governmentattic.org
"Rummaging in the government's attic"

Description of document:	Unpublished internal FEMA reports and studies concerning risks from geomagnetic storms and solar flares, 2010*
Requested date:	09-February-2016
Released date:	24-May-2017
Posted date:	12-June-2017
* Note:	Some records undated
Source of document:	FEMA Information Management Division FOIA Request 500 C Street, S.W., Mailstop 3172 Washington, D.C. 20472 Email: fema-foia@dhs.gov Online FOIA Request Form

The governmentattic.org web site ("the site") is noncommercial and free to the public. The site and materials made available on the site, such as this file, are for reference only. The governmentattic.org web site and its principals have made every effort to make this information as complete and as accurate as possible, however, there may be mistakes and omissions, both typographical and in content. The governmentattic.org web site and its principals shall have neither liability nor responsibility to any person or entity with respect to any loss or damage caused, or alleged to have been caused, directly or indirectly, by the information provided on the governmentattic.org web site or in this file. The public records published on the site were obtained from government agencies using proper legal channels. Each document is identified as to the source. Any concerns about the contents of the site should be directed to the agency originating the document in question. GovernmentAttic.org is not responsible for the contents of documents published on the website.

-- Web site design Copyright 2007 governmentattic.org --

U.S. Department of Homeland Security
500 C Street, S.W. Mail Stop 3172
Washington, DC 20472-3172

FEMA

May 24, 2017

SENT VIA EMAIL

Re: **FEMA 2016-FEFO-00962 Final Response**

This is the final response to your Freedom of Information Act (FOIA) request to the Department of Homeland Security (DHS)/Federal Emergency Management Agency (FEMA), dated and received by this office on February 9, 2016. You requested a copy of any unpublished internal FEMA or unpublished contractor technical or management reports and studies concerning risks from geomagnetic storms, risks from solar flares, and risks from electromagnetic pulse.

A search of FEMA's National Preparedness Directorate (NPD), and th .fice of Response and Recovery's Recovery – Public Assistance (ORR-PA) for documents responsive to your request produced a total of 83 pages. Of those pages, we have determined that 67 pages are releasable in their entirety, and 16 pages are being withheld in their entirety pursuant to Title 5 U.S.C. § 552(b)(5), FOIA Exemption 5.

FOIA Exemption 5 protects from disclosure those inter- or intra-agency documents that are normally privileged in the civil discovery context. The three most frequently invoked privileges are the deliberative process privilege, the attorney work-product privilege, and the attorney-client privilege. After carefully reviewing the responsive documents, we determined that portions of the responsive documents qualify for protection under the Deliberative Process Privilege. The deliberative process privilege protects the integrity of the deliberative or decision-making processes within the agency by exempting from mandatory disclosure opinions, conclusions, and recommendations included within inter-agency or intra-agency memoranda or letters. The release of this internal information would discourage the expression of candid opinions and inhibit the free and frank exchange of information among agency personnel.

You have the right to appeal if you disagree with FEMA's response. The procedure for administrative appeals is outlined in the DHS regulations at 6 C.F.R. § 5.8. In the event you wish to submit an appeal, we encourage you to both state the reason(s) you believe FEMA's initial determination on your FOIA request was erroneous in your correspondence, and include a copy of this letter with your appeal. Should you wish to do so, you must send your appeal within

FEMA 2016-FEFO-00962

90 days from the date of this letter to fema-foia@fema.dhs.gov, or alternatively, via mail at the following address:

FEMA
Office of the Chief Administrative Officer
Information Management Division (FOIA Appeals)
500 C Street, SW, Seventh Floor, Mail Stop 3172
Washington, D.C. 20472-3172

As part of the 2007 FOIA amendments, the Office of Government Information Services (OGIS) was created to offer mediation services to resolve disputes between FOIA requesters and Federal agencies. You may contact OGIS in any of the following ways:

Office of Government Information Services
National Archives and Records Administration
8601 Adelphi Road- OGIS
College Park, MD 20740-6001
E-mail: ogis@nara.gov
Web: https://ogis.archives.gov
Telephone: 202-741-5770/Toll-free: 1-877-684-6448
Facsimile: 202-741-5769

Provisions of the FOIA allow us to recover part of the cost of complying with your request. In this instance, because the cost is below the $25 minimum, there is no charge.

If you need any further assistance or would like to discuss any aspect of your request, please contact us and refer to FOIA case number **2016-FEFO-00962**. You may send an e-mail to fema-foia@fema.gov, call (202) 646-3323, or you may contact our FOIA Public Liaison in the same manner.

Sincerely,

ERIC A NEUSCHAEFER

Digitally signed by ERIC A NEUSCHAEFER
DN: c=US, o=U.S. Government, ou=Department of Homeland Security, ou=FEMA, ou=People, cn=ERIC A NEUSCHAEFER, 0.9.2342.19200300.100.1.1=0647718256.FEMA
Date: 2017.05.22 15:05:54 -04'00'

Eric Neuschaefer
Chief, Disclosure Branch
Information Management Division
Mission Support

Enclosure: Responsive Documents (67 pages)

Mitigation strategies for FEMA command, control, and communications during and after a solar superstorm

Historical Background

Morse Telegraph Table
Photo from www.telegraphlore.com

In 1847, W. H. Barlow, a telegraph engineer with the Midland railroad in England, noted "anomalous current" on the telegraph line between Derby and Birmingham, marking the first recorded impact of solar weather on technological systems (Lanzerotti, 2001). During the next solar maximum in 1859, a solar superstorm disrupted telegraph service in North and South America, Europe, and Australia on 28-29 August, followed by the strongest solar storm on record on 1-2 September in what is now known as the Carrington-Hodgson event (Green & Boardsen, 2005). Telegraph operators around the globe reported intense currents on telegraph lines, some so strong that operators disconnected their batteries and sent messages using "auroral current" (Green et al, 2006). Other operators reported electrical sparking, shocks, and even fires.

As technology increased, so too did the impact of space weather. Guglielmo Marconi, a pioneer of radio, commented ". . . times of bad fading [of radio signals] practically always coincide with the appearance of large sunspots and intense aurora-boreali . . . the same periods when cables and land lines experience difficulties or are thrown out of action" (Lanzerotti, 2001). In 1921, what may have been the second largest superstorm on record "interfered with telephones, telegraphs and cables over many part[s] of Europe. In this country, where interferences with telegraphing were said to be the worst ever experienced, stray currents of 1,000 [amps] were registered. . . ." (The New York Times, 1921a). The storm burned out undersea cables, caused fires that disrupted train service in New York City, and in Brewster, NY, a railroad station telegraph operator was "driven away from his instrument by a flare of flame which enveloped the switchboard and ignited the building" (The New York Times, 1921a). One French telegrapher referred to his equipment as "possessed by evil spirits" (The New York Times, 1921b).

More recent storms have been smaller than those seen in 1859 and 1921. In 1989, one such storm collapsed the Quebec power grid for nine hours and rendered "nearly inoperable" the first fiber optic transatlantic cable (Lanzerotti, 2001). As recently as 2003, the "Halloween Storms" interrupted Global Positioning System (GPS) services, caused High-Frequency (HF) radio blackouts, induced powerful currents that required power stations and nuclear power plants in Canada and the Northeastern United States to take emergency protective measures (National Academy of Sciences, 2008), and destroyed several large electrical power transformers in South Africa (Gaunt & Coetzee, 2007).

Executive Summary

Most space weather events do not significantly impact FEMA's operations or readiness, nor are their effects noticeable to U.S. communities. Communications disruptions, reductions in GPS reliability, and power blackouts—when they occur—generally last for minutes or hours. However, low-frequency, high-consequence events like the Carrington-Hodgson superstorm of 1859 or the Great Storm of 1921 have the potential for catastrophic impact on our nation and FEMA's ability to respond.

Solar superstorms cannot be predicted, but the conditions that give rise to them can be foreseen. Their impact on FEMA's ability to maintain internal command, control, and communications (C3) and external critical communications can be mitigated. This paper recreates the 1859 event today using the latest research to explain and understand: 1) The nature and effects of radio blackouts, solar radiation storms, and geomagnetic storms; 2) their potential for cascading effects on global power and telecommunications systems; and, 3) the implications for FEMA—based on the July 25, 2007 National Communications System Directive 3-10, "Minimum Requirements for Continuity Communications Capabilities"—in planning for and responding to such an event. It concludes with specific recommendations for maintaining FEMA C3 and critical communications with external partners throughout all phases of a superstorm.

The timeline for this scenario is adapted with permission from a briefing by William "Bill" Murtagh of the NOAA Space Weather Prediction Center (SWPC) in Boulder, Colorado.

The Scenario

The September 1, 1859, superstorm was the result of a massive solar flare (Figure 1) and coronal mass ejection (CME) launched from a near-center-disk sunspot group aimed directly at the Earth. The CME was one of the fastest on record, arriving at the Earth in approximately 17 hours (Green & Boardsen, 2005), and had a southward-oriented interplanetary magnetic field (Koskinen & Huttunen, 2006). According to the National Academy of Sciences (2008), a perfect solar storm must:

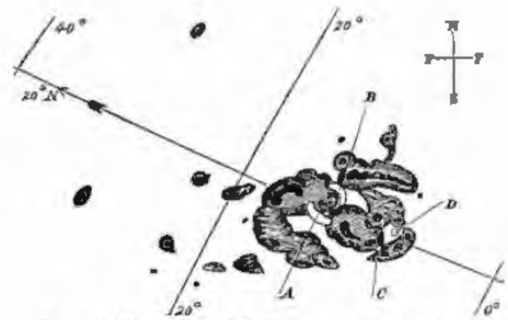
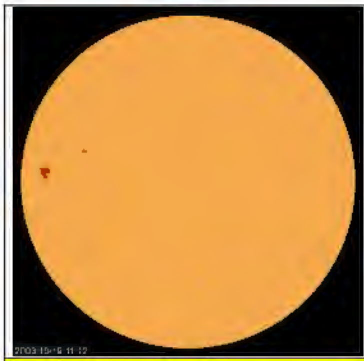
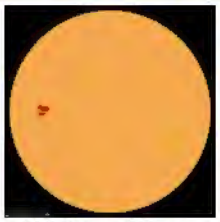
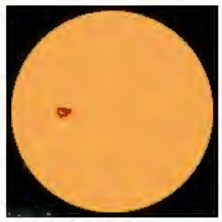


Figure 1: Drawing of 1859 sunspot group and flare (A and B) by Richard C. Carrington. © Royal Astronomical Society. Courtesy of NASA

1) Be launched from near the center of the Sun onto a trajectory that will cause it to impact Earth's magnetic field;
2) Be fast (≥1000 kilometers/second) and massive, thus possessing large kinetic energy; and
3) Have a strong magnetic field whose orientation is opposite that of Earth's.

By this definition, the Carrington-Hodgson event was a perfect storm, "the maximum of maximums," and serves as the model for the scenario used in this paper. Typically, the sun can produce three primary types of space weather events—radio blackouts, solar radiation storms, and geomagnetic storms—that each have specific effects on communications and power systems. The Carrington-Hodgson event combined all three primary types of space weather.

Table 1: G minus 5 Days

<table>
<tr><td colspan="4"></td><td colspan="10">Trigger:
• A very large, complex sunspot group emerges near the solar equator
o Complex magnetic fields produce frequent solar flares
o May also produce solar radiation storms or trigger coronal mass ejections (resulting in geomagnetic storms)
Note: Large equatorial sunspot groups are worrisome because their massive eruptions are more likely to be aimed at the Earth
SOHO images of sunspot group courtesy of NASA</td></tr>
<tr><td colspan="4">NOAA SWPC Action</td><td colspan="10">Solar Activity Forecast: High, 80% prohability of ≥ R4 events</td></tr>
<tr><td colspan="4">Scenario</td><td colspan="10"> G Minus 4 Days
 G Minus 3 Days
 G Minus 2 Days
 G Minus 1 Day
Over the period from G -4 to -1 days, Earth is struck by multiple R1 (minor) - R3 (strong) radio blackout events.</td></tr>
<tr><td colspan="4">Warning Time</td><td colspan="10">None</td></tr>
<tr><td colspan="4">Duration</td><td colspan="10">Minutes to 3 hours on Earth's daylight side</td></tr>
<tr><td colspan="14">FEMA Impact</td></tr>
<tr><td colspan="11">Basic Connectivity</td><td colspan="3" rowspan="2">Mobile/ In-Transit</td></tr>
<tr><td colspan="4">Telephone/Fax</td><td colspan="3">Data Networks and Email</td><td>Video</td><td colspan="2">Backup</td><td></td></tr>
<tr><td>Non-Secure Telephone</td><td>Non-Secure Fax</td><td>Secure Telephone</td><td>Secure Fax</td><td>Unclassified</td><td>Secret</td><td>Top Secret/SCI</td><td>Top Secret/SCI VTC</td><td>Top Secret HF ALE</td><td>Top Secret Satellite Telephone</td><td>Top Secret Cellular Telephone</td><td>Top Secret Satellite Telephone</td><td>Top Secret UHF and/or VHF</td><td></td></tr>
<tr><td colspan="14">• HF radio communications may be disrupted for periods of minutes up to hours per flare. Note: FEMA does not use HF in normal operations except for testing.
• GPS disruptions may last from seconds to 15 minutes and should not significantly impact FEMA's mission</td></tr>
</table>

Five days prior to the CME striking Earth, NASA satellites spot a large, complex sunspot group emerge around the limb of the Sun (Table 1). Such sunspot groups have very complex magnetic fields and can produce frequent solar flares (Figure 2), the largest explosions in the solar system (NOAA, 2010). They can also produce solar radiation storms and may trigger coronal mass ejections (NOAA, 2010). According to W. Murtagh, (personal communication, November 10, 2010), large, complex sunspot groups 40° west of center disk to 20° east of center disk near the sun's equator are of particular interest. Each solar flare is capable of showering the Earth with intense radiation across the entire electromagnetic spectrum.

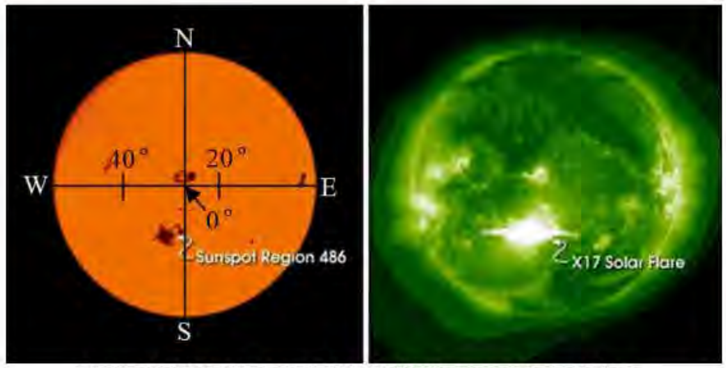


Figure 2: SOHO images of 2003 "Halloween Storm" Flare
Photos courtesy of NASA

Traveling at the speed of light, x-ray and ultra-violet radiation impact Earth's ionosphere (Figure 3) without warning and cause radio blackouts on the daylight side of the planet, disrupting high-frequency (HF) radio communications and low-frequency (LF) marine navigation systems for a period of minutes up to three hours *per flare* (NOAA, 2010). The radiation causes absorption and frequency deviation of HF signals and fadeout, noise, and phase change in LF and VLF navigation signals (Tulunay, & Bradley, 2004). Military and public safety very-high frequency (VHF) radio systems that rely on reflection from the ionosphere may experience severe distortion and scatter effects (Tulunay, & Bradley, 2004).

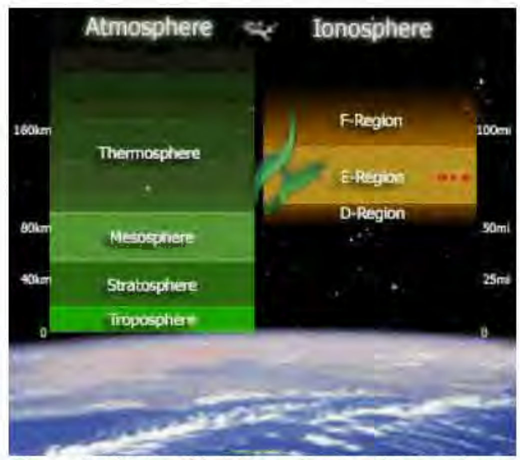


Figure 3: The Earth's Atmosphere and Ionosphere
Image courtesy of solar-center.stanford.edu

Microwave radiation can also interfere with some communications satellites that operate in the microwave bands, and GPS location signals may be degraded or disrupted for periods up to fifteen minutes (W. Murtagh, personal communication, November 10, 2010).

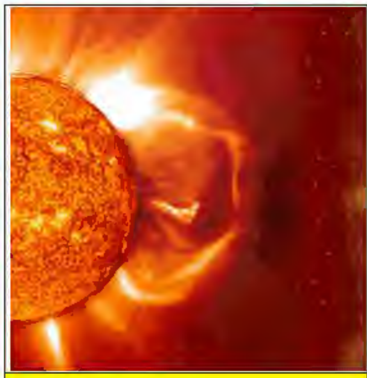
Shortly after the sunspot group is observed, the NOAA Space Weather Prediction Center issues a space weather forecast of high solar activity with an 80% probability of an R4 or greater radio blackout event (see Appendix A) (NOAA, 2010).

FEMA Impact

Over the next several days, Earth is struck by multiple R1 (minor) - R3 (strong) events. HF communications are blacked out for periods of minutes to hours on the daylight side of the planet *per event*. Though FEMA does not use HF during normal operations, these radio blackouts may affect the FEMA National Radio System (FNARS) and FEMA's Mobile Emergency Response

Support (MERS) during testing, exercises, and disasters where HF voice and HF Automatic Link Establishment (ALE) are being used. HF disruptions may also affect FEMA's partners at all levels, specifically state and local emergency management organizations that rely on amateur HF for incident operations support. All FEMA personnel may experience minor GPS disruptions, but these should not significantly impact FEMA's mission.

Table 2: G minus 17 Hours

	Trigger:
	• **Massive solar flare erupts above near-center-disk sunspot group**
	  ○ Releases intense radiation at the speed of light across the entire electromagnetic spectrum
	  ○ Launches a solar radiation storm, a cloud of high-energy protons and other particles at near-relativistic speeds
	  ○ Triggers colossal, fast moving CME
	Image of flare and coronal mass ejection courtesy of NASA

NOAA SWPC Action	• **R5 Radio Blackout Alert issued** • **S4 Radiation Storm Warning issued** • **G5 Geomagnetic Storm Watch issued**
Scenario	• R5 (extreme) radio blackout event arrives without warning. **Note:** The interplanetary magnetic field orientation of the CME cannot be measured until it reaches the NASA ACE satellite.
Warning Time	None
Duration	Several hours on Earth's daylight side (possible night side spread)

FEMA Impact

Basic Connectivity											**Mobile/ In-Transit**		
Telephone/Fax				**Data Networks and Email**			**Video**	**Backup**					
Non-Secure Telephone	**Non-Secure Fax**	**Secure Telephone**	**Secure Fax**	**Unclassified**	**Secret**	**Top Secret/SCI**	**Top Secret/SCI VTC**	**Top Secret HF ALE**	**Top Secret Satellite Telephone**	**Top Secret Cellular Telephone**	**Top Secret Satellite Telephone**	**Top Secret UHF and/or VHF**	

- **Dayside HF communications not possible for next 17 hours.** HF ground wave possible up to 10-60 miles (FNARS, MERS).
- During periods of radio blackouts, several assets are available to maintain C3; however, **satellite-based systems have only ≈20 minutes before the arrival of the solar radiation storm in this scenario.**
- GPS disruptions may impact FEMA's mission

The first indication of the coming superstorm is the arrival of the R5 (extreme) radio blackout event (Table 2). Traveling at the speed of light, it arrives without warning. X-ray and ultra-violet radiation strike the ionosphere, causing a complete HF radio blackout on the daylight side of Earth with possible spread to the night side (NOAA, 2010). Simultaneously, solar radiation at microwave frequencies causes noise in communications satellite transmissions and GPS signals, a form of "natural jamming" (W. Murtagh, personal communication, November 10, 2010).

Table 3: G minus 16 Hours 40 Minutes

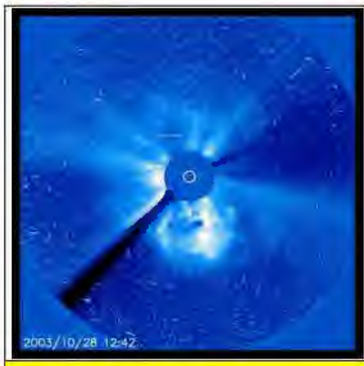
<table>
<tr><td colspan="4">
</td><td colspan="9">Trigger:
• Solar radiation storm arrives at Earth
o ≈15% of satellite fleet lost due to solar panel damage
o ≈50 times normal satellite "anomaly" rate ranging from single event upsets (generally minor) to complete loss of satellite
o Loss of GPS satellites below required 24 possible

Image of 2003 "Halloween" solar radiation storm impact at SOHO courtesy of NASA</td></tr>
<tr><td colspan="4">NOAA SWPC Action</td><td colspan="9">• S5 Solar Radiation Storm Alert issued</td></tr>
<tr><td colspan="4">Scenario</td><td colspan="9">• S5 (extreme) solar radiation storm arrives 20 minutes after radio blackout event.</td></tr>
<tr><td colspan="4">Warning Time</td><td colspan="9">≈20 minutes</td></tr>
<tr><td colspan="4">Duration</td><td colspan="9">≈3-24 hours (various effects)</td></tr>
<tr><td colspan="13">FEMA Impact</td></tr>
<tr><td colspan="10">Basic Connectivity</td><td colspan="3" rowspan="2">Mobile/ In-Transit</td></tr>
<tr><td colspan="4">Telephone/Fax</td><td colspan="3">Data Networks and Email</td><td>Video</td><td colspan="2">Backup</td></tr>
<tr><td>*Non-Secure Telephone</td><td>*Non-Secure Fax</td><td>*Secure Telephone</td><td>*Secure Fax</td><td>*Unclassified</td><td>*Secret</td><td>*Top Secret/SCI</td><td>*Top Secret/SCI VTC</td><td>Top Secret HF ALE</td><td>Top Secret Satellite Telephone</td><td>Top Secret Cellular Telephone</td><td>Top Secret Satellite Telephone</td><td>*Top Secret UHF and/or VHF</td></tr>
<tr><td colspan="13">* Potential temporary or permanent loss of satellite support for BGAN, MSAT G2, Ku- and C-band systems – (IMAT, MERS, US&R).
• Iridium and Globalstar satellite networks may experience disruptions in service
• Daylight side HF communications blackout continues; HF ground wave possible up to 10-60 miles (FNARS, MERS).
• Some cellular disruption/dropped calls possible
• Commercial land line networks should remain operational
• GPS disruptions may impact FEMA's mission, E911, and network timing used in various industries such as telecommunications and power.</td></tr>
</table>

Twenty minutes after the radio blackout event, the solar radiation storm arrives (Table 3). Showers of energetic protons, electrons, and other particles accelerated to near-relativistic speeds damage the solar panels which provide power to satellites and can cause "anomalies" from minor electrical system upsets and command failures to complete loss of the satellite (Odenwald, Green, & Taylor, 2005).

Typically, solar and cosmic radiation decreases the efficiency of the solar panels that power satellites by 2% per year at geosynchronous orbit (GEO) and 5% per year at mid-earth orbit (MEO) (Odenwald et al., 2005). Satellites are generally designed with a 30-50% power margin of safety and can remain fully functional until they reach 30% power, allowing for a planned lifetime of 15 years for GEO and 10 years for MEO satellites (Odenwald et al., 2005). Although "[low-earth orbit (LEO)] satellites are considerably less vulnerable to [solar proton events] and solar panel degradation," they "may experience large increases in total radiation dosage and reduction in lifetime" (Odenwald et al., 2005). The solar radiation superstorm adds 3-5 years worth of exposure to solar panels, degrading many older satellites below their minimum operating power and resulting in a loss of approximately 15% of the satellite fleet and premature aging of the remaining satellites (Odenwald et al., 2005).

Odenwald et al (2005) also calculated an approximately 50 times increase in the anomalies normally experienced across the entire satellite fleet, which will create a challenging environment for ground controllers attempting to mitigate problems and could result in temporary or permanent loss of service for given satellites (Odenwald et al., 2005). Overall, "The superstorm may result in a sharp rise in mission-critical anomalies in satellite power and orientation systems, which lead to complete satellite failure, especially for GEO and MEO satellites that are not as atmospherically well shielded as LEO systems" (Odenwald et al., 2005).

GPS: A Special Concern

This scenario is particularly troublesome for the GPS network over the next few years. The Global Positioning System constellation provides location and timing information for users worldwide and requires a minimum of 24 MEO satellites to provide complete global coverage (GAO, 2010). The current GPS fleet consists of 30 operational Block IIA and Block IIR satellites with designed lifetimes of 7.5 and 7.8 years respectively (GAO, 2010 & USNO, 2010). The last IIA satellite was launched in 1997, thus all 11 surviving IIA satellites are well past their designed lifetimes (USNO, 2010). The IIR satellites began launching in 1997 and 6 of the 19 are now beyond their designed lifetime (USNO, 2010). The first of a new series of GPS satellites, the Block IIF, launched in May of 2010 and is undergoing orbital testing before additional satellites are launched to replace the aging fleet, but the program is already three and half years behind schedule (GAO, 2010). Even without a solar superstorm impact, "DOD predicts that over the next several years many of the older satellites in the constellation will reach the end of their operational life faster than they will be replenished" (GAO, 2010). Based on current launch schedules, the Government Accountability Office (GAO) reported in September of 2010 that the GPS network could fall to 25 usable satellites by the end of 2012 and 24 satellites by late 2014, provided there are no further program delays. Again, this is without the impact of a solar superstorm. Should such a storm occur, ". . . there is also the possibility that a number of the older GPS satellites may fail so that the full complement of 24 satellites needed to operate the network will be unavailable . . . It may take months or years to restore the GPS system to full operating status" (Odenwald et al., 2005). The solar maximum in 2013 comes at a time when the GPS network will be at its most vulnerable.

Should the network fall below the required 24 satellites, position information "may not be available for portions of the day when the requisite four to six satellites are not above the horizon for specific geographic locations" (Odenwald et al., 2005). This could mean that E911 GPS location data for mobile phones, normally provided to 911 operators, may not be available. Loss of GPS timing could also cause some cellular towers to go into "island mode" where they are unable to hand off calls from one cell tower to another, resulting in dropped calls for users moving between tower coverage areas (C. Obreg, personal communication, December 10, 2010).

The SWPC issues an S5 (extreme) solar radiation storm alert (NOAA, 2010).

FEMA Impact

The primary danger to FEMA C3 and critical communications during this phase of the storm is the potential loss—during disaster operations—of GEO communications satellite services that support FEMA's Broadband Global Area Network (BGAN) terminals, MSAT G2s (satellite phone), and satellite Ku- and C-band Very Small Aperture Terminals (VSATs). This could impact Incident Management Assistance Teams (IMATs), MERS, Urban Search & Rescue (US&R) teams, and other partner agencies and jurisdictions supporting disaster operations.

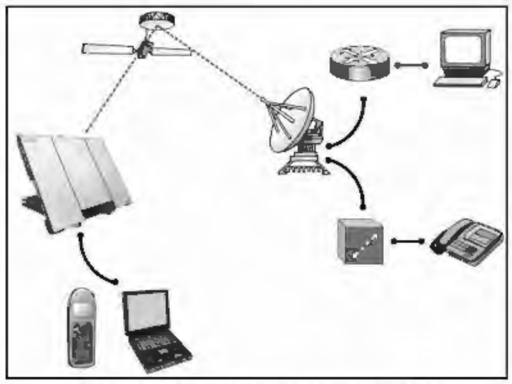


Figure 4: BGAN network connectivity
Image courtesy of Inmarsat

HF voice and HF ALE communications on the daylight side of the planet (with possible spread to the night side) will be essentially unusable during this period due to impact on the ionosphere from the radio blackout event and ionospheric disturbances at higher latitudes from the solar radiation storm (NOAA, 2010). HF ground wave may be possible out to a range of 10-60 miles. HF is a backup system in normal FEMA operations but this could impact disaster operations where HF is being used (FNARS, MERS).

Cellular callers in transit may experience dropped calls, but stationary callers should not be effected (C. Obreg, personal communication, December 10, 2010). Commercial providers of telecommunications, cable, and terrestrial broadcast should not experience significant outages during this phase of the storm. Excess capacity in the GEO communications satellite fleet and high reliance on terrestrial fiber optic networks in the U.S. should allow for rapid rerouting of commercial voice and data traffic (Comm ISAC, personal communication, November 8, 2010).

While GPS is not a critical component of FEMA operations, many FEMA employees rely on GPS for travel and facility or customer location information. Further, many of FEMA's customers and government and private sector partners rely on GPS. Even without loss of GPS satellites, GPS receivers may lose lock or experience significant position errors (Odenwald et al., 2005).

Table 4: G minus ≈15 Minutes

	Trigger:
	• **CME arrives at NASA ACE satellite**
	   o CME interplanetary magnetic field has southward orientation, which drives strongest geomagnetic storms
	   o Fast moving CME is now only ≈15 minutes from Earth
	
	ACE Logo courtesy of NASA

NOAA SWPC Action	• **G5 Geomagnetic Storm Warning issued**

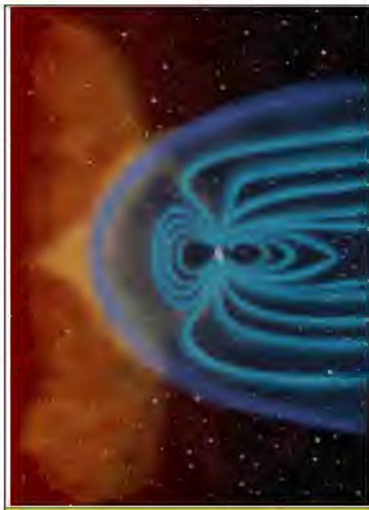
The NASA Advanced Composition Explorer (ACE) satellite possesses the only real-time space-based instrument capable of determining the interplanetary magnetic field (IMF) orientation of a CME. The magnetic orientation of a CME determines its impact at Earth. It can be in any direction and often changes in different parts of the plasma cloud (Koskinen & Huttunen, 2006). Like a bar magnet, two poles of the same polarity will repel and two poles of opposite polarity will attract. The Earth's magnetic field will repel a northward oriented IMF and attract—or "couple with"—a southward oriented IMF; therefore, a CME with a south magnetic orientation drives the strongest geomagnetic storms (Koskinen & Huttunen, 2006). Typically, ACE can provide about a one hour warning (NASA, 2008). However, the 1859 CME traveled faster than "normal" storms. A repeat of the 1859 event, therefore, would arrive at ACE approximately 15 minutes before striking the Earth (Table 4) (W. Murtagh, personal communication, November 10, 2010). This provides a very narrow window for warnings and notifications.

0 Hour

Catastrophe arrives with a spectacular celestial show. From Canada to the Caribbean, Sweden to the Middle East, Australia to Southern Africa, nighttime skies light up with beautiful red aurora shot with spears of white light (Green et al., 2005).

Figure 5: Aurora Australis during a strong geomagnetic event
Image courtesy of NOAA

Table 5: 0 Hour



Trigger:

- **CME arrives at Earth causing geomagnetic storm**
  - GEO satellites on daylight side exposed to solar plasma
  - Some satellite communications and GPS signals severely disrupted due to scintillation in ionosphere
  - HF systems may work due to increased ionization at ionosphere F Layer
  - Significant power grid collapses may occur in North America and elsewhere; could require 4-10 years to fully restore
  - "Last mile" telecommunications lost where no backup power available (e.g. cable, VoIP, data networks, etc.)

Image of CME impact on Earth's magnetic field courtesy of NASA

NOAA SWPC Action	• **G5 Geomagnetic Storm Alert issued** • **Forecast for G5 conditions to continue for 24 hours**
Scenario	• G5 (extreme) geomagnetic storm arrives.
Warning Time	≈15 minutes for geoeffectivity (≈17 hours from flare sighting)
Duration	≈12-24 hours (various effects)

FEMA Impact

Basic Connectivity											Mobile/ In-Transit		
Telephone/Fax				Data Networks and Email			Video	Backup				
Non-Secure Telephone	Non-Secure Fax	Secure Telephone	Secure Fax	Unclassified	Secret	Top Secret/SCI	Top Secret/SCI VTC	Top Secret HF ALE	Top Secret Satellite Telephone	Top Secret Cellular Telephone	Top Secret Satellite Telephone	Top Secret UHF and/or VHF

- BGAN, MSAT G2, Iridium, and Globalstar satellite communications may be severely disrupted due to scintillation in the ionosphere – (IMAT, MERS, US&R).
- Ku- and C-band satellite communications may be disrupted due to GEO satellite service loss; **surviving Ku- and C- Band systems less effected by scintillation.**
- HF communications may be possible but spotty on daylight side (FNARS, MERS).
- Commercial land line networks should remain operational with temporary disruptions – with exception of **"last mile" communications (i.e. VoIP, cable broadband),** which **could fail immediately without local power**
- Some cellular network degradation probable
- FEMA UHF Command and Control radio net should remain operational.
- CWIN should remain operational if "last mile" power available.
- Severe GPS disruption.

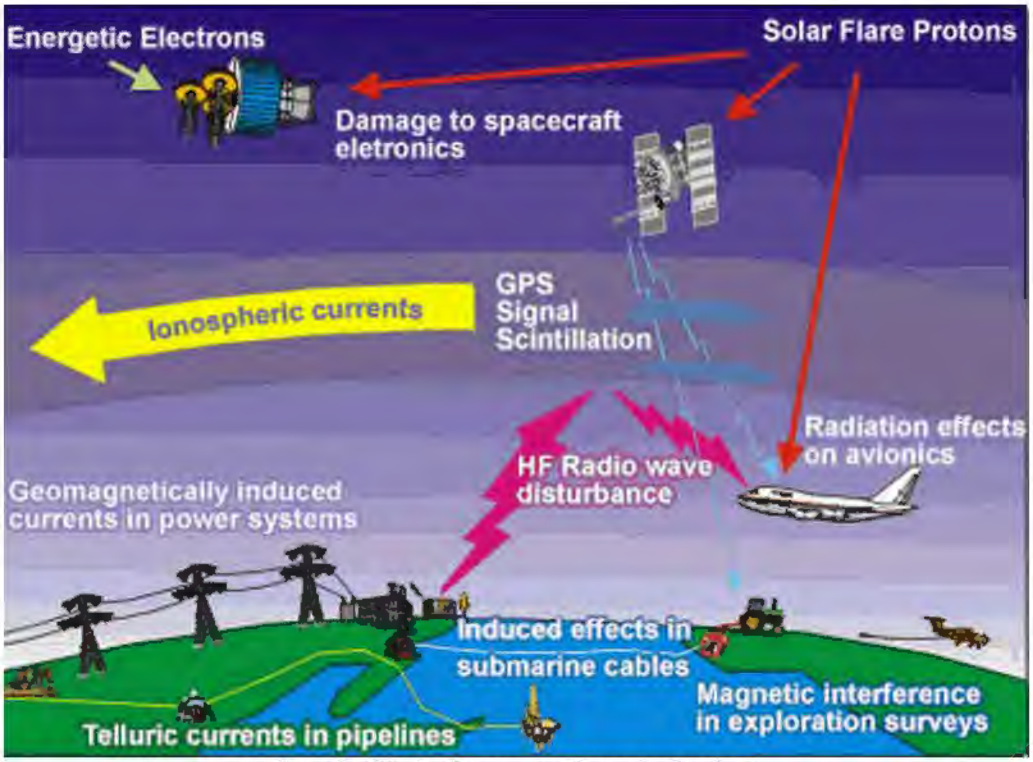


Figure 6: Affects of space weather on technology
Image from Natural Resources Canada sst.rncan.gc.ca/rrnh-rran/proj3_e.php
Image adapted from original by L. J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.

Geomagnetic Storm Impact

The physical shock of the fast moving CME shakes the entire magnetosphere as it strikes (Table 5). "If the IMF ahead of a fast [interplanetary] CME already has a southward component, the shock increases it typically by a factor of 3–4" (Koskinen & Huttunen, 2006). This shock "pushes the dayside magnetopause from its nominal distance of about 10 [earth radii] inside the geostationary orbit at 6.6 [earth radii]" thus exposing GEO satellites on the daylight side of the planet directly to the solar plasma (Pulkkinen, 2007). For individual satellites exposed to ". . . hot, tenuous plasmas . . . Differential charging of spacecraft surfaces can lead to harmful discharges, which introduce noise . . . [or] cause physical damage" (Pulkkinen, 2007). Thus, additional satellite anomalies, to include loss of satellites, may be assumed for the daylight-side GEO satellite fleet, but no statistical data exists to suggest the extent of the potential damage for an event of this magnitude.

The southward magnetic orientation of the CME allows the solar plasma to perturb the magnetosphere, creating immense currents called "electrojets" in the ionosphere. These currents, which can exceed one million amps, cause scintillation—variations of amplitude, phase, polarization, and angle-of-arrival of signals—which can become "so severe that they represent a practical limitation for communication systems" (Lanzerotti, 2001). "As the signals propagate through the ionosphere, they are refracted and slowed especially when they traverse regions of intense auroral currents" (Pulkkinen, 2007). Scintillation can degrade or even prevent signals to and from satellites for 12-24 hours (W. Murtagh, personal communication, November 10, 2010).

Radio Frequency Communications

Radio Frequency (RF) communications that rely on reflection from the ionosphere (Figure 7) may also be effected by scintillation. Counter intuitively, HF communications ("short wave" in the diagram) may actually be helped during this period due to enhancement of the ionosphere F Layer that could improve reflectivity, though HF will remain spotty for 1-2 more days (W. Murtagh, personal communication, November 10, 2010). Military and emergency management agencies that use VHF or ultra-high frequency (UHF) sky wave communications could also experience severe disruption. FEMA does not use these types of communications. Ground wave HF and line-of-sight VHF, UHF, and microwave communications may experience increased noise but should otherwise operate normally.

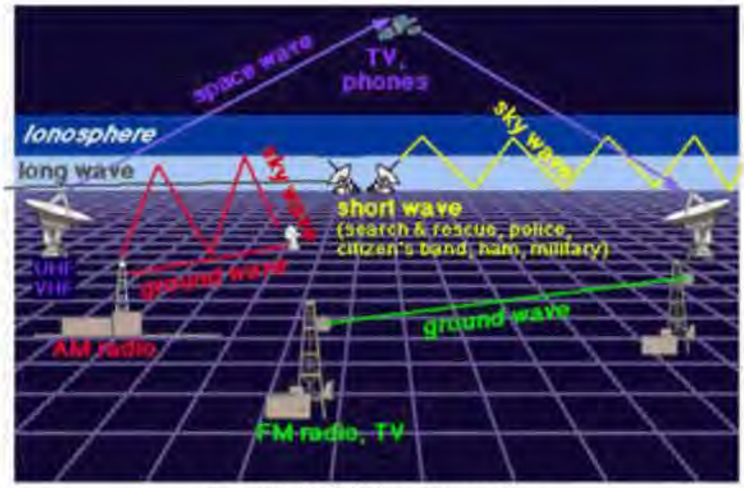


Figure 7: Radio Wave Propagation
Image courtesy of Windows to the Universe

North American Power Grid

Shocks to the magnetosphere and large voltage potential differences induced on the Earth's surface from electrojets (Figure 8) cause geomagnetically-induced currents (Lanzerotti, 2001). Geomagnetically-induced currents (GICs) are quasi-DC currents that can affect power systems at all latitudes, affect many power transformers simultaneously at multiple points across regional and continental scale networks (Thomson et al., 2010), and can reach in excess of 2000 amps (Pulkkinen, Pirjola, & Viljanen, 2008). Long-distance transmission lines, pipelines, and undersea cables typically have low resistances (NERC, 2010). Current induced in the Earth seeks the path of least resistance and enters power systems through the same ground connections that normally protect power systems from lightning or stray currents. "The US high-voltage power grid . . . extends more than 160,000 miles with approximately 12,000 major substations and nearly innumerable lower voltage distribution transformers, which can serve as potential GIC entry points from their respective ground connection" (Kappenman, 2005). A June, 2010, report by the North American Electric

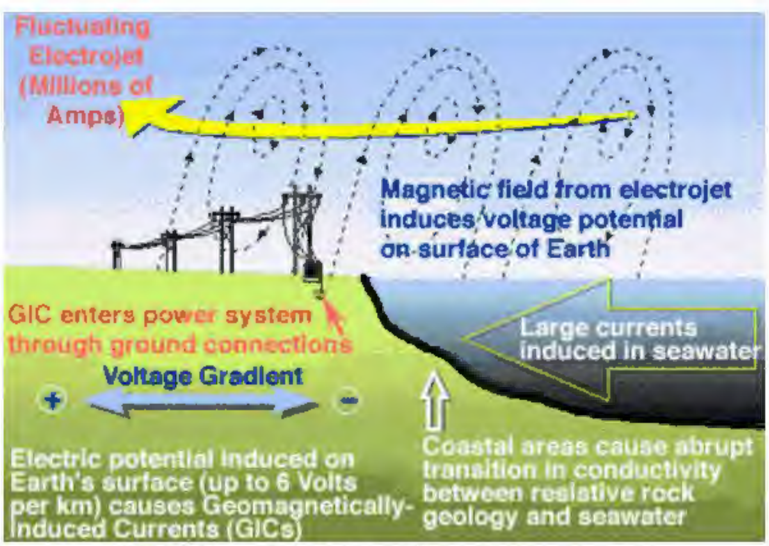


Figure 8: Geomagnetic storm effects on power systems
Image courtesy of John G. Kappenman

Reliability Corporation (NERC), in conjunction with the Department of Energy, warned that "Geomagnetic storms . . . not only can develop rapidly but also have continental footprints that can result in widespread, simultaneous impact to many points on the system. The system is not designed to operate through the simultaneous loss of many key assets. . . ." Power grids around the world rely on extra-high voltage (EHV) custom-built transformers for power transmission. In an extreme geomagnetic storm, the 2010 NERC report estimates—based on the scenario in Figure 9—that ≈350 EHV transformers in the United States "will exceed levels where the transformer is at risk of irreparable damage," collapsing large portions of the power grid. "These multi-ton apparatus generally cannot be repaired in the field, and if damaged in this manner, they need to be replaced with new units, which have manufacture lead times of 12 months or more" (National Academy of Sciences, 2008). Full recovery could take 4-10 years (National Academy of Sciences, 2008).

The actual impact on the power grid will depend on the location of the electrojet relative to North America. Figure 9 shows the projected impact on the U.S. power grid based on an electrojet at 50 degrees north latitude with the main effect over the Atlantic Coast. Figure 10 shows the same electrojet at 45 degrees north latitude. In the scenario in Figure 10, ≈600 EHV transformers could be at risk (J. Greenhill, personal communication, December 10, 2010). Neither figure accounts for cascading effects due to voltage regulation problems on the remaining portions of the power grid; therefore, the actual impacted areas will be larger than shown (Kappenman, Warner, & Radasky, 2007). Power system collapse can occur in less than one minute (NERC, 2010).

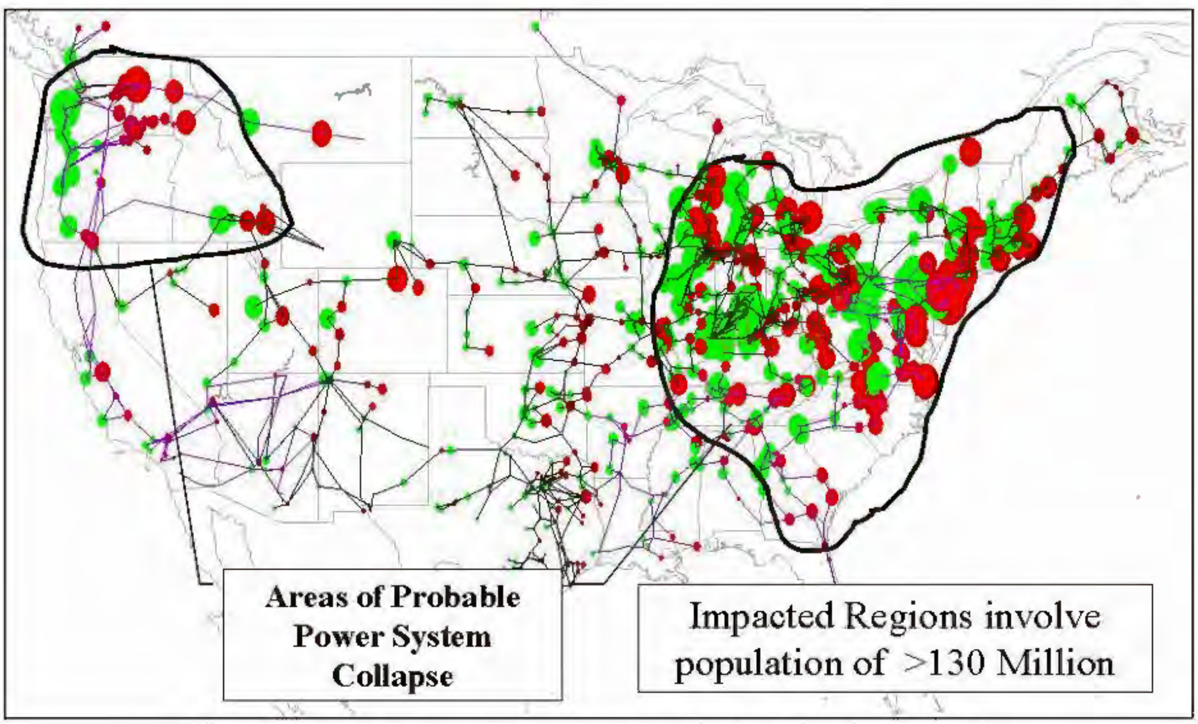


Figure 9: 100 Year Geomagnetic Storm Impact on the North American Power Grid
Electrojet at 50 degrees north latitude with main effect over Atlantic Coast
Image courtesy of NASA, Original by Metatech Corp

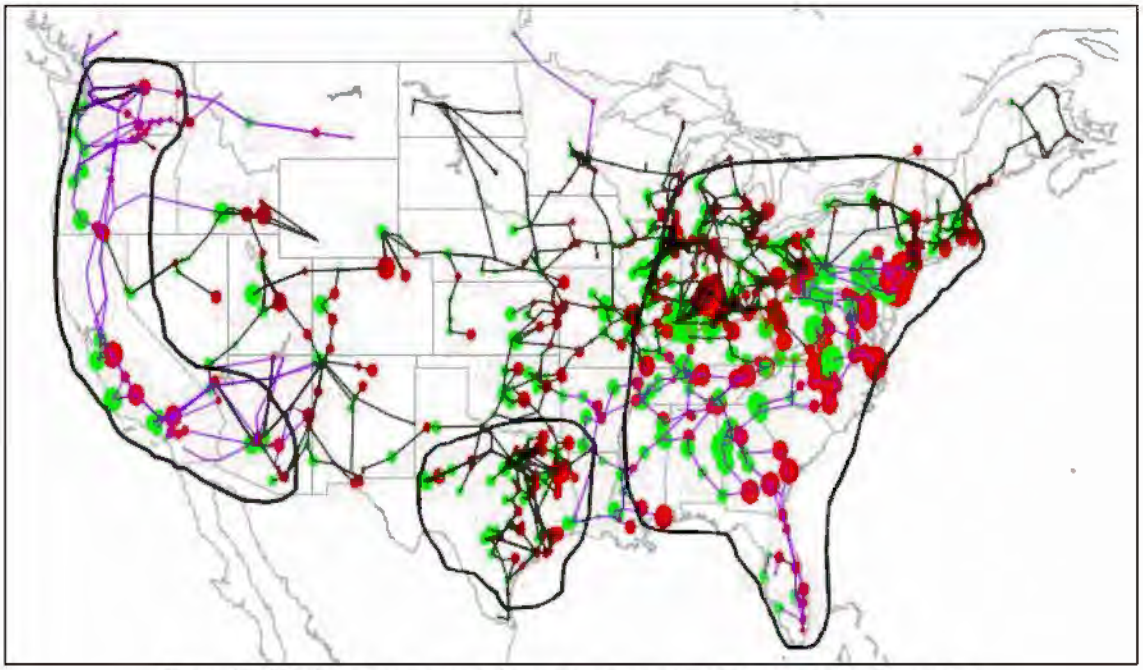


Figure 10: 100 Year Geomagnetic Storm Impact on the North American Power Grid
Electrojet at 45 degrees north latitude with main effect over Atlantic Coast
Image courtesy of Metatech Corp

Power Loss and "Last Mile" Communications

Last mile communications encompasses all connections from a telephone or cable central office—or from the communications satellite for satellite service providers—to the end user. Traditionally, homes and offices received service over a copper "Plain Old Telephone Service" (POTS) line that received power directly from the central office. Even if power was lost in the home or office, such lines and the traditional telephones attached to them would still operate. That architecture is becoming less common, especially in urban and suburban areas (Bowen & Underhill, 2010). Today, fiber and coaxial cables, which do not provide power, are used in part or all of the links from the central office to the home or office, and often pass through local distribution nodes (Table 6) that also require power (Bowen & Underhill, 2010).

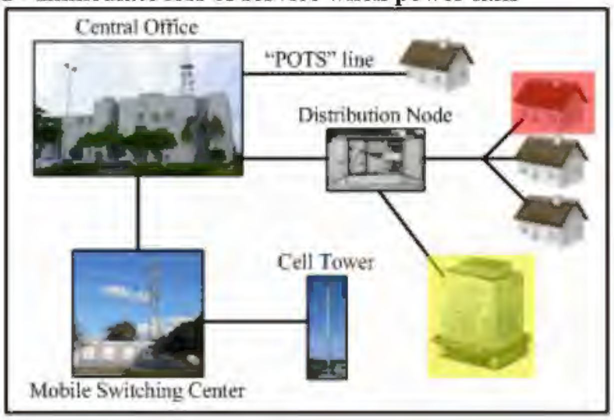
Home and office users who receive their cable, internet, and phone services from a broadband service provider must have local power available to operate wireless phones, Voice-over-Internet-Protocol (VoIP) phones, and cable or satellite phone and internet modems. Uninterruptable power supplies, if installed, can supply power for 10-45 minutes to computers and electronics. Some modems have battery power that can last from 2-8 hours. Cable and telecommunications distribution nodes generally have backup battery power for 8-24 hours (Bowen & Underhill, 2010).

Any end-user communications device or local distribution node that relies on local power will not operate once primary and backup power is lost.

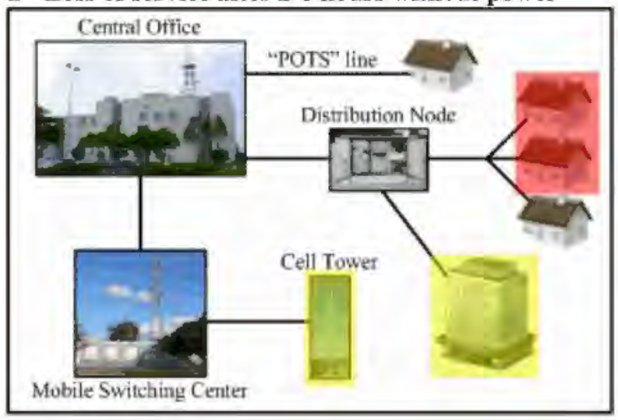
Table 6: Cascading Loss of Last Mile Telecommunications over Time

Original images by Mark MacAlester, photos courtesy of Kent Bowen, AT&T

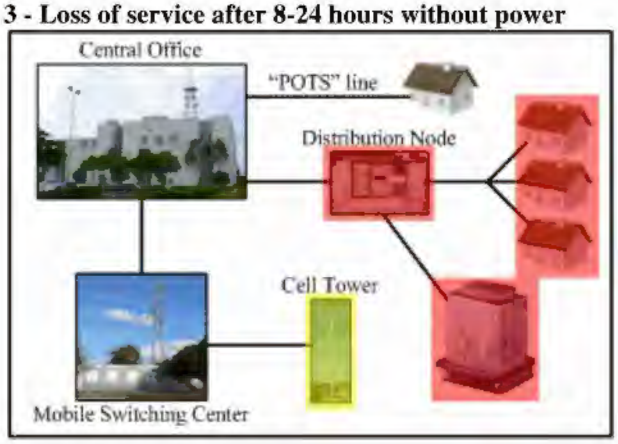
1 - Immediate loss of service when power fails



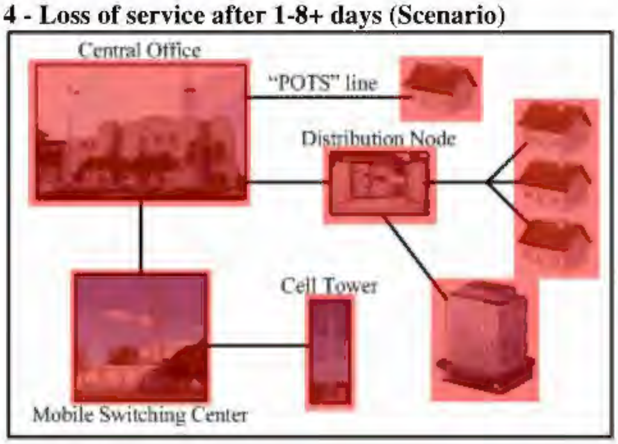
2 - Loss of service after 2-8 hours without power



3 - Loss of service after 8-24 hours without power



4 - Loss of service after 1-8+ days (Scenario)



Iridium and Globalstar Networks

As previously mentioned, low earth orbiting communications satellites may have a higher probability of surviving an extreme solar weather event and remaining operational. The two primary providers of LEO satellite voice and data services are Iridium and Globalstar.

The Iridium constellation consists of 66 LEO satellites with 6 in-orbit and 9 on-ground spare satellites (Iridium, 2010). Iridium satellites are cross-linked in orbit providing users with voice and low-bandwidth data communications from one Iridium device to another Iridium device without touching the PSN (Iridium, 2010). Users are authenticated at either the gateway in Arizona (commercial users) or Hawaii (Department of Defense). Links to the PSN allow Iridium users to connect to anyone on the PSN (Iridium, 2010).

The Globalstar constellation consists of 48 LEO satellites with 8 in-orbit spares (Crystal Communications, 2007). Current generation Globalstar satellites are "bent-pipe" repeaters without satellite cross-linking, thus voice and low-bandwidth data services rely on ground stations connected to the PSN to complete calls (Crystal Communications, 2007).

FEMA Impact

Any FEMA employee using devices that are not connected to backup power when power fails will lose service on those devices. For example, assuming the power grid collapses as shown in Figures 9 or 10, FEMA headquarters will lose commercial power. A backup generator will start that will supply power to IT network server racks, to the UHF FEMA Command and Control (C2) net radio repeater on the roof, and to the National Response Coordination Center (NRCC) on the Mezzanine Level. All other users in FEMA headquarters will immediately lose power for their VoIP desk phones and for their computers if not on battery (laptops) or backup power (UPS). This will also impact FEMA employees in their homes who rely on broadband internet and phone services.

The NRCC has backup power for approximately 12 hours. Mount Weather and the MERS Detachments have extensive backup generator power and fuel stores. FEMA Regional Offices collocated with Federal Regional Center (FRC) bunkers have backup generators and bulk fuel storage for the FRCs. FEMA Regional Offices not collocated with MERS or an FRC have varying degrees of backup generator power, fuel stores, and service to their offices.

At the outset of the power failure, FEMA employees may still have voice and data communications via cell phones, smart phones (e.g. Blackberry, etc.), and laptops on battery power using tethered smart phones or air cards. However, this event will likely cause rapid and severe congestion on the cellular infrastructure and Public Switched Network (PSN), potentially rendering voice and data services inoperable for hours or longer. Cell phones and smart phones with Wireless Priority Service (WPS) will have a greater probability of making successful voice calls in this environment, though cellular users in transit may experience dropped calls. WPS does not apply to data services. SMS texting may have a greater probability of success than voice or email. Those FEMA employees with access to POTS lines and traditional (not wireless or VoIP) telephones may still have voice connectivity, and use of Government Emergency Telecommunications Service (GETS) cards should improve their chance of completing a call.

The FEMA UHF C2 net should remain fully operational during this phase of the storm. HF communications (FNARS, MERS) may be possible during this period but should not be relied upon except as a last resort. HF ALE, which automatically seeks usable HF frequencies under changing ionospheric conditions, may prove more reliable than traditional HF voice communications.

During this phase of the storm, BGAN (Inmarsat), MSAT G2 (LightSquared), Iridium, and Globalstar L-band satellite communications may be severely disrupted due to scintillation in the ionosphere (W. Murtagh, personal communication, December 14, 2010). Higher-frequency C-band and Ku-band satellite communications (On Call Communications and iDirect) are less impacted by scintillation and may operate if satellite service is available (W. Murtagh, personal communication, December 14, 2010).

The DHS Critical Infrastructure Warning Information Network (CWIN) should also remain operational. CWIN provides a critical, survivable network that connects DHS to other Federal Departments & Agencies (to include FEMA), State Emergency Operation Centers (EOCs), and core critical infrastructure owners and operators. It does not connect to the public Internet, the PSN, or any other public or private network, but it does rely on privately-leased lines from AT&T central offices.

Severe GPS disruptions continue throughout this period and could impact FEMA's mission.

Table 7: G plus 2-24 Hours

	Trigger:
	• **Loss of power begins to effect critical systems**
	  ○ Battery backup fails in homes and facilities
	  ○ Numerous cellular towers begin to fail
	  ○ Small central offices and larger central offices without water begin to fail
	  ○ HF communications intermittent for next three days
	Image of power lines at sunrise courtesy of NASA

NOAA SWPC Action	Solar Activity Forecast: **High, 80% probability of ≥ R4 events**
Scenario	• Earth is struck by multiple R1 (minor) – R4 (strong) radio blackout events. • This scenario assumes significant loss of satellite resources
Warning Time	None
Duration	≈48-72 hours

FEMA Impact

Basic Connectivity										**Mobile/ In-Transit**		
Telephone/Fax				**Data Networks and Email**			**Video**	**Backup**				
Non-Secure Telephone	**Non-Secure Fax**	**Secure Telephone**	**Secure Fax**	**Unclassified**	**Secret**	**Top Secret/SCI**	**Top Secret/SCI VTC**	**Top Secret HF ALE**	**Top Secret Satellite Telephone**	**Top Secret Cellular Telephone**	**Top Secret Satellite Telephone**	**Top Secret UHF and/or VHF**

- BGAN, MSAT, and Ku- and C-band communications may be disrupted due to satellite service loss – (IMAT, MERS, US&R, & Emergency Management at all levels).
- Iridium and Globalstar satellite networks may have service.
- HF communications intermittent but improving (FNARS, MERS).
- FEMA UHF Command and Control radio net should remain operational.
- CWIN should remain operational.
- Severe GPS disruption could impact FEMA's mission.

The impact of the geomagnetic storm is a catastrophe in slow motion. Within the first few hours, UPS and battery backup fails in homes and offices, rendering any end-user communications devices attached to them inoperable. This can also affect the ability to charge cell phone and laptop batteries. As time progresses without power, more critical systems begin to fail (Table 7).

Telecommunications in the First 24 Hours

The terrestrial telecommunications infrastructure is heavily shielded and filtered and should not be significantly impacted by GICs (Comm ISAC, personal communication, November 8, 2010). However, the critical dependency of the telecommunications industry on power will have immediate and cascading effects that will degrade communications.

The core of the telecommunications infrastructure relies on several types of electronic switches and servers that are physically housed in facilities called "central offices." A central office (CO) may house equipment for several telecommunications service providers regardless of the owner of the building (i.e. an AT&T building may contain Verizon, Sprint, Qwest, and local carrier equipment) (Bowen & Underhill, 2010). Switches and distribution equipment can also be housed in local buildings and distribution nodes that feed service from a CO to local users (Bowen & Underhill, 2010).

A central office has filtered ventilation and air-conditioning systems to keep out dust and contaminants, and requires air conditioning to prevent overheating and failure of the critical network switches. Without air conditioning, equipment in a large CO will overheat and fail in approximately 6-8 hours, while smaller COs with less equipment should last longer (Comm ISAC, personal communication, November 8, 2010). Large air conditioning units generally cannot run on battery power and many require water for cooling, thus they require generator backup power and a source of water for chillers (Comm ISAC, personal communication, November 8, 2010).

Telecommunications service providers maintain their own, independent levels of reserve battery power, stationary and portable generators, and fuel storage in the event of power outages (NCS, personal communication, March 8, 2010). Most central offices in the U.S. have backup generators and fuel for approximately 1-9 days with larger COs generally having larger fuel stores (Comm ISAC, personal communication, November 8, 2010). A very small number of smaller central offices do not have generator backup power.

Approximately 60% of the cellular towers in the U.S. have battery backup only for 2-24 hours. As these towers lose power, large portions of the cellular network will begin to fail. Urban and populated suburban areas are more likely to have cell towers with generator backup with fuel reserves ranging from 1-7 days, depending on location and equipment owner.

FEMA Impact

All FEMA employees, partner agencies, and customers will lose communications from any end-user device not connected to generator or other long-term backup power (i.e. solar, wind, etc.)

within the first 24 hours following the collapse of the power grid. Individuals without long-term backup power will not be able to recharge pbones or portable computers.

Cellular networks will be impacted as backup power (battery and small generator) at cell towers fails. Without refueling and/or backup generators or alternative power sources, all cell towers will eventually fail. Availability of power for tower equipment will also impact public safety radio for the same reasons. Additionally, increased call traffic on shrinking cell tower footprints may increase congestion and call blocking, making the use of WPS and GETS even more critical for voice calls (Comm ISAC, personal communication, December 13, 2010).

Failure of smaller central offices or remote switches may effect some FEMA employees, especially in rural areas, but should not have a significant impact on FEMA's overall operations. Shutdown of larger central offices due to lack of power or water for A/C units could impact the PSN on a national or regional basis, but rerouting of network traffic by commercial providers should minimize or localize this impact (Comm ISAC, personal communication, November 8, 2010).

CWIN should remain operational during this period provided end users have power for their last mile communications.

HF communications will continue to suffer periods of radio blackout for the next few days, but conditions for HF voice and HF ALE should steadily improve. FEMA's nationwide C2 UHF radio network relies on the PSN and may be effected by the network degradation and loss of service previously mentioned. Local area HF ground wave, VHF, UHF, and microwave line-of-sight will be operable during this period provided power is available.

FEMA primarily relies on Iridium for LEO satellite non-secure and secure voice communications as the Iridium network is considered more robust. The current Iridium satellite constellation is aging and the impact of this scenario on the network is unknown. Iridium currently has 6 in-orhit spares, and predictions of lower radiation exposure and fewer anomalies at LEO suggest the Iridium constellation should remain available. As ionospheric scintillation decreases, non-secure and secure Iridium-to-Iridium voice calls should be possible. Iridium-to-PSN calls will be subject to the status of the PSN at the time of the call attempt.

GEO communications satellite services may experience significant degradation and loss, but the satellite services that FEMA uses may still be available or may become available as ground controllers correct or mitigate satellite damage. Satellite services should be tested at the earliest opportunity and regularly after that to determine availability. MERS has the capability to make VSAT-to-VSAT calls independent of the PSN.

Table 8: G plus 8 Days and Beyond

<table>
<tr><td></td><td colspan="13">Trigger:
• Extended loss of power and breakdown of distribution systems
o Widespread failure of central offices, loss of PSN
o Widespread failure of operations centers
o Cascading effects throughout critical infrastructure</td></tr>
<tr><td>NOAA SWPC Action</td><td colspan="13">None</td></tr>
<tr><td>Scenario</td><td colspan="13">Concluded</td></tr>
<tr><td>Warning Time</td><td colspan="13">N/A</td></tr>
<tr><td>Duration</td><td colspan="13">N/A</td></tr>
<tr><td colspan="14">FEMA Impact</td></tr>
<tr><td colspan="11">Basic Connectivity</td><td colspan="3" rowspan="2">Mobile/ In-Transit</td></tr>
<tr><td colspan="4">Telephone/Fax</td><td colspan="3">Data Networks and Email</td><td colspan="2">Video</td><td colspan="2">Backup</td></tr>
<tr><td>Non-Secure Telephone</td><td>Non-Secure Fax</td><td>Secure Telephone</td><td>Secure Fax</td><td>Unclassified</td><td>Secret</td><td>Top Secret/SCI</td><td colspan="2">Top Secret/SCI VTC</td><td>Top Secret HF ALE</td><td>Top Secret Satellite Telephone</td><td>Top Secret Cellular Telephone</td><td>Top Secret Satellite Telephone</td><td>Top Secret UHF and/or VHF</td></tr>
<tr><td colspan="14">• Loss of the PSN severely impacts satellite communications unless ground-based network control stations can be supported – (IMAT, MERS, US&R, & Emergency Management at all levels).
• HF communications operable if power available (FNARS, MERS).
• Local UHF, VHF, and microwave line-of-sight links operable if power available (MERS).
• Portions of FEMA UHF Command and Control radio net may remain operational (MERS).
• Iridium satellite network may provide in-system calls if power available and gateways operational.
• Severe GPS disruption could impact FEMA's mission.</td></tr>
</table>

Most critical infrastructure and operations centers can operate for approximately 3-7 days on generator backup without refueling, with larger centers averaging 7 days. Government and private sector emergency managers operate on the assumption that fuel contracts and pre-arranged fuel deliveries will be available after 7 days. This may not be a safe assumption in an extreme solar weather event.

"Loss of key infrastructure for extended periods due to the cascading effects from a space weather event (or other disturbance) could lead to a lack of food, given low inventories and reliance on just-in-time delivery, loss of basic transportation, inability to pump fuel, and loss of refrigeration" (National Academy of Sciences, 2008). Cascading losses throughout the complex and highly interdependent technological systems that our society relies on for food, water, fuel, billing, contracting, and transportation may become unreliable or breakdown completely. Without resupply, the infrastructure that supports the PSN will eventually fail. Further, operations centers that support satellite operations will also fail without resupply. Finally, while not within the scope of this white paper, family and societal pressure could impact the availability of personnel to maintain critical systems.

FEMA Impact

Loss of the PSN will have severe consequences for FEMA C3 and critical communications to external partners and customers. Even if power is available to FEMA—and eventually DHS—data centers, it may not be possible for users to connect, rendering FEMA and DHS computer networks unavailable. If satellite services are lost in conjunction with loss of the PSN, no path of sufficient bandwidth will remain to maintain the viability of FEMA's IT enterprise network across the nation.

CWIN relies on the same central offices that support the PSN, thus loss of central offices would also result in loss of CWIN.

Landline and cellular wireless voice and data services will not be available. Broadband internet services will not be available.

Iridium and other satellite providers will lose operations centers if not resupplied, resulting in the eventual loss of satellite communications through loss of data centers and ground control stations.

In the worst-case scenario, the following systems will be usable if local power is available:

- HF and HF ALE for voice and low-bandwidth non-secure and secure nationwide communications (MERS, FNARS).
- Local VHF, UHF, and microwave line-of-sight voice communications (5-80 miles depending on system and setup) (MERS).

Assessing the Risk

While this scenario presents the "worst case" scenario based on the Carrington-Hodgson superstorm of September 1-2, 1859, it is not the "maximum of maximums" in the truest sense. Scientific literature and research has focused on the September 1-2 storm, the largest in the last 500 years, but what is often missed is the superstorm four days earlier on August 28-29. The 1859 event actually consisted of two perfect storms separated by four days. This is logical. It takes approximately 14 days for a large, complex sunspot group to traverse the visible disk of the sun. During that time, multiple flares and coronal mass ejections can occur. The damage from multiple storms could be far worse than the damage from a single storm.

How often do these events occur? According to the NOAA SWPC, there are on average 4 G5 geomagnetic storms per solar cycle. The 1859 Carrington-Hodgson event is the strongest on record in the approximately 500 years of data that is available. Anecdotal observational records of low-latitude red aurora hint that the largest events may occur roughly every 500-600 years (Silverman, 2005). However, events strong enough to severely impact modern systems may occur as frequently as once in 100 years (Kappenman et al., 2007). Indeed two storms, 1859 and 1921, were of sufficient strength that their repeat today could cause large-scale power grid collapse. Further, the March 13, 1989 storm that collapsed the Hydro Quebec power grid in Canada came within seconds of collapsing the Northeast and northern Midwest U.S. power grid (Kappenman, 2005). Kappenman (2005) reports that "the size and intensity of this Westward Electrojet structure, had it developed 5–7 h later, would have extended from east coast to west coast of the entire northern-latitude portions of the US power grid, and is likely to have produced much more significant consequential impacts. . . ." It should be noted that the power grid, due to deregulation since 1989, is actually more vulnerable today (National Academy of Sciences, 2008).

The next solar maximum will occur in 2013 and is expected to be the smallest cycle maximum since the 1930s (SWPC, personal communication, December 13, 2010). The largest solar superstorms have occurred in less active solar cycles, though less active cycles do not imply greater storms. The GPS fleet of satellites will be at its most vulnerable between 2012 and 2014 (assuming no further slips in the program schedule). The threat is real.

Recommendations

FEMA, in conjunction with the NOAA SWPC, has already taken the first step toward preparing for a solar superstorm. In 2010, FEMA adopted a solar alert and warning system for FEMA's network of operations, watch, and coordination centers using threat specific notification protocols and plain language messaging. As presented in the scenario, FEMA's current redundant and resilient means and mode of communications should allow for a minimum of non-secure and secure voice and low-bandwidth data communications during all phases of an extreme solar weather event. Large bandwidth data and VTC capabilities may be compromised depending on the exact incident scenario. FEMA can take steps to mitigate these risks:

Terrestrial Broadband (T-1 equivalent):

Course of Action (COA) 1: Build a survivable fiber optic network between FEMA headquarters, Mount Weather, 6 MERS Detachments, and "non-hosted" FEMA Regional Offices.

Advantages	Most Survivable
	FEMA owned and operated
	T-1 or better bandwidth
Disadvantages	Cost to build (≈ \$100,000 per mile) ≈ \$1 Billion
	Cost to operate and maintain (not scoped)
	Years to build

COA 2: Lease a survivable fiber optic network between FEMA headquarters, Mount Weather, 6 MERS Detachments, and "non-hosted" FEMA Regional Offices.

Advantages	Less expensive than building (≈ $1,200 per mile)
	FEMA owned and operated
	T-1 or better bandwidth
Disadvantages	CWIN already provides this capability; FEMA has access to CWIN
	Cost to operate and maintain (not scoped)
	Relies on PSN infrastructure

COA 3: Use CWIN which already has a presence at FEMA headquarters, Mount Weather, and 6 MERS Detachments. **(Recommended)**

Advantages	Least expensive option; FEMA already has access
	Resilient and redundant network includes State EOCs
	T-1 bandwidth
Disadvantages	DHS could cancel program in any given budget year
	Proprietary network (no connection to FEMA, DHS, or other networks)
	Relies on PSN infrastructure

Note: It would be possible to obtain all key node locations that support CWIN network and potentially determine key node long-term support and resupply requirements.

Satellite Communications (GEO):

COA 1: Maintain current exclusive contract with On Call Communications.

Advantages	Existing contract and relationship
	Bandwidth on request
	T-1 bandwidth
Disadvantages	Greatest risk due to no diversity of service provider
	Access to fewer GEO satellites
	Ground stations rely on PSN for FEMA.net connectivity

COA 2: Let contracts with multiple commercial providers. **(Recommended)**

Advantages	Greater diversity of providers
	Access to larger number of GEO satellites
	Leverage market forces to reduce on-demand costs
Disadvantages	Potentially more expensive
	No guarantee that any service will operate
	May need to provide support post-event to multiple vendor sites

Note: MERS already uses iDirect as a secondary vendor to provide "dirty" internet. It may also be possible to partner with DoD.

Satellite Communications (GPS Navigation):

COA 1: Maintain status quo (single-frequency GPS receivers).

Advantages	Least expensive
	No change in procurement requirements
	GPS important but not essential to FEMA's mission
Disadvantages	Greater chance for interference during normal space weather
	Greater likelihood of position errors during normal space weather

COA 2: Purchase dual-frequency GPS receivers. **(Recommended)**

Advantages	Less susceptible to interference
	More accurate position data
Disadvantages	More expensive
	Severe solar storm will have same impact as to single-frequency rcv'r
	No advantage if significant loss to GPS network

Satellite Communications (LEO):

COA 1: Maintain current use of Iridium phones. **(Recommended)**

Advantages	More robust and survivable network
	Non-secure and secure voice
	In-network calls do not require PSN
	Only two facilities would require support (Arizona and Hawaii)
	Next generation network will have high-speed data
Disadvantages	Next generation network not until 2015
	Single service provider
	Current satellites aging and may be susceptible to severe space weather

COA 2: Add Globalstar phone to inventory.

Advantages	Multiple vendors
	Next generation will have high-speed data
Disadvantages	Relies on ground stations and PSN to connect calls
	Not global coverage
	Satellites more vulnerable to space weather

HF Communications:

COA 1: Maintain status quo for FNARS and MERS

Advantages	Least expensive option
	Existing equipment and locations with connectivity to state EOCs
	Non-secure and secure voice and low-bandwidth data
Disadvantages	FNARS current state does not provide nationwide coverage
	No long-term maintenance program
	Lack of trained operators

COA 2: Reinvigorate the FNARS program and MERS HF through equipment upgrades, long-term maintenance program, radio operation procedures, and operator training **(Recommended)**

Advantages	Existing equipment and locations with connectivity to state EOCs
	Non-secure and secure voice and low-bandwidth data
	Maintenance program will significantly improve system availability
	Procedures and personnel training will improve system operations
Disadvantages	Funding is required for antenna repairs and/or upgrades
	FNARS long-term maintenance program not currently budgeted
	No procedures or training exist for non-technical personnel

COA 3: Establish 24/7/365 FNARS network control center **(Recommended)**

Advantages	Provide continuous HF operability and availability under all conditions
	Regular HF operations with other federal and state HF networks
	Will create a cadre of skilled HF operators
Disadvantages	Programmatic funding required (not budgeted)
	Dedicated personnel required (could use existing operation center)
	Development of doctrine, policies, procedures, and training required

Conclusion

A repeat of the 1859 Carrington-Hodgson event could be catastrophic, but FEMA can maintain some measure of command, control, and communications during and after the event with existing capabilities. Those capabilities could also be extended to partner agencies and customers with similar capabilities, which is especially true for HF voice communications. The recommendations presented above, if adopted, would improve FEMA's C3 survivability, particularly in the area of data communications.

Every FEMA employee will be affected. Knowing what communications systems will work or may work at different phases of an extreme solar weather event, and the order and progression of cascading effects will serve as a guide for planning efforts, education, and outreach within FEMA and to partner agencies.

Acknowledgements

The author would like to thank William ("Bill") Murtagh, the Program Coordinator for NOAA's Space Weather Prediction Center in Boulder, CO, and his staff for their assistance with space weather physics and effects on communications, and especially for the scenario timeline used in this paper. The author would also like to thank the members of the Communications Infrastructure Information Sharing and Analysis Center (Comm ISAC), the Federal Communications Commission (FCC), and Kevin Briggs of the National Communications System (NCS) for their assistance in understanding the effects of extreme solar weather on the telecommunications industry. Finally, the author is indebted to the communications technicians of FEMA's own Mobile Emergency Response Support (MERS) Detachment in Denver, CO, for understanding the challenges and potential solutions for HF and satellite communications.

APPENDIX A

NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
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; (number of storm days)
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 (see www.sec.noaa.gov/Aurora)

Scale	Descriptor	Effect	Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
Solar Radiation Storms				
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: 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.
*** High energy particle measurements (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

Scale	Descriptor	Effect	GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
Radio Blackouts				
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 ($2x10^{-3}$)	Fewer 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 ($5x10^{-5}$)	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·m^{-2}. Based on this measure, but other physical measures are also considered.
** Other frequencies may also be affected by these conditions.

URL: www.sec.noaa.gov/NOAAscales

March 1, 2005

APPENDIX B

Summary of Solar Weather Impact on Current FEMA Communications

NCS Directive 3-10 Minimum Requirements for Continuity Communications Capabilities			Current (15 DEC 2010)	-4 to -1 Days	-17 Hours	-16 Hours 40 Minutes	0 Hour	+24 Hours	+8 Days
Basic Connectivity	Telephone/Fax	Non-Secure Telephone	Green	Green	Green	Green	Yellow	Yellow	Red
		Non-Secure Fax	Green	Green	Green	Green	Yellow	Yellow	Red
		Secure Telephone	Green	Green	Green	Green	Yellow	Yellow	Red
		Secure Fax	Green	Green	Green	Green	Yellow	Yellow	Red
	Data Networks and Email	Unclassified	Green	Green	Green	Green	Yellow	Yellow	Red
		Secret	Green	Green	Green	Green	Yellow	Yellow	Red
		Top Secret/SCI	Green	Green	Green	Green	Yellow	Yellow	Red
	Video	Top Secret/SCI VTC	Green	Green	Green	Green	Yellow	Yellow	Red
	Backup	Top Secret HF ALE	Yellow	Yellow	Red	Red	Yellow	Yellow	Yellow
		Top Secret Satellite Telephone	Green	Green	Green	Yellow	Yellow	Yellow	Yellow
Mobile/ In-Transit		Top Secret Cellular Telephone	Green	Green	Green	Yellow	Yellow	Red	Red
		Top Secret Satellite Telephone	Green	Green	Green	Yellow	Yellow	Yellow	Yellow
		Top Secret UHF and/or VHF	Green	Green	Green	Green	Green	Green	Yellow
FEMA Communications Systems									
Satellite	GEO	VSAT (Ku-band and C-band)	Green	Green	Green	Yellow	Yellow	Yellow	Red
		BGAN	Green	Green	Green	Yellow	Yellow	Yellow	Red
		MSAT G2	Green	Green	Green	Yellow	Yellow	Yellow	Red
	MEO	GPS	Green	Green	Green	Yellow	Yellow	Yellow	Yellow
	LEO	Iridium	Green	Green	Green	Yellow	Yellow	Yellow	Yellow
		Globalstar	Green	Green	Green	Yellow	Yellow	Yellow	Red
Radio	HF	FNARS	Yellow	Yellow	Red	Red	Yellow	Yellow	Yellow
		Mobile HF	Green	Green	Red	Red	Yellow	Yellow	Green
	VHF	Handhelds & Repeaters	Green	Green	Green	Green	Green	Green	Green
	UHF	FEMA C2 Net	Green	Green	Green	Green	Green	Yellow	Yellow
		Handhelds & Repeaters	Green	Green	Green	Green	Green	Green	Green
	Microwave	Mobile LOS Systems	Green	Green	Green	Green	Green	Green	Green
Cellular		Phones (various)	Green	Green	Green	Yellow	Yellow	Yellow	Red
Land Line	Phones	VoIP, STE	Green	Green	Green	Green	Yellow	Yellow	Red
	IT Enterprise	Wide Area Network	Green	Green	Green	Green	Yellow	Yellow	Red
	CWIN	CWIN Terminals	Green	Green	Green	Green	Yellow	Yellow	Red

References

Bell, T. & Phillips, T. (2008, May 6). *A super solar flare*. Retrieved from http://science.nasa.gov/headlines/y2008/06may_carringtonflare.htm

Boteler, D. H. (2006). The super storms of August/September 1859 and their effects on the telegraph system. *Advances in Space Research, (38)*2, 159-172. doi:10.1016/j.asr.2006.01.013

Bowen, K. D. & Underhill, H.W. (2010, December). The last mile. In Chatry, P. (Chair), *ESF-2 training conference*. Breakout session conducted at the National Communications System Winter Workshop, Washington, D.C.

Carrington, R. C. (1860). Description of a singular appearance seen in the sun on September 1, 1859. *Royal Astronomical Society, 20,* 13-15. Retrieved from http://www-spof.gsfc.nasa.gov/Education/whcarr.html

Cliver, E. W. (2006). The 1859 space weather event: Then and now. *Advances in Space Research, (38)*2, 119-129. doi:10.1016/j.asr.2005.07.077

Crystal Communications. (2007). *About Globalstar*. Retrieved from http://www.crystalcommunications.net/satellite/globalstar/about_globalstar.htm

Gaunt, C. T., & Coetzee, G. (2007, July). Transformer failures in regions incorrectly considered to have low GIC-risk. *Power Tech, 2007 IEEE Lausanne*, 807-812. doi:10.1109/PCT.2007.4538419

Government Accountability Office. (2010, September). *Global positioning system: Challenges in sustaining and upgrading capabilities persist*. Retrieved from http://www.gao.gov/new.items/d10636.pdf

Green, J. L., & Boardsen, S. (2006). Duration and extent of the great auroral storm of 1859. *Advances in Space Research, (38)*2, 130-135. doi:10.1016/j.asr.2005.08.054

Green, J. L., Boardsen, S., Odenwald, S., Humble, J., & Pazamicka, K. A. (2006). Eyewitness reports of the great auroral storm of 1859. *Advances in Space Research, (38)*2, 145-154. doi:10.1016/j.asr.2005.12.021

Grubesic, T. H., & Murray, A. T. (2006). Vital nodes, interconnected infrastructures, and the geographies of network survivability. *Annals of the Association of American Geographers, 96*(1), 64-83. doi:10.1111/j.1467-8306.2006.00499.x

Humble, J. E. (2006). The solar events of August/September 1859 – Surviving Australian observations. *Advances in Space Research, (38)*2, 155-158. doi:10.1016/j.asr.2005.08.053

Iridium. (2010). *Iridium Next satellite constellation*. Retrieved from http://www.iridium.com/solutions/library/Brochures.aspx

Kappenman, J. G. (2005). Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921. *Advances in Space Research, (38)*2, 188-199. doi:10.1016/j.asr.2005.08.055

Kappenman, J. G., Warner, P., & Radasky, W.A. (2007). *An assessment of the threat potential to the US electric power grids from extreme space weather storms – analysis of the US power system impacts from large geomagnetic storm events*. Report prepared by Metatech Corp. for contract HSFEMW-06-0302.

Kos, T., Botinčan, M., & Dlesk, A. (2009). Mitigating GNSS positioning errors due to atmospheric signal delays. *Pomorstvo / Journal of Maritime Studies, 23*(2), 495-513. Retrieved from Academic Search Complete database.

Koskinen, H. E., & Huttunen, K. E. (2006). Geoeffectivity of coronal mass ejections. *Space Science Reviews, 124*(1-4), 169-181. doi:10.1007/s11214-006-9103-0

Lanzerotti, L. J. (2001). *Space weather effects on communications*. Retrieved from http://128.235.88.54/preprints/lanzerotti1284.pdf

North American Electric Reliability Corporation. (2010, June). *High-impact, low-frequency event risk to the North American bulk power system*. Retrieved from http://www.nerc.com/files/HILF.pdf

National Academy of Sciences. (2008). *Severe space weather events--understanding societal and economic impacts: A workshop report*. Retrieved from http://www.nap.edu/catalog.php?record_id=12507#toc

National Aeronautics and Space Administration. (2008). *Advanced Composition Explorer (ACE)*. Retrieved from http://www.srl.caltech.edu/ACE/ace_mission.html

National Aeronautics and Space Administration. (2003, October 23). *Solar superstorm*. Retrieved from http://science.nasa.gov/headlines/y2003/23oct_superstorm.htm

National Oceanographic and Atmospheric Administration. (2010). *A primer on space weather*. Retrieved from http://www.swpc.noaa.gov/primer/primer.html

National Oceanographic and Atmospheric Administration. (2005, March 1). *NOAA space weather scales*. Retrieved from http://www.swpc.noaa.gov/NOAAscales/

Odenwald, S., Green, J., & Taylor, W. (2005). Forecasting the impact of an 1859-calibre superstorm on satellite resources. *Advances in Space Research, (38)*2, 280-297. doi:10.1016/j.asr.2005.10.046

Pireau, S., Defraigne, P., Wauters, L., Bergeot, N., Baire, Q, & Bruyninx, C. (2009). Influence of ionospheric perturbations in GPS time and frequency transfer. *Advances in Space Research, (45)*9, 1101-1112. doi:10.1016/j.asr.2009.07.011

Pirjola, R. (2002). Fundamentals about the flow of geomagnetically induced currents in a power system applicable to estimating space weather risks and designing remedies. *Journal of Atmospheric and Solar-Terrestrial Physics, (64)*18, 1967-1972. doi:10.1016/S1364-6826(02)00228-6

Pulkkinen, T. (2007). Space weather: Terrestrial perspective. *Living Reviews in Solar Physics, 4*(1), 1-60. Retrieved from Academic Search Complete database.

Pulkkinen, A., Pirjola, R., & Viljanen, A. (2008). Statistics of extreme geomagnetically induced current events. *Space Weather, (6)*. doi:10.1029/2008SW000388

Silverman, S. M. (2005). Low latitude auroras prior to 1200 C.E. and Ezekiel's vision. *Advances in Space Research, (38)*2, 200-208. doi:10.1016/j.asr.2005.03.158

Silverman, S. M., & Cliver, E. W. (2001). Low-latitude auroras: The magnetic storm of 14–15 May 1921. *Journal of Atmospheric and Solar-Terrestrial Physics, 63*(5), 523-535. doi:10.1016/S1364-6826(00)00174-7

The New York Times. (1921a, May 17). *Cables damaged by sunspot aurora*. Retrieved from http://query.nytimes.com/mem/archive-free/pdf?res=9407E2D61E3FEE3ABC4F52DFB366838A639EDE

The New York Times. (1921b, May 17). *Electric disturbances affect French wires*. Retrieved from http://query.nytimes.com/mem/archive-free/pdf?res=FB0A14FE345B1B7A93CAA8178ED85F458285F9

Thomson, A. W. P., Gaunt, C. T., Cilliers, P., Wild, J. A., Opperman, B., McKinnell, L.-A., Kotze, P., Ngwira, C. M., & Lotz, S. I. (2010). Present day challenges in understanding the geomagnetic hazard to national power grids. *Advances in Space Research, (45)9*, 1182-1190. doi:10.1016/j.asr.2009.11.023

Tulunay, Y. K., & Bradley, P. A. (2004). The impact of space weather on communication. *Annals Of Geophysics, 47*(2-3 Sup.). Retrieved from http://www.annalsofgeophysics.eu/index.php/annals/article/view/3279/3325

United States Naval Observatory. (2010). *Block II satellite information*. Retrieved from ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt

Welling, D. (2010). The long-term effects of space weather on satellite operations. *Annales Geophysicae (09927689)*, *28*(6), 1361-1367. doi:10.5194/angeo-28-1361-2010

UNIT 4A:

SPACE WEATHER

RESOURCES

- **Space Weather Prediction Center (SWPC)**
  - ➩ **http://www.swpc.noaa.gov/**
- **SWPC Space Weather 3-Day Forecast**
  - ➩ **http://www.swpc.noaa.gov/ftpdir/latest/three_day_forecast.txt**
- **SWPC Space Weather Scales for Geomagnetic Storms, Solar Radiation Storms and Radio Blackouts**
  - ➩ **http://www.swpc.noaa.gov/NOAAscales/index.html**
- **SWPC Space Weather Forecast Discussion**
  - ➩ **http://www.swpc.noaa.gov/ftpdir/latest/forecast_discussion.txt**
- **Free Aviation Space Weather Training Module**
  - ➩ **http://www.meted.ucar.edu/spaceweather/aviation_space_wx_navmenu.php**
- **NASA Solar and Heliospheric Observatory (SOHO)**

KEY TERMS

Sunspots: Dark spots that are transient and contains concentrated magnetic fields that form and dissipate over days or weeks

Solar Cycle: A 11-year period between maxima (or minima) of solar activity

Solar Flare: Intense, temporary release of energy from the Sun equivalent to a hundred million hydrogen bombs.

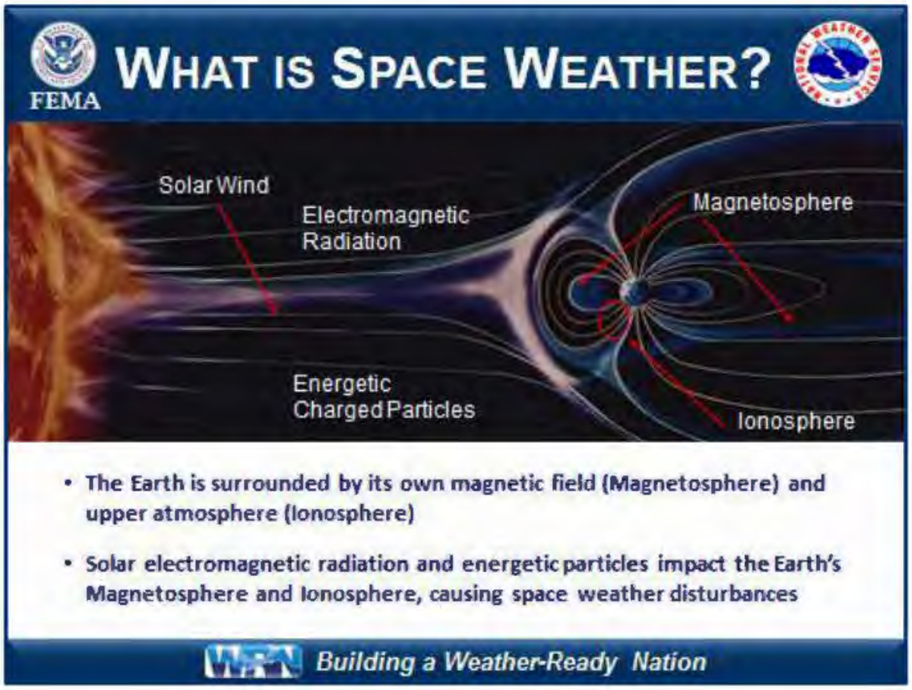
Geomagnetic Storm: Gust in the solar wind, such as a Coronal Mass Ejection (CME)

Coronal Mass Ejection (CME): A powerful geomagnetic storm that sends a huge mass of plasma (protons, neutrons) toward the Earth.

OBJECTIVES

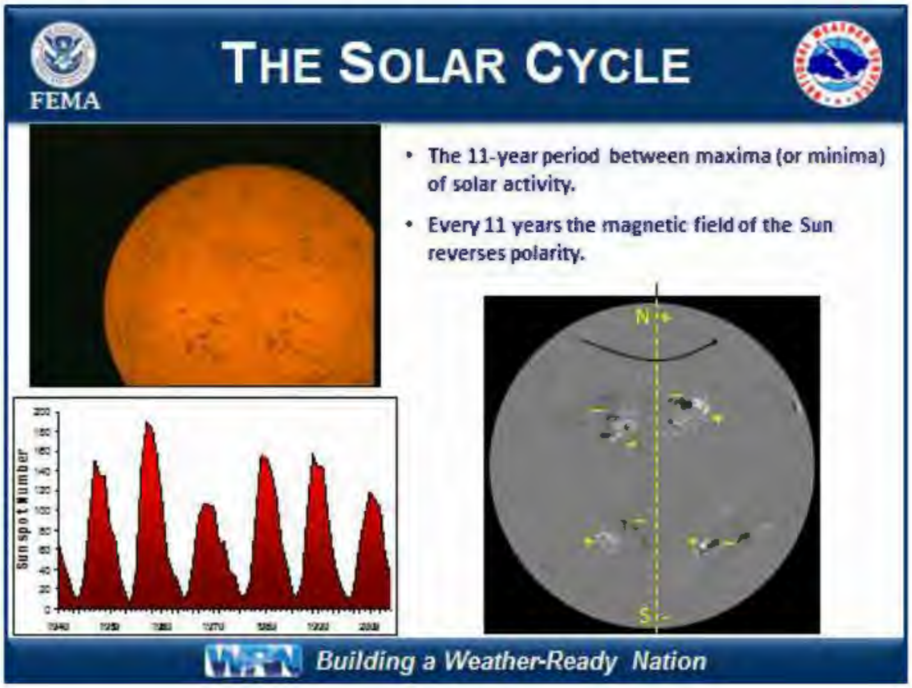
- Define Space Weather and associated hazards
- Gain knowledge of terminology
- Gain knowledge of storm types and associated measuring scales
- Locate resources and relevant information and forecasts
- Analyze and interpret information and assess threats and impacts

NOTES



KEY POINTS

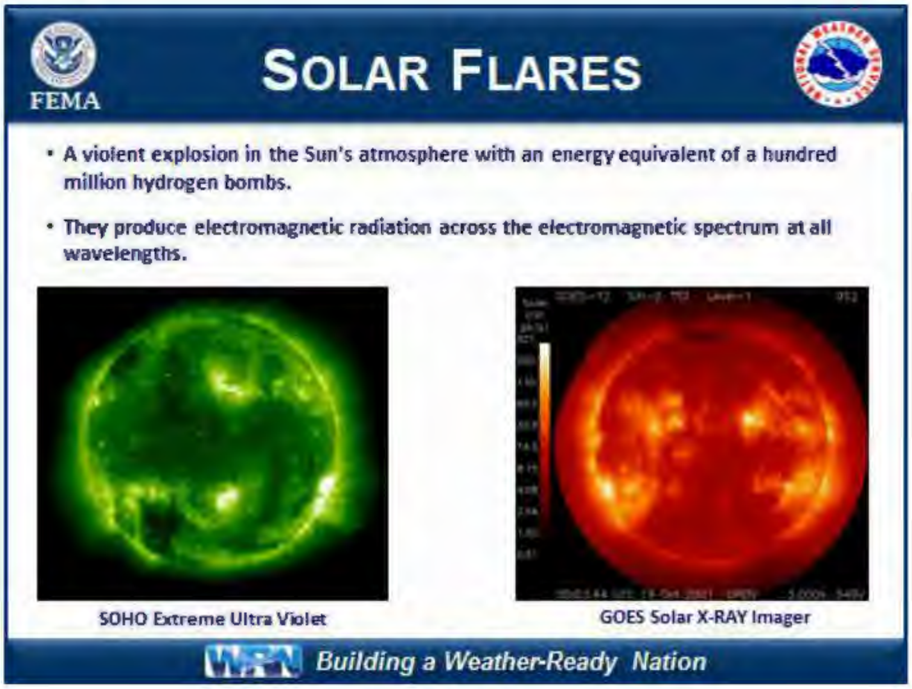
NOTES



KEY POINTS

- **Sunspots are the most prominent visible feature on the Sun. It takes about 27 days for a sunspot to rotate around the Sun's surface.**
- **Groups of sunspots are often the site of solar flares, though not all sunspots produce solar flares.**
- **The darkest area at the center of the sunspot is called the umbra and the less-dark, striated area around the umbra is called the penumbra.**

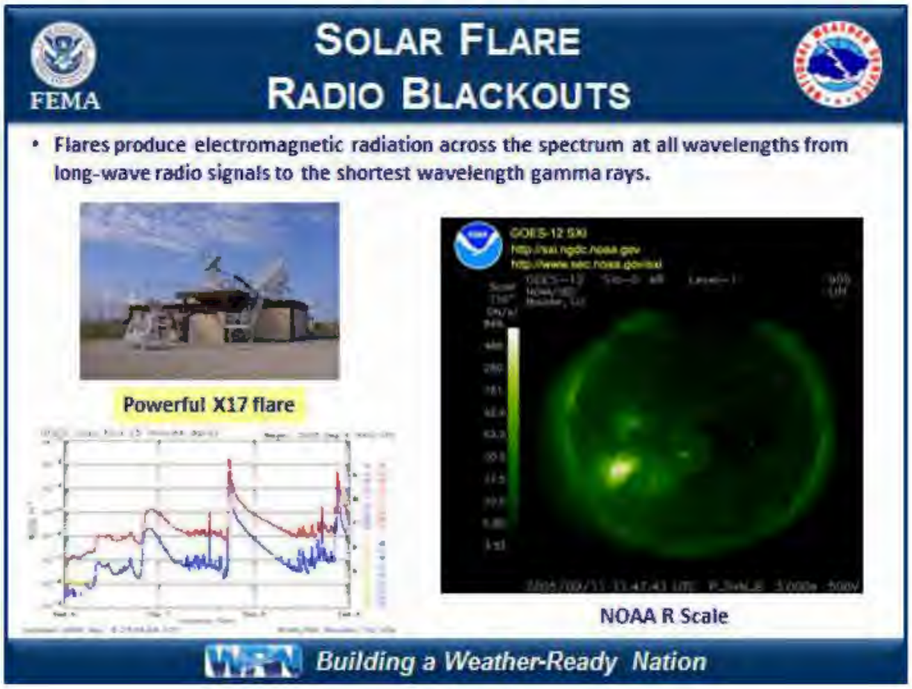
NOTES



KEY POINTS

- **Solar flares are temporary releases of energy that are generally accompanied by sunspots.**
- **Over the past 300 years, the average number of sunspots has regularly waxed and waned in an 11-year solar cycle.**
- **The Sun is the source of all the Earth's energy and correlations can be drawn between sunspot records and the Earth's climate.**

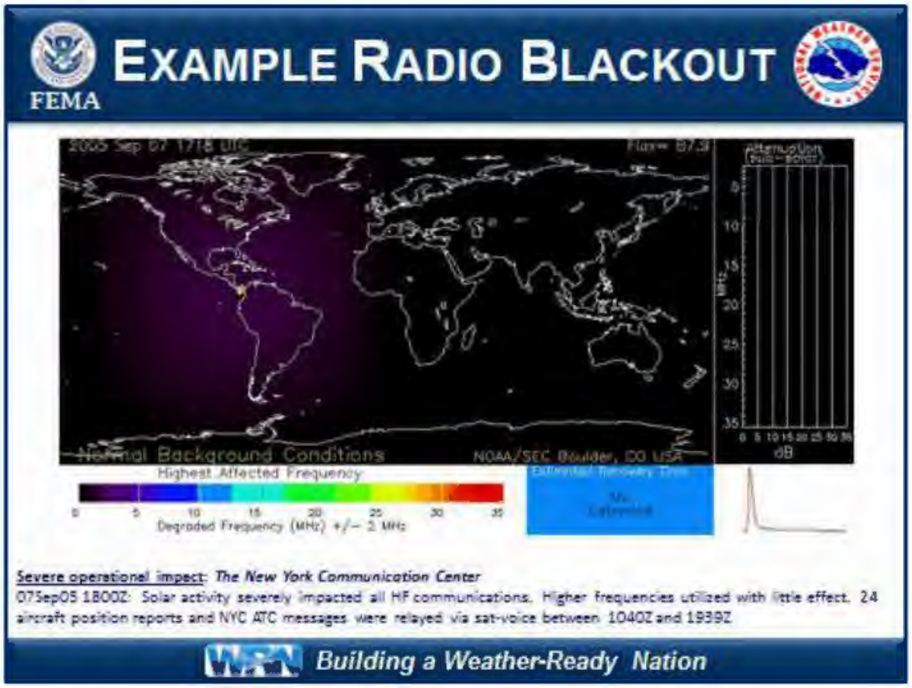
NOTES



KEY POINTS

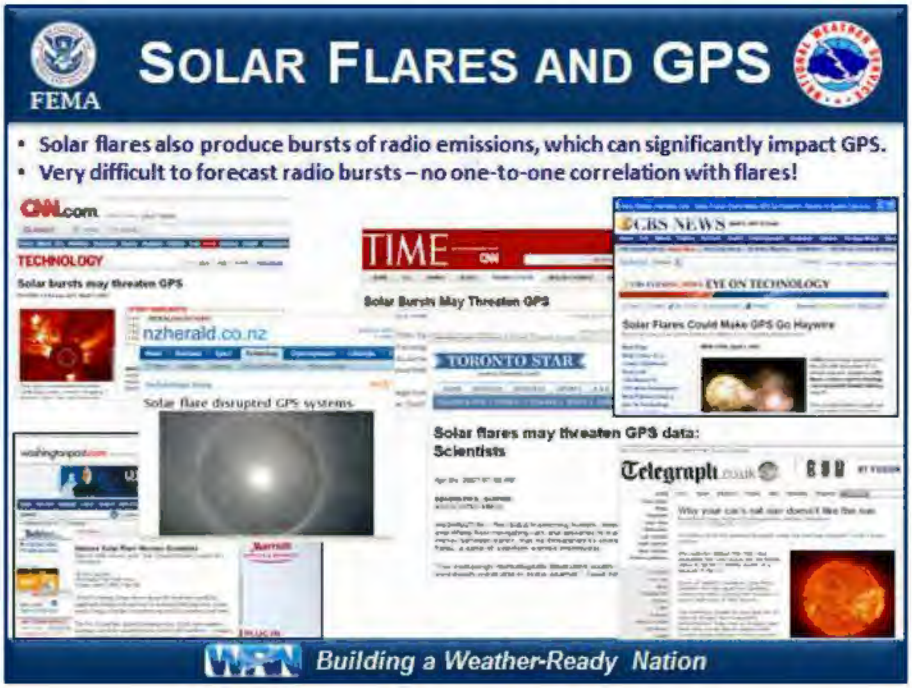
- **Radio blackouts are the most common space weather event to affect the Earth (occurring, on average, over 2500 times during each solar cycle).**
- **Since these bursts of radiation travel at the speed of light (Sun to Earth in 8 minutes), advance notice is not possible.**
- **Radio blackouts affect airplanes, boats/ships, commercial and amateur radio users since they use High Frequency (HF) radio communication.**
- **SWPC uses the "R Scale" to warn about the severity.**

NOTES



KEY POINTS

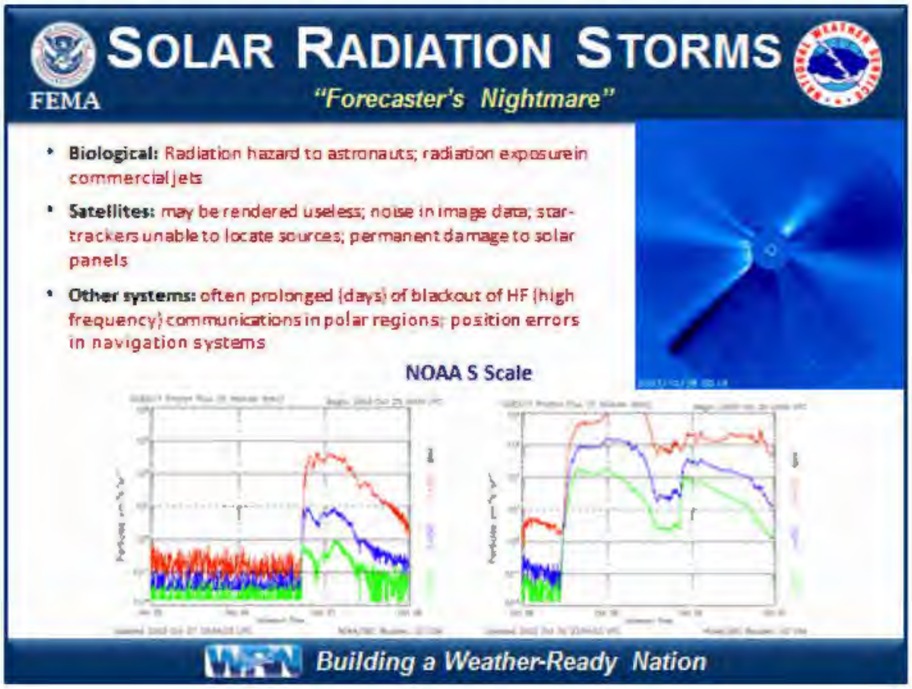
NOTES



KEY POINTS

- **It is challenging to predict which solar flares will affect GPS measurements.**

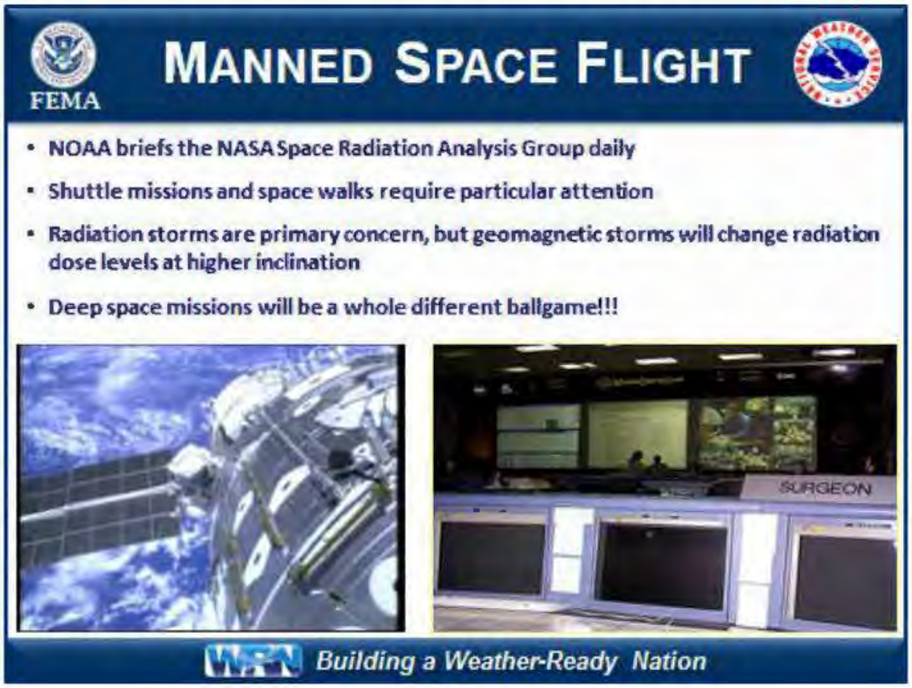
NOTES



KEY POINTS

- **Radiation storms can cause radiation levels above what the Earth's atmosphere can protect us, mainly to astronauts and to a lesser degree passengers on commercial jets at high latitudes (e.g. poles). Damage may occur to satellites, radio communication in polar areas may be temporarily lost.**
- **SWPC uses the "S Scale" to warn about the severity of a Solar Radiation Storm.**

NOTES



KEY POINTS

NOTES

DEEP SPACE MISSIONS

Mars Odyssey – *Oct 28 2003 (radiation storm)* - The MARIE instrument had a temperature red alarm leading it to be powered off on October 28. The MARIE instrument is not expected to recover.

Mars Odyssey
Photo courtesy of NASA/JPL

Mars Express - radiation made it impossible to navigate using stars as reference points (orbiter's star trackers blinded for 15 hours). The flares also delayed a scheduled Beagle 2 checkout procedure.

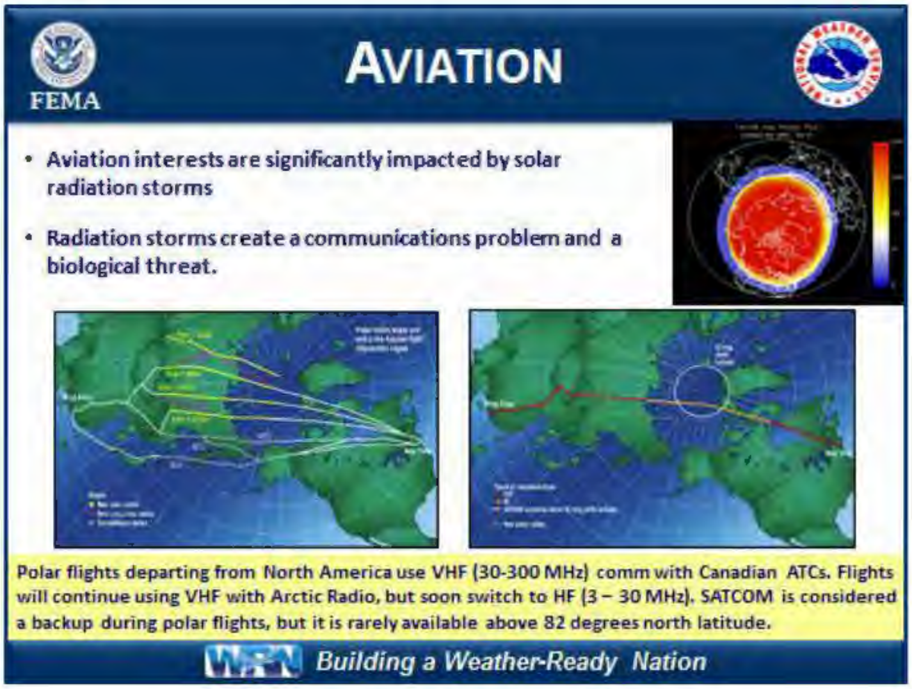
SMART-1 - Auto shutdown of engine due to radiation levels in lunar transfer orbit. Reported a total of 3 shutdowns.

Building a Weather-Ready Nation

KEY POINTS

- **Deep space missions have been used to assess radiation levels that may affect future astronauts if they went to Mars.**

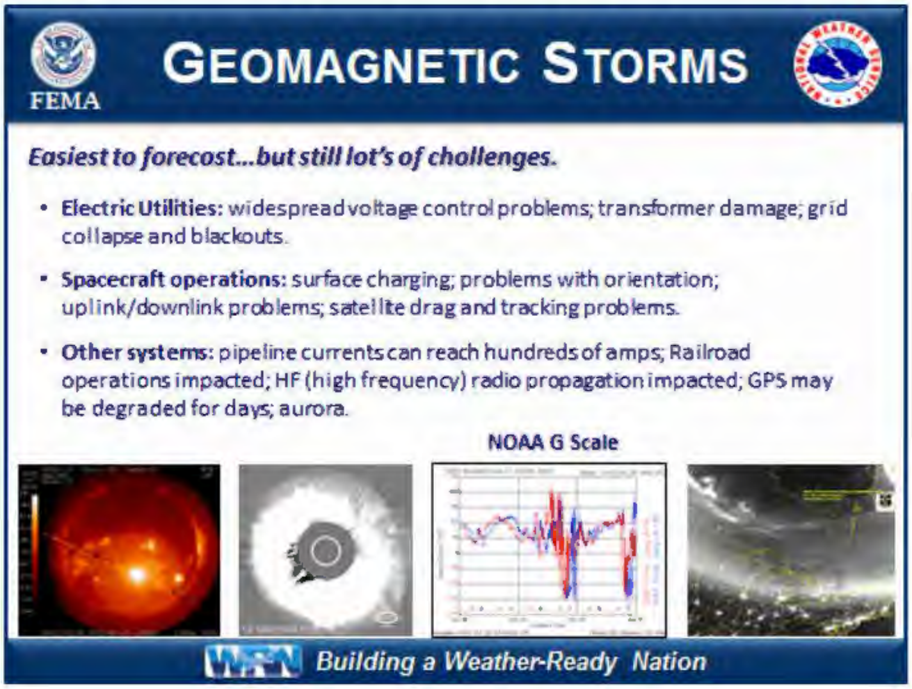
NOTES



KEY POINTS

- **Disruptions of HF communications and GPS over the polar latitudes mean that planes often must be rerouted. This usually means higher costs for the airlines and delays due to rerouting of flights.**
- **As previously stated, passengers on commercial jets, particularly high latitude routes (e.g. poles) are more at risk to radiation exposure.**

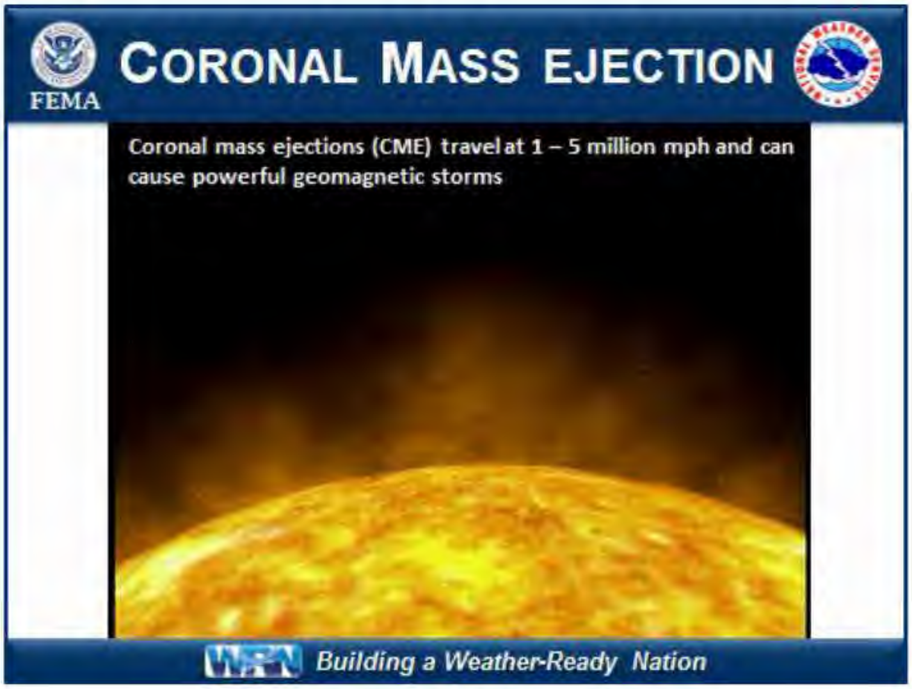
NOTES



KEY POINTS

- **Geomagnetic storms can reach the Earth anyway from 18 hours to 4 days after leaving the Sun. These storms generally have a duration of 1-2 days.**
- **Impacts to electric utilities, spacecraft, railroads, pipelines, HF radio and GPS.**
- **SWPC uses the "G Scale" to warn about the severity of Geomagnetic Storms.**

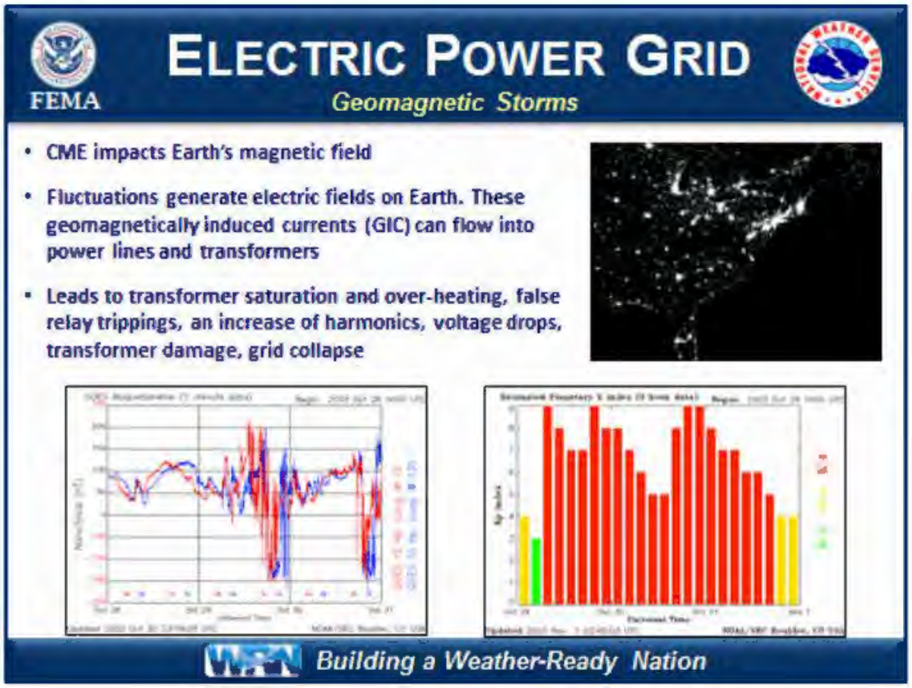
NOTES



KEY POINTS

- Coronal mass ejections (CMEs) will distort the Earth's magnetic field.
- Auroras Borealis and Australus (Northern and Southern Lights, respectively) are produced by CMEs.

NOTES



KEY POINTS

- **CMEs can cause power grid failures, creating energy blackouts.**

NOTES

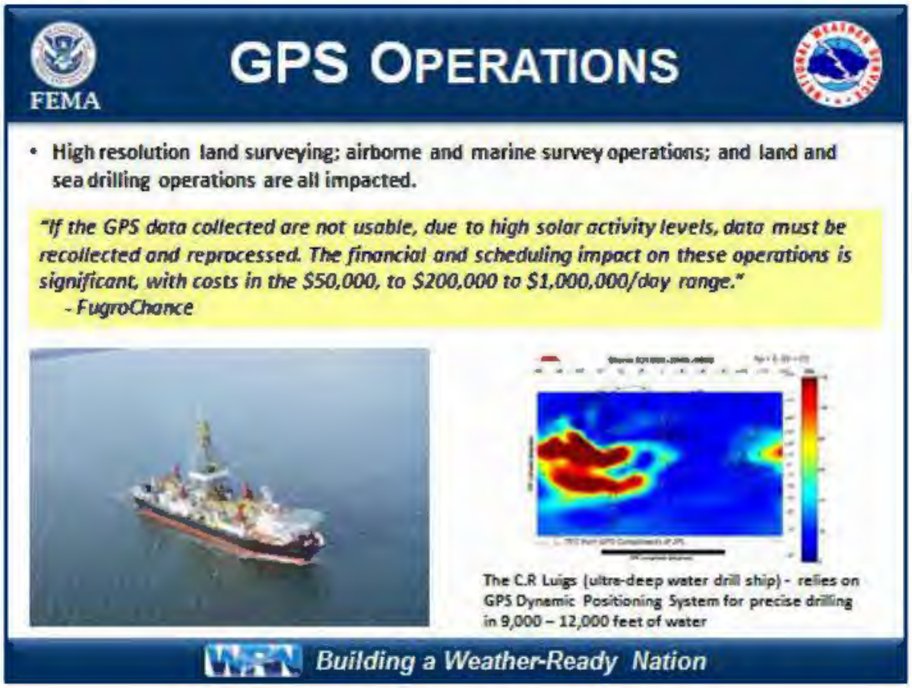
KEY POINTS

NOTES

KEY POINTS

- **Railroads depend on remote observation and manipulation of sensors/switches to control railroad traffic.**

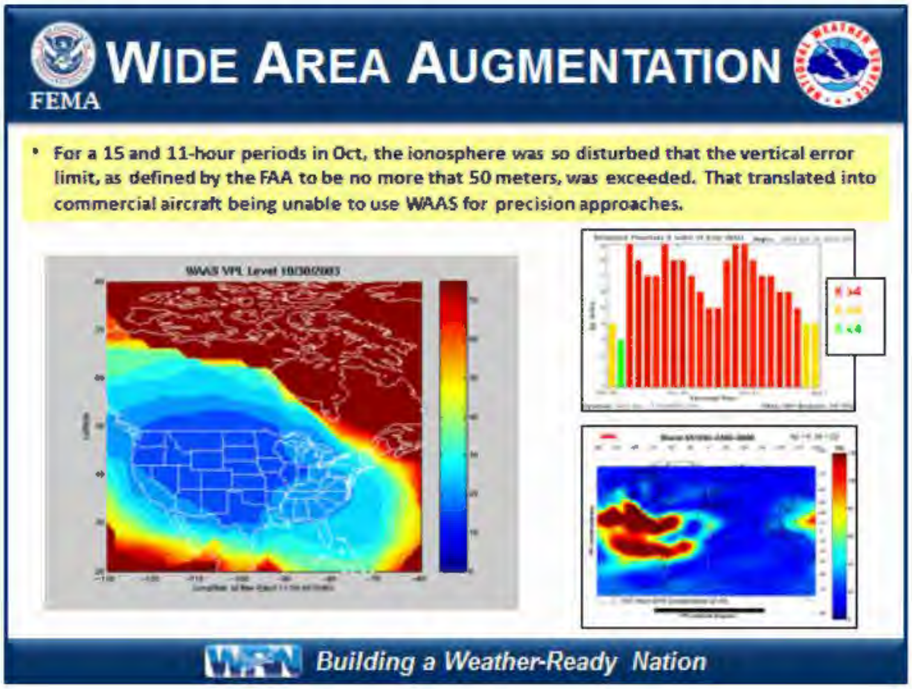
NOTES



KEY POINTS

- **Disturbances in the ionosphere can influence radio wave propagation, degrading GPS ranging measurements.**
- **In a severe magnetic storm, GPS may lose the capability to provide positioning information.**

NOTES



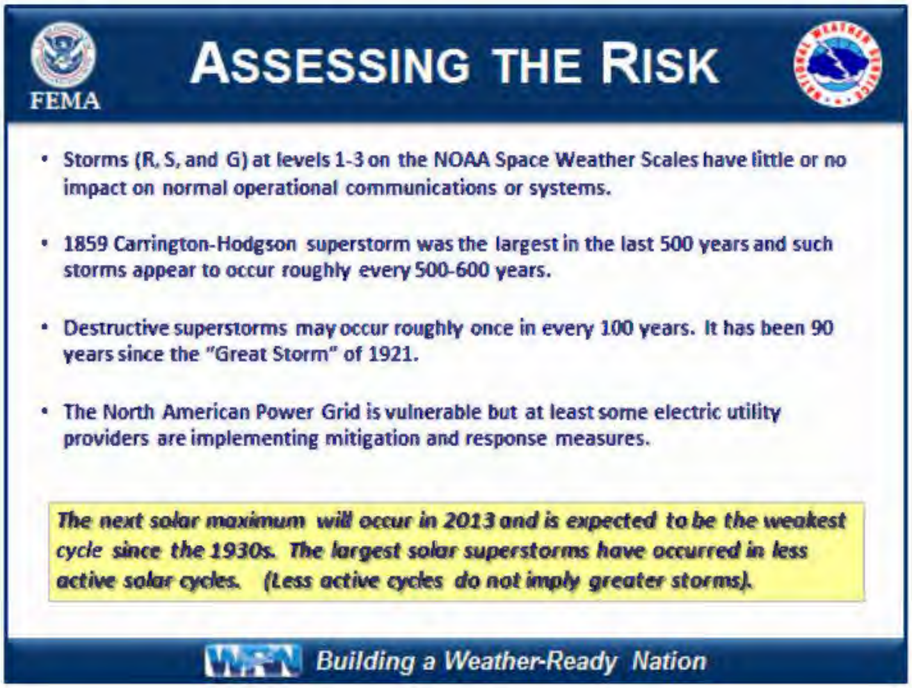
KEY POINTS

- **Wide Area Augmentation System (WAAS) relies on GPS to provide corrections for time to meet strict requirements for accuracy, availability and integrity. In a magnetic storm, the performance can be degraded.**

NOTES

KEY POINTS

NOTES



KEY POINTS

- **Technological advances in communication and power have made us increasingly vulnerable to space weather.**

NOTES

RECOVERY

- Custom extra-high voltage (EHV) transformers for the electric power grid take 12-24 months to produce. Total replacement will take years.
- Estimates for national economic recovery are between 4 and 10 years.
- Line-of-sight public safety and commercial radio (HF, VHF, UHF, microwave) WILL work if power can be supplied to systems and receivers.
- HF radio can provide communications over extended distances in the absence of other means, if power is available.

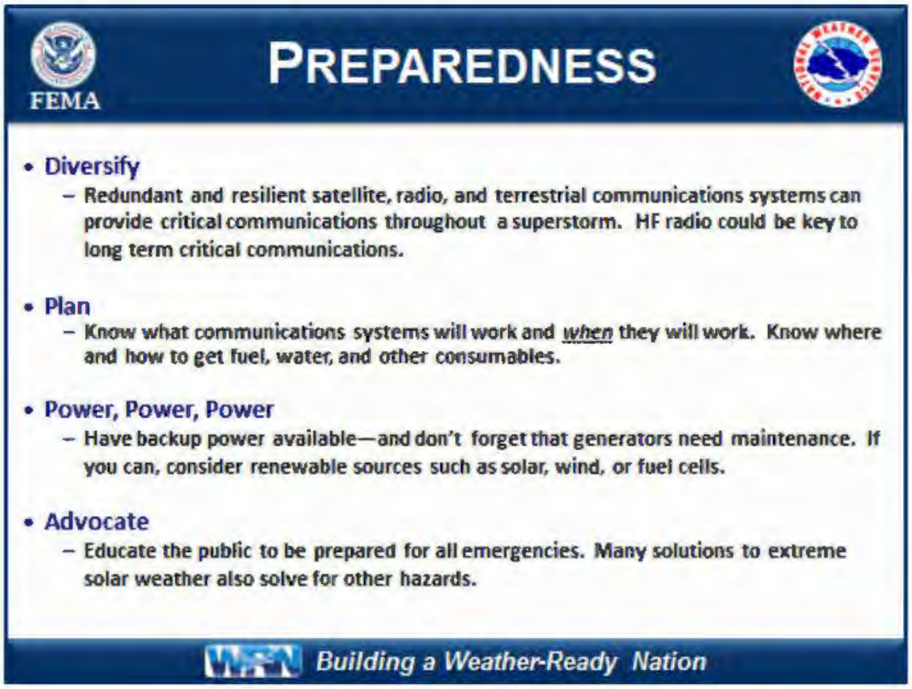
"Loss of key infrastructure for extended periods due to the cascading effects from a space weather event (or other disturbance) could lead to a lack of food, given low inventories and reliance on just-in-time delivery, loss of basic transportation, inability to pump fuel, and loss of refrigeration" (National Academy of Sciences, 2008)

Building a Weather-Ready Nation

KEY POINTS

- **A major event could have significant effects on a large spatial and temporal scale.**

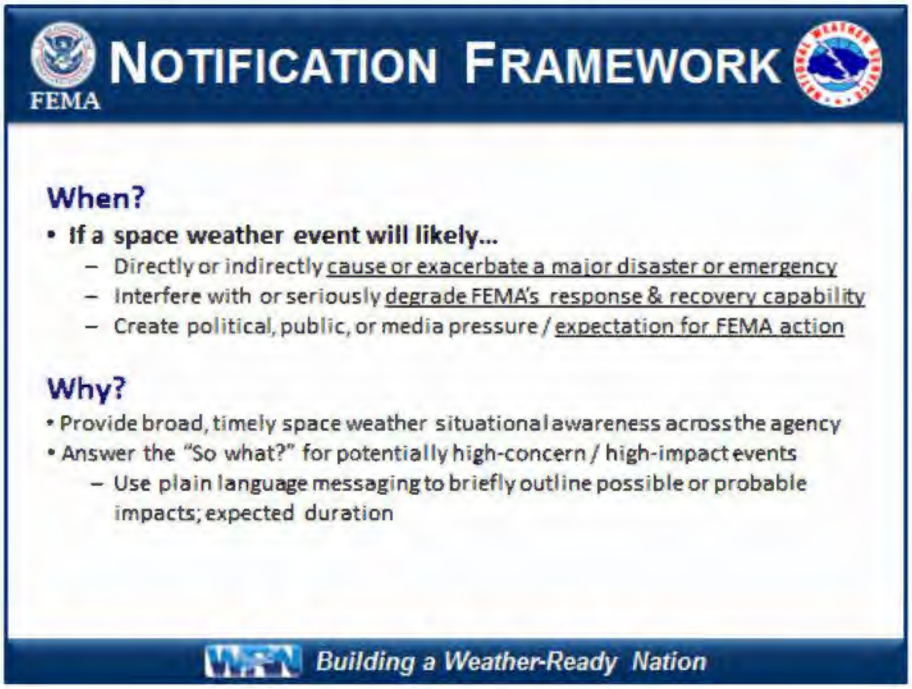
NOTES



KEY POINTS

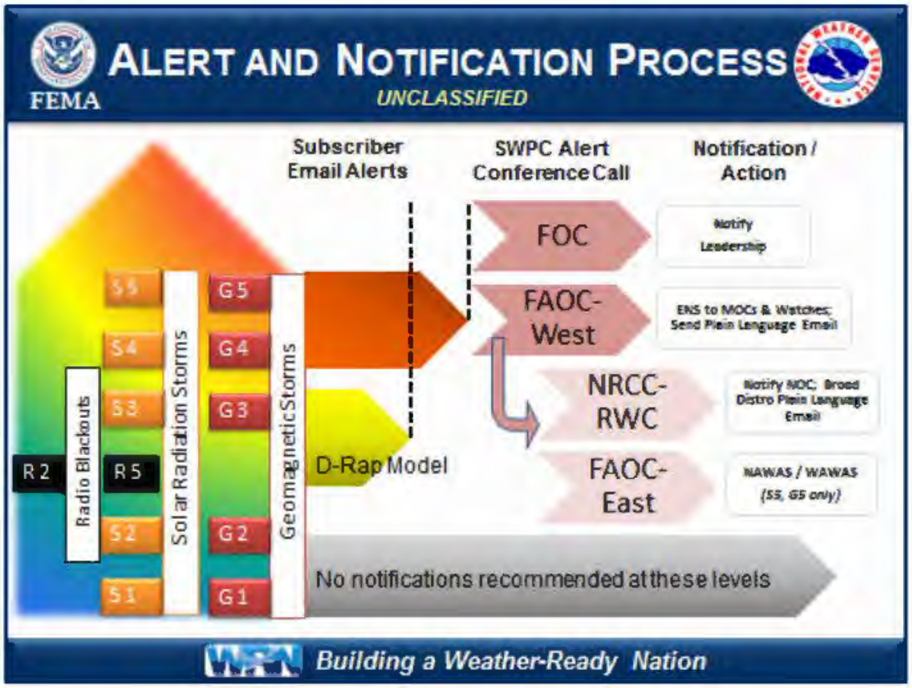
- **To prepare for the various solar storms, communication needs to be redundant and resilient. Develop plans on how and when communication systems will work. Ensure that you have backup power that can run for extended period of time.**

NOTES



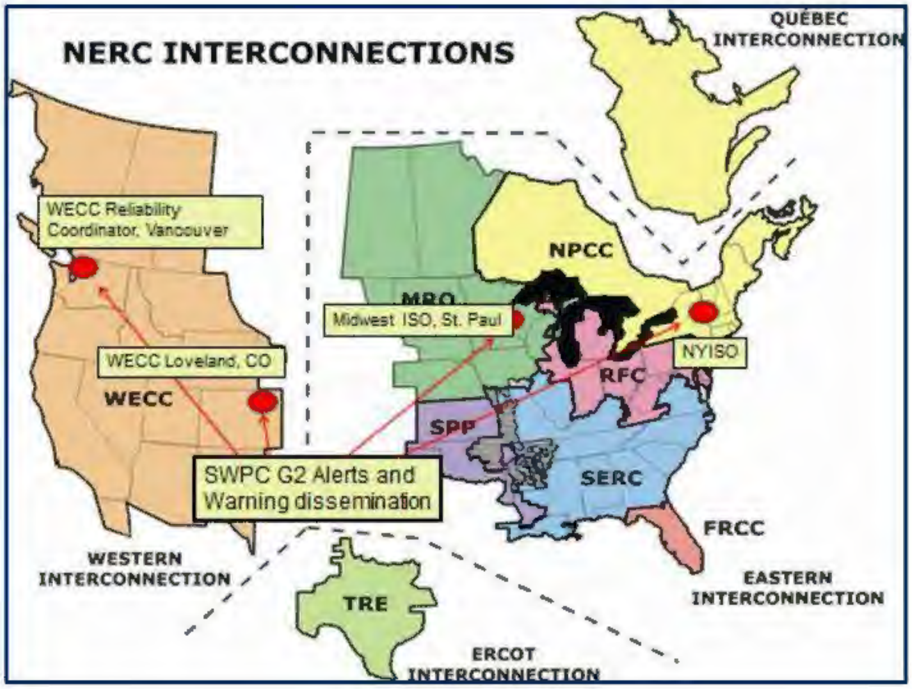
KEY POINTS

NOTES



KEY POINTS

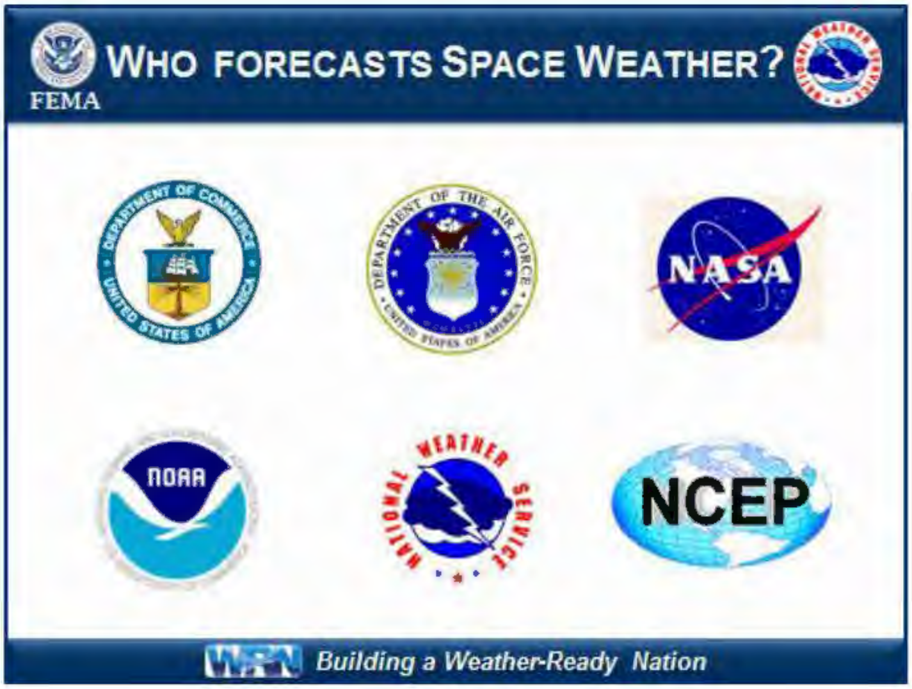
NOTES



KEY POINTS

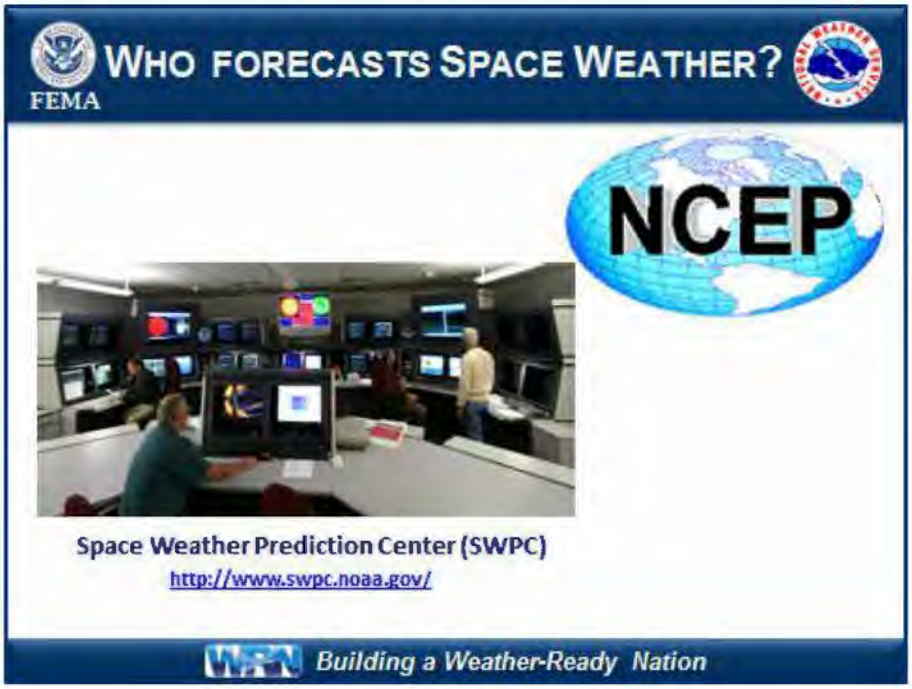
- **SWPC disseminates information to the Midwest ISO (and others) to distribute to key stakeholders**

NOTES



KEY POINTS

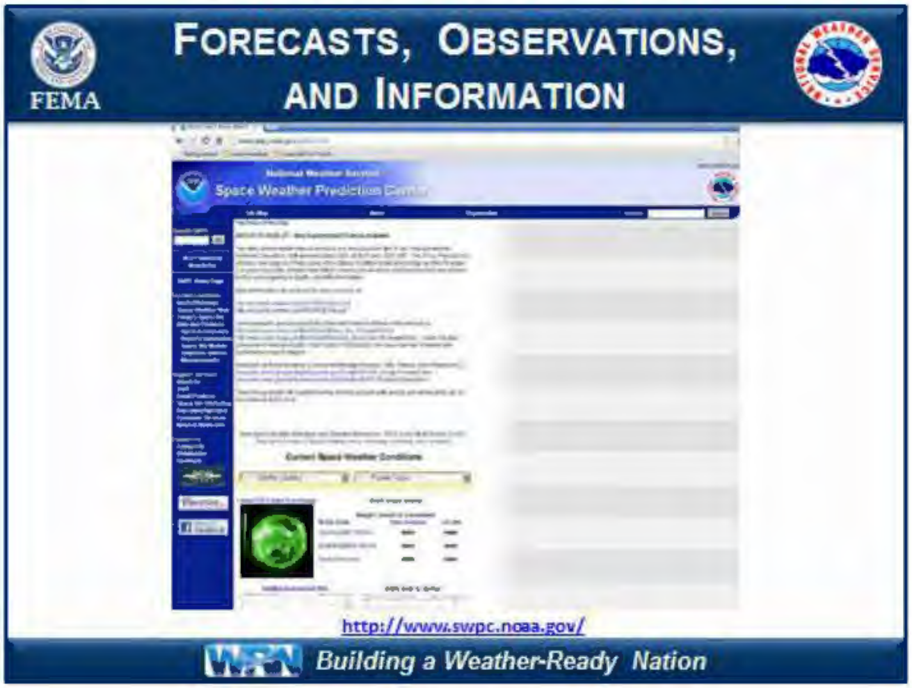
NOTES



KEY POINTS

- SWPC operations 24/7/365 and issue alerts and warnings for the United States.

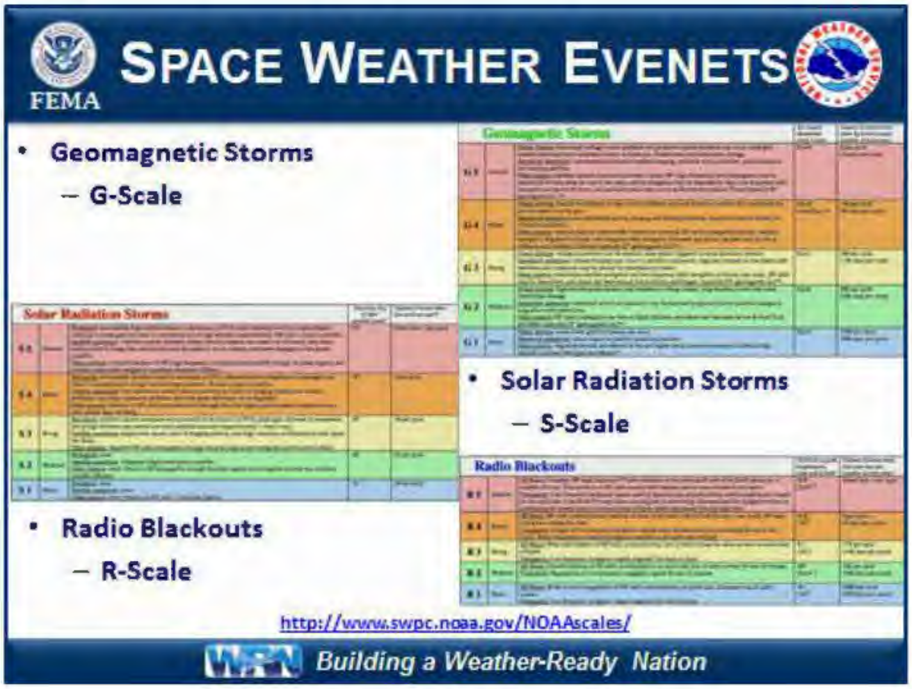
NOTES



KEY POINTS

- http://www.swpc.noaa.gov

NOTES



KEY POINTS

- **NOAA Space Weather Scales are 5-tiered scales for Geomagnetic Storms (G-Scale), Solar Radiation Storms (S-Scale) and Radio Blackouts (R-Scale).**
- **http://www.swpc.noaa.gov/NOAAscales/index.html**

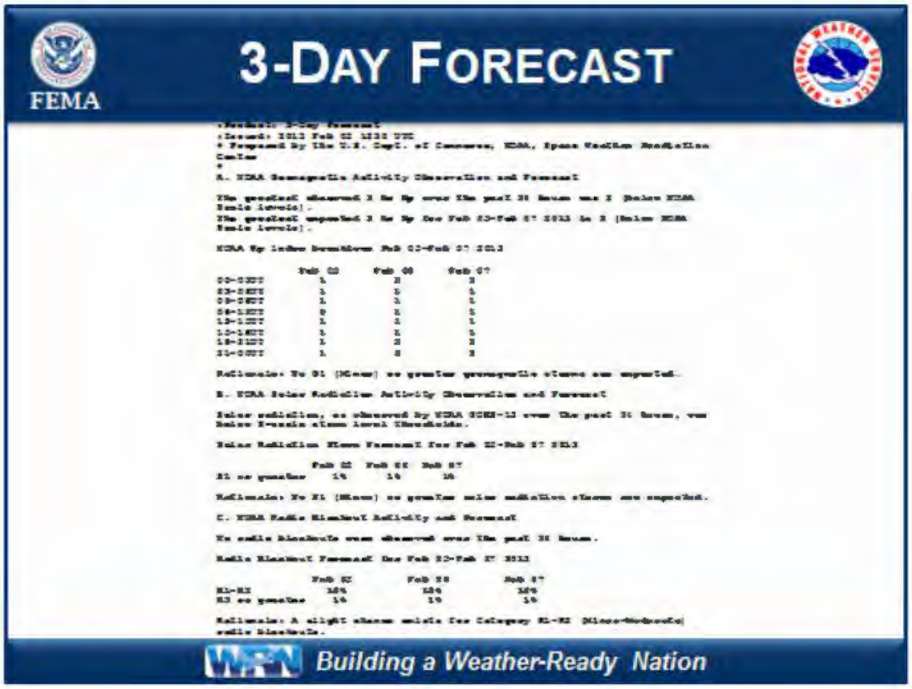
NOTES

KEY POINTS

- **3-day forecast:**
http://www.swpc.noaa.gov/ftpdir/latest/three_day_forecast.txt

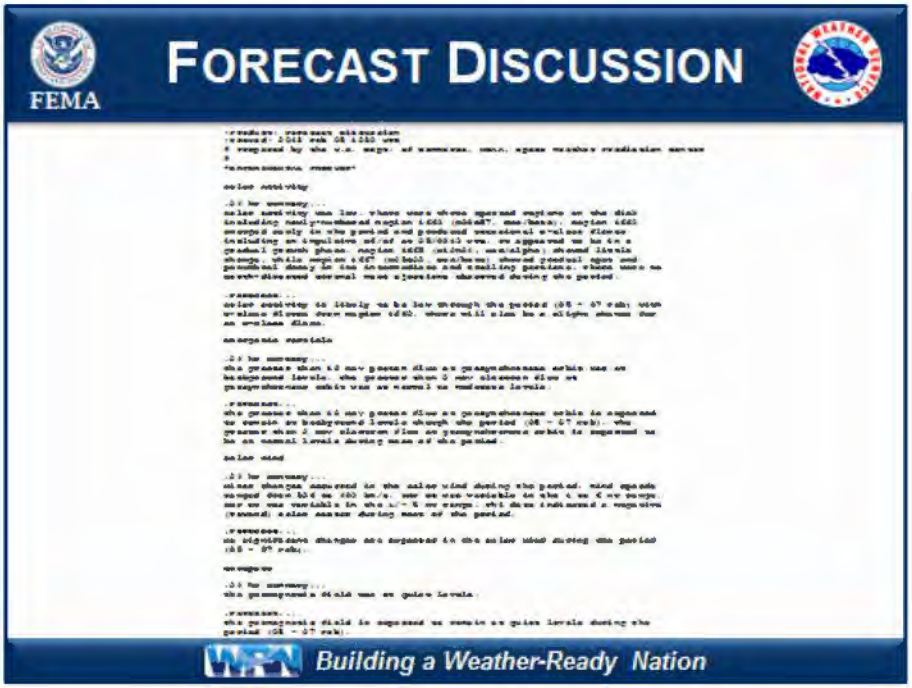
- **Forecast discussion:**
http://www.swpc.noaa.gov/ftpdir/latest/forecast_discussion.txt

NOTES



KEY POINTS

NOTES



KEY POINTS

NOTES

FEMA

CONCLUSION

- An ever-growing dependence on space-based technology will result in an increasing need for space weather services and actions to mitigate event impacts
- The health of many technological systems around the globe will depend heavily on our understanding of the space environment, and our ability to predict hazardous space weather storms

WRN *Building a Weather-Ready Nation*

KEY POINTS

- **The Earth's magnetic field and atmosphere protects us from most harmful energy from the Sun.**
- **Radio blackouts, solar radiation event and geomagnetic storms can have significant impacts to large areas for extended periods of time.**
- **Recovery from severe space weather events could take considerable time and resources.**

NOTES

SPACE WEATHER ACTIVITY

FEMA

- **Review the SWPC website: http://www.swpc.noaa.gov/**
- **Identify and Record the following:**
  - **Number of:**
    - Geomagnetic Storms in the past 24 hours? Currently? Next 24?
    - Solar Radiation Storms in the past 24 hours? Currently? Next 24?
    - Solar Radio Flare Blackouts in the past 24 hours? Currently? Next 24?
    - Sunspots?
  - **Impacts of each above**
  - **Forecasts:**
    - Solar Activity?
    - Geophysical Forecast?
  - **HF Communication Impact**
  - **Current alerts**

Building a Weather-Ready Nation

KEY POINTS

NOTES