SPACE WEATHER EFFECTS ON COMMUNICATIONS SYSTEMS

EFFECTS, OPERATIONAL IMPACTS, MITIGATIONS, AND RESEARCH GAPS FOR COMMUNICATIONS SYSTEMS
Premise

What is the *operational impact* caused by a space weather *effect*

- On a specific communications *technology*
- Operated according to a set of *procedures*
- At a specific geographical *location*
- At a specific *time* during a space weather event
“While Hurricanes Harvey, Irma, Jose, and Maria tore through the Caribbean region, X-class flares, solar energetic particle (SEP) events, and Earth-directed coronal mass ejections (CMEs) plowed through the heliosphere. Caribbean emergency communication system operators reported critical impacts to high-frequency (HF) radio links used in disaster response and aviation tracking.”


Federal Emergency Management Agency (FEMA) operators, their federal, state, and local emergency management partners supporting operations in the U.S. Virgin Islands and Puerto Rico used HF communications extensively. None reported any space weather related impacts to HF communications.
Radio Blackout Event

Radio Spectrum

Solar Flare “Radio Blackout”

5 – 40 MHz Skywave only!

Possible interference to VHF, UHF, and microwave satellite communications with direct line-of-sight from receiver to the sun for seconds up to ~15 minutes
SW Effects on Ionosphere (Day)

Geomagnetic Storm (G Scale) decreases electron density causing higher frequencies to pass through instead of refracting:
- Higher frequencies pass through for ~1-3 days. Polar effects last ~1-2 days longer. Often called “Auroral trough” but that can be misleading.
- Increased ionization associated with aurora increases absorption at E Layer and above, disrupting communications < 20MHz. “Auroral E” may arise allowing skywave from 28-144 MHz, predominately on an east-west path.
- In an extreme event, increased ion density equatorward and distant from aurora may enhance skywave signals within first ~2 hours. Where this may occur cannot be forecast.

Solar Radiation Storm (S Scale) Solar Energetic Protons increase ionization which increases absorption of radio near poles (“polar cap absorption”) for ~minutes to days. Full-coverage event from pole to equatorward extent. Higher ion density on day side. Absorption may extend to higher layers.

Solar Flare (R Scale) X-Rays increase electron density which increases absorption of radio signals from lower frequencies to higher frequencies for ~minutes to 3 hours. (If ultraviolet (UV) light in addition to X-ray, UV increases F layer ionization which can enhance F Layer HF communications.)
Geomagnetic Storm (G Scale) decreases electron density causing higher frequencies to pass through instead of refracting.

- Higher frequencies pass through for ~1-3 days. Polar effects last ~1-2 days longer.
- If storm arrives late afternoon, may not see impacts until after sunrise of the next day.
- Increased ionization associated with aurora increases absorption at E Layer and above, disrupting communications < 20MHz. “Auroral E” may arise allowing skywave from 28-144 MHz, predominately on east-west path.
- In an extreme event, increased electron density equatorward and distant from aurora may enhance skywave signals within first ~2 hours. Where this may occur cannot be forecast.

Solar Radiation Storm (S Scale) No D Layer to absorb radio signals. Absorption may extend to higher layers.

Solar Flare (R Scale) No D Layer to absorb radio signals.
X-Rays increase electron density which increases absorption of radio signals in D Layer from lower frequencies to higher frequencies for ~minutes to 3 hours.

No D Layer to absorb radio signals.

Solar Flare Radio Blackout Effect (Visual)
Polar Cap Absorption event: Lower frequencies impacted first, recover last

Full-coverage from pole to equatorward extent

Not highly correlated to the visible aurora

Higher ion density on day side (higher absorption)

Density and extent varies with storm intensity

Solar Radiation Storm

Aurora heats atmosphere

Molecular neutrals rise to F Layer over all of auroral oval and move toward the equator: Suppresses ion creation, increases ion loss in F Layer.

Extent varies with storm intensity

If storm arrives late afternoon, may not see effects until after sunrise of next day

Downwelling of ions pushed out of F Layer can enhance HF skywave equatorward and distant from the aurora for ~2 hours

Geomagnetic Storm

NOT TO SCALE
Mitigation Techniques

**D Layer Absorption: Move to Higher Frequency**

- Use Digital over Analog
- Use Data over Voice

**F Layer Depletion: Use Lower Frequency**

- Use NVIS if practical

**Use Higher Power**
Use Networks

• Station Relay
  - If origin and destination stations cannot talk directly, manually pass traffic between stations that can talk.

• Internet Connected

(Example) WINLINK Global Radio Email Live System Information
# Applying a Risk Profile for HF Skywave

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Technology</th>
<th>Frequency</th>
<th>Station Configuration</th>
<th>Power</th>
<th>Skill</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Worst Case</strong></td>
<td>Analog Voice</td>
<td>Single Frequency</td>
<td>Single Station Pair</td>
<td>Low Power</td>
<td>Low Skill</td>
</tr>
<tr>
<td><strong>Hurricane Watch Net</strong></td>
<td>Analog Voice</td>
<td>Single Frequency</td>
<td>Station Relay</td>
<td>High Power</td>
<td>High Skill</td>
</tr>
<tr>
<td>2017</td>
<td>7.268 MHz &amp; 14.325 MHz</td>
<td>40m Band</td>
<td>20m Band</td>
<td>~50 Stations in Net</td>
<td></td>
</tr>
<tr>
<td><strong>FEMA PR/USVI</strong></td>
<td>Digital Voice</td>
<td>Automatic Link Establishment</td>
<td>Station Relay</td>
<td>High Power</td>
<td>Medium Skill</td>
</tr>
<tr>
<td>7.268 MHz &amp; 14.325 MHz</td>
<td>&gt; 40 Channels from 2 MHz to 28 MHz</td>
<td></td>
<td></td>
<td>* Used Near Vertical Incident Skywave for intra- and inter-island HF</td>
<td></td>
</tr>
<tr>
<td><strong>US Government</strong></td>
<td>Digital Voice</td>
<td>Automatic Link Establishment</td>
<td>Networked Stations</td>
<td>High Power</td>
<td>Medium Skill</td>
</tr>
<tr>
<td>(e.g. SHARES, COTHEN)</td>
<td>(and data)</td>
<td></td>
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</tr>
<tr>
<td><strong>Amateur Austin, TX</strong></td>
<td>Digital Data</td>
<td>Multiple Frequencies</td>
<td>Networked Stations</td>
<td>High Power</td>
<td>High Skill</td>
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</tbody>
</table>

* Used Near Vertical Incident Skywave for intra- and inter-island HF
Terrestrial LOS Communications are not directly impacted by space weather. (with one exception)
Solar Radio Bursts (the exception)

Omnidirectional antennas likely not impacted — unless transmitting and receiving antennas are on a direct line of sight with the Sun when a SRB occurs.

Directional sun-facing antennas may be impacted when the sun is within their line of sight, which can occur at dawn and dusk.

~ 20 Min.
Solar Radio Bursts (Continued)

In radio networks with multiple directional antennas, only sun facing antennas are effected.

Overall, risk to line-of-sight radio from space weather—excluding power—is assessed as LOW.

If sun facing antenna impacted, devices in the coverage area of a non-sun-facing antenna may not be impacted.

Outages impacting a subset of customers for less than 20 minutes are not considered significant outages.
Satellite Communications
Solar Radiation & Geomagnetic Storm (S & G Scales) Physical damage to satellite.

Radio Blackout (R Scale) and Solar Radio Burst Electromagnetic interference.

Geomagnetic Storm (G Scale)
- Scintillation.
- Absorption, diffusion.
- Refraction.
- Faraday Rotation.

Upper atmosphere expansion.
Solar Energetic Particle damage to solar panels shortens useful life.
- Mitigated by proper design, quality control, and operational monitoring

Upper atmosphere expansion from geomagnetic storms increases drag for very-low-earth-orbit satellites and debris.
- Not a significant issue for LEO satellite constellations above 500 - 600 km
- Mitigated by extra fuel reserve for station keeping as part of operational design
- New artificial intelligence can maneuver satellites to avoid collisions

Single Event Upset creates command or memory errors, usually temporary.
- New artificial intelligence can diagnose and fix upsets on the satellite with little or no human intervention

Surface and Deep Dielectric charging during geomagnetic storms causes arcs that can damage electronics.
- Mitigated by proper design and quality control
### VHF
- 70-150 MHz

### UHF
- 200-400 MHz

### L Band
- 1-2 GHz

### S Band
- 2-4 GHz

### C Band
- 4-8 GHz

### X Band
- 8-12 GHz

### Ku Band
- 12-18 GHz

### K Band
- 18-27 GHz

### Ka Band
- 27-40 GHz

### V Band
- 40-75 GHz

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**Scintillation and Frequency**

A curious thing about the telegraphers’ experience is that it has been intermittent. For some periods the wires and instruments worked normally and then would start on a dance that puzzled the operators. The phenomenon was first noticed in Western France late on Friday evening and gradually spread eastward. All lines were not affected similarly, neighboring ones behaving normally or eccentrically from no known reason. One feature was that while earth currents were disturbed, the wireless apparatuses remained unaffected.
Scintillation Effects on SATCOM

Effects are not continuous and may be highly localized. Close relationship between scintillation and the auroral oval.

- **DAY**
  - ~300+ km: F2
  - ~150-300 km: F1
  - ~95-150 km: E
  - ~75-95 km: D

- **NIGHT**
  - ~300+ km: F2
  - Auroral Electrojet (blobs)
  - Diffusion Scatter

- Faraday Rotation
- Refraction
- Absorption
- Phase Change

Scintillation Effects on SATCOM
Mitigation Techniques (and limitations)

- **If possible, use a higher frequency**
  - Dependent on equipment and service provider
  - Multiband satellite receivers and service providers generally cost more

- **If possible, use multiple, geographically separated receivers connected over a terrestrial network**
  - (e.g. Wireline or LOS radio/microwave)
  - Increased cost and complexity

- **If possible, use a higher power**
  - Output power is strictly regulated by service provider (and the FCC) and **MUST BE** coordinated

- **If possible, avoid phase-sensitive equipment**
  - Mission dependent
Satellite Communications Risk

User Operational Risk = Technology + Implementation + Disruption Tolerance

<table>
<thead>
<tr>
<th>Cost</th>
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</thead>
<tbody>
<tr>
<td>Single Satellite</td>
</tr>
<tr>
<td>Single Orbit</td>
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</table>

<table>
<thead>
<tr>
<th>Satellite Dependency</th>
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<tr>
<td>Single Satellite</td>
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<tr>
<td>Single Orbit</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Satellite Service(s)</th>
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</thead>
<tbody>
<tr>
<td>Single Provider</td>
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<tr>
<td>Single Sat/GEP</td>
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<table>
<thead>
<tr>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHF – L Band</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Receivers</th>
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</thead>
<tbody>
<tr>
<td>Single Receiver</td>
</tr>
<tr>
<td>Single Band</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Disruption Tolerance</th>
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</thead>
<tbody>
<tr>
<td>&lt; 5 minutes</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Low vs. Higher Skill</th>
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</thead>
<tbody>
<tr>
<td>Low Skill</td>
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</tbody>
</table>
Fiber Optic Cables on land do not conduct electricity (mitigation).

- Damaging geomagnetically induced currents (GIC) require long-distance conductors (10s to 100s of km/mi).
Wireline Case Study – L4 Cable System

August 4, 1972

L4 Coax Cable System from Plano, Illinois to Cascade, Iowa

- 242 kilometers long (150 miles)
- Low ground conductivity *(current seeks path of least resistance)*
- Protection from Electrical Architecture ~ 6.5 V/km

Induced Geo-Electric Field ~ 7.0 V/km = cable outage (shutdown)

- **Other cables in the area remained operational**
Undersea Repeaters regenerate optical signals approximately every ~40-70 kilometers.

Repeaters require power, which is provided by copper conduit built into the undersea cable.

- Copper conduit is susceptible to geomagnetically induced currents
- Research into vulnerability is ongoing and depends on cable length, geographic orientation, and electrical architecture

Long distances between landing stations can lead to significant voltage differentials, which induce electric current.

* Risk currently unknown
• Carrington-scale event and timeline, well-connected
• All three main types of space weather + SRB
  ✓ R5 Solar Flare Radio Blackout
  ✓ Solar Radio Burst
  ✓ S5 Solar Radiation Storm
  ✓ G5 Geomagnetic Storm
• Continental United States (and Arctic)
• Communications impacts only!
Extreme Event Warning Times

- **Solar Flare Radio Blackout + Solar Radio Bursts**: No Warning
- **Solar Radiation Storm**: ~ 20 minutes
- **Geomagnetic Storm**: 15-24 Hours

Warning times can be as short as 15-20 minutes for magnetic field orientation.
Based on the five phenomena associated with space weather events as identified in the “Space Weather Phase 1 Benchmarks” report: **Induced geo-electric fields, Ionizing radiation, Ionospheric disturbances, Solar radio bursts, and Upper atmospheric expansion** + Terrestrial line-of-sight radio.
Carrington Scale Solar Flare Radio Blackout (R5 – Extreme) arrives with forecasted probability but no operational warning.

Ionospheric Disturbances – HF Radio

<table>
<thead>
<tr>
<th>CONUS</th>
<th>F2 (1-60 MHz)</th>
<th>Groundwave</th>
<th>Relay</th>
<th>Networked</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F1 (10-20 MHz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>(~5-20 MHz)</td>
<td></td>
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</tbody>
</table>

Ionospheric Disturbances - Satellite

<table>
<thead>
<tr>
<th>VHF</th>
<th>UHF</th>
<th>L Band</th>
<th>S Band</th>
<th>C Band</th>
<th>X Band</th>
<th>Ku Band</th>
<th>K Band</th>
<th>Ka Band</th>
<th>V Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>~150 MHz</td>
<td>200-400 MHz</td>
<td>3.3 GHz</td>
<td>2.4 GHz</td>
<td>4.6 GHz</td>
<td>8.12 GHz</td>
<td>13.44 GHz</td>
<td>18.2 GHz</td>
<td>27.4 GHz</td>
<td>40.75 GHz</td>
</tr>
</tbody>
</table>

Terrestrial Line-of-Sight Radio

Solar Radio Bursts

SRB, if present, impacts sun facing antennas for up to ~20 minutes.

Induced Geo-electric Fields

Solar emissions at radio & microwave frequencies may “jam” satellites for seconds to 15 minutes.
Ionospheric Disturbances – HF Radio

**Ionospheric Disturbances - Satellite**

** Ionizing Radiation & Upper Atmospheric Expansion**

Solar emissions at radio & microwave frequencies may “jam” satellites for seconds to 15 minutes.

- Single Event Upsets
- Dielectric charging
- Solar panel damage
- Satellite Drag

**Terrestrial Line-of-Sight Radio**

- Interference possible if antennas are on a direct line of sight with the Sun

**Induced Geo-electric Fields**

Solar Flare Radio Blackout (R5 – Extreme) and arrival of Solar Radiation Storm (> S1 – intensity increases over time).
Ionospheric Disturbances – HF Radio

**CONUS**
- Skywave (F2 (~1-60 MHz))
- Relay (F1 (~10-20 MHz))
- Networked (E (~5-20 MHz))

**Arctic**
- Groundwave (F2 (~1-60 MHz))
- Gyro (F1 (~10-20 MHz))
- E (~5-20 MHz)

Interference possible if antennas are on a direct line of sight with the Sun.

Terrestrial Line-of-Sight Radio

- Skywave
- Groundwave
- Relay
- Networked

Day side only, higher freqs impacted last and recover first.

Ionospheric Disturbances - Satellite

<table>
<thead>
<tr>
<th>HF</th>
<th>UHF</th>
<th>L Band</th>
<th>S Band</th>
<th>C Band</th>
<th>X Band</th>
<th>Ku Band</th>
<th>K Band</th>
<th>Ka Band</th>
<th>V Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-30 MHz</td>
<td>200-400 MHz</td>
<td>3-6 GHz</td>
<td>2-4 GHz</td>
<td>4-8 GHz</td>
<td>8-12 GHz</td>
<td>13-18 GHz</td>
<td>18-27 GHz</td>
<td>27-40 GHz</td>
<td>40-75 GHz</td>
</tr>
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</table>

Solar Radio Bursts

- Solar Flare Radio Blackout (R5 – Extreme) and Solar Radiation Storm (S5 – Extreme).

Ionizing Radiation & Upper Atmospheric Expansion

- Solar emissions at radio microwave frequencies may “jam” satellites for seconds to 15 minutes.
  - Single Event Upsets
  - Dielectric charging
  - Solar panel damage
  - Satellite Drag

Induced Geo-electric Fields

- Interference possible if antennas are on a direct line of sight with the Sun.
09:30 ET – 3 Hours (S5)

**Ionospheric Disturbances – HF Radio**
- CONUS HF recovers. If UV present, may enhance F Layer ionization.
- Artic HF severely impacted from S5

**Ionospheric Disturbances - Satellite**
- Up to ~10% of satellites may experience issues, most of them temporary
  - Single Event Upsets
  - Dielectric charging
  - Solar panel damage
  - Satellite Drag

**Terrestrial Line-of-Sight Radio**
- Interference possible if antennas are on a direct line of sight with the Sun

**Induced Geo-electric Fields**
23:45 ET – 17.25 Hours (S5 + G5)

Ionospheric Disturbances – HF Radio
- Electron depletion at F Layer
- HF enhanced equatorward of aurora for ~2 hr?
- “Auroral E”
- Arctic severely impacted from G5 and S5

Ionospheric Disturbances - Satellite
- VHF
- UHF
- L Band
- S Band
- C Band
- X Band
- Ku Band
- K Band
- Ka Band
- V Band
- Severe scintillation at lower satellite bands.
- Note: GNSS networks operate at L Band and may suffer positioning errors, timing less so.

Ionizing Radiation &
Upper Atmospheric Expansion
- Up to ~10% of satellites may experience issues, most of them temporary
- Single Event Upsets
- Dielectric charging
- Solar panel damage
- Satellite Drag

Solar Radio Bursts

Terrestrial Line-of-Sight Radio
- VHF
- UHF (Includes FirstNet)
- LOS Microwave
- Land Mobile Radio
- Air
- Marine

Induced Geo-electric Fields
- Undersea Cable GIC
- Long haul copper GIC

Geoeffective Geomagnetic Storm arrives (G5 – Extreme) and Solar Radiation Storm (S5 – Extreme).
Ionospheric Disturbances – HF Radio

CONUS
- Electron depletion at F Layer
- “Auroral E”
- Arctic severely impacted from G5 and S5
- D layer may be usable

Arctic
- F2 (~1-60 MHz)
- F1 (~10-20 MHz)
- E (~5-20 MHz)
- D

Ionospheric Disturbances - Satellite

<table>
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<tr>
<th>VHF</th>
<th>UHF</th>
<th>L Band</th>
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<th>K Band</th>
<th>Ka Band</th>
<th>V Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-15 MHz</td>
<td>30-50 MHz</td>
<td>1-2 GHz</td>
<td>2-4 GHz</td>
<td>4-6 GHz</td>
<td>8-12 GHz</td>
<td>13-18 GHz</td>
<td>18-21 GHz</td>
<td>27-40 GHz</td>
<td>40-70 GHz</td>
</tr>
</tbody>
</table>

- Scintillation at lower satellite bands possible.
- Note: GNSS networks operate at L Band and may suffer positioning errors, timing less so.

Ionizing Radiation &
Upper Atmospheric Expansion

- Upper atmosphere expansion increases satellite drag, particularly below 400 km
- Single Event Upsets
- Dielectric charging
- Solar panel damage
- Satellite Drag

Solar Radio Bursts

SRB, if present, impacts sun facing antennas for up to ~20 minutes

Terrestrial Line-of-Sight Radio

- Land Mobile Radio
- Air
- LOS Microwave

Induced Geo-electric Fields

- Undersea Cable GIC
- Long haul copper GIC

Geoeffective Geomagnetic Storm (G5 – Extreme) and Solar Radiation Storm (S5 – Extreme).
Solar Radio Bursts

CONUS
- Electron depletion of F layer
- Artic remains impacted

Arctic
- F2 (~1-60 MHz)
- E (~5-20 MHz)

Ionospheric Disturbances - HF Radio

Ionospheric Disturbances - Satellite

Ionizing Radiation & Upper Atmospheric Expansion

- Atmospheric drag changes orbit of debris
- Single Event Upsets
- Dielectric charging
- Solar panel damage
- Satellite Drag

Terrestrial Line-of-Sight Radio

Induced Geo-electric Fields

Geomagnetic storm ends.
Solar Radiation Storm diminishes over time.

Mark MacAlester
Communications Liaison
June 17, 2020
06:30 ET – 3 Days

Ionospheric Disturbances – HF Radio

CONUS
- F2 (~1-60 MHz)
- F1 (~10-20 MHz)
- E (~5-20 MHz)
- D

Arctic
- F2 (~1-60 MHz)
- F1 (~10-20 MHz)
- E (~5-20 MHz)
- D

Artic takes an additional 1-2 days to recover.

Solar Radio Bursts

Terrestrial Line-of-Sight Radio

Ionizing Radiation &
Upper Atmospheric Expansion

Atmospheric drag changes orbit of debris
Increased fuel use for station keeping may shorten satellite life

Ionospheric Disturbances – Satellite

CONUS

Arctic

Artic takes 1-2 days longer to recover.
Longer storms may take longer to recover.
Extreme Events Can Bring Friends

The “Great Storm” of 1921 was the largest of several storms over a period of almost two weeks.

The “Carrington Event” of 1859 was the second and largest of two extreme events.

The “Halloween Storms” of 2003 saw 17 major flares over roughly two weeks.

It takes ~ 2 weeks for a sunspot group to traverse the visible disk of the sun.
It Takes the Whole Community

Researchers

- Observations and Measurements
- Advisories
- Alerts
- Warnings
- Conferences

Operations

- Critical Infrastructure
- Emergency Response
- Plans, Training, and Exercises

Engineers

- Bz, E, V/km, Timing
- Vulnerabilities Identified
- Analysis of Impact
  - Customers Affected
  - Timing
  - Severity
  - Duration

Model Runs

Confidence Level

Operational Products
Conclusion

Need
Research that moves beyond space weather effects and includes operational impacts
• On a specific communications technology
• Operated according to a set of procedures
• At a specific geographical location
• At a specific time during an event

Goal
Risk-informed official guidance for resilient communications engineering and operations best practices.
Questions
Acknowledgements

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For more information:
cisa.gov

Questions?
Email: mark.macalester@hq.dhs.gov
Phone: 719-556-2134
References


References (Continued)