JWST Space Environments Launch Constraints

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Fall 2022, Natural Environments Day-of-Launch Working Group
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Introduction

- An ESA Ariane 5 rocket launched the James Webb Space Telescope (JWST) at 12:20 UTC on 25 December 2021 from Kourou, French Guiana

- JWST is an infrared astronomy space telescope designed for observations of the first galaxies, formation of stars and planets, and investigations of exoplanet atmospheres
  - Partners: NASA, ESA, CSA
  - High value program (~$10B at time of launch)
  - Largest space telescope launched to date

- Spacecraft is designed for a 12-year mission in a halo orbit about the Sun-Earth L2 Lagrange point, ~1.51x10^6 km (237 R_E) from Earth

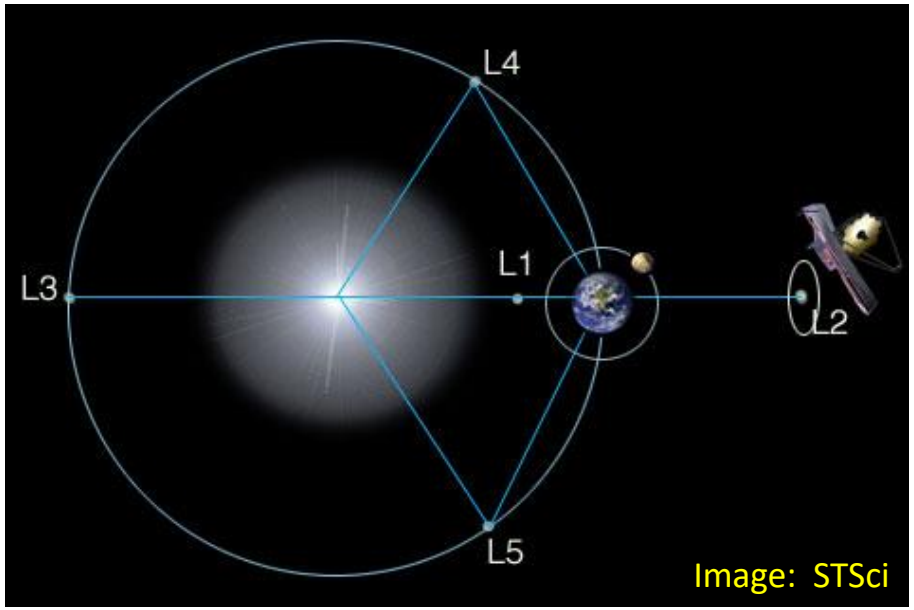


Image: STSci


Image: NASA

JWST Spacecraft

- Science instruments
  - Near Infrared Camera (NIRCam)
  - Near Infrared Spectrograph (NIRSpec)
  - Mid-Infrared Instrument (MIRI)
  - Fine Guidance Sensor and Near Infrared Imager and Slitless Spectrograph) FGS/NIRISS

- Astronomical instrumentation conducting infrared observations of faint, distant objects must be cold in order to maintain a minimal background of infrared light:
  - A 5-layer sunshield structure divides the spacecraft into a "warm" side facing the Sun and "cold" side facing deep space
  - Warm side: ~300 K (27° C)
    - Spacecraft bus including power, communications, and guidance systems
  - Cold side <50 K (-223.2° C)
    - Telescope mirrors and support structures, astronomical instruments and detector syster

- Spacecraft is very large!!
  - Sunshield: 21.2 m x 14.2 m
  - Primary mirror: 6.5 m
  - Hubble mirror: 2.4 m

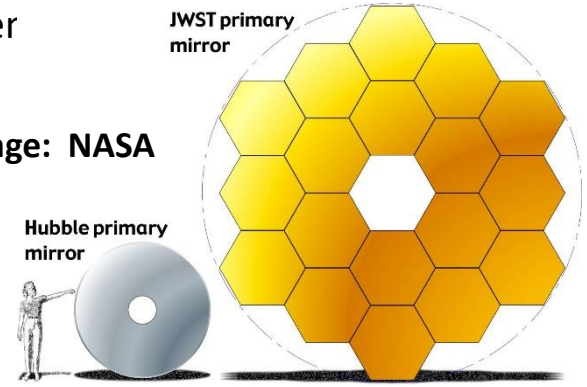


Image: NASA

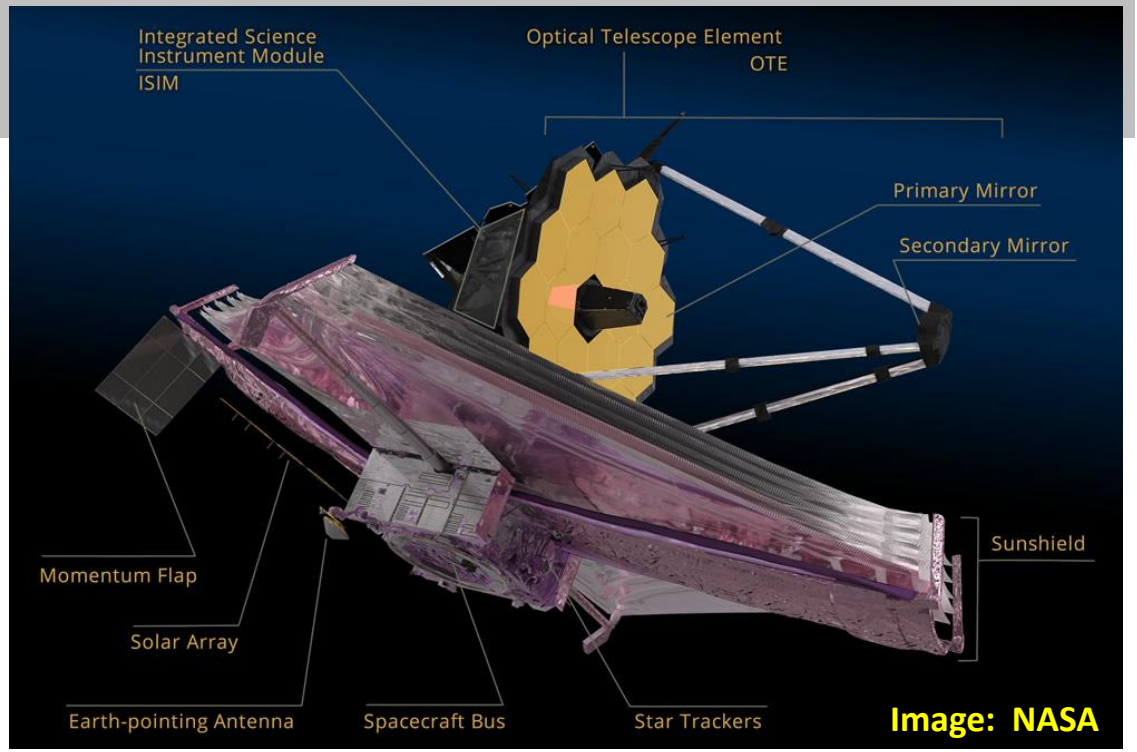
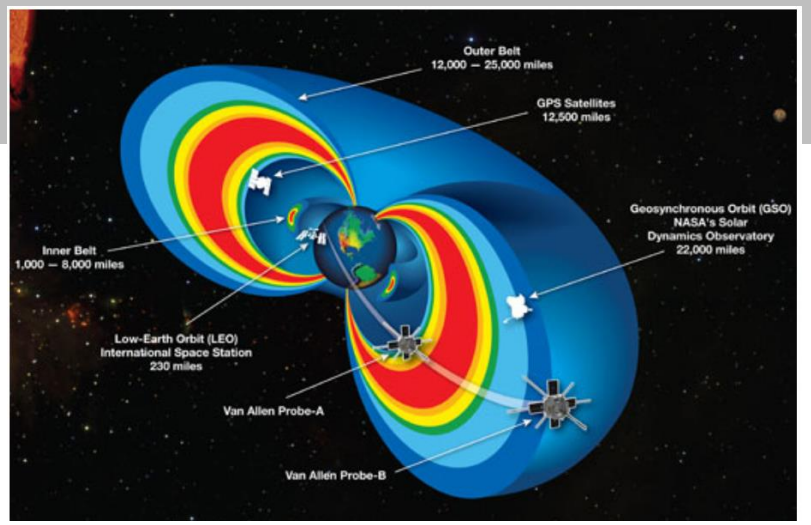


Image: NASA

Image: Northrop Grumman

JWST Space Weather (SWx) Launch Constraints

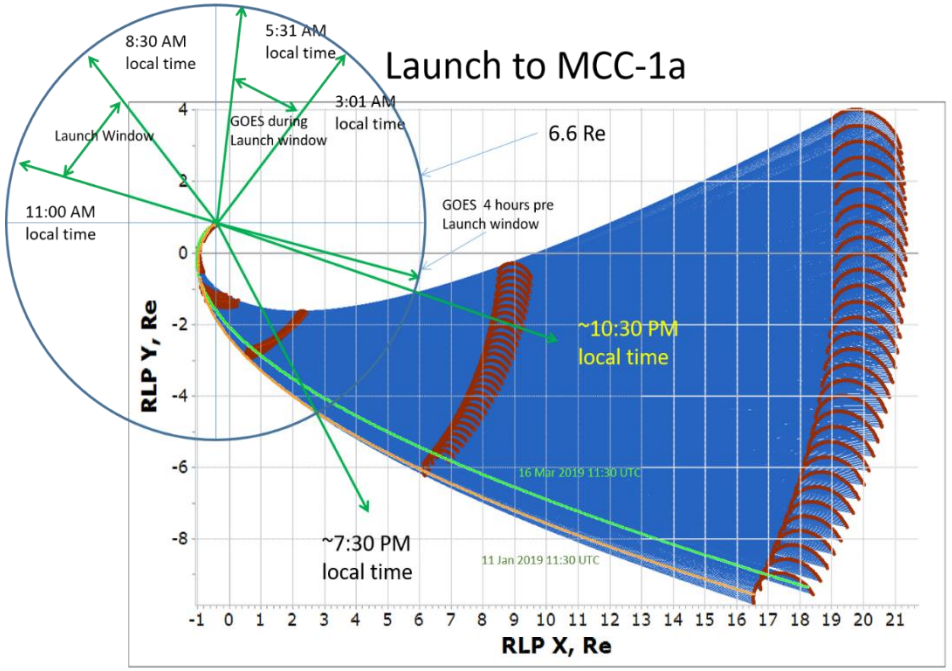


- NASA Engineering and Safety Center (NESC) independent assessment *TI-15-01079, JWST Space Environment Launch Constraints (*completed 06/2019) recommended the JWST Program should utilize space environment constraints to avoid exposing spacecraft to severe space environment during initial operations following launch:
  - Implement a solar proton launch constraint developed by JWST Program prime contractor (Northrop Grumman)
  - Implement an NESC developed surface charging constraint
  - Implement an NESC developed internal charging constraint

- Goal: protect <u>spacecraft</u> from extreme space environments during initial flight operations and radiation belt transit in hours following launch:
  - Single event effects (SEE) in mission critical electronics from protons and heavy ions in solar particle event (SPE) during initial critical flight operations (Launch + 18 hr)
  - Electrostatic discharge (ESD) damage from surface and internal charging during transit of the Earth's radiation belts (Launch + 4 hr)

- Constraints are for JWST <u>spacecraft</u>, the Ariane 5 launch vehicle does not utilize space weather launch constraints

- *Risk reduction technique only!!* JWST is designed to operate during and after exposure to the ionizing radiation and spacecraft charging environments during transit from Earth to L2 and during mission operations in orbit about L2



French Guiana GMT -3 hrs

JWST Launch Operations SWx Constraint Team

GSFC/JWST Program
- Mike Menzel — JWST Program, Mission Systems Engineer, launch console
- Bob Meloy — EMC/EMI and charging SME, SWx team POC for console personnel

LaRC/NASA Engineering and Safety Center
- Linda Parker — Space environments SME
- Joe Minow — Space environments SME

Northrop Grumman
- Mike Bodeau — Space environment test SME

GSFC/Moon to Mars Space Weather Office
- Yari Collado-Vega — M2M Director, space weather analyst
- Michelangelo Romano — M2M space weather analyst
- Carina Alden — M2M space weather analyst
- Robert Loper — M2M space weather analyst
- Anna Chulaki — M2M space weather analyst
- Mary Aronne — M2M space weather analyst
- Mattie Anastopulos — M2M space weather analyst
- Chris Stubenrauch — M2M space weather analyst

Space Weather Launch Commit Criteria (LCC)

- **Protons (single event upsets from SPE protons, heavy ions)**

  From L-12 hours to L-10 minutes, NO-GO if

  – There is an active SPACE WEATHER ADVISORY WARNING or EXTENDED WARNING issued by the NOAA Space Weather Prediction Center for a proton event of >100 MeV integral flux >1 pfu expected, or,

  – Any time the >50 MeV integral proton flux exceeds 5 pfu*

- **>2 MeV Electrons (electrostatic discharge from internal charging)**

  From L-5 hours to L-10 minutes, NO-GO if

  – >2 MeV flux >4.98x10^4 pfu* measured at GOES West (GOES 17)

- **Kp (electrostatic discharge from surface charging)**

  From L-1 hours to L-10 minutes, NO-GO if

  – Kp ≥ 4

*pfu = particle flux unit (particles/cm^2-sec-sr)

Data Sources

NOAA SWPC e-mail subscription products:

- https://www.swpc.noaa.gov/products/alerts-watches-and-warnings
- https://www.swpc.noaa.gov/content/subscription-services

NOAA SWPC GOES real-time proton flux:

- https://www.swpc.noaa.gov/products/goes-proton-flux

NOAA SWPC GOES real-time electron flux:

- https://www.swpc.noaa.gov/products/goes-electron-flux

NOAA SWPC GOES real-time planetary k index:

- https://services.swpc.noaa.gov/json/planetary_k_index_1m.json

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NOAA SWPC GOES real-time proton flux:
- https://www.swpc.noaa.gov/products/goes-proton-flux

NOAA SWPC GOES real-time electron flux:
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NOAA SWPC GOES real-time planetary k index:
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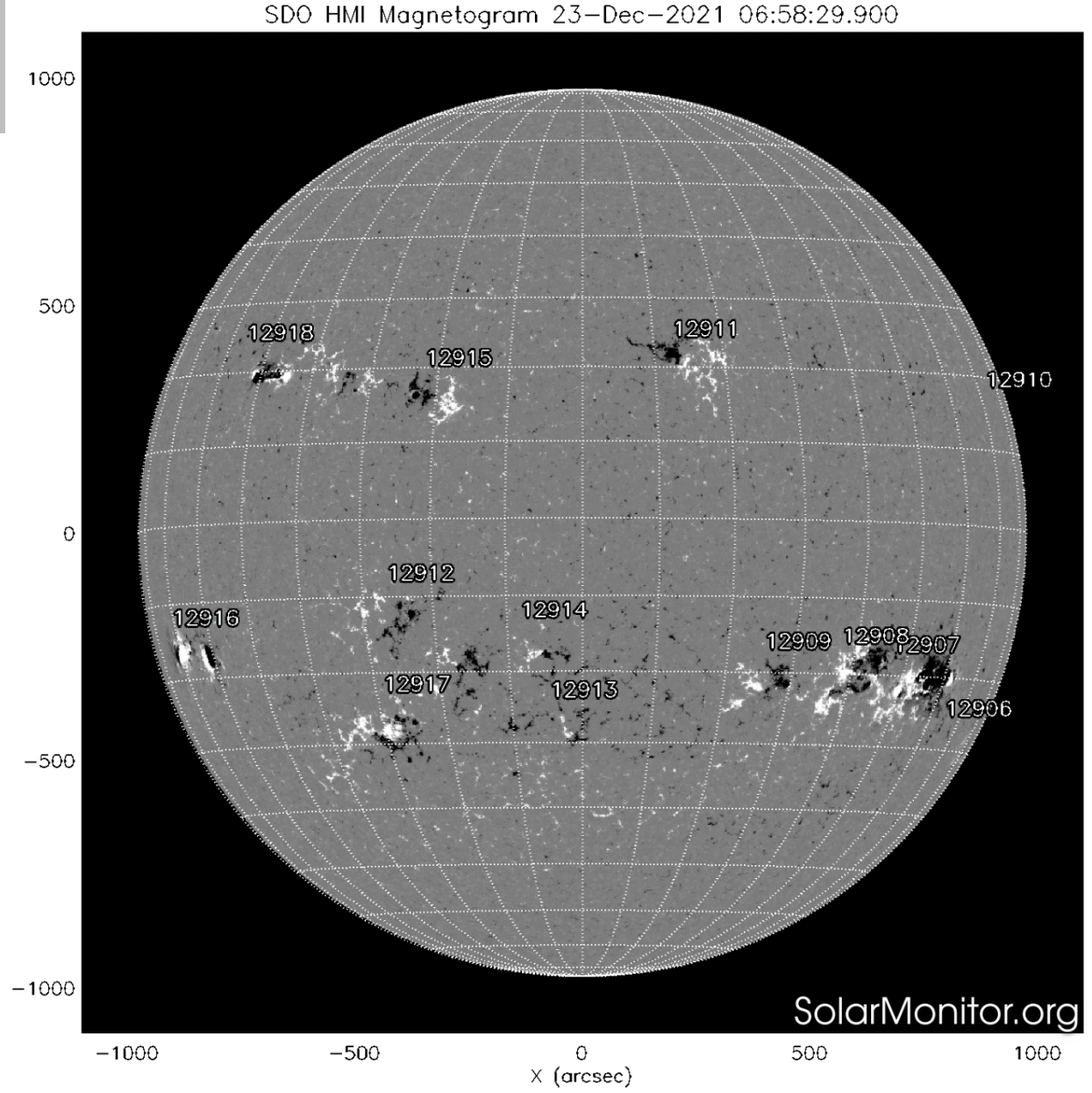
In addition to monitoring data required for launch constraints, team used a number of additional space environment data sources for situational awareness

www.SolarMonitor.org

Today's/Yesterday's NOAA Active Regions

NOAA Number	Latest Position	Hale Class	McIntosh Class	Sunspot Area [millionths]	Number of Spots	Recent Flares
12907	S21W55 (747",-332")	βγ/βγ	Eai/Dai	0230/0200	14/14	C2.5(03:33) C1.7(03:19) C1.1(02:28) C1.1(02:13) C1.4(00:45) / C1.9(23:44) C1.1(21:20) C1.3(20:42) C2.4(19:31) C8.8(17:56) C3.4(10:14) C4.0(05:15) C1.5(04:36)
12908	S20W44 (638",-311")	βγ/β	Dai/Dsi	0100/0100	16/18	- / C2.9(10:04)
12909	S21W31 (470",-323")	α/α	Hsx/Hax	0070/0080	03/03	-
12911	N20W17 (268",364")	α/α	Axx/Hrx	0010/0020	01/01	-
12912	S12E22 (-358",-173")	α/α	Hrx/Hsx	0020/0030	01/01	-
12915	N16E17 (-275",300")	β/β	Dro/Dso	0030/0030	03/03	-
12916	S17E64 (-839",-271")	β/α	Dso/Hsx	0240/0100	03/01	-
12917	S27E25 (-368",-417")	β/-	Bxo/---	0010/----	02/--	-
12918	N20E47 (-672",355")	β/-	Cro/---	0020/----	04/--	-
12906	S29W90 (852",-472")	/	/	/	/	-
12910	N15W91 (941",251")	/β	/Cro	/0020	/03	-
12913	S28W00 (0",-429")	/α	/Axx	/0010	/01	-
12914	S17E04 (-65",-254")	/β	/Bxo	/0010	/02	-



βγ or βγδ magnetic complexity required for significant solar activity

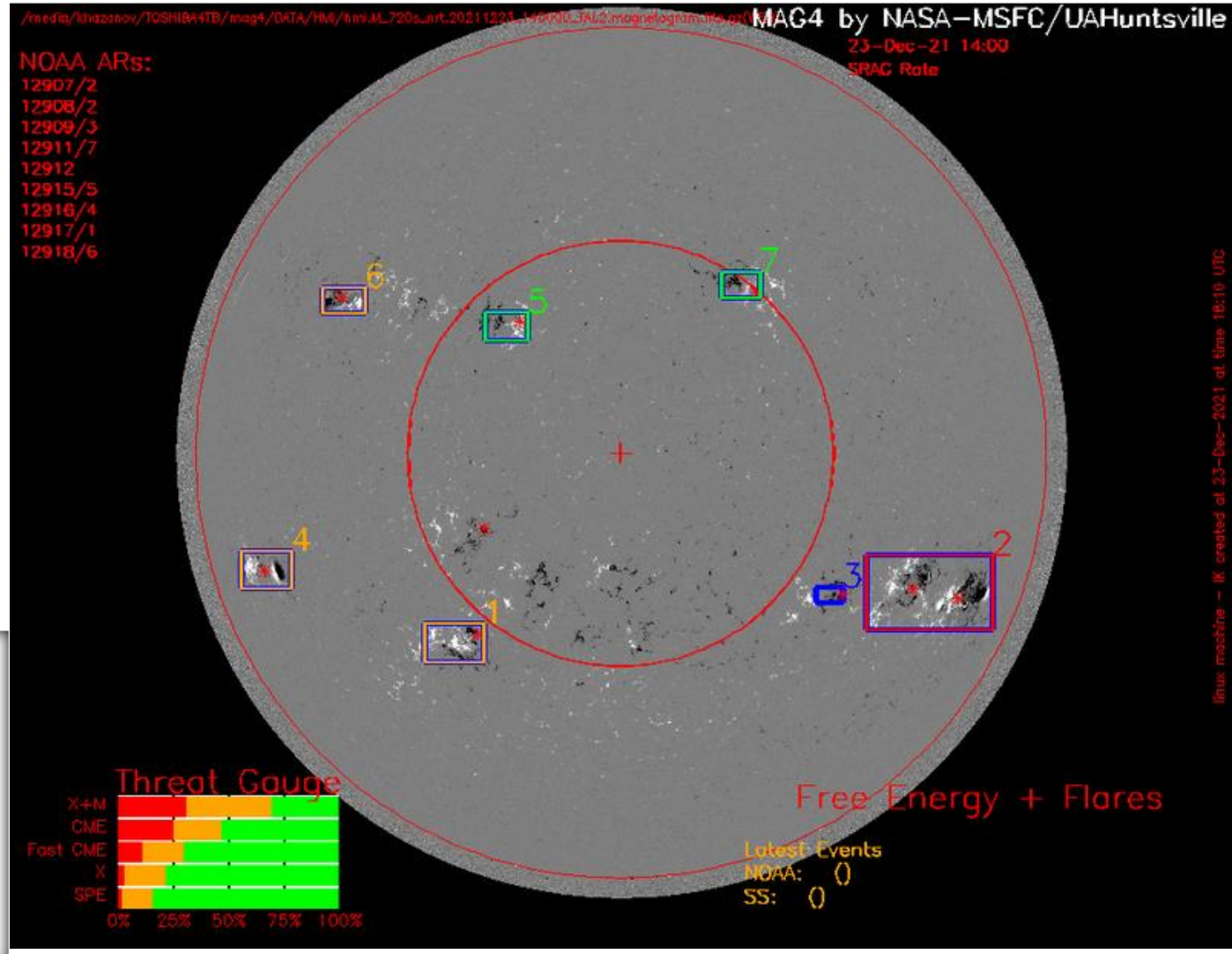
Situational awareness only…
…not used for launch constraints!

UAH MAG4 Pre-launch X-ray Flare, CME, and SPE Probability

- **Mag4 solar x-ray flare, CME, and SPE forecast tool based on computation of the magnetic free energy available for generating solar disturbances capable of producing x-ray flares, CMEs, and SPEs**
- **Near Real Time Forecast: Free Energy + Flares**
- **Team monitored 24-hour event rates for**
  - M&X flare potential SPE
  - CME, FCME potential geomagnetic storm
  - X flare potential SPE
  - SPE potential SPE

2021/12/23 14:00 WF=W+Flare

#	AR#	WL!DSG!N (kG)	Lng (deg)	Lat	24 Hour Event Rate M&X	CME	FCME	X	SPE	Dist (deg)
2	12907+	41	57	-21	0.620	0.370	0.200	0.120	0.078	60!
7	12911	1	19	20	0.000	0.000	0.000	0.000	0.000	27
5	12915	0	-14	16	0.000	0.000	0.000	0.000	0.000	21
4	12916	17	-61	-17	0.044	0.037	0.015	0.005	0.006	63!
1	12917	11	-22	-27	0.018	0.017	0.007	0.002	0.003	34!
6	12918	9	-44	20	0.013	0.013	0.005	0.001	0.002	48!
		Disk Forecast Rates			0.690	0.440	0.230	0.130	0.090	
		Multiplicative Uncertainties			1.8x	1.5x	1.7x	2.3x	2.4x	
Disk All-Clear Forecast Probabilities					50.00%	64.00%	80.00%	88.00%	91.00%	
		Uncertainties			19.00%	11.00%	9.50%	9.20%	7.20%	



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M2M SWx Briefings and Reports

- NASA's Moon to Mars Space Weather Analysis Office (GSFC) provided daily space weather briefings and written reports to the JWST Program and SWx launch constraint team personnel (the example here is the final 25 December report)

- Situational awareness insight into:
  - Solar activity, x-ray flares, CMEs, CH/HSS, and other solar wind disturbances at 1 AU that could be a factor during launch operations
  - Current state of constraint values
  - Forecast of constraint values for launch operations

- Very helpful to team in preparation for monitoring constraint values during launch operations

M2M Primary Analyst: A. Chulaki **M2M Secondary Analyst:** R. Loper **Briefing Date:** 2021-12-25

ID	Parameter	Threshold(s)	Assessment/Forecast

201	Proton Radiation Effects, Solar Flare Activity	**Monitoring begins at L-12 hours with LCC applicable at L-5 hours:**
		• Active NOAA SWPC **SPACE WEATHER ADVISORY WARNING** or **EXTENDED WARNING** for proton event 100 MeV integral flux above 1pfu
		• Solar radiation proton flux exceeds 5 pfu for energy thresholds > 50 MeV.
			• The proton fluxes observed by GOES for energy channels > 50 MeV and > 100 MeV have remained at background levels.
			• The MAG4 model continues to show an increased probability for flaring/CMEs, which could possibly result in a proton flux enhancement.
			• The AR 12907 with the highest magnetic complexity (beta-gamma) has almost reached the SW limb, while ARs 12908, and 12909 are currently still at longitudes favorable for magnetic connectivity with Earth.
			  ○ These ARs (specifically AR 12909 and 12907) produced a few lower C-class flares today.
			• More eastern ARs 12916, 12917 and 12918 are not yet magnetically connected to Earth and will not be connected for a couple of days. Observed proton flux enhancement from these regions is less likely to be observed in the near-Earth environment.
			  ○ These ARs (especially AR 12918) produced multiple low C-class flares today.
			• There are currently no active SPACE WEATHER ADVISORY WARNINGS or EXTENDED WARNINGS from NOAA SWPC for an SEP event.
			  ○ NOAA SWPC 3-Day Forecast Product (issued 2021-12-25T12:30Z) indicates the following probabilities for a Solar Radiation Storm (S1 or greater):
			  ▪ Dec 25: 10%
			  ▪ Dec 26: 1%
			  ▪ Dec 27: 1%

202	Internal Charging, Electron Flux Level	**From L-5 hours to L-10 minutes:** • Electron flux for energies greater than 2 MeV is greater than 4.98×10^4 e/sec/cm²/ster as measured at the GOES West spacecraft.	• The >2 MeV electron flux observed by GOES West has continued to be elevated above background levels, reaching the peak of ~1800 pfu today. ○ This radiation belt enhancement is likely associated with the waning influence of the HSS at arriving at L1 on 2021-12-19. • The >2 MeV electron flux levels were below the JWST threshold of 4.98×10^4 e/sec/cm²/ster during the post-launch period on 2021-12-25.
203	Surface Charging from Geomagnetic Substorms	**From L-1 hour to L-10 minutes:** • Geomagnetic Kp Index is equal to or greater than 4.	• The Geomagnetic Kp Index varied between 1 and 3 (below minor levels) within 12 hours of the launch today, reaching the maximum of 3 during the synoptic period from 2021-12-25T06:00Z to 2021-12-25T 09:00Z. • For 3-4 hours before the launch there was a possibility that Kp might cross into 4 due to a prolonged period of negative Bz (with the maximum negative value of Bz just below –5nT) from ~2021-12-25T05:00Z to the launch time. This prolonged period of negative Bz was possibly the

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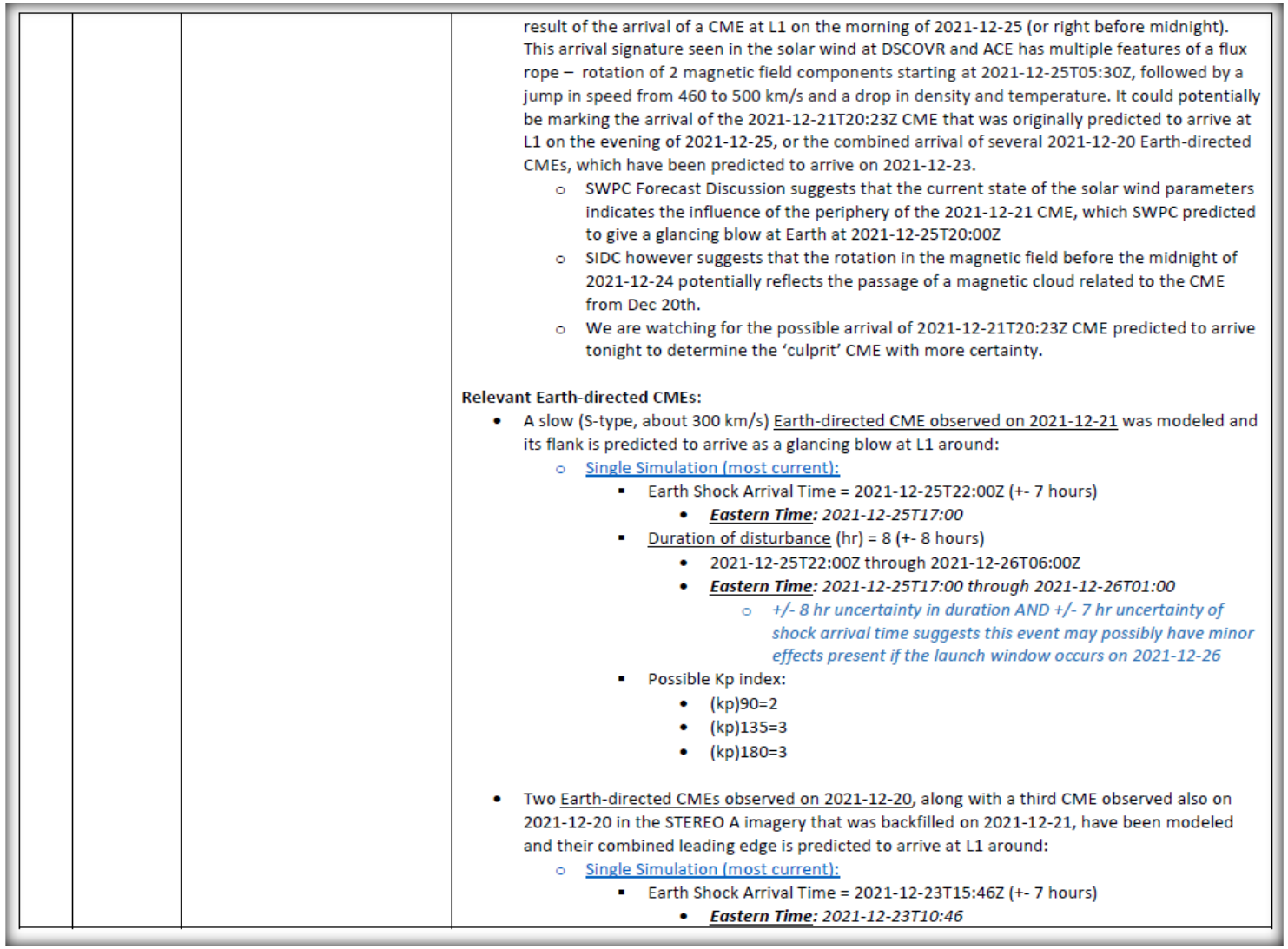

result of the arrival of a CME at L1 on the morning of 2021-12-25 (or right before midnight). This arrival signature seen in the solar wind at DSCOVR and ACE has multiple features of a flux rope – rotation of 2 magnetic field components starting at 2021-12-25T05:30Z, followed by a jump in speed from 460 to 500 km/s and a drop in density and temperature. It could potentially be marking the arrival of the 2021-12-21T20:23Z CME that was originally predicted to arrive at L1 on the evening of 2021-12-25, or the combined arrival of several 2021-12-20 Earth-directed CMEs, which have been predicted to arrive on 2021-12-23.

- SWPC Forecast Discussion suggests that the current state of the solar wind parameters indicates the influence of the periphery of the 2021-12-21 CME, which SWPC predicted to give a glancing blow at Earth at 2021-12-25T20:00Z
- SIDC however suggests that the rotation in the magnetic field before the midnight of 2021-12-24 potentially reflects the passage of a magnetic cloud related to the CME from Dec 20th.
- We are watching for the possible arrival of 2021-12-21T20:23Z CME predicted to arrive tonight to determine the 'culprit' CME with more certainty.

Relevant Earth-directed CMEs:

- A slow (S-type, about 300 km/s) Earth-directed CME observed on 2021-12-21 was modeled and its flank is predicted to arrive as a glancing blow at L1 around:
  - Single Simulation (most current):
    - Earth Shock Arrival Time = 2021-12-25T22:00Z (+- 7 hours)
      - ***Eastern Time:*** *2021-12-25T17:00*
    - Duration of disturbance (hr) = 8 (+- 8 hours)
      - 2021-12-25T22:00Z through 2021-12-26T06:00Z
      - ***Eastern Time:*** *2021-12-25T17:00 through 2021-12-26T01:00*
        - *+/- 8 hr uncertainty in duration AND +/- 7 hr uncertainty of shock arrival time suggests this event may possibly have minor effects present if the launch window occurs on 2021-12-26*
    - Possible Kp index:
      - (kp)90=2
      - (kp)135=3
      - (kp)180=3

- Two Earth-directed CMEs observed on 2021-12-20, along with a third CME observed also on 2021-12-20 in the STEREO A imagery that was backfilled on 2021-12-21, have been modeled and their combined leading edge is predicted to arrive at L1 around:
  - Single Simulation (most current):
    - Earth Shock Arrival Time = 2021-12-23T15:46Z (+- 7 hours)
      - ***Eastern Time:*** *2021-12-23T10:46*

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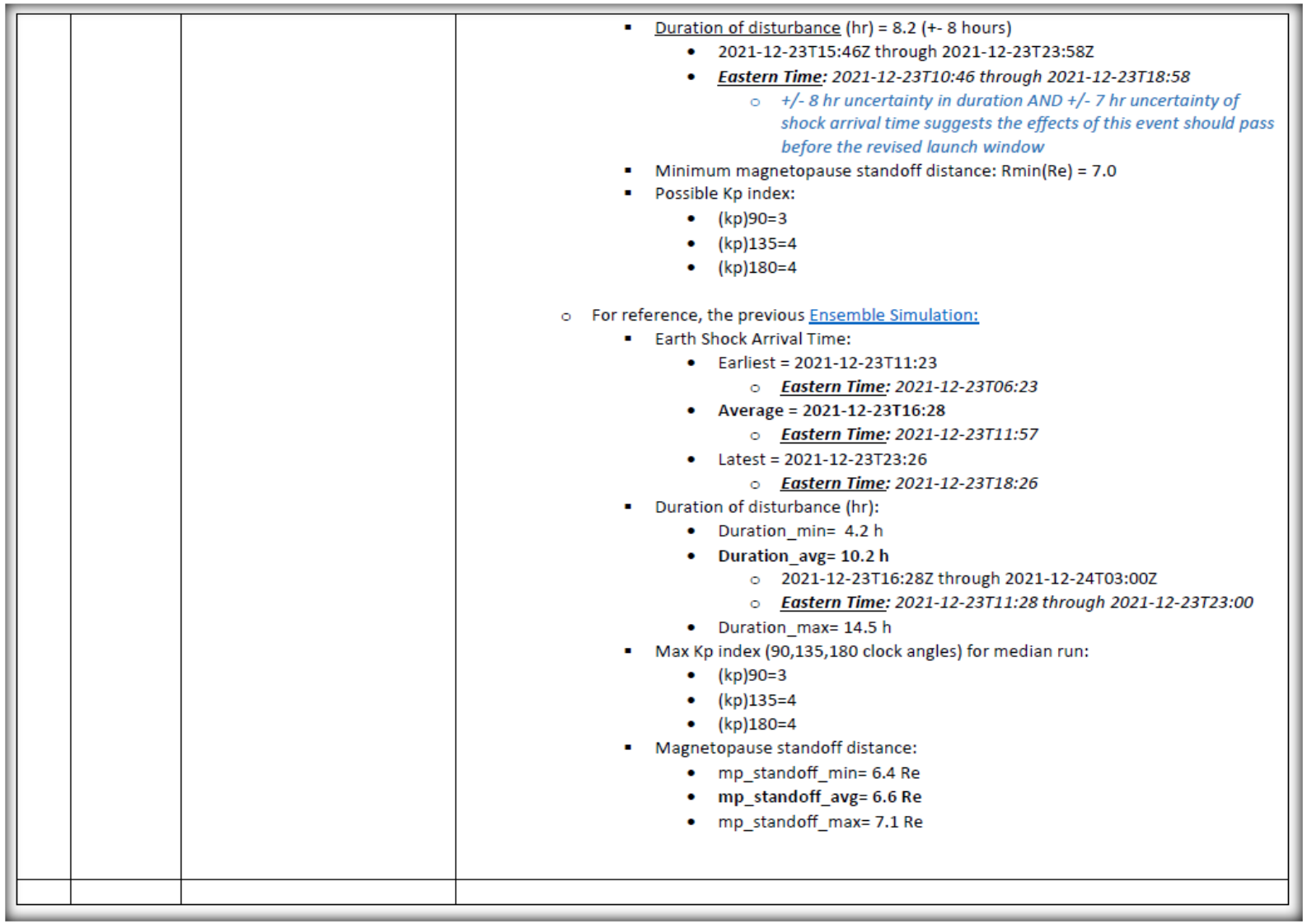


- Duration of disturbance (hr) = 8.2 (+- 8 hours)
  - 2021-12-23T15:46Z through 2021-12-23T23:58Z
  - ***Eastern Time:*** *2021-12-23T10:46 through 2021-12-23T18:58*
    - *+/- 8 hr uncertainty in duration AND +/- 7 hr uncertainty of shock arrival time suggests the effects of this event should pass before the revised launch window*
- Minimum magnetopause standoff distance: Rmin(Re) = 7.0
- Possible Kp index:
  - (kp)90=3
  - (kp)135=4
  - (kp)180=4

- For reference, the previous Ensemble Simulation:
  - Earth Shock Arrival Time:
    - Earliest = 2021-12-23T11:23
      - ***Eastern Time:*** *2021-12-23T06:23*
    - **Average = 2021-12-23T16:28**
      - ***Eastern Time:*** *2021-12-23T11:57*
    - Latest = 2021-12-23T23:26
      - ***Eastern Time:*** *2021-12-23T18:26*
  - Duration of disturbance (hr):
    - Duration_min= 4.2 h
    - **Duration_avg= 10.2 h**
      - 2021-12-23T16:28Z through 2021-12-24T03:00Z
      - ***Eastern Time:*** *2021-12-23T11:28 through 2021-12-23T23:00*
    - Duration_max= 14.5 h
  - Max Kp index (90,135,180 clock angles) for median run:
    - (kp)90=3
    - (kp)135=4
    - (kp)180=4
  - Magnetopause standoff distance:
    - mp_standoff_min= 6.4 Re
    - **mp_standoff_avg= 6.6 Re**
    - mp_standoff_max= 7.1 Re

Launch Operations Support

- Launch initially scheduled for 16 December 2021, but delayed multiple times due to issues unrelated to space weather
  - Team started monitoring state of space weather at this time for situational awareness
  - Planned to notify JWST should any serious concerns appear

- Final launch window opened 12:20 UTC on 25 December 2021

- SWx team provided real-time support to launch operations starting at L-12 hours

- Space weather input timeline started 12 hours before launch:
  - L-12 hrs to L–10 min — solar proton monitoring
  - L-6 hrs — solar proton for LV fueling poll
  - L-5 hrs to L-10 min — >2 MeV electrons
  - L-1 hr to L-10 min — Kp
  - L-10 min — all-inclusive Go/No-Go for launch

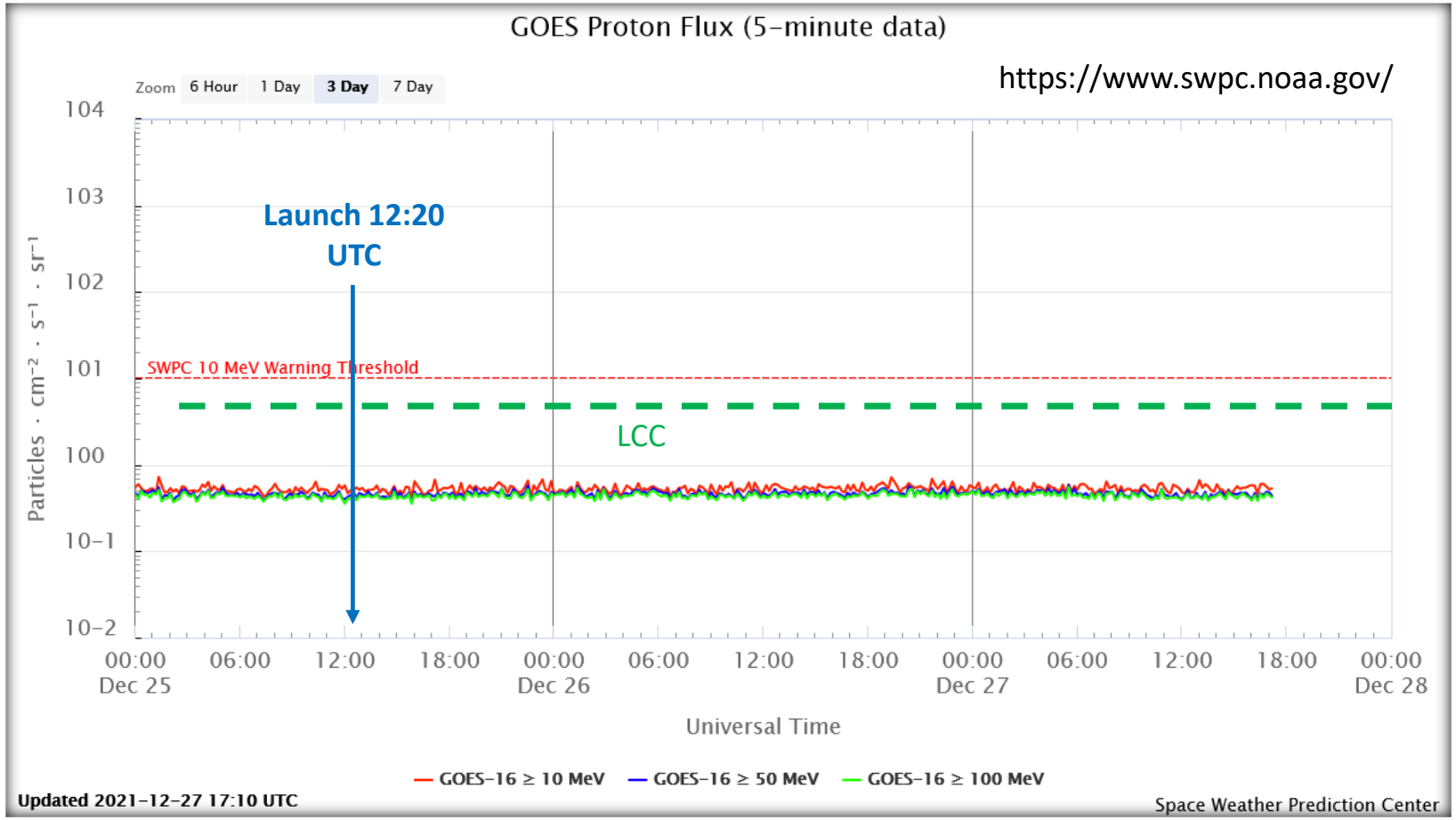
GOES Protons: SPE LCC

- Solar Proton LCC (No Go):

  J(>50 MeV) proton flux > 5 pfu

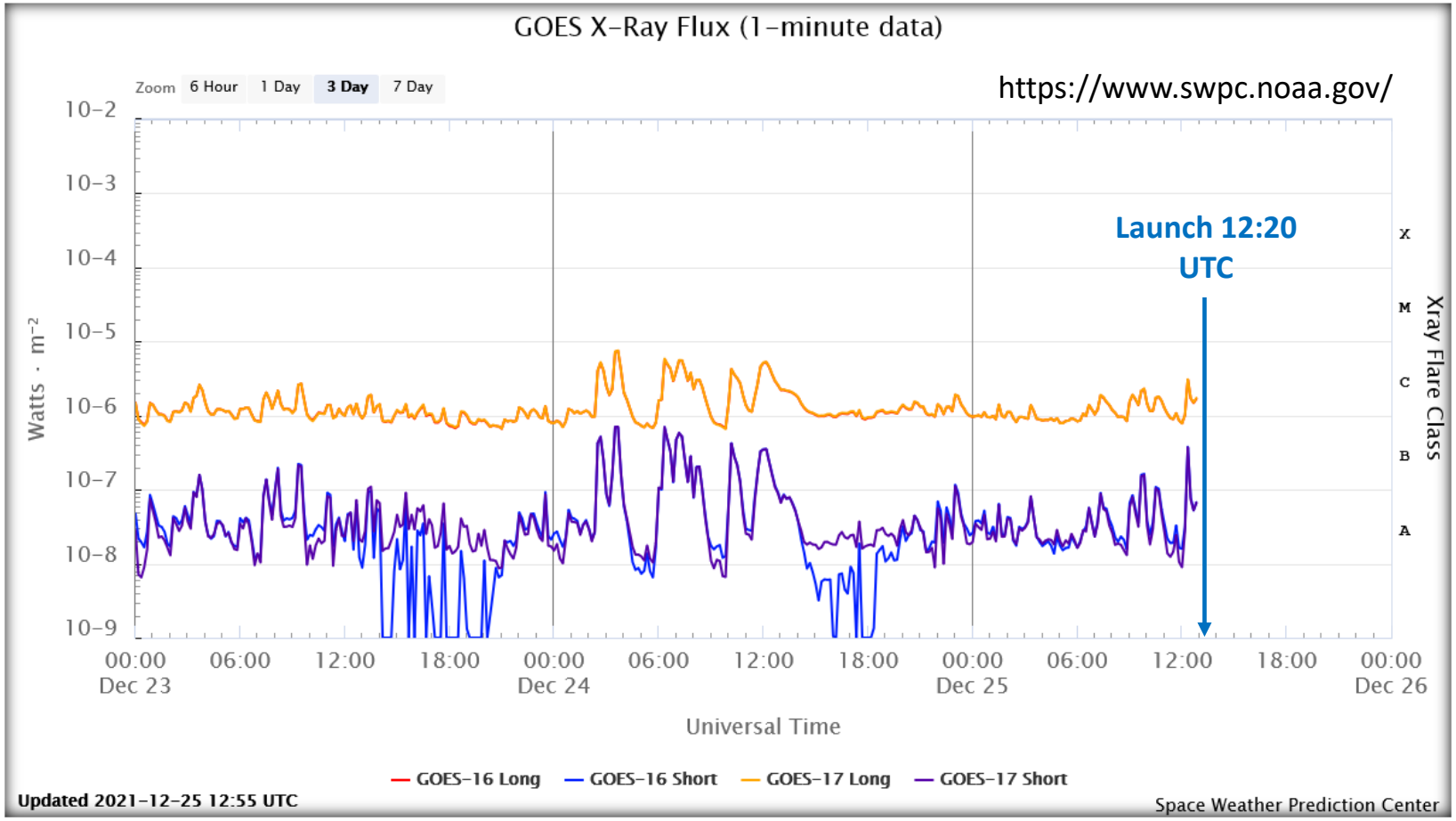
- >50 MeV protons remained at background levels during launch ops period

- >50 MeV protons no constraint for launch



GOES X-Ray Flux: situational awareness

- Team monitored GOES x-ray flux to watch for potential flare, CME activity that could generate SPE, geomagnetic activity
- M, X class flares are correlated with flare, CME, and SPE activity, provides an advanced warning since x-ray protons travel at light speed (~8 minutes from Sun) while solar protons and CMEs travel slower
- Data not used in SWx LCC
- Only C-class flare activity during launch ops, no M or X flares



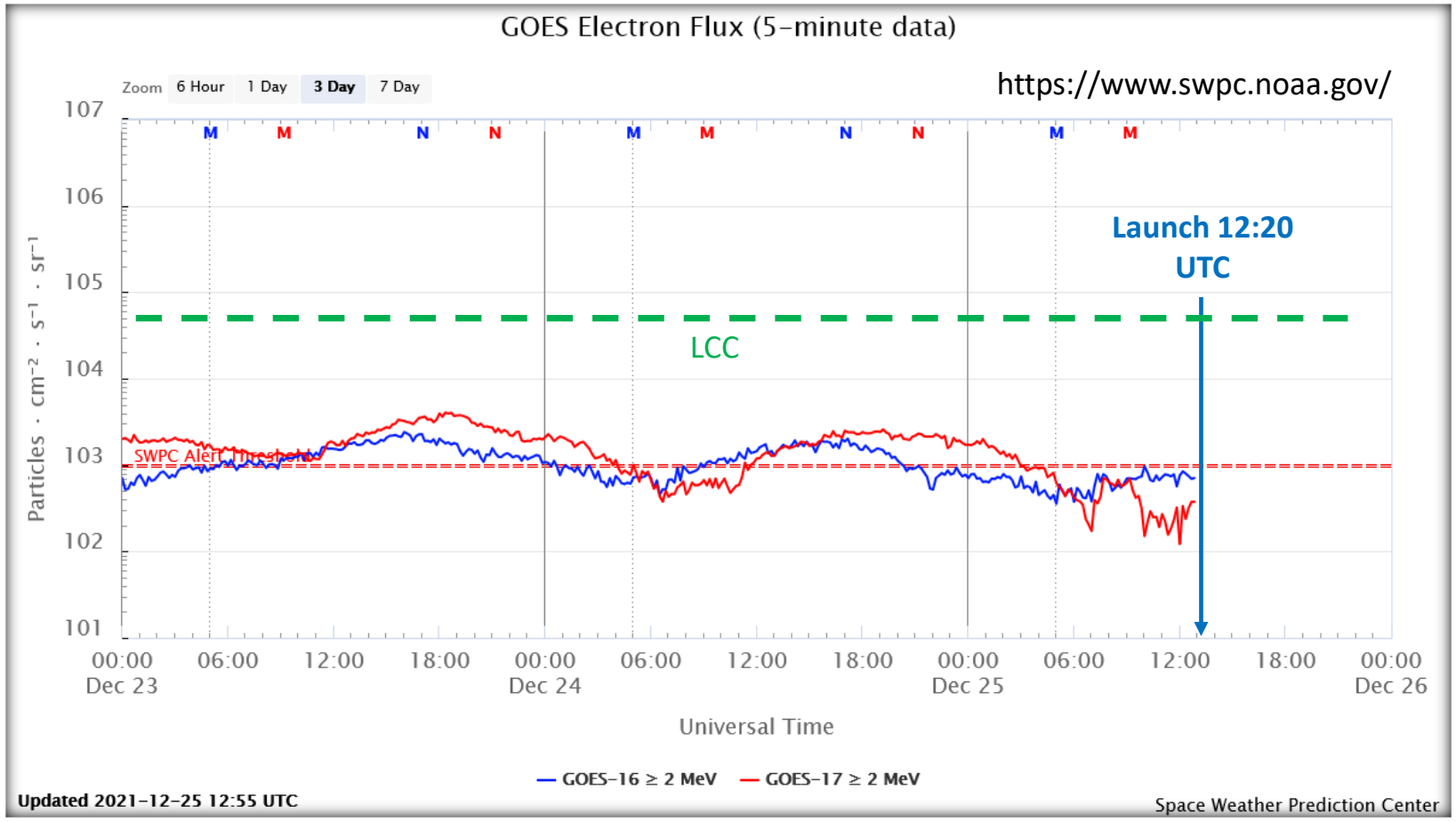
GOES >2 MeV Electrons: Internal Charging LCC

- GOES >2 MeV LCC (No-Go):

  J(>2 MeV) electrons >4.98x10^4 pfu

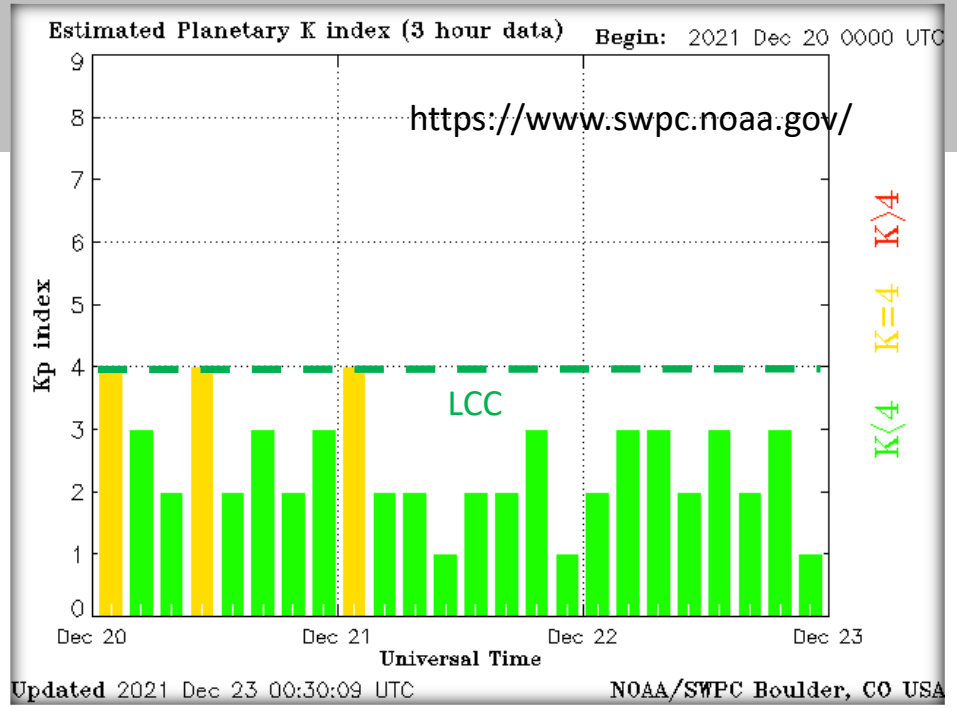
- Electron flux exceeded the NOAA SWPC alert levels during the launch ops but never exceeded the LCC constraint level

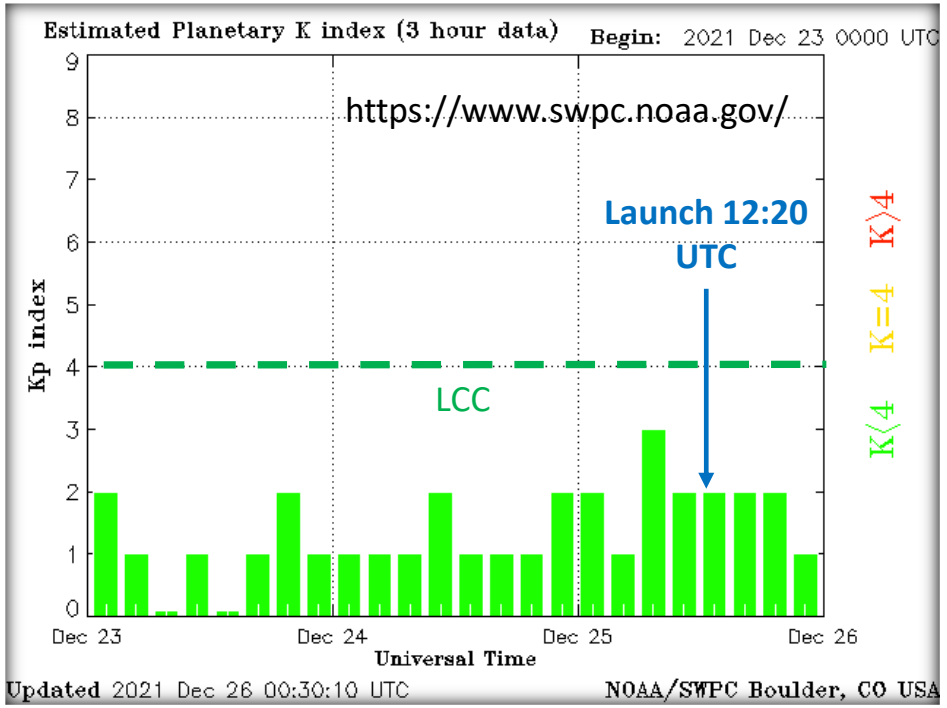
- >2 MeV electrons no constraint for launch



Kp Index: Surface Charging LCC

- Kp LCC (No-Go): Kp ≥ 4
- Kp reached levels of Kp = 4 due to minor geomagnetic storm in days preceding launch ops on 20-21 December, but activity decreased to levels below Kp=4 by the time the launch operations started on 24 December
- Planetary Kp Index never exceeded 3 during launch ops period
- Real time Kp from NOAA SWPC reached a maximum value of 3 during launch ops but never reached or exceed the constraint value of 4
- Kp no constraint for launch





Summary

- JWST used SWx LCCs as a risk reduction technique to protect JWST spacecraft from detrimental effects of severe space weather environments in the 4 to 18 hours following launch:
  - >50 MeV solar protons

    Single event effects in avionics
  - >2 MeV electrons

    Electrostatic discharge damage from internal charging
  - Kp ≥ 4

    Electrostatic discharge damage from surface charging

- All SWx LCC parameters remained at levels acceptable for launch during the launch operations period

- JWST launched successfully by Ariane 5 at 12:20 UTC on 25 December 2021 (at the opening of the launch window)
  - Space weather had no impact on launch operations

- Initial flight operations, satellite structural deployment, and transit from Earth to L2 was successful. JWST is now conducting science operations in orbit about Sun-Earth L2!


Image: NASA, ESA, CSA, and STScI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