Critical Communications During and After a Solar Superstorm

Overview

- FEMA's Mission
- Problem Statement
- Extreme Solar Weather Has Happened Before
- Assessing the Risk
- The Scenario (Maximum of maximums)
- Conclusions
- Questions

FEMA's Mission

FEMA's mission is to support our citizens and first responders to ensure that as a nation we work together to build, sustain, and improve our capability to prepare for, protect against, respond to, recover from, and mitigate ALL HAZARDS.

Critical Communications

- When communications fail, the mission can fail, often with tragic results
- Public Safety emergency responders need effective communications to do their jobs in any environment
- The ability to communicate can mean the difference between LIFE AND DEATH

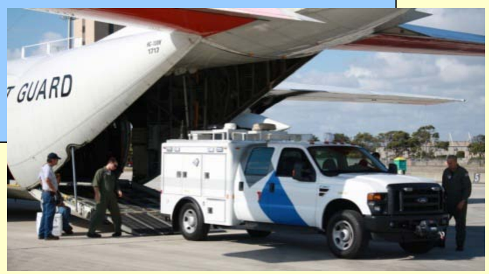
MERS Task Force-Haiti Mission Support

Forward Communications Vehicle (FCV) TEAM

3 personnel

4 vehicles:

- FCV
- F-350
- 60kW GenSet
- Excursion



Toussaint L'Ouverture International Airport, Port-au-Prince, Haiti

U.S. Embassy, Port-au-Prince, Haiti

Incident Response Vehicle (IRV) TEAM

7 personnel

5 vehicles:

- IRV
- LOS Van
- LMR Tower Trailer
- Excursion
- F-350

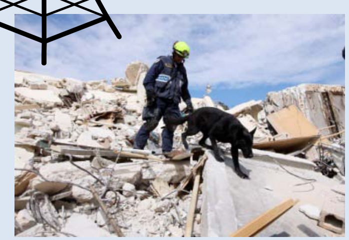
13 BGAN

4 PDR-3500 Repeater (2 VHF, 2 UHF)

64 XTS-5000 (40 VHF, 24 UHF)

10 Iridium satellite phones

Wide-Area Search and Rescue Support Port-au-Prince, Haiti



Land Mobile Radio (LMR) TEAM

2 personnel

1 FCV

6 PDR3500 UHF repeaters

Base stations

Portable LMR assets

Satellite assets

Problem Statement

How can emergency managers and responders, at all levels of government and in the private sector, maintain critical communications during and after an extreme space weather event?

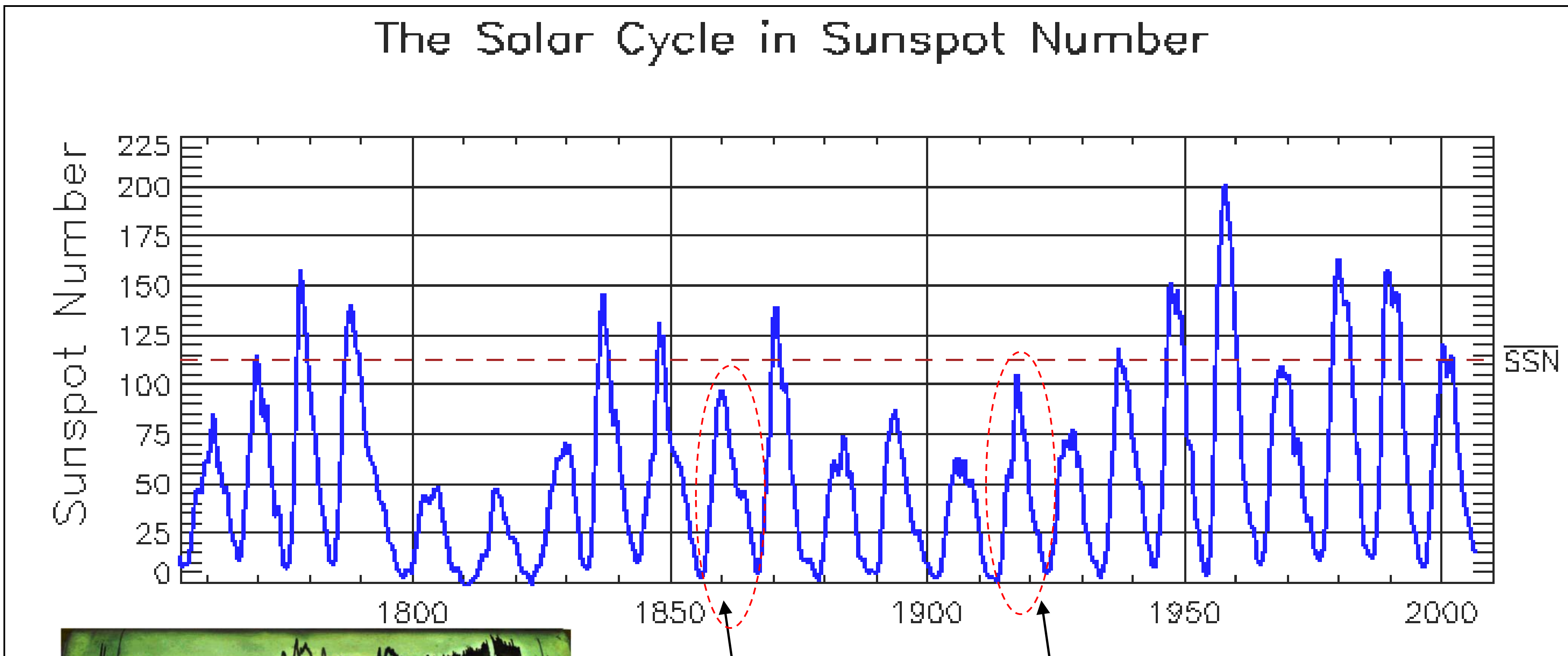
Extreme Space Weather Has Happened Before

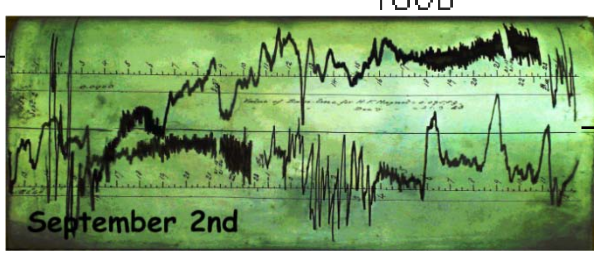
Morse Telegraph Table
Photo from www.telegraphlore.com

- 1847 – "Anomalous current" noted on telegraph line between Derby and Birmingham. First recorded impact of solar weather on technology.
- August 28-29, 1859 – Telegraph service disrupted worldwide by geomagnetic superstorm.
- September 1-2, 1859 – Carrington-Hodgson event is largest geomagnetic storm in 500 years.
- May 16, 1921 – The "Great Storm" disrupted telegraph service, caused fires, burned out cables. **Storms like this may occur roughly every 100 years.**
- March 13, 1989 – Geomagnetic storm collapsed Quebec power grid. Northeast U.S. and Midwest power grid came within seconds of collapse.
- October 19 – November 7, 2003 – "Halloween Storms" interrupted GPS, blacked out High Frequency (HF) radio, forced emergency procedures at nuclear power plants in Canada and the Northeastern United States, and destroyed several large electrical power transformers in South Africa.

Historical Solar Cycles

- Large geomagnetic storms can occur with smaller cycles
- The largest geomagnetic storms on record occurred during lower than average cycles



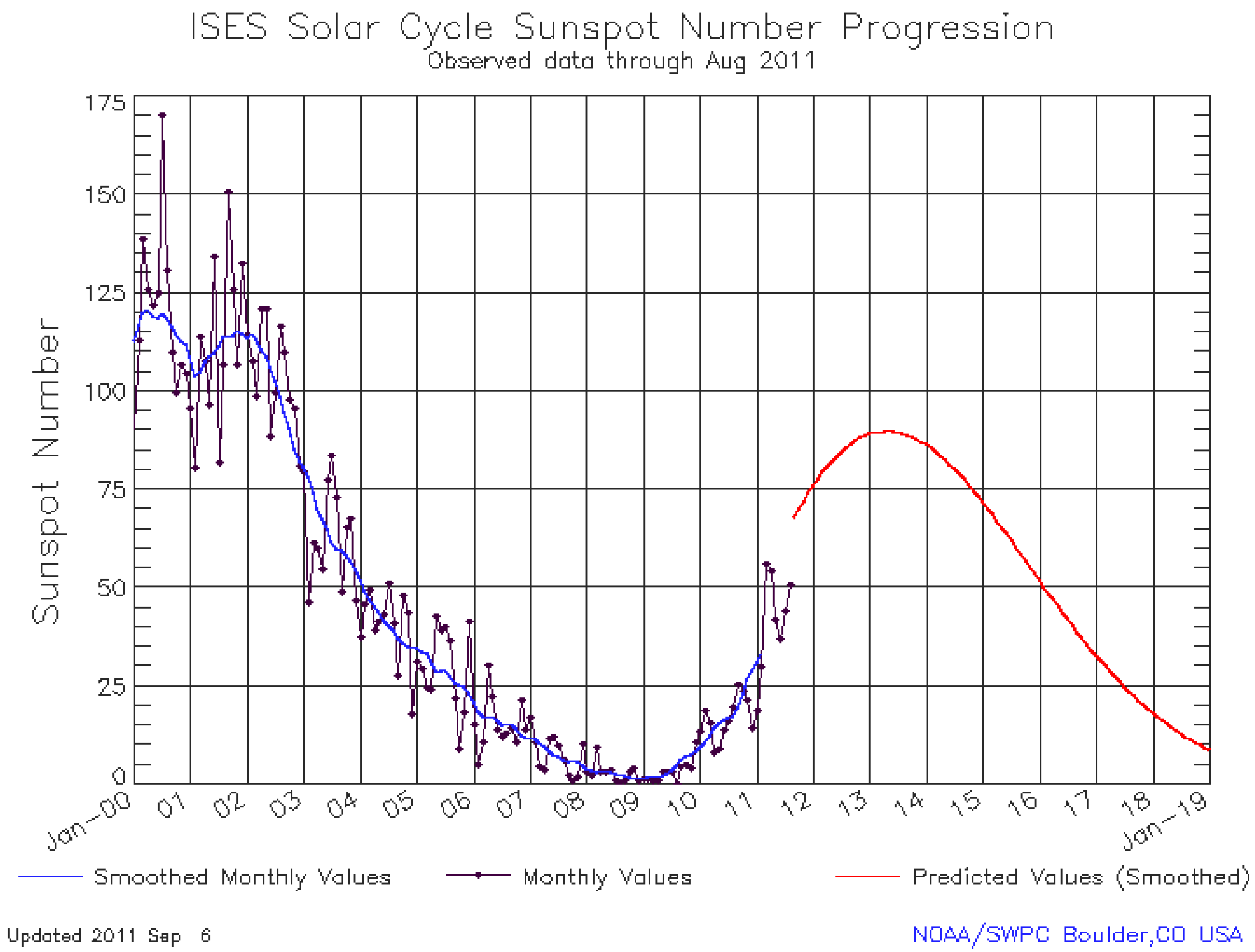


1859 Storm

1921 Storm

Status of Solar Cycle

- **Solar minimum in December 2008**
- **Solar Cycle 24 now well underway**
- **Cycle 24 maximum forecast - May 2013**



NOAA Space Weather Scales

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

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
Scale	Descriptor	Duration of event will influence severity of effects		
		Radio Blackouts		
R 5	Extreme	**HF Radio:**Complete HF (high frequency**) radio blackout on t sunlit side of the Earth lasting for a number of hours. This result radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritim aviation systems experience outages on the sunlit side of the Ear hours, causing loss in positioning. Increased satellite navigation positioning for several hours on the sunlit side of Earth, which m into the night side.		
R 4	Severe	**HF Radio:** : HF radio communication blackout on most of the s Earth for one to two hours. HF radio contact lost during this time **Navigation:** Outages of low-frequency navigation signals cause error in positioning for one to two hours. Minor disruptions of sa navigation possible on the sunlit side of Earth.		
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, los contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for abo		
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sur of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals fo minutes.		
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communica side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for bri		

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

Radio Blackouts

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yr)
Scale	Descriptor	Duration of event will influence severity of effects		
		Solar Radiation Storms	Flux level	Number of
S 5	Extreme	**Biological:** unavoidable high radiation hazard to astronauts on EV vehicular activity); high radiation exposure to passengers and cre commercial jets at high latitudes (approximately 100 chest x-rays **Satellite operations:** satellites may be rendered useless, memory cause loss of control, may cause serious noise in image data, star- be unable to locate sources; permanent damage to solar panels po **Other systems:** complete blackout of HF (high frequency) comm possible through the polar regions, and position errors make navi operations extremely difficult.		
S 4	Severe	**Biological:** unavoidable radiation hazard to astronauts on EVA; radiation exposure to passengers and crew in commercial jets at h (approximately 10 chest x-rays) is possible. **Satellite operations:** may experience memory device problems a imaging systems; star-tracker problems may cause orientation pr solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through th regions and increased navigation errors over several days are like		
S 3	Strong	**Biological:** radiation hazard avoidance recommended for astrona passengers and crew in commercial jets at high latitudes may rec radiation exposure (approximately 1 chest x-ray). **Satellite operations:** single-event upsets, noise in imaging syste reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the pola navigation position errors likely.		
S 2	Moderate	**Biological:** none. **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the pol navigation at polar cap locations possibly affected.		
S 1	Minor	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.		

Radiation Storms

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

Geomagnetic Storms

Solar Flare Radio Blackouts

R-scale

- Arrival: No warning *(speed of light)*
- Duration: minutes to 3 hours
- Daylight-side impact only

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

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

Radiation Storms

S-scale

- Arrival: 30 minutes to several hours
- Duration: hours to days

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yr)
Scale	Descriptor	Duration of event will influence severity of effects		
		Solar Radiation Storms	Flux level of >= 10 MeV particles (ions)*	Number of events when flux level was met **
S 5	Extreme	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) is possible. **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays) is possible. **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest x-ray). **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** none. **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.	10	50 per cycle

Geomagnetic Storms

G-scale

- Arrival: 18 - 90 hours
- Duration: hours to 1-2 days

- NOTE: High levels of solar activity can produce prolonged periods (several days) of geomagnetic storming.

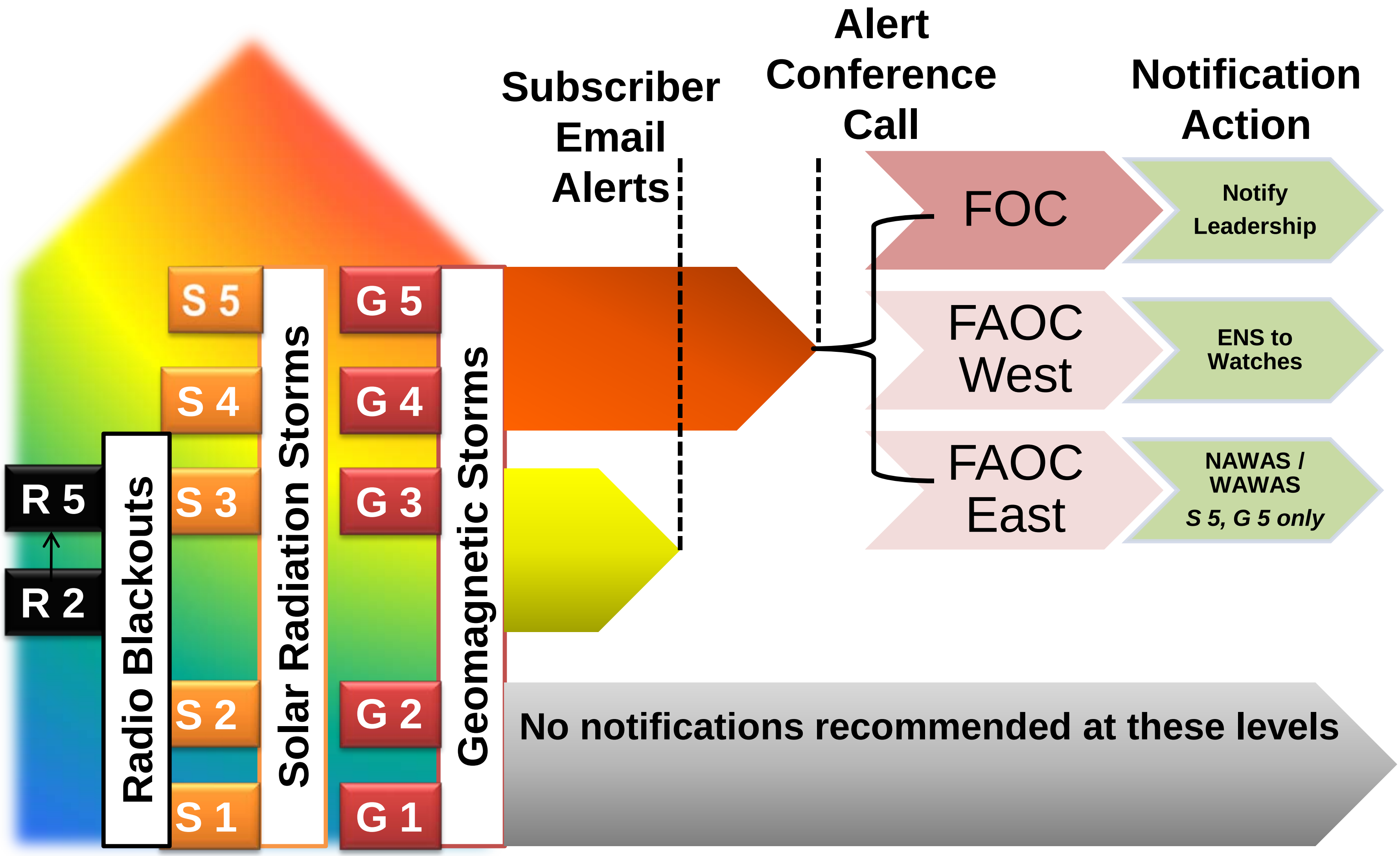
Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
Scale	Descriptor	Duration of event will influence severity of effects		
		Geomagnetic Storms	Kp values* determined every 3 hours	Number of storm events when Kp level was met
G 5	Extreme	**Power systems:** : widespread voltage control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

Assessing the Risk

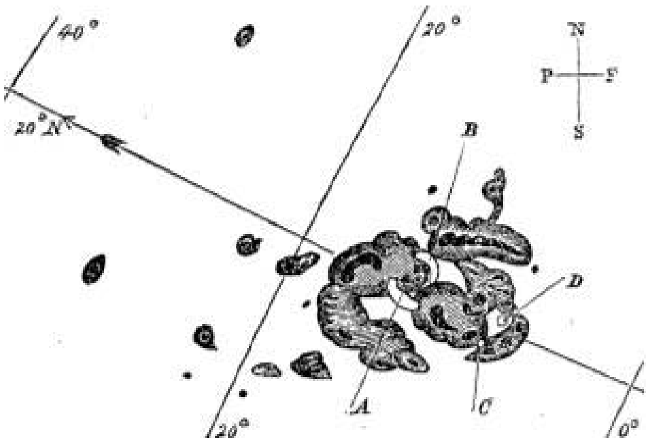
- Storms (R, S, and G) at levels 1-3 on the NOAA Space Weather Scales have little or no impact on normal operational communications or systems.
- 1859 Carrington-Hodgson superstorm was the largest in the last 500 years and such storms appear to occur roughly every 500-600 years.
- Destructive superstorms may occur roughly once in every 100 years. It has been 90 years since the "Great Storm" of 1921.
- The North American Power Grid is vulnerable but at least some electric utility providers are implementing mitigation and response measures.

The next solar maximum will occur in 2013 and is expected to be the weakest cycle since the 1930s. The largest solar superstorms have occurred in less active solar cycles. (Less active cycles do not imply greater storms).

Space Weather Alerts and Notifications



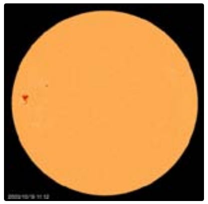
The Scenario



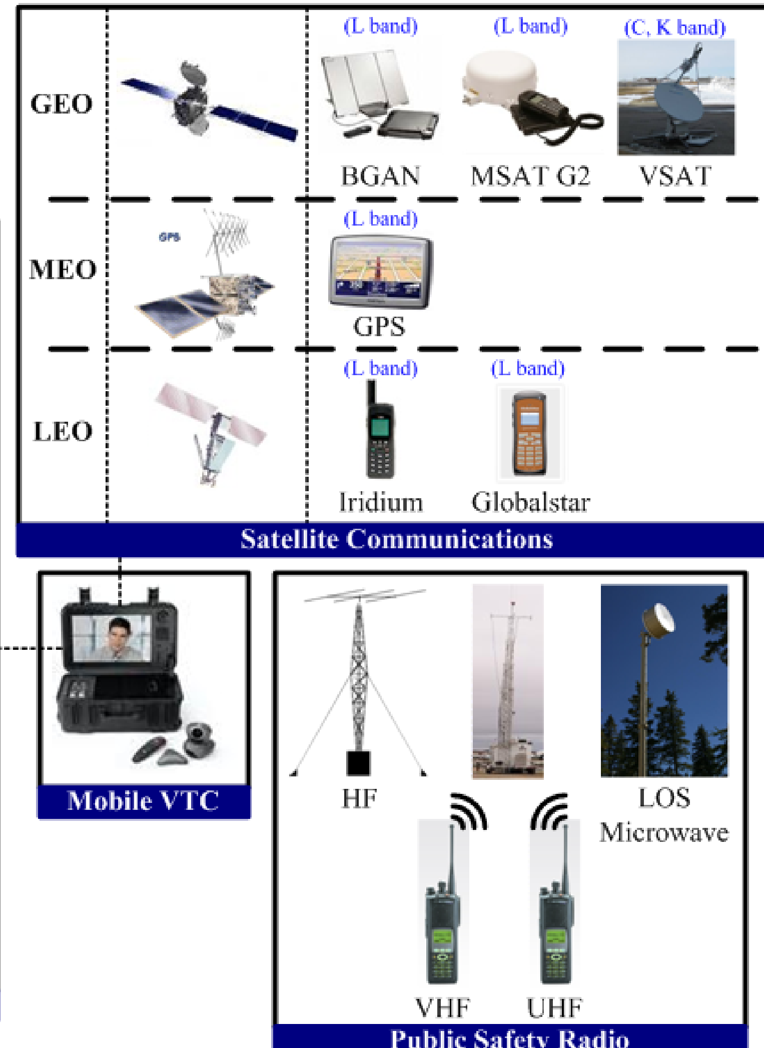
Drawing of 1859 sunspot group and flare (A and B) by Richard C. Carrington.

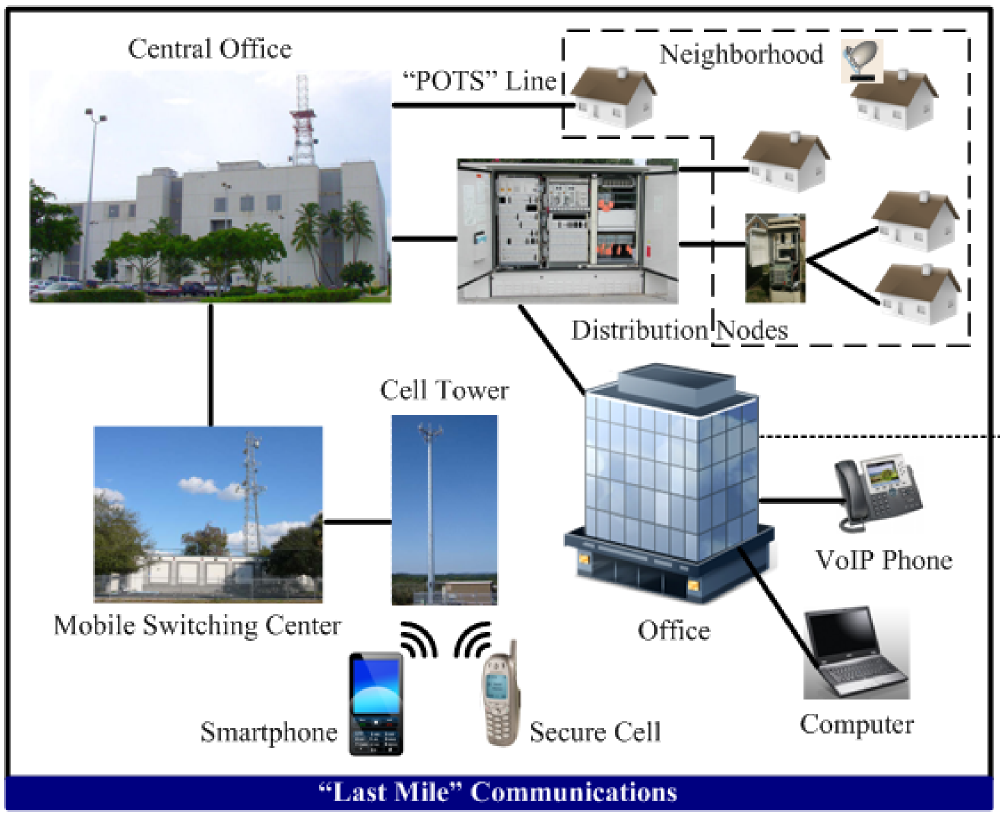
- Repeat of September 1-2, 1859, Carrington-Hodgson event
- All three primary types of space weather
  - Radio blackout
  - Solar radiation storm
  - Geomagnetic storm

Scenario: (Baseline)



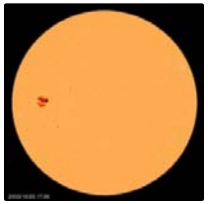
A very large, complex sunspot group emerges near the solar equator



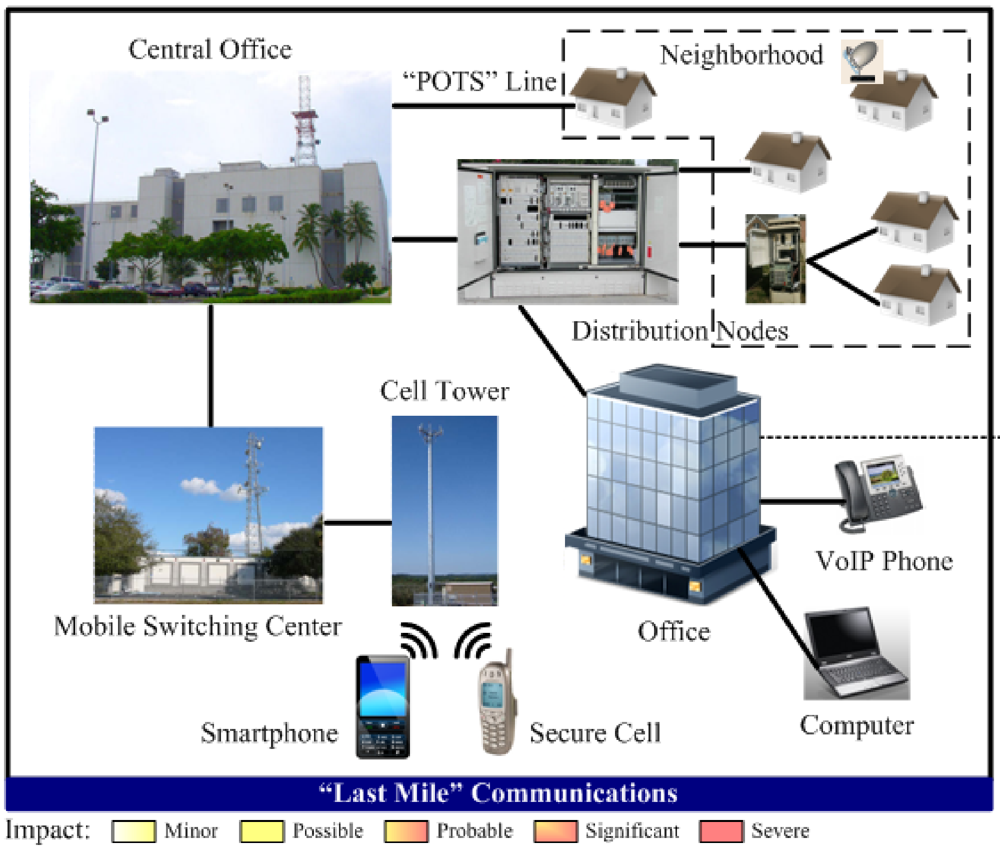


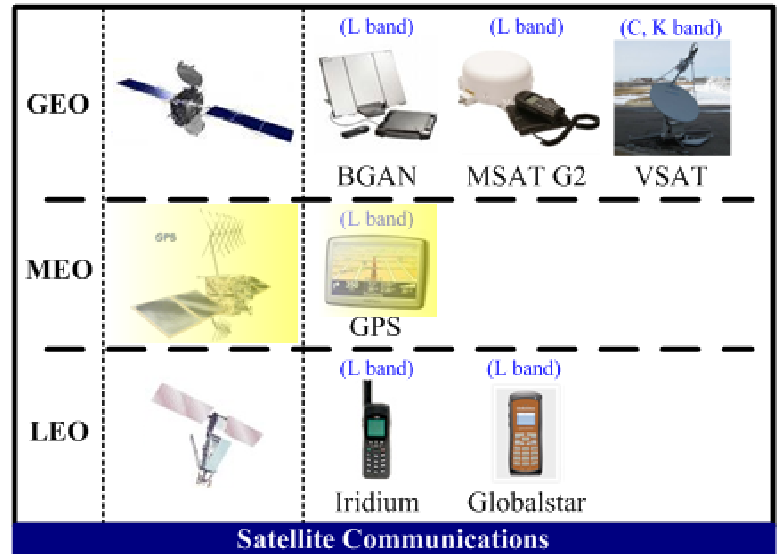
"Last Mile" photos courtesy of AT&T

Scenario: R1-R3 Radio Blackout Events

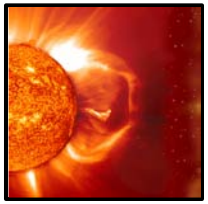


Earth is struck by multiple R1 (minor) - R3 (strong) events.
- HF: Minutes to 3 hours (daylight side)
- GPS: Seconds to 15 Minutes
- Line-of-sight public safety radio not impacted





Scenario: R5 Radio Blackout Event

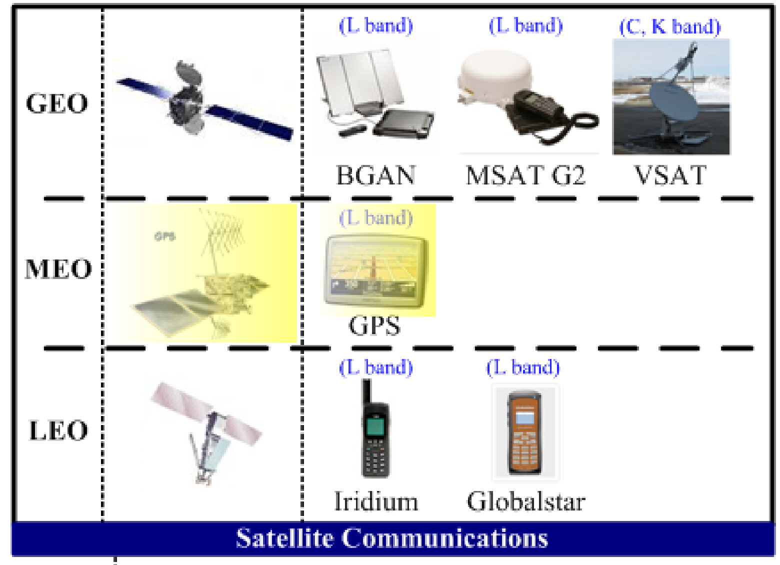


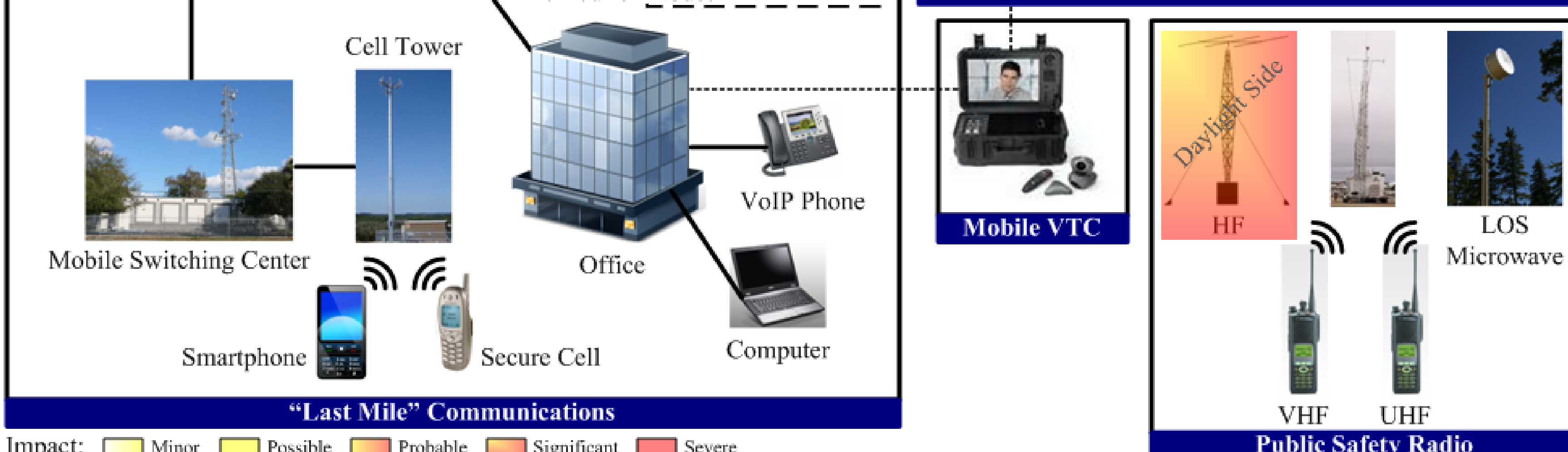
Massive solar flare erupts above near-center-disk sunspot group.

- HF: Several hours (daylight side)

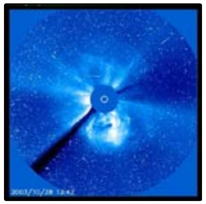
-GPS: Seconds to 15 Minutes

- Little or no impact to line-of-sight public safety radio





Scenario: S5 Solar Radiation Storm

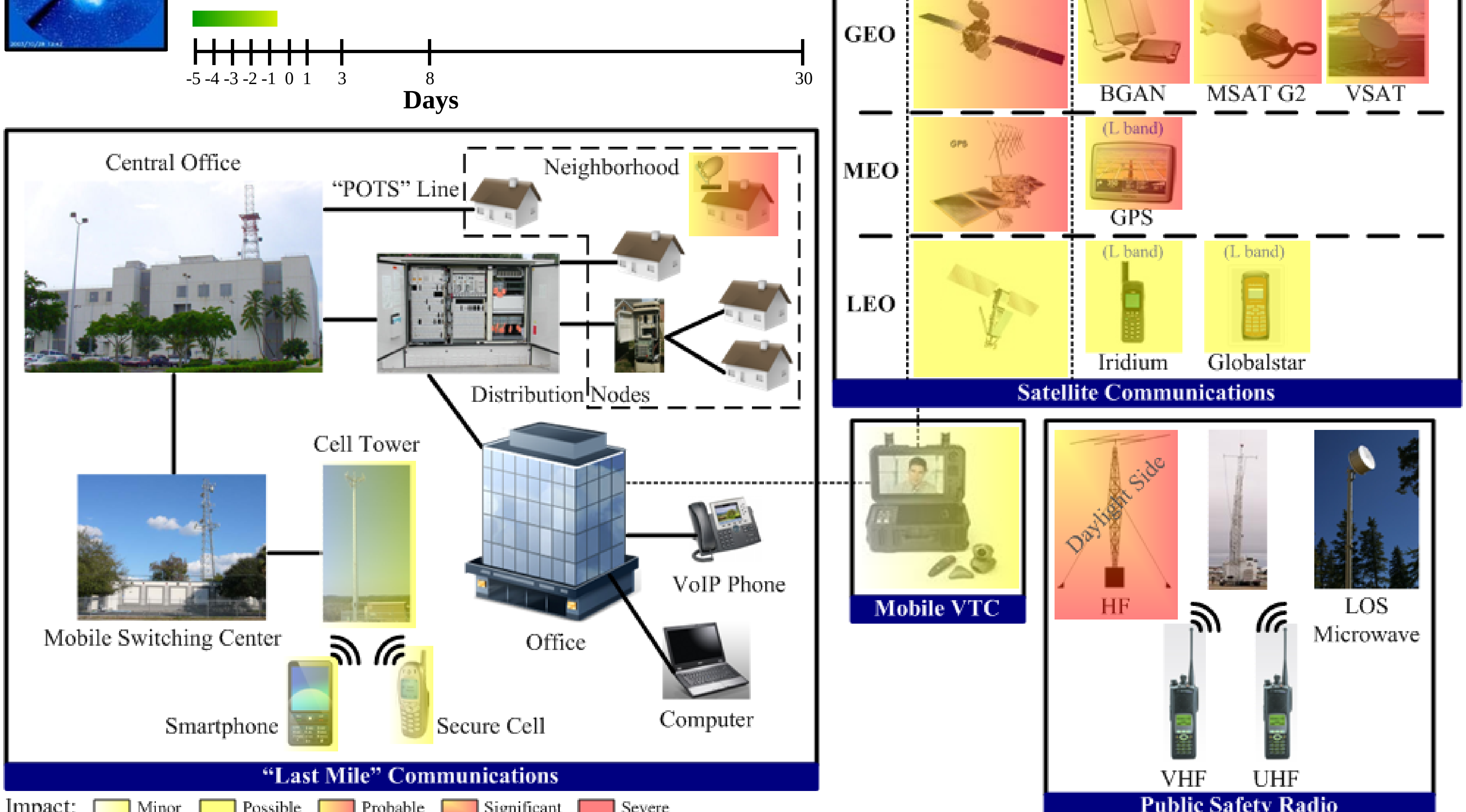


Solar radiation storm arrives twenty minutes after solar flare. Radio blackout event continues.

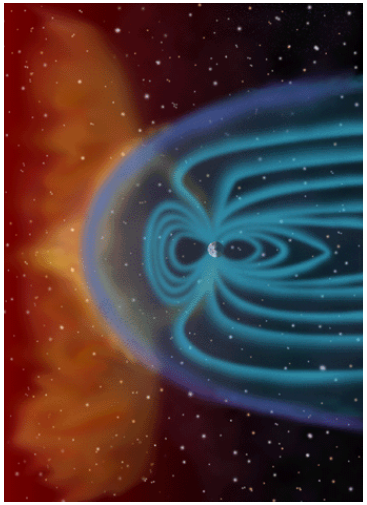
- 3-24 hours (various effects)

≈ 15% of satellite fleet lost due to solar panel damage

≈ 50 times normal satellite anomalies



Scenario: G5 Geomagnetic Storm



- NASA ACE satellite provides approximately 15 minutes warning of the southward interplanetary magnetic field orientation of the coronal mass ejection.
- Approximately 18 hours after the initial solar flare, the massive, fast-moving CME arrives at the Earth.
- The physical shock of the CME pushes the daylight side of the magnetosphere inside the geostationary orbit, exposing GEO satellites on the daylight side directly to the solar plasma.

Scenario: Scintillation

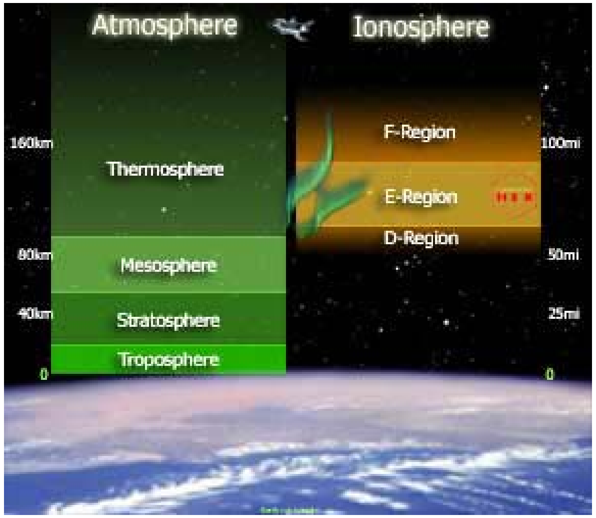


Image courtesy of solar-center.stanford.edu

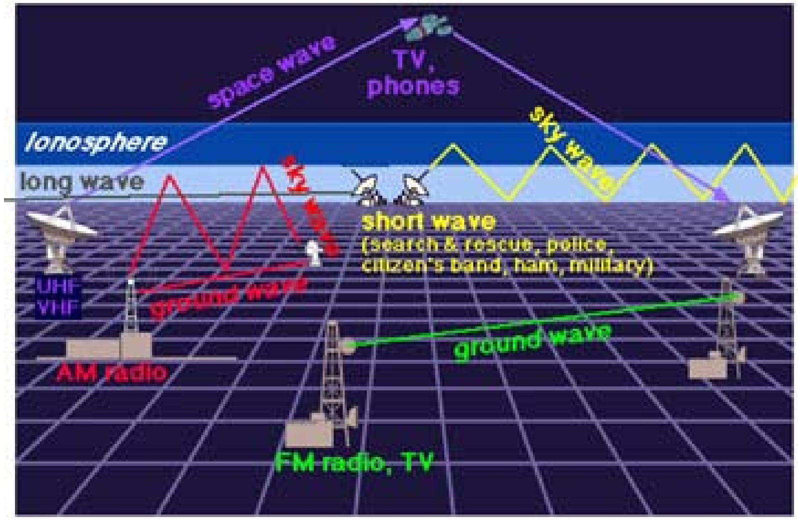
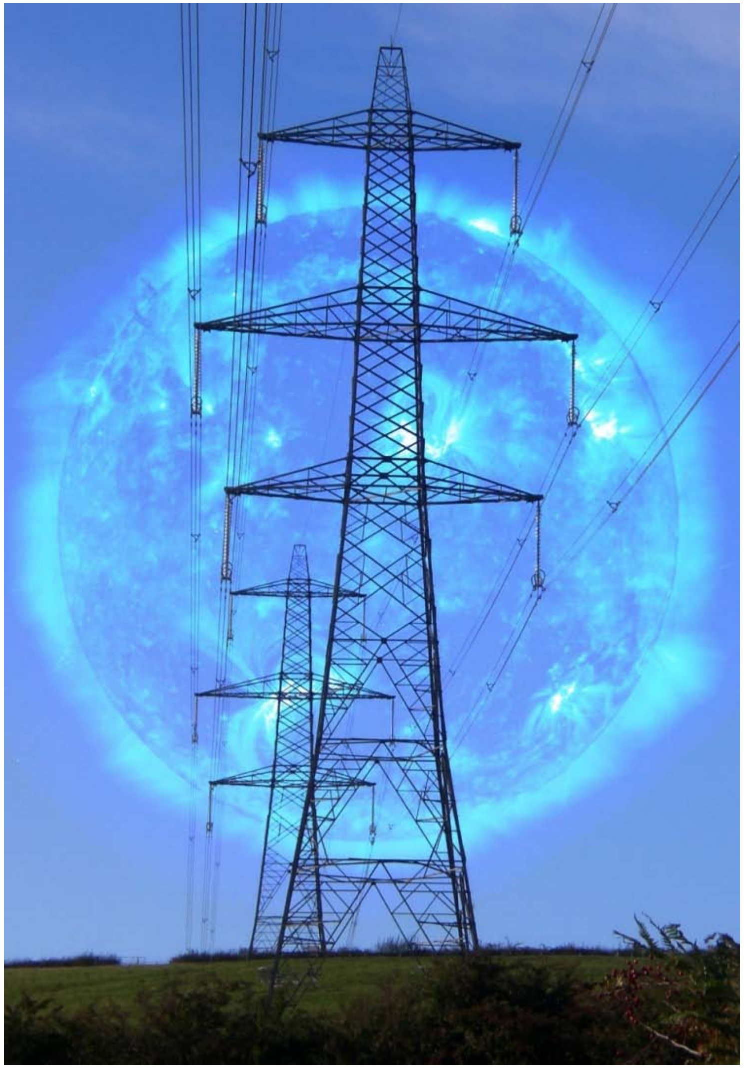


Image courtesy of Windows to the Universe

- Southward magnetic orientation of the CME creates immense currents in the ionosphere called "electrojets."
- These currents cause scintillation, which can change the amplitude, phase, polarization, and angle-of-arrival of signals. Scintillation can become so severe that it represents a practical limitation for communication systems.
- Scintillation can degrade or even prevent signals to and from satellites for 12-24 hours.
- HF communications may be helped during this period due to enhancement of the ionosphere F Layer that could improve reflectivity.
- **Little if any direct impact to public safety line-of-sight radio, to include VHF air-to-ground radio below 30,000 feet (air search & rescue).**

Scenario: Power

- Almost all modern technology relies on the reliable delivery of electric power
- Dependencies between complex systems are difficult to understand



(Credit: K. Turnbull / J. Wild / ESA)

Scenario: Power

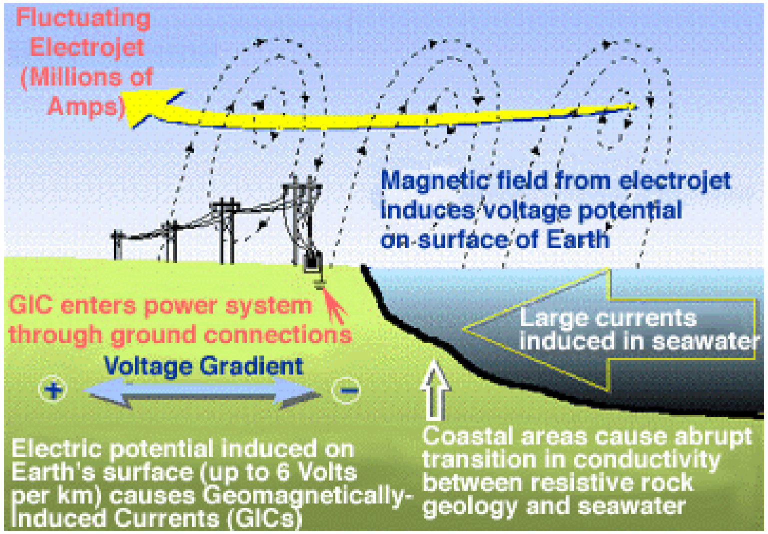


Image courtesy of John G. Kappenman

- Electrojet magnetic fields induce currents in the Earth.
- Geomagnetically-induced currents (GICs):
  - Are quasi-DC currents – effects electrical transformers
  - Can affect power systems at all latitudes
  - Can affect many power transformers simultaneously at multiple points across regional and continental scale power networks
  - Can reach 100s of amps?
  - Seek “path of least resistance” – high-voltage power lines and pipelines have very low resistance
  - Enter power networks through ground connections

Scenario: 50 ° Electrojet over East Coast

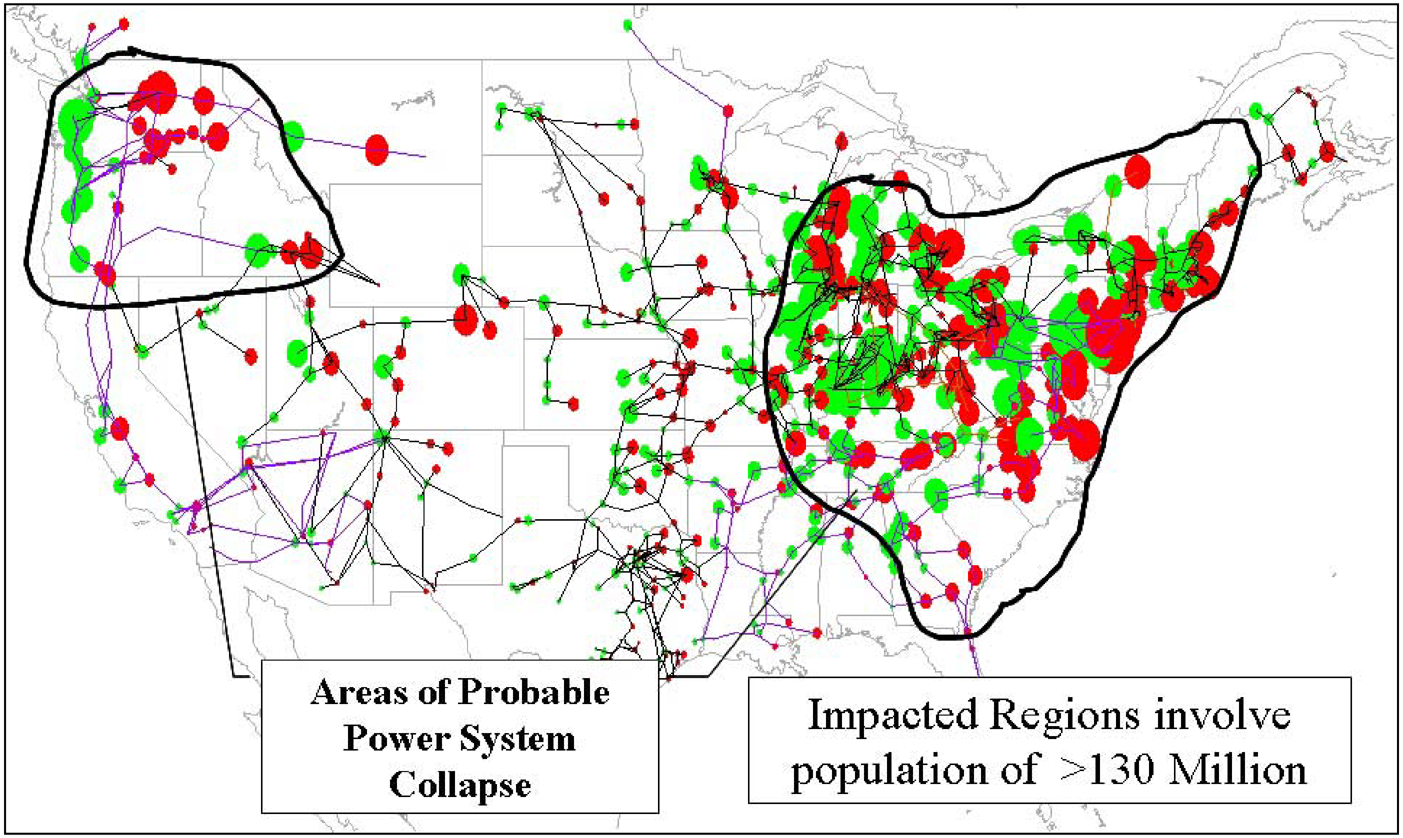


Image courtesy of NASA, Original by Metatech Corp

- 100 Year Geomagnetic Storm Impact on the North American Power Grid Electrojet at 50 north latitude with main effect over Atlantic Coast.
- ≈350 extra-high voltage (EHV) transformers permanently damaged?

Scenario: 45° Electrojet over East Coast

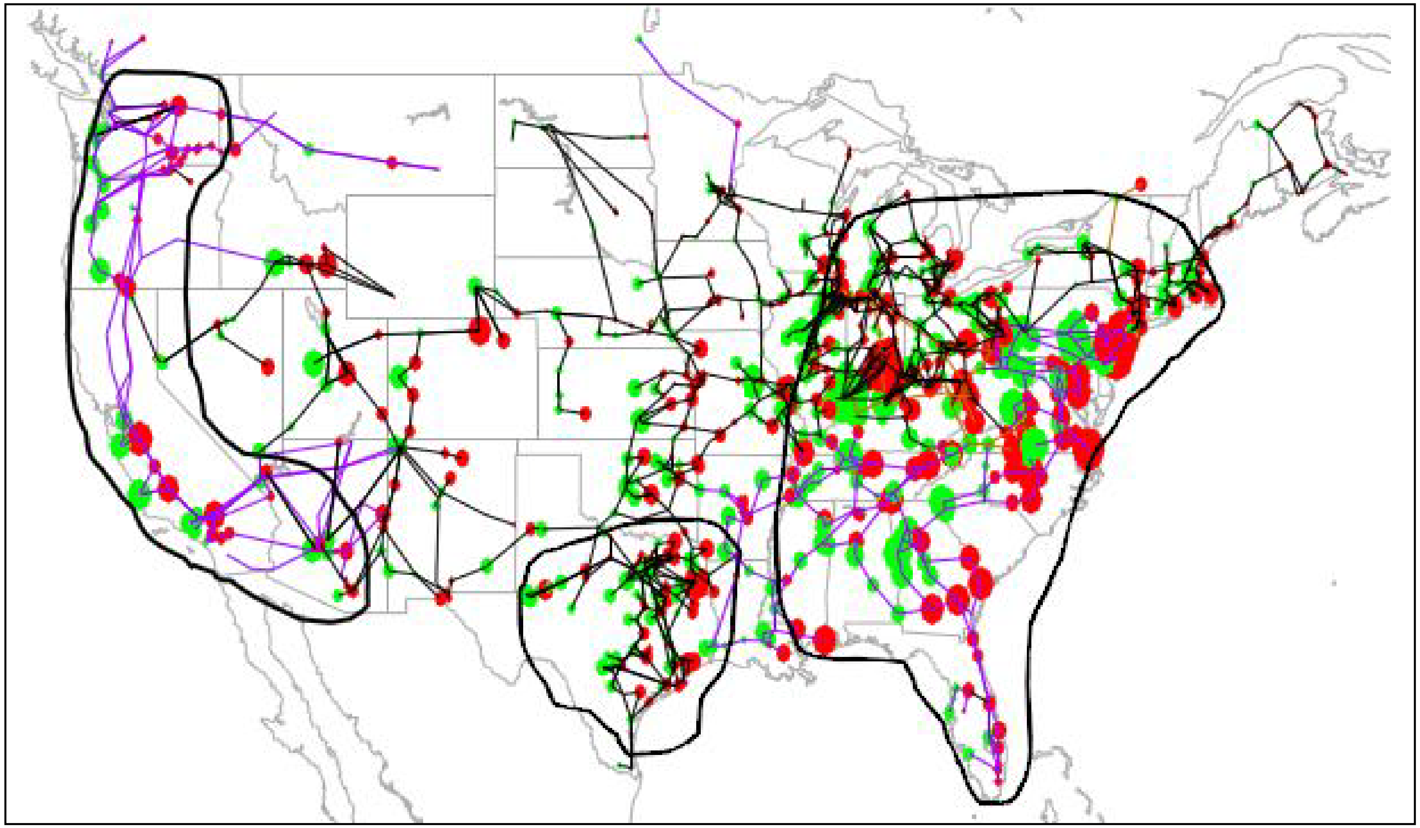
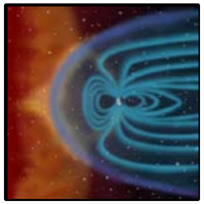


Image courtesy of Metatech Corp

- 100 Year Geomagnetic Storm Impact on the North American Power Grid Electrojet at 45 north latitude with main effect over Atlantic Coast.

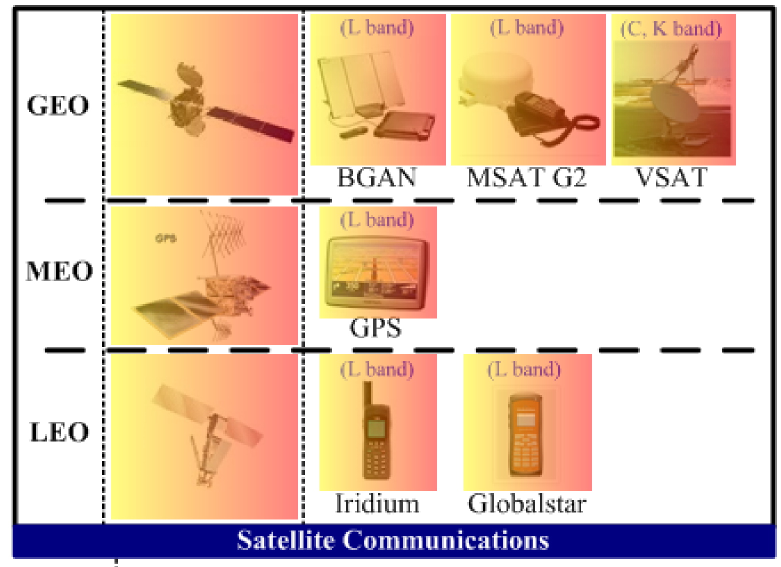
- ≈600 extra-high voltage (EHV) transformers permanently damaged?

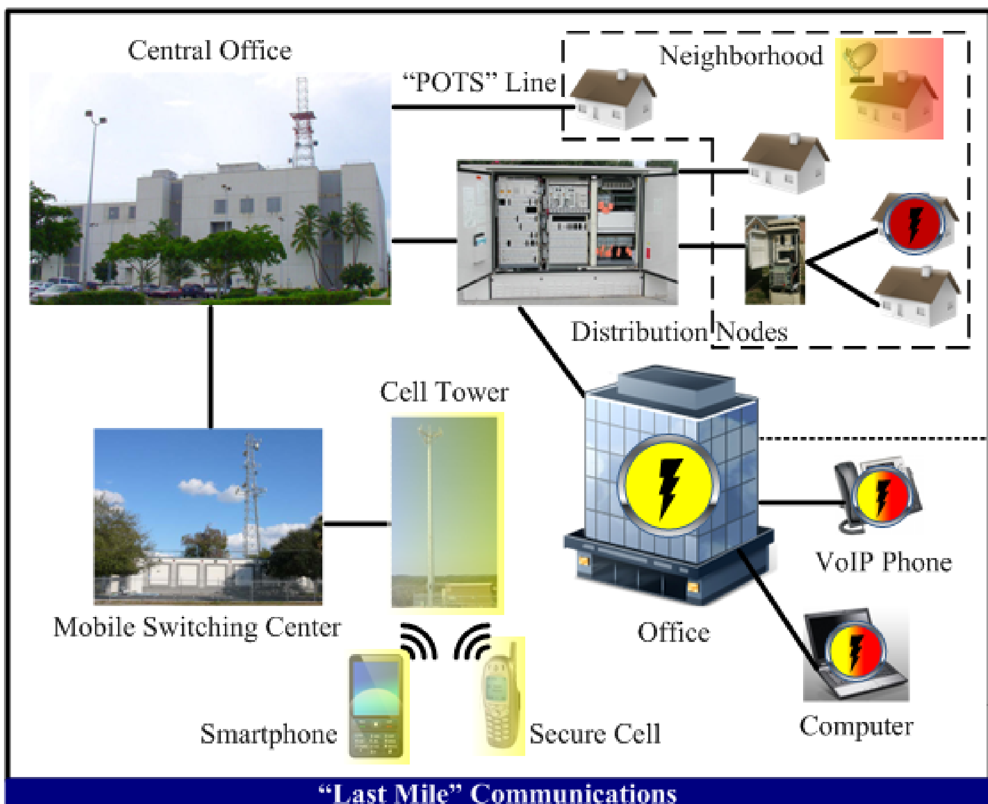
Scenario: G5 Geomagnetic Storm

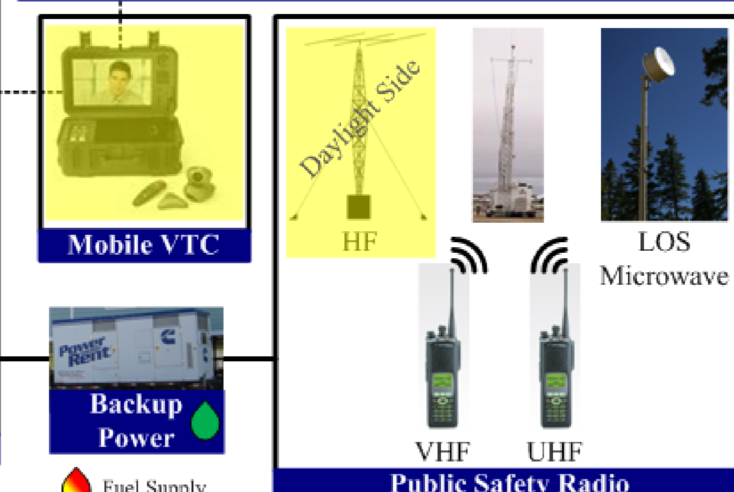


CME with southward magnetic orientation arrives at Earth causing extreme geomagnetic storm.

- 12-24 hours (various effects)
- SATCOM/GPS severely disrupted due to scintillation
- HF may be possible



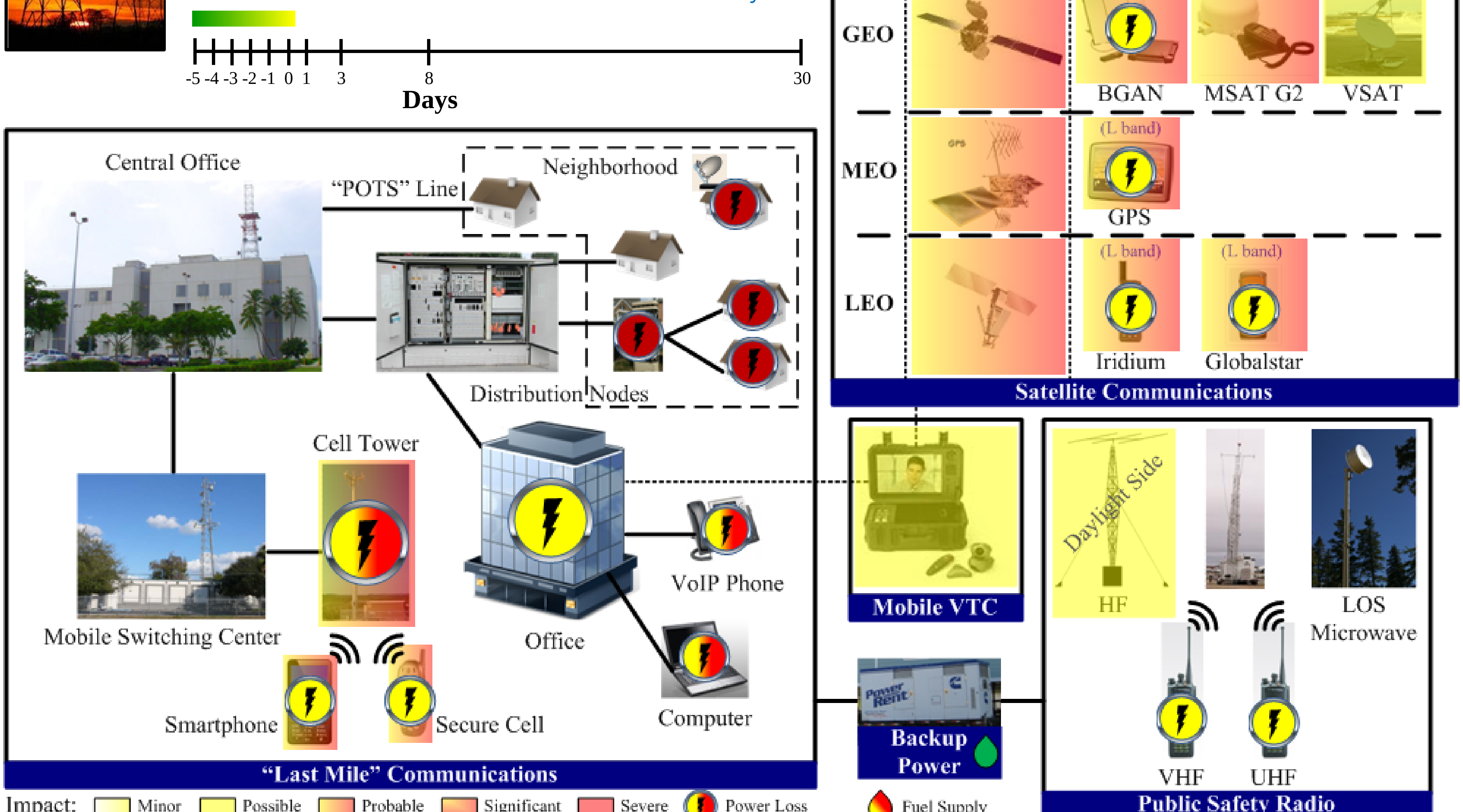




Impact: Minor Possible Probable Significant Severe Power Loss Fuel Supply

Scenario: G + 8 Hours

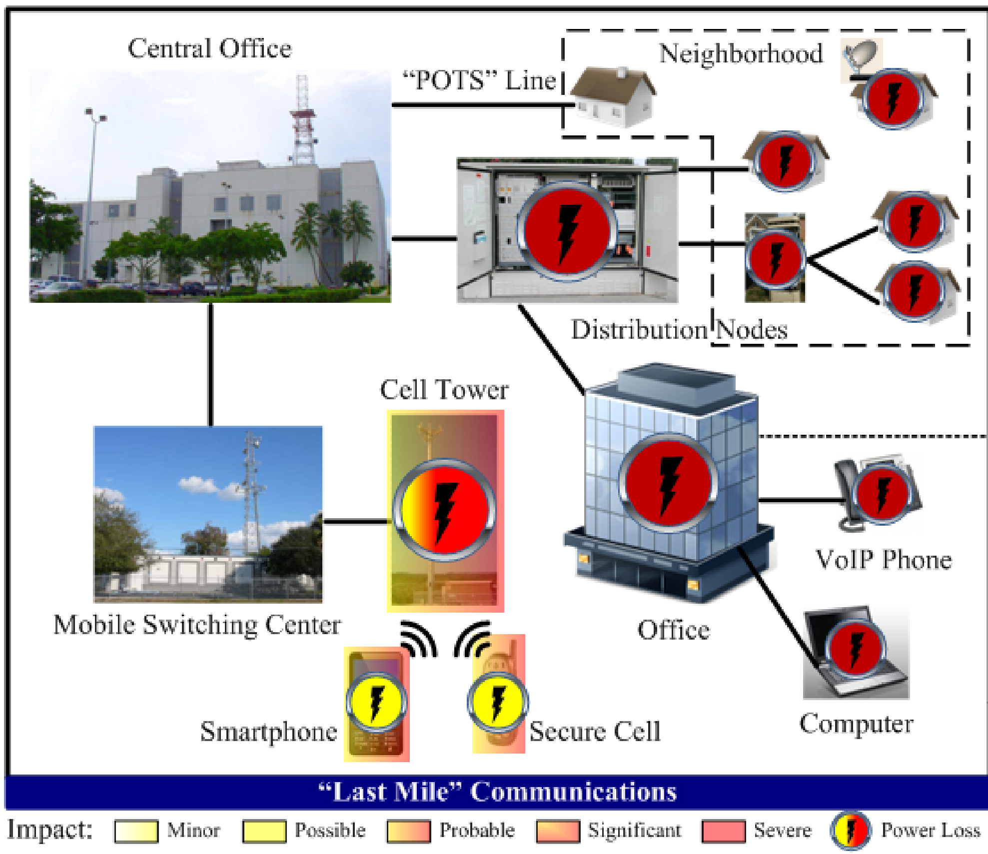
Loss of power begins to effect “last mile” communications
- Numerous cellular towers begin to fail
- Battery backup fails in homes and offices
- HF communications intermittent for next three days

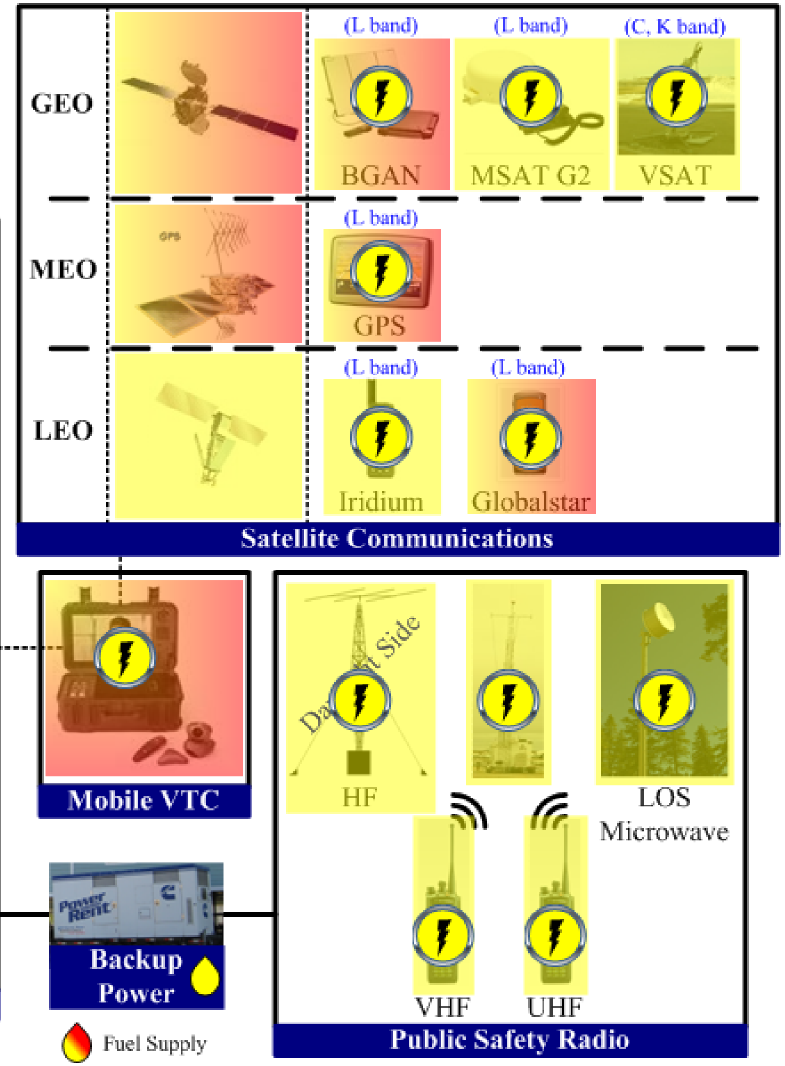


Scenario: G + 24 Hours

Loss of power begins to effect critical systems

- Telecommunications distribution nodes begin to fail; may impact Land Mobile Radio repeater towers
- Power required to recharge equipment batteries

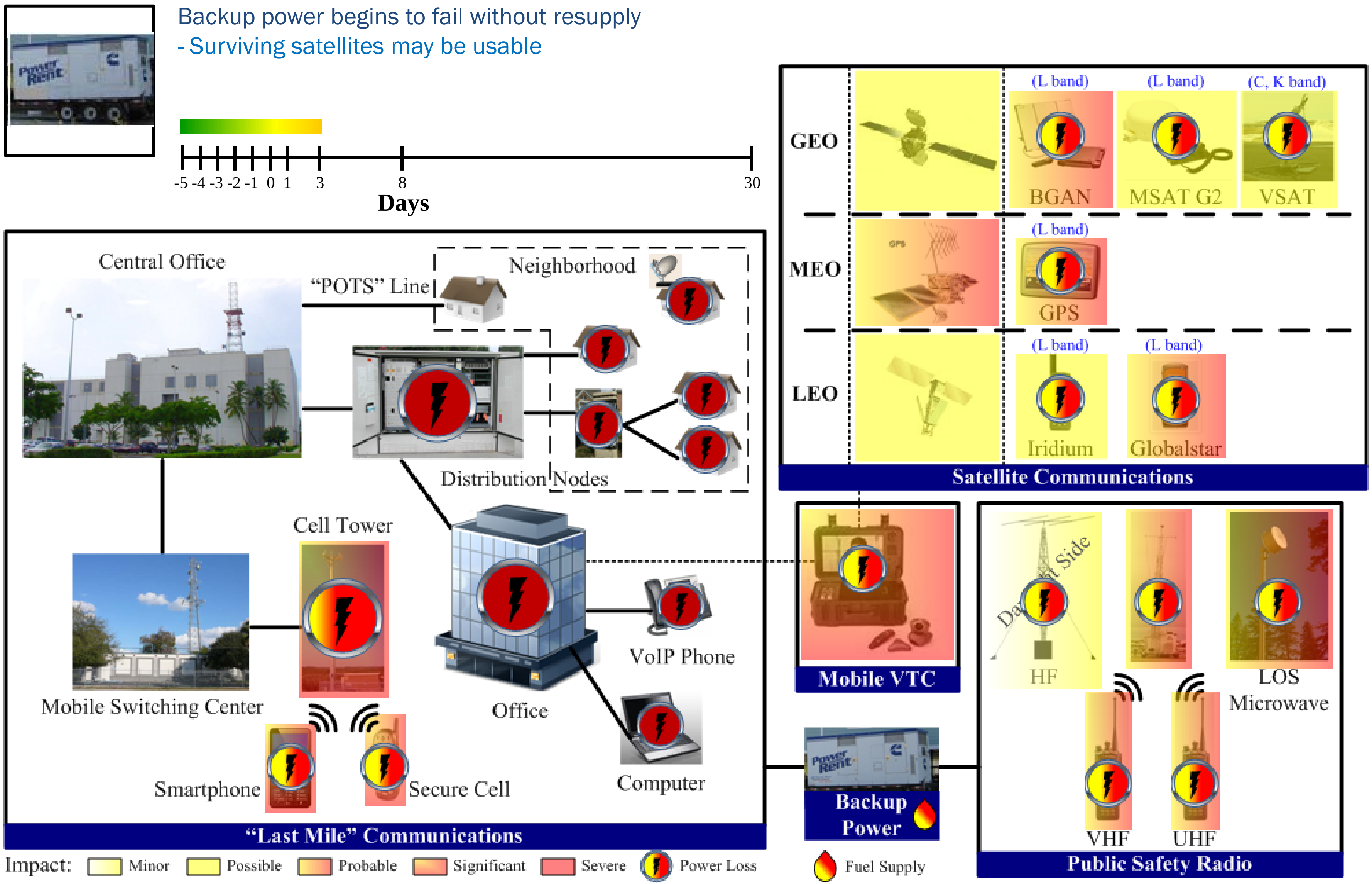




Scenario: G +72 Hours

Backup power begins to fail without resupply

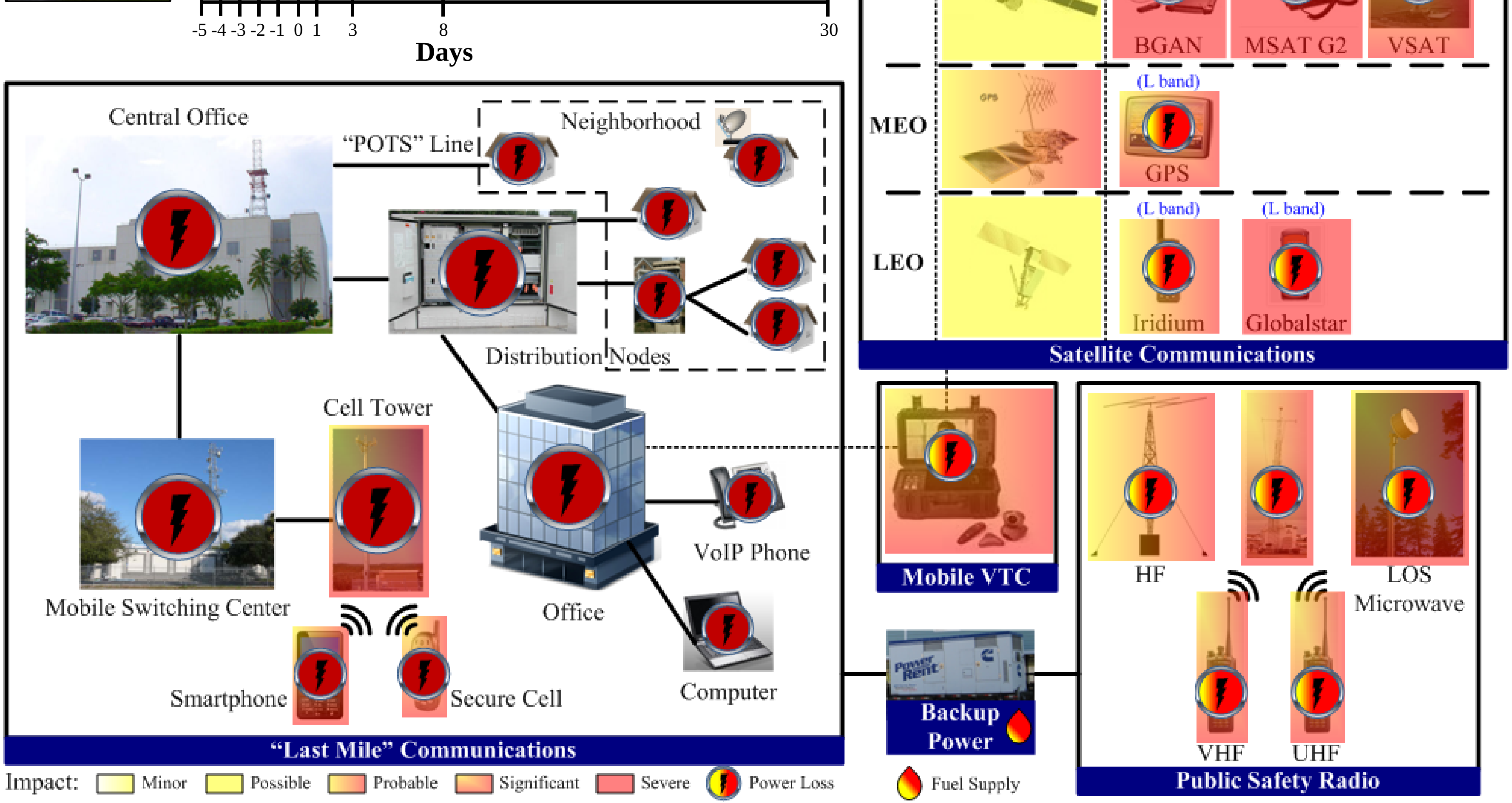
- Surviving satellites may be usable



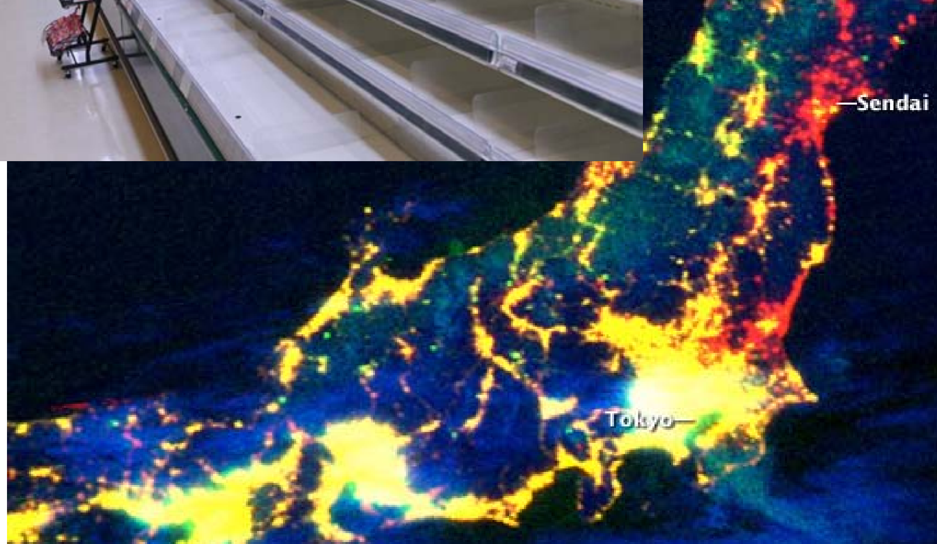
Scenario: G +8 Days

Without fuel and water, the Public Switched Network begins to fail.

- Widespread failure of telecommunications infrastructure; Internet "cloud" fails
- Any system that relies on the PSN cannot talk
- Widespread failure of operations centers



Scenario: Lessons Learned from Japan



“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)

Conclusions

- If we remove electric power from the equation, extreme space weather will cause:
  - The intermittent loss of HF and similar sky wave radio systems;
  - Little if any direct impact to public safety line-of-sight radio;
  - Relatively small loss of satellites as a percentage of the total satellite fleet;
  - Potential interference or intermittent loss of L band SATCOM (GPS, satellite phones)
  - Minimal direct impact to the Public Switched Telephone Network.

In other words, if electric power remains available, even the worst space weather event would be inconvenient, not catastrophic, for society.

Conclusions

- The actual impact from a 100- or 500-year storm on the electric power grid is ***hotly*** debated. It is unclear, at present, what the real impact will be.
  - Most government emergency operations centers can function for approximately 3-30 days on generator backup without refueling.
  - Most commercial operations centers and central offices can function for 3-18 days without refueling.
  - Government and private sector emergency managers operate on the assumption that fuel contracts and pre-arranged fuel deliveries will be available for resupply.

This may not be a safe assumption in an extreme space weather event!

Conclusions

- Diversify
  - Redundant and resilient satellite, radio, and terrestrial communications systems can provide critical communications throughout a superstorm. HF radio could be key to long term critical communications.
- Plan
  - Know what communications systems will work and ***when*** they will work. Know where and how to get fuel, water, and other consumables. **Don't forget your people.**
- Power, Power, Power
  - Have backup power available—and don't forget that generators need maintenance. If you can, consider renewable sources such as solar, wind, or fuel cells.
- Advocate
  - If you don't, who will. Many solutions to extreme space weather also solve for other hazards.

Questions

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