

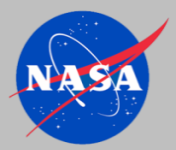


Spacecraft Anomalies and Failures Workshop 2023: NASA Introductory Comments

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NASA Engineering and Safety Center
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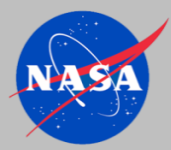
Spacecraft Anomalies and Failures 2023 Workshop
29 March 2023, GSFC, Greenbelt, MD
joseph.minow@nasa.gov





Outline

- Introduction and SCAF background
- Spacecraft, launch vehicle anomalies and failures in 2022 and 2023
- State of Solar Cycle 25 space environment
- Satellite traffic and orbital debris
- Summary



Introduction

- Welcome to NASA GSFC and SCAF 2023!
- Logistics
 - Fire, weather, restrooms
 - Maps to cafeteria at check-in desk
- Session chairs
 - Day 1: Joe Minow NASA/MSFC
 - Day 2: Dong Ryu NRO
- Organizing committee
 - Mike Campola NASA/GSFC
 - Martha Obryan GSFC/SSAI
 - Linda Parker MSFC/Space Weather Solutions
 - Mike Squire NASA/LARC
 - Yihua Zheng NASA/GSFC
- Let us know if you have questions or need help today!



SPACECRAFT ANOMALIES & FAILURES WORKSHOP
"Creating a Community Solution for Anomaly Attribution"

Co-Sponsored by NRO and NASA
MARCH 29-30, 2023

Locations:
DAY 1 (UNCLASSIFIED): NASA Goddard Space Flight Center
DAY 2 (CLASSIFIED): NRO HQ Westfields

Presentations run from 9:00 AM to 4:00 PM EDT.
Check-In begins at 8:00 AM

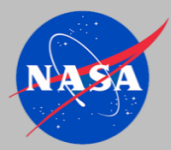
AGENDA TOPICS:

- Spacecraft Anomalies, Failures, and Operations.
- Space Environmental Effects and Debris.
- Anomaly Recovery Operations and Anomaly Investigations.

OBJECTIVES:

- Review & share lessons learned from spacecraft anomalies & failures.
- Improve tradecraft for anomaly attribution & root cause determination.
- Reinforce relationships in the Space Community that do not regularly interact.

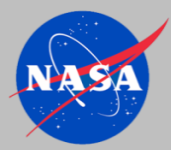
NRO POC: Dong Ryu, ryudong@nro.mil, 703-460-3697
NASA POC: Joseph Minow, joseph.minow@nasa.gov, 256-544-2850



SCAF Workshop History

- SCAF 2023 is the 10th in the SCAF workshop series that started in 2013
- Dr. Darren McKnight, Technical Director, Integrity Applications Incorporated (IAI) developed the original SCAF Workshop concept as an IAI organized event in 2013
- Workshops organized as annual event starting in 2013 through 2022 (no workshop in 2020) using a two-day format with invited presentations:
 - Day 1 unclassified sessions
 - Day 2 classified sessions
- NRO sponsorship of SCAF started with the 2016 workshop and NASA was included as a co-sponsor beginning in 2018 with Dr. McKnight/IAI and NRO continuing to serve as the primary organizer for the workshop
- In addition to the domestic SCAF workshops, Dr. McKnight organized an international Spacecraft Environmental Anomalies and Failures (SEAF) Workshop held in Toulouse, France in 2017 and Los Angeles, CA in 2019
- NASA and NRO took over as the co-organizers in 2021 with NASA organizing and hosting Day 1 (unclassified) presentations with NRO continuing to organize the Day 2 (classified) workshop



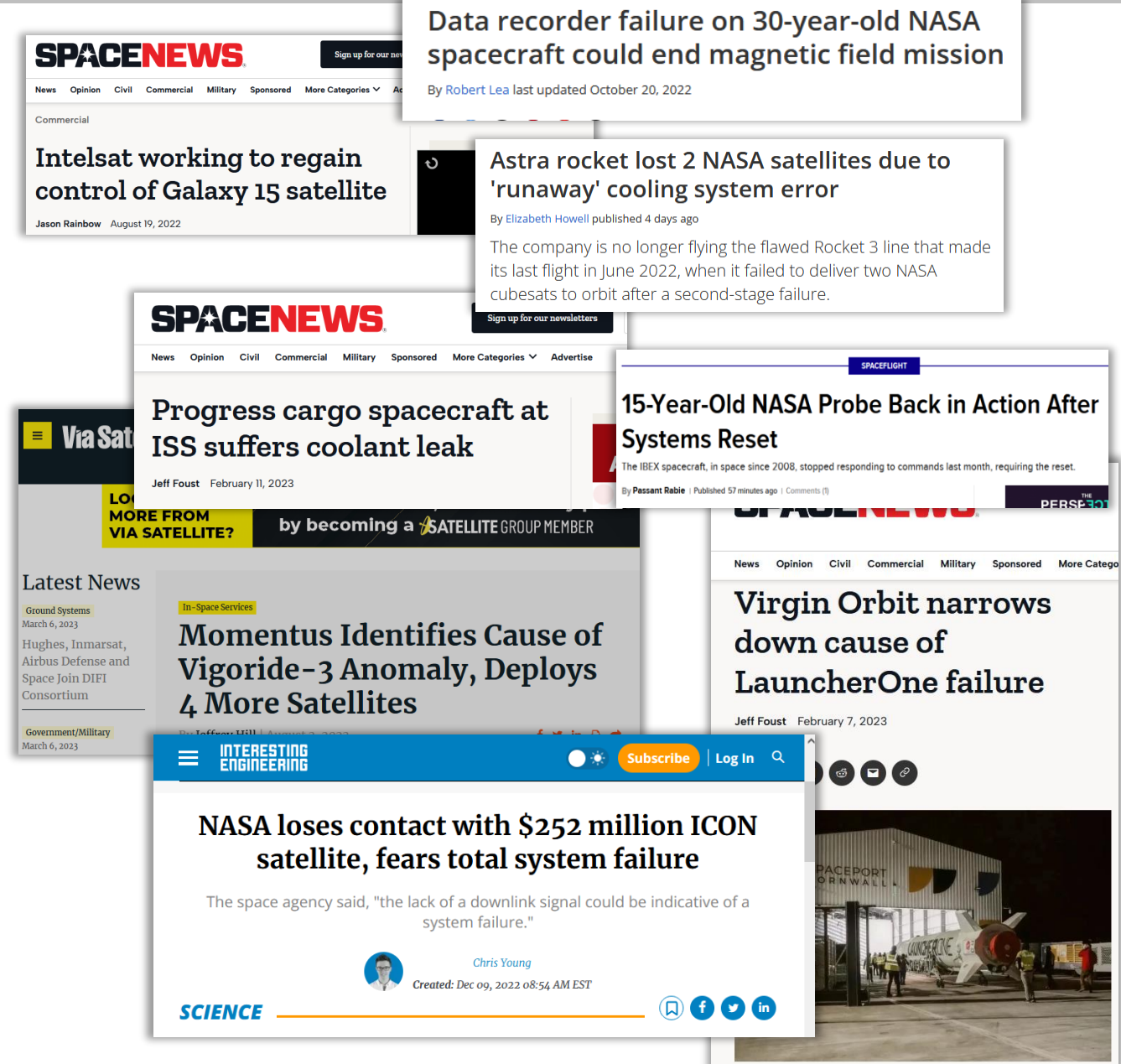


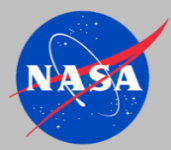
Spacecraft, Launch Vehicle Anomalies and Failures 2022-2023

- We are now 60+ years into the space age since the launch of the first spacecraft in 1957, space operations in many respects have become routine...
- However, anomalies and failures do continue to occur
 - Testing of new hardware
 - Aging of old hardware
 - Unexpected interactions with the space environment
 - In-space accidents and collisions
- Some failures occur early in the mission, others after many years on orbit
- The next few slides give examples of the range of anomalies and failures in both spacecraft and launch vehicles that occurred in 2022 and the first months of 2023
 - Wide range of environments
 - No one is immune: government, industry, academia
 - Public sources only

Sources:

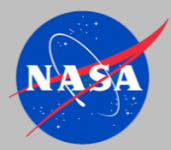
- <https://www.space.com/astra-rocket-loss-nasa-satellite-runaway-event>
- <https://www.space.com/nasa-geotail-magnetic-field-spacecraft-recorder-failed>
- <https://spacenews.com/intelsat-working-to-regain-control-of-galaxy-15-satellite/>
- <https://spacenews.com/progress-cargo-spacecraft-at-iss-suffers-coolant-leak/>
- <https://gizmodo.com/nasa-ibex-probe-operational-after-systems-reset-1850198754>
- <https://www.satellitetoday.com/in-space-services/2022/08/02/momentus-identifies-cause-of-vigorde-3-anomaly-deploys-4-more-satellites/>
- <https://interestingengineering.com/science/nasa-loses-contact-with-icon-satellite>
- <https://spacenews.com/virgin-orbit-narrows-down-cause-of-launcherone-failure/>





Selected Spacecraft Anomalies and Failures: 2022 and 2023

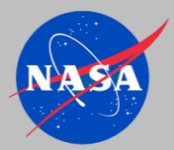
Date	Mission	Affiliation	Environment	Event	Cause/Notes	Ref*
5 Jan 22	ELSA-d	Astroscale	LEO	Anomalous spacecraft conditions required delay of orbital debris capture technology demo mission	Four of eight thrusters have technical difficulties and are now non-functional	1,2
3 Feb 22	Starlink	SpaceX	LEO	38 satellites lost	Loss of control, reentry due to high drag	3,4
4 Feb 22	SWIFT	NASA		Safe mode, February 2022	Failed reaction wheel, mechanical	5
31 Mar 22	Aqua	NASA	LEO	Safe mode 2022/090/17:59:08, Return to ops 2022/105/00:38	Unexpected power controller swap	6
22 Feb 22	MAVEN	NASA	Mars	Safe mode, 22 Feb – 28 May 2022	Inertial Measurement Unit anomaly during routine power cycle	7
19 May 22	Starliner OFT-2	NASA/Boeing	LEO	Two thrusters failed during orbital insertion burn	Primary and secondary units failed Tertiary backup operated successfully	8,9
25 May 22	JWST	NASA/ESA/CSA	Sun-Earth L2	Primary mirror damaged by hypervelocity impact between 23-25 May	Meteoroid impact on primary mirror	48,49
25 May 22	Vigoride-3	Momentus	LEO	Orbital transfer vehicle failure, failure to deploy 7 of 9 payloads	Solar arrays failed to deploy, reduced power and comm	10,11,52
20 Jun 22	Cygnus	NASA/NG	LEO	ISS reboost test ends early	Cygnus engine shut down 5 sec into 5 min burn	12
28 Jun 22	Geotail	JAXA/NASA	10x30 Re	Remaining data recorder failure, 28 June 2022	Shut down 28 Nov 22 after 30 years operations	14,47
5 Jul 22	CAPSTONE	NASA	Cislunar	Safe mode	Improperly formatted command	15
19 Aug 22	Galaxy 15	Intelsat	GEO	Loss of comm and control, drifting	Geomagnetic storm, broadcast payloads shut down as satellite drifts out of control	17,18, 19,55,56
24 Aug 22	JWST	NASA/ESA/CSA	Sun-Earth L2	Mid-Infrared Instrument grating wheel anomaly	Increased friction on grating wheel mechanism	20



Selected Spacecraft Anomalies and Failures: 2022 and 2023

Date	Mission	Affiliation	Environment	Event	Cause/Notes	Ref*
8 Sep 22	CAPSTONE	NASA	Cislunar	Tumble during trajectory correction maneuver	Vehicle attitude rates growing beyond the capacity of the onboard reaction wheels to control, propulsion system valve	15,16
10 Oct 22	TESS	NASA	LEO	Safe mode 10-13 Oct 22	Unexpected flight computer reset, recovered	22
25 Nov 22	ICON	NASA	LEO	Loss of contact with spacecraft 25 Nov 22, not recovered as of 10 Feb 23	Unknown; operating in extended mission since completing 2-yr prime mission science objectives	23,24
16 Nov 22	Orion (Artemis I)	NASA/ESA	Cislunar	RAM error in star tracker system, power conditioning and distribution unit (PCDU) fault	Thruster glow impact star tracker PCDU umbilical latching current limiter opened without command	25,26
16 Nov 22	Artemis I CubeSats	NASA	Cislunar	No comm with 5 of 10 deployed cubesats	LunaHMap (thruster failure), OMOTENASHI (no stable comm), NEAScout (no comm), CuSP (comm failed), LunIR (weak comm)	27
3 Nov 22	Orion (Artemis I)	NASA	Cislunar	Loss of comm with Orion for 47 minutes		28
7 Nov 22	Cygnus	NASA/NG	LEO	1 of 2 solar arrays fail to deploy	Vehicle successfully arrived at ISS to complete cargo mission	13
11 Dec 22	Orion (Artemis I)	NASA	LEO	Unpredicted loss of thermal protection (reentry heat shield) material	Vehicle survived reentry, but heat shield lost more charred material than expected	29
14 Dec 22	Lunar Flashlight	NASA	Cislunar	Reduced thruster performance	Fuel line obstruction	30
14 Dec 22	Soyuz MS-22	RSA	LEO	Coolant leak from thermal control system while docked to ISS	0.8 mm hole, meteoroid or orbital debris impact, Geminid meteor eliminated as cause	31,32,33, 34,35
3 Jan 23	Falcon-9/Transporter-6	SpaceX/USSF (US)	LEO	EWS RROCI spacecraft failed to deploy from launch vehicle, 113 of 114 payloads successfully deploy	Unclear if failure to deploy is spacecraft or launch vehicle failure; 195th flight	44,45,46

*References in backup

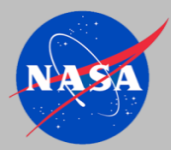


Selected Spacecraft Anomalies and Failures: 2022 and 2023

Date	Mission	Affiliation	Environment	Event	Cause/Notes	Ref*
3 Jan 23	Orbiter SN1	Launcher	LEO	Loss of power and control; failure to deploy 6 payloads, 4 hosted payloads lost	Orientation issue due to GPS antennae fault resulted in loss of power	37,38,53, 54
15 Jan 23	JWST	NASA/CSA	L2	NIRISS instrument comm delay, software timeout	GCR upset in FPGA, recovered	21
Mid Jan 23	SWOT	NASA	LEO	Ka-band Radar Interferometer (KaRIn) instrument high-power amplifier unexpectedly shut down		39,40
11 Feb 23	Progress MS-21	RSA	LEO	Coolant leak from thermal control system while docked to ISS	12 mm hole caused by “external influences”	36
16 Feb 23	MAVEN	NASA	Mars	Safe mode 16-17 Feb 22	Inertial Measurement Unit anomaly	41
18 Feb 23	IBEX	NASA	86,000 km x 260,000 km x 10.99°	Unresponsive to commands following flight computer reset	External reset successful on 2 March 23, reestablishing control of spacecraft (2 days before IBEX scheduled for autonomous power reset)	42,43
27 Feb 23	Starlink 6-1	SpaceX	LEO	Issues with new Starlink V2 design	<i>“...new technology in Starlink V2... experiencing some issues, as expected. Some sats will be deorbited, others will be tested thoroughly before raising altitude above Space Station.”</i> E. Musk	50,51

Notes:

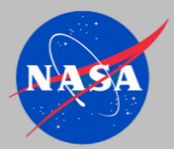
- **End of mission:** Starlink (38), Geotail, Galaxy-15?, ICON? Artemis CubeSats (5), Soyuz MS-22, EWS RROCI, Orbiter SN1 (and 10 payloads)
- **Anomalies/failure attributed to space environment:** (6/30 missions)
 - Ionizing radiation 2 (Orion, JWST)
 - M/OD 2 (Soyuz, JWST)
 - Atmospheric drag 1 (Starlink: 38 satellites)
 - Charging 1 (Galaxy-15)



Selected Launch Vehicle* Anomalies and Failures: 2022 and 2023

Date	Launch Vehicle	Affiliation	Mission	Event	Cause/Notes	Payloads Lost	Ref**
10 Feb 22	Rocket 3.3 (LV0008)	Astra (US)	Orb	Upper stage engine ignition before fairing separation, vehicle tumbling after the off-nominal stage separation	Fairing separation mechanism fired in incorrect order resulted in electrical anomaly and fairing separation failure; Upper stage engine unable to use Thrust Vector System due to software issue; Rocket 3.3 third flight	4	1,2,3
13 May 22	Hyperbola 1	iSpace (China)	Orb	2 nd stage failed to ignite? Attitude control system anomaly?	iSpace = Beijing Interstellar Glory Space Tech. Ltd; third flight (all failures)	1	1,4,5
12 Jun 22	Rocket 3.3 (LV0010)	Astra (US)	Orb	Upper stage engine failure	Engine ran out of fuel and shut down early; fifth flight Rocket 3.3, only 2 of 5 3.3 missions were successful, 3.3 cancelled	2	1,6
7 Aug 22	SSLV	ISRO (India)	Orb	Final Velocity Trimming Module (VTM) stage failure, payloads in unstable orbits and lost	Unexpectedly strong shock during separation of 2 nd stage saturated guidance system accelerometers, triggered "salvage mode"; payload deployed into unacceptably low orbit; first flight	2	1,7,8
12 Sep 22	New Shepard	Blue Origin (US)	Suborb	Rocket failure (uncrewed science mission); fire in BE-3 engine, escape system carried capsule away from exploding rocket	Single BE-3PM booster engine suffered structural fatigue failure of nozzle, caused thrust misalignment that triggered the capsule's emergency escape system; 23rd launch	---	1,9,10 , 42,45
1 Oct 22	Alpha	Firefly (US)	Orb	Payloads inserted into incorrect orbits, reenter early	Provider declare launch success, but payloads decayed early; second flight	3	1,11,12
8 Oct 22	Skylark L	Skyrora (Scotland)	Suborb	Booster failure	First flight	---	1,13
11 Oct 22	Epsilon	JAXA (Japan)	Orb	3 rd stage ignition failure	Attitude control anomaly during 2 nd stage coast; first flight	8	1,14,15,16,41
4 Nov 22	Long March 6A	China	Orb	Upper stage breakup, uncontrolled reentry	Successfully deployed Yunahi 3 satellite, subsequent breakup event initially released 50+ debris objects, over 350 cataloged by December; second flight LM 6A (LM 6 launched 10 successfully)	0	1,17,18,39,40

*Does not include pre-launch delays ("scrubs") or suborbital missile tests **References in backup



Selected Launch Vehicle* Anomalies and Failures: 2022 and 2023

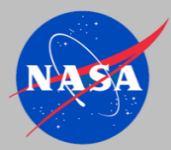
Date	Launch Vehicle	Affiliation	Mission	Event	Cause/Notes	Payloads Lost	Ref**
14 Dec 22	Zhuque-2	Landspace (China)	Orb	Early shutdown of 2nd stage engine	2 nd stage vernier engine anomaly; first flight	14	1,19,20,21
20 Dec 22	Vega-C	Arianespace (France)	Orb	2 nd stage engine anomaly	Under pressure in 2 nd stage engine following launch and trajectory deviation, nozzle erosion; second flight	2	1,22, 23,36, 38
9 Jan 23	LauncherOne	Virgin Orbit (US)	Orb	2 nd stage engine failure (Boeing 747 launch)	Filter dislodged in engine (\$100 part); 6th flight	9	24,25,26, 37
10 Jan 23	RS1	ABL Space Systems (US)	Orb	Premature shutdown of all 9 of the RS1 first-stage engines at T+11 sec	Fire in RS1 avionics system, total electrical failure triggered engine shutdown; first flight	2	27,28,29, 30
7 Mar 23	H3	JAXA (Japan)	Orb	H3 rocket fails following launch, 2 nd engine fails to ignite	H3 first test flight	1	34,35
22 Mar 23	Terran-1	Relativity Space	Orb	2 nd stage engine anomaly	First 3-D printed rocket; first flight	---	43,44

Notes:

- Launch anomalies/failures typically result in loss of mission (reporting bias?) 14/15 missions, 48 payloads lost
- Many LV anomalies/failures occur early in program development:
 - 1st flight 7
 - 2nd flight 3
 - 3rd flight 2
 - 5th flight 1
 - 6th flight 1
 - >10 flights 1 (New Shephard: 23rd flight)

Total

15

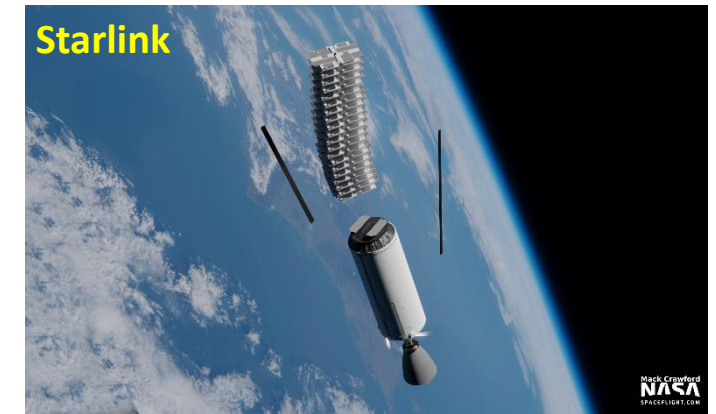


Anomalies and Failures

- The term “anomaly” often has a negative connotation for a spacecraft operator, in many cases the “anomaly” turns out to be:
 - Unexpected or unpredicted space environment interactions
 - Accidental: *collision, design flaws leading to breakup*
 - Deliberate: ASAT test, EOL destruct
 - Engineering failures that could have been prevented: *well, these are truly design or ops failures*
- Anomalies and failure investigations and mitigation processes can be grouped into four broad categories:
 - **Initial stage:** anomaly identified, cause(s) under investigation
 - **Mid-stage:** potential cause(s) identified, mitigation strategy(s) under development
 - **Mature stage:** cause(s) well understood, mitigation procedures in place
 - **Failure:** end of mission, cause(s) may have been identified, but no mitigation is possible
- I have three examples to show that demonstrate these stages:
 - Soyuz radiator anomaly (initial)
 - Starlink satellite losses (mid)
 - Chandra X-ray Observatory radiation interrupts (mature)

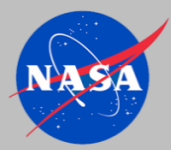


Robotic arm surveys Soyuz MS-22 after a radiator leak (NASA TV)



<https://www.nasaspacesflight.com/2022/02/starlink-geostorm/>





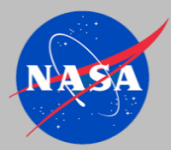
Soyuz, Progress Coolant Leaks

- Soyuz and Progress vehicles both experienced coolant leaks in radiator system on the spacecraft service module while docked to ISS
 - Soyuz MS-22 (crew) 14 Dec 2022 0.8 mm hole
 - Progress MS-21 (cargo) 11 Feb 2023 12 mm hole
- Roscosmos indicated the cause for the leaks was
 - Soyuz meteoroid or orbital debris
 - Progress “external influences” but not necessarily MMOD
- Mission impacts:
 - Russian EVA scheduled 14-15 Dec cancelled (crew suited up and waiting in airlock to egress when notified)
 - Crew rotation delayed while new Soyuz MS-23 launched to ISS to replace MS-22
- Two similar anomalies in similar locations on similar vehicles within a period of 2 months is unusual!
 - Investigation continues, trying to understand if there is a common cause or other causal factor in radiator panel leaks
 - Ground tests planned to simulate the damage



Sources::

- <https://www.space.com/soyuz-spacecraft-leak-photos-russia-space-agency>
- <https://spacepolicyonline.com/news/progress-ms-21-leak-due-to-external-impact/>
- <https://spaceflightnow.com/2023/02/21/russia-blames-progress-coolant-leak-on-external-influences-as-replacement-soyuz-rolls-to-launch-pad/>
- <https://spacenews.com/replacement-soyuz-arrives-at-space-station/>



Starlink Group 4-7

- SpaceX Group 4-7 launch of 49 Starlink satellites on 3 Feb 2022 encountered a minor geomagnetic storm on the day following launch, resulting in the loss of 38 Starlink satellites

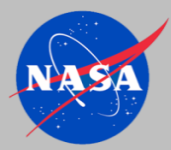
SpaceX Update, February 8, 2022 (<https://www.spacex.com/updates/>)

Unfortunately, the satellites deployed on Thursday [Feb 3] were significantly impacted by a geomagnetic storm on Friday. These storms cause the atmosphere to warm and atmospheric density at our low deployment altitudes to increase. In fact, onboard GPS suggests the escalation speed and severity of the storm caused atmospheric drag to increase up to 50 percent higher than during previous launches. The Starlink team commanded the satellites into a safe-mode where they would fly edge-on (like a sheet of paper) to minimize drag—to effectively “take cover from the storm”—and continued to work closely with the Space Force’s 18th Space Control Squadron and LeoLabs to provide updates on the satellites based on ground radars.

Starlink reentry over Puerto Rico



<https://room.eu.com/news/spacex-starlink-satellites-fall-out-of-sky-after-storm>



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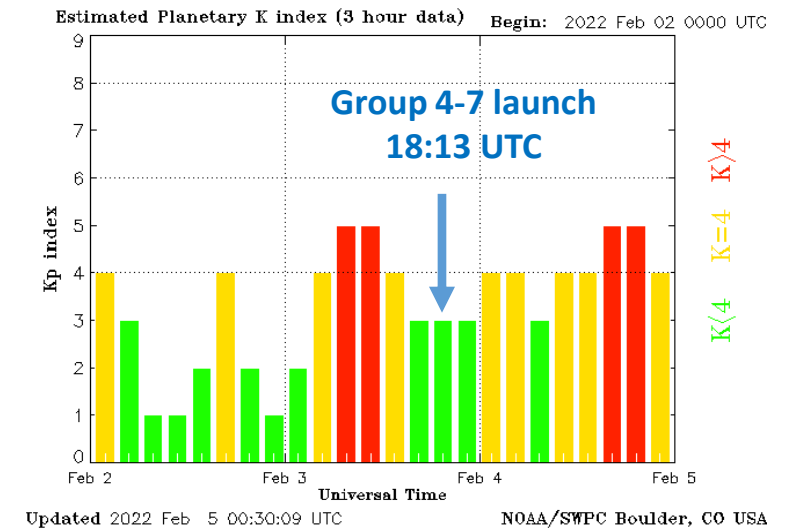
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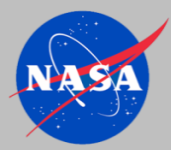
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- Geomagnetic activity on 3 and 4 February were not that severe, at best only minor storm levels:
 - Maximum Kp never exceeded Kp 4 or 5 during the minor geomagnetic storms on both days
 - Hourly ap values never exceeded 56
 - Peak Dst was only -66 nT



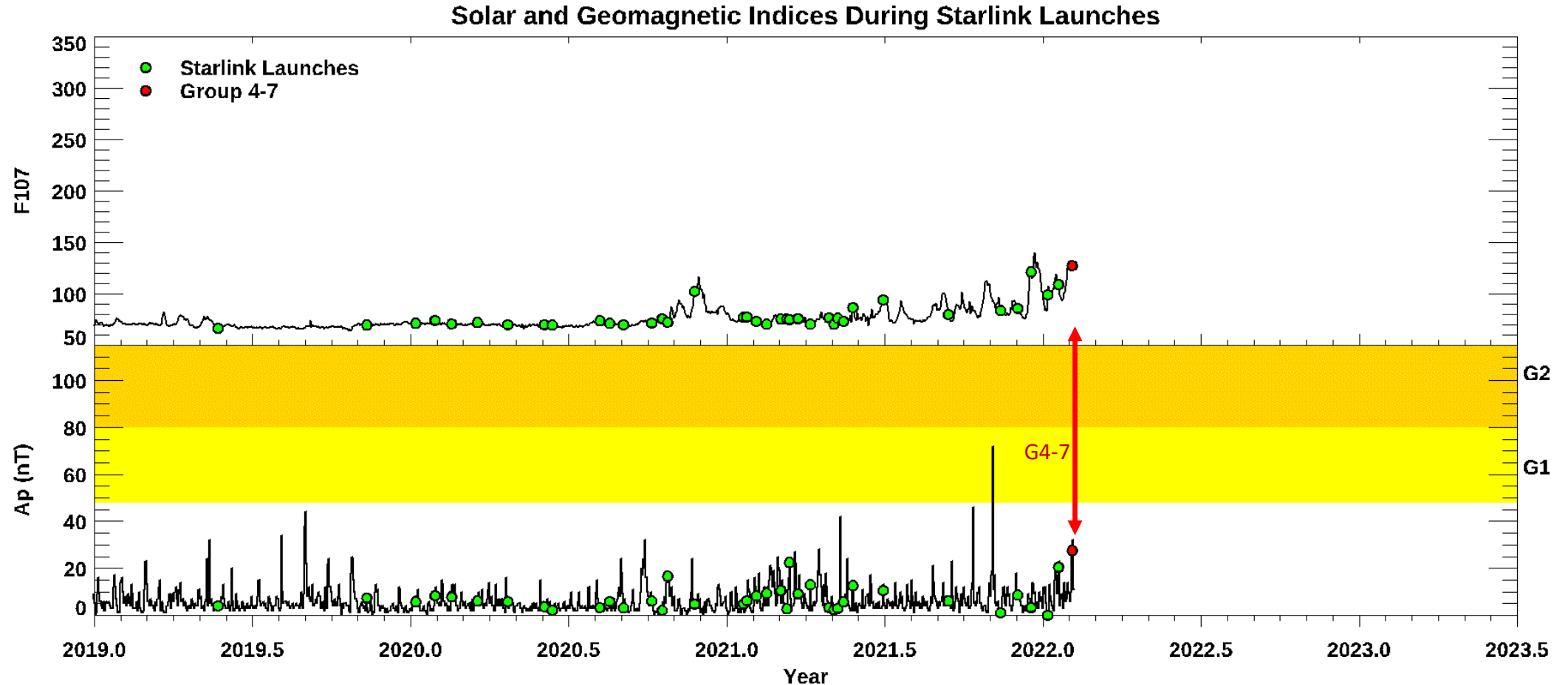
<https://room.eu.com/news/spacex-starlink-satellites-fall-out-of-sky-after-storm>



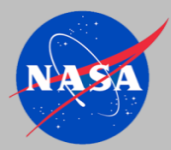


Starlink Group 4-7

- SpaceX Starlink launch operations started during the solar minimum period between Solar Cycle 24 and 25
- Solar and geomagnetic activity are both increasing as we move into Solar Cycle 25

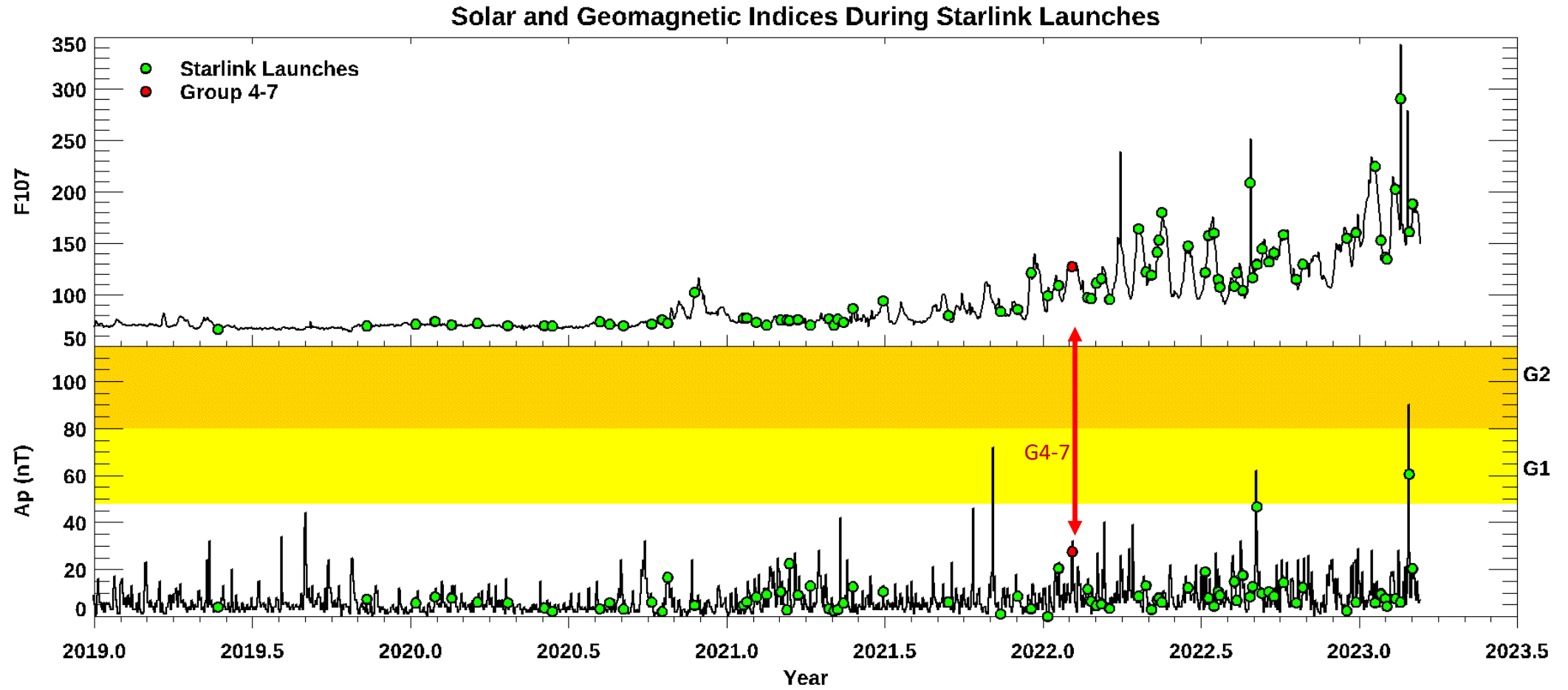


Note: if 3-hour ap had been used instead of the daily average Ap, the hourly ap 48 and 56 values would have been in the low G1 range.

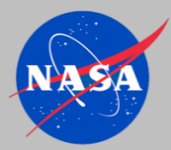


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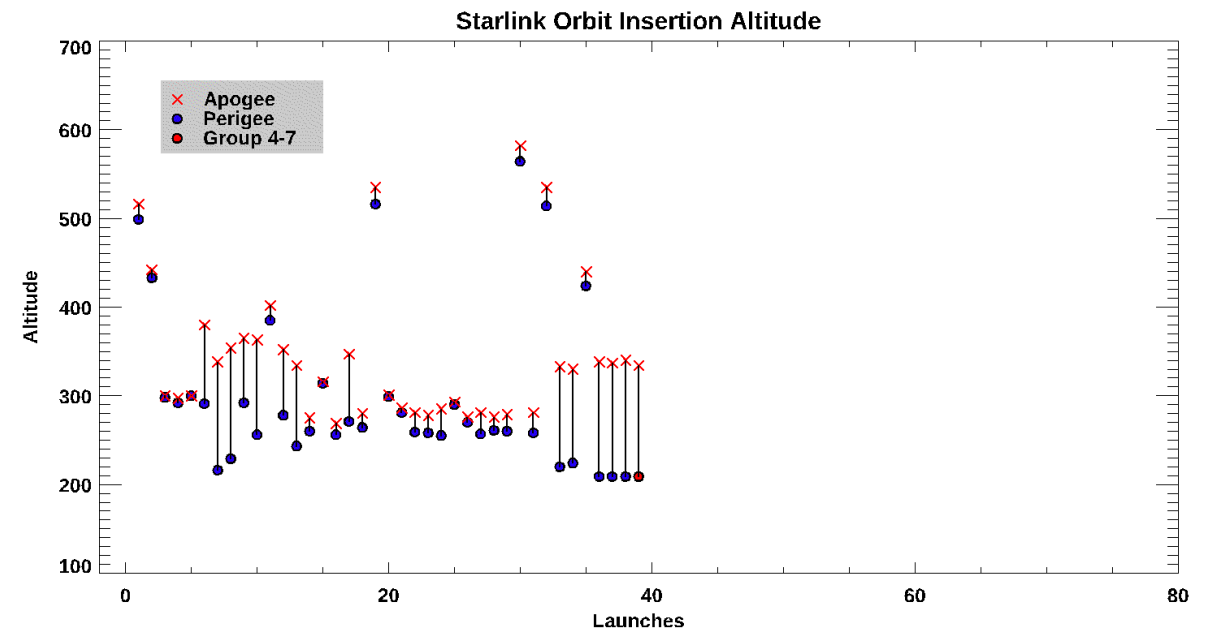
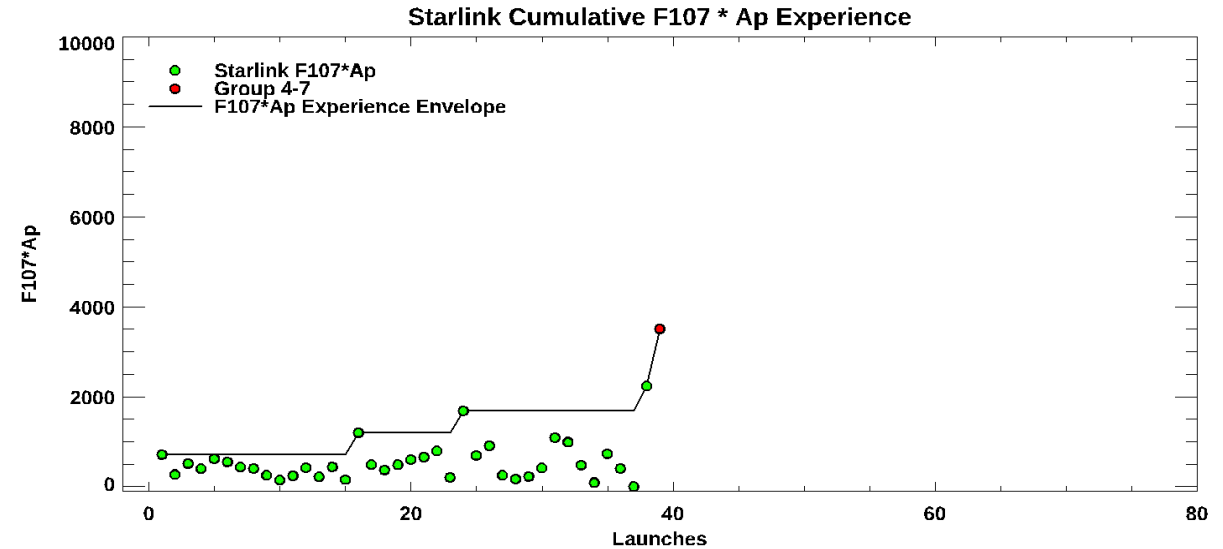


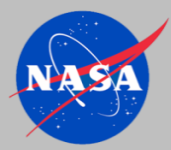
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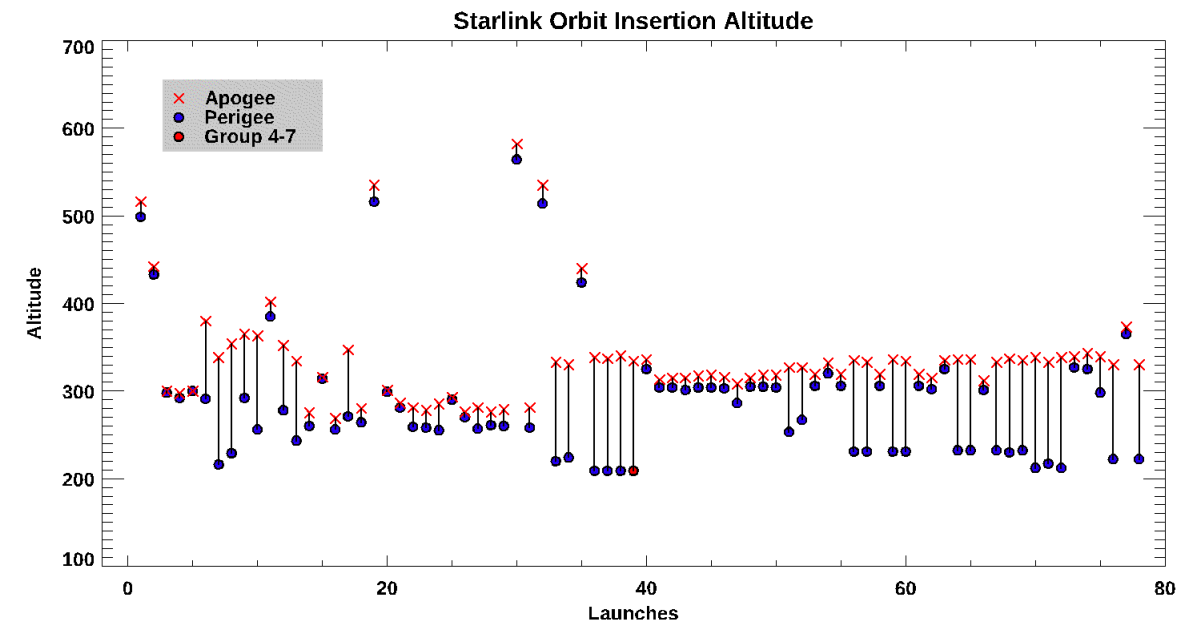
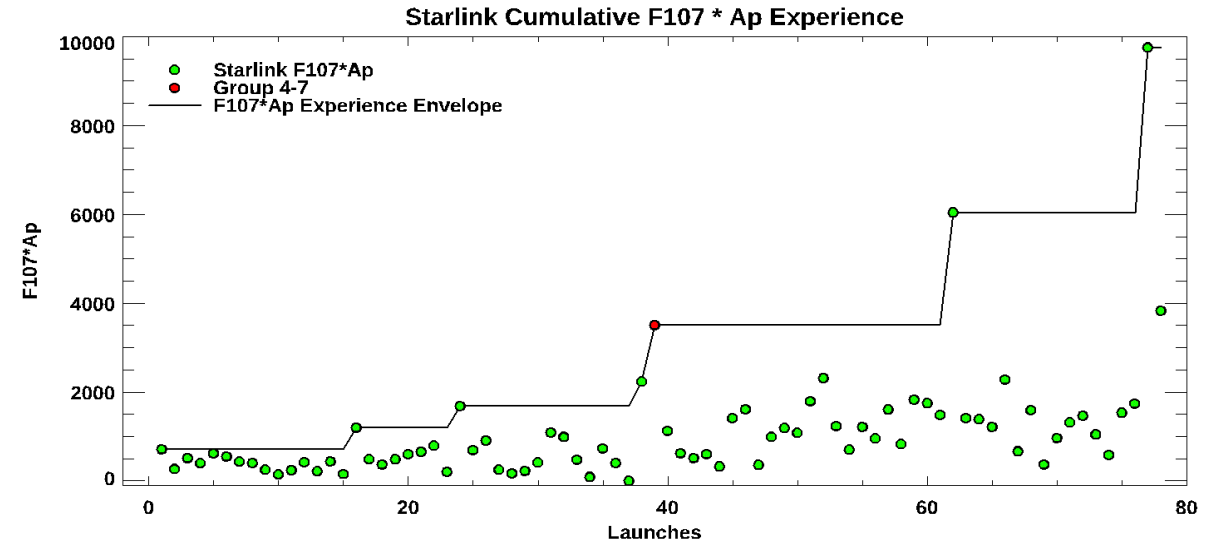
- The F107*Ap product is a proxy for the combined effects of solar and geomagnetic activity, demonstrating an “experience envelope” for space weather conditions associated with atmospheric drag during Starlink launches
- Starlink “experience envelope” in solar and geomagnetic activity gradually increased until the Feb 2022 events where 38 satellites were lost

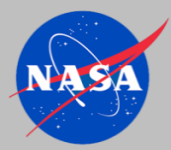




Starlink Group 4-7

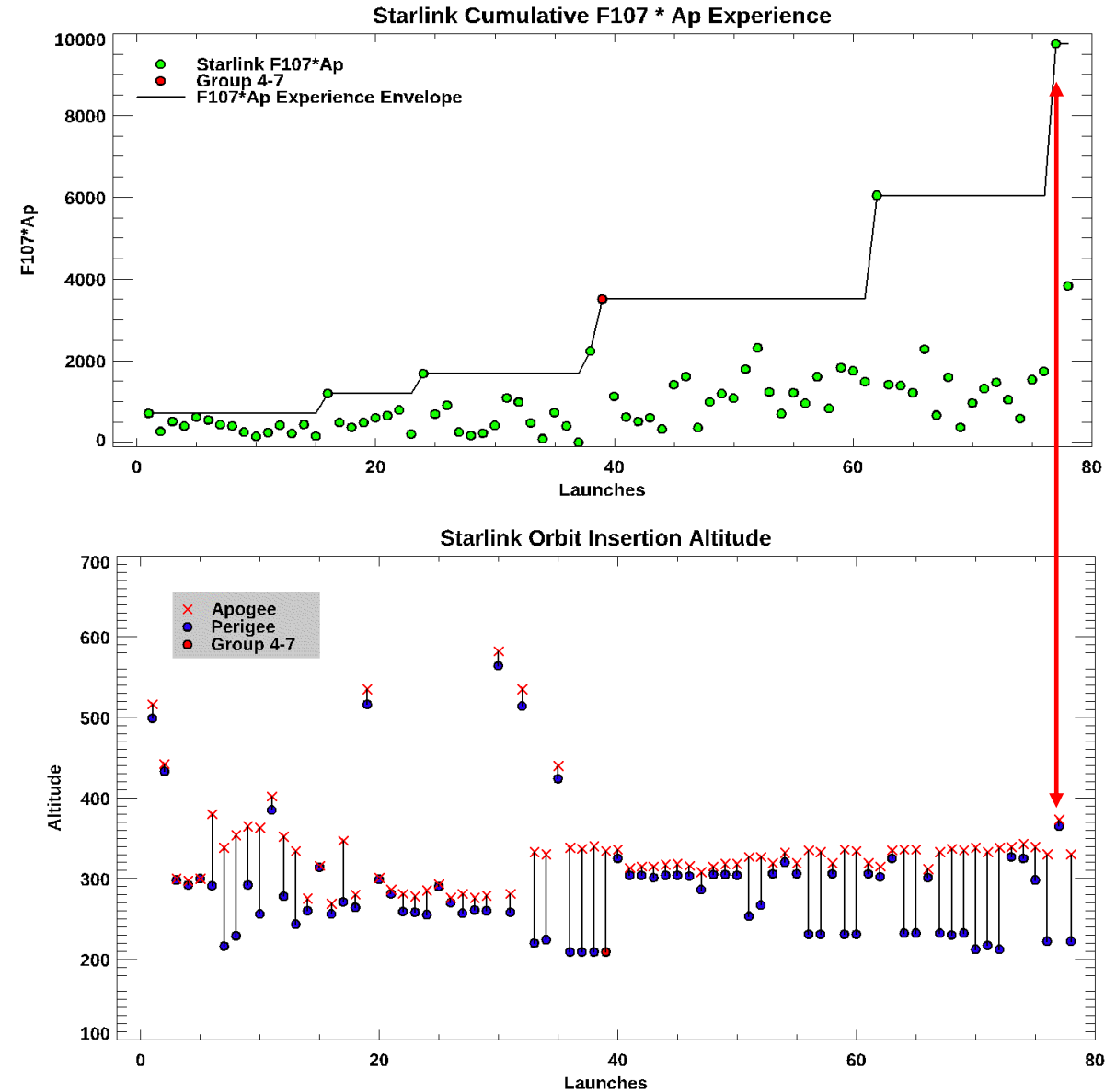
- The F107*Ap product is a proxy for the combined effects of solar and geomagnetic activity, demonstrating an “experience envelope” for space weather conditions associated with atmospheric drag during Starlink launches
- Starlink “experience envelope” in solar and geomagnetic activity gradually increased until the Feb 2022 events where 38 satellites were lost
- Following the Group 4-7 satellite losses, SpaceX altered their orbit insertion altitude to reduce the threat of increased drag at low altitudes during high solar and geomagnetic activity
- More recent launches are back to using low altitude perigee but the apogee altitude remain ≥ 300 km which does reduce the overall drag, however many insertion orbits are now similar to the one used for Group 4-7

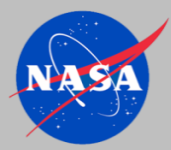




Starlink Group 4-7

- The F107*Ap product is a proxy for the combined effects of solar and geomagnetic activity, demonstrating an “experience envelope” for space weather conditions associated with atmospheric drag during Starlink launches
- Starlink “experience envelope” in solar and geomagnetic activity gradually increased until the Feb 2022 events where 38 satellites were lost
- Following the Group 4-7 satellite losses, SpaceX altered their orbit insertion altitude to reduce the threat of increased drag at low altitudes during high solar and geomagnetic activity
- More recent launches are back to using low altitude perigee but the apogee altitude remain ≥ 300 km which does reduce the overall drag, however many insertion orbits are now similar to the one used for Group 4-7
- Group 6-1 launched 23:13 UT on 27 February 2023 at the end of a day with $K_p = 6, 6+,$ and $7-$ geomagnetic storm conditions, one of the strongest geomagnetic storms this solar cycle! Launch deployed 21 Starlink v2-mini satellites at ~ 370 km with new spacecraft design.

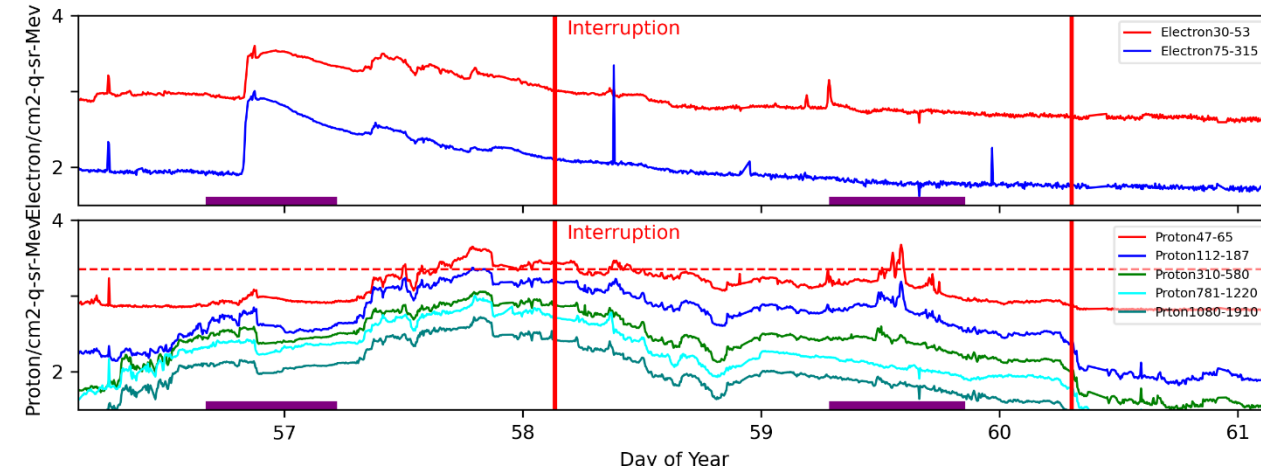




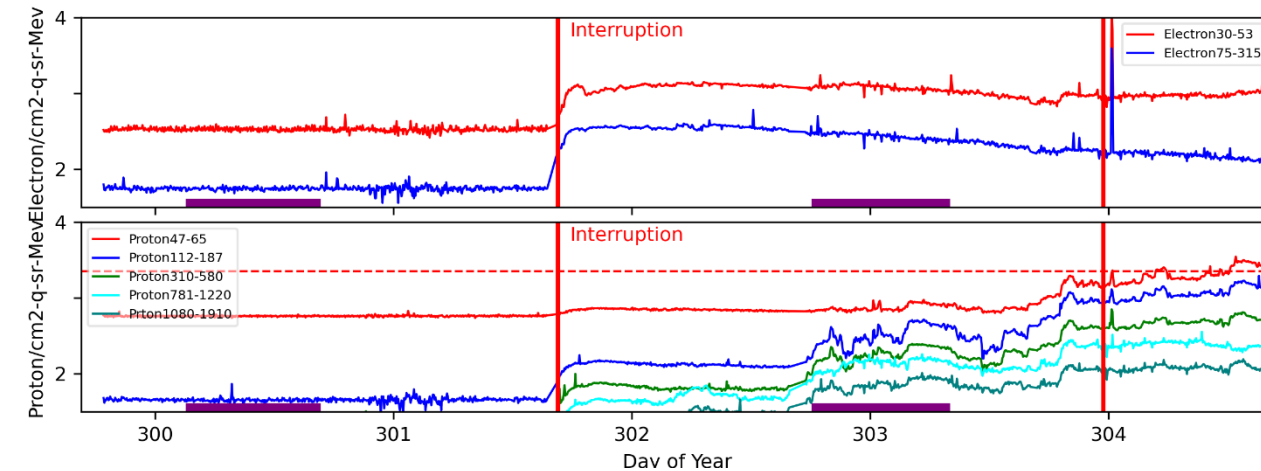
Chandra X-Ray Observatory

- Launched July 1999, Chandra is now in the 24th year of operations
 - Initial orbit 16,000 km x 133,000 km x 28.5° (~64 hr)
 - Current orbit 1,538 km x 147,259 km x 38.8°
- The *Advanced CCD Imaging Spectrometer* (ACIS) instrument experienced an anomaly characterized by rapid performance degradation in front illuminated CCDs with no damage to back illuminated CCDs during initial flight operations in 1999
- Chandra identified weakly penetrating, low energy (0.1-0.5 MeV) protons present during radiation belt transits and solar particle events as the cause
- The low energy radiation damage mechanism was not predicted before flight
- Operating procedures were modified to move ACIS to a protected location out of the focal position during radiation belt passes, solar particle events
- While the radiation-protection program impacts science operations, it has been highly successful in limiting radiation damage to the ACIS CCDs to acceptable levels

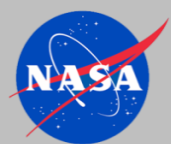
2023/02/27 140.8 ks (39.1 hrs) manual



2021/10/28 197.7 ks (54.9 hrs) auto



<https://cxc.harvard.edu/mta/RADIATION/>



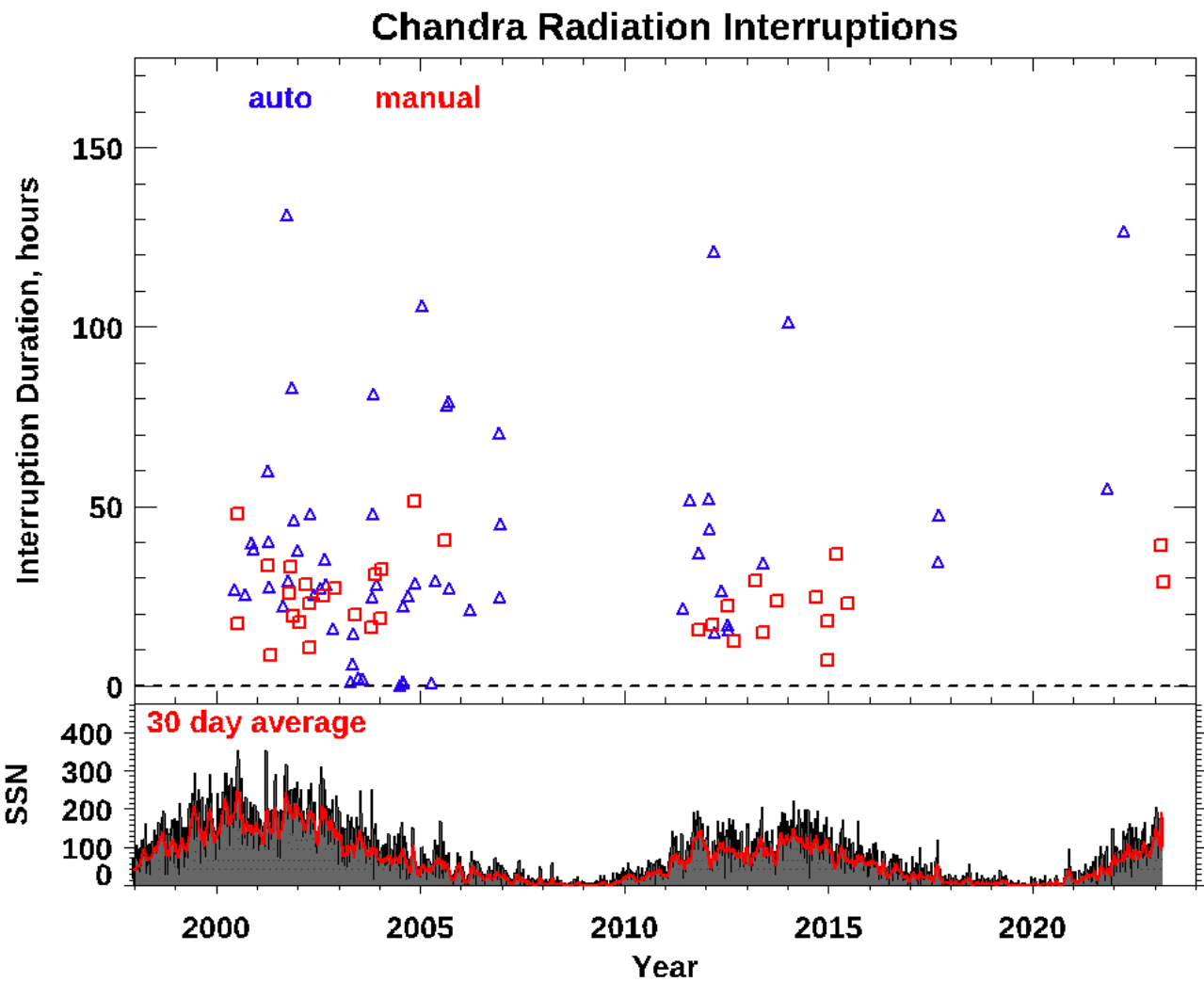
Chandra X-Ray Observatory

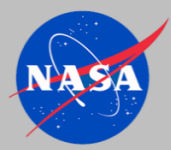
- Protecting the operational life of ACIS with auto and manual radiation interventions comes at the cost of lost science time
- Chandra science observations have been interrupted 95 times due to radiation events for a total of 3197.9 hours (~0.36 year) in its ~25 year operational life

Solar Cycle	Number of Interrupts		Lost Science Time (hours)	
	auto	manual	auto	manual
23	45	20	1556.3	528.2
25	14	12	619.0	244.6
25	2	2	181.6	68.2
Total	61	34	2356.9	841.0

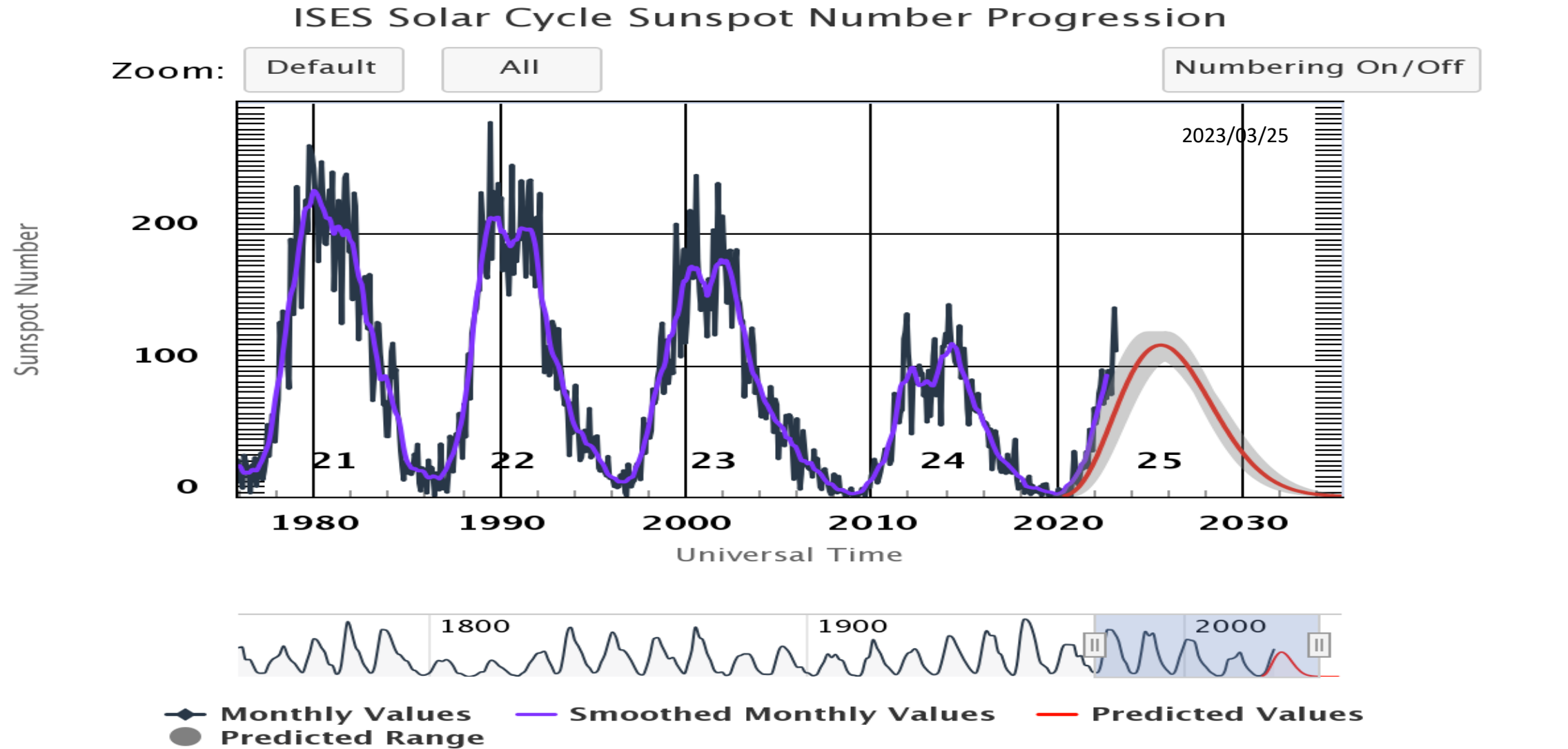
Sources:

- O'Dell et al., Managing radiation degradation of CCDs on the Chandra X-ray Observatory III, *Proc. SPIE 6686, UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XV*, 668603 (18 September 2007)
<https://doi.org/10.1117/12.734594>
<https://ntrs.nasa.gov/api/citations/20070039074/downloads/20070039074.pdf>
- <https://cxc.harvard.edu/mta/RADIATION/>
- <https://chandra.harvard.edu/about/tracking.html>
- <https://www.space-track.org/>



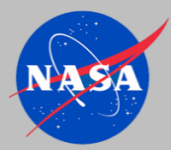


Solar Activity



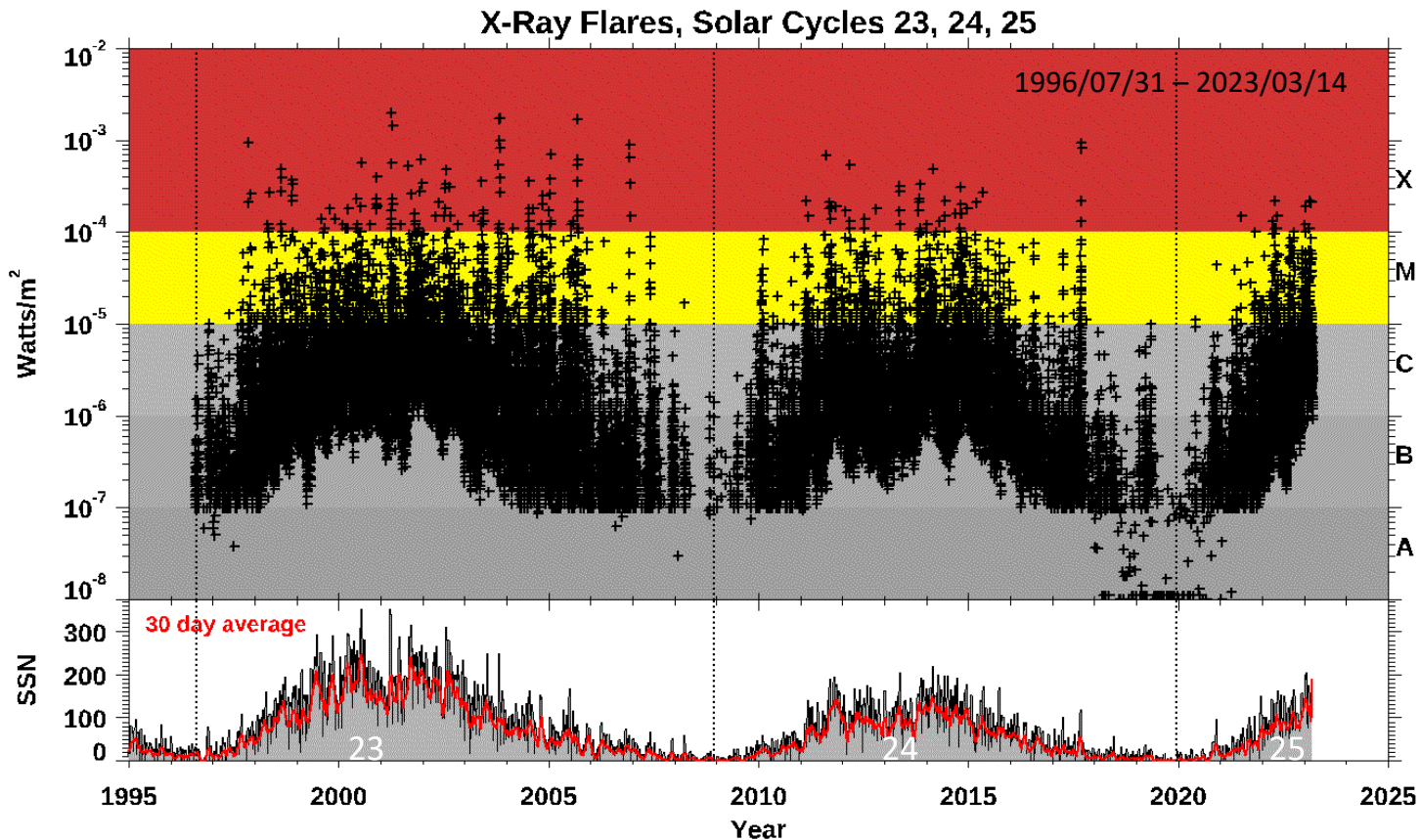
Space Weather Prediction Center

<https://www.swpc.noaa.gov/products/solar-cycle-progression>



Solar X-Ray Flares

- Major SWx impact of x-ray flares is increased ionization in the D-region ionosphere which interferes with terrestrial HF radio systems
- Large M and X class flares are correlated with coronal mass ejections and solar particle events (SPE) which can potentially impact satellite operations
- X-ray flares can provide advanced warning for geomagnetic storms, SPEs



X-ray flare data source:

<https://www.swpc.noaa.gov/products/solar-and-geophysical-event-reports>

100 Largest X-Ray Flares in Cycles 23, 24, and 25

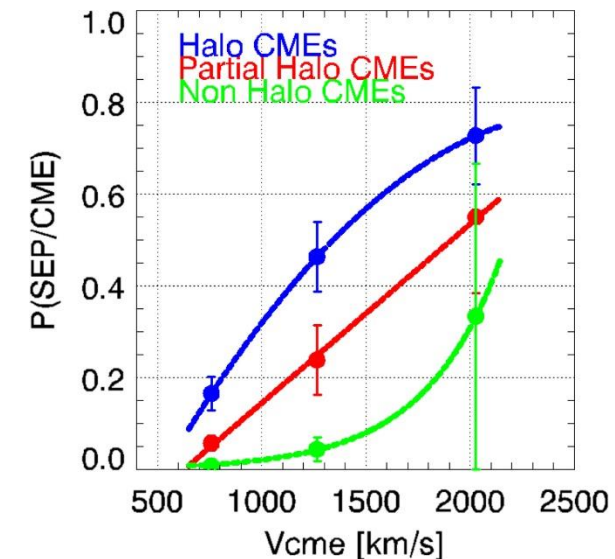
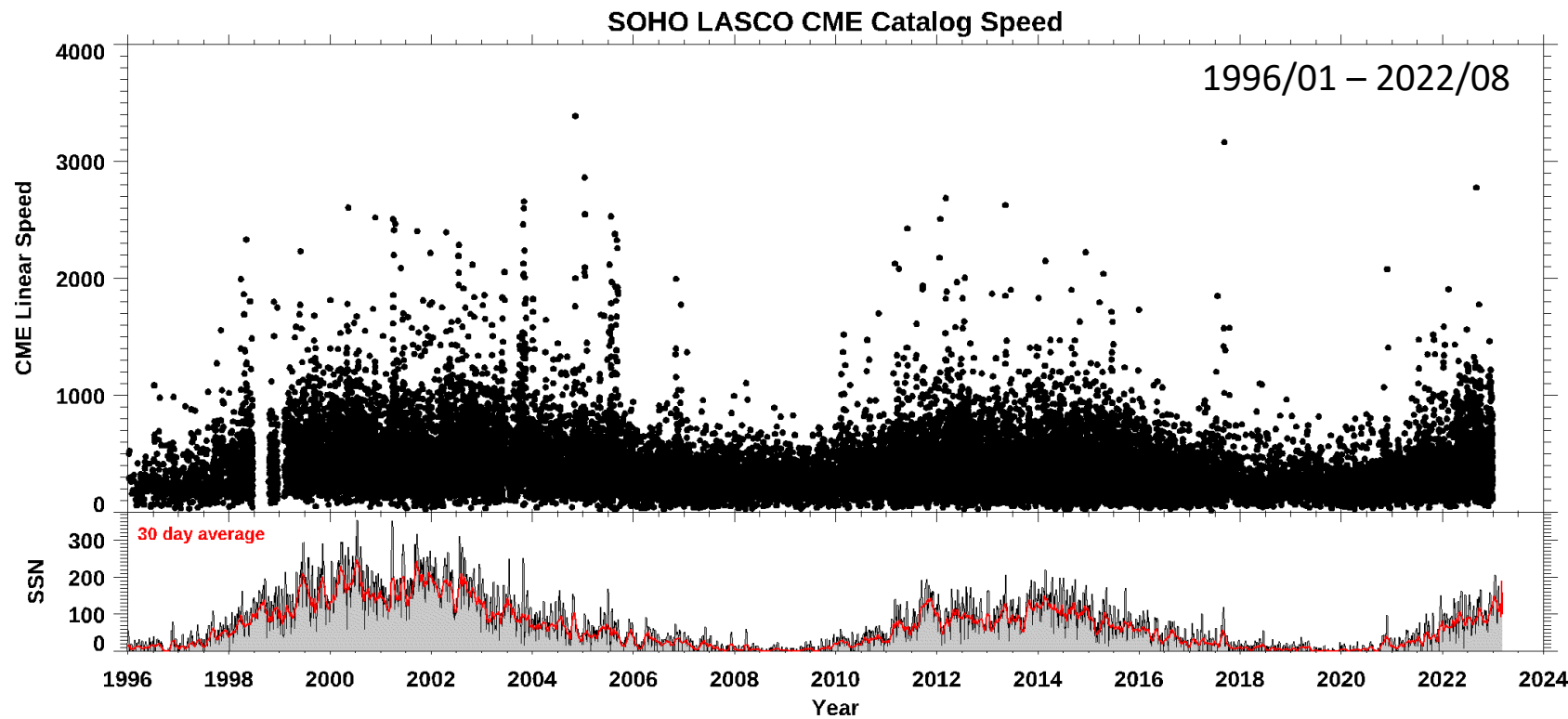
Rank	YYYY	DOY	HH:MM	Class	Cycle
1	2001	092	21:51	X2.0	23
2	2003	308	19:53	X17.4	23
3	2003	301	11:10	X17.2	23
4	2005	250	17:40	X17.0	23
5	2001	105	13:50	X14.4	23
6	2003	302	20:49	X10.0	23
7	1997	310	11:55	X9.4	23
8	2017	249	12:02	X9.3	24
9	2006	339	10:35	X9.0	23
10	2003	306	17:25	X8.3	23
11	2017	253	16:06	X8.2	24
12	2005	020	07:01	X7.1	23
13	2011	221	08:05	X6.9	24
14	2006	340	18:47	X6.5	23
15	2005	252	20:04	X6.2	23
16	2001	347	14:30	X6.2	23
17	2000	196	10:24	X5.7	23
18	2001	096	19:21	X5.6	23
19	2012	067	00:24	X5.4	24
20	2005	251	21:06	X5.4	23
21	2003	296	08:35	X5.4	23
22	2001	237	16:45	X5.3	23
23	1998	230	22:19	X4.9	23
24	2014	056	00:49	X4.9	24
25	2002	204	00:35	X4.8	23
26	2000	331	16:48	X4.0	23
27	2003	307	09:55	X3.9	23
28	1998	231	21:45	X3.9	23
29	2005	017	09:52	X3.8	23
30	1998	326	06:42	X3.7	23
31	2005	252	09:59	X3.6	23
32	2003	148	00:27	X3.6	23
33	2004	198	13:55	X3.6	23
34	2006	347	02:40	X3.4	23
35	2001	362	20:45	X3.4	23
36	2002	201	21:30	X3.3	23
37	1998	332	05:52	X3.3	23
38	2013	309	22:12	X3.3	24
39	2013	134	01:11	X3.2	24
40	2002	236	01:12	X3.1	23
41	2014	297	21:41	X3.1	24
42	2002	196	20:08	X3.0	23
43	2013	133	16:05	X2.8	24
44	1998	230	08:24	X2.8	23
45	2001	345	08:08	X2.8	23
46	2003	307	01:30	X2.7	23
47	1998	126	08:09	X2.7	23
48	2015	125	22:11	X2.7	24
49	1997	331	13:17	X2.6	23
50	2005	015	23:02	X2.6	23
51	2001	267	10:38	X2.6	23
52	1998	326	16:23	X2.5	23
53	2004	315	02:13	X2.5	23
54	2000	158	15:25	X2.3	23
55	2000	329	15:13	X2.3	23
56	2013	302	21:54	X2.3	24
57	2001	100	05:26	X2.3	23
58	2023	048	20:16	X2.2	25
59	2022	110	03:57	X2.2	25
60	2017	249	09:10	X2.2	24
61	2014	161	11:42	X2.2	24
62	1998	327	06:44	X2.2	23
63	2011	046	01:56	X2.2	24
64	1997	308	05:58	X2.1	23
65	2013	298	15:03	X2.1	24
66	2023	062	17:52	X2.1	25
67	2011	249	22:20	X2.1	24
68	2015	070	16:22	X2.1	24
69	2002	140	15:27	X2.1	23
70	2005	253	22:11	X2.1	23
71	2001	102	10:28	X2.0	23
72	2004	312	16:06	X2.0	23
73	2000	329	05:02	X2.0	23
74	2014	300	14:47	X2.0	24
75	2014	299	10:56	X2.0	24
76	2023	009	18:50	X1.9	25
77	2011	307	20:27	X1.9	24
78	2011	267	09:40	X1.9	24
79	2000	194	10:37	X1.9	23
80	2000	330	18:44	X1.9	23
81	2014	354	00:28	X1.8	24
82	2000	329	21:59	X1.8	23
83	2004	231	17:40	X1.8	23
84	2012	297	03:17	X1.8	24
85	1999	287	09:00	X1.8	23
86	2002	199	07:44	X1.8	23
87	2000	084	07:52	X1.8	23
88	2004	197	01:41	X1.8	23
89	2011	250	22:38	X1.8	24
90	2003	160	21:39	X1.7	23
91	2013	298	08:01	X1.7	24
92	2005	001	00:31	X1.7	23
93	2001	088	10:15	X1.7	23
94	2012	027	18:37	X1.7	24
95	2005	256	23:22	X1.7	23
96	2013	133	02:17	X1.7	24
97	2003	162	20:14	X1.6	23
98	2014	253	17:45	X1.6	24
99	2001	292	01:05	X1.6	23
100	2014	311	17:26	X1.6	24

Largest Cycle 25 x-ray flares to date have only been low X-class events

- CME linear speeds from the SOHO LASCO CME Catalog provides a good summary of CME occurrence and velocity as a function of phase in solar cycle
- Fast CMEs are particularly geoeffective, driving geomagnetic storms and solar energetic particle events
- Relativistic electron enhancements in the radiation belts (internal charging), magnetospheric hot plasma (surface charging), and solar protons and heavy ions (single event effects) are correlated with CME activity



<https://soho.nascom.nasa.gov/gallery/Movies/flares.html>

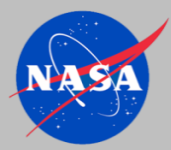


Papaoiou et al., 2018

Plane-of-sky velocity from SOHO LASCO images

URL: https://cdaw.gsfc.nasa.gov/CME_list/

- This CME catalog is generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory.
- SOHO is a project of international cooperation between ESA and NASA.

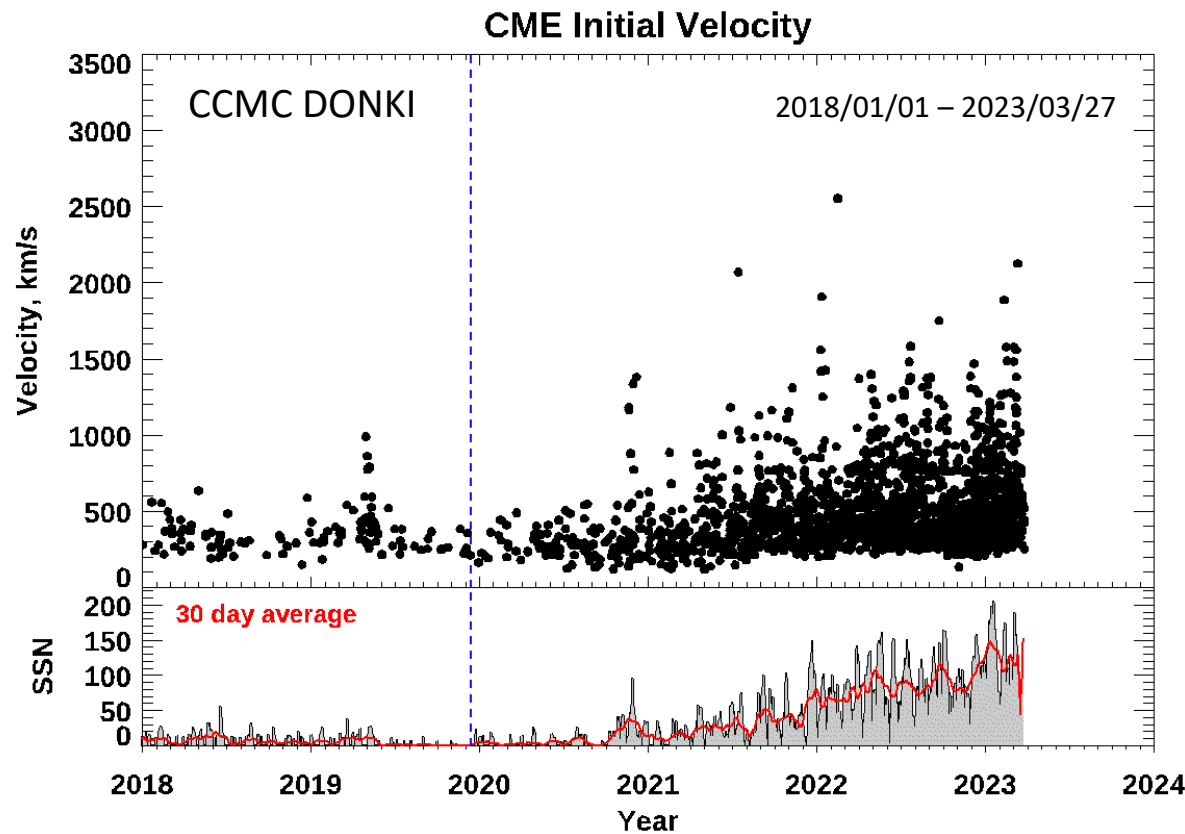


CME Initial Velocity: 2018 to present

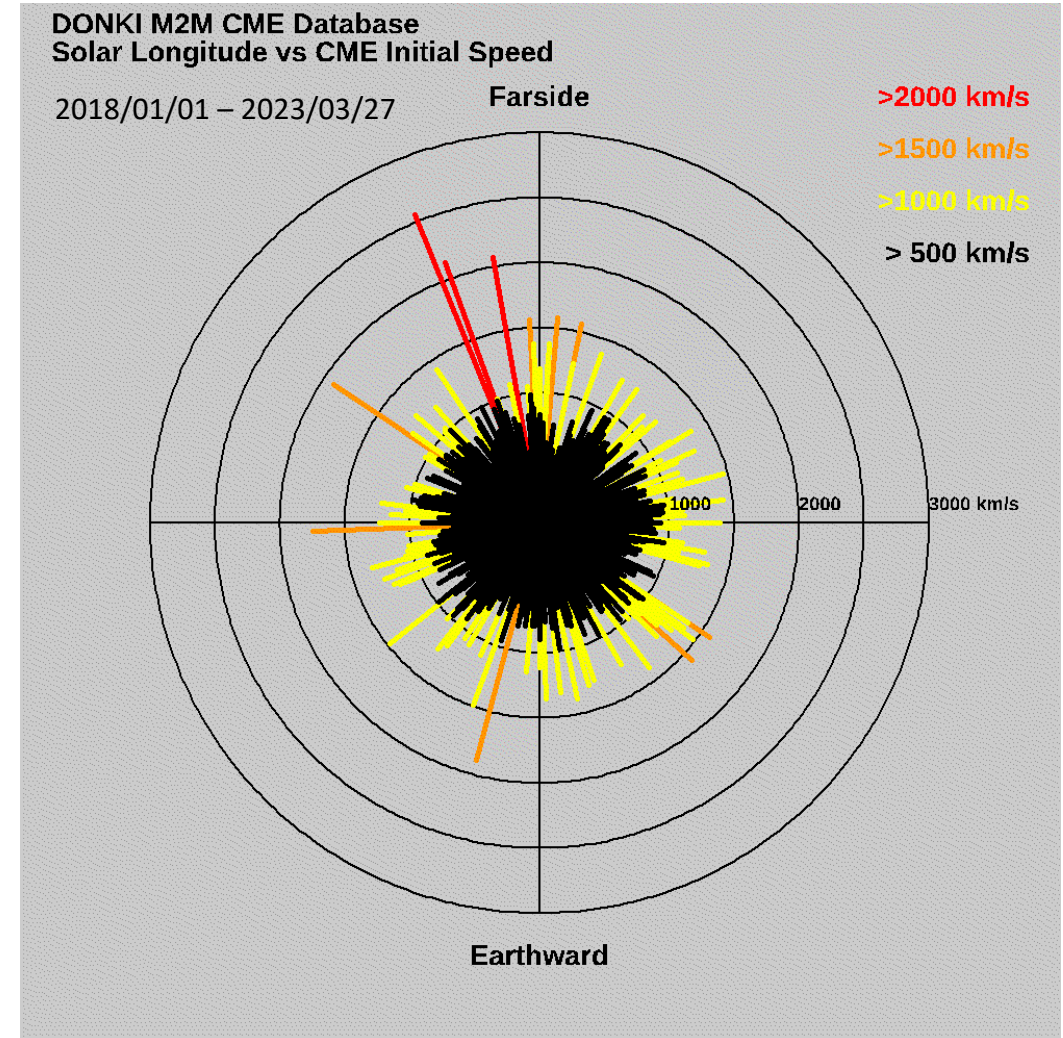
- CMEs are increasing in number and larger number of high speed CMEs as solar activity increases
- Fastest CMEs (>2000 km/s) to date are farside events with no direct impact on near Earth space
- Data source: NASA/GSFC: CCMC *Space Weather Database of Notifications, Knowledge, Information* (DONKI)

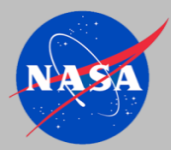
URL: <https://ccmc.gsfc.nasa.gov/tools/DONKI/>

CME from Moon to Mars Catalog (most accurate only)



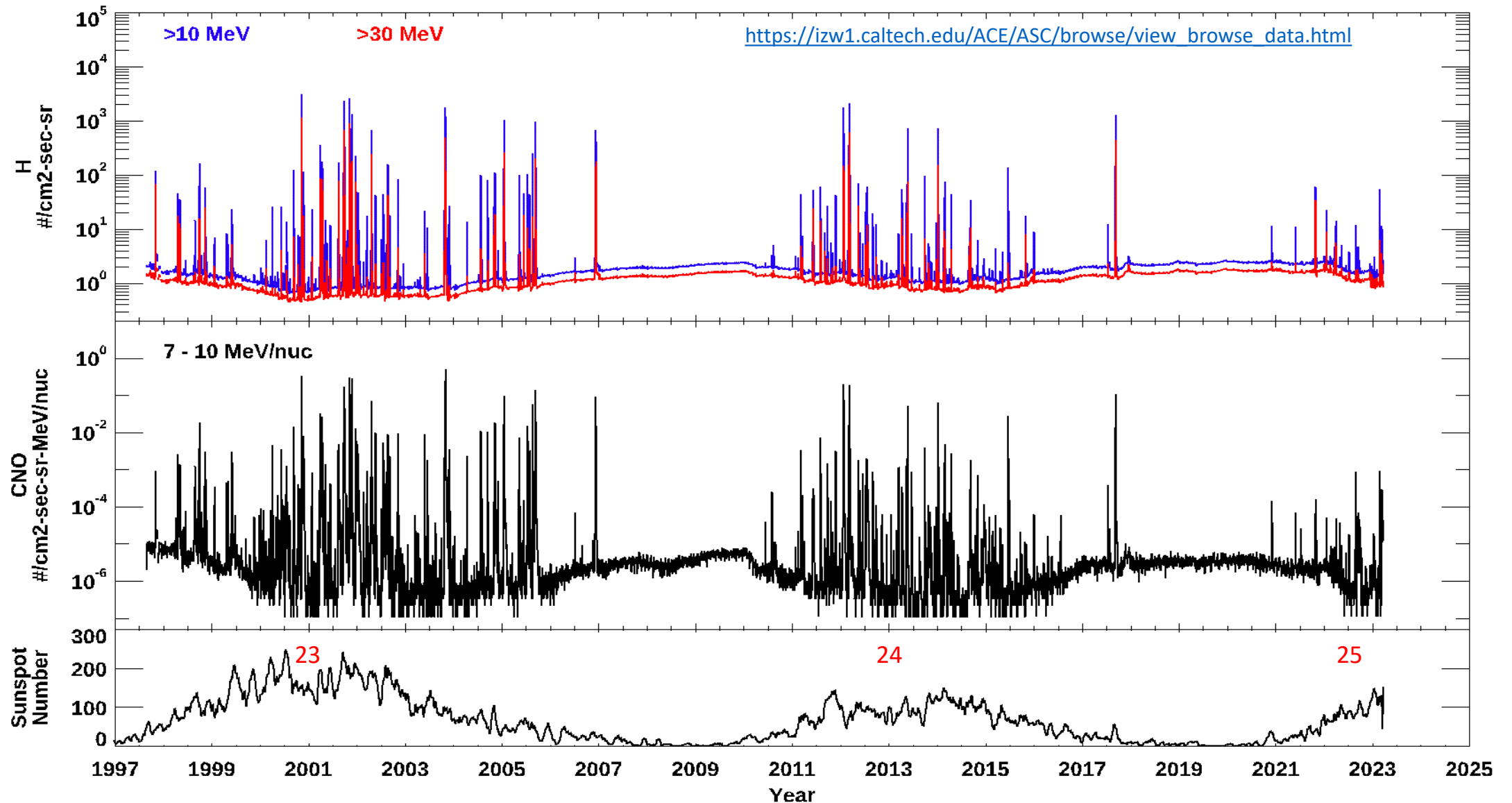
M2M estimates of CME 3-D kinematic properties (including velocity) are from StereoCaT tool

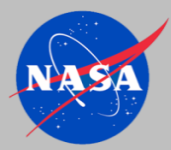




Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR)

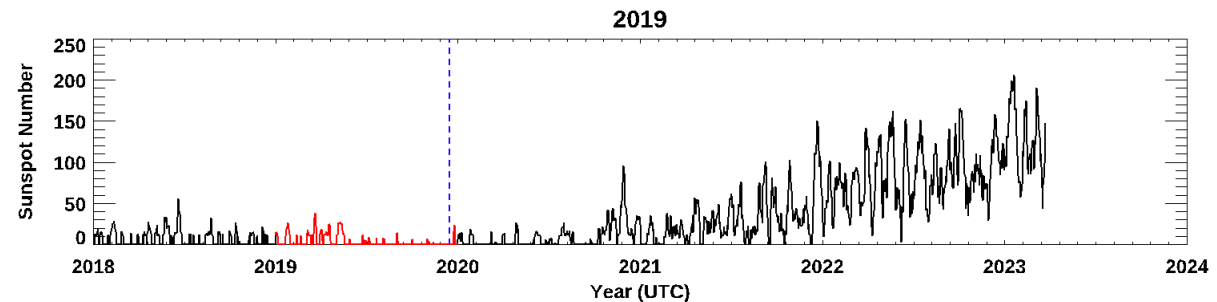
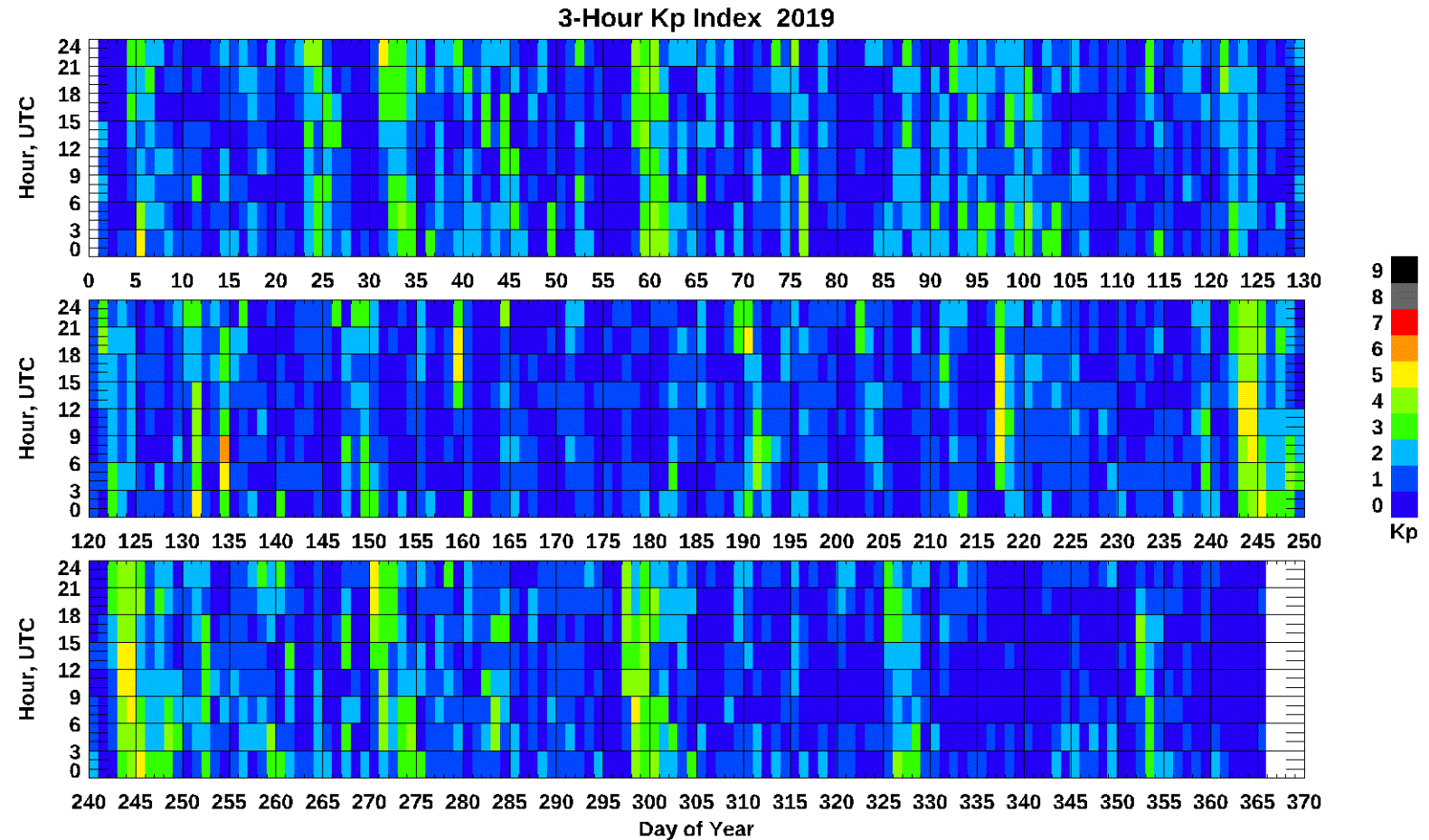
ACE Browse Data (Daily Averages) from 1997/08/25 to 2023/03/22





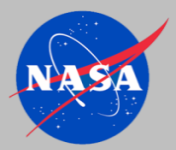
Geomagnetic Activity: Kp 2019

- Kp index is a measure of the greatest disturbance in the horizontal component of the Earth's magnetic field at mid-latitudes in a 3-hour period: useful index for characterizing the magnitude of geomagnetic storms
- Kp index at solar minimum exhibits a 27-day periodicity due to recurrent geomagnetic storms caused by high speed solar wind flows from coronal holes (solar rotation period is ~27 days)



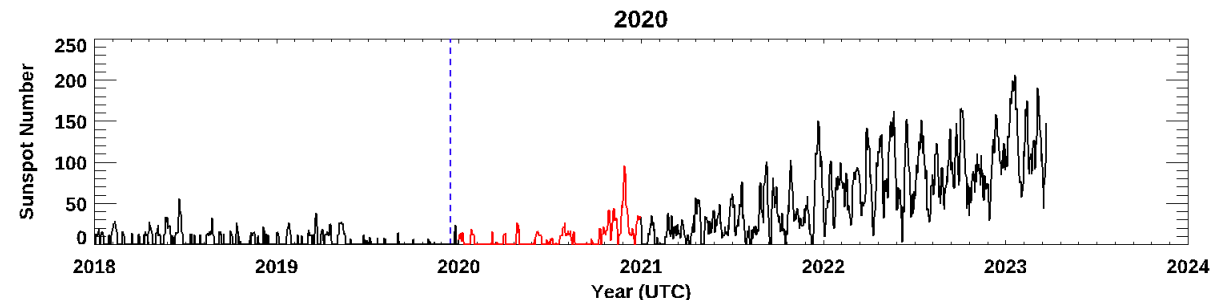
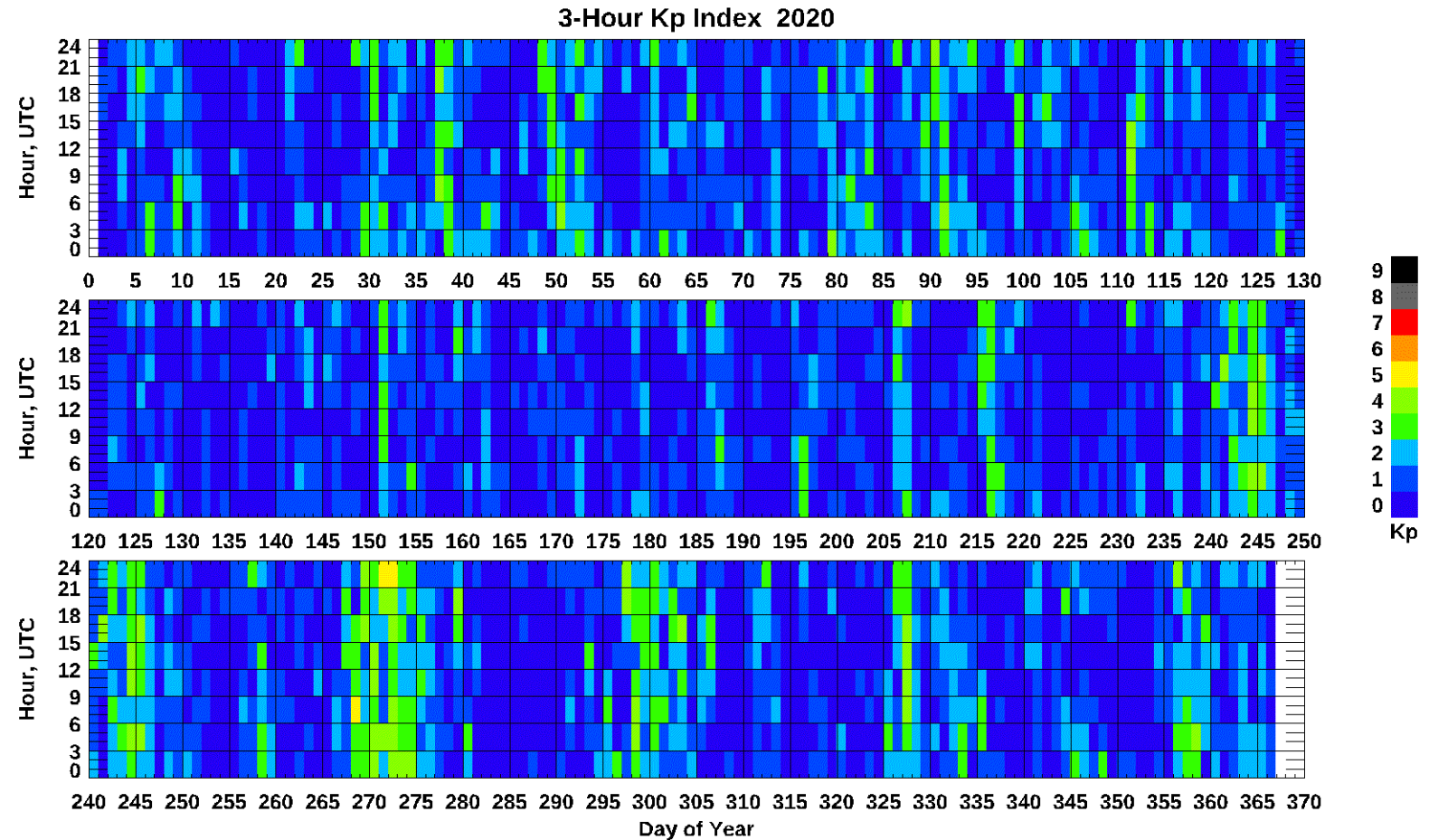
Kp data: GFZ Potsdam

<https://kp.gfz-potsdam.de/en/>



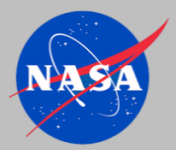
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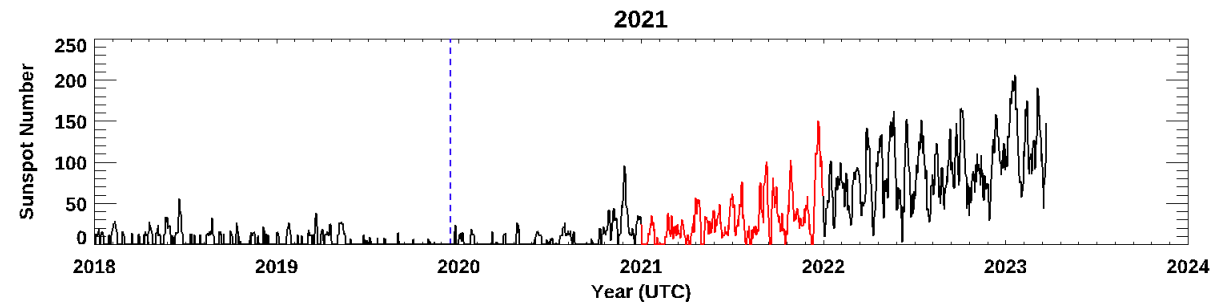
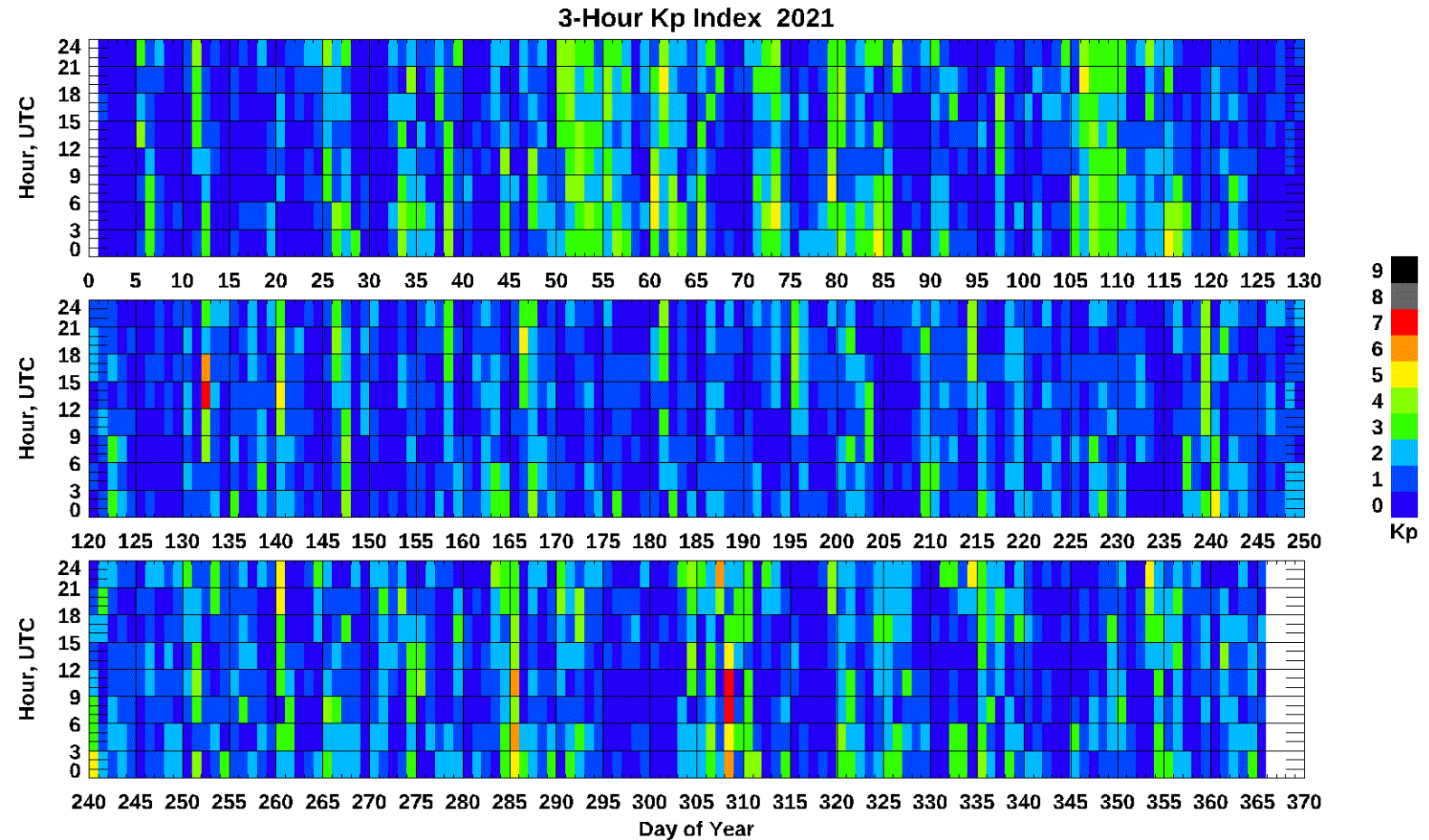
Kp data: GFZ Potsdam

<https://kp.gfz-potsdam.de/en/>



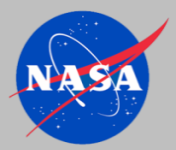
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- CME driven storms increase in number as solar activity increases and coronal hole geometry becomes more complex, washing out the ~27 day periodicity
- Cycle 25 Kp ~ 7 periods first showed up in 2021 for Cycle 25



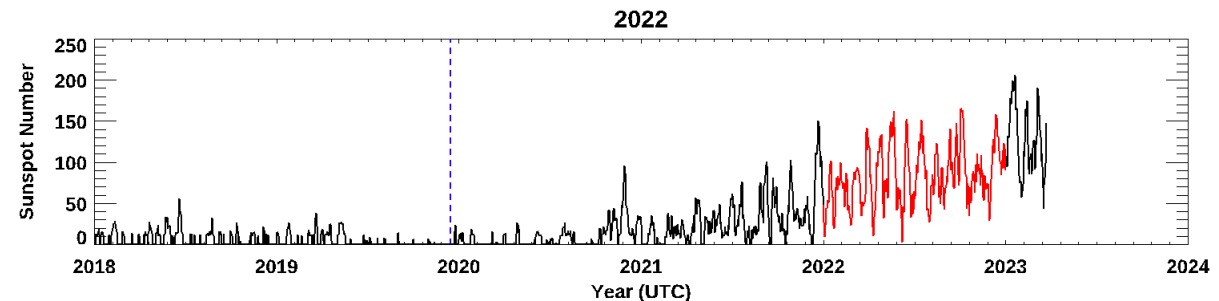
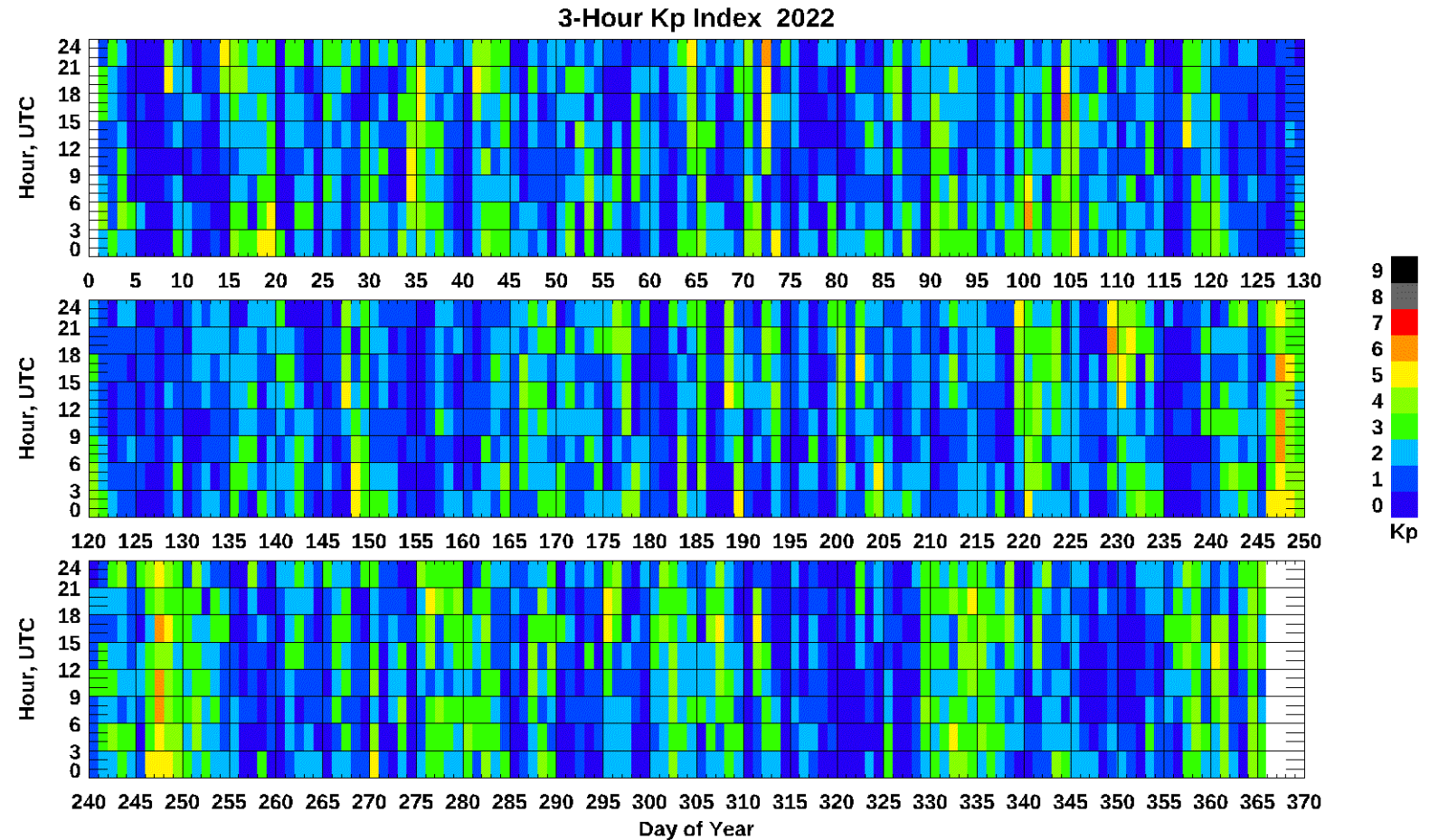
Kp data: GFZ Potsdam

<https://kp.gfz-potsdam.de/en/>



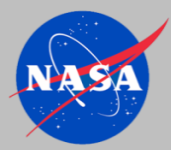
Geomagnetic Activity: Kp 2022

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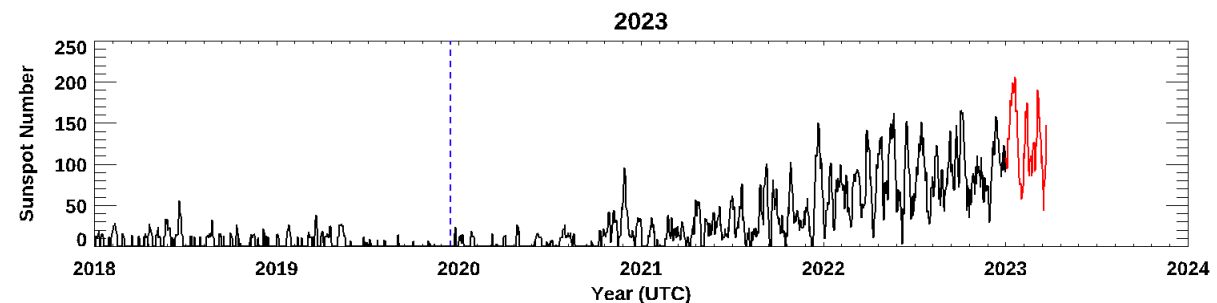
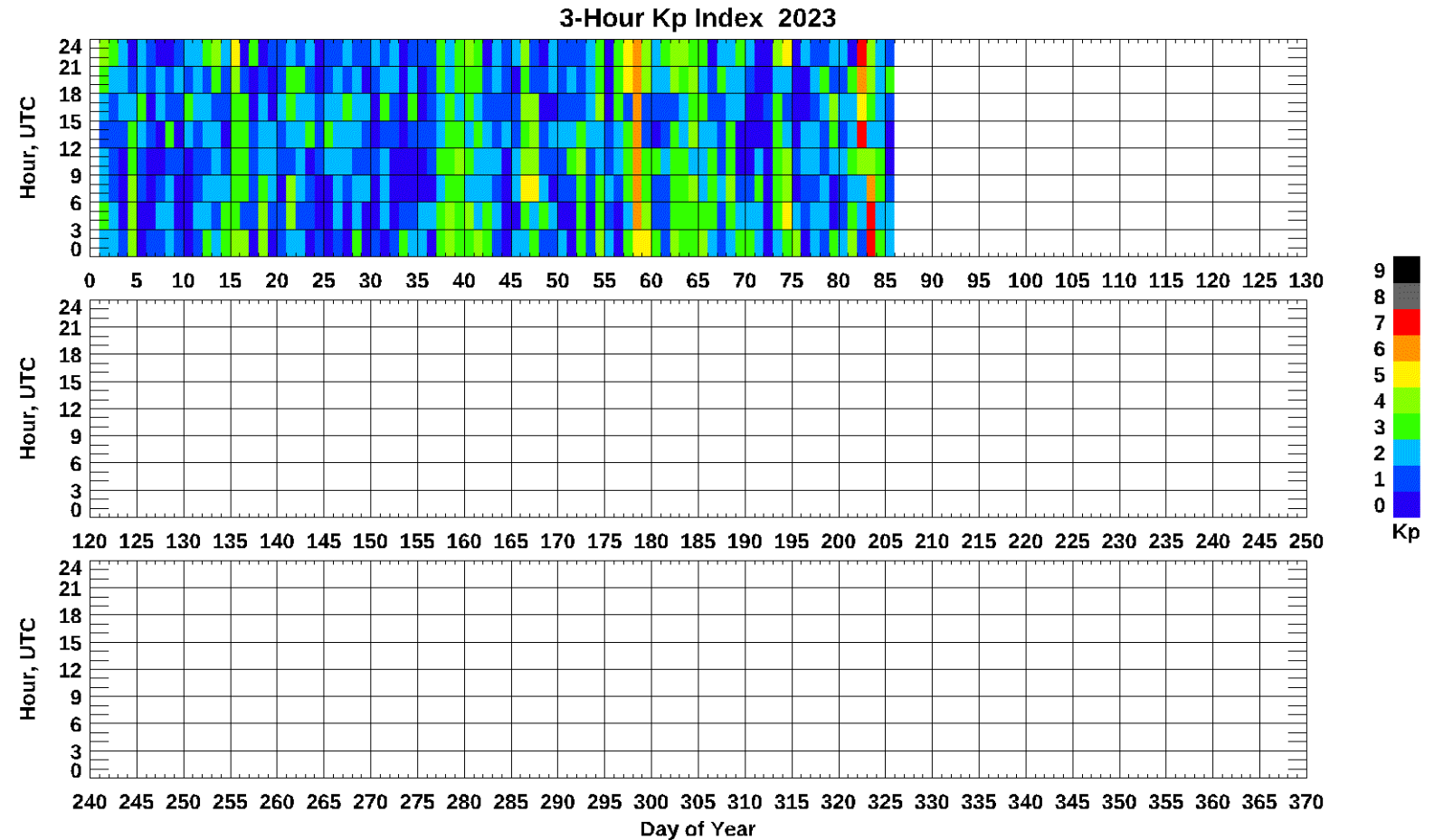
Kp data: GFZ Potsdam

<https://kp.gfz-potsdam.de/en/>



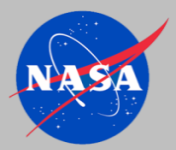
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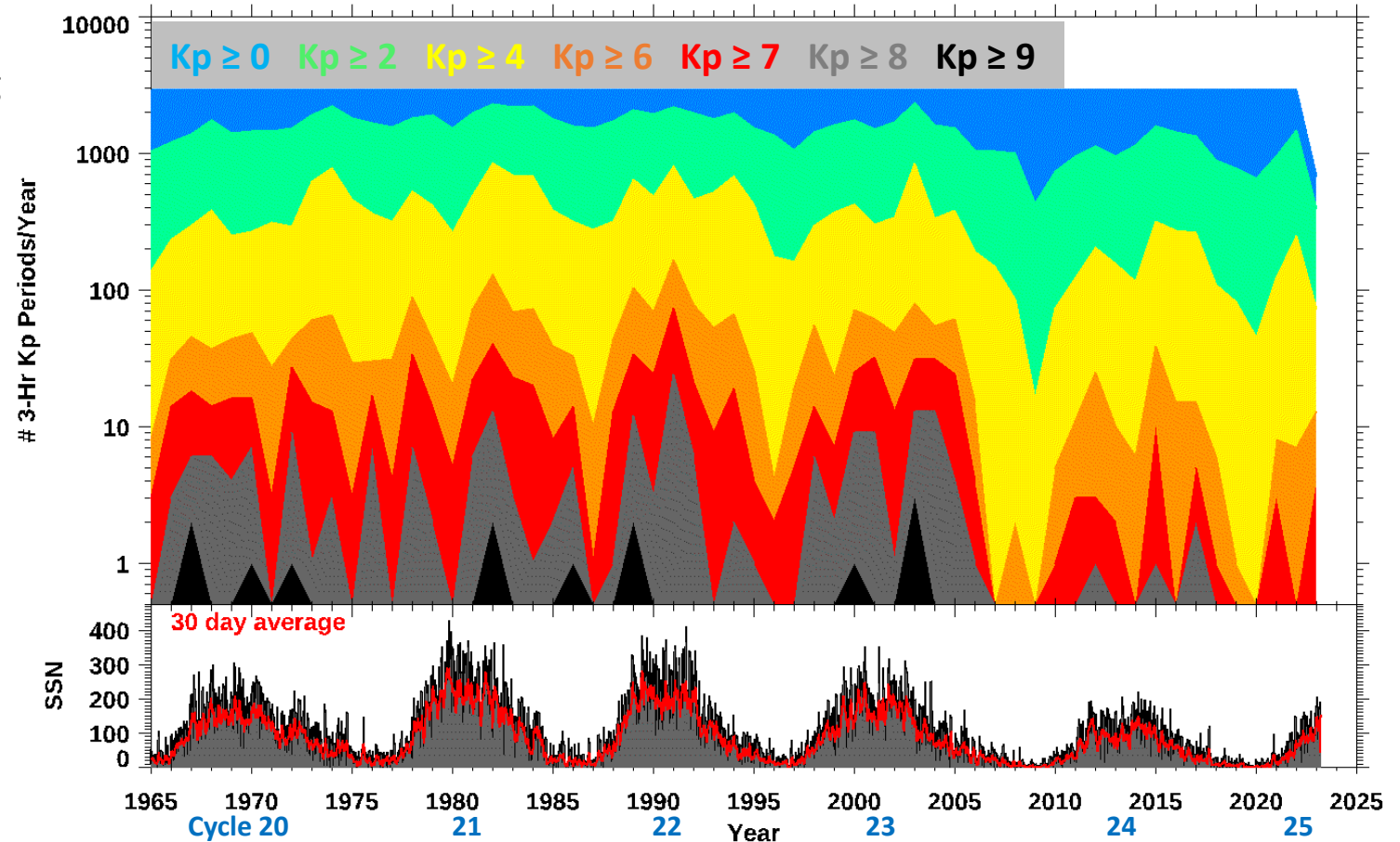
Kp data: GFZ Potsdam

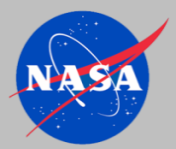
<https://kp.gfz-potsdam.de/en/>



Geomagnetic Activity: Kp Statistics

- 3-hr Kp periods with $Kp \geq 6$ occurred at the rate of ~30 to 100 periods/year for Solar Cycles 20 – 23
- Cycles 24 and 25 have been less active, only producing $Kp \geq 6$ conditions at a rate of ~6 to 30 periods/year



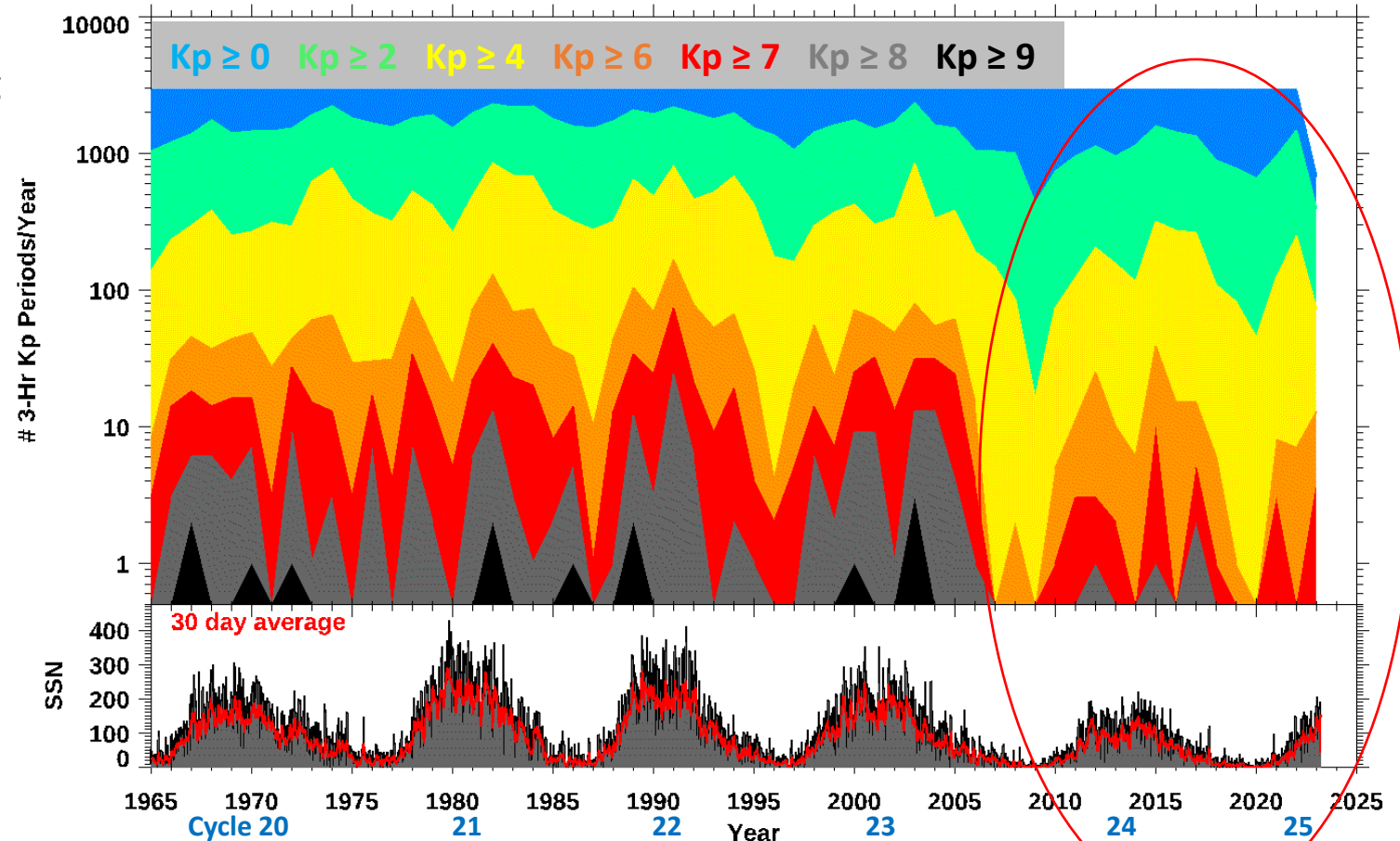


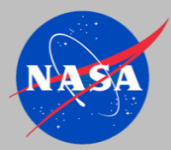
Geomagnetic Activity: Kp Statistics

- 3-hr Kp periods with $K_p \geq 6$ occurred at the rate of ~30 to 100 periods/year for Solar Cycles 20 – 23
- Cycles 24 and 25 have been less active, only producing $K_p \geq 6$ conditions at a rate of ~6 to 30 periods/year
- Cycle 25 appears to be following a similar trend as Cycle 24 with respect to geomagnetic storms:
 - Fewer $K_p \geq 6$ periods than previous cycles
 - Very few $K_p \geq 7$ periods
 - No $K_p \geq 8$ periods to date
- Solar Cycle 25 has produced only seven periods with $K_p \geq 7$ (from three storms) to date, no Kp 8 or above:

YYYY	Number of 3-Hr Kp Periods with $K_p \geq$ Value									
	0	1	2	3	4	5	6	7	8	9
2019	2920	1732	770	272	81	21	1	0	0	0
2020	2928	1587	651	217	45	3	0	0	0	0
2021	2920	1853	950	387	123	26	8	3	0	0
2022	2920	2282	1476	697	248	54	7	0	0	0
2023	680	562	392	200	72	23	13	4	0	0

(to 2023/03/26)





Satellite and Orbital Debris Populations

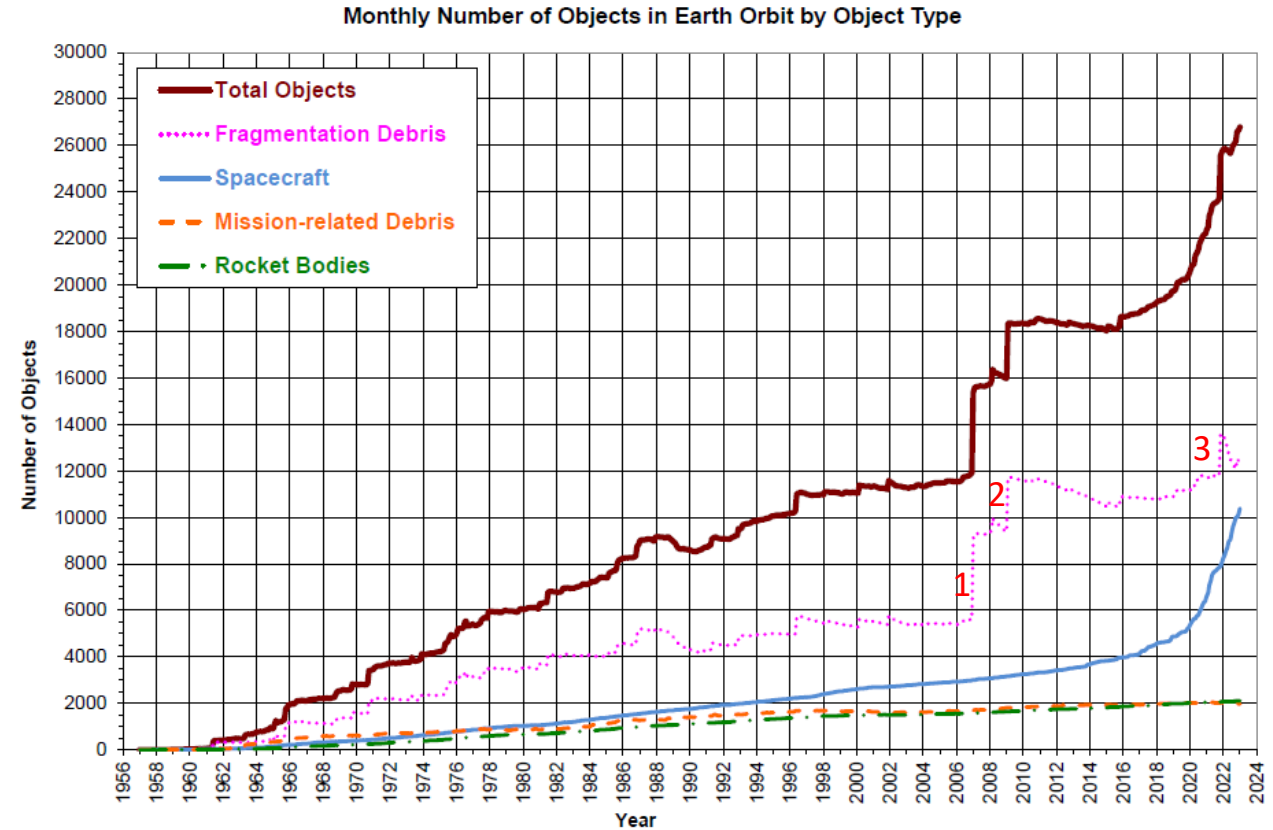
- Active satellite and debris populations continue to grow
- LEO debris environments remain a significant concern for potential collisions and an increasing need for collision avoidance maneuvers
- Large fragmentation debris increases are due to
 - 1) Fengyun-1C Chinese ASAT test, 2007
 - 2) Iridium 33/Cosmos 2251 Accidental collision, 2009
 - 3) Cosmos 1408 Russian ASAT test, 2021
- Large increase in spacecraft numbers in recent years is due in large part to satellite constellations, cubesats, and smallsats

Space Scoreboard 2023/03/27

Object Type	Objects
Active payloads	7,700
Debris	19,400
Analyst Objects*	19,800
Total	46,800

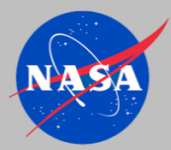
<https://www.space-track.org/>

Cataloged Active and Debris Objects (as of 3 Feb 2023)



<https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv27i1.pdf>

*Analyst objects are variably tracked and in constant flux, Space Track does not provide their catalog and element set data



On-Orbit Breakups 2020 - 2023

- On-orbit breakups are a significant orbital debris source, producing both short and long term threats to satellites depending on altitude of the breakup
 - Low altitude debris populations reenter quickly
 - High altitude populations will remain in orbit for years to come
- Breakups:
 - Over 250 objects have fragmented in LEO over the last 60 years (LeoLabs, 2022)
 - As of April 2017, 290+ break-ups since 1961 (ESA)
- Causes for breakups include:
 - Residual fuel explosions
 - Power system explosions
 - Accidental collisions with other objects (satellite, debris)
 - Anti-satellite tests
 - Unknown
- Long March 6A breakup, 12 Nov 2022
 - Breakup at 813 x 847 x 98.8° following payload deployment
 - 18th SDS identified 533 fragments from SSN data
 - Hundreds of thousands of fragments as small as 1 mm were likely generated from this breakup.

On-orbit Breakups: 2020 - 20023

Date	Object	Int'l Designator	Orbit (km x km x deg)	Debris*	Ref
9 Jan 2020	Cosmos 2535	2019-039A	604 x 618 x 97.9°	26	1
12 Feb 2020	SL-14 Tsyklon 3 rd Stage	1991-056B	1186 x 1206 x 82.6°	112	1
8 May 2020	SL-23 Zenit Fregat tank	2011—037B	422 x 3606 x 51.5°	325	1
12 Jul 2020	H-2A fairing cover	2018-084C	595 x 643 x 97.9°	87	1,5
27 Aug 2020	Resurs-O1	1994-074A	633 x 660 x 97.9°	72	1
10 Mar 2021	NOAA-17	2002-032A	800 x 817 x 98.62°	102	1,5
18 Mar 2021	Yunhai 1-02	2019-063A	780 x 785 x 98.54°	43	1,5,7
15 Apr 2022	SL-12 (SOZ) Motor	2007-065F	400 x 19068 x 64.8°	19	1
23 Oct 2021	Cosmos 2499	2014-02E	1152 x 1507 x 82.44°	21	1
15 Nov 2021	Cosmos 1408 (ASAT test)	1982-092A	465 x 490 x 82.60°	1600+	1,5
18 Nov 2021	ORBCOMM	1997-084F	758 x 771 x 45°	8	1
26 Nov 2021	Minotaur 4 th Stage		567 x 580 x 53.98°	21	1
15 Apr 2022	SL-12 R/B	2007-065F	388 x 19074 x 64.8°	16	5,6
3 Jul 2022	H-2A fairing Cover	2018-084D	579 x 615 x 98°	52	1,5
12 Nov 2022	Long March 6A upper stage	2022-151B	813 x 847 x 98.8°	533	2,5,8
17 Nov 2022	H-2A DEB	2012-025F	609 x 633 x 98.2°	50+	5,8
4 Jan 2023	Cosmos 2499	2014-028E	~1169	85	3,4
10 Feb 2023	SSLV R/B	2023-019D	~350	6	5

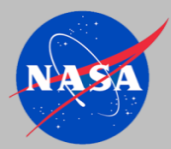
*Debris objects in public catalog in addition to parent body

(references in backup)

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https://www.esa.int/ESA_Multimedia/Images/2017/03/Satellite_break-up



LEO Satellite Populations

- Payload launch traffic into LEO has increased dramatically in recent years with the commercial sector dominating the increase

ESA Space Environment Statistics (22 December 2022)

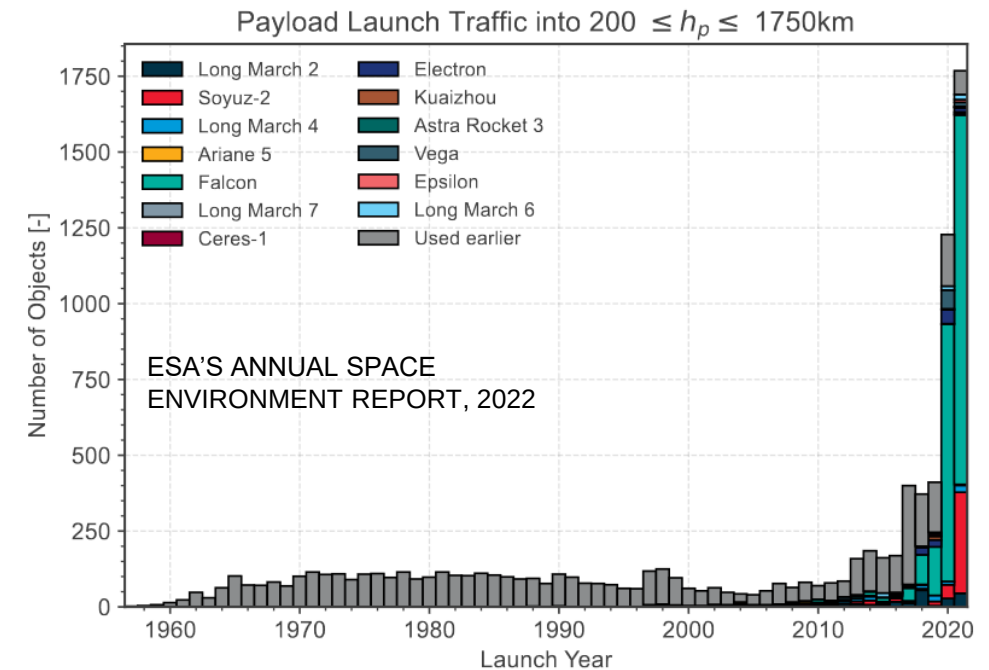
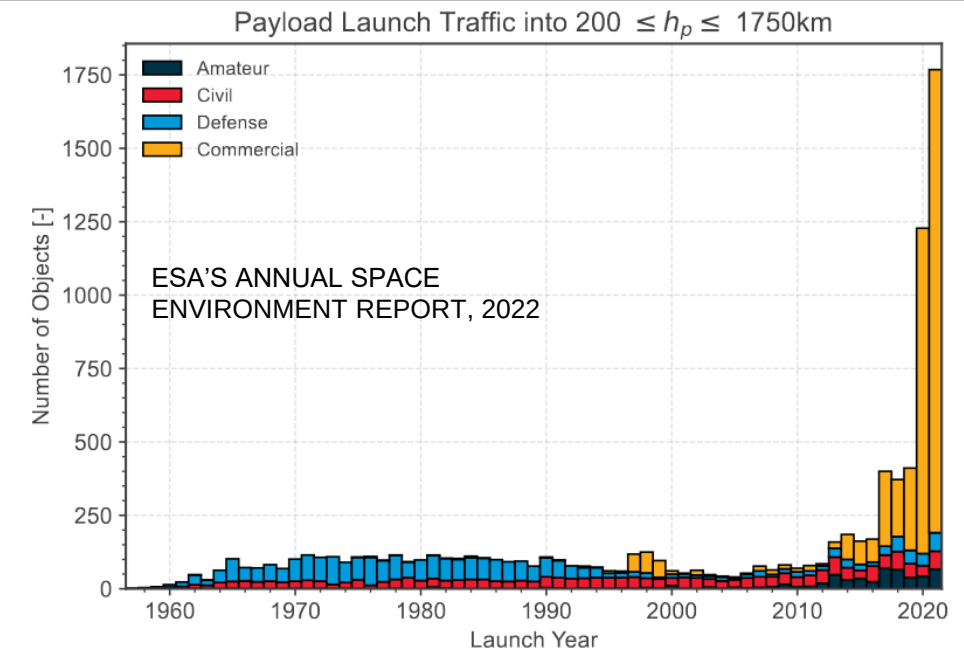
Rocket launches since 1957 (excluding failures)	~ 6,370
Objects placed into Earth orbit	~ 15,070
Objects still in space	~ 9,790
Still functioning	~ 7,200
SSN tracked and cataloged debris	~ 32,000

Debris objects estimated based on statistical models to be in orbit ([MASTER-8](#), future population 2021)

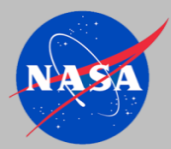
>10 cm	36,500
>1 cm to 10 cm	1,000,000
>1mm to 1 cm	130,000,000

<https://sdup.esoc.esa.int/discosweb/statistics/>

- SpaceX is a main contributor for the number of new payloads deployed in LEO



https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf



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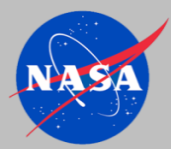
<https://sdup.esoc.esa.int/discosweb/statistics/>

- Traffic characteristics of the LEO operational environment could dramatically change in the coming years if even a fraction of the planned constellations reach their targets for planned spacecraft

Constellation	Alt (km)	In orbit	Active	Planned
Starlink G1 (US)	540-577	3,814	3,165	4,408
Starlink G2A (US)	530-559	239	52	7,500
Starlink G2 (US)	340-614	---	---	22,488
OneWeb, Phase 1 (UK)	1182-1221	584	426	716
OneWeb, Phase 2 (uk)	1185-1221	---	---	6,372
Kuiper (US)	590-630	---	---	3,232
Guangwan (CH)	508-1145	---	---	12,992
Galaxy Space (CH)	500	---	---	1,000
Hanwha Systems (KR)	500	---	---	2,000
Lynk Global (US)	500	---	---	2,000
Astra (US)	380-700	---	---	13,620
Boeing (US)	670-10,000	---	---	5,841
Telesat (Canada)	1015-1325	---	---	1,969
HVNET (US)	1150	---	---	1140
SpinLaunch (US)	830	---	---	1190
Globalstar3 (Germany)	485-700	---	---	3080
E-SPACE (US)	528-635	---	---	337,323
Total		4,637	3,643	427,171

<https://planet4589.org/space/con/conlist.html> (17 Mar2023)

<https://planet4589.org/space/con/largecon.html> (17 Mar 2023)



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Telesat				
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SpinLaunch				
Globalstar				
E-SPACE (US)	528-635	---	---	337,323
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In addition, there are many smaller constellations (<1000 spacecraft) planned or in operation representing:

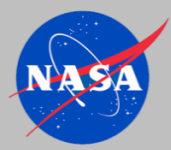
Total launched: 2244

Total in operational shells: 956

Total planned: 4831

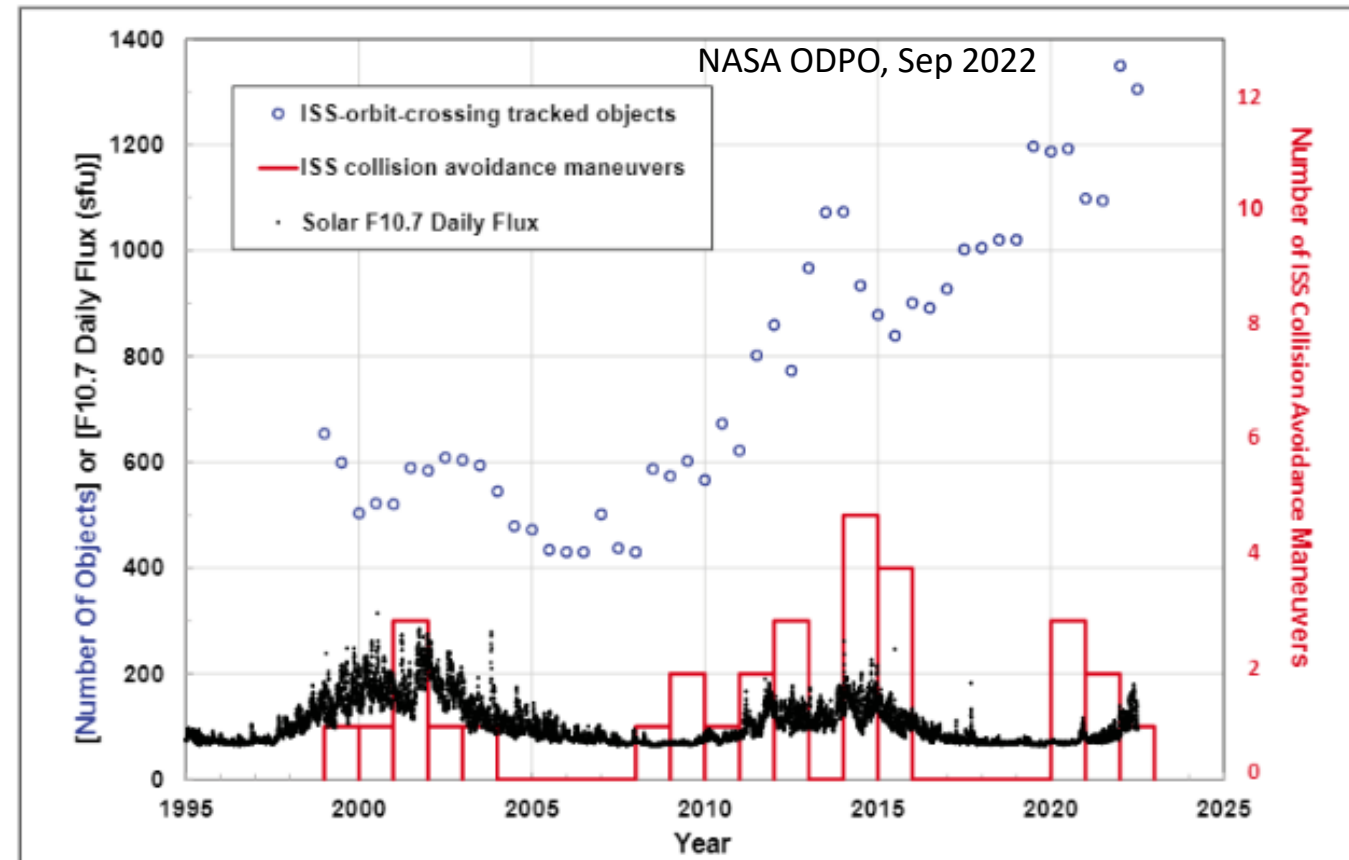
<https://planet4589.org/space/con/conlist.html> (17 Mar2023)

<https://planet4589.org/space/con/largecon.html> (17 Mar 2023)



ISS Orbit-Crossing Objects and Collision Avoidance Maneuvers

- ISS conducted 33 collision avoidance maneuvers since 1999
- Frequency of maneuvers depends on multiple factors including:
 - Solar activity
 - Number of objects crossing ISS orbit
 - Tracking capability of the Space Surveillance Network
- Cosmos 1408 ASAT test generated 1700+ trackable debris objects, ISS has experienced many conjunctions with these objects but only two collision avoidance maneuvers have been executed to date to avoid Cosmos 1408 debris



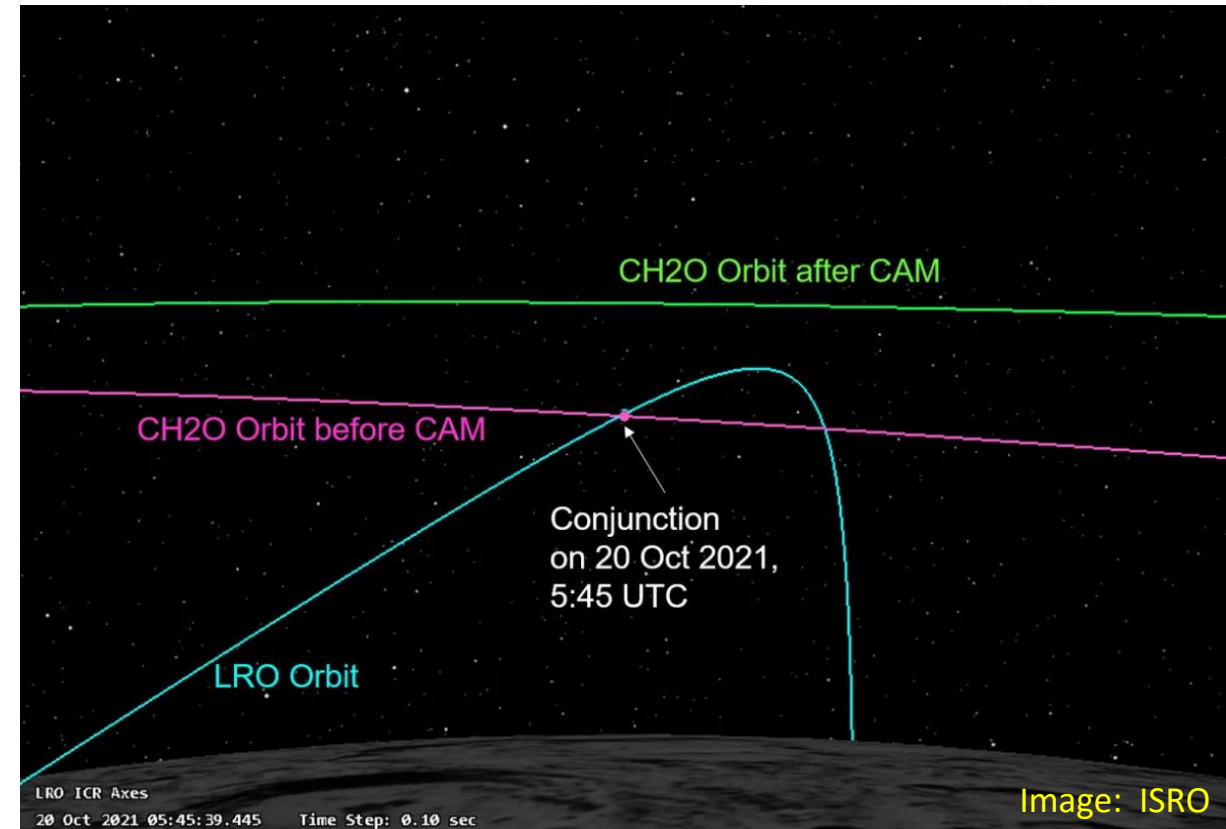
The number of ISS-orbit-crossing objects tracked by the SSN (blue circles), the solar F10.7 daily flux (black dots), and the ISS collision avoidance maneuvers (red histogram) as functions of time.

Sources:

- Orbital Debris Quarterly News, Vol 26, Issue 3, Sept 2022
- Orbital Debris Quarterly News, Vol 26, Issue 4, Dec 2022
- Orbital Debris Quarterly News, Vol 27, Issue 1, Mar 2023
- <https://orbitaldebris.jsc.nasa.gov/quarterly-news/>
- <https://www.space.com/international-space-station-avoid-satellite>

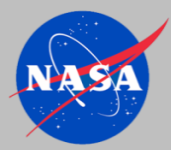
LRO/Chandrayaan-2 Collision Avoidance Maneuver

- NASA's Lunar Reconnaissance Orbiter (LRO) and ISRO's Chandrayaan-2 (CH2) spacecraft operate in low lunar orbit
 - LRO 20 km x 165 km x polar
 - CH2 100 km x 100 km x polar
- Conjunction on 20 Oct 2021 (DOY 293) at 05:45 UTC with predicted radial separation <100 meters and closest approach of ~3 km
- NASA and ISRO agreed to maneuver CH2 on 18 Oct 2021 to avoid a potential collision. Increased CH2 altitude will prevent future close LRO/CH2 conjunctions
- Collision avoidance maneuvers are a fact of life for low Earth orbit, is this a sign of the future for lunar operations as well as lunar exploration activities increase?



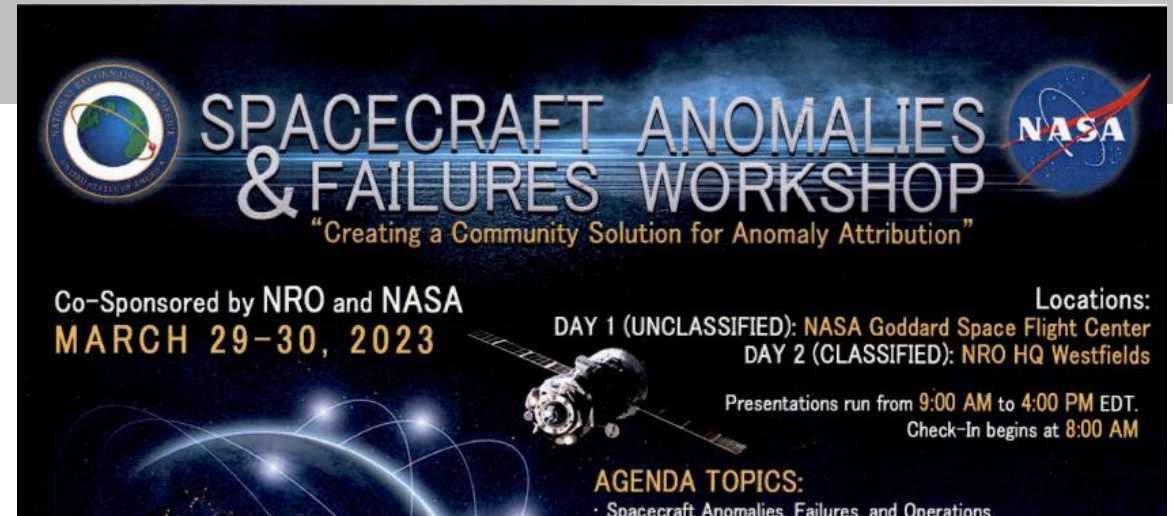
Source:

- <https://spacenews.com/indias-chandrayaan-2-maneuvered-to-avoid-close-approach-to-nasas-lunar-reconnaissance-orbiter/>
- <https://www.cnet.com/google-amp/news/a-spacecraft-made-an-evasive-maneuver-to-avoid-nasas-lunar-orbiter/>



Summary

- Space operations continue to be a challenge for both launch vehicles and spacecraft
- Attribution and mitigation of anomalies and failures remains an important concern for space system designers, operators, and users
- The space environment is becoming more hazardous for operations as solar activity increases towards the peak of Solar Cycle 25
- Today's SCAF presentations continue the workshop legacy of reporting case studies relevant to space operations in general and spacecraft anomalies and failures in particular and discussion of methodologies and techniques for evaluating the space environment and its effects on space systems



Case Studies

- DART Lessons Learned (Adams)
- Shuttle and Orion Re-entry Temperature Anomalies (Squire)
- JWST Meteoroid Impacts (Menzel)
- Risks for Human Spaceflight Beyond LEO (Vera)
- Space Environments Ops Perspective (Kilzer)

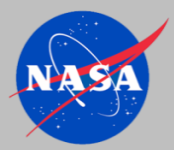
Tools and Resources

- Moon to Mars Space Weather Office (Collado- Vega)
- Long-term Environmental Forecast Tool (O'Brien)
- Models and Applications for Assessing Space Weather from Earth to the Moon (Green)
- NASA Small Spacecraft Anomaly Reporting (Burkhard)



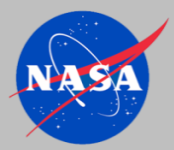
Questions?





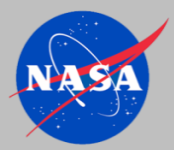
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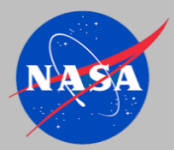
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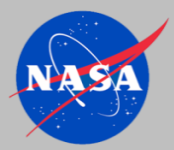
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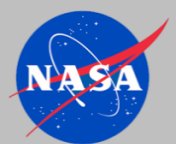
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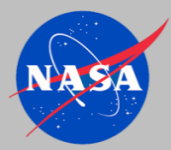
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Acronyms and Nomenclature

ACE	Advanced Composition Explorer (s/c)	JAXA	Japan Aerospace Exploration Agency	SSN	sunspot number
Ap	daily planetary magnetic index	JWST	James Webb Space Telescope (s/c)	SWIFT	Neil Gehrels Swift Observatory (s/c)
ap	3-hour planetary magnetic index	km	kilometers	SWOT	Surface Water and Ocean Topography (s/c)
ASAT	anti-satellite	Kp	planetary K index	SWx	space weather
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (s/c)	LaRC	Langley Research Center	TESS	Transiting Exoplanet Survey Satellite (s/c)
		LASCO	Large Angle and Spectrometric Coronagraph Experiment	US	United States
CCMC	Community Coordinated Modeling Center	LEO	low Earth orbit	USSF	US Space Force
CDAWeb	Coordinated Data Analysis Web	LM	Long March (LV)	3-D	three dimensional
CH2	Chandrayaan-2 (s/c)	LRO	Lunar Reconnaissance Orbiter (s/c)		
CME	coronal mass ejection	LV	launch vehicle		
CNO	carbon, nitrogen, oxygen	L2	second Lagrange point		
CSA	Canadian Space Agency	MAVEN	Mars Atmosphere and Volatile Evolution (s/c)		
DEB	debris	MeV	million electron volts		
DONKI	Database of Notifications, Knowledge, Information	mm	millimeter		
Dst	disturbance storm-time index	M/OD	meteoroids and orbital debris		
EOL	end of life	MS	Soyuz model		
ESLA-d	End-of-Life Services by Astroscale-demonstration (s/c)	MSFC	Marshall Space Flight Center		
ESA	European Space Agency	M2M	Moon to Mars Space Weather Analysis Office		
EUV	extreme ultraviolet	NASA	National Aeronautics and Space Administration		
EVA	extravehicular activity	NG	Northrop Grumman		
EWS RROCI	Electro Optical/Infrared Weather System Rapid Revisit Optical Cloud Imager (s/c)	NOAA	National Oceanic and Atmospheric Administration		
		NRO	National Reconnaissance Office		
F9	Falcon 9	nuc	nucleon		
F107	10.7 cm radio flux (solar EUV proxy)	OFT	Orbital Flight Test		
GCR	galactic cosmic rays	R/B	rocket body		
GFZ	<i>GeoForschungsZentrum</i> (Geo-research Centre)	Re	Earth radius		
GSFC	Goddard Space Flight Center	s/c	spacecraft		
H	hydrogen	18 th SDS	18 th Space Defense Squadron		
IAI	Integrity Applications Incorporated	SOHO	Solar and Heliospheric Observatory (s/c)		
IBEX	Interstellar Boundary Explorer (s/c)	SPE	solar particle event		
ICON	Ionospheric Connections Explorer (s/c)	SCAF	Spacecraft Anomalies and Failures		
ISRO	Indian Space Research Organization	SL	Russian rocket body		
ISS	International Space Station	SSLV	Small Satellite Launch Vehicle (LV))		
		SSN	Space Surveillance Network		