Second Read-Ahead Document for the Space Weather Tabletop Exercise (SWx TTX)

Space Weather (SWx) TTX Scenario Overview

The hypothetical TTX scenario involves a series of solar events that drive a range of adverse space weather effects on Earth and in near-Earth space. The TTX scenario incorporates solar and geomagnetic activity that is posited to result in multiple hazards, including:

- intense radiation exposure to satellites, astronauts, and commercial aviation
- radio communications outages and disruptions
- loss of functionality or degraded performance of GPS for precision navigation and timing
- satellite failures and on-orbit collisions
- local- to regional-scale power outages

These effects can last for hours to days or even longer. Power outages may even last weeks or months depending on event severity and mitigation measures.

The TTX scenario takes place over approximately 8 days of scenario time from late January to early February 2028. In the hypothetical scenario, the National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center (SWPC) has been tracking an evolving active region on the solar surface. Over approximately 7 days, the active region has rotated into the location where, if it erupts, it is most likely to result in space weather at Earth (i.e., it will be "geoeffective"). During the scenario, NASA's Artemis IV mission is in progress, with two astronauts in the Orion command module in orbit around the Moon and two astronauts having just landed in the lunar module on the surface of the Moon. Those two astronauts on the Moon are preparing for a 7-day-long mission of lunar exploration, including rover activity. At the start of the exercise on January 26 in the scenario timeline, it is around 3 p.m. Eastern Time (i.e., afternoon on the U.S. East Coast and around noon on the West Coast).

TTX Environment

This TTX will provide a low-stress, no-fault environment to generate dialogue about various challenges associated with preparing for and responding to an impending space weather event. Participants should become familiar with their organization's policies or procedures relevant to this scenario and are encouraged to share information during the exercise. Such information may include, but need not be limited to, disaster preparedness and response procedures, space weather policies, organizational structures, contingency plans, and information-sharing and communications protocols, including public engagement.

During the TTX, participants will engage in an interactive dialogue regarding information requirements for senior leaders to make actionable decisions. They will also be given opportunities to learn from each other and enhance cross-agency communications and coordination. (Please note: The views expressed during the TTX will *not* be official government or organizational positions.)

Questions will be posed to the participants during the TTX, such as:

- Are you familiar with the potential impact a severe space weather event might have on your department or agency's day-to-day mission operations?
- What resources does your department or agency depend on that could be at risk given a major space weather event?
- Does your agency or organization have policies or protocols for information-sharing and decision-making given this type of threat?
- How would you develop and share crisis information with the public?

Typical Questions

What is space weather?

Space weather encompasses variability of the solar and space environments that results in adverse effects on human systems (both biological and technological) in deep space, lunar, near-Earth space, and Earth (i.e., ionosphere, atmosphere, and ground) environments. Some of the most common and impactful space weather effects include:

- Enhanced radiation (total ionizing dose) exposure to personnel and technology on aircraft (military, private, and commercial) and astronauts in space and on the Moon, as a result of solar and magnetospheric radiation variability
- Satellite damage and anomalies due to natural galactic, solar, and magnetospheric radiation variability and auroral activity

- Satellite drag (orbital degradation including station-keeping and ground-repeat times) and position uncertainty (e.g., for collision avoidance) due to thermospheric variability for near-Earth-orbit regimes
- Radio and satellite communications disruptions and outages due to solar radio noise, ionospheric disturbances, and auroral activity
- Degradation of global navigation satellite system (e.g., GPS) position, navigation, and timing services due to ionospheric disturbances and auroral activity
- Induced currents affecting pipelines, long transmission cables, and railways, due to geoelectric fields induced by geomagnetic storms
- Power grid infrastructure impacts, including the possibility of regional power outages and critical infrastructure damage, as a result of large currents induced in long-distance power lines by geomagnetic storms


Figure 1. The aurora borealis. Image credit: Bigstock.

The most visible and well-known phenomena associated with space weather are the aurora (i.e., the northern and southern lights). During extremely active periods, the aurora can be observed at latitudes reaching the southern United States and beyond.

NOAA's SWPC is part of the U.S. National Weather Service and responsible for civil space weather monitoring and maintaining operational products relevant to space weather end-user needs. Other U.S. government departments and agencies with stake and interest in space weather include: NASA, the National Science Foundation, the Department of Defense, the Intelligence Community, the U.S. Geological Survey, the Federal Aviation Administration, and the Federal Emergency Management Agency. As our society becomes more and more dependent on advanced technology, including space-based and satellite technology, space weather is becoming of higher and higher consequential relevance and will have a measurable impact on everyday people.

How often does space weather occur?

Severe space weather can occur at any time. However, there are certain times when the likelihood and intensity of space weather are higher. Solar activity and corresponding space weather effects follow an 11-year periodicity known as “the solar cycle.” Figures 2 and 3 show this solar cycle in two different formats, as recorded in sunspot number and with solar imagery. Throughout the solar cycle, and particularly during the peak in the cycle known as solar maximum, solar drivers of space weather include large, eruptive events such as solar radio bursts (SRBs), solar flares, and coronal mass ejections (CMEs). Toward the cycle minima, large eruptions become less frequent, but occurrences of a different type of solar driver, fast solar wind streams, increase in frequency, causing less intense but still serious space weather effects.

Space weather events known as geomagnetic storms occur approximately once per week on average, regardless of solar-cycle phase. During geomagnetic storms, solar drivers result in intense activity within Earth’s magnetic field. Space weather can also occur even outside of geomagnetic storm periods. For example, spacecraft charging anomalies, enhanced radiation hazards, and communications and navigation disruptions can occur during periods of enhanced auroral activity, known as substorms.

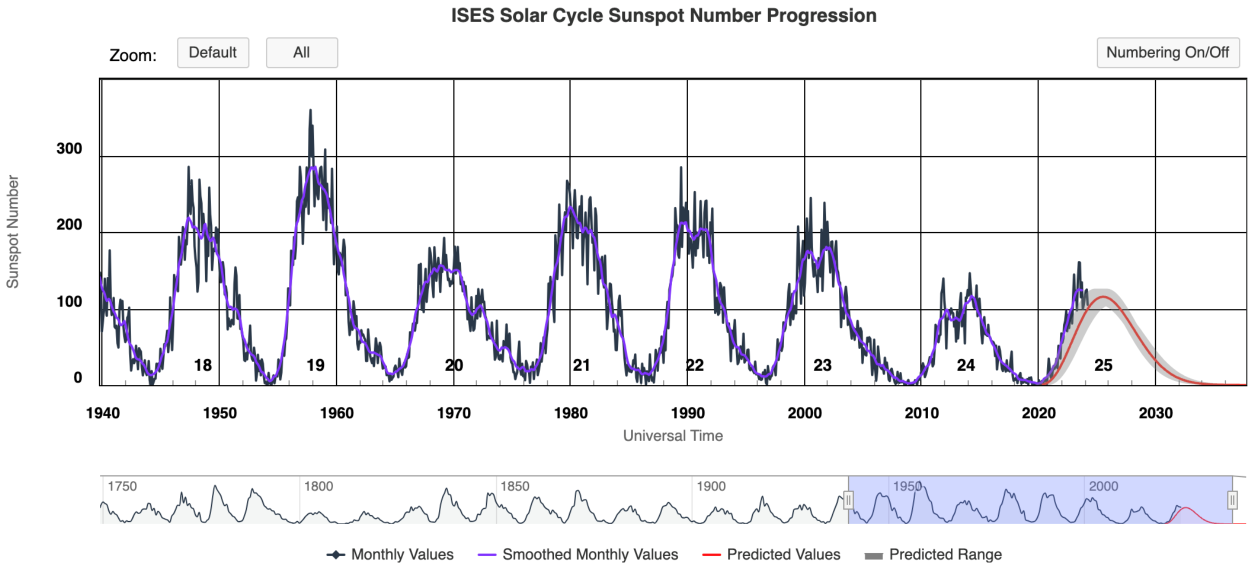

Figure 2. Solar cycle as quantified by the sunspot number, a count of solar active regions on the solar disk. The upper plot shows the cycle of sunspot number versus time from the year 1940 to present, including the predicted range of the current cycle (number 25). The bottom plot shows the same data back to 1750. Image credit: NOAA SWPC.

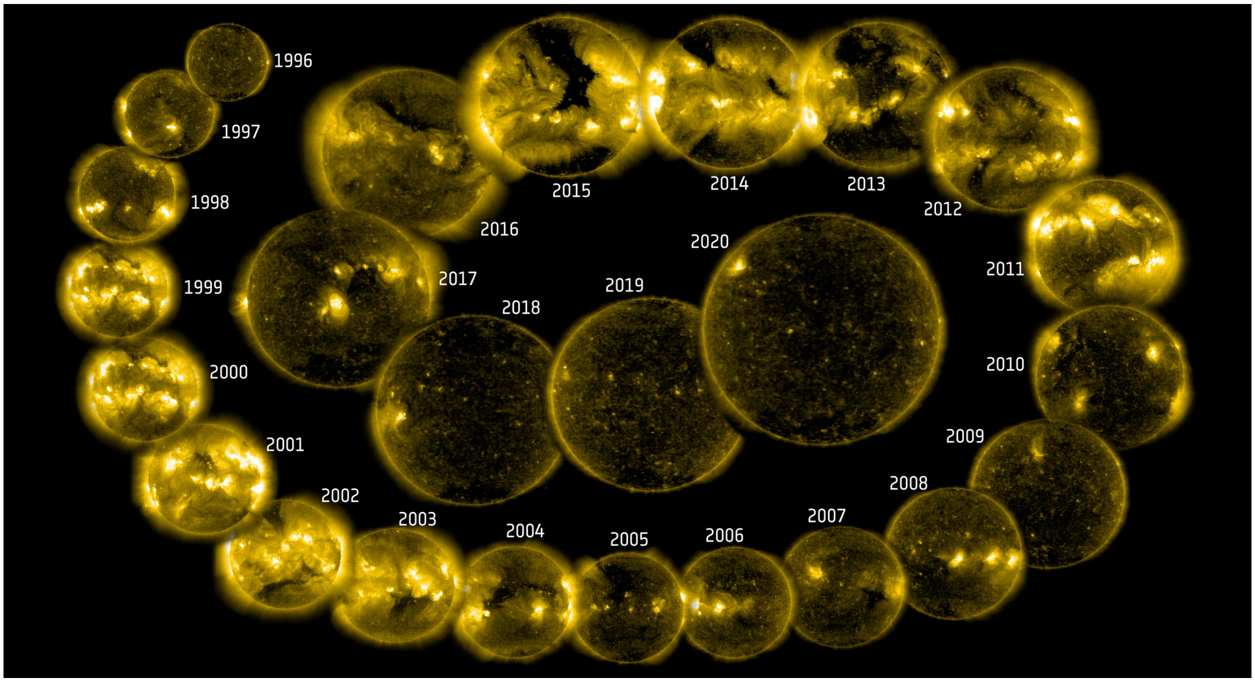

Figure 3. Solar cycle as quantified with solar imagery. Around solar minima years (e.g., 1996, 2009, 2020), the Sun showcases little activity (appearing darker in this particular wavelength), while around solar maxima years (e.g., 2001, 2012), the Sun's activity levels, including the drivers of extreme space weather, peak (active regions appear brighter in this wavelength). During these active periods, severe-to-extreme space weather events are more likely to occur. Image credit: European Space Agency (ESA)/Solar and Heliospheric Observatory (SOHO).

Drivers of Space Weather

Space weather is the result of extremely complex, natural systems extending from the Sun itself to Earth's interior. The Sun is a variable, enormous sphere of superheated plasma (the fourth state of matter) that sporadically erupts, producing direct drivers of space weather at Earth and throughout the solar system. Active regions consisting of concentrations of intense magnetic fields on the solar surface, known as "sunspots" (see Figure 4, black spots in the image), are the sources of solar eruptive events such as SRBs, flares, and CMEs, each of which is discussed below.

SRBs and solar flares (see Figure 5) involve the explosive release of intense electromagnetic emissions in the radio wavelengths (SRBs) and X-ray to gamma-ray wavelengths (flares) from active regions on the solar disk. SRBs can result in communications disruptions on the sunlit side of Earth. X-ray flares pose a radiation concern and significantly enhance Earth's ionosphere, which causes the subsequent loss of use of high-frequency (HF, 3–30 MHz) radio bands and disruptions to satellite communications and navigation signals. Flares and SRBs are of a space weather concern only when they occur on the solar disk visible from Earth.

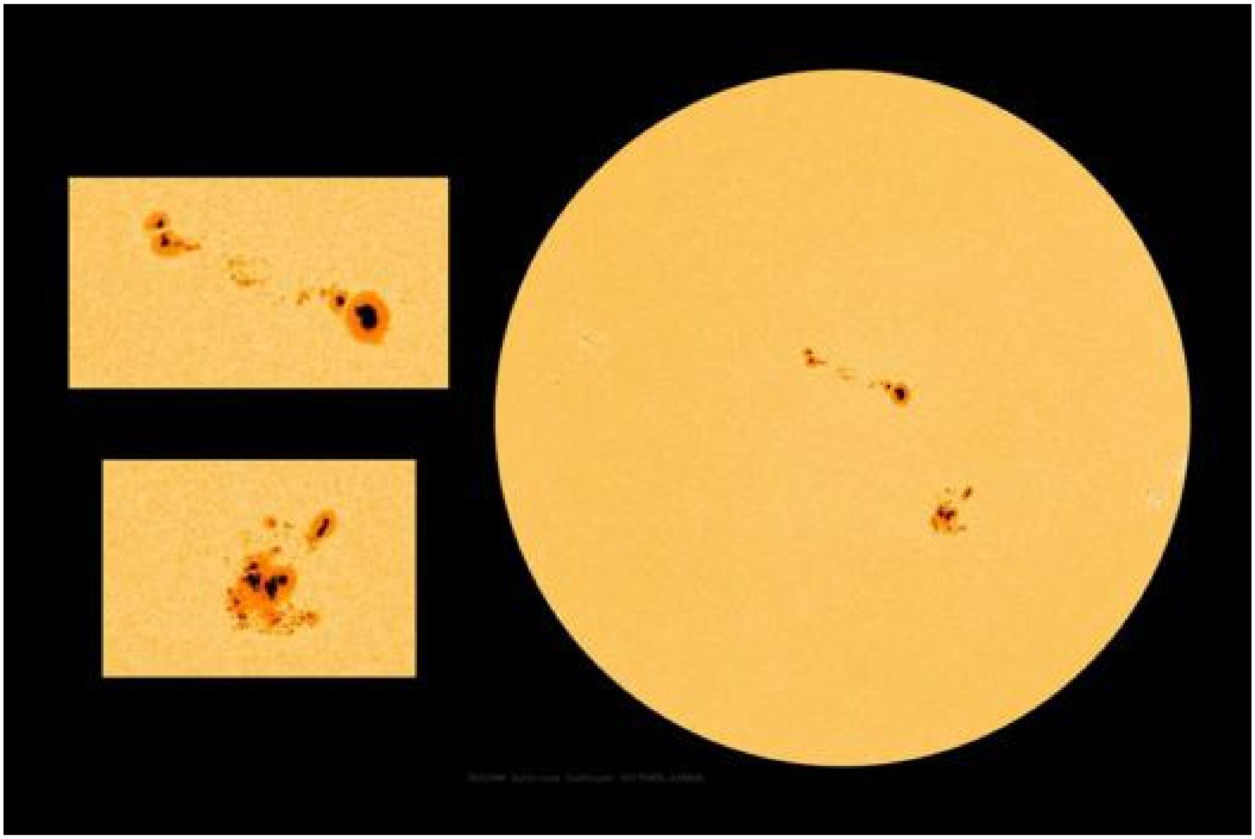

Figure 4. Examples of solar active regions (“sunspots”) on the solar disk. Sunspots correspond to regions of intense solar magnetic fields, which can explosively erupt in solar flares, radio bursts, and coronal mass ejections. Note that each of the largest sunspots shown here is many times the size of the entire planet Earth. Image credit: NOAA SWPC.

CMEs (see Figure 6) involve the explosive release of up to billions of tons of magnetized material from the outermost layers of the solar atmosphere (the corona) that travel at approximately 1 million miles per hour into interplanetary space. CMEs form shock waves on their forward edges, and when those blast waves and material hit Earth’s system, the combination can result in some of the most extreme geomagnetic storms.

Also often associated with solar eruptive events are intense periods of enhanced particle (e.g., protons, alpha particles, electrons) radiation known as solar energetic particle (SEP) events. SEPs pose the most significant natural radiation hazard to astronauts, satellites, and high-altitude aircraft and crews and can also result in ionospheric disturbances that affect communications and navigation signals.

Even in the absence of solar eruptions, the Sun emits the solar wind. Even typical, everyday changes in the solar wind can drive severe space weather at Earth, including auroral substorms and enhancements to the Van Allen radiation belts that surround Earth.

Why Is Space Weather So Challenging to Predict and Deal With?

The natural systems and drivers of space weather are complex, and the volume of space contributing to space weather spans the entirety of the inner solar system and is drastically under-observed. The state of space weather observatories today is analogous to the state of terrestrial weather observatory networks during the 1940s (full Earth satellite imagery of weather patterns and atmospheric data were entirely unavailable prior to the Space Age). Space weather observatories are few and far between, and there are no true global pictures of the full system. Because of these system complexities and known observational blind spots, the current state-of-the-art predictive and forecasting models for space weather offer only short-notice warnings (if any) and very high uncertainties. Furthermore, we are still establishing exactly how and why space weather detrimentally impacts human systems and technology, yet as human society becomes more and more dependent on advanced technology (e.g., electrical power; GPS position, navigation, and timing data; and satellite communications, internet, and other services) and our critical infrastructure systems become more global in scale, we are also becoming much more vulnerable to the threat of space weather.

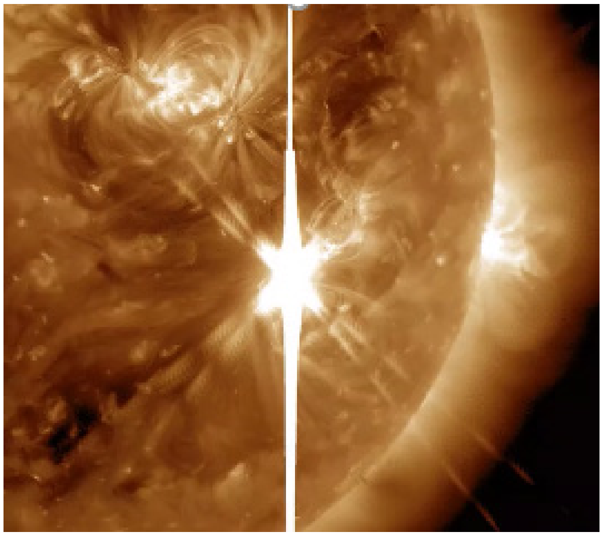

Figure 5. Example of a solar flare, in an intense burst of electromagnetic emissions up through X-ray and sometimes even gamma-ray wavelengths. Image credit: NASA.

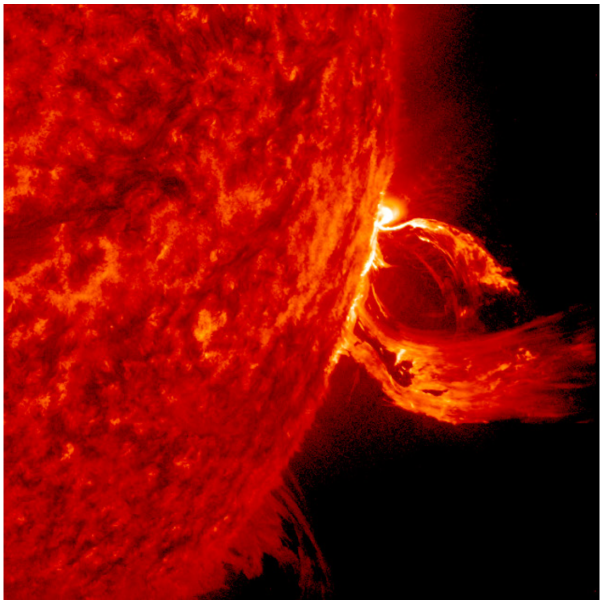

Figure 6. Example of a coronal mass ejection erupting from the Sun. This image is a composite of three instruments that continually observe the Sun from near Earth. Image credit: Solar Dynamics Observatory, NASA.

Appendices

Appendix A: Resources for Background Information

Primers on impending space weather events are available via the following:

- Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT Congressional Act S.881): https://www.congress.gov/bill/116th-congress/senate-bill/881/text
- NOAA Space Weather Prediction Center (SWPC) resources: https://www.swpc.noaa.gov
- National Space Weather Strategy and Action Plan: https://trumpwhitehouse.archives.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf
- Implementation Plan of the National Space Weather Strategy and Action Plan: https://www.whitehouse.gov/wp-content/uploads/2023/12/Implementation-Plan-for-National-Space-Weather-Strategy-12212023.pdf
- Federal Operating Concept for Impending Space Weather Events: https://www.fema.gov/sites/default/files/2020-07/fema_incident-annex_space-weather.pdf
- Space weather YouTube shorts:

  https://www.youtube.com/shorts/YU6wmS9hctc
  https://www.youtube.com/shorts/3FHbn5wMfFs
  https://www.youtube.com/shorts/zRrhDEK8yzo

- Space Weather Effects on Technology: https://www.nesdis.noaa.gov/events/space-weather-effects-technology
- Space Weather for Hazard Mitigation and Emergency Management (webinar, recorded October 11, 2023): https://piepc.org/october-2023-webinar/
- IS-66: Preparing the Nation for Space Weather Events: https://training.fema.gov/is/courseoverview.aspx?code=IS-66&lang=en
- Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise: https://www.weather.gov/media/nws/REPORT-Findings-and-Recommendations-04202023.pdf
- Space Weather Science and Observation Gap Analysis for the National Aeronautics and Space Administration (NASA): https://science3.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport_full_final.pdf

Appendix B: Selected Examples of Significant Documented Space Weather Events

The SWx TTX is based on observations, scientific calculations and analysis, and documented impacts. Below are multiple documented instances of actual historical space weather impacts on human systems.

1859 Carrington Event: This event comprised an extreme solar flare, geomagnetic storm, and geomagnetically induced currents that occurred in September 1859. During this period of extreme space weather, the solar flare was visible to the naked eye, and the aurora was observed as far south as Panama. The geomagnetically induced currents in telegraph lines were so intense that they resulted in fires at multiple telegraph stations. The Dst index (a geomagnetic index compiled from low-latitude, ground-based magnetometers used to qualify geomagnetic storm events and classify their intensity) for this storm was estimated at ≤1600 nT, over three times more intense than anything that has been observed in the last 50 years. See Tsurutani et al. (2003), Li et al. (2006), and Green and Boardsen (2006) for further detail.

1967 Solar Flare: On May 23, 1967, a large solar flare enhanced the polar ionosphere, which resulted in jammed radars and communications loss with U.S. military assets. The Department of Defense first attributed the loss to a Soviet attack, and the U.S. Air Force started preparing to launch a nuclear counterstrike. The counterstrike was aborted once space weather experts attributed the effects to the solar flare. See this American Geophysical Union (AGU) press release for further details.

1972 Solar Eruptions and Solar Energetic Particles (SEPs): In August 1972, the Sun erupted with a large flare, coronal mass ejection (CME), and intense SEPs. The events were associated with (and potentially the cause of) a near-simultaneous and entirely unintended detonation of dozens of sea mines deployed off the coast of North Vietnam by the U.S. Navy to interdict shipping during the Vietnam War. The event occurred between the Apollo 16 (April 1972) and Apollo 17 (December 1972) missions, and had the astronauts been in space at the time, the SEPs would have been sufficient to result in potentially fatal levels of radiation exposure. See Knipp et al. (2018) and this NOAA National Environmental Satellite, Data, and Information Service (NESDIS) webpage for further detail.

1989 Geomagnetic Storm and Hydro-Québec Outage: In March 1989, an extreme (Dst ≤ 500 nT) geomagnetic storm resulted in the sudden collapse of the power grid and a power outage in Québec, Canada. The outage was attributed to the compounding effects of multiple CMEs hitting Earth within a short period while the electrical grid was under stress. See Boteler (2019) and references therein for further detail.

2002 Battle of Takur Ghar Incident: This incident—an ultra-high-frequency (UHF)-SatCom communications failure during the U.S. War in Afghanistan—resulted in the deaths of three U.S. active service members. The incident occurred around solar maximum, and ionospheric disturbances capable of disrupting the UHF signals were observed between the ground forces and the communications satellite, suggesting a possible root cause of the communications link failure. See Kelly et al. (2014) for further detail.

2003 Halloween Storms: This series of extreme (G5 [see Appendix C for an explanation of the space weather G-scale]) CME-driven geomagnetic storms in late October and early November 2003 (around solar maximum) resulted in widespread space weather effects, including multiple satellite anomalies and losses, power grid disruptions and outages, recorded impacts on GPS, loss of the satellite tracking catalog, emergency diversions of polar flights to lower latitudes, and aurora observed across the southern United States (Arizona, New Mexico, Texas, Oklahoma). See Pulkkinen et al. (2005) for further details.

2010 Galaxy 15 Satellite Event: This event is one of hundreds of documented cases of satellite anomalies associated with and attributed to space weather. The Galaxy 15 anomaly resulted in a loss of capability to receive ground commands and the satellite drifting uncontrollably out of its orbit, affecting services for Intelsat customers. The fault was attributed to an electrostatic discharge affecting an electrical device onboard the space vehicle. See Loto'aniu et al. (2015) for further details.

2022 Starlink Event: Shortly after their launch in February 2022, SpaceX lost control of the majority of 49 Starlink satellites as a result of thermospheric expansion and enhanced density during a moderate geomagnetic storm. Ultimately, 38 of those 49 satellites were lost as a result of unanticipated atmospheric reentry—a loss of $10–20 million to SpaceX within only a matter of hours. See Berger et al. (2023) and Fang et al. (2022) for further details.

December 2023 Solar Radio Burst and Aviation Blackout: A solar radio burst—the most intense ever recorded—effectively jammed high-frequency line-of-sight communications over much of the sunlit portion of Earth. All communications were lost between air traffic control and every plane flying over the U.S. West Coast for approximately 8 minutes. See this CBS News report for more details.

Appendix C: NOAA SWPC and the Space Weather Scales

NOAA SWPC can provide approximately 18–72 hours of advance warning before a space weather event impact. However, many of the important characteristics of the space weather event will not be known until approximately 30 minutes before it impacts Earth. The SWPC warning provides limited information concerning a geomagnetic storm's impacts and what locations will be impacted; the true effects will only be determined once the storm arrives and impacts to critical infrastructure become evident. If a G4–G5 geomagnetic storm event is predicted with S4–S5 solar radiation (see the explanation of the space weather R-, S-, and G-scales on the next page), the Federal Emergency Management Agency (FEMA) Operations Center will notify FEMA leadership and the National and Regional Watch Centers, and an email will be distributed. In the case of an S5 or G5 event, notification will be sent over the National Warning System NAWAS/Washington Metropolitan Area Warning System (WAWAS).

For further details on these scales, see NOAA SWPC's website. Throughout the exercise, participants can expect to receive updates on the current scale levels during the scenario timeline. These scales do not offer definitive or comprehensive insight into all aspects of space weather effects. There is an ongoing discussion within the space weather research and operations community to consider upgrades to the scales system.

Currently, NOAA SWPC uses three scale systems—the R-, S-, and G-scales—to evaluate the severity of space weather at Earth. The R-scale corresponds to solar radio blackouts:

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	**Extreme**	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2 x 10^{-3})	Less than 1 per cycle
R 4	**Severe**	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	**Strong**	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	**Moderate**	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5 x 10^{-5})	350 per cycle (300 days per cycle)
R 1	**Minor**	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

The S-scale corresponds to solar radiation “storms”:

Scale	Description	Effect	**Physical measure** (Flux level of >= 10 MeV particles)	**Average Frequency** (1 cycle = 11 years)
S 5	**Extreme**	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	**Severe**	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	**Strong**	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	**Moderate**	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	**Minor**	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

The G-scale corresponds to geomagnetic activity and storms:

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	**Extreme**	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	**Strong**	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	**Moderate**	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	**Minor**	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Appendix D: Glossary of Key Terms

See the SWx TTX1 glossary (https://spaceweather-ttx.jhuapl.edu/files/SWx_TTX_Glossary.pdf) for a listing of key terms, including links for more information.