METEOROLOGY PANEL

METP SWX User Workshop, 20 October 2025, Rome, Italy

Space Weather Radiation Mitigation in Low Earth Orbit

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ENAC - Italian Civil Aviation Authority

Low Earth Orbit (LEO), ranging from 160 to 2000 km, is vital for satellites and the ISS (International Space Station) but presents a challenging radiation environment increasing health risks for astronauts and threatening spacecraft reliability.

This research evaluates radiation dose rates in LEO at ISS altitude (400 km) under varying space weather conditions to highlight the need for integrated monitoring and mitigation strategies to enhance radiation protection and ensure safe human operations in orbit.

https://www.forbes.com/sites/valeriestimac/2022/02/03/nasa-announces-end-to-iss-plans-crash-into-pacific-ocean/

Solar Wind

Characteristic	Solar Wind
Definition	Continuous plasma flow from the solar corona
Frequency	Permanent
Speed	300 – 900 km/s
Composition	Protons (H^+) ~95% ; Helium nuclei (He^{2+}) ~5%; Free electrons; Heavy ions (C, O, Fe) traces
Origin	Slow wind: equatorial corona; Fast wind: coronal holes
Duration	Constant
Arrival on Earth	~1–5 days
Ejected Mass	Continuous flow (~5–10 particles/cm^3 near Earth)
Main Effects	Constant pressure on magnetosphere

https://www.livescience.com/what-are-coronal-mass-ejections

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Solar Flares

Characteristic	Solar Flares
Definition	Sudden burst of electromagnetic radiation
Frequency	Episodic
Speed	300,000 km/s (EM radiation)
Composition	Photons (X-rays, UV, γ-rays) No massive particles
Origin	Magnetic reconnection in active regions (often with CMEs)
Duration	Minutes–hours
Arrival on Earth	8 minutes
Ejected Mass	No mass (only photons, EM radiation)
Main Effects	- Radio disruptions (shortwave); - Immediate ionization increase

https://www.livescience.com/what-are-coronal-mass-ejections

Galactic Cosmic Rays (GCR)

Characteristic	Galactic Cosmic Rays (GCR)
Definition	Extremely high-energy particles from outside the solar system
Frequency	Permanent
Speed	~300,000 km/s
Composition	Protons (H^+) ~85%; Helium nuclei (He^{2+}) ~12% Free electrons <1%; Heavy ions (C, O, Fe) traces
Origin	Supernovae, galactic nuclei accelerators, extragalactic sources
Duration	Constant
Arrival on Earth	~8 minutes
Ejected Mass	Minimal mass per unit volume (ultra-energetic particles)
Main Effects	Ionizing radiation risk for astronauts & crews; Effects on cells and space tech

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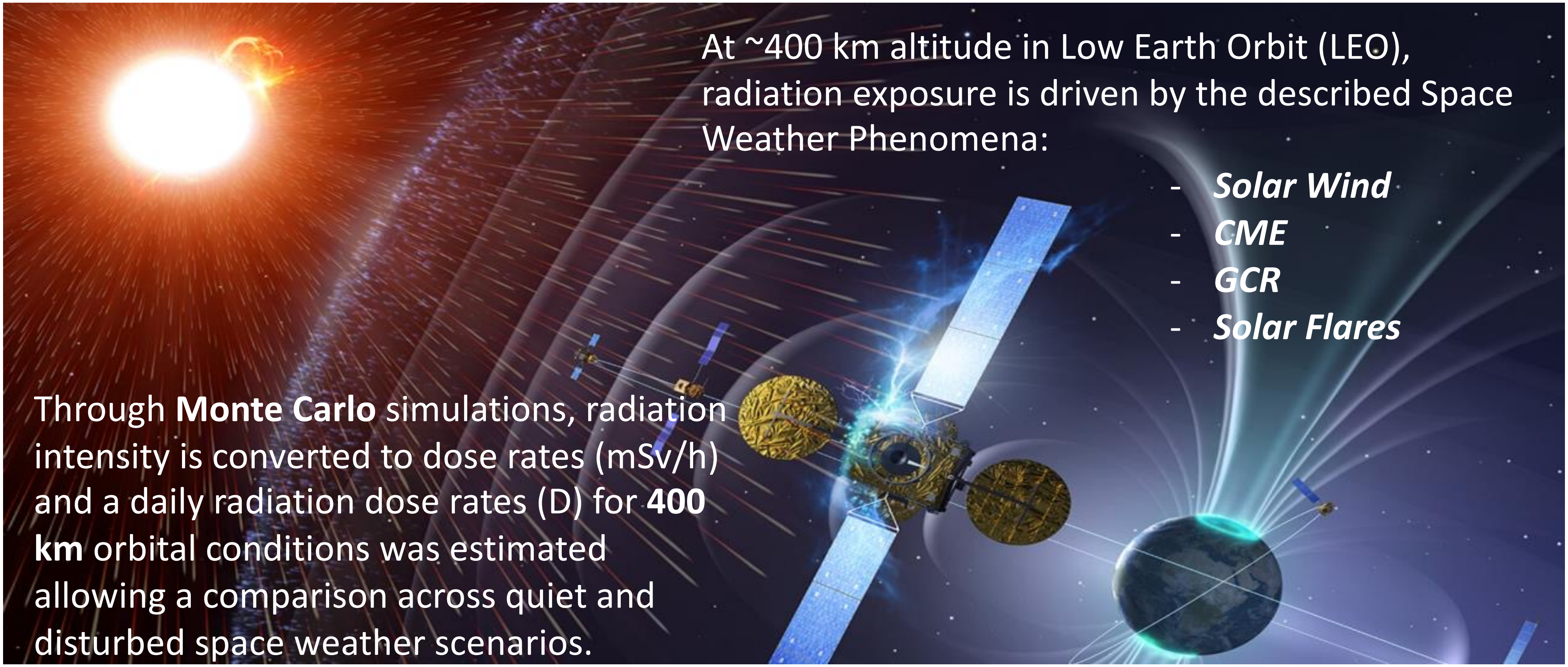
Materials and Methods



At ~400 km altitude in Low Earth Orbit (LEO), radiation exposure is driven by the described Space Weather Phenomena:

- ***Solar Wind***
- ***CME***
- ***GCR***
- ***Solar Flares***

Through **Monte Carlo** simulations, radiation intensity is converted to dose rates (mSv/h) and a daily radiation dose rates (D) for **400 km** orbital conditions was estimated allowing a comparison across quiet and disturbed space weather scenarios.

https://www.esa.int/Enabling_Support/Space_Engineering_Technology/ESA_missions_team_up_to_map_cosmic_rays_across_Solar_System

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Material and Methods - Dose Rate (mSv/h)

$$D = I \times \alpha \times f(h) \times t$$

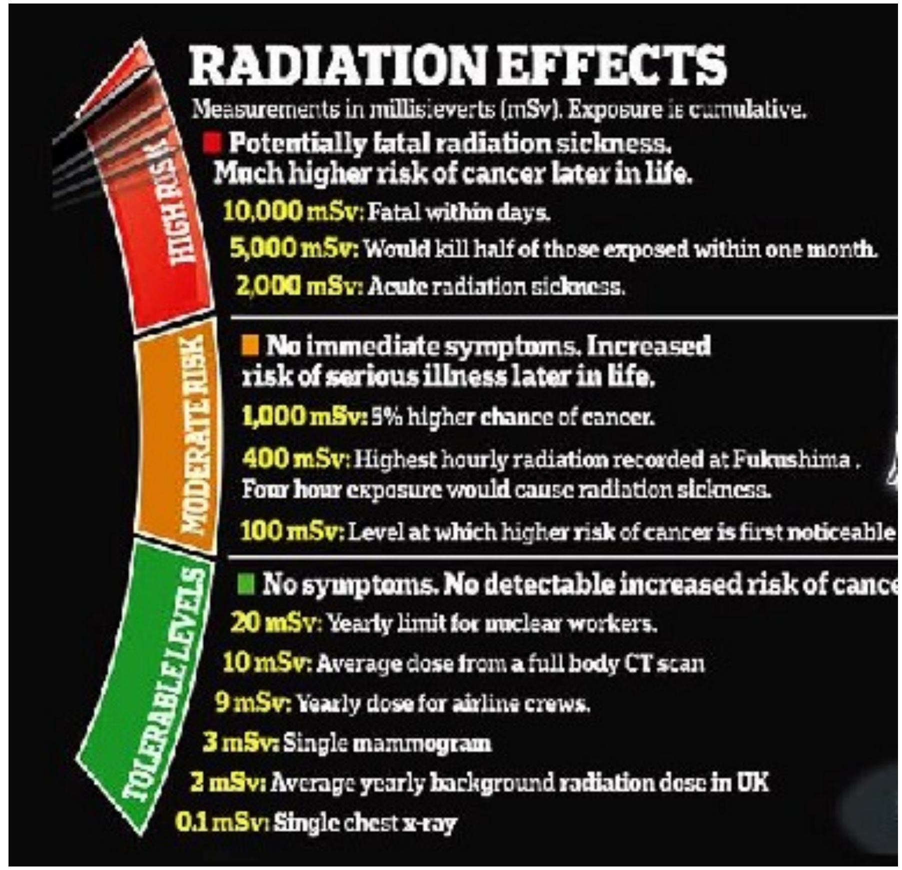
I: radiation intensity, which varies depending on the solar event;

α: conversion factor that standardizes radiation intensity into dose equivalents;

f(h): shielding factor, which varies depending on the specific altitude (h);

t: time spent at a specific altitude.

$$Cumulative\ Total\ Dose = \sum_{i=1}^{N} D_{\ event,i}$$



https://www.researchgate.net/figure/Radiation-Level-and-its-Effect-on-Human-Body_fig3_361279453

Input Parameters

Solar radiation intensity quantifies the energy flux emitted by solar events and received at a specific location:

$$I = \frac{P}{A}$$

Conversion Factor streamlines the relationship between radiation intensity and biological effects:

$$\alpha = \frac{D}{I}$$

Shielding Effect represents the protective effect of the Earth's atmosphere:

$$f(h) = \frac{D_{actual}}{D_{unshielded}}$$

Input Parameters - Shielding Effect of Earth's Atmosphere f(h)

Altitude	Shielding Factor f(h)	Radiation Penetration	Description
Ground Level	~ 0.01	1% of incoming radiation reaches the surface	The atmosphere effectively blocks most cosmic and solar radiation.
Aviation Altitudes (9–12 km)	0.1 – 0.2	10–20% of solar radiation penetrates	Radiation exposure increases as shielding from the atmosphere decreases.
Lower Thermosphere (~100 km)	0.5 – 1.0	Nearly all incoming radiation reaches this altitude	The atmosphere becomes very thin, providing minimal shielding against radiation.
Low Earth Orbit (~400 km)	~ 2.0	Twice the unshielded radiation dose compared to Earth	Virtually no atmospheric shielding, exposing astronauts to significant radiation.

Altitude	No Solar Storm	G1 (Minor)	G2 (Moderate)	G3 (Strong)	G4 (Severe)	G5 (Extreme)
f(h) @ 400 km	2.0	~2.2	~2.5	~3.0	~4.0	≥5.0

https://starlinkspot.com/low-earth-orbit/

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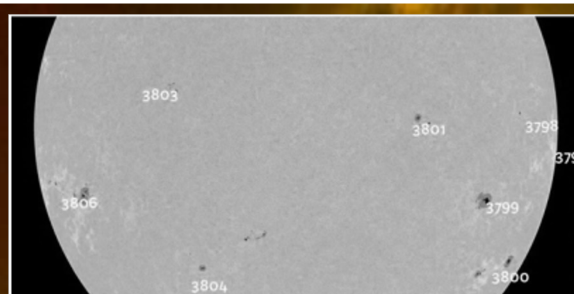
Scenarios Comparison – Active regions

Reference Scenario

Dec 13 th, 2024

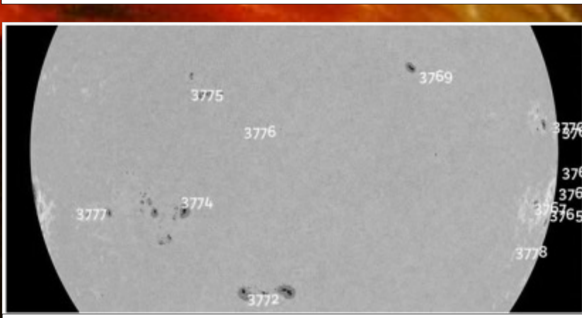


Scenario 1 - Aug 31st, 2024

(G1 Class)

Scenario 2 – May 17th, 2024

(G2 Class)



Scenario 3 – Aug 4th, 2024

(G3 Class)

Scenario 4 – Mar 24th, 2024

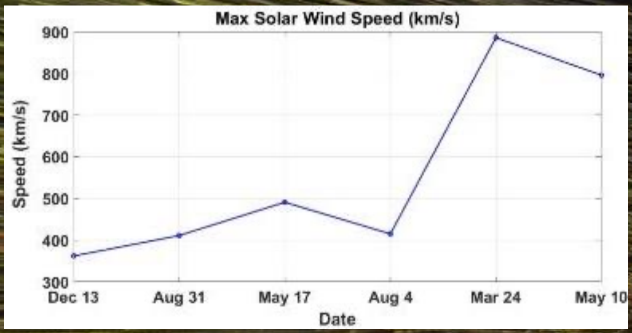
(G4 Class)

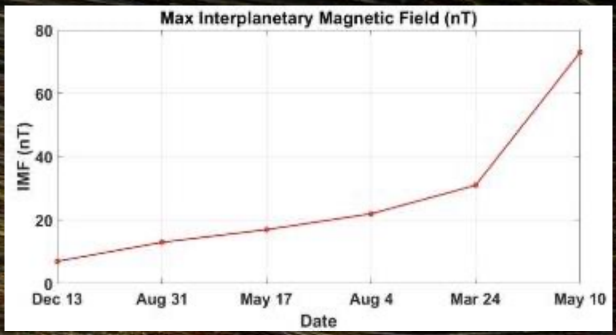
Scenario 5 – May 10th, 2024

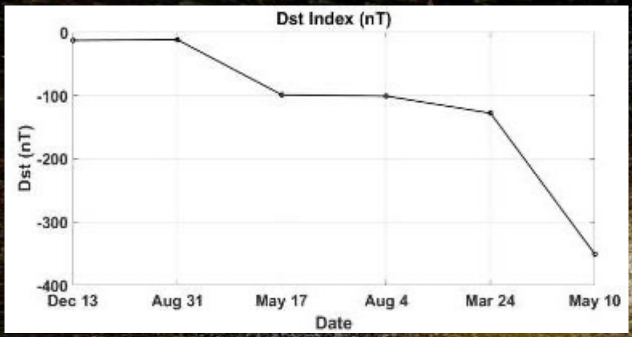
(G5 Class)

https://www.abc.net.au/news/science/2020-05-01/sun-is-big-lebowski-of-middle-aged-stars/12192916
https://www.spaceweatherlive.com/en/archive/2024/.html

Scenarios Comparison – Parameters



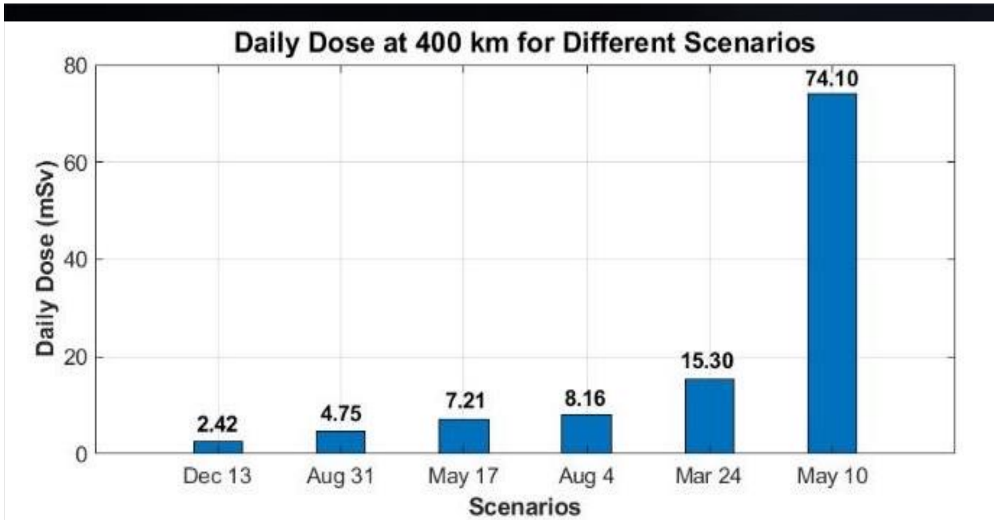




Scenario	Day	G Class	Max Solar Wind Speed (km/s)	Max IMF (nT)	Southward Bz (nT)	Dst Index (nT)	Kp Index
Reference Scenario	Dec 13th, 2024	-	362	7	- 7	-13	~2
Scenario 1	Aug 31st, 2024	G1	411	13	-12	-12	~5
Scenario 2	May 17th, 2024	G2	491	17	-15	-99	~6
Scenario 3	Aug 4th, 2024	G3	415	22	-17	-101	~7
Scenario 4	Mar 24th, 2024	G4	886	31	-24	-128	~8+
Scenario 5	May 10th, 2024	G5	796	73	-50	-351	~9-

https://www.space.com/22215-solar-wind.html

Monte Carlo Simulations – Output



	Day	G Class	Daily Dose @ 400 km (mSv)
Reference Scenario	Dec 13th, 2024	-	2.424
Scenario 1	Aug 31st, 2024	G1	4.752
Scenario 2	May 17th, 2024	G2	7.212
Scenario 3	Aug 4th, 2024	G3	8.158
Scenario 4	Mar 24th, 2024	G4	15.302
Scenario 5	May 10th, 2024	G5	74.100

https://www.extremetech.com/science/what-is-low-earth-orbit-leo

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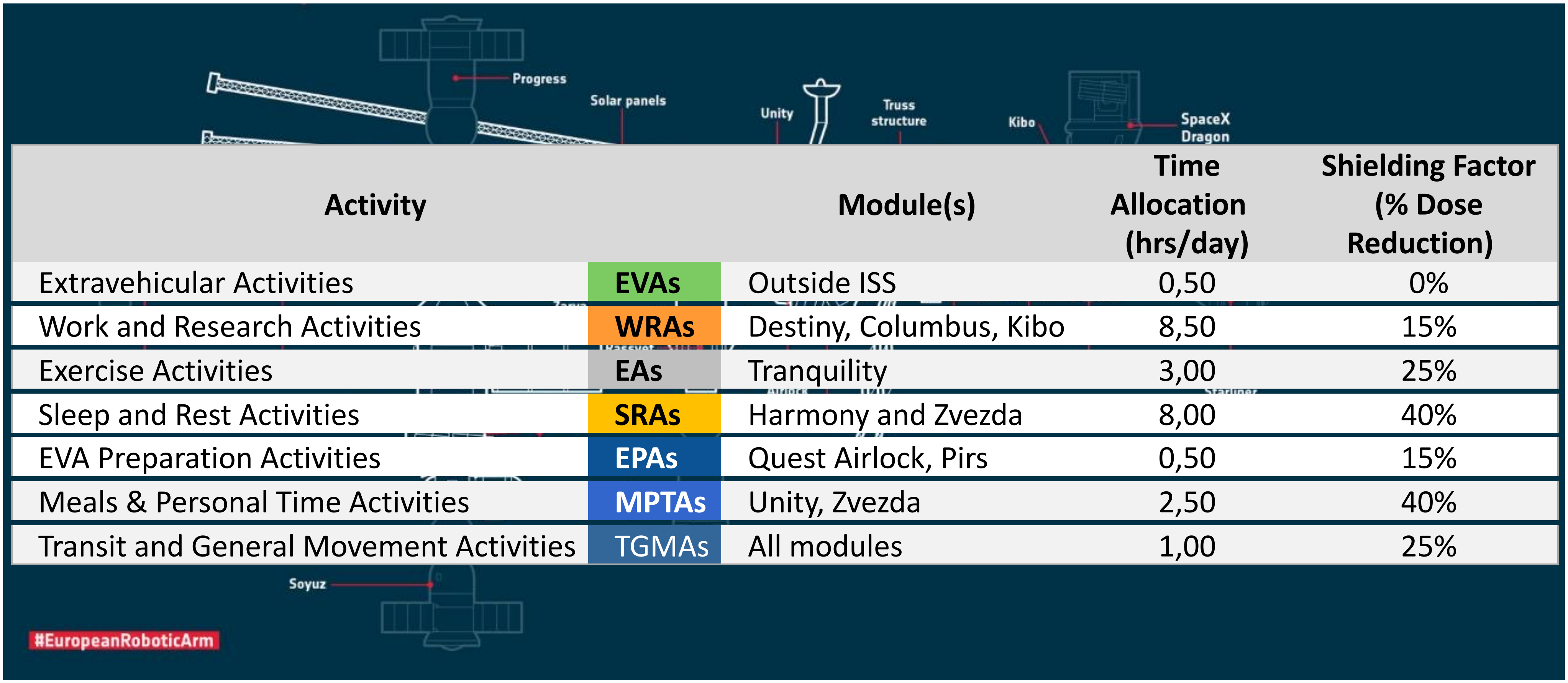
Time Allocation – (hrs/day)



Activity		Module(s)	Time Allocation (hrs/day)	Shielding Factor (% Dose Reduction)
Extravehicular Activities	**EVAs**	Outside ISS	0,50	0%
Work and Research Activities	**WRAs**	Destiny, Columbus, Kibo	8,50	15%
Exercise Activities	**EAs**	Tranquility	3,00	25%
Sleep and Rest Activities	**SRAs**	Harmony and Zvezda	8,00	40%
EVA Preparation Activities	**EPAs**	Quest Airlock, Pirs	0,50	15%
Meals & Personal Time Activities	**MPTAs**	Unity, Zvezda	2,50	40%
Transit and General Movement Activities	TGMAs	All modules	1,00	25%

https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/Building_the_International_Space_Station3

Zvezda Shielding Variability during Geomagnetic Storm

No Geomagnetic Storm Galactic Cosmic Rays are prevalent

Geomagnetic Storms (G1–G5) Solar Flares and CME are prevalent

Zvezda’s shielding factor varies according to the geomagnetic storm class and shielding response as follows

G Class	Typical External Dose (mSv/day)	Zvezda Dose (mSv/day)	% Shielding Factor	% Mean Shielding Factor	% Change
No Storm	1.3–1.5	0.8–1.0	33–46%	39.5%	-
G1 (Minor)	1.7–2.0	1.0–1.2	41–50%	45.5%	+15.2%
G2 (Moderate)	2.5–3.0	1.3–1.5	40–50%	45%	-1.1%
G3 (Strong)	3.5–5.0	2.0–2.5	43–50%	46.5%	+3.3%
G4 (Severe)	6.0–8.0	3.5–4.5	44–53%	48.5%	+4.3%
G5 (Extreme)	9.0–12.0+	6.0–7.0	38–50%	44%	-9.2%

https://www.nasa.gov/international-space-station/zvezda-service-module/

Daily Dose Comparison in LEO for Different Activities

All pressurized modules were modeled with Zvezda-like shielding properties and for each module, it was assumed:

- a % mean shielding factor typical for each module;
- a Zvezda module % mean shielding factor change from G1 to G5;
- the time spent in every module.

Scenario	G Class	Effective Daily Dose (mSv)							
		EVA	WRAs	EAs	RSAs	MPTAs	EPAs	TGMAs	TOTAL
Reference	-	0.0505	0.7309	0.2272	0.4891	0.1529	0.0429	0.0757	**1.7692**
Scenario 1	G1	0.0990	1.3950	0.4234	0.8637	0.2700	0.0819	0.1411	**3.2741**
Scenario 2	G2	0.1503	2.1215	0.6451	1.3222	0.4133	0.1245	0.2150	**4.9919**
Scenario 3	G3	0.1708	2.3859	0.7206	1.4553	0.4559	0.1400	0.2402	**5.5687**
Scenario 4	G4	0.3188	4.4324	1.3258	2.6263	0.8224	0.2601	0.4419	**10.2277**
Scenario 5	G5	1.5438	21.9326	6.6794	13.8320	4.3115	1.2863	2.2265	**51.8121**

https://www.nasa.gov/leomicrogravitystrategy/

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Analysis of Events

Year 2024 was characterized by days with the following Kp values:

Kp Matrix	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Jan 24	4	3-	3+	3-	2	1	0+	2	2+	2+	2	1+	1-	2	2+	3-	1+	2+	3-	2+	2	3+	3-	3+	2+	2	2+	3	3-	2+	2+
Feb 24	2	1	1-	3	3-	3	1+	2-	3	2+	4+	2+	4-	3	1+	2	2	3+	0+	2+	1+	2-	1+	2+	3	3	4+	2	2-		
Mar 24	3-	2+	6+	4	3-	3	4-	4-	4	2+	2	2+	3+	3	3+	1-	0+	3-	3-	2+	5-	3+	6-	8+	5	3	3	3-	2-	2-	4-
Apr 24	4-	3-	3-	3+	3+	3	2+	3+	3+	3-	3-	2+	2	2-	3-	5+	3	2-	2-	3-	4	2+	3-	1	1-	5	3+	4-	3-	4+	
May 24	4-	7-	4	3	4+	5+	3-	2	2+	9-	9	7	6	2+	3	6	6	4	3-	2+	3-	2-	3+	3	2+	3-	3	2	2+	3+	4
Jun 24	2+	2+	4+	3-	2+	2	6+	5-	2	4	4	1+	1	2+	5-	4	3+	3+	3+	2+	1+	1+	3+	2-	3-	3-	3+	8-	4	4-	
Jul 24	2-	1+	1+	3	3	1	3-	3+	2+	2-	2	2	1+	1+	3	3+	2+	1+	1+	3-	2-	3	3-	2-	3+	5	4	3-	2	5+	5-
Aug 24	5+	3-	3-	7	3	2-	2+	3-	2	2+	5	8	4+	4-	2	3-	6+	4-	3	3+	3+	3	2+	3	2+	2-	3+	6-	2	5-	5-
Sep 24	4-	3-	2	4+	2-	3	2+	2+	3-	2+	4-	7	6	4+	4	4	7+	4-	4+	3+	2	2	4+	4+	5-	4	2+	3	4-	4	
Oct 24	2	2	3	3	2+	5-	6+	7	4+	9-	8+	5-	2-	4-	3+	3	3	4-	5	3	2	3	3	4+	1	4	3-	5-	4	4	4-
Nov 24	3-	4	4	4+	3-	3+	3	4-	5	6-	3	2-	3-	4-	3+	3+	3-	2	3-	3-	3	3+	3-	4	3+	3	2+	2-	3-	4+	
Dec 24	3-	2+	3+	2	2+	2+	2-	2+	4+	2+	2	2+	2-	3+	3	4-	5+	4-	4-	4-	3+	3+	4-	3+	2	0+	1+	1+	2-	2+	4

https://www.spaceweatherlive.com/en/archive.html

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Analysis of Events

It was estimated the 2024 astronauts yearly dose rate:

Kp Value	Classification	G Class	Events
Kp ≤ 4	No Storm	-	320
Kp = - 5, 5, + 5	Minor	G1	21
Kp = - 6, 6, + 6	Moderate	G2	10
Kp = - 7, 7, + 7	Strong	G3	7
Kp = - 8, 8, + 8	Severe	G4	4
Kp = - 9, 9	Extreme	G5	3

Scenario	Day	G Class	Events	Unshielded Yearly Dose @400km (mSv)	Effective Yearly Dose @400km (mSv)
Reference	Dec 13th,2024	-	320	775,5200	566,1440
Scenario 1	Aug 31st, 2024	G1	21	99,7920	68,7561
Scenario 2	May 17th, 2024	G2	10	72,1200	49,9190
Scenario 3	Aug 4th,2024	G3	7	57,1032	38,9809
Scenario 4	Mar 24th, 2024	G4	4	61,2080	40,9108
Scenario 5	May 10th, 2024	G5	3	222,3000	155,4363
2024 Yearly Dose Rate				**1288,0432**	**920,15**

https://dailygalaxy.com/2024/11/how-long-can-humans-survive-in-space/

Exposure Limits

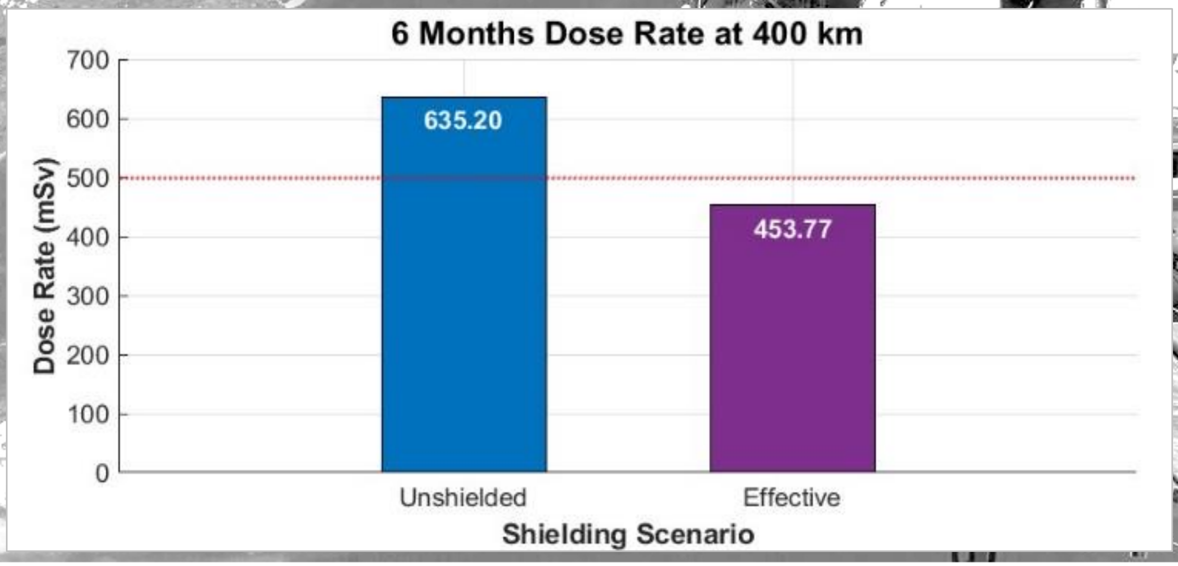
Category	LEO Crew
Monthly Regulatory Limit	250 mSv
Annual Regulatory Limit	500 mSv
Regulatory Agencies	NASA, ESA, Roscosmos

	Unshielded Dose (mSv)	Effective Dose (mSv)
2024 Annual Dose Rate	1288,0432	920,15
Annual Regulatory Limit Dose Rate	500	500
Difference	+157.61%	+84.03%

https://orbitaltoday.com/2022/03/30/roskosmos-appeals-to-nasa-and-esa-to-lift-russia-sanctions-save-the-iss/

Mitigation - Mission Duration

6 months - 182,5 Days	Unshielded Dose (mSv)	Effective Dose (mSv)
2024 Semesterly Dose Rate	635,1994	453,7700
Annual Regulatory Limit Dose Rate	500	500
Difference	+27.04%	-9.25%



https://www.nasa.gov/international-space-station/space-station-astronaut-record-holders/

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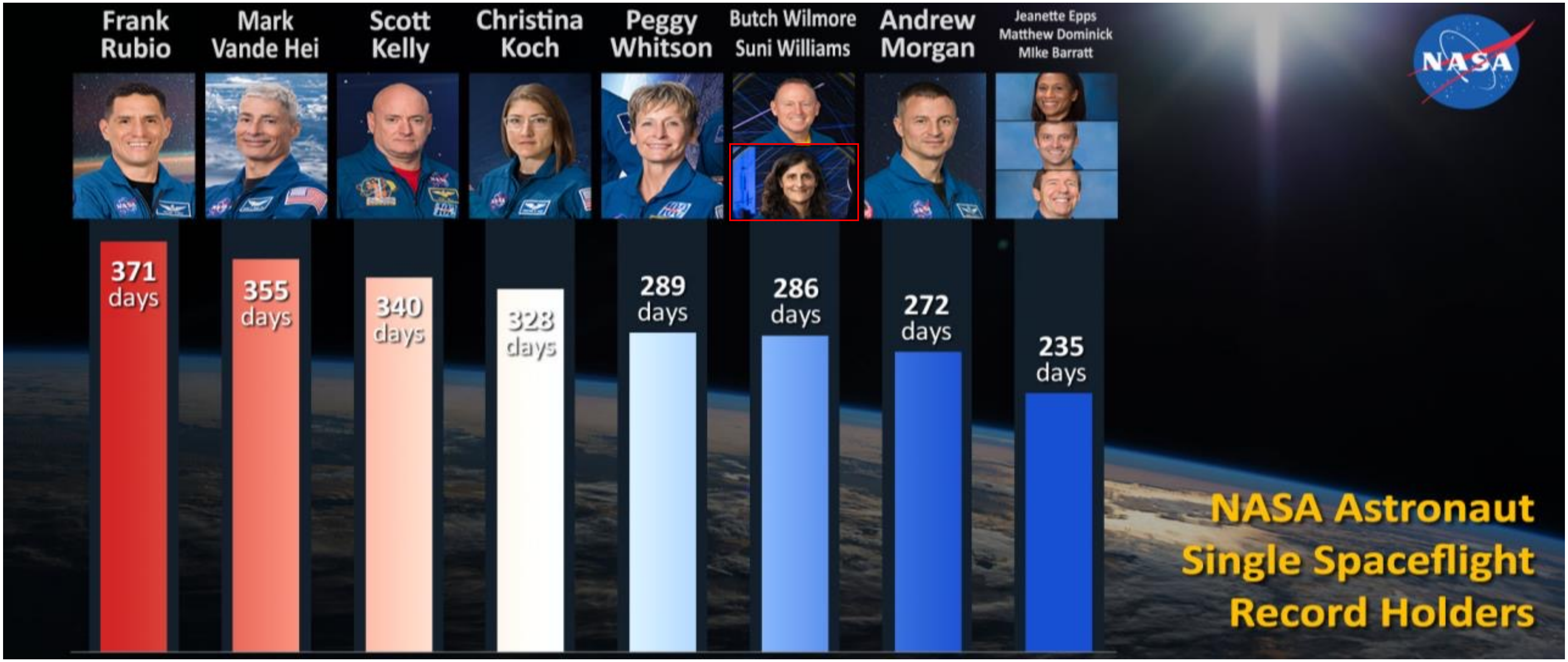
Conclusions

Radiation remains a major health risk for astronauts in low Earth orbit, where Earth's magnetic field provides only partial shielding

form a proactive defense, limiting cumulative radiation doses and enhancing crew safety, particularly during extended missions or periods of high solar activity.

https://stemrad.com/astrorad-4/?srsltid=AfmBOooQPVQWuaQay5Br54GT4ATa3iA0M6NFVVbA0SGV96NF81RzL94F

Mitigation Mission Duration



https://www.nasa.gov/international-space-station/space-station-astronaut-record-holders/

https://sandrarose.com/2025/03/nasa-astronaut-suni-williams-aged-10-years-after-being-stranded-in-space-for-9-months-she-is-unable-to-walk/

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Mitigation Mission Duration

https://nss.org/dragon-2-and-cst-100-starliner-spacecraft-compared/


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METEP SWX User Workshop, 20 October 2025, Rome, Italy
Questions?
THANK YOU!