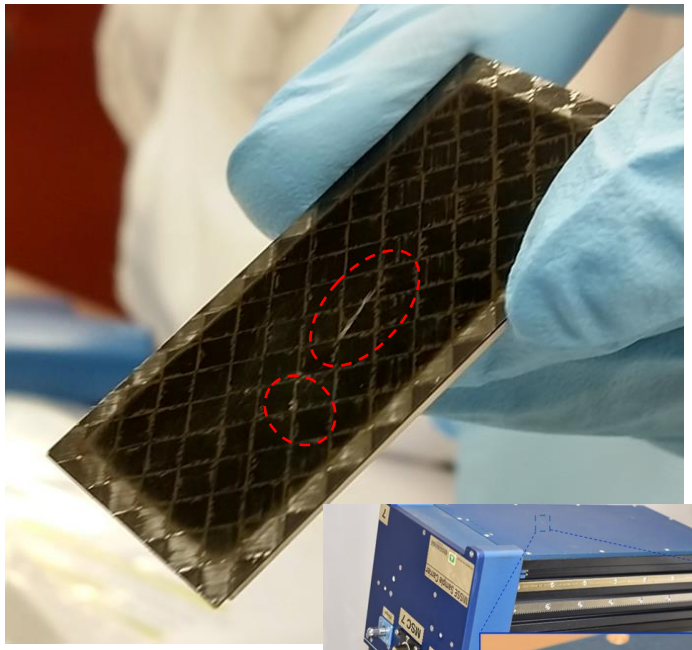


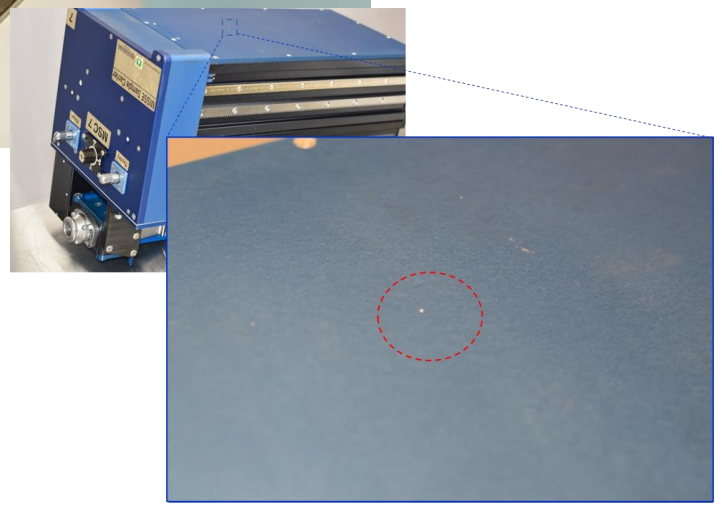


2.54 cm × 5.08 cm

Exposed surface was eroded and became matte

Edge and 2nd layer kept shiny surface





Significant erosion on the sample surface was found after total 133 days exposure in Ram direction. MMOD suspected impact damage was found.

In-Flight Image [Al-Met PEN (M14-BK-R7), Ram]

MISSE 14

Al (100nm)/PEN (2μm)/Cr (15nm)

5.08 cm × 5.08 cm
(4.70 dm × 4.70 cm opening)

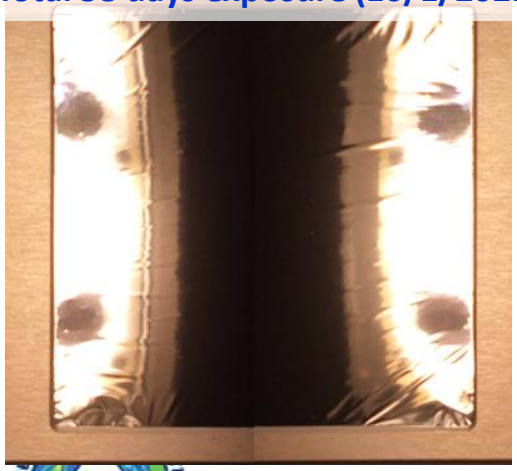
Total 5 days exposure (7/19/2021)

No image

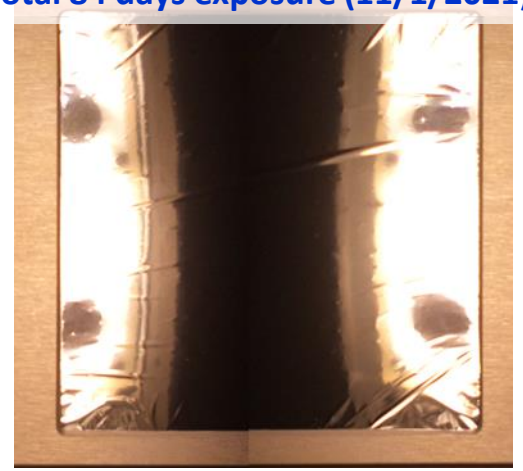
Total 8 days exposure (8/3/2021)

Total 57 days exposure (9/23/2021)

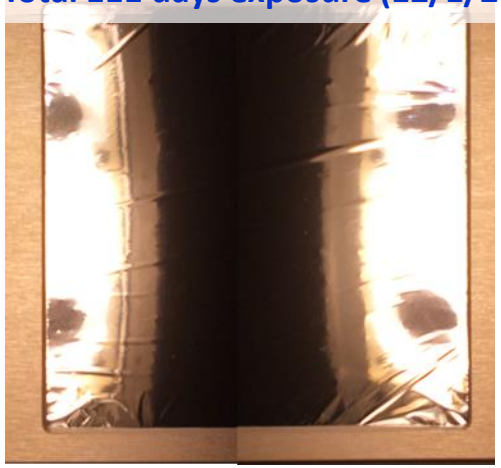
Total 58 days exposure (10/1/2021)



Total 84 days exposure (11/1/2021)



Total 111 days exposure (12/1/2021)



Post Flight (133 days exposure)

No significant change except some wrinkles was found after total 133 days exposure in Ram direction. Sample was shrunk and taut

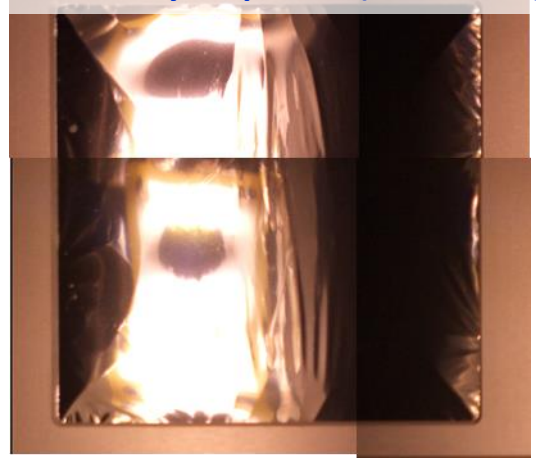
In-Flight Image [Al-Met PEN (M14-BK-Z3), Zenith)

MISSE 14

Total 15 days exposure (7/16/2021)

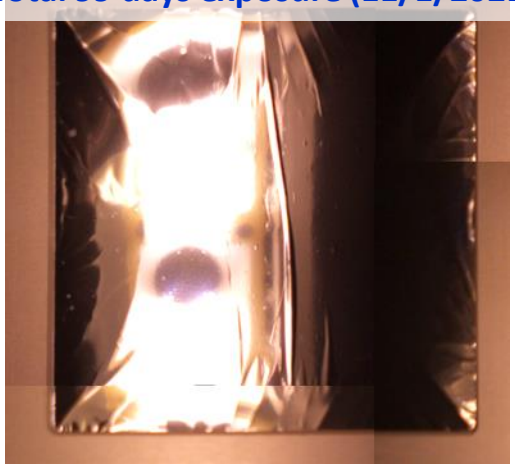
Total 19 days exposure (8/3/2021)

Total 57 days exposure (9/13/2021)



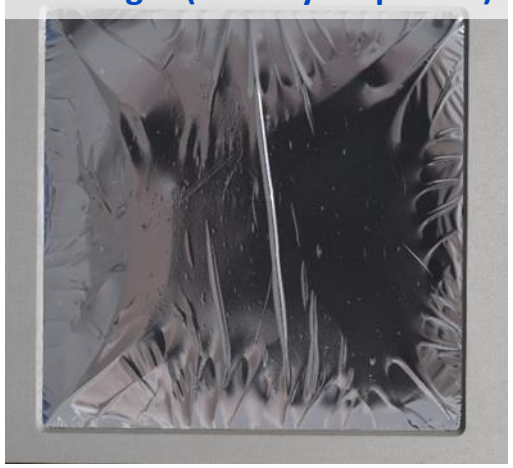
Total 73 days exposure (10/1/2021)

Total 99 days exposure (11/1/2021)



Total 126 days exposure (12/1/2021)

Post Flight (149 days exposure)



Significant change in wrinkle was found after total 15 days exposure in Zenith direction. Sample was shrunk and taut.

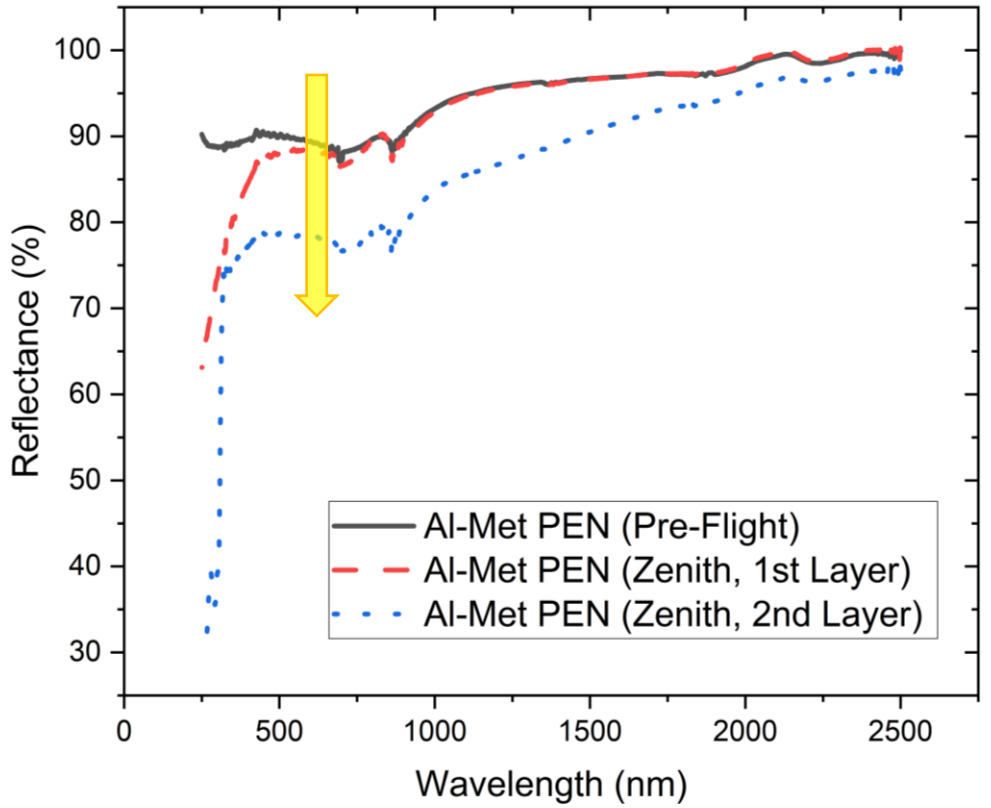
Post-Flight Image [Al-Met PEN (M14-BK-Z3), Zenith)

Post Flight (149 days exposure)

5.08 cm × 5.08 cm
(4.70 cm × 4.70 cm opening)

1st Layer

2nd Layer



Hydrogen blistering by solar particles (proton radiation)?

No visible change on the first layer (direct exposure to space) but visible foggy (diffuse reflective) mark on the second layer and reduction in reflectance was found

In-Flight Image [Seamed Met PEN (M14-BK-Z5), Zenith)

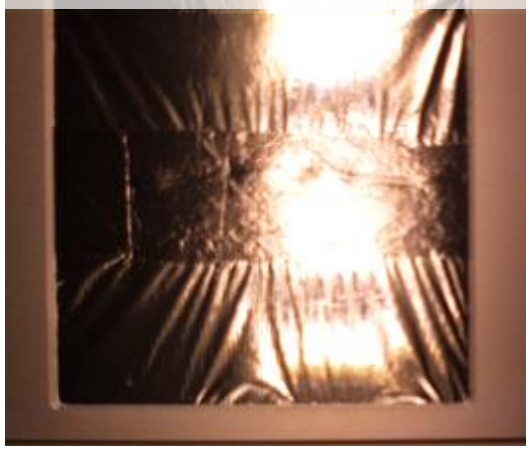
MISSE 14

Before Flight

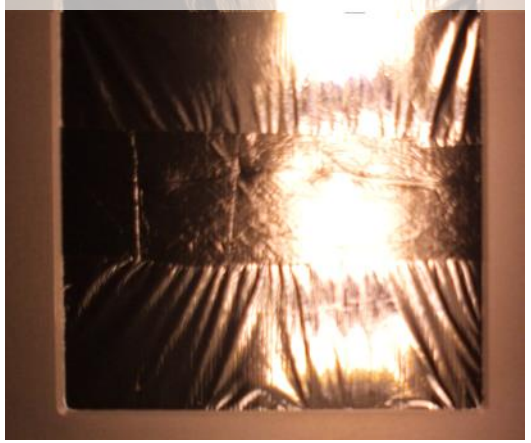
5.08 cm × 5.08 cm
(4.70 cm × 4.70 cm opening)

Total 15 days exposure (7/16/2021)

Total 19 days exposure (8/3/2021)



Total 57 days exposure (9/13/2021)



Total 73 days exposure (10/1/2021)

Total 99 days exposure (11/1/2021)

Total 126 days exposure (12/1/2021)

Post Flight (149 days exposure)

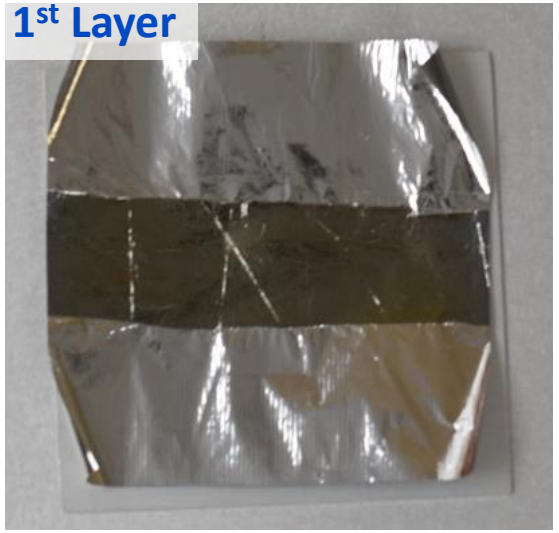
Significant change in wrinkle was found after total 15 days exposure in Zenith direction. Sample was shrunk and taut, but no visible delamination/bubbles on the seamed joint was found.

Post-Flight Image [Seamed Met PEN (M14-BK-Z5), Zenith)

Post Flight (149 days exposure)

5.08 cm × 5.08 cm

1st Layer



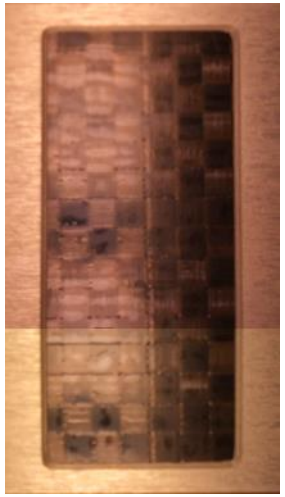
2nd Layer

No visible change in reflectiveness on the first layer (direct exposure to space) but some foggy (diffuse reflective) mark on the second layer was found.

In-Flight Image [Epoxy PMT F7/M30S-4 (M14-BK-Z10), Zenith)

MISSE 14

[45PW$_4$]

Before Flight	Total 15 days exposure (7/16/2021)	Total 19 days exposure (8/3/2021)	Total 57 days exposure (9/13/2021)	Total 73 days exposure (10/1/2021)	Total 99 days exposure (11/1/2021)	Total 126 days exposure (12/1/2021)	Post Flight (149 days exposure)
							

2.54 cm × 5.08 cm
(2.16 cm × 4.70 cm opening)

No significant change was found after total 149 days exposure in Zenith direction.

AO Erosion Rate (Ey) of Sail Membrane

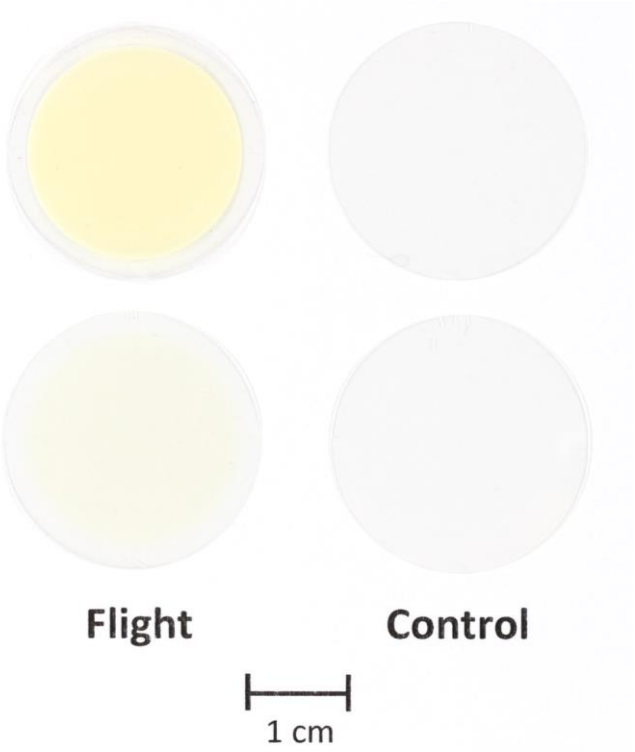
MISSE 10, Ram (1.90 year on orbit, 1.17 year of direct space exposure)

MISSE 10, Zenith (1.20 year on orbit, 0.69 year of direct space exposure)

Pristine PEN (M10R-C11)

Top (space exposed) Layer

Second Layer

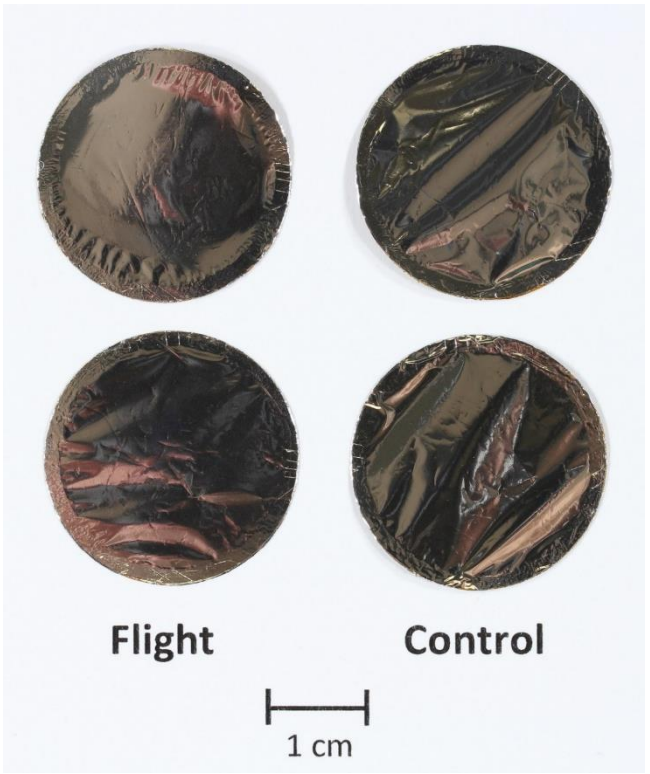


AO Ey ~ 3.30E-24 cm^3/atom

Al-Met PEN (M10R-C12)

AO Ey ~ -1.64E-27 cm^3/atom
(Mass loss within error)

Al-Met PEN (M10Z-C9)



AO Ey ~ 9.73E-25 cm^3/atom

Thermal Optical Properties of Sail System Materials

MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

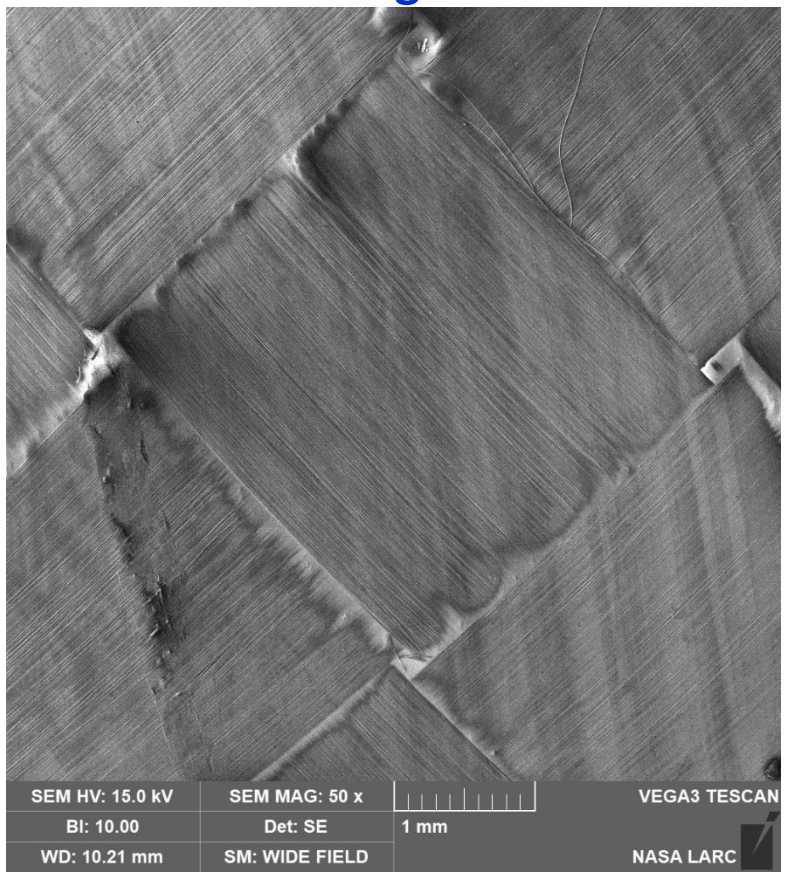
Material	Direction	Thermal Emissivity (ε_T)				
		Pre-flight	Post-Flight, 1st layer	$\Delta\varepsilon_T$ for 1st layer	Post-Flight, 2nd layer	$\Delta\varepsilon_T$ for 2nd layer
Kapton H	Ram	0.711	0.587	-0.124	0.617	-0.094
	Zenith	0.711	0.625	-0.086	0.627	-0.085
PMT F7	Ram	0.888	0.937	0.049		
	Zenith	0.888	0.902	0.015		
Al-Met PEN	Ram	0.032	0.029	-0.003	0.038	0.006
	Zenith	0.032	0.044	0.013	0.044	0.0123
Seamed Met PEN	Ram	0.063	0.031	-0.033	0.053	-0.010
	Zenith	0.033	0.027	-0.007	0.038	0.004
Epoxy PMT F7/M30S-1	Ram	0.795	0.791	-0.004	0.797	0.003
	Zenith	0.795	0.799	0.004	0.856	0.061
Epoxy PMT F7/M30S-3	Ram	0.833	0.799	-0.034	0.834	0.001
	Zenith	0.833	0.860	0.027	0.795	-0.037

Surface Morphology of PMT F7-M30S-1

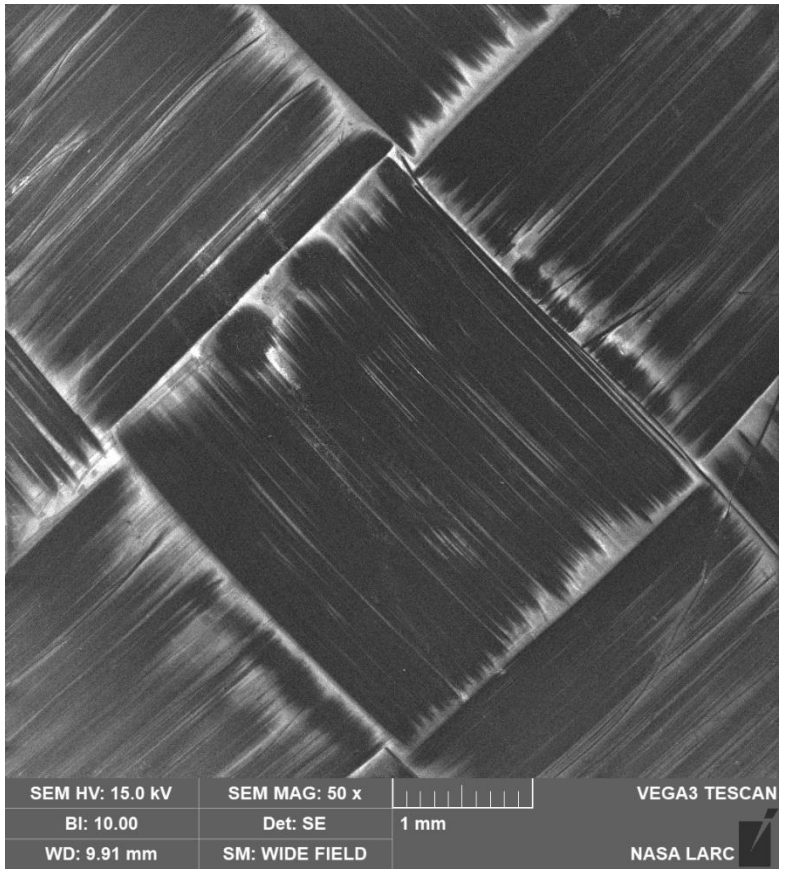
MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

Pre-Flight

Post-Flight: Ram



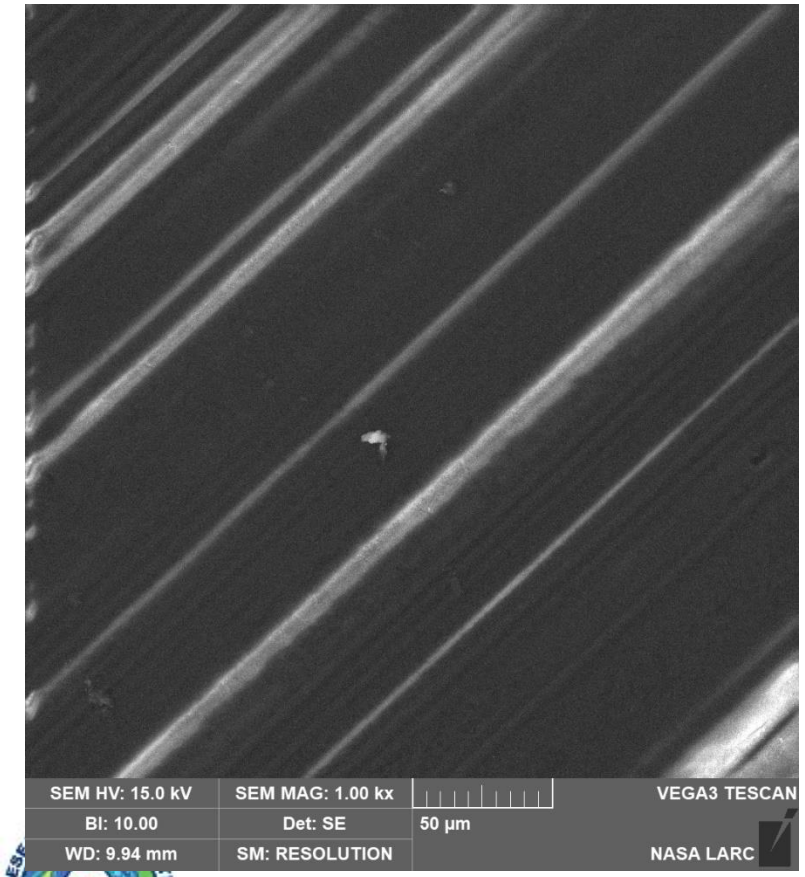
Post-Flight: Zenith



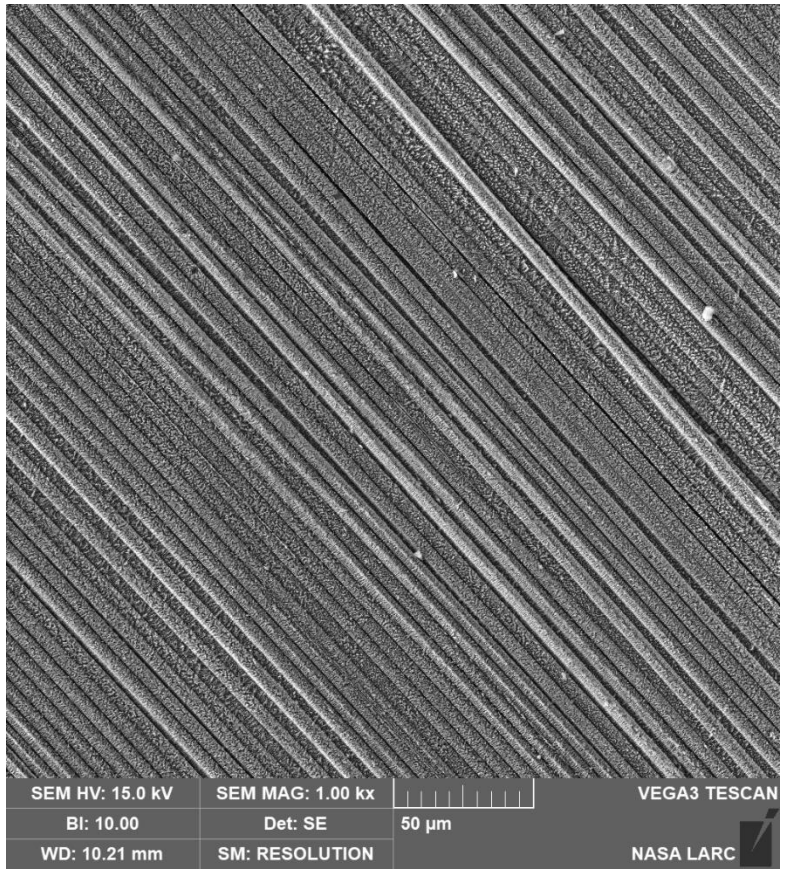
Surface Morphology of PMT F7-M30S-1

MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

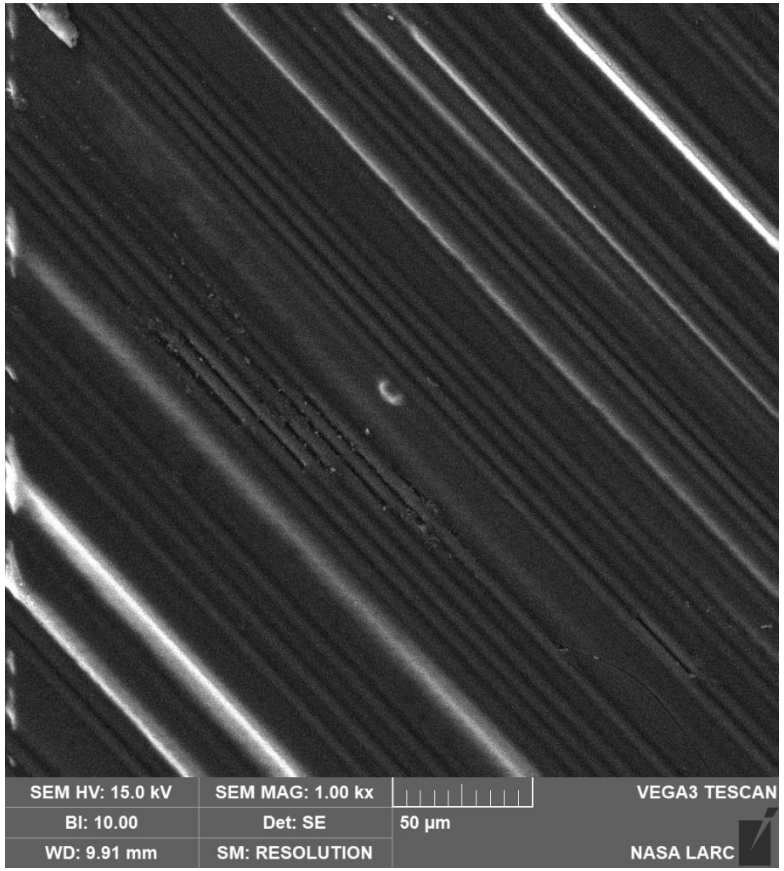
Pre-Flight



Post-Flight: Ram



Post-Flight: Zenith

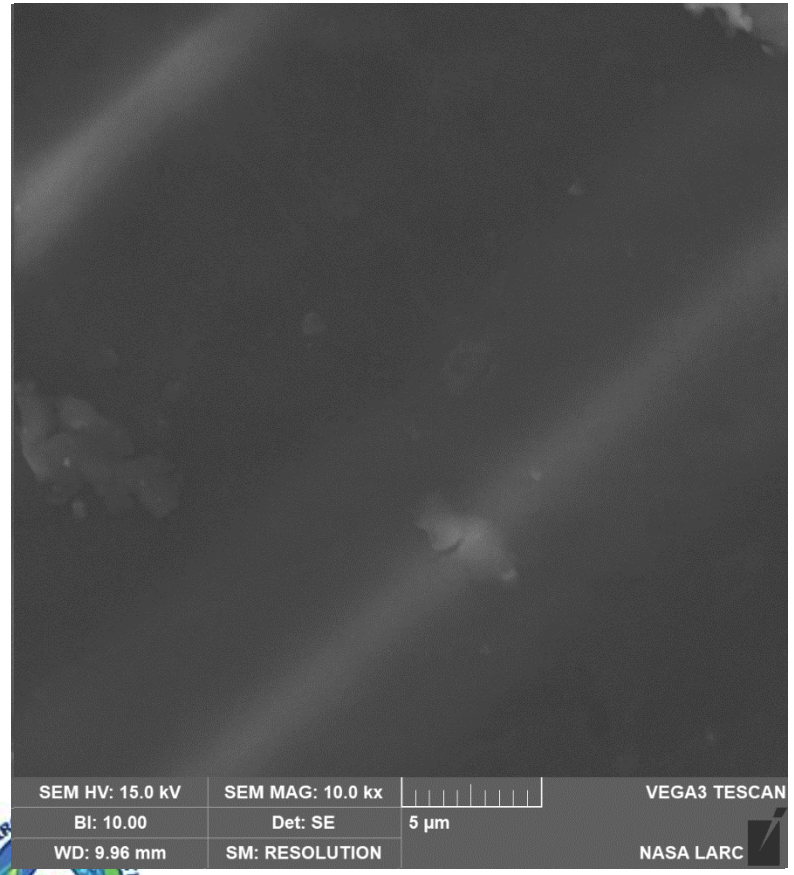


Dried carbon fiber (CF) morphology was found with Ram sample

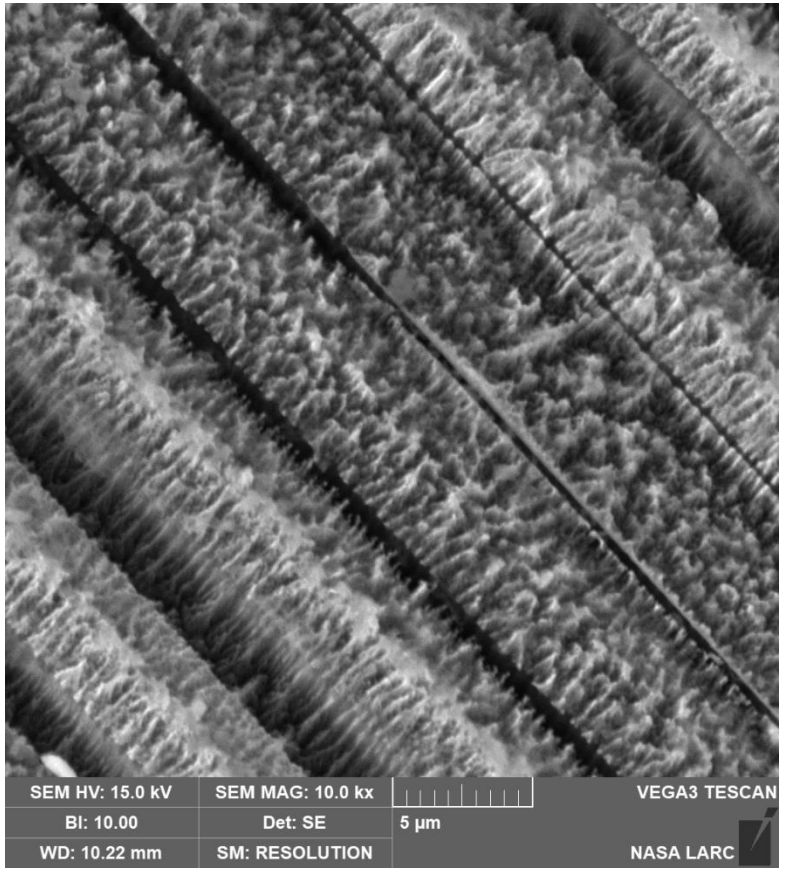
Surface Morphology of PMT F7-M30S-1

MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

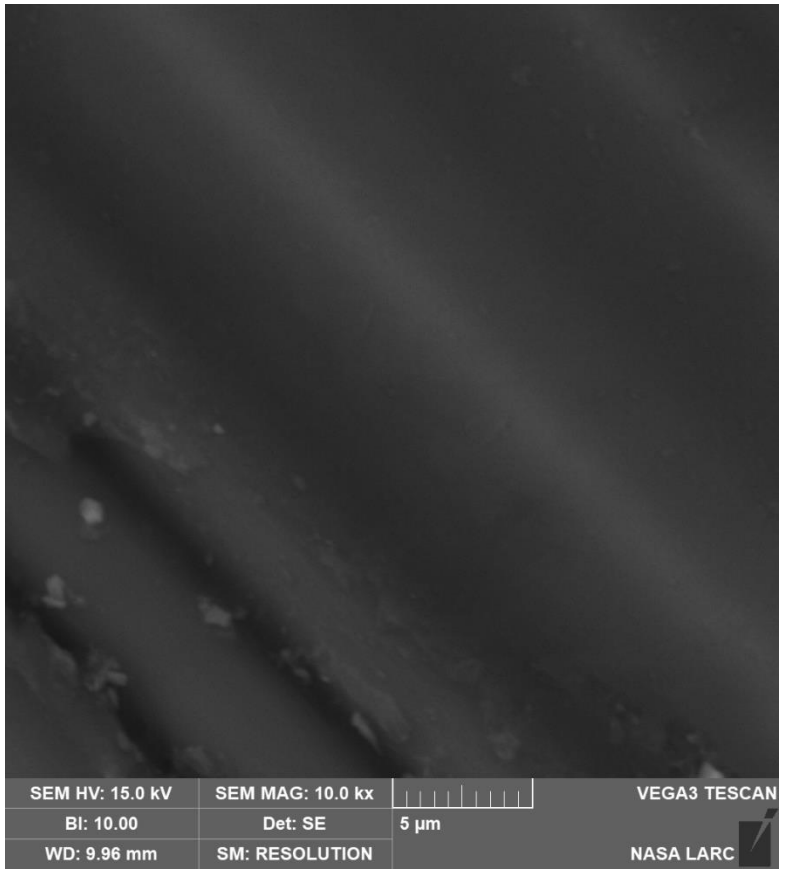
Pre-Flight



Post-Flight: Ram



Post-Flight: Zenith

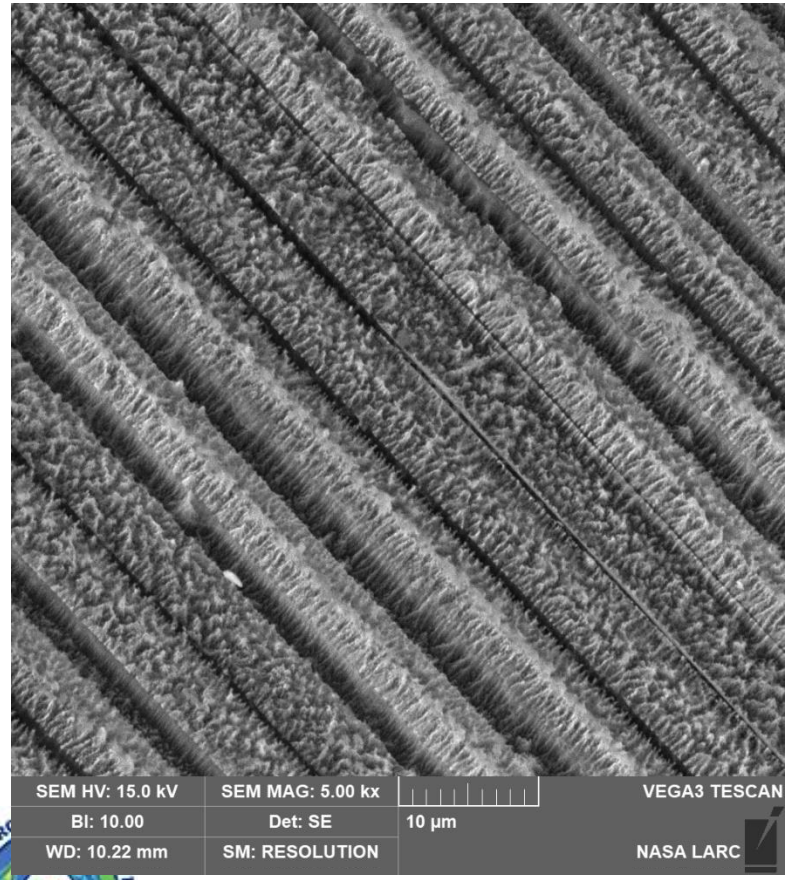


Severe erosion on CF surface was found with Ram sample

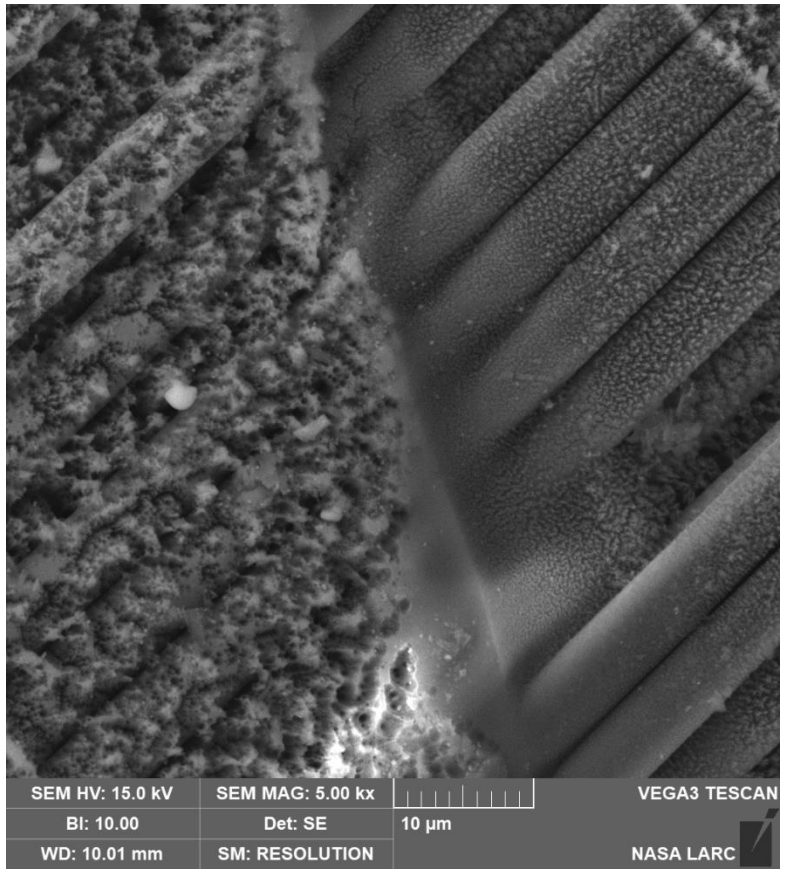
Surface Morphology of PMT F7-M30S-1

MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

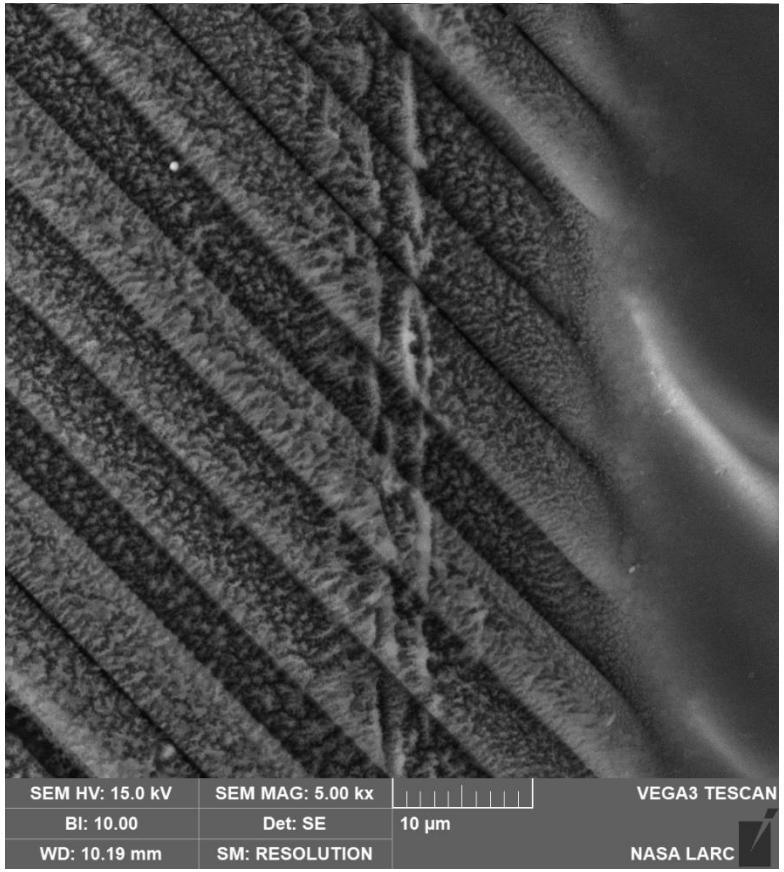
Post-Flight: Ram, Location 1



Post-Flight: Ram, Location 2



Post-Flight: Ram, Location 3

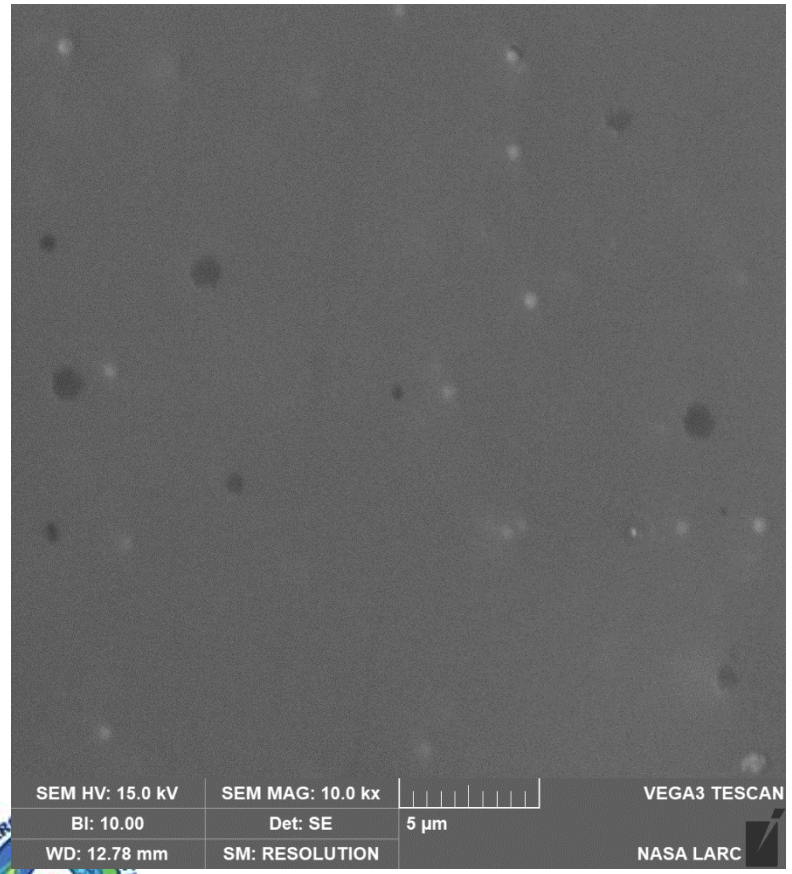


Severe erosion on CF surface was found with Ram sample

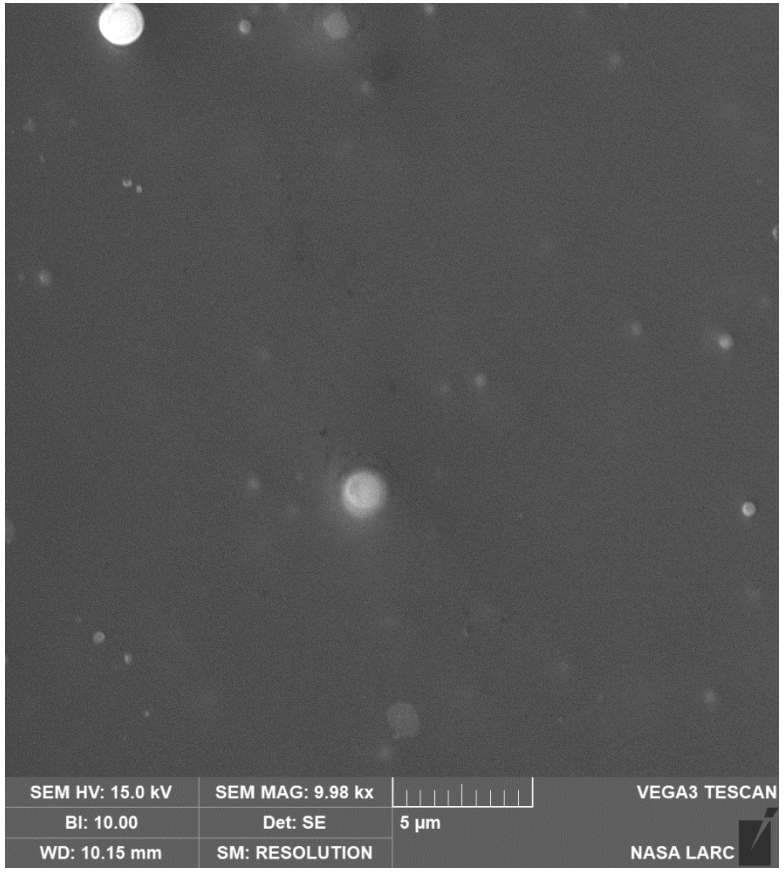
Surface Morphology of 1st Layer of Al-Met PEN

MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

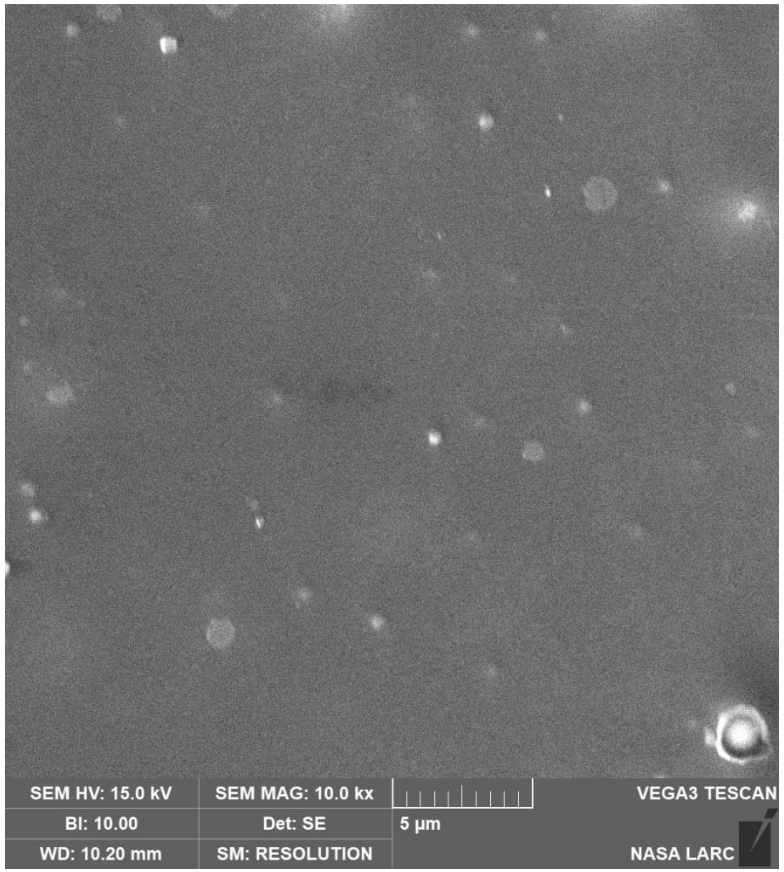
Pre-Flight



Post-Flight: Ram



Post-Flight: Zenith



No significant difference of 1st layer samples was found

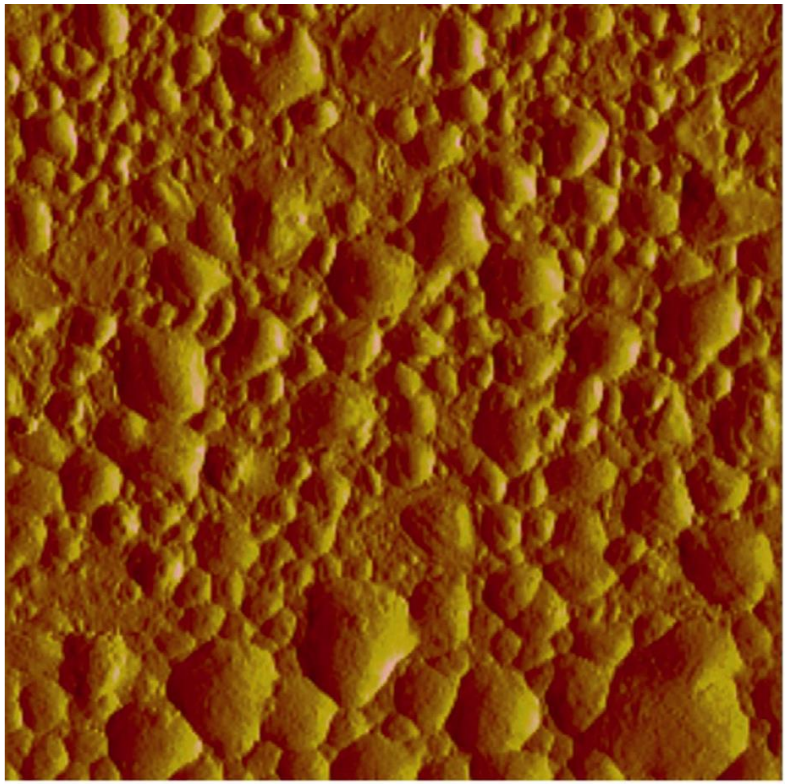
Surface Morphology of 2nd Layer of Al-Met PEN

MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

Post-Flight: Zenith

≈

Hydrogen Blistering on Aluminum layer of Metallized PEN film by proton radiation



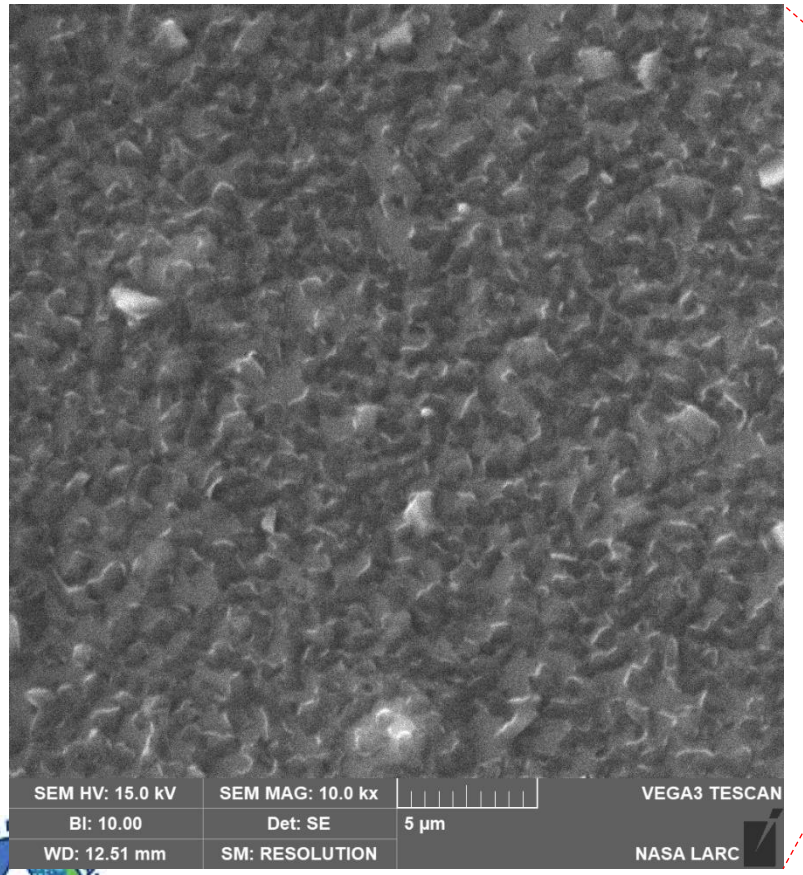
Foggy diffusive reflection of the 2nd layer of Met PEN on Zenith is similar to the hydrogen blistering by proton radiation (<2.5 keV)

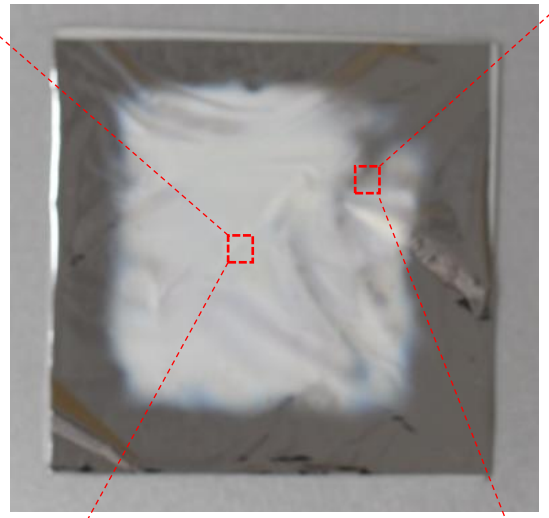
Ref. M. Sznjader, P. Seefeldt, T. Sprowitz, T., J. H. Kang, R. Bryant and W. Wilkie, "Solar sail propulsion limitations due to hydrogen blistering", Advances in Space Research, 67 (2021), 2655-2668.

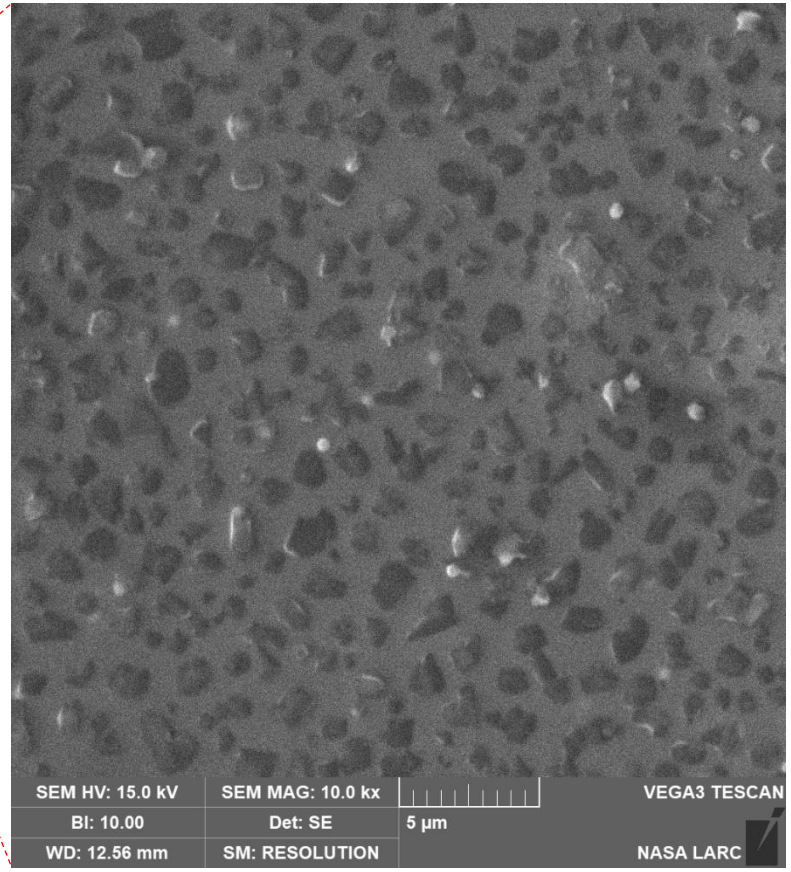
Surface Morphology of 2nd Layer of Al-Met PEN

MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

Post-Flight: Zenith





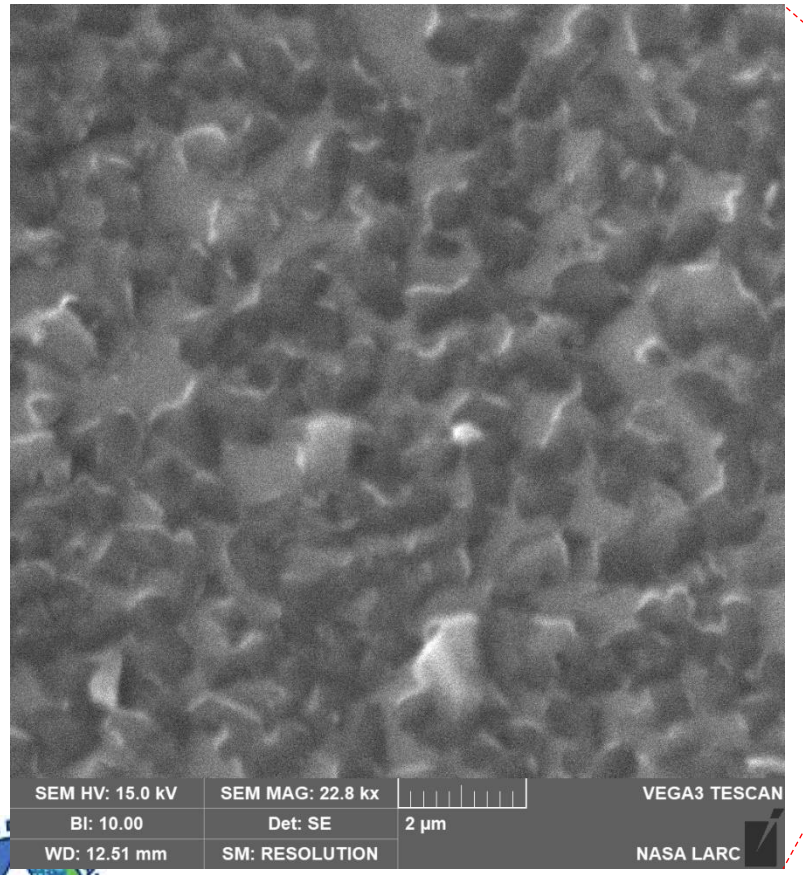


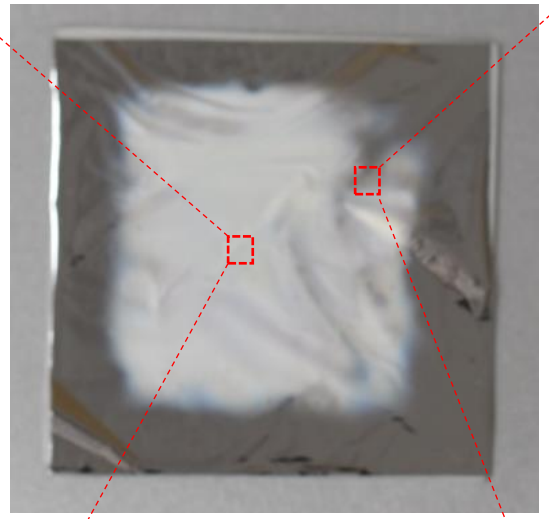
Hydrogen Blistering like morphology was found in the 2nd layer

Surface Morphology of 2nd Layer of Al-Met PEN

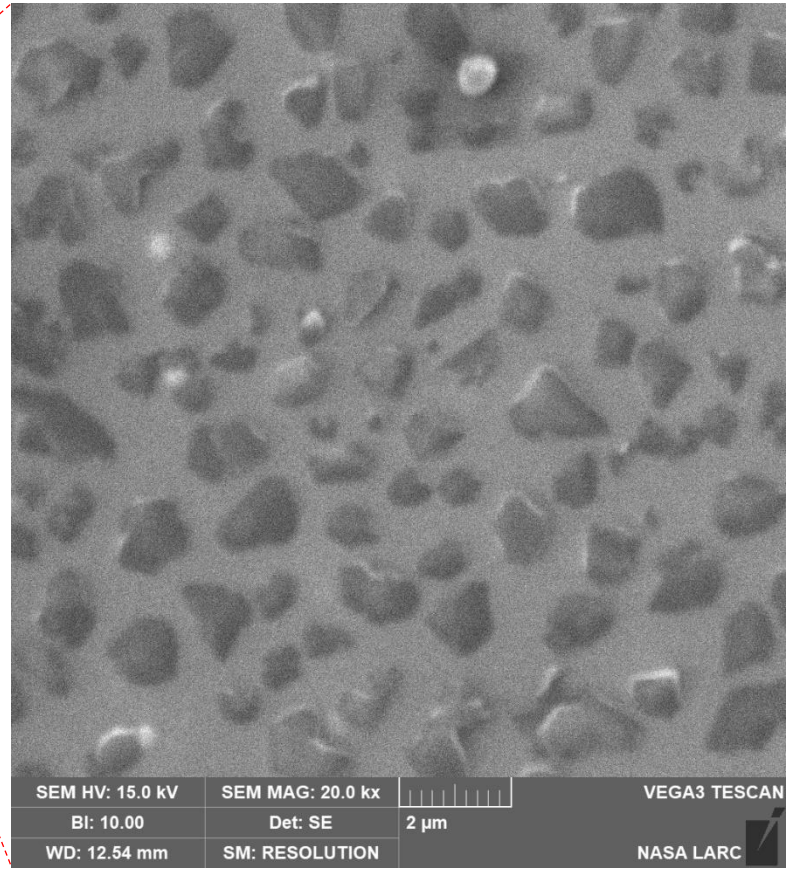
MISSE 14 (0.68 year on MISSE-FF, about 0.4 year of direct space exposure)

Post-Flight: Zenith





1st Layer (space exposed)
PET (12.7µm) liner
2nd Layer



Polyethyleneterephthalate (PET) liner might work as a proton moderator to create hydrogen blistering

Summary and Future Works

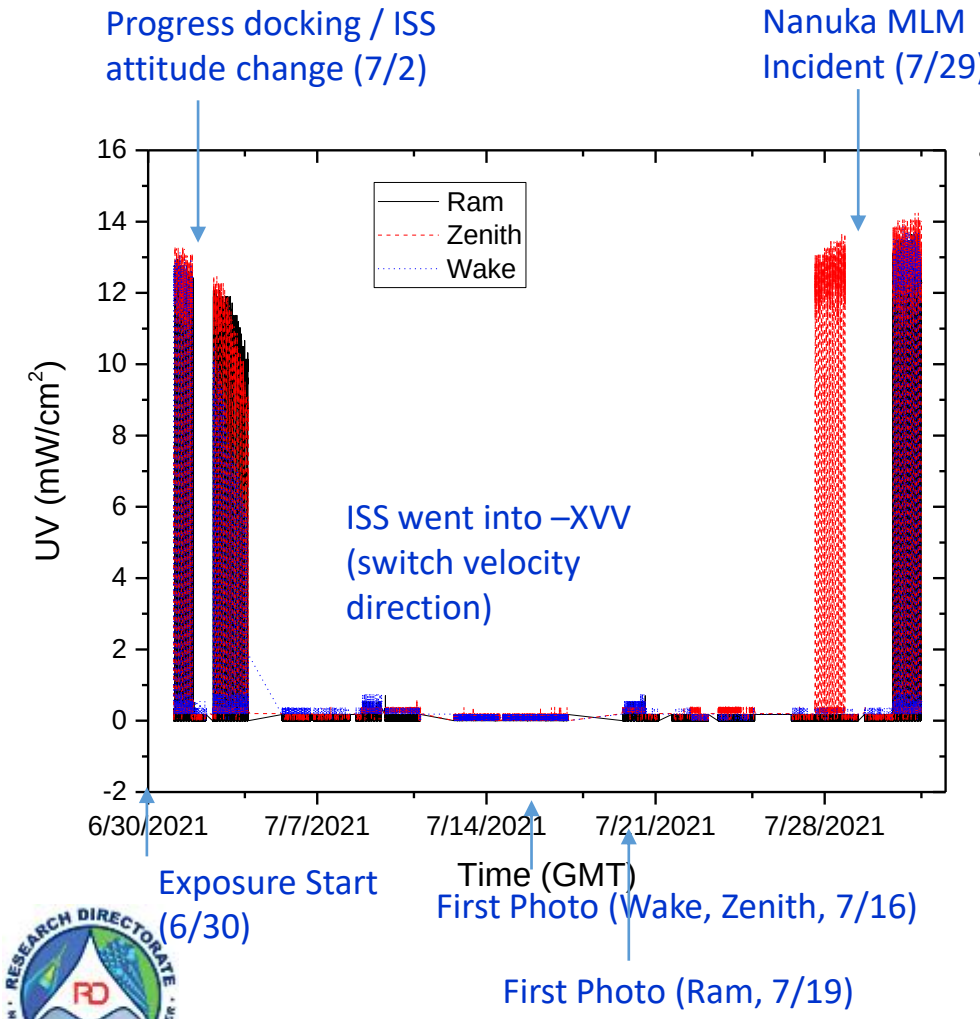
1. The space environmental effects on sail materials were evaluated on the ISS as part of the two MISSE 10 and 14 projects (2019 – 2021).
2. ACS3 solar sail membrane materials and composite boom laminate samples were exposed to the space environment outside of the ISS (vacuum, UV, atomic oxygen, solar particle events, etc.).
3. Samples were retrieved after 1.2 year (MISSE 10) or 0.4 year (MISSE 14) space flight for post-flight evaluation.
4. Significant color change (Yellowing) was found with pristine polymer samples.
5. Severe erosion on non-metallized sample surface (polyimide and carbon fiber composite) was found with Ram direction.
6. Slight change in wrinkles (shrunk, taut) was found with metallized sail membranes, while no visible delamination or bubbles was found with the seamed joints of metallized sail membranes.

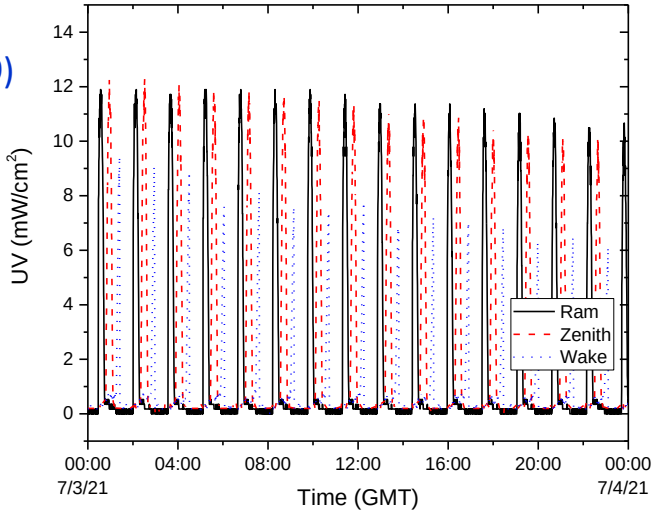
Summary and Future Works

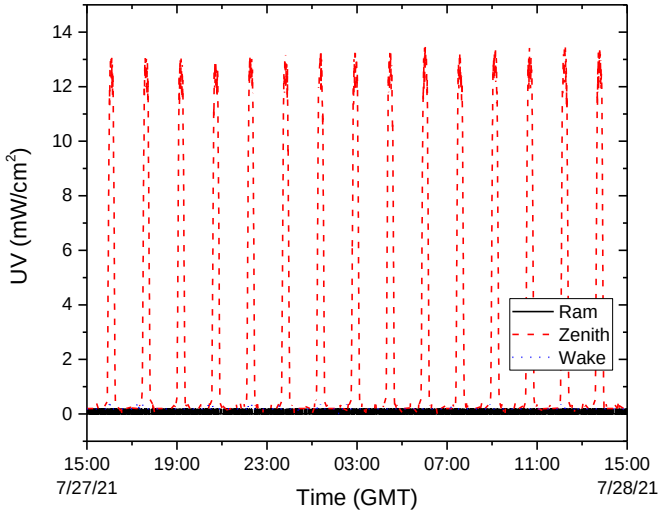
7. Morphology change in sail membrane might be originated from polymer chain degradation or entropy driven polymer chain recoil of the biaxially-oriented thin film by external stimulus (solar radiation, temperature).
8. Foggy (diffuse reflection) mark on the aluminum coating surface was found with the 2nd layer of Met PEN of MISSE 14 while no foggy mark on Met PEN of MISSE 10 was found. This seems to be originated from hydrogen blistering by moderated proton radiation through PET film liner of MISSE 14.
9. The change of thermal emissivity of samples was not significant.
10. Mechanical, thermal properties and molecular structure change will be studied.
11. Further investigation on the blistering phenomena will be performed.
12. The methods of protection of composite boom against AO erosion will be studied.

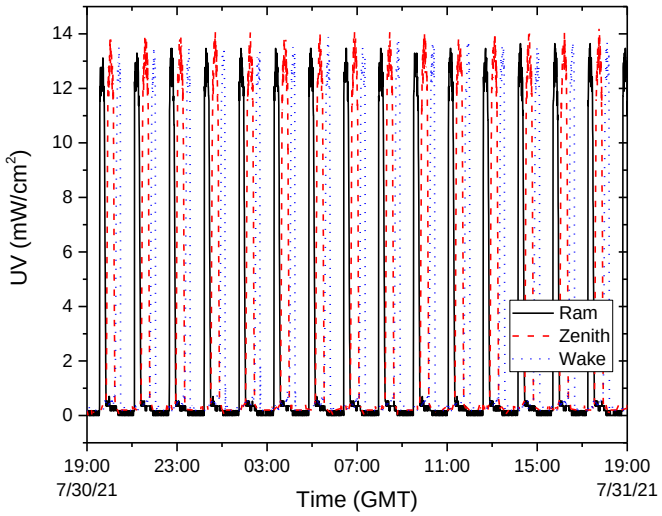
Backup

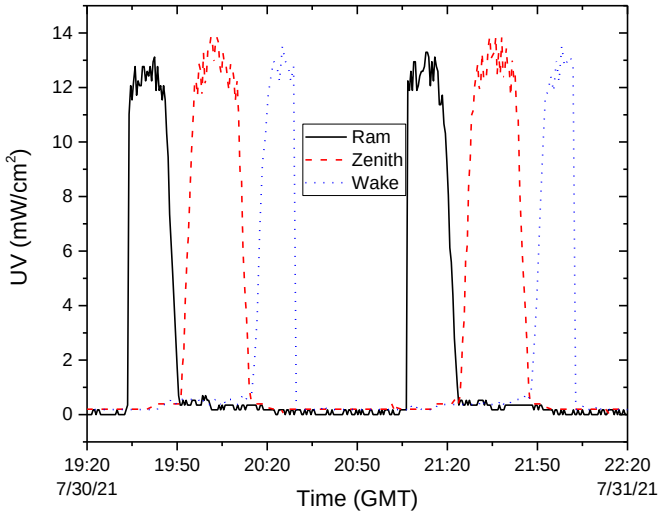
Space Environment of ISS: *UV (July 2021)*



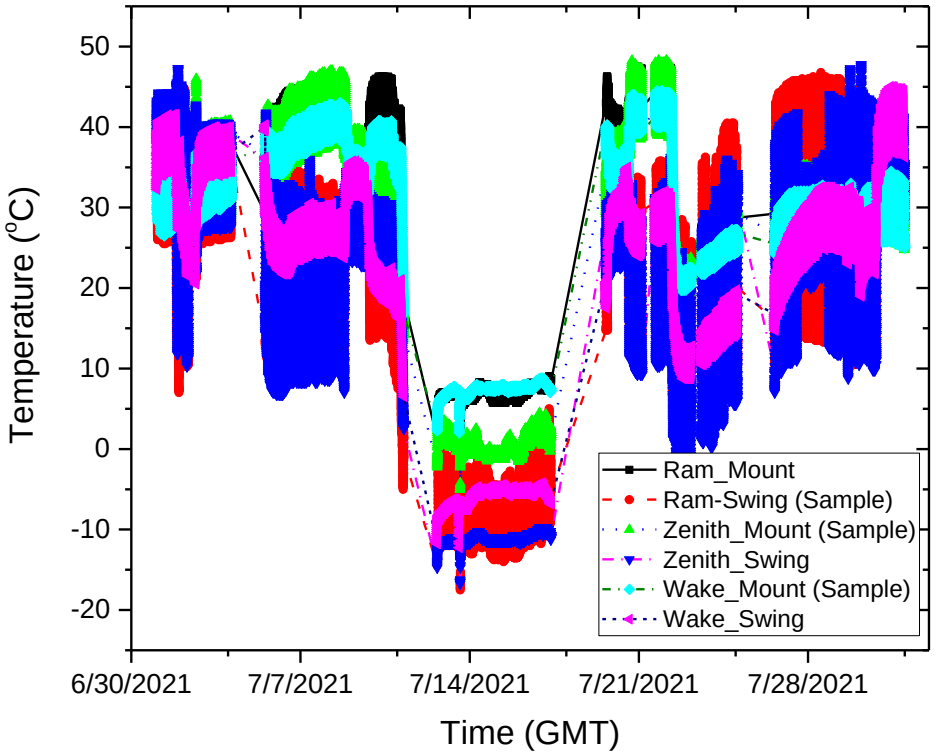




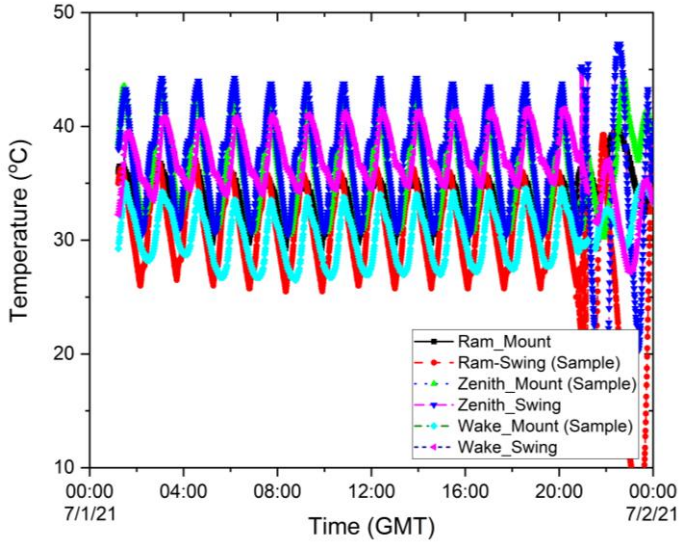


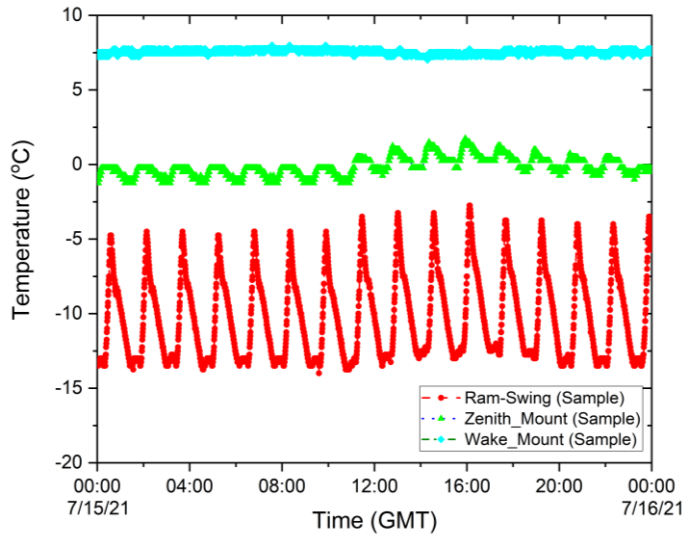


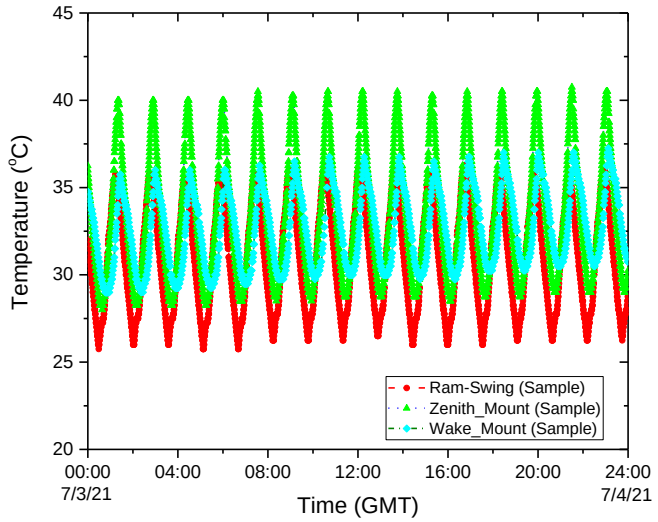
Space Environment of ISS: *Temperature (July 2021)*

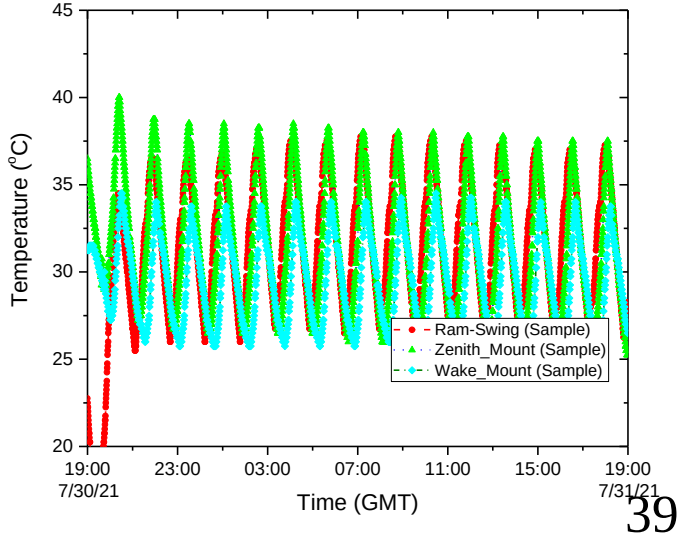


The temperature of MSC varied from about -17°C to 47°C in July, and was greatly affected by the ISS attitude/orbit adjustment.

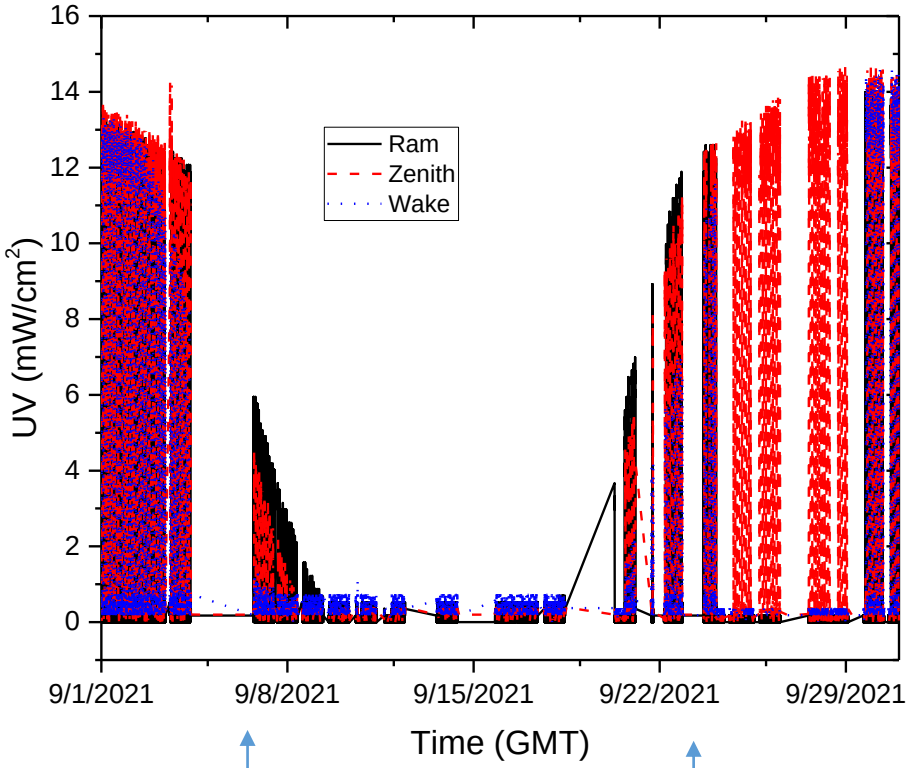








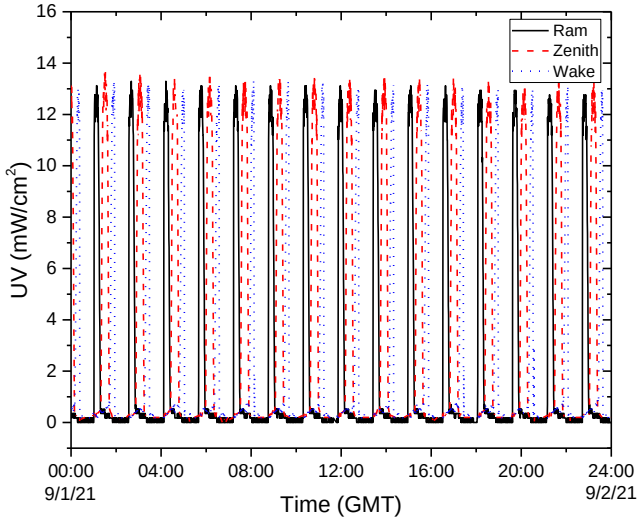
Space Environment of ISS: *UV (September 2021)*

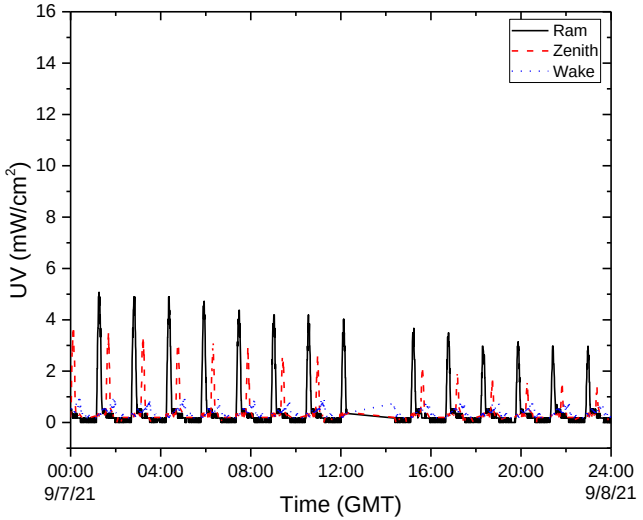


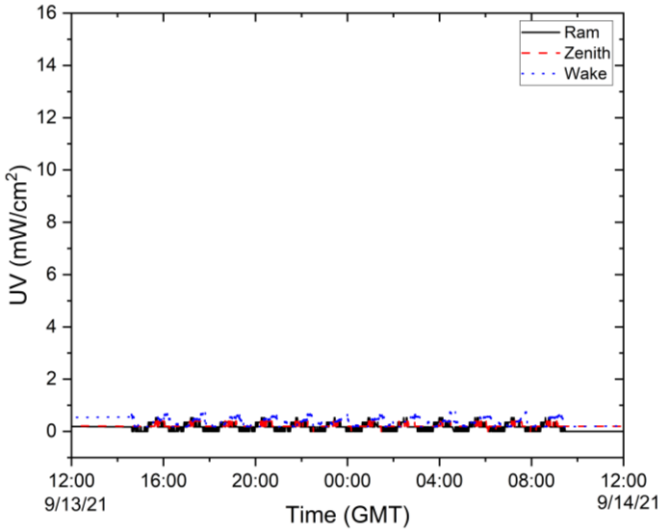
3rd Photo (Wake, Sep. 7th)

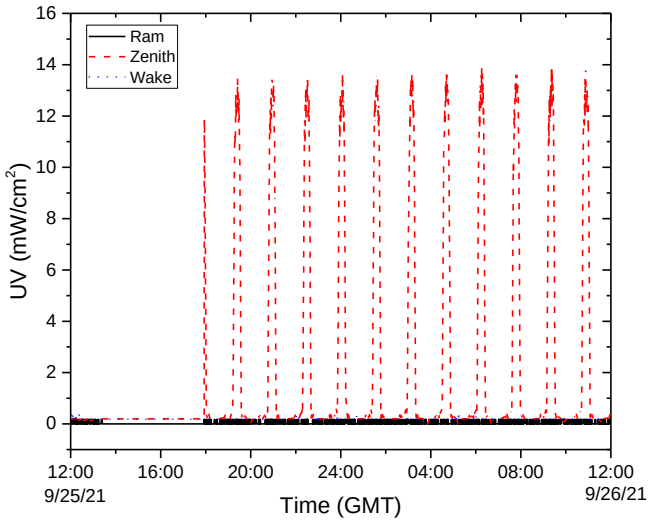
3rd Photo (Zenith, 9/13)

3rd Photo (Ram, 9/23)

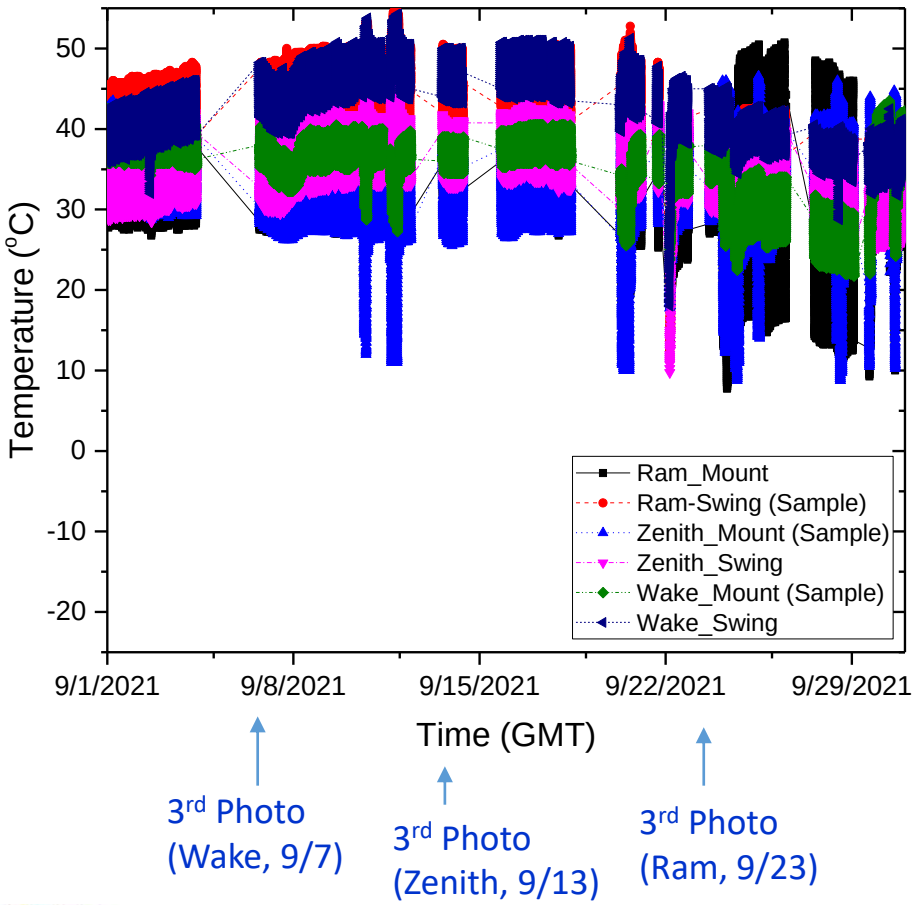


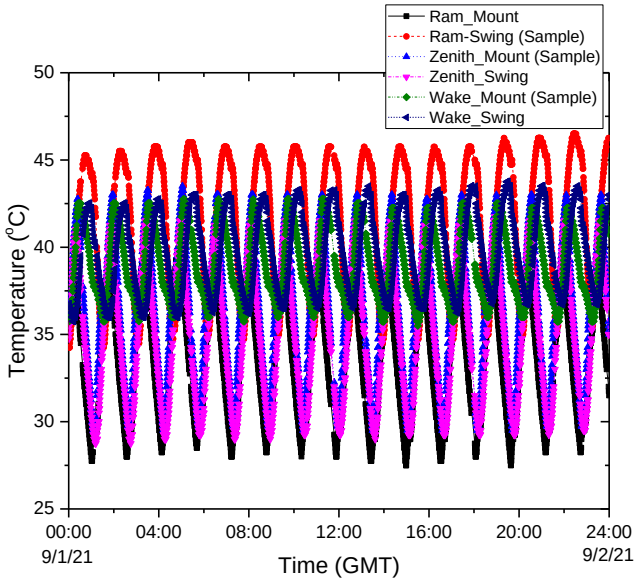


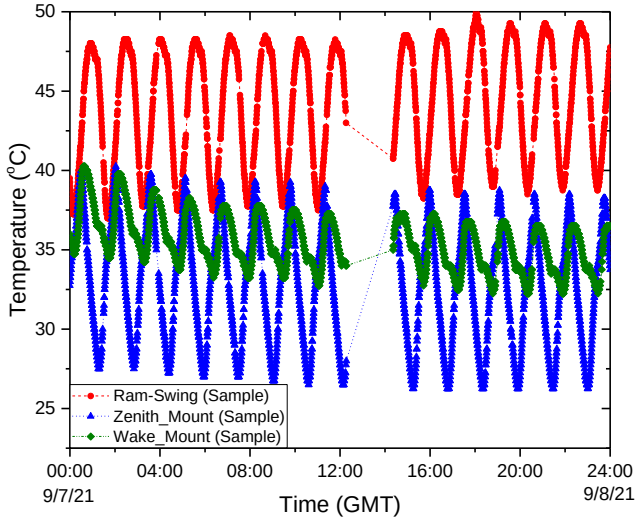


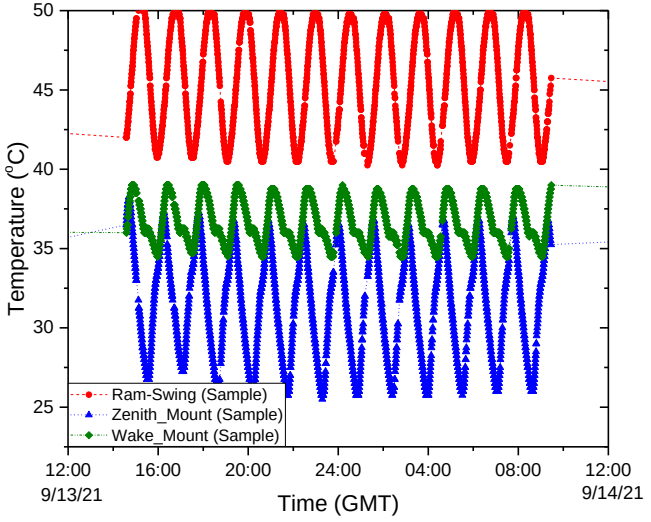


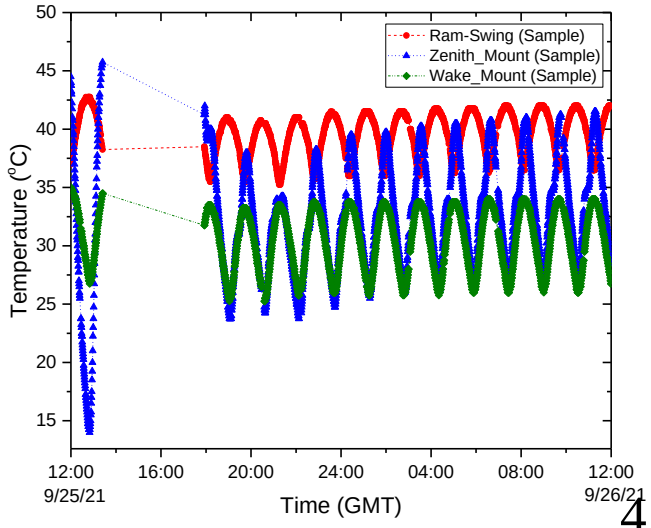
Space Environment of ISS: *Temperature (September 2021)*









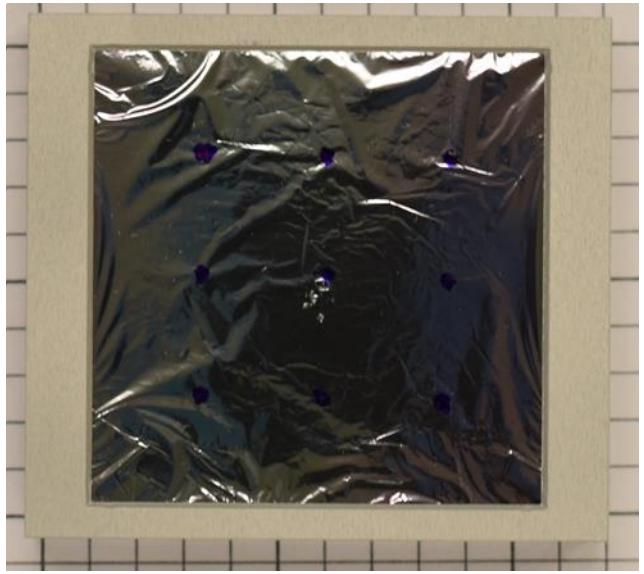


The temperature of MSC varied from about 8°C to 54°C in September.

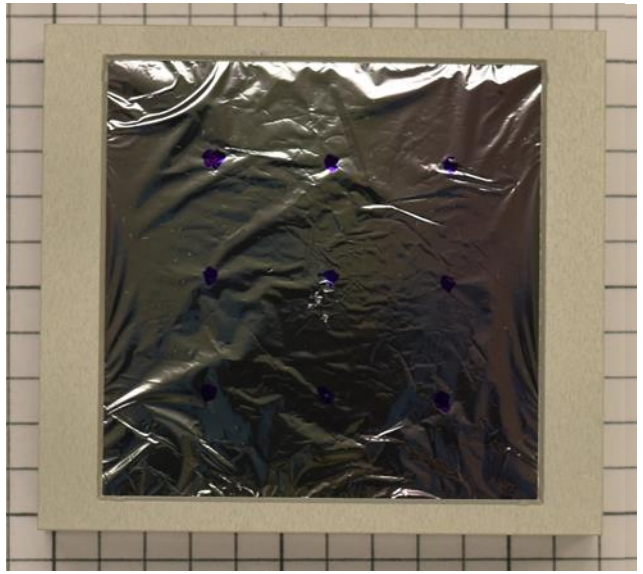
Simulated Thermal Aging Test

Cr (15nm)/PEN (2µm)/Al (100nm)

- Measured Temperature of MSC on orbit: about -17°C to 54°C
- Calculated Temperature of Al-met PEN toward Sun: 0.1°C to 4.6°C
- Calculated Temperature of Cr-met PEN toward Sun: 131°C to 131.5°C



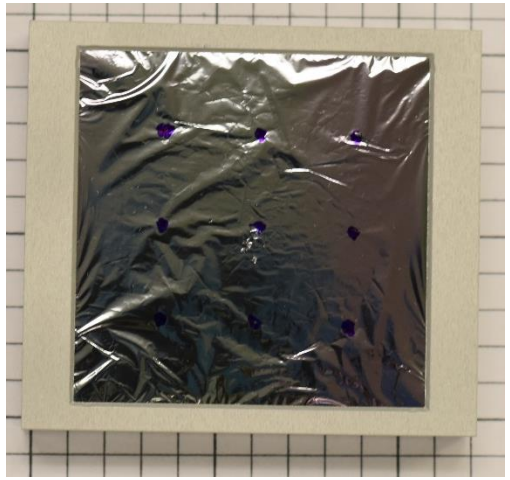
80°C, 5 days



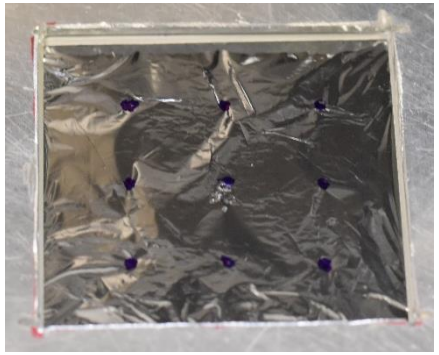
No significant change

Simulated *UV/Vis/NIR Light Aging Test

- Sample is exposed to 1 Sun at atmosphere using a Solar Simulator (AM0 filter, 1 Sun equivalent)

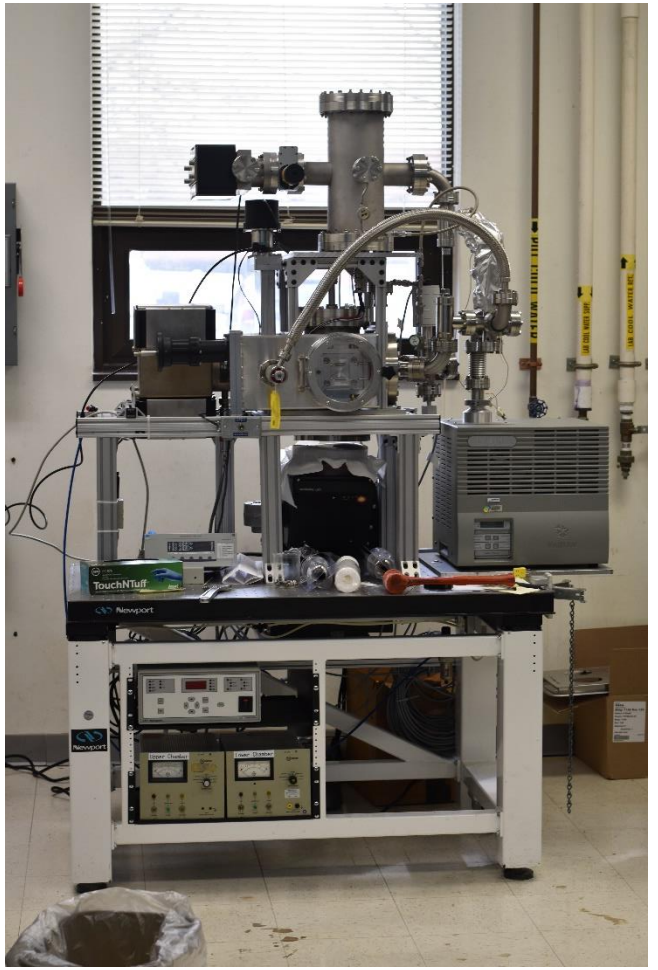


Before exposure



Before exposure

Cr (15nm)/PEN (2µm)/Al (100nm)



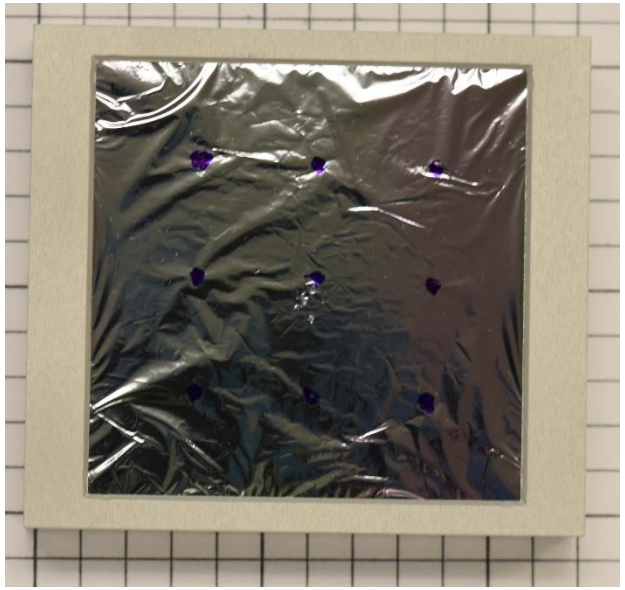
Solar Pressure Measurement System (Solar simulator/Cahn balance) under development

*Ultraviolet/Visible/Near Infrared (UV/Vis/NIR)

Simulated UV/Vis/NIR Light Aging Test

- Sample is exposed to 1 Sun (AM0-in space) at atmosphere

Cr (15nm)/PEN (2μm)/Al (100nm)



Before exposure

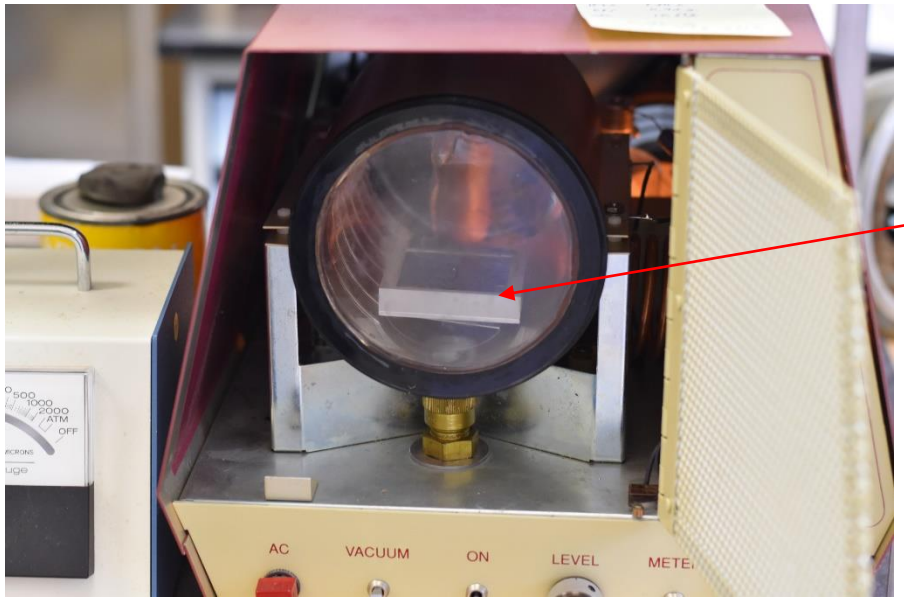
1 Sun (AM0),
23 days
(551.3 ESH)

Sample was stretched and taut, Blue marking was faded.
Many wrinkles were created. Fine cracks on chrome layer were found.
No rupture occurred after about 551 ESH.

Atomic Oxygen Simulation Test

Using SPI Plasma Prep II

Power: about 100 W
Radio Frequency: 13.56 MHz
Gas supply: Oxygen (5 psi)
Vacuum: about 200 millitorr to 250 millitorr
AO flunence estimation: witness sample of Kapton HN and erosion rate (E_O ~ 2.81E-24 cm^3/AO)



Plasma OFF

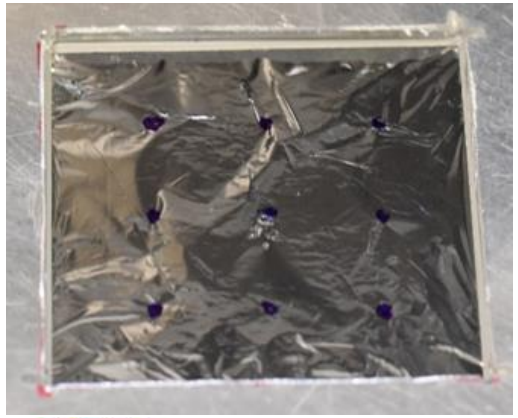
Sample
(Met-PEN)
In the MIISE
sample holder

Plasma ON

Summary of UV/Vis/NIR and Atomic Oxygen Simulation Test

Using Solar Simulator and SPI Plasma Prep II

Cr side of Met-PEN

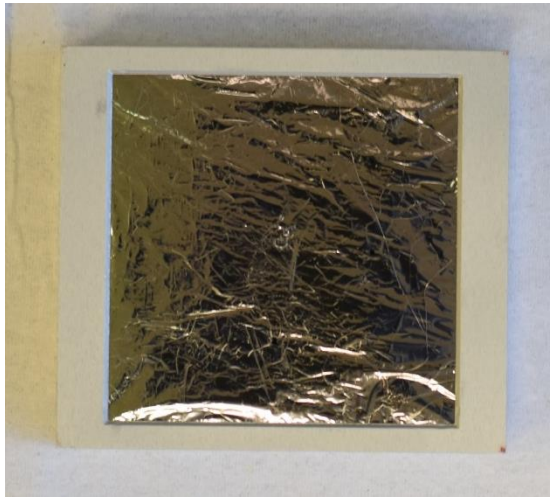


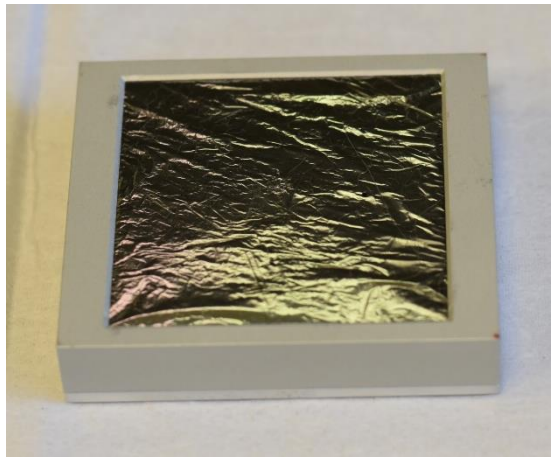
Before exposure

Solar Simulator

(AM0, One sun equivalent, UV/Vis/NIR)

23 days exposure (551.3 ESH)



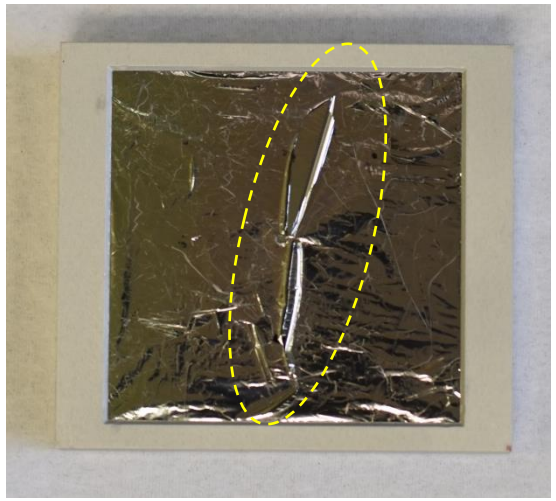


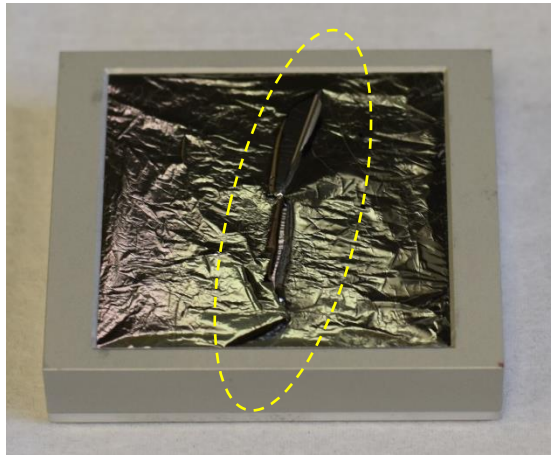
Wrinkles were found, but
No Crack/Rupture was created by UV/Vis/NIR

Oxygen Plasma

(estimated AO fluence ~ 5.44E19 AO/cm^2)

→ Equivalent to 28.5 days on Ram; 264 days on Zenith; 183 days on Wake at LEO (~413km)





Crack/Rupture was reproduced by Oxygen Plasma

In-Flight Image [Seamed Met PEN (M14-BK-R9), Ram]

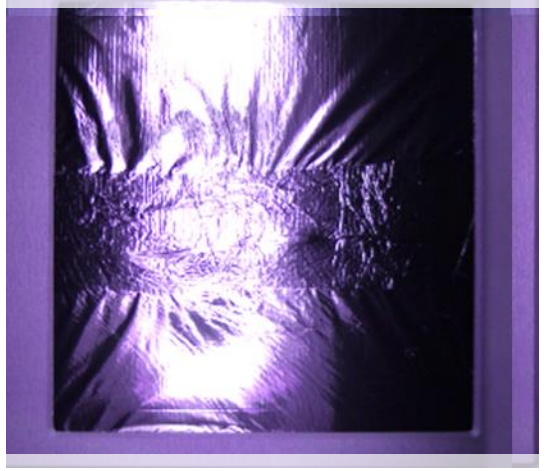
MISSE 14

5.08 cm × 5.08 cm
(4.70 cm × 4.70 cm opening)

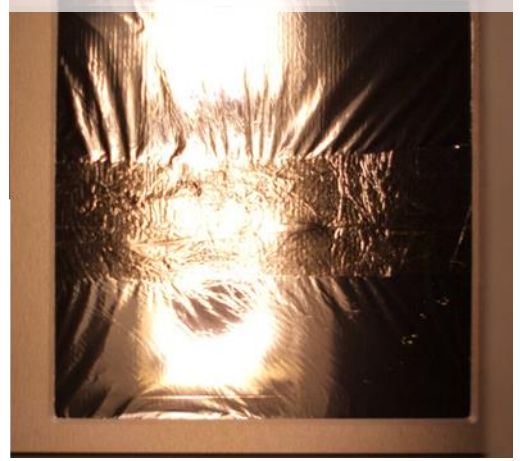
Total 5 days exposure (7/19/2021)

No image

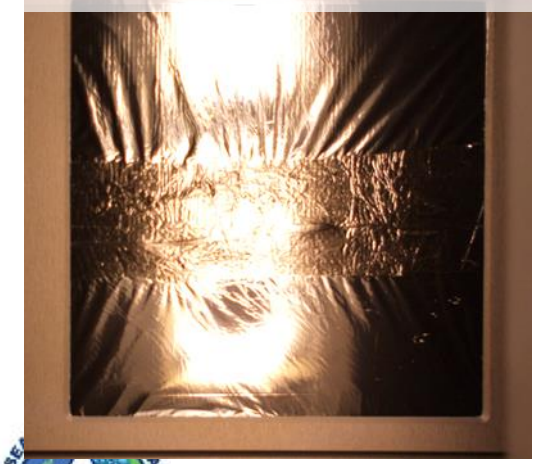
Total 8 days exposure (8/3/2021)



Total 57 days exposure (9/23/2021)



Total 58 days exposure (10/1/2021)



Total 84 days exposure (11/1/2021)

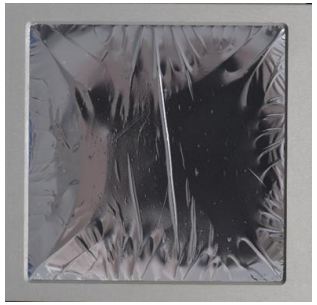
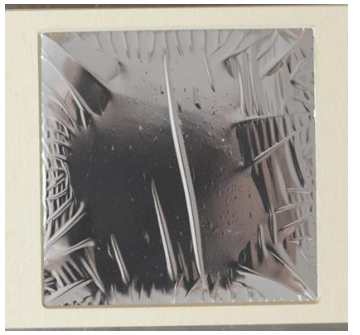
Total 111 days exposure (12/1/2021)

Post Flight (133 days exposure)

No significant change was found after total 133 days exposure in Ram direction. Sample was slightly shrunk and taut.

Sail Membrane Image Highlights

MISSE 14

	Ram		Zenith		Wake	
Al/Met PEN	 Before Flight	 Total 133 days	 Before Flight	 Total 149 days	 Before Flight	 Total 133 days
Seamed Met PEN	 Before Flight	 Total 133 days	 Before Flight	 Total 149 days	 Before Flight	 Total 133 days

Samples look shrunk and taut. No delamination in the seamed joint was found

Composite Boom Sample Image Highlights

MISSE 14

Ram

PMT F7

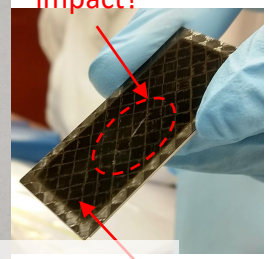

Before Flight


Total 133 days

PMT F7/M30S-1 (ACS3)


Before Flight


Total 133 days



PMT F7/M30S-2 (*DCB)

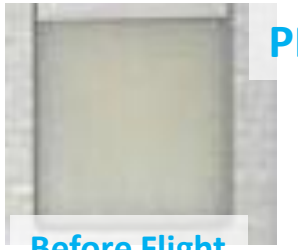

Before Flight


Total 133 days

*Deployable composite boom (DCB)

Zenith

PMT F7


Before Flight


Total 149 days

PMT F7/M30S-1 (ACS3)


Before Flight


Total 149 days

PMT F7/M30S-2 (DCB)


Before Flight


Total 149 days

Wake

EA 9696


Before Flight


Total 133days

PMT F7/M30S-1 (ACS3)


Before Flight


Total 133 days

PMT F7/M30S-2 (DCB)


Before Flight


Total 133 days

Ram samples were eroded significantly