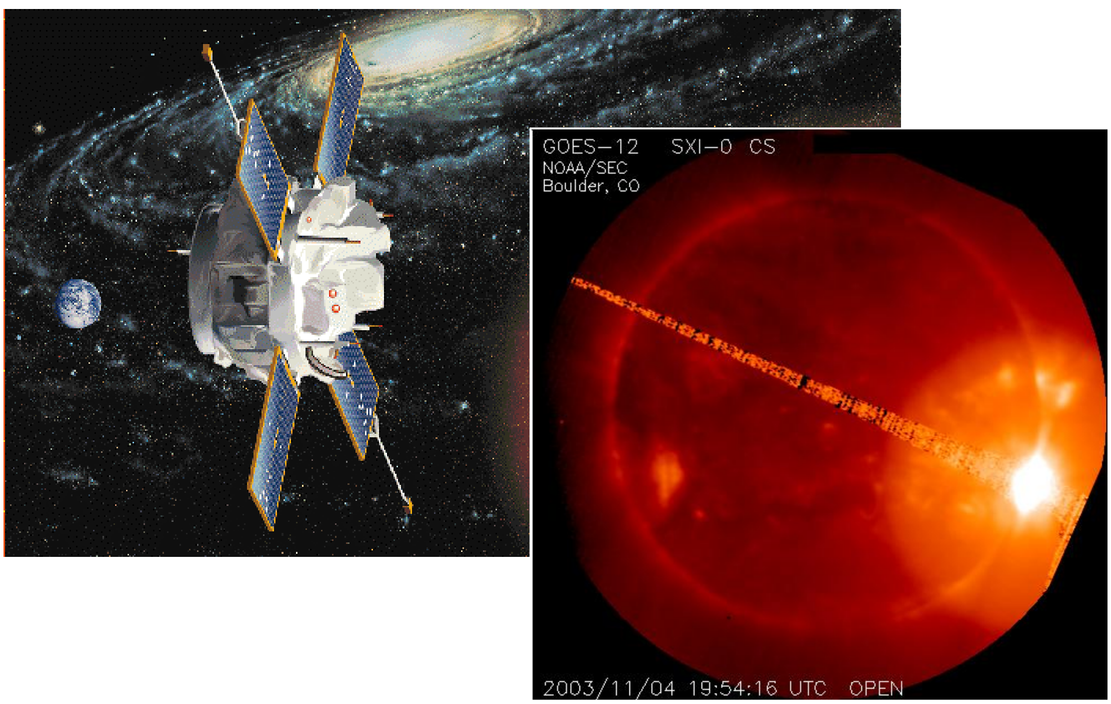
Service Assessment

Intense Space Weather Storms October 19 – November 07, 2003



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service
Silver Spring, Maryland

Cover Photographs:

Left: From a vantage point approximately 1/100 of the distance from Earth to the Sun, the Advanced Composition Explorer (ACE) satellite provides critical advance warning of geomagnetic storms that can overload power grids, disrupt spacecraft operations, and interrupt communications on Earth. The ACE satellite was one of many spacecraft that experienced significant problems during the late October 2003 solar activity.

Right: A dramatic depiction of the November 04 flare, probably the brightest X-ray solar flare ever seen by the GOES XRS X-ray sensor (estimated at X28), seen here in an SXI image.

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April 2004

U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

National Oceanic and Atmospheric Administration
Vice Admiral Conrad C. Lautenbacher, Jr., Administrator

Oceanic and Atmospheric Research
Richard D. Rosen, Assistant Administrator

National Weather Service
David L. Johnson, Assistant Administrator

Preface

The October-November 2003 solar storms rank as one of the largest outbreaks of solar activity in recent history. The global effects were wide-ranging, impacting power grids, airline flights, spacecraft operations, and much more. Media interest and public awareness of this activity was at the highest levels ever.

Due to the magnitude of this space weather event, a service assessment team was formed to examine the space environment warning and forecast services provided by the NOAA Space Environment Center. Service assessments provide a valuable contribution to our ongoing efforts to improve the quality and timelessness of our products and services for the protection of life and property. Findings and recommendations from the assessment team are offered to improve techniques, products, services, and the information provided to the American public and citizens around the world.

Richard D. Rosen

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Assistant Administrator
Oceanic and Atmospheric Research

David L. Johnson
Brigadier General, USAF (Ret.)
Assistant Administrator
National Weather Service

April 2004

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Service Assessment Team

The service assessment team was activated on December 01, 2003. Team members interviewed many on SEC's diverse customer list. Customers included multiple government agencies and private sector parties, with both U.S. and international interests. Their concerns were wide-ranging, from biological impacts of radiation storms to space weather effects on technology infrastructure, in space and on Earth. The team was comprised of the following individuals:

Christopher Balch	*Team Leader*, Lead Space Weather Forecaster, NOAA Space Environment Center (SEC), Boulder, Colorado
Bill Murtagh	*Lead Author*, Space Weather Forecaster, NOAA Space Environment Center, Boulder, Colorado
LT David Zezula	NOAA Corps, Space Weather Forecaster, NOAA Space Environment Center, Boulder, Colorado
Larry Combs	Space Weather Forecaster and SEC Media Spokesperson, NOAA Space Environment Center, Boulder, Colorado
Gayle Nelson	Lead Space Weather Operations Specialist, NOAA Space Environment Center, Boulder, Colorado
Ken Tegnell	Space Weather Operations Specialist, NOAA Space Environment Center, Boulder, Colorado
Misty Crown	Space Weather Operations Specialist, NOAA Space Environment Center, Boulder, Colorado
Barbara McGehan	NOAA Public Affairs Officer, Boulder, Colorado

Other valuable contributors include:

Joe Kunches	Chief, Space Weather Operations, NOAA Space Environment Center, Boulder, Colorado
Capt. Kelly Doser	Officer-In-Charge (OIC), Operating Location P, Air Force Weather Agency, Boulder, Colorado
Terry Onsager	Physicist, NOAA Space Environment Center, Boulder, Colorado

The following provided significant inputs to the storm impact lists:

Mike Golightly	Manager, NASA Space Radiation Analysis Group, NASA Johnson Space Center, Houston, Texas
John Kappenman	Manager, Applied Power Solutions Division, Metatech Corporation, Duluth, Minnesota
David Webb	Air Force Research Lab (AFRL), Solar and Solar Wind Disturbance Prediction group (VSBXS), Hanscom AFB, Massachusetts
Joe Allen	Scientific Secretary - Scientific Committee On Solar-Terrestrial Physics (SCOSTEP), NOAA-NGDC, Boulder, Colorado
Capt. Herbert Keyser	Chief, Space Weather Branch, A.F. Weather Agency, HQ AFWA/XOGX, Omaha, Nebraska

Acronyms

ACE	Advanced Composition Explorer - NASA research satellite monitoring the space environment beyond Earth's magnetic field
ADEOS	Advanced Earth Observing Satellite
Afr	A daily index of geomagnetic activity at Fredericksburg, VA, derived as the average of the eight 3-hourly a indices
AFWA	Air Force Weather Agency
Ap	A 3 hourly equivalent amplitude of magnetic activity derived from the Kp index
ATC	Air Traffic Controllers
CDS	Coronal Diagnostic Spectrometer on SOHO
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer satellite
CME	Coronal Mass Ejection
DGPS	Differential Global Positioning System
DHS	Department of Homeland Security
DMSP	Defense Meteorological Satellite Program
DP	Dynamic Positioning
EDP	Electron Density Profile
EIT	Extreme ultraviolet Imaging Telescope - used to view the sun in extreme ultraviolet wavelengths
EPAM	Electron, Proton, and Alpha Monitor – its data disclose approaching shocks
ESA	European Space Agency
EUV	Extreme UltraViolet
FAA	Federal Aviation Administration
GALEX	Galaxy Evolution Explorer
GIC	Geomagnetically Induced Current
GOES	Geostationary Orbiting Environmental Satellite
GPS	Global Positioning System
GSFC	NASA Goddard Space Flight Center
Ha	Hydrogen Alpha - 6353 Angstrom filtered imagery used to detect features on the Sun
HALOE	Halogen Occultation Experiment (on UARS)
HF	High Frequency (3-30 MHz)
ICESat	Ice, Cloud, and Land Elevation Satellite
IMF	Interplanetary Magnetic field
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency

JSC	Johnson Spaceflight Center
km/s	Kilometers per Second
Kp	A 3 hourly planetary index of geomagnetic activity
L1	Lagrangian point. A point on the Sun – Earth line about 1/100 of the distance from Earth to the Sun
LASCO	Large Angle Spectrometric Coronagraph - used for detecting coronal mass ejections
LEMS	Low Energy Magnetic Spectrometers
mph	Miles Per Hour
NASA	National Aeronautics and Space Administration
NERC	North American Electric Reliability Council
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
nT	nanoTesla – Unit of magnetic field measurement
OAR	Office of Oceanic and Atmospheric Research
Pfu	Particle Flux Units (1 pfu = particle/cm^2-s-ster)
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
RSTN	Radio Solar Telescope Network
RXTE	Rossi X-ray Timing Explorer (satellite)
SEC	Space Environment Center
SEM	Space Environment Monitor - instrument package aboard GOES spacecraft
sfu	Solar Flux Units (1 sfu = 10^-22 W/m^2/Hz)
SI	Sudden Impulse - sudden perturbation in Earth's magnetic field due to compression from a shock in the solar wind
SIRTF	Space Infrared Telescope Facility
SOHO	SOlar and Heliospheric Observatory - a joint NASA/ESA research satellite
SOON	Solar Observing Optical Network
SSIES	Special Sensor - Ions, Electrons, and Scintillation (instrument on DMSP)
SSN	Smoothed Sunspot Number - an average of 13 monthly RI numbers, centered on the month of concern
SWEPAM	Solar Wind Electron, Proton, and Alpha Monitor - used to monitor solar wind
SXI	Solar X-ray Imager on GOES - used to detect flare location
TEC	Total Electron Content
TOMS	Total Ozone Mapping Spectrometer (satellite)
TRMM	Tropical Rainfall Measuring Mission (satellite)
UARS	Upper Atmosphere Research Satellite
UTC	Universal Time Coordinated
VHF	Very High Frequency (30 – 300 MHz)
XRS	X-ray Sensor on GOES

Service Assessment Report

Introduction

Solar Cycle 23 began its 11-year cycle in May 1996 with a monthly smoothed sunspot number (SSN) of 8.0, and peaked in April 2000 at 120.8. October 2003 marked the 92nd month in Cycle 23 and the early-October sunspot count reflected another quiet month in the unremarkable waning phase of an average solar cycle. The quiet period would abruptly end. With little warning, large and intense sunspot groups developed on the solar surface, and by the end of October 2003, NOAA Space Weather Forecasters were engaged in the most active and demanding solar activity epoch in years. In the 60 days prior to this outbreak, two solar energetic event alerts were issued. In contrast, during the late October – early November three week period, NOAA SEC staff issued over 250 solar energetic event watches, warnings, and alerts, as three of the largest sunspot clusters in over 10 years emerged on the surface of the Sun.

Impacts were wide ranging. The Sydkraft utility group in Sweden reported that strong geomagnetically induced currents (GIC) over Northern Europe caused transformer problems and even a system failure and subsequent blackout. Radiation storm levels were high enough to prompt NASA officials to issue a flight directive to the ISS astronauts to take precautionary shelter. Airlines took unprecedented actions in their high latitude routes to avoid the high radiation levels and communication blackout areas. Rerouted flights cost airlines \$10,000 to \$100,000 per flight. Numerous anomalies were reported by deep space missions and by satellites at all orbits. GSFC Space Science Mission Operations Team indicated that approximately 59% of the Earth and Space science missions were impacted. The storms are suspected to have caused the loss of the \$640 million ADEOS-2 spacecraft. On board the ADEOS-2 was the \$150 million NASA SeaWinds instrument. Due to the variety and intensity of this solar activity outbreak, most industries vulnerable to space weather experienced some degree of impact to their operations.

Widespread concerns by affected commercial sectors generated intense global media interest. The storms were covered by major media organizations around the world. SEC staff participated in over 300 news broadcasts and interviews, assisting media outlets from Chile to Hong Kong. The high levels of activity fueled more public and media interest than any other solar event or period this cycle. Customer concerns and heightened public awareness produced a frenzy of interest in the SEC web page, which saw the daily average hit-rate of 500,000 rise to over 19 million hits on October 29. Solar images and solar activity stories were flashed on newspapers around the world, making "solar flares" a household term.

This activity outbreak occurred 42 months after Cycle 23's peak in April 2000. While late cycle active periods have occurred in the past, it is unusual to see this extreme level of activity during this stage of the solar cycle. Seventeen major flares erupted on the sun between October 19 – November 05, 2003, including perhaps the most intense flare ever seen by a GOES XRS instrument – a huge X28 flare (NOAA scale R5 – see Appendix A and B) on November 04. Many of these flares had associated radiation storms, including an S4 (severe) storm on October 29. Geomagnetic storm periods were observed on 12 of the 20 days, with two storms reaching the G5 (extreme) level on October 29 and 30. The last occurrence of such late cycle activity was April/May 1984 during Cycle 21. That period saw a total of nine major flares, 52 months after the December 1979 peak of the Cycle. It should also be noted that 28 major flares occurred in 1973 during the late stages of Cycle 20. Cycle 20 peaked in November 1968.

Overview

Solar activity from October 19 to November 05, 2003 originated from three sunspot regions, numbered by SEC forecasters as Regions 484, 486, and 488. While each of these regions was remarkable in size and magnetic complexity, Region 486 was by far the most significant. With a size exceeding 2600 millionths of the solar disk (over 13 times the size of Earth), Region 486 was the largest sunspot group observed since November of 1990. It maintained its extreme size, complex magnetic structure, and thus, great flare potential, during its entire transit across the visible disk (Figure 1). Twelve of the seventeen major flares that occurred during this period came from Region 486. Of the twelve major flares, three stand out as defining events: the X17 (R4) on October 28, X10 (R4) on October 29, and X28e (R5) on November 04.

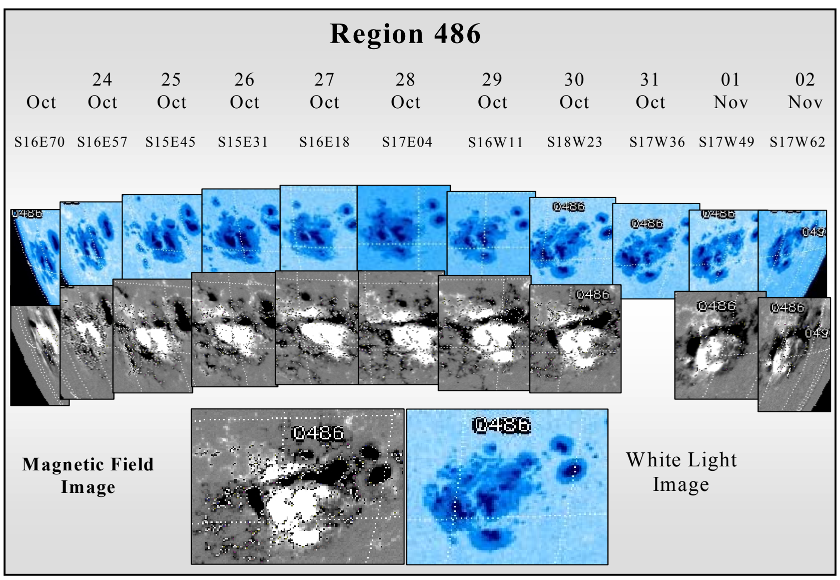


Figure 1. White light and magnetic imagery showing the solar disk transit of super Region 486. *Courtesy of Big Bear Solar Observatory.*

Solar flares are measured by their X-ray emissions as recorded by the GOES XRS instrument (Appendix B). On October 28 at 1110 UTC, a powerful X17 flare occurred from Region 486 (Figure 2), producing a category R4 (severe) radio blackout on the NOAA Space Weather Scales (Appendix A). This flare had intense radio bursts including a 245 MHz burst near 500,000 sfu – one of the largest ever recorded. The flare occurred near center disk and was promptly followed by a very fast coronal mass ejection (CME) and a strong radiation storm. The solar radiation storm quickly reached category S3 (strong) levels and, after 13 hours, exceeded S4 (severe) levels. This was the second most intense radiation storm this cycle, and the fourth most intense since measurements began in 1976. The CME was observed by the LASCO coronagraph on board the SOHO spacecraft and had an estimated speed of 2125 km/s (over 5 million mph). The CME Sun-to-Earth transit took just 19 hours, arriving at Earth on October 29 at 0613 UTC (the fastest on record is 14.6 hours in August 1972). The fast CME impacted Earth's magnetic field and produced a G5 (extreme) geomagnetic storm. The storming lasted for twenty-seven hours and was the sixth most intense geomagnetic storm on record (since 1932).

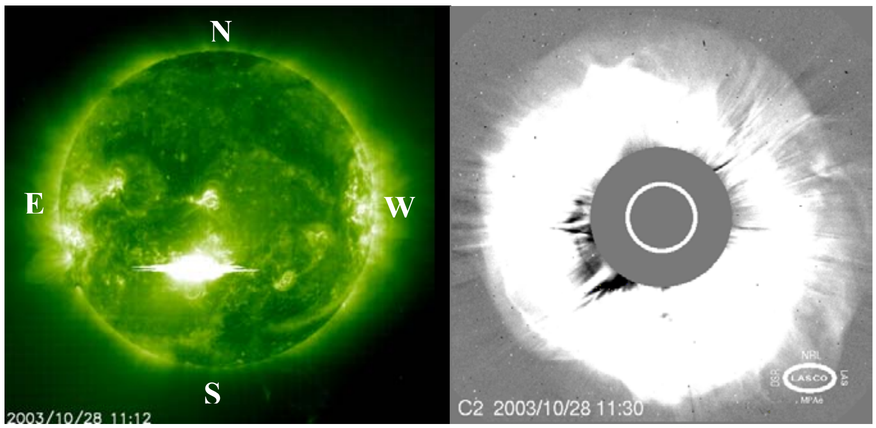


Figure 2. EIT 195 (left) and LASCO imagery (right) of R4 flare and full halo CME on October 28. Note the bright emission that surrounds the Sun (the halo), indicating that the CME is directed toward Earth. (NASA/ESA)

Less than 24 hours after the X17 flare, Region 486 produced another major eruption. On October 29 at 2049 UTC, an X10 flare (S4 - severe radio blackout) erupted, followed by an S3 (strong) radiation storm and another powerful, Earth-directed CME (Figure 3). The estimated speed for this extremely fast CME was 1948 km/s and the transit time was, again, 19 hours, arriving at Earth at 1600 UTC on October 30. Another G5 (extreme) geomagnetic storm followed quickly on the heels of the powerful October 29 storm (Figure 4) and lasted for twenty-four hours.

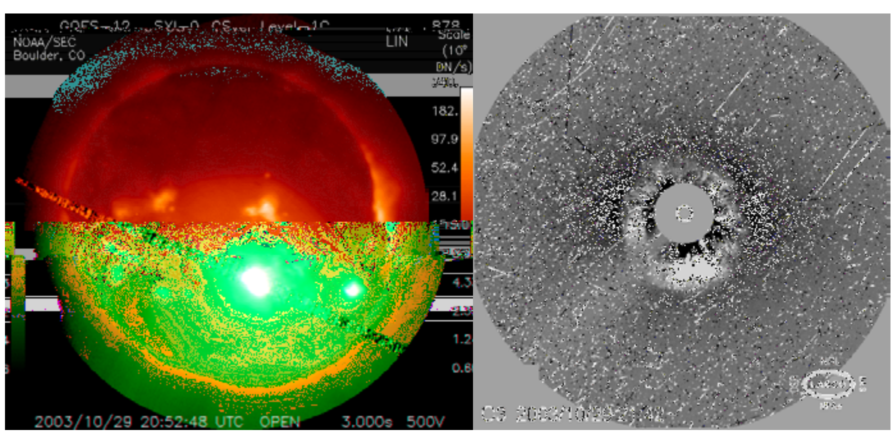


Figure 3. GOES SXI (left) and LASCO imagery (right) of S4 flare and halo CME on October 29. (NOAA/NASA)

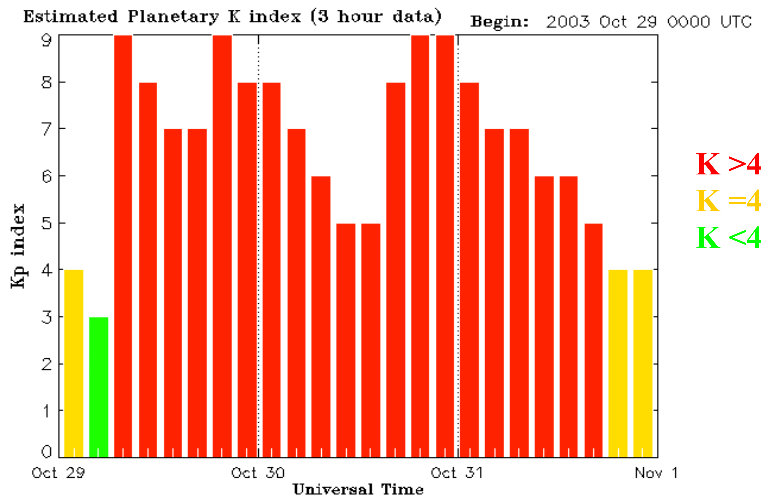


Figure 4. The Kp index for the back-to-back G5(extreme) geomagnetic storms. (NOAA/NCEP/SEC)

The last event of significance during this outbreak was an X28e (estimated) major flare from Region 486, producing category R5 (extreme) radio blackout levels on November 04 at 1950 UTC (Figure 5). The GOES XRS instrument became saturated at the X17.5 level for 12 minutes during this flare. Using historical flare data and mathematical modeling, an estimated peak flux of X28 was assigned. This flare was one of the strongest flares since GOES XRS measurements began in 1976. Despite the record size of the flare, its location near the west limb of the Sun limited its impact. The associated CME, as seen in Figure 5, was directed away from Earth. As a result, the subsequent radiation storm and geomagnetic storm only reached category S2 (moderate) and G1 (minor) levels.

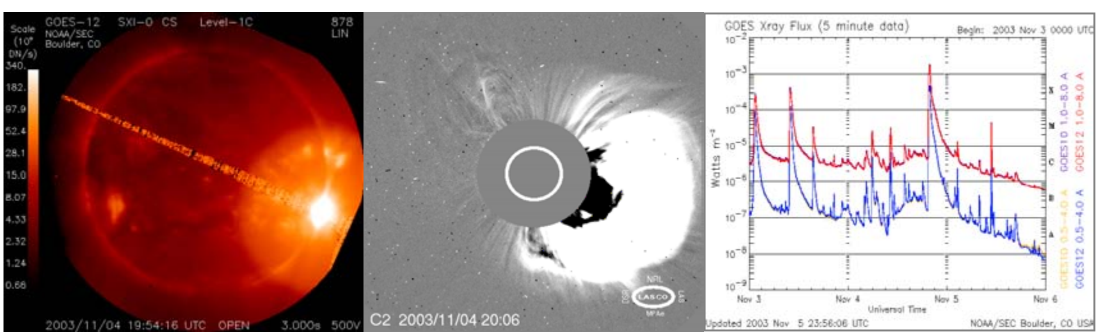


Figure 5 – GOES SXI (left) and LASCO imagery (center) of November 04, X28e flare And CME. On the right GOES XRS measurement of the record event. (NOAA/NCEP/SEC, NASA)

A total of 17 major flares (>R2), six radiation storms (>S1), and four severe geomagnetic storms (>G2) occurred in this 20-day period.

Warning and Forecast Services

NOAA's Space Environment Center is the national and world warning center for disturbances in the space environment. The Space Environment Center provides real-time monitoring and forecasting of solar and geophysical events, and issues space weather watches, warnings and alerts to multiple government and private entities in the United States.

The first of the three big sunspot groups (Region 484) emerged rapidly near the southeast limb of the Sun on October 18. The daily forecast on the 18th showed increased percentage probabilities for flare activity. This region continued in a growth phase through October 19 and by midday produced an X1 flare (R3 radio blackout). The flare's impulsive signature and location near the southeast limb suggested to forecasters that no radiation or geomagnetic storm was likely. No warnings were issued and no storms occurred.

By October 21, Region 484 maintained considerable size and complexity, but it was the activity originating from behind the southeast limb that alarmed forecasters. At least four large coronal mass ejections were observed to occur from a source behind the east limb between October 18 - 22. The combined potential of this new region (numbered by SEC as Region 486 on October 22) and the existing Region 484 prompted SEC to issue a Space Weather Advisory. This, in turn, led to a NOAA Press Release. The advisory alerted customers that a prolonged period of solar activity was expected:

SEC Space Weather Advisory

Official Space Weather Advisory issued by NOAA Space Environment Center, Boulder, Colorado, USA
SPACE WEATHER ADVISORY BULLETIN #03- 2
2003 October 21 at 06:11 p.m. MDT (2003 October 22 0011 UTC)

******* INTENSE ACTIVE REGIONS EMERGE ON SUN *******

Two very dynamic centers of activity have emerged on the sun. NOAA Region 484 developed rapidly over the past three days and is now one of the largest sunspot clusters to emerge during Solar Cycle 23, approximately 10 times larger than Earth. This region, which is nearing the center of the solar disk, already produced a major flare (category R3 Radio Blackout on the NOAA Space Weather Scales) on 19 October at 1650 UTC. The region continues to grow, and additional substantial flare activity is likely.

A second intense active region is rotating around the southeast limb of the sun. Though the sunspot group is not yet visible, two powerful eruptions occurred on 21 October as seen from the LASCO instrument on the SOHO spacecraft. These eruptions may herald the arrival of a volatile active center with the potential to impact various Earth systems.

Further major eruptions are possible from these active regions as they rotate across the face of the sun over the next two weeks. Agencies impacted by solar flare radio blackouts, geomagnetic storms, and solar radiation storms may experience disruptions over this two-week period. These include satellite and other spacecraft operations, power systems, HF communications, and navigation systems.

Early on October 22, an Earth-directed coronal mass ejection (CME) was observed to originate from Region 484, which was nearing disk center. SEC forecasters viewed the ejection as a moderate event and expected the CME to arrive at Earth a few days later. It was expected to create some periods of strong storming, but a G4 (severe) or G5 (extreme) geomagnetic storm was not expected. Geomagnetic storm watches were issued for October 24 – " *The CME from today is expected to arrive mid-day on the 24th of October and may produce periods of strong storming…Afr prediction for 24 Oct: 040."* The timing of a NASA press release concerning an historical solar event that occurred in 1859 unfortunately coincided with the NOAA press release on the current activity. Confusion among certain national media sources led to some suggestions that the predicted CME impact would be one of the strongest ever. SEC staff spent a considerable amount of time quelling the concerns of the public and correcting misconceptions in the media. The over-hyped event even took its toll on Wall Street where several companies with space assets saw their stock suffer a sell off as investors feared impact from the CME. The CME impacted Earth's magnetic field on October 24 at 1530 UTC. The sudden impulse (SI) was followed by approximately two hours of G3 (strong) geomagnetic activity, and the maximum Afr was 41.

Sun-Spot Worries Flare at Sirius

By Scott Moritz
Senior Writer
10/24/2003 03:20 PM EDT

Sirius (SIRI:Nasdaq - commentary - research) investors were sweating it out Friday. The stock sold off in unusually heavy trading as investors worried that solar flares could damage the company's satellites.

The Street.com – Oct 24, 2003

"…the storm created big headaches for the Space Environment Center in Boulder. Forecasters there spent much of Friday trying to correct misconceptions about the storm's severity."

Rocky Mountain News – Oct 25, 2003

Nine significant flares occurred between October 22 - 27, most of them from Region 486 and all of them in the R2 (moderate) - R3 (strong) range. As Region 486 approached center disk, new Region 488 emerged rapidly, also at center disk. Three major sunspot groups now populated the visible solar disk. By October 27, solar storm forecast probabilities were at the highest levels of the solar cycle.

Arguably, the largest solar event of Solar Cycle 23 erupted on October 28 at 1110 UTC. Over 500 customers immediately received the severe flare alert. The huge X17 flare from disk center prompted forecasters to immediately issue radiation storm warnings. The radiation storm began just 20 minutes after the flare onset and lasted for days. LASCO coronagraph imagery showed a powerful and fast, Earth-directed CME. The extreme magnitude and speed of the event led the forecasters to examine the historical record to provide some guidance for the likely Sun-Earth transit time. It was found that the fastest Sun-Earth transit of a CME observed to date for the current solar cycle was 28 hours, from the X5 flare on July 14, 2000. Forecasters expected this CME transit to be even faster, and predicted a transit time of 24 hours. Geomagnetic storm watches were issued predicting the strongest geomagnetic storm of Solar Cycle 23.

SPACE WEATHER ADVISORY BULLETIN #03- 3
2003 October 28 at 10:55 a.m. MST (2003 October 28 1755 UTC)

******* SOLAR ACTIVE REGION PRODUCES INTENSE SOLAR FLARE *******

The dynamic solar regions reported on October 21 continue to produce high levels of solar activity. NOAA Region 486 produced a category R4 (severe) radio blackout with an associated category S3 (strong) solar radiation storm on October 28 at 1110 UTC (6:10 A.M. EST). The SOHO/LASCO instruments also observed a full halo coronal mass ejection with this activity, which is Earth directed. This region is the second largest in size this solar cycle.
As a result of this activity a category G4 (severe) geomagnetic storm is expected with periods of category G5 (extreme) levels possible. The solar radiation storm is also expected to continue at strong (S3) levels for the next 48 hours. Further major eruptions are possible from these active regions as they rotate across the face of the Sun over the next few days.

SEC had additional staff on duty in anticipation of the CME arrival. By 0400 UTC on October 29, low-energy particle sensors on the ACE satellite hinted that the CME was fast approaching. Power grid customers were notified of the imminent threat. At 0601 UTC on the 29^{th}, a remarkably fast CME impacted the ACE spacecraft. Important sensors on ACE were already rendered useless due to the severe radiation storm; however, the transit time alone pointed to a powerful geomagnetic storm. Forecasters immediately issued severe geomagnetic storm warnings, and with just 13 minutes elapsed since the impact at ACE, the CME slammed Earth’s magnetic field at almost 5 million mph. An extreme (G5) geomagnetic storm ensued and persisted for over 24 hours.

Forecasters continued to ascribe very high flare probabilities on October 29, and theses were validated at 2010 UTC when another powerful flare erupted from Region 486. The X10 (R4 – severe radio blackout) flare generated another fast Earth-directed CME. Radiation storm warnings already in effect for the previous day’s storm were now extended an additional 24 hours. Geomagnetic storm watches were issued for another extreme (G5) geomagnetic storm, which was expected to arrive within 24 hours. The CME impacted the ACE spacecraft at 1440 UTC on October 30. Severe geomagnetic storm warnings were issued, and within one hour, the geomagnetic field was once again undergoing severe geomagnetic storming.

The X8 flare that erupted on November 02 (Figure 6) from Region 486 (nearing the west limb of the sun) highlighted the importance of a space-based coronagraph for CME measurements. LASCO imagery was unavailable on November 02 and Type II radio sweeps (a proxy for CME speed) were proven unreliable as a CME speed indicator in the previous week's CMEs. Forecasters could assume with confidence that a large CME occurred, but knew that its direction and speed were highly uncertain. Historical data revealed that the geomagnetic response from large CMEs that originated from near the west limb varied dramatically. Given the intensity of the recent storms, forecasters predicted another severe storm with an onset in less than 25 hours. Updated LASCO imagery on November 03 (Figure 6), revealed that while there was an Earth-directed component (full halo CME was identified), most of the ejecta were directed away from Earth: an impact was likely, but the storming would be considerably less than initially expected. Also significant was the deceleration of the CME as it moved away from the Sun. The initial prediction for a <25 hour arrival was changed to ~40 hours. A short-lived geomagnetic storm began early on November 04 (36.5 hour transit) and briefly reached severe levels before quickly subsiding.

> Date: Mon, 3 Nov 2003 19:06
>
> *Subject: Full Halo CME on 2003/11/02, frontsided*
>
> *LASCO and EIT observed a full halo CME on 2003/11/02. The event was first Observed in C2 at 17:30… The mean plane-of-sky speed for this event was 1826 km/s at PA 272, <u>with evidence for strong deceleration</u>.*

Excerpt from the LASCO halo CME message received November 03. (NASA)

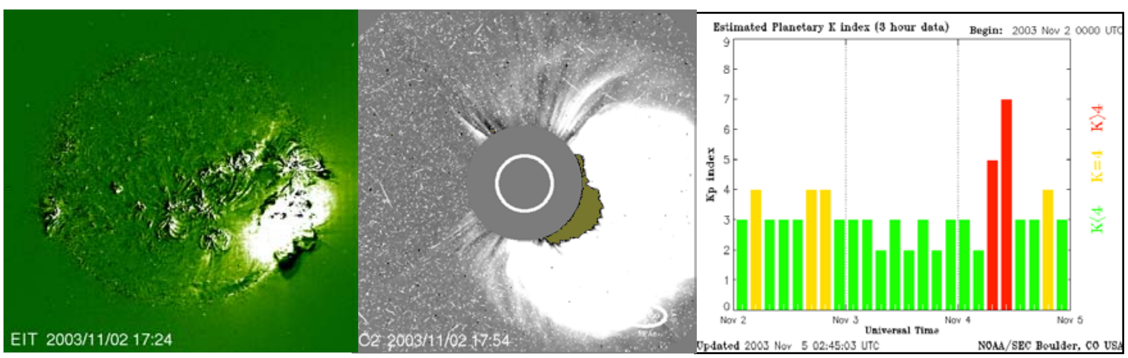


Figure 6. EIT image showing location of X8 flare on November 02 (left), with associated large CME off SW limb (center), and relatively weak geomagnetic response on November 04 (right). (NASA, NOAA/NCEP/SEC)

The November 03 forecast issued by SEC indicated that major flare probabilities would remain at record highs for at least two more days. The X-class flare probability for November 04 - 05 was 75%.

Event Probabilities 04 Nov-06 Nov	
Class M	90/90/70
Class X	75/75/50
Proton	99/75/50

Excerpt from the Joint USAF/NOAA Report of Solar and Geophysical Activity

On November 04, Region 486 produced what is estimated to be an X28 flare, one of the largest solar flares on record. Statistical databases indicate that radiation storm and geomagnetic storm potential was high from large flares on the west limb, but storm intensities would likely be weak - "*Day two's geomagnetic activity may stay enhanced due to a glancing blow from the X28 flare from today.*" Forecasters accurately predicted the subsequent radiation storm and geomagnetic storm as category S2 (moderate) and G1 (minor) levels.

NOTE: The GOES-12 Solar X-ray Imager (SXI) experienced a high voltage anomaly on Sepember 02, 2003. SXI imagery was not available in the Space Forecast Center from September 02 to October 28, 2003. SEC Operations submitted a formal request to NOAA and NESDIS management to resume SXI operations, and real-time SXI imagery was made available in the forecast center on October 28, 2003.

Customer Support and Impacts

SEC's customer base is wide ranging and includes multiple organizations (private and public) involved in deep space missions, satellite and space operations in near-Earth orbits, the airline industry, electric utilities, communications and navigation interests, and more. Support provided by SEC during the high solar activity period differed considerably from agency to agency. The following paragraphs address the impact of space weather on the various technologies both on Earth and in space. While addressing impacts, it is important to categorize the effectiveness of SEC services in aiding customers to prepare and react to a rapidly changing and hostile space environment. In all, 278 alerts, watches and warnings were issued totaling 93,680 customer contacts in the 20-day period. Of this total, 253 alerts, watches, and warnings were issued following energetic events from the three large sunspot groups. In contrast, the average monthly number of alerts, watches, and warnings for energetic events during the 12-month period, October 2002 – September 2003, was 25. The October – November 2003 tally does not include the critical services provided on the SEC webpage, nor does it take into account the hundreds of phone inquiries from industry interests around the globe.

NASA SRAG/ISS

Close coordination between SEC and the NASA Space Radiation Analysis Group (SRAG) at Johnson Spaceflight Center (JSC) is vital. SRAG is responsible for ensuring that the radiation exposure received by astronauts remains below established safety limits. Telephone briefings between both agencies are conducted daily, and the support tempo increases significantly during special operations such as space shuttle missions and extra-vehicular activity (space walks). SEC also provides close support to the ISS Environments System Team (Boeing/NASA). During periods of high solar activity, SEC maintains constant communication with NASA. The coordination between the agencies during this solar activity outbreak was at a level unseen since 1991.

During this 20-day period, SEC conveyed via telephone to NASA, over 140 alerts, watches and warnings. Detailed discussion on the analysis and prediction of solar events occurred daily. The extensive coordination between SEC and NASA resulted in actions by SRAG that ensured astronauts would not exceed acceptable risk from exposure to radiation. Management at NASA/JSC released the following:

"Solar flare activity caused flight controllers to issue contingency directives for the ISS Expedition 8 crew to briefly relocate to the aft portion of the station's Zvezda Service Module and the Temporary Sleep Station (TeSS) in the U.S. Lab. The Expedition 8 crew of Commander Mike Foale and Flight Engineer Alexander Kaleri spent brief periods of time in the aft end of the Zvezda Service Module, which is the most shielded location aboard the International Space Station from higher levels of radiation. During Tuesday (Oct. 28) there

The ISS
Courtesy of NASA/SRAG

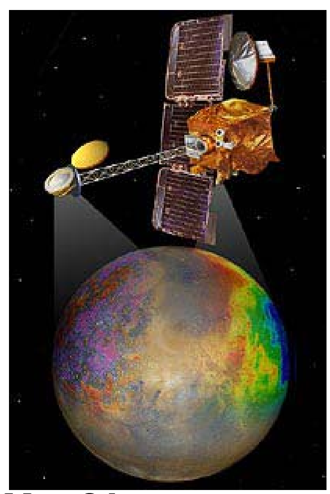
were five, 20-minute periods during which the crew was asked to remain in the aft end of Zvezda."

These actions cut the potential radiation exposure of the crew by approximately 50%. Only twice before has NASA asked the ISS crew to seek shelter during solar radiation storms - November 2000 and November 2001.

NASA also decided to do a ground-commanded powerdown of the billion dollar robotic arm and workstation, which are sensitive to radiation events. They also prepared to take other precautionary actions (e.g., shut down the S-band antenna controller and external color TV cameras) if radiation levels were to increase more than they did. The ISS Environments System Team also reported that the ISS experienced abnormal frictional drag.

Deep-Space Missions

Numerous deep-space missions in progress during the October-November time frame were impacted by the severe solar activity. All these missions rely on NOAA data for anomaly assessment, and most, if not all, subscribe to SEC's alert list. Scientists stressed the importance of situational awareness during solar storms – "*If we had not known about the flare we could have floundered for days and perhaps even sent commands that would have been detrimental." – Stardust Team.* The most significant impact during the October-November activity was the likely loss of the Martian Radiation Environment Experiment (MARIE) on the NASA Mars Odyssey mission. The list of impacts below highlights some details of known anomalies at this time. It is expected that further details will emerge in the months ahead, but the true assessment of the October-November 2003 solar activity impacts may never be fully understood or revealed.



Mars Odyssey
Photo courtesy of
NASA/ *JPL*

Mars Odyssey - Spacecraft entered safe mode during the severe radiation storm. During downloading on October 29, the spacecraft had a memory error that was corrected with a cold reboot on October 31. The **MARIE** instrument on the Mars Odyssey had a temperature red alarm leading it to be powered off on October 28. The MARIE instrument is not expected to recover. Ironically, MARIE's mission was to assess the radiation environment at Mars to determine the radiation risk that astronauts on a Mars mission may encounter.

NASA Newsroom Press Release

2001 Mars Odyssey *November 26, 2003* *Mars Odyssey Mission Status* *The martian radiation environment experiment on NASA's 2001 Mars Odyssey orbiter has collected data continuously from the start of the Odyssey mapping mission in March 2002 until late last month. The instrument has successfully monitored space radiation to evaluate the risks to future Mars-bound astronauts. Its measurements are the first of their kind to be obtained during an interplanetary cruise and in orbit around another planet. On Oct. 28, 2003, during a period of intense solar activity, the instrument stopped working properly. Controllers' efforts to restore the instrument to normal operations have not been successful. These efforts will continue for the next several weeks or months.*

Stardust - Comet mission went into safe mode due to read errors; recovered.

SMART-1 - Had auto shutdown of engine due to radiation levels in lunar transfer orbit. Reported a total of 3 shutdowns; decided not to thrust below altitude of 10,000 km.

Mars Explorer Rover - Spacecraft entered "Sun Idle" mode due to excessive star tracker events. Waited out event and recovered.

Microwave Anisotropy Probe - Spacecraft star tracker reset, and backup tracker autonomously turned on. Prime tracker recovered.

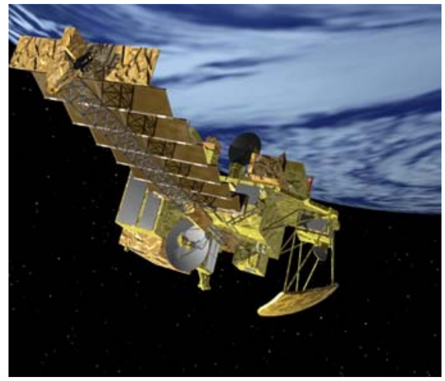
Mars Express - Spacecraft had to use gyroscopes for stabilization, because the flare made it impossible to navigate using stars as reference points. The radiation storm blinded the orbiter's star trackers for 15 hours. The flares also delayed a scheduled Beagle 2 checkout procedure.

Earth Orbiting Spacecraft

The GSFC Space Science Mission Operations Team indicates that approximately 59% of the Earth and Space science mission spacecraft and 18% of the instrument groups (both deep space and near-Earth missions) experienced effects from the October-November activity. And though space weather is a major consideration during spacecraft design, several missions either turned off their instruments or took other protective action in response to the severe solar activity.

All organizations involved with space operations rely on NOAA data for situational awareness and anomaly assessment, but during the October-November activity, the importance of NOAA data and SEC services for pursuing mitigating actions were also very apparent. The anomalies identified in this document are just some of the impacts reported. Many anomalies will never be reported and many others are still in the investigation stage.

ADEOS-2 - Japan Aerospace Exploration Agency (JAXA) lost contact with the ADEOS-2 satellite, following an intense CME, which impacted Earth's magnetic field on October 24. ADEOS-2 is an environmental observation LEO satellite, launched in December 2002 by the Japanese Space Agency. It was designed to collect data on global warming and other climate-change phenomena. Developed at a cost of 70 billion yen ($640 million), it had an expected lifespan of three years. On board the ADEOS-2 platform was the NASA SeaWinds instrument, designed to map wind speed and direction across much of the Earth's ice-free oceans each day. The SeaWinds had a total cost of $154 million ($138 million for development; $16 million for five years of operations); additional NASA ground network costs of $11 million, which was to support the overall ADEOS-2 mission. NOAA was contributing $14 million for the NASA ground network support to the overall Adeos-2 mission. Loss of the Sea Winds instrument caused a major system acquisition and development loss to the U.S. Navy. ADEOS-2 is not expected to recover. Though space weather is suspected as a major contributor to the ADEOS-2 demise, no official cause has been identified at the time of this writing.



ADEOS-2 (Midori-II) JAXA

Japan Aerospace Exploration Agency Press Release

Earth Observation Operation of Midori-II
(Advanced Earth Observing Satellite-II, ADEOS-II)

The Japan Aerospace Exploration Agency has been investigating the possibility of recovering the observations of Midori-II after an anomaly was detected in the satellite on October 25 (Saturday), 2003. JAXA has been continually trying to send the satellite commands to restore its functions, and analyze its current status.

However, as a result of our investigation, analysis, and inability to re-establish any communications with the satellite, JAXA found today that the possibility of restoring the operations of Midori-II is extremely slim.
JAXA would like to express our sincere apologies to all Japanese citizens, Midori-II users, and parties concerned, including the Ministry of Environment, NASA (the National Aeronautics and Space Administration) and CNES (Center National d'Etudes Spatiales), whose observation equipment is onboard Midori-II.

SEC staff assisted JAXA in their recovery efforts and anomaly assessment. A note from Tateo Goka of JAXA to SEC expressed appreciation – "*Thank you again for your great help on ADEOS-2 anomaly study.*"

Advanced Composition Explorer (ACE) - *EPAM* Low Energy Magnetic Spectrometer (LEMS 30) damaged: Noise levels increased in several ion channels and remain abnormally elevated. This instrument is not expected to recover.

Note: While ACE is not Earth orbiting, it is not as far away as deep space missions so is included here.

***Kodama, Data Relay Test Satellite (DRTS)* -** Went into safe mode on the morning of October 29 during the severe (S4) solar radiation storm. The DRTS is a geostationary communications satellite that relays data among Low Earth Orbit (300-1,000 km altitude) spacecraft (including the International Space Station) and ground stations. JAXA's associate executive director indicated, "*The excessive signal noise coming from the Earth sensor assembly suggests the satellite was affected by a proton barrage. The most likely culprit is the solar fla*re." From a Tokyo press release:

> *TOKYO -- The massive solar flare that erupted Oct. 28 has shut down and possibly crippled an experimental communications satellite owned by the Japanese Aerospace Exploration Agency (JAXA), officials said. The Data Relay Test Satellite (DRTS), also known as Kodama, went into safe mode, essentially shutting down all noncritical functions, the morning of Oct. 29, according to Tsuguhiko Katagi, JAXA's associate executive director.*

.

Status: Kodama was recovered on November 07, 21:19 JST

CHIPS - Satellite computer went offline on October 29, and contact was lost with the spacecraft for 18 hours (loss of 3-axis control because its single board computer stopped executing). When contacted, the spacecraft was tumbling, but was recovered successfully. It was offline for a total of 27 hrs.

***DMSP F16* -** *SSIES* sensor lost data twice, on October 28 and November 03; Microwave sounder lost oscillator; Switched to redundant system.

CHANDRA - Observations halted on several occasions during the October-November activity, including an extended outage from October 28 – November 01.

GOES-9, 10 and 12 - High bit error rates (9 and 10) and magnetic torquers disabled (12) due to solar activity.

Inmarsat (fleet of 9 geosynchronous satellites) - Controllers at their Satellite Control Center had to quickly react to the solar activity to control Inmarsat's fleet of geosynchronous satellites. Two experienced speed increases in momentum wheels requiring firing of thrusters, and one had an outage when its CPU tripped out.

Other satellites with known anomalies during this timeframe include: ***FedSat, POLAR, GALEX, Cluster, RXTE, RHESSI, Integral***, ***Genesis,*** and more**.** On October 28, 2003 the **NOAA-17** spacecraft experienced a significant problem with the scan motors of the AMSU-A1. The instrument was powered down and no recovery efforts are planned. The cause of this failure is unclear at this time. SEC staff assisted NASA, JAXA, ESA, and commercial satellite companies with spacecraft anomaly assessments.

"During the recent large solar activity, our company did not experience any anomalies. Thanks to the availability of NOAA SEC space weather data, we decided with confidence not to take any spacecraft safing actions. Safing procedures will power off all components except those required to maintain spacecraft health and safety, and will maneuver the spacecraft to a "defensive" posture.

Continued availability of the NOAA SEC data is vital to our safe operations in the presence of elevated solar activity."

Airlines

Airlines have long recognized the potential cost benefits of flying polar routes for the North America to Asia flights. The end of the cold war opened these flight paths, and by the end of the last decade, several airlines were operating on these new efficient routes (Figure 7). Airlines using polar routes benefit from additional passenger revenue, while producing significant savings on fuel and crew costs. Typical time and cost savings for a polar flight from New York to Singapore is 209 minutes and $44,000. A polar route from Boston to Hong Kong will save 138 minutes and $33,000 as compared with previous non-polar routing.

Polar flights departing from North America use VHF (30-300 MHz) communication with the Canadian ATCs. Flights will communicate initially with the Edmonton control center and then transition to Arctic Radio - the responsible agency for relaying messages between the flight crew and controllers at the various control centers. While the flight's initial communication with Arctic Radio is generally on VHF, they soon switch to HF (3 – 30 MHz). Satellite communication (SATCOM) is considered a backup during polar flights, but it is rarely available above 82 degrees north latitude (Figure 8).

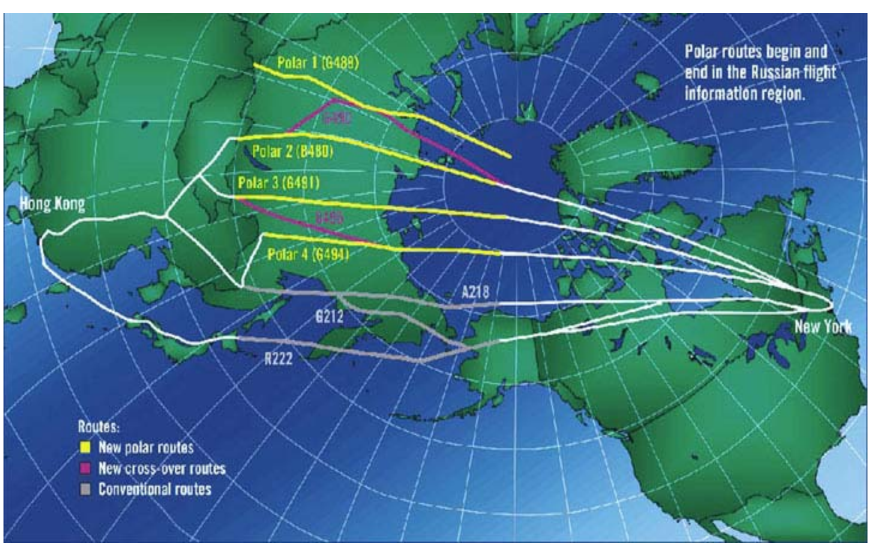


Figure 7. North America routes to Asia.

Flying time for airline pilots is restricted to 16 hours per day. A typical flight duration for a polar route from a North American destination to Asia is over 15 hours. If the flight must divert for any reason, an additional stop-off is required. This results in considerable time loss, additional fuel, and the added time will require a whole new crew. The average cost of this kind of diversion is approximately $100,000.

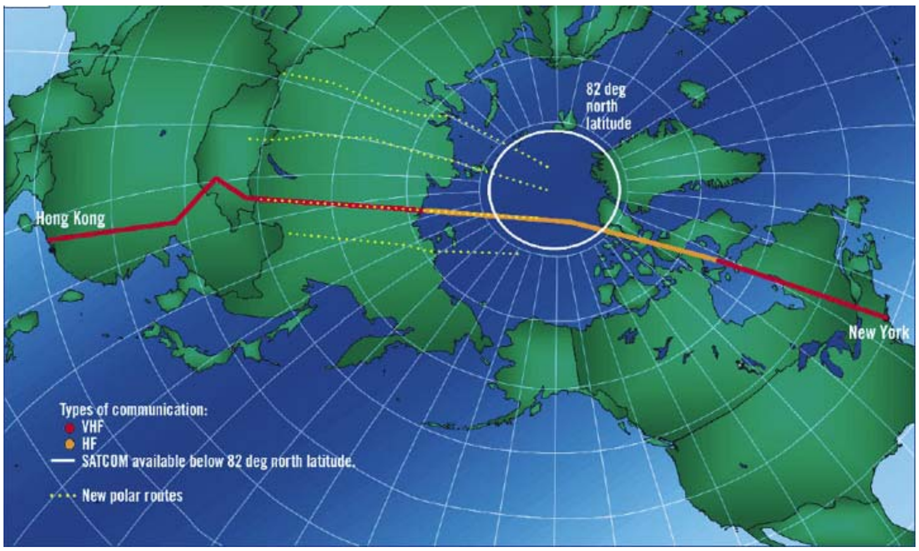


Figure 8. Typical communication modes for polar routes.

Although there may be many reasons for an airline to want to fly over the poles, it is these regions that are impacted most by solar activity. Airlines on polar routes must contend with degraded communications; potential biological impacts from radiation storms; impacts to navigational systems (generally a lesser concern); and as avionics evolve, a potential impact to electronic systems. The October-November solar storms created a significant disruption to airline operations, and though difficult to accurately assess, the dollar cost was likely in the millions.

Airlines and ground controllers experienced communications problems almost daily during the October – November solar activity outbreak. Initially (October 19 – 23), the degraded HF communications were due to elevated X-ray solar emissions and the moderate to strong solar flare activity. On October 19, following the X1 (R3) flare, Air Traffic Centers reported moderate-to-severe impacts on all HF groups and HF service was degraded for over two hours. In response, a major carrier rerouted three polar flights from Polar Route 3 to Polar Route 4 (Figure 7), which is more desirable for data-link and Satcom. This required an additional 26,600 pounds of fuel and resulted in over 16,500 pounds of cargo being denied. More impacts to airline operations were reported on October 24 following the onset of a G3 (strong) geomagnetic storm. Solar radiation remained at background levels, but high latitude communications were severely degraded due to the geomagnetic storm. These communication problems forced the Edmonton Center to release the following notice to airmen (NOTAM):

CZEG EDMONTON CENTRE (ACC)

A8577/03 - ROUTE AND LEVEL RESTRICTIONS DUE TO GEO-MAGNETIC STORM IMPACT ON COMM IN EDMONTON ACC ALL FLT TRANSITING CZEG FIR N OF 5700N AT FL290 OR ABOVE: 1. NORTHBOUND POLAR FLT PROCEEDING OVER DEVID, ORVIT OR RAMEL SHALL ROUTE VIA: A) 7500N 8000W - 8000N 8300W - PIGSO - 8852N 14100W - DEVID B) YRB - TAPSA - OVDON - 7810N 14100W - ORVIT C) 7000N 10500W - TAVRI - 8415N 14100W - RAMEL 2. ALL ACFT SHALL OPR ON PUB TRACKS 3. NO LATERALS, NO DIRECTS WHILE E OF 7000W 4. ACFT THAT ARE UNABLE TO OPR ON PUB TRACKS DUE TO THE NATURE OF FLT SHALL REQUIRE PRIOR APPROVAL OF THE ROUTE FROM SHIFT MANAGER AT 1-(780)890-8397 5. ZAN SHALL RESTRICT ALL EASTBOUND ACFT ENTERING CZEG FIR AT AND N OF 6900N TO 20 MIN IN TRAIL. 6. OPR ARE ADVISED THAT VHF AND HF COMM RELAYED FROM THE TRANS SITE TO ATC VIA SATELLITE MAY FAIL DUE TO THE EFFECTS OF THE CURRENT INTENSE MAGNETIC STORM. CZEG WILL UPDATE THESE MEASURES AS THE STORM IMPACTS BECOMES BETTER KNOWN. FOR INFO CONTACT: CZEG SHIFT MANAGER 1-(780)890-8397/1-(877)342-2276 NATIONAL OPS CENTRE

These were the first of several such periods of severely degraded communication. As each major flare occurred, HF communications at low and mid-latitudes underwent a range of problems from minor signal degradation to complete HF blackout. Higher latitudes would experience even more difficulty following the onset of the radiation storms on October 26. Air traffic operators reported minor to severe impacts on HF communications every day between October 26 and November 05. Communications were so poor on October 30 that additional staff was necessary to handle air traffic. The radiation storms would also introduce a second major concern for the airlines - radiation effects on passengers and crew.

SEC staff participated in teleconferences with major airlines at an average rate of three to five times a day. Teleconferences were conducted by SEC staff with airline dispatchers, pilots, and airline safety personnel as an important part of their decision making process. With SEC's help, airlines made critical decisions about route and/or altitude restrictions to flight operations during solar activity. Flight Centers restricted flight paths due to degraded communications, but it was each individual airline's responsibility to assess the radiation threat and take appropriate action. All commercial aviation interests were made aware of the radiation storm levels on October 28-29, when the Federal Aviation Administration (FAA) issued their first ever advisory suggesting that flights traveling north and south of 35 degrees latitude were subject to excessive radiation doses (Figure 9). This FAA product is based on data from the NOAA GOES particle sensors and is an advisory only. Airlines are not required to take action based on this advisory. Currently, two major U.S. airline companies conduct flight operations over the poles, and both took action to limit radiation exposure to passengers and crew. Polar flights were rerouted during this period (e.g., between October 24 – 31, one major airline rerouted six polar flights to non-polar routes requiring fuel stops in Japan and/or Anchorage). Flights on the U.S. to Europe routes did fly at lower altitudes during this severe radiation storm. The FAA issued a Solar Radiation Alert for the following timeframes:

Start	End	Duration
10/28 1208 UT	10/29 0603 UT	17h 55min
10/29 2123 UT	10/30 1158 UT	14h 35min
11/02 1808 UT	11/02 2343 UT	05h 35min

Airlines have established their "go/no-go" radiation storm threshold at the S3 level. Dispatchers informed SEC that they must make route decisions several hours in advance of the scheduled takeoff time and that a prediction of a storm being above or below the S3 level is vital. Maximum radiation storm intensity predictions are not part of SEC's radiation storm warning procedures. Forecasters adjusted to this need and provided dispatchers with radiation storm maximum intensity predictions. Perhaps the best example of the value of an intensity prediction was on November 04, when the X28 (R5 extreme) flare erupted. Airline companies immediately assumed a flare this large would surely produce a significant radiation storm. Forecasters advised dispatchers that because of the source location on the sun, an S3 storm was not likely. No route alterations were made, and the prediction materialized when a moderate size S2 radiation storm unfolded. SEC's radiation storm warnings are currently under review. The support provided to the airlines by SEC was recognized in the following correspondence:

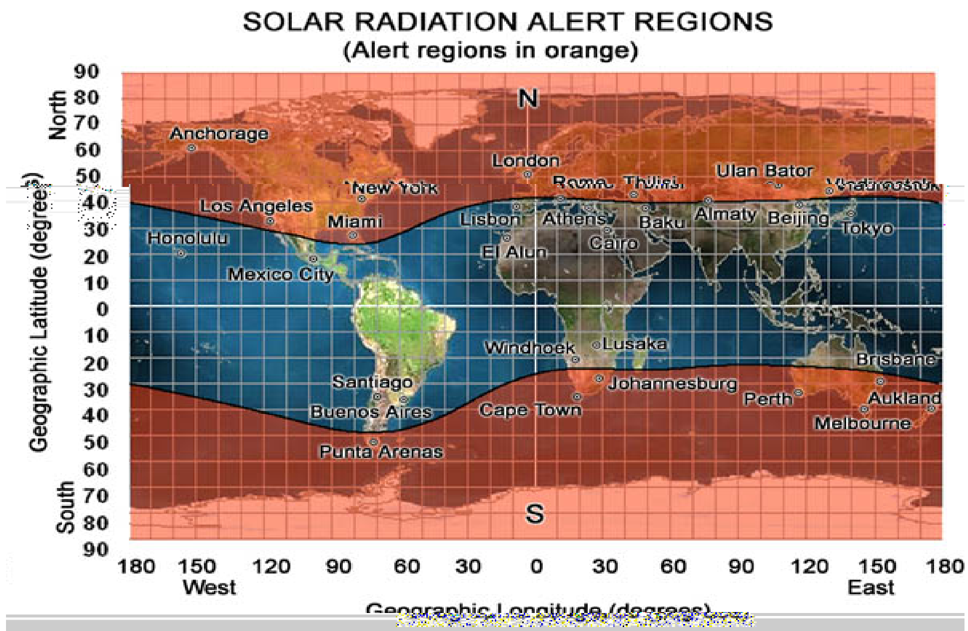
Continental Airlines wants you to know how appreciative we are for the fantastic support we have received from the whole team at the NOAA Space Environment Center. The insight provided by your experts was extremely beneficial to the Continental Airlines operations team. We consider the information obtained from your web site and the conference calls with your experts to be an important component of our decision making process when it comes to applying route and/or altitude restrictions to our flight operations due to solar activity. Continental Airlines effectively used your information and input to define appropriate operational parameters for our flight operation thereby improving our safety and efficiency.

Your willingness to share your expertise and expectations concerning the solar event should be a model for other agencies when it comes to working together with industry.

Sincerely,
Sr Mgr SOCC

Department of Defense

A maritime interdiction mission, requiring 100% communications, was cancelled based on scintillation forecasts issued by AFWA Space Weather Operations Center.



Space Weather Message Code: ALTPAV   Issue Time: 2003 Oct 28 2123 UTC
ALERT: Solar Radiation Alert at Flight Altitudes
Conditions Began: 2003 Oct 28 2113 UTC

Comment:
Satellite measurements indicate unusually high levels of ionizing radiation, coming from the sun. This may lead to excessive radiation doses to air travelers at Corrected Geomagnetic (CGM) Latitudes above 35 degrees north, or south.

Avoiding excessive radiation exposure during pregnancy is particularly important.

Reducing flight altitude may significantly reduce flight doses. Available data indicates that lowering flight altitude from 40,000 feet to 36,000 feet should result in about a 30 percent reduction in dose rate. A lowering of latitude may also reduce flight doses but the degree is uncertain. Any changes in flight plan should be preceded by appropriate clearance.

Figure 9 – Map and text of the FAA Solar Radiation Alert issued on October 28, 2003. A Solar Radiation Alert indicates a radiation storm is in progress that may lead to a substantial increase in radiation at aircraft altitudes in shaded areas shown on the map. (FAA)

GPS Users

GPS operations are affected by the changes in total electron content (TEC) of the ionosphere along the path to the satellite during large solar flares and geomagnetic storms. These kinds of solar activity can cause large increases and decreases in TEC, which impacts the accuracy of single-frequency GPS. Dual-frequency GPS receivers can better adjust to a disturbed ionosphere, but still experience some difficulty.

GPS is used by millions of people around the world. Many GPS users will experience little or no impact during geomagnetic storms, but those requiring precise GPS measurements have a great need for SEC alerts and warnings. Those with the greatest concerns include FAA's Wide-Area Augmentations Systems (WAAS), surveying companies using GPS measurements for land surveying, topographic work, and property boundary analysis; deep-sea drilling operations; land drilling and mining, and various DoD operations.

The WAAS system was seriously impacted. For a 15-hour period on October 29 and an 11-hour interval on October 30, the ionosphere was so disturbed that the vertical error limit, as defined by the FAA's Lateral Navigation Vertical Navigation (LNAV/VNAV) specification to be no more that 50 meters, was exceeded. That translated into commercial aircraft being unable to use the WAAS for precision approaches.

Operators relying on GPS can and will take important actions during geomagnetic storms. During the October-November activity, companies delayed high resolution land surveying; postponed airborne and marine survey operations; cancelled drilling operations; and some, as was the case with the C.R. Luigs deep water drill ship, resorted to backup systems to ensure continuity of operations. An international oilfield services company issued an internal "technical alert" via their worldwide network, to alert their surveying and drilling staff on potential impacts from solar storms. They reported six cases of survey instrument interference in late October from sites around the world. By early November, the value of space weather services became very apparent to many agencies relying on the Global Positioning System. This is well reflected in this feedback from operators on the C.R. Luigs:

The Solar warnings were very helpful. We encountered DGPS interruptions at the height of solar activity. These interruptions made the DGPS solutions un-reliable at the worst times. We ended up using primarily our acoustic array at the seabed as the primary solution for position when the DGPS solutions were affected. We now follow the Space Weather regularly. Thanks for your assistance.

DP Operator
C.R Luigs

The **C.R Luigs** is the largest state of the art ultra-deep water drill ship in the world. It relies on its Dynamic Positioning System (which partially relies on GPS) for precise drilling in 9.000 – 12,000 feet of water (drills wells 35,000 feet below sea level). When operating efficiently, this Positioning System can hold the ship to within 3 meters of the required location.

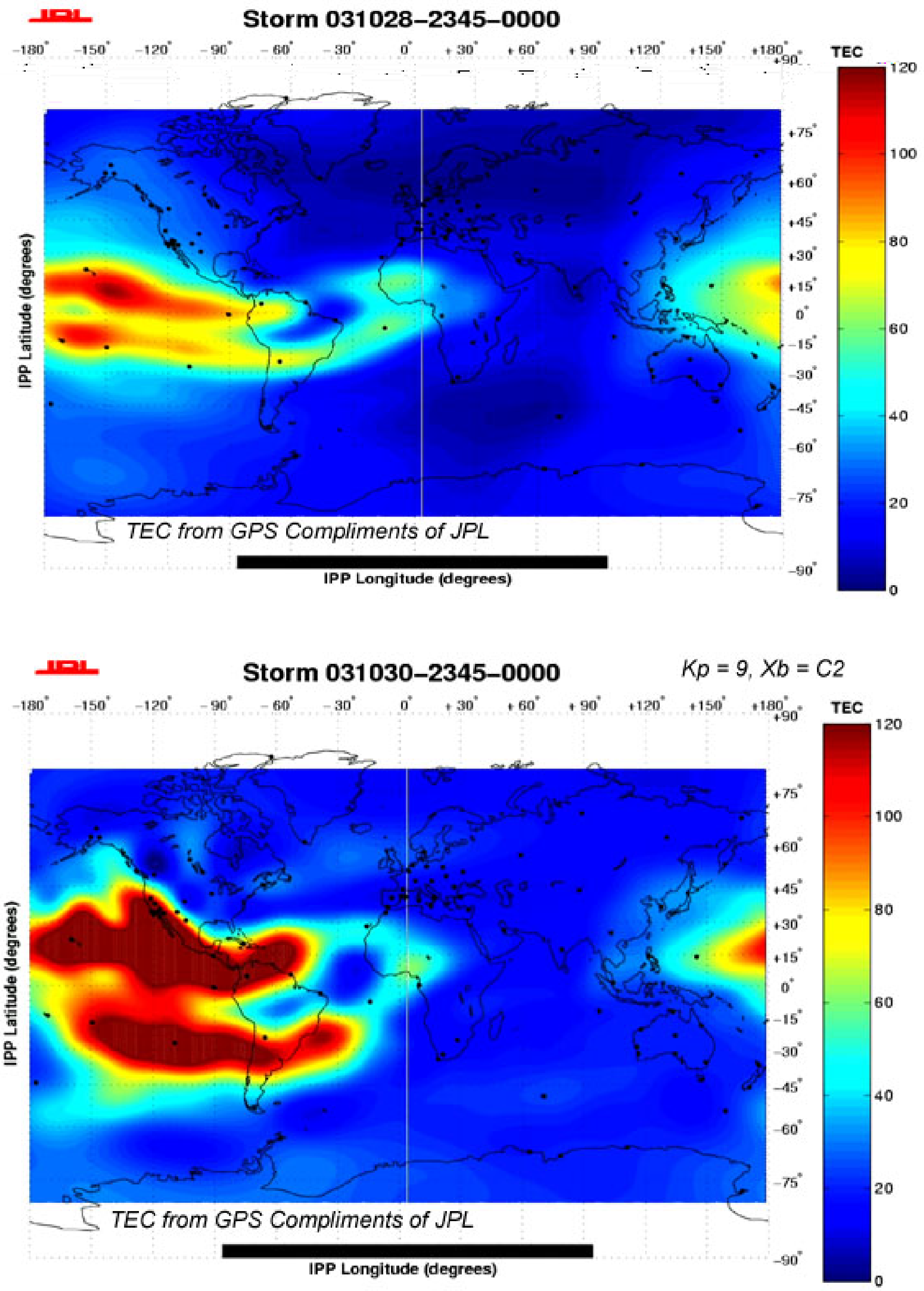


Figure 10. TEC measurements from GPS following the X17 flare on October 28 (top) and during the extreme geomagnetic storm on October 30 (bottom). Typical TEC background values in the enhanced areas above are approximately 100-130 TEC units. The geomagnetic storm on October 30 produced TEC measurements that exceeded 250 TEC units (extremely high) over portions of North America. (NASA/JPL)

Antarctic Operations

The Antarctic science groups and staff rely on MacRelay radio operations to provide essential radio communications between McMurdo Station and remote sites on the Antarctic. MacRelay is also responsible for communication links with aircraft and ships supporting the United States Antarctic Program. The primary source of communication is HF radio.

MacRelay member checks SEC data (Photo courtesy Kris Kuenning – The Antarctic Sun)

MacRelay experienced over 130 hours of HF communication blackout during the October – November activity.

Following an extended solar flare-induced HF outage earlier in this solar cycle, McMurdo staff developed a contingency plan to use Iridium satellite phones as backup during HF outages. During these previous periods of severe solar activity (2000 – 2001), numerous support flights were delayed for several days. During the October – November 2003 activity, the LC-130 aircraft that service the remote sites used Iridium phones to communicate with McMurdo and the remote locations. And to ensure safety, take-off and landing restrictions changed during the HF blackout periods. The 150-meter cloud ceiling and 3.2 km of visibility was increased to 900 meters with 4.8 km of visibility.

Scientific missions in the field (at camp) in Antarctica are required to 'check in' with MacRelay communications under normal circumstances via HF. If they miss their 'check in' then a rescue mission is considered. MacRelay was made aware that space weather was causing significant HF blackout conditions, allowing them to implement contingency plans. MacRelay received SEC alerts and warnings, but SEC staff also coordinated with MacRelay staff via telephone during the October-November activity.

Electric Utilities

The geomagnetic storms on October 29 and 30 were certainly among the strongest this cycle. When a CME impacts Earth's magnetic field, the fluctuations generate electric fields on Earth, and the potentially damaging geomagnetically induced currents (GIC) can flow into power lines and transformers. The late October storms caused GICs that impacted power grids around the globe.

Typically, when smaller, less powerful CMEs impact the geomagnetic field, GICs at a few amps to a few tens of amps can occur which can cause some problems for grid operators. Larger CMEs can generate GICs of well over 100 amps which can lead to transformer saturation and over-heating, false relay trippings, an increase of harmonics, voltage drops, and in worst case scenarios - a blackout of an entire grid and/or permanent damage to transformers.

How impacting a CME is on the power grid depends on several factors. One of the most important variables is how the CME magnetic field will couple with Earth's magnetic field. Relatively weak CMEs will on occasion generate much stronger geomagnetic storms than larger CMEs that had greater potential, but coupled differently with the geomagnetic field. But even when strong storms occur, the potential impact on the grid depends on several factors. How much load is on the grid at the time of the storm onset is critical. During those times of the day and year when electrical demands are low, the grid is not as vulnerable to impacts from GICs. The location on Earth where GICs are most intense is also important, because strong GICs in remote locations of the world won't make much difference to the North American grid. Equipment type and preventive actions will also affect the degree of impact on the grid.

The X17 and X10 flares that occurred on October 28 and 29, respectively, produced powerful geomagnetic storms. However, the magnetic storm coupling was considerably less than it could have been, and the resultant geomagnetically induced currents were not as large as many in the past. According to John Kappenman of the Metatech Corporation, both storms were "far less severe than a Superstorm status, and resulting GICs that did occur could perhaps be a factor of 3 to 10 times larger in most regions than those observed." GICs in excess of 100 amps were observed, and Kappenman suggest that larger GIC's were observed globally during the large shock on October 29, following the arrival of the first large CME from the X17 flare.

Power companies in North America did experience some problems. Impacts and actions reported by grid operators included: less use and switching between systems; high levels of neutral current observed at stations throughout the country; a capacitor trip in the northwest (known to be GIC susceptible); transformer heating in the east – precautions were implemented; and a 'growling' transformer that was backed down to help cool it down. GIC impacts were more significant in Northern Europe where heating in a nuclear plant transformer was reported and a power system failure occurred on October 30 in Malmo, Sweden resulting in blackout conditions (Figure 12).

Electrical companies took considerable effort to prepare for and be aware of the storm onsets. Companies received the standard suite of geomagnetic storm watches, warnings and alerts, but SEC staff also supplemented standard support with several phone discussions. Preventive action helped to counter the GIC stresses that were observed. A representative from the North American Electric Reliability Council (NERC) commented - "*Although the bulk electric system was not significantly affected by the solar activity, some systems reported higher than normal GICs that resulted in fluctuations in the MW and MVAR output of some generating units, while the output of other units was reduced in response to the K-index forecast*." Responses to warnings included reducing system load, disconnecting system components, and postponing maintenance. Some actions taken by the U.S. Nuclear Regulatory Commission were included in their Power Reactor Status Report for October 30, 2003 (Figure 11). Many utility companies expressed their appreciation for SEC's efforts during the high solar activity – "*Central Maine Power appreciates and values NOAA's SEC's efforts in keeping* *the public and electric utilities informed of pending space weather events (Nov 06, 2003).*"

The military was forced to switch an Early Warning Radar from commercial to generator power to avoid damage from GICs.

U.S. Nuclear Regulatory Commission
Power Reactor Status Report for October 30, 2003

Unit	*Power*	*Reason or Comment*
Hope Creek 1	*80*	*REDUCED POWER DUE TO SOLAR*
		MAGNETIC DISTURBANCES
Salem 1	*80*	*REDUCED POWER DUE TO SOLAR*
		MAGNETIC DISTURBANCES
Braidwood 2	*90*	*COASTDOWN TO REFUELING OUTAGE*
		REVIEWING SYSTEM PLANNING OPERATING
		GUIDE FOR SOLAR FLARE RESPONSE
Arkansas Nuclear 1	*100*	*HOLDING OFF ON SWITCHYARD*
		MAINTENANCE FOR SOLAR FLARE
Palo Verde 1	*98*	*T-HOT LIMITED TAKING EXTRA READINGS*
		ON PLANT COMPUTE DUE TO SOLAR FLARE
Comanche Peak 1	*100*	*CANCELLED D/G SURVEILLANCE*
		DUE TO SOLAR FLARE RESPONSE

Figure 11. Extracted from NRC Status Report on October 30, 2003 (NRC)

Department of Homeland Security
Information Analysis and Infrastructure Protection
Daily Open Source Infrastructure Report
for 03 November 2003

Current Nationwide Threat Level is
ELEVATED
SIGNIFICANT RISK OF TERRORIST ATTACKS
For info click here
www.whitehouse.gov/homeland

Energy Sector

Current Electricity Sector Threat Alert Levels: Physical: Elevated, Cyber: Elevated
Scale: LOW, GUARDED, ELEVATED, HIGH, SEVERE [Source: ISAC for the Electricity Sector (ES–ISAC) – http://esisac.com]

October 31 ***- Sun storm causes problems for Swedish power system. The solar storm has caused technical glitches in Sweden's power system in the past few days and may be to blame for a blackout that affected 50,000 people on Thursday, October 30.*** *Magnetic solar storms can wreak havoc with electricity grids, and the effects continued to be felt on Friday, October 31, in the Nordic region, particularly in Sweden where problems with transformers at a nuclear station and in the grid were observed, officials said. Power was cut around 9 p.m. on Thursday in the southern Sweden city of Malmo and lasted 20 minutes to a half hour, utility Sydkraft said in a statement. "We have not 100 percent identified the solar storm as the cause, but it might have been," said Sydkraft official Peter Sigenstam. A spokesperson for Sweden's national grid, Svenska Kraftnat said that two transformers had malfunctioned, but the problems were quickly fixed and had not caused power outages to consumers.*

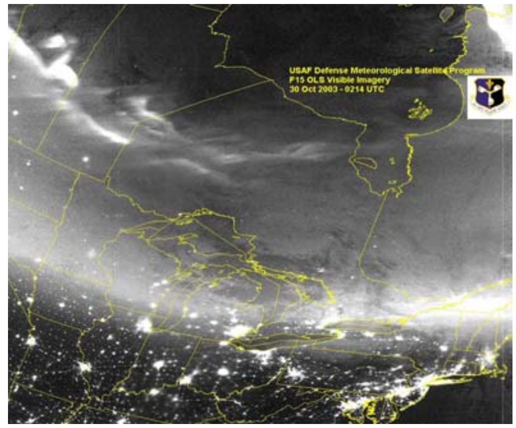
Figure 12. Power grid problems in Sweden are discussed in this excerpt from the Department of Homeland Security Infrastructure Report, November 03, 2003. (DHS)

Aurora

The Aurora Borealis and Aurora Australis (northern and southern lights) are the visible manifestation of geomagnetic disturbances. With the advent of the Internet and other advances in communication mediums, entrepreneurs are seizing commercial opportunities to provide aurora alerts, image galleries and photo sales, and even aurora viewing tours. The public's interest in aurora viewing generated numerous contacts from media and the general public alike.

Though not a part of SEC's product line, SEC staff assisted with dozens of inquiries about aurora viewing. The extreme and prolonged geomagnetic storms on October 29 and 30 ensured widespread middle and even low latitude aurora. Aurora sightings occurred from California to Houston to Florida. Tremendous aurora viewing was also reported from Australia, mid-Europe and even as far south as the Mediterranean countries.

Aurora over Colorado – October 29, 2003 (Photo by Ginger Mayfield)



Aurora over North America – October 30, 2003 (USAF DMSP satellite)

Media Response

The media response was undoubtedly the largest volume ever experienced at SEC. Over 300 media contacts occurred over this 20-day period. Details of the solar activity were sent over the AP network, CNN, NE Paging Service, NPR, Reuters News, Metro Network, and others. SEC staff provided daily updates and interviews to TV, Radio, and Internet sources (national and local – ABC, NBC, CBS, FOX, CNN, Weather Channel, PBS, and many more). Several live interviews were conducted for International media such as the Canadian Radio Corporation, BBC, and the Voice of America. SEC members participated in an hour-long worldwide interview on VOA, fielding questions from listeners on every continent. Newspapers and magazines around the world (Washington Post, NY Times, Chicago Tribune, USA Today, Herald Newspaper Glasgow, LePress Canada, London Times, PC Magazine, New Scientist, Discover, and more) would check daily to update their stories and do articles concerning the forecasts and possible problems and effects from this flurry of activity. The NY Times sent a reporter to SEC to shadow a forecaster for two days. The subsequent Times article included an extended front section article. Other agencies such as NASA and ESA also experienced a deluge of media interest in the activity outbreak.

Internet Services

The SEC Web site and the Internet proved to be an invaluable information tool. This fact became most apparent when the web site could no longer handle the volume of interested users. Prior to the onset of the late October-November activity, SEC's webpage averaged 0.5 million hits daily. Following the first SEC Space Weather Advisory Bulletin and NOAA Press Release in late October, web site access increased to around 3 million hits per day. This overwhelmed the system, and the site had to switch to an OAR Web Farm in order to handle the volume of file transfers. The site received 19 million hits on October 29 (Figure 13). In July 2003, during Hurricane Claudette, the NOAA National

Hurricane Center website averaged 3.7 million hits per day. During the 15-day period – October 24 through November 07, the SEC website averaged 6.2 million hits per day.

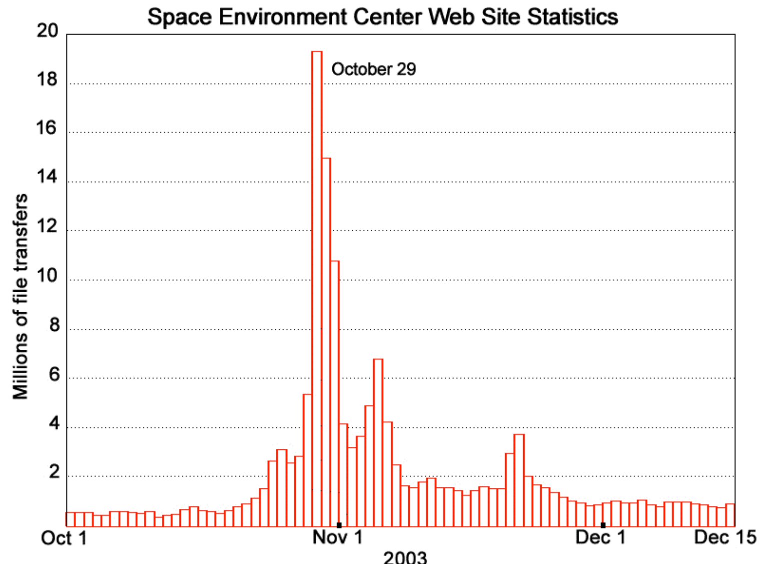


Figure 13. SEC Web site statistics (NOAA/NCEP/SEC)

Partner Coordination

Space Weather Operations Center, Air Force Weather Agency (AFWA): SEC works closely with its Air Force sister center in Offutt AFB, Nebraska. Daily coordination calls are standard procedure and play an important role in developing accurate and consistent forecasts of space weather. During the October-November activity period, coordination between the centers was at unprecedented levels.

Both centers relied on each other's data to ensure accurate and timely products were provided to their respective customers. Both SEC and AFWA have internal models for forecasting energetic particle events and geomagnetic storming. SEC has additional models they make available on their website, which AFWA uses to help in their forecasting processes. Immediate and intense coordination occurred between the two centers to produce the best-possible forecast of the space weather parameters for both customer bases. This complementary utilization of resources provided enhanced warning to the nation's DOD and civilian concerns impacted by space weather.

SEC relied on solar observations provided by the Air Force's Solar Electro Optical Network (SEON). AFWA operates five observatories (Figure 14) that monitor solar activity in both optical and radio wavelengths. These observations of flare location, radio burst intensity, and radio sweep characteristics were all used in radiation storm and geomagnetic storm forecasts. The 24-hour (global network) solar observations were vital in assessing the complexity and potential of the three major active regions. This was especially important during the October activity, because the SXI imager was not operational during the first 11 major flares from October 19 – 28. Knowing the solar source of the large X-ray flares was imperative for radiation storm forecasting. Radio data from the sites were key inputs to SEC products and support for the FAA and the NWS Doppler radar sites. Solar activity discussion bulletins from the SEON sites provided forecasters with critical details on the developments in the three large active regions. The mix and integration of information between these two centers ensured consistent, accurate and timely alerts and predictions. The Chief of the Space Weather Operations Center at AFWA had this to say: "*Daily forecast discussions were irreplaceable. These helped our forecasters focus, and provided a consolidated forecast for the nation. Also, the expertise from SEC in evaluating the significant events allowed us to focus on the resulting impacts to our customers.*"

The AFWA Space Weather Branch issued 458 unclassified warnings and 99 National Intelligence Community (NIC) warnings for space weather during the October–November outbreak.

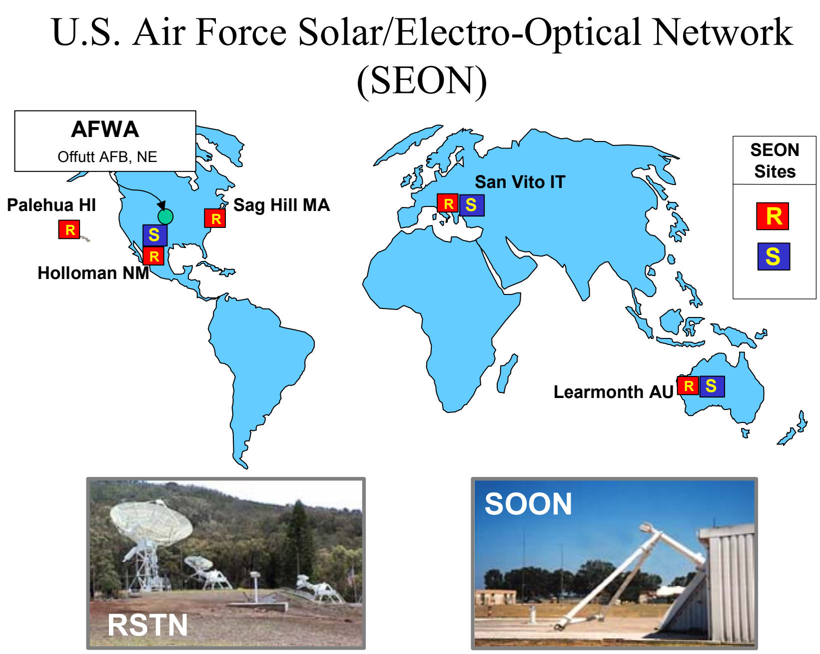


Figure 14. The SEON Network provided critical real-time optical and radio patrol during the severe October-November solar storms. (AFWA)

NASA SOHO-LASCO Operations Team - Coronagraph observations are the only way to directly observe coronal mass ejections (CME). In addition, they are able to indicate halo CMEs, which, when Earth-directed, are the best and earliest predictor of strong geomagnetic disturbances. The LASCO team issues coded and plain language alerts when Earth-directed halo CMEs are observed (Figure 15). The LASCO team's detailed analysis and reporting of the many CMEs during the October-November period was very valuable in operations. Additionally, LASCO scientists were available for consultation, and SEC staff gleaned important details on the various events.

UCMEO 93001 301028 1500/
31028 61054 91420 0001/ 360// 233// 42125
31028 61036 91212 20916 10486 1111/
99999

PLAIN

LASCO and EIT observed a full halo CME on 2003/10/28. The event was first observed in C2 at 10:54 UT as a bright loop front over the W limb; by 11:30 UT the front had developed into a full halo CME, very bright all around the occulting disk. The front first appeared as a full halo CME in C3 images at 11:42 UT. The mean plane-of-sky speed for this event was 1785 km/s at PA 92, with evidence for strong acceleration below 5Rs. The height-time profile above 5Rs I is moderately linear and has a mean plane- of-skyspeed of 2125 km/s

The CME was probably associated with an X17.2 X-ray flare observed by EIT between 10:36 – 12:012 UT, centered at S16E09 with peak emission at 11:12 UT. GOES records this flare from AR 0486 between 09:51 - 11:24 UT with peak emission at 1110 UT. A very large EIT wave, and dimming,were observed in association with this event. This event has therefore been determined frontsided. Please note that a large prominence can be seen erupting slightly below the active region prior to the flare, and this prominence material can clearly be seen in LASCO images, to the S.

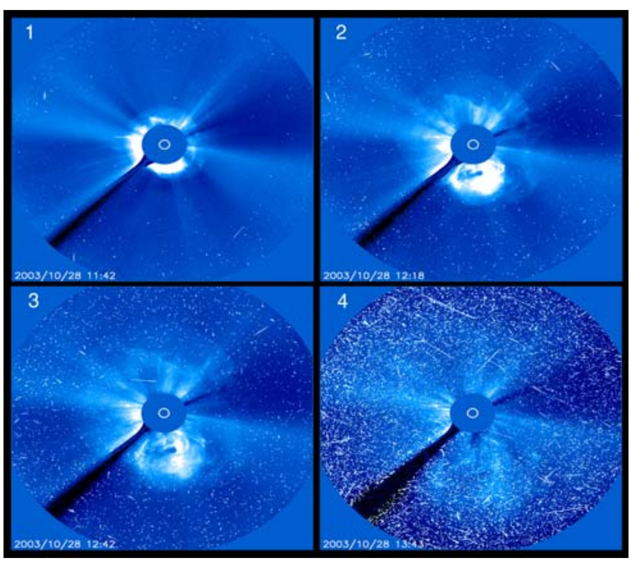


Figure 15. LASCO CME message and images following the X17 flare on October 28, 2003 (NASA/ESA)

FACTS

FACT: A total of 17 major X-ray flares (R2 – R5) were observed during the late October – early November time frame. These flares and the associated solar activity were some of the strongest on record. The November 04, 2003 flare saturated the GOES X-ray sensor for 12 minutes and is estimated at X28 (R5 extreme). This event is perhaps the largest flare ever measured by GOES X-ray sensors (measurements began in 1975).

FACT: The solar activity produced some of the most intense geophysical events on record. Six distinct radiation storms were discerned, including the second largest storm (S4 severe) of Solar Cycle 23. This storm ranked 4th in the all-time list dating back to 1976.

FACT: There were two distinct, intense geomagnetic storms associated with this activity. The coronal mass ejections that created these storms made the Sun-Earth transit in ~ 19 hours, making their average speed at near 5 million mph. These may be the fastest transits since August 1972. The storms were ranked as number 6 and 15 on the Top 30 Ap Geomagnetic Storm List, which dates back to 1932.

FACT: For the first time this solar cycle, three major active sunspot regions populated the visible disk at the same time. At its largest, Region 486 was equivalent in size to over 13 Earths, making it the largest sunspot group this cycle and the largest since November 1990.

FACT: This activity occurred 3.5 years after the peak month of Solar Cycle 23 (April 2000).

FACT: NOAA/SEC staff participated in numerous teleconferences with dispatchers, pilots, and airline safety personnel from major airlines. Airlines rerouted over a dozen flights due to HF/VHF communications problems and potential biological impacts of radiation storms. Airlines (both U.S. and foreign) made important route and/or altitude restrictions to flight operations during the solar activity. SEC information was an important part of their decision making process.

FACT: Several satellites and deep space instruments were put into safe mode in response to storm predictions.

FACT: The astronauts on the International Space Station (ISS) were directed to take shelter in the service module during the peak exposure intervals of the October 28-30 radiation storms. NASA also stowed the 56-foot-long Space Station Remote Manipulator System (robotic arm) during this period to prevent damage to this billion-dollar instrument.

FACT: Operators in at least 13 nuclear power reactors took precautionary actions to mitigate the impacts of geomagnetically induced currents during geomagnetic storms.

They expressed their appreciation to NOAA for helping them to counter the potential impacts and emphasized the importance of SEC data during extreme storming periods.

FACT: The Space Weather Operations (SWO) alone logged over 300 media contacts from agencies around the world. SEC representatives participated in numerous live radio and TV interviews. Solar activity stories were sent over every major news agency.

FACT: SEC issued four Space Weather Advisory Bulletins and assisted with eight NOAA Press Releases between October 22 – November 06.

FACT: For the first time ever, the Federal Aviation Administration issued an advisory suggesting that airline pilots fly at lower altitudes when traveling above 35 degrees latitude, both north and south. This was in response to the strong – severe radiation storms that began on October 28.

FACT: In late October, SEC's web site usage increased from the average 0.5 million hits per day, to around 3 million hits per day. The site received over 19 million hits on October 29.

Findings and Recommendations of the Assessment Team

Observations

Finding: The coronagraph proved to be an invaluable tool during this high solar activity period. Currently, there is no coronagraph instrument dedicated to real-time operational use. Those periods when LASCO coronagraph data were not available seriously limited NOAA/SEC's ability to accurately assess and predict a rapidly changing space weather environment.

Recommendation: NOAA should make the coronagraph a baseline instrument on future GOES spacecraft or other space-based platform. If the coronagraph is not deployed as an operational instrument, NOAA will suffer degradation in its current capability to provide space weather alerts and warnings.

Finding: The only way to forewarn about geomagnetic storms and to drive models of the magnetosphere is to use measurements of the solar wind upstream of Earth. The current source of these data is a NASA research satellite (ACE), which has already outlived its expected period of service, and will not be replaced by NASA. Certain operationally important sensors on this research satellite are rendered useless during moderate to large radiation storms, which seriously impacted SEC's storm assessment and warning ability. When solar data are no longer available from ACE, storms will be detected only when they have arrived at Earth; there will be no possibility to give reliable warnings.

Recommendation: NOAA should either procure, launch, operate, and acquire data from a series of real-time solar wind monitors placed near the Sun-Earth line, or NOAA should buy such data from a commercial supplier.

Internal and External Coordination

Finding: Teleconferences were conducted between airline representatives and SEC staff on a daily basis. Some difficulty in the understanding of solar phenomena and interpretation of SEC products was evident.

Recommendations 1a: Develop a website for the airline user community. Pending developments in the private sector, post the applicable services and explanations that apply to airline operational needs.

Recommendations 2a: Provide training for airline staff and management. Best options are for SEC staff to visit airline companies and/or facilitate a workshop for all interested parties (airline personnel, FAA, DOT, medical, etc).

Finding: The deluge of media contacts at times overwhelmed SEC staff. The response to media requests was performed in a professional and timely manner; however, it had the potential to interfere with SEC operations.

Recommendation: Improve the SEC web page to better facilitate the needs of media and the NOAA Public Affairs Office. Make plain language forecasts, Space Weather Bulletins, Alerts, Watches, and Warnings readily available and easily accessible. This would help alleviate the distraction during high solar activity.

Models and Guidance

Finding: The current D-Region Absorption Prediction model does not provide a true overall representation of space weather effects on communications for airline operations. The D-Region plot only identifies the impact of solar flares on communications. The additional impact of radiation storms and geomagnetic storms is not depicted. This caused some confusion to the airlines when making their decisions to route flights, especially on high latitude routes.

Recommendation: Pending developments in the private sector, improve the D-Region Absorption Plot to include impacts of radiation storms and geomagnetic storms on communications, or develop a product for airlines that would depict high latitude HF and VHF communication effects.

Finding: The Major Event Database proved to be a very valuable statistical tool in estimating a geophysical response from large flares. The database and interactive tool are still being developed, but the limited information available was used extensively.

Recommendation: Complete this database and interactive software and install in the Forecast Center.

Finding: Significant shortfalls exist in warning and forecast capability due to inadequate models and tools to derive forecast products. There is currently limited capability to warn for solar flare radio blackouts, high energy radiation storms, and many other aspects of space weather.

Recommendation: NOAA and SEC must assist in and support modeling efforts such as the Center for Integrated Space weather Modeling (CISM) and the Community Coordinated Modeling Center (CCMC) as well as other research and commercial institution modeling capabilities. Fully functional Rapid Prototyping Centers (RPCs), operations testbeds, or commercially outsourced engineering implementation contracts must be in place for rapid, focused development and transition of required models into Space Weather operations. The recent activity highlighted the need for the following models:

- Coronal Mass Ejection Propagation - CME characterization (mass, speed, direction, and magnetic structure) for predicting time of CME arrival and onset and intensity of geomagnetic storming.

- Solar Energetic Particles (SEP) - SEP spectra for airlines, satellite anomaly, and manned space flight hazard prediction. Airline companies and satellite operators requested more detailed SEP onset time and duration predictions.

- Radiation Belt Particle distribution (>100 keV) for satellite upset prediction. Precipitating particle characterization (location, energy, timing) for polar ionosphere prediction. Requested by both government and commercial satellite companies.

- Ionosphere - Global EDP for radar and communications signal path bending prediction. Global TEC for radar and communications signal path delay prediction. Global ionospheric currents for ionospheric event propagation prediction - A three-dimensional Global Assimilative Ionospheric Model (GAIM)**.** This would help meet the communication needs identified by HF users including airlines.

- Polar Scintillation - Arctic spatial and frequency distribution for communications, radar, and navigation signal corruption and outage prediction. Both DoD and commercial high latitude interests identified this need.

- Neutral Environment - Global neutral density and composition (>90 km) for accurate satellite, space debris, and missile orbit prediction. Global neutral winds (>90 km) for accurate communications, radar, and navigation signal corruption and outage prediction. Global neutral temperature (>90 km) for accurate communications, radar, and navigation signal corruption and outage prediction.

Warnings and Forecasts

Finding: Customers have established radiation storm thresholds to mitigate potential impacts. SEC does not currently provide predictions of the maximum flux of a radiation storm.

Recommendation: Utilize developments in modeling efforts, including those in the academic and vendor community, to provide improved radiation storm warnings to include maximum flux expected.

Finding: SEC provides a daily forecast at 2100 UT. This forecast is not amended as conditions change during the day, and consequently, it can be used only as guidance and not as an operational tool.

Recommendation: Establish requirements for amending the forecast or develop a new web-based dynamic forecast product.

Dissemination

Finding: The file transfer requests from the SEC web pages slowed our system after the first couple days of high solar activity. This halted processes, and as a result, many users attempting to access SEC's web site during peak periods could not get in. It was resolved by configuring software and systems to begin mirroring SEC web site content on the NOAA Network Operations Center (NOC) Web Farm in Boulder, Colorado.

Recommendation: Establish a permanent networking agreement with the NOC to continue this expanding service.

Best Practices

1. Maintaining Focus on the Space Environment

Forecasters focused on the space environment in teleconferences with the airlines. Forecasters are not qualified to assess and predict the biological impacts of the high radiation storms. Varying opinions would only serve to confuse both the public and the airlines in regard to this issue. Appropriate references are available in the Forecast Center, and SEC staff routinely and consistently distributed this information.

2. Media Management

Management ensured additional staff members were on duty to handle the deluge of media interests in this solar activity outbreak. As a consequence, forecasters could concentrate on product generation and dissemination and maintain high quality customer support.

3. Airline Teleconferences

Additional staff members were also made available to support airline operations. Teleconferences were, on occasion, quite lengthy, and the duty forecaster could not afford to be involved in lengthy discussions.

4. Daily Staff Meetings

Daily operations meetings were initiated to ensure consistency among SEC staff. It was important for SEC staff to be aware of the rapidly changing space weather conditions when advising media and public alike. These meetings also gave the staff an opportunity to share their expertise and provide input to the forecasts and warnings.

5. OAR Web Farm

Switching over the overwhelmed SEC website to an OAR Web Farm in order to handle the volume of file transfers was critical. The web farm servers were available to mirror SEC's website content to the public.

6. SXI Activation

SEC Operations submitted a formal request to NOAA and NESDIS management to resume SXI operations. The expedited request was immediately approved, and real-time SXI imagery was made available in the forecast center.

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APPENDIX A

NOAA SPACE WEATHER SCALES

APPENDIX A – NOAA SPACE WEATHER SCALES

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yr)
Scale	**Descriptor**	**Duration of event will influence severity of effects**		
		Solar Radiation Storms	**Flux level of >= 10 MeV particles (ions)***	**Number of events when flux level was met ****
S 5	**Extreme**	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) is possible. **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; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays) is possible. **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 commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest x-ray). **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:** none. **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

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2}. Based on this measure, but other physical measures are also considered.
** These events can last more than one day.

APPENDIX A – NOAA SPACE WEATHER SCALES

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
Scale	Descriptor	Duration of event will influence severity of effects		
		Radio Blackouts	**GOES X-ray peak brightness by class and by flux***	**Number of events when flux level was met**
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 (2×10^{-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 (5×10^{-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)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.
** Other frequencies may also be affected by these conditions.

APPENDIX A – NOAA SPACE WEATHER SCALES

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
Scale	Descriptor	Duration of event will influence severity of effects		
		Geomagnetic Storms	**Kp values* determined every 3 hours**	**Number of storm events when Kp level was met**
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)

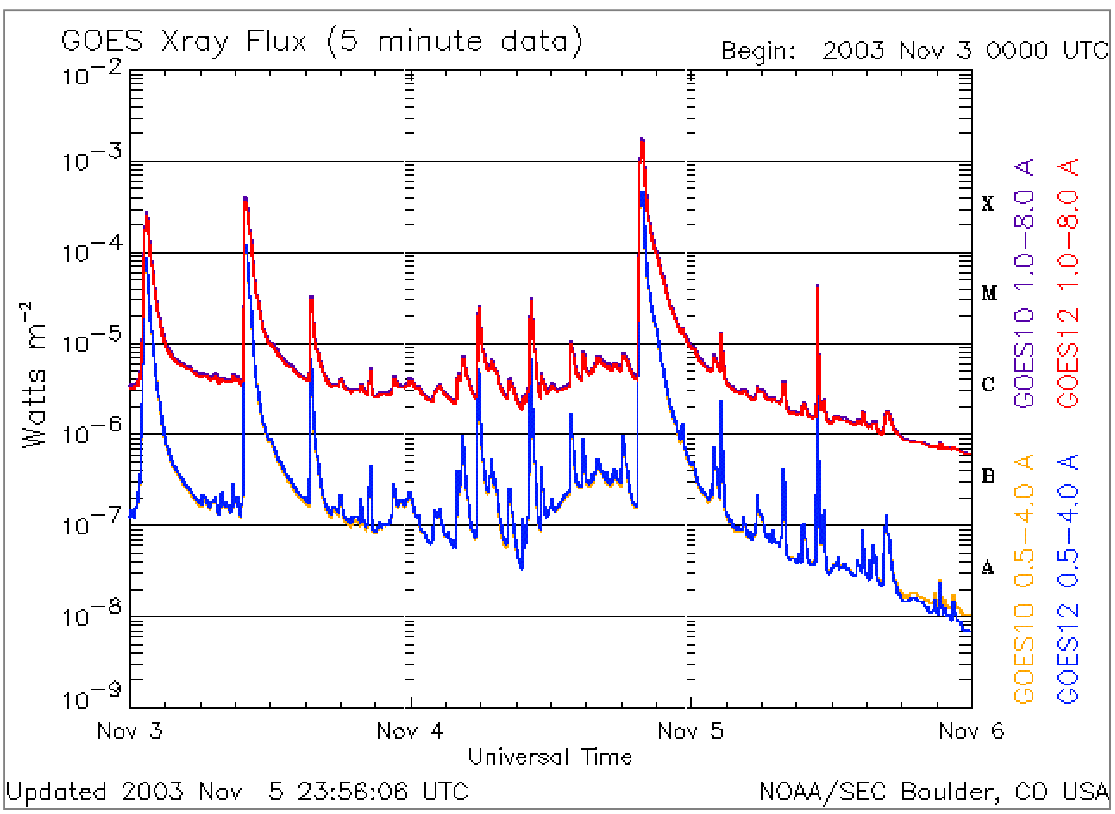
* Based on this measure, but other physical measures are also considered.
** For specific locations around the globe, use geomagnetic latitude to determine likely sightings.

APPENDIX B

X-RAY FLARE CLASSIFICATION

The X-ray flare class is the rank of a flare based on its X-ray energy output. Flares are classified by the order of magnitude of the peak burst intensity (I) measured by the X-ray sensor on GOES satellites in the 1 to 8 angstrom band as follows:

Class	(in Watt/sq. Meter)
B	I < 1.0E-06
C	1.0E-06 <= I <= 1.0E-05
M	1.0E-05 <= I <= 1.0E-04
X	I >= 1.0E-04



APPENDIX C

EVENT STATISTICS

Radio Blackouts

	October													November						
Days	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02	03	04	05	06	07
Intensity	R3	R1	R2	R2	R3	R2	R1	R3	R2	R4	R4	R1	R1	R1	R3	R3	R5	R2		

Number of Days with Radio Blackouts: 18

Number of Alerts (>R1): 17

NOTE 1: Warnings are not issued for Radio Blackouts

Geomagnetic Storms

	October													November						
Days	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02	03	04	05	06	07
Intensity	G1	G2	G2	G1		G3				G1	G5	G5	G4	G1			G3		G1	

Number of Days with Storming:	**12**
Number of Watches Issued:	**14**
Number of Warnings Issued:	**12**
Number of Alerts Issued:	**41**
Avg Leadtime:	**14 mins**
Avg Leadtime for G2-G5 Warnings:	**21 mins**
False alarm rate:	**20%**
Missed warnings:	**1**

Radiation Storms

	October													November						
Days	19	20	21	22	23	24	25	26	27	28	29	30	31	01	02	03	04	05	06	07
Intensity																				

Number of Radiation Storm Days:	**13**
Number of Warnings Issued:	**4**
Number of Alerts Issued:	**31**
Avg Leadtime:	**195 mins**
False Alarm Rate:	**0%**
Missed Warnings:	**0**

NOTE 1: Intensity is highest storming level for each day, i.e., the S4 storm on October 29 began on October 28, but did not reach the S4 level until October 29.

NOTE 2: Eleven additional radiation storm warnings were issued, but all were continuations of existing warnings.

NOTE 3: Lead times on the four radiation storm warnings ranged from 14 minutes to 10 hours.

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APPENDIX D

HISTORICAL PERSPECTIVE

Top 30 Geomagnetic Storms

(Potsdam Running Ap - since 1932)

Rank	Intensity	Date	Rank	Intensity	Date
1	312	09/18/1941	16	220	10/30/2003
2	293	11/12/1960	17	216	07/08/1958
3	285	03/13/1989	18	215	03/28/1946
4	277	03/23/1940	19	214	09/22/1946
5	258	10/04/1960	20	212	03/01/1941
6	252	10/29/2003	21	212	07/26/1946
7	252	07/15/1959	22	203	08/19/1950
8	251	03/31/1960	23	201	09/04/1982
9	241	05/25/1967	24	199	02/07/1946
10	229	07/11/1982	25	199	02/11/1958
11	228	02/07/1986	26	196	05/12/1949
12	226	03/29/1940	27	196	06/04/1991
13	223	08/04/1972	28	195	03/24/1946
14	222	07/05/1941	29	193	05/09/1992
15	221	09/02/1957	30	192	07/14/2000

NOTE: Potsdam, Germany, is the official world center for the Ap geomagnetic indices.

Top 20 Radiation Storms

(NOAA GOES >10 MeV Proton Data - since 1976)

Rank	Intensity (pfu)	Date	Rank	Intensity (pfu)	Date
1	43,000	03/23/1991	11	7,300	11/30/1989
2	40,000	10/19/1989	12	4,600	05/09/1982
3	31,700	11/04/2001	13	4,500	09/29/1989
4	29,500	10/28/2003	14	3,500	03/08/1989
5	24,000	07/14/2000	15	3,000	06/04/1991
6	18,900	11/22/2001	16	2,900	06/11/1982
7	14,800	11/08/2000	17	2,700	10/30/1992
8	12,900	09/24/2001	18	2,520	04/21/2002
9	10,000	02/20/1994	19	2,500	04/25/1984
10	9,200	08/12/1989	20	2,360	10/01/2001

NOTE: The X10 flare on October 29 produced a peak of 3300 pfu on October 30, but this new peak occurred in the waning stages of the October 28, 29,500 pfu radiation storm. Overlapping radiation storms are identified on this list as one storm.

Top Solar Flares

(NOAA GOES X-ray Flares - since 1976)

Date	X-ray	Region	Date	X-ray	Region
11/04/03	X28e	486	12/15/82	X12	4026
08/16/89	X20e	5629	06/04/91	X12e	6659
04/02/01	X20e	9393	06/06/91	X12e	6659
10/28/03	X17	486	06/11/91	X12e	6659
07/11/78	X15e	1203	06/15/91	X12e	6659
03/06/89	X15e	5395	12/17/82	X10	4025
04/24/84	X13e	4474	05/20/84	X10	4492
10/19/89	X13e	5747	01/25/91	X10	6471
06/06/82	X12e	3763	06/09/91	X10	6659
06/01/91	X12e	6659	10/29/03	X10	486

NOTE: Flares with an "e" suffix are estimated due to saturation of the GOES XRS instrument. The saturation level was increased to X17.4 in 1993.

DEPARTMENT OF COMMERCE

UNITED STATES OF AMERICA