SPACE WEATHER EFFECTS ON COMMUNICATIONS SYSTEMS

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

Mark MacAlester
Communications Liaison
June 17, 2020

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

Who's Right?

Hurricane Watch Net

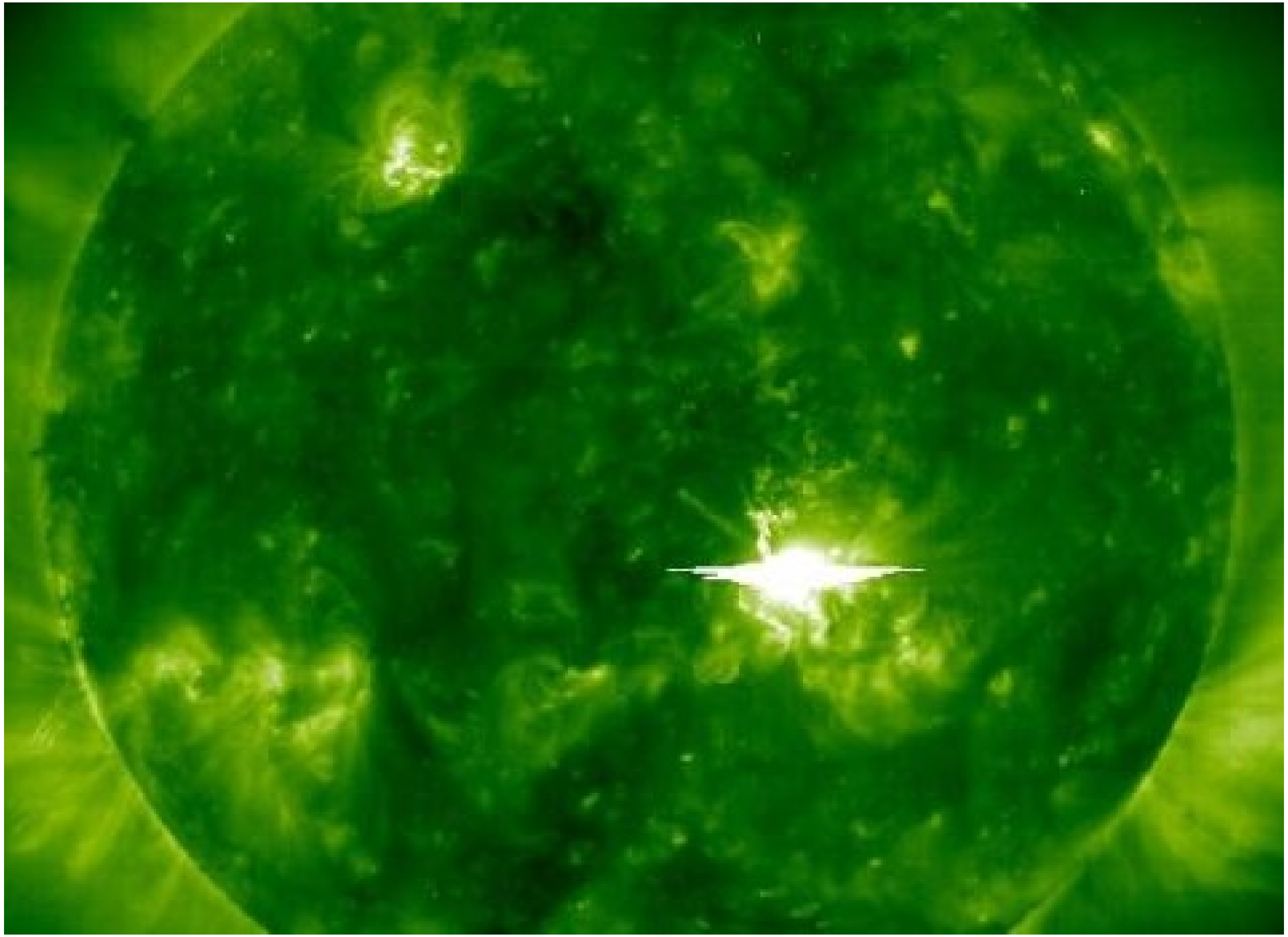
"While Hurricanes Harvey, Irma, Jose, and Maria tore through the Caribbean region, X-class flares, solar energetic particle (SEP) events, and Earth-directed coronal mass ejections (CMEs) plowed through the heliosphere. Caribbean emergency communication system operators reported **critical impacts to high-frequency (HF) radio links used in disaster response** and aviation tracking."

- Redmon, R. J., Seaton, D.B., Steenburgh,R., He, J., & Rodriguez, J. V. (2018). September 2017's geoeffective space weather and impacts to Caribbean radio communications during hurricane response. Space Weather, 16. https://doi.org/10.1029/2018SW001897

Government Operators

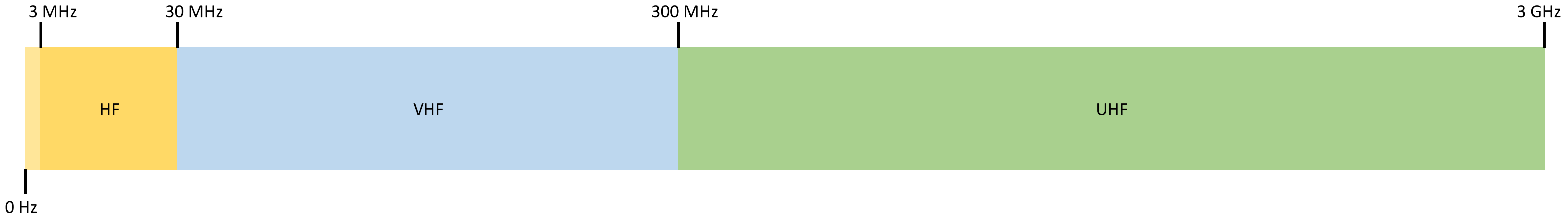
Federal Emergency Management Agency (FEMA) operators, their federal, state, and local emergency management partners supporting operations in the U.S. Virgin Islands and Puerto Rico used HF communications extensively. None reported any space weather related impacts to HF communications.

Radio Communications

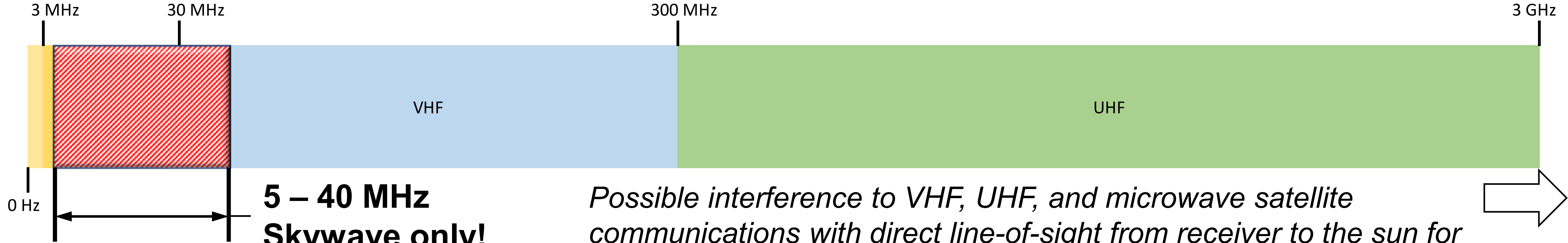


[Not a] Radio Blackout Event

Radio Spectrum



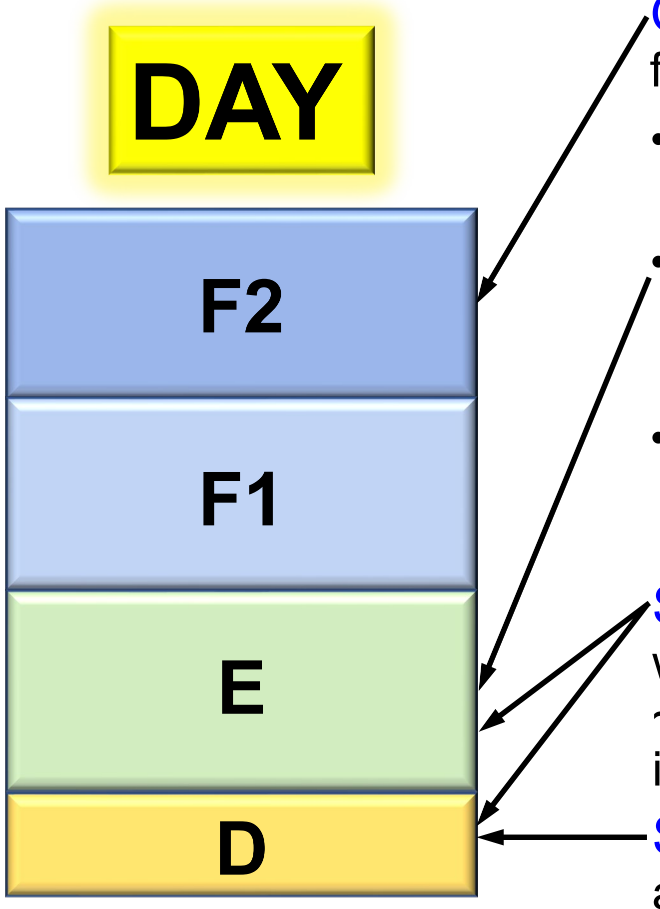
Solar Flare “Radio Blackout”



5 – 40 MHz
<u>Skywave</u> 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.)*

SW Effects on Ionosphere (Night)

NIGHT

F2

E

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.

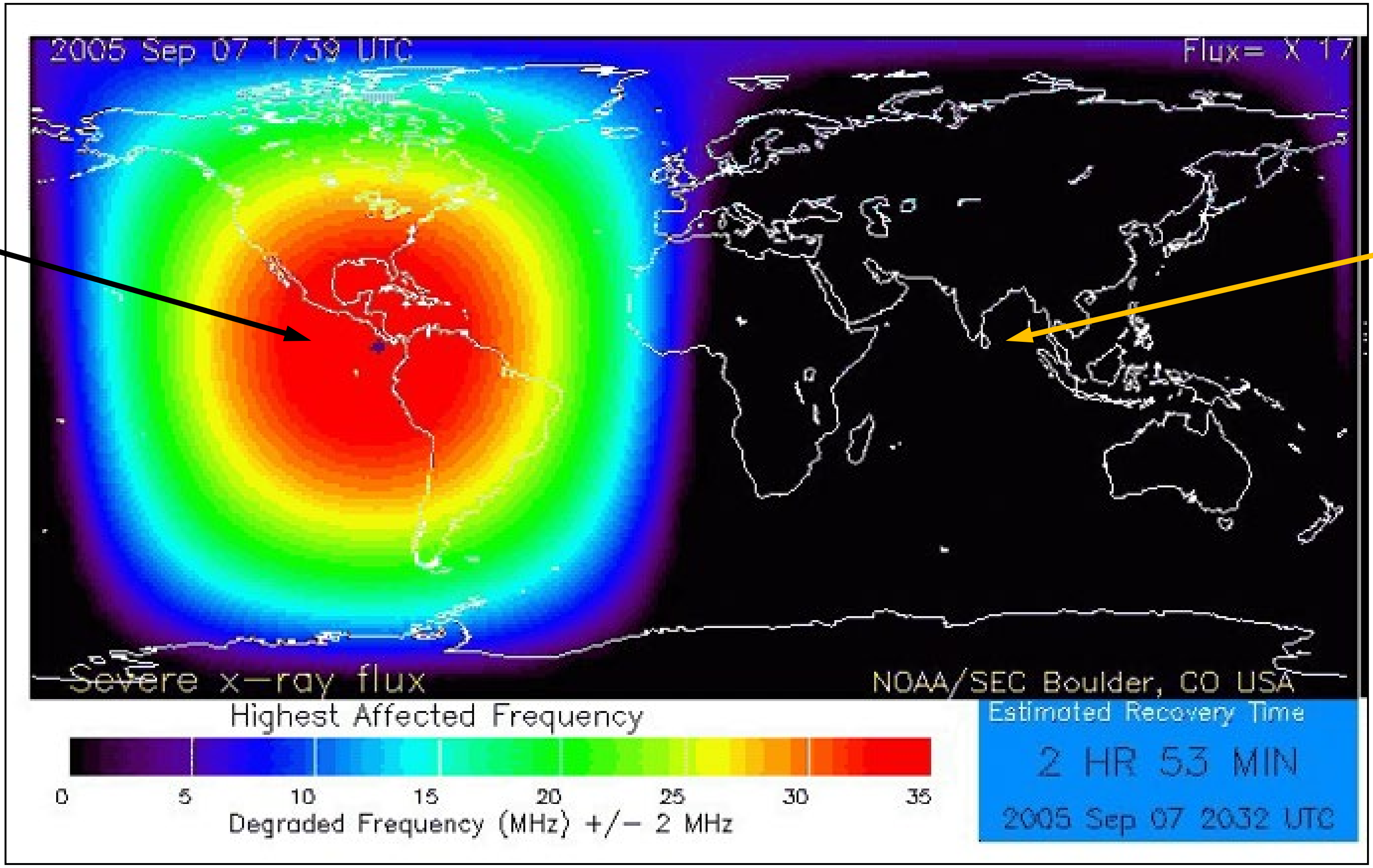
Solar Radiation Storm (S Scale) No **D** Layer to absorb radio signals. Absorption may extend to higher layers.

Solar Flare (R Scale) No **D** Layer to absorb radio signals.

Solar Flare Radio Blackout Effect (Visual)

DAY

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

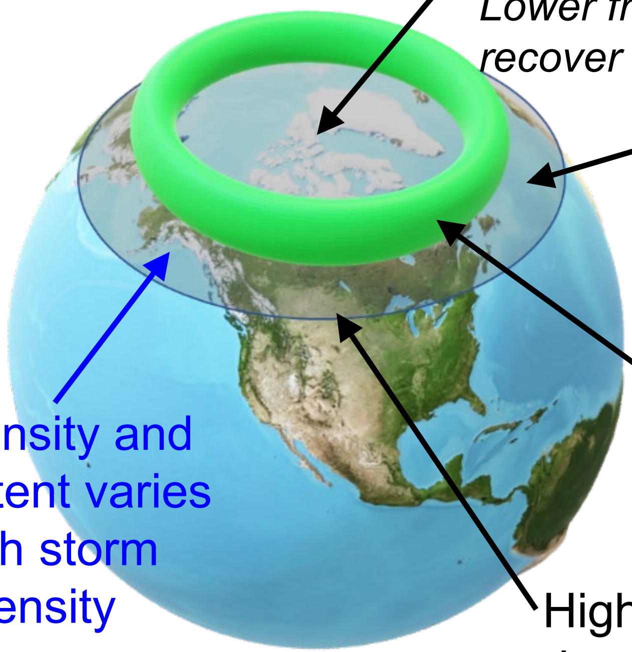


NIGHT

No **D** Layer to absorb radio signals.

Radiation and Geomagnetic Storms (Visual)

Solar Radiation Storm



Polar Cap Absorption event: *Lower frequencies impacted first, recover last*

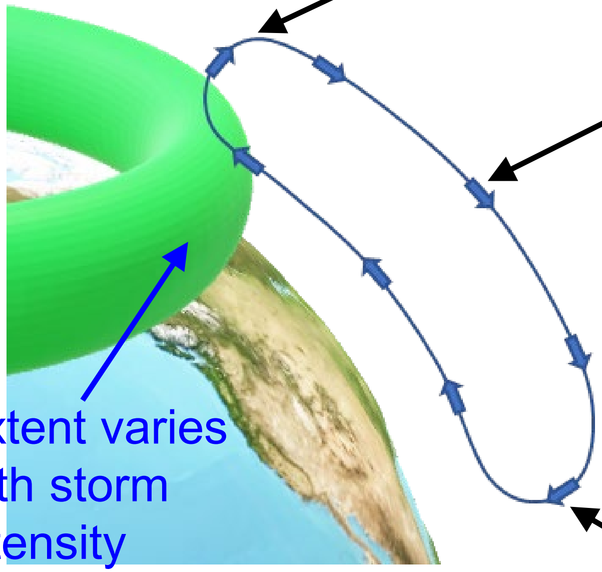
Full-coverage from pole to equatorward extent

Not highly correlated to the visible aurora

Higher ion density on day side (higher absorption)

Density and extent varies with storm intensity

Geomagnetic 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.*

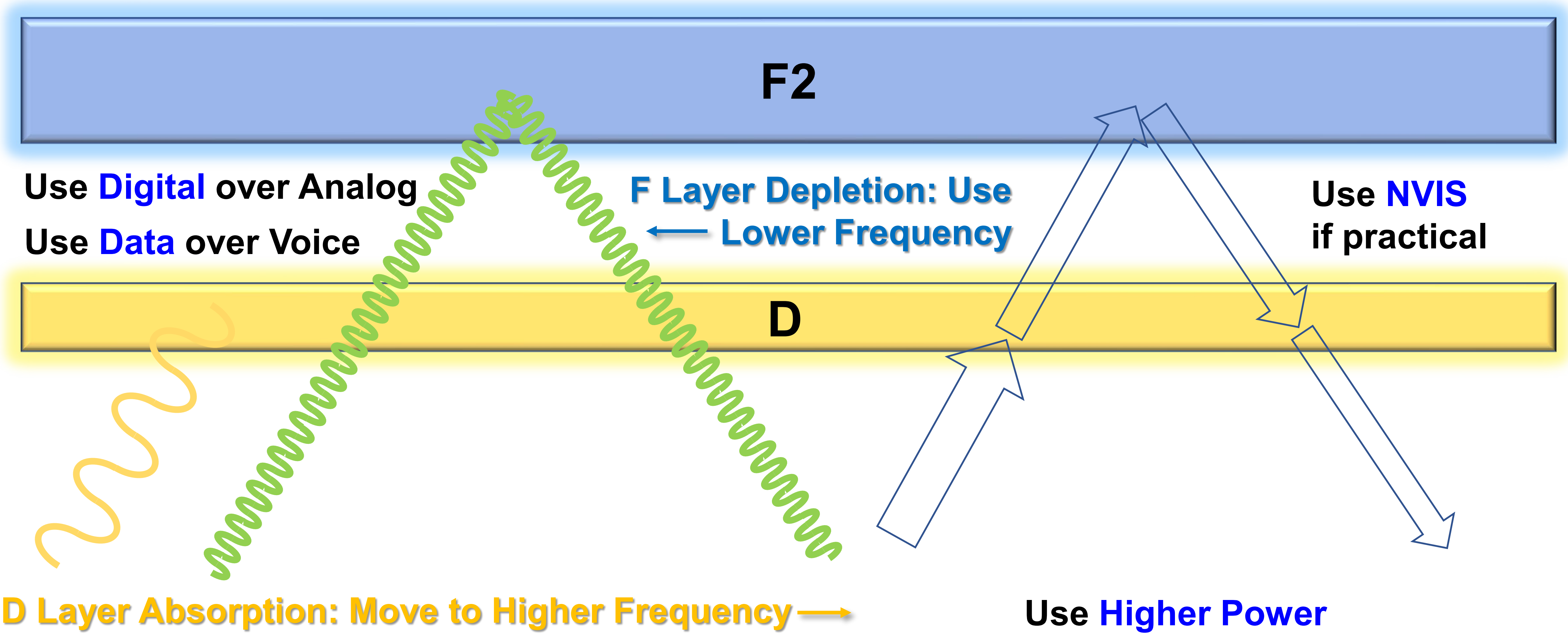
Extent varies with storm intensity

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

NOT TO SCALE

Mitigation Techniques



Mitigation Techniques (Continued)

Use Networks

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

LEGEND:
'H' markers - Winlink Hybrid Network participants. They offer RF message forwarding if local internet links are not available.
GREEN - gateway reporting normally
YELLOW - more than 2 hours since last report
RED - more than 4 hours since last report
Gateways disappear from the display after 6 hours without a report.

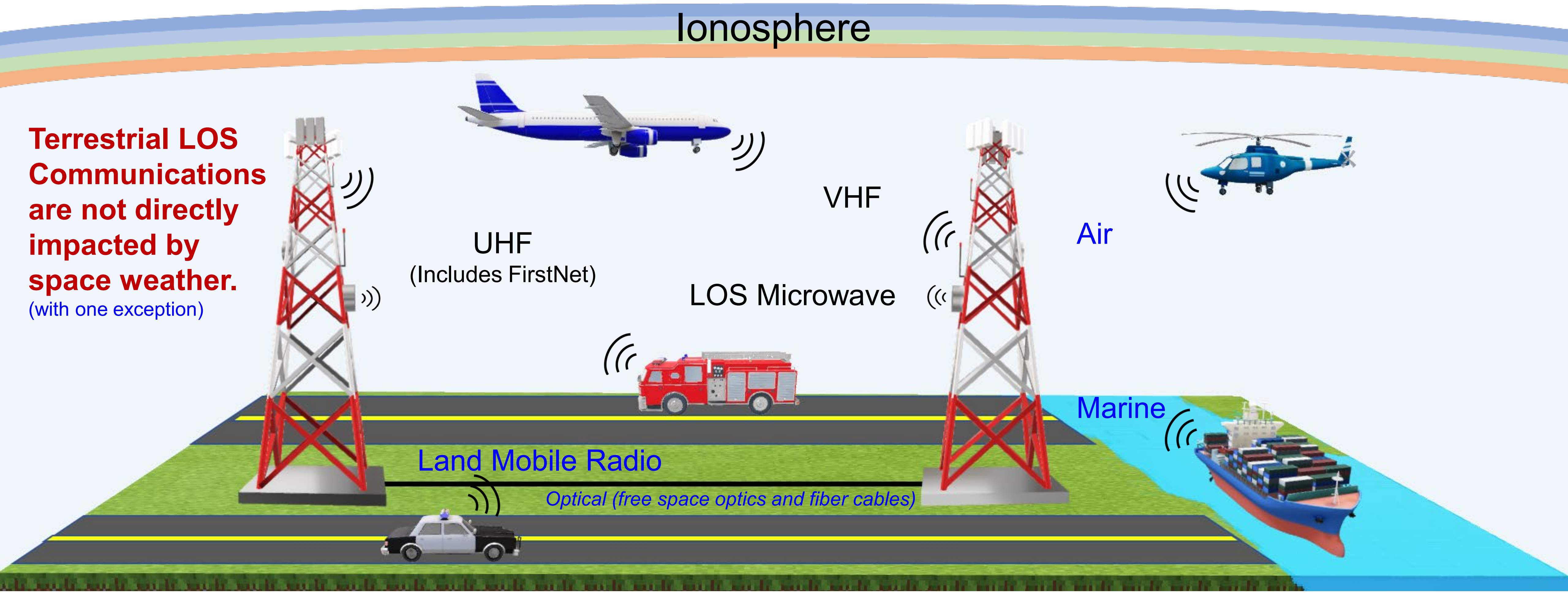
(Example)
WINLINK
Global Radio Email Live System Information

Applying a Risk Profile for HF Skywave

Worst Case	Analog Voice	Single Frequency	Single Station Pair	Low Power	Low Skill
Hurricane Watch Net (2017)	Analog Voice	Single Frequency 7.268 MHz & 14.325 MHz 40m Band 20m Band	Station Relay ~50 Stations in Net	High Power	High Skill
FEMA PR/USVI	Digital Voice (and data)	Automatic Link Establishment > 40 Channels from 2 MHz to 28 MHz	Station Relay	High Power	Medium Skill
US Government (e.g. SHARES, COTHEN)	Digital Voice (and data)	Automatic Link Establishment	Networked Stations	High Power	Medium Skill
Amateur Austin, TX	Digital Data	Multiple Frequencies	Networked Stations	High Power	High Skill

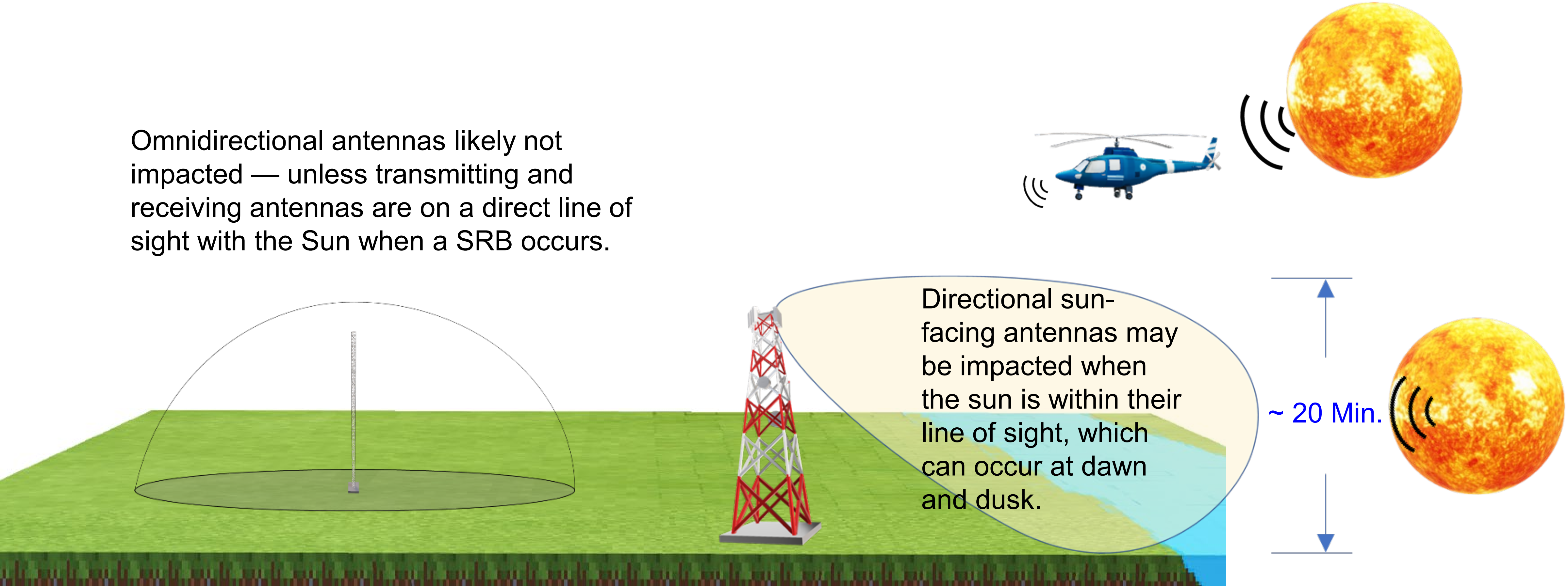
* Used Near Vertical Incident Skywave for intra- and inter-island HF

Terrestrial Line-of-Sight (LOS) Radio



Solar Radio Bursts (the exception)

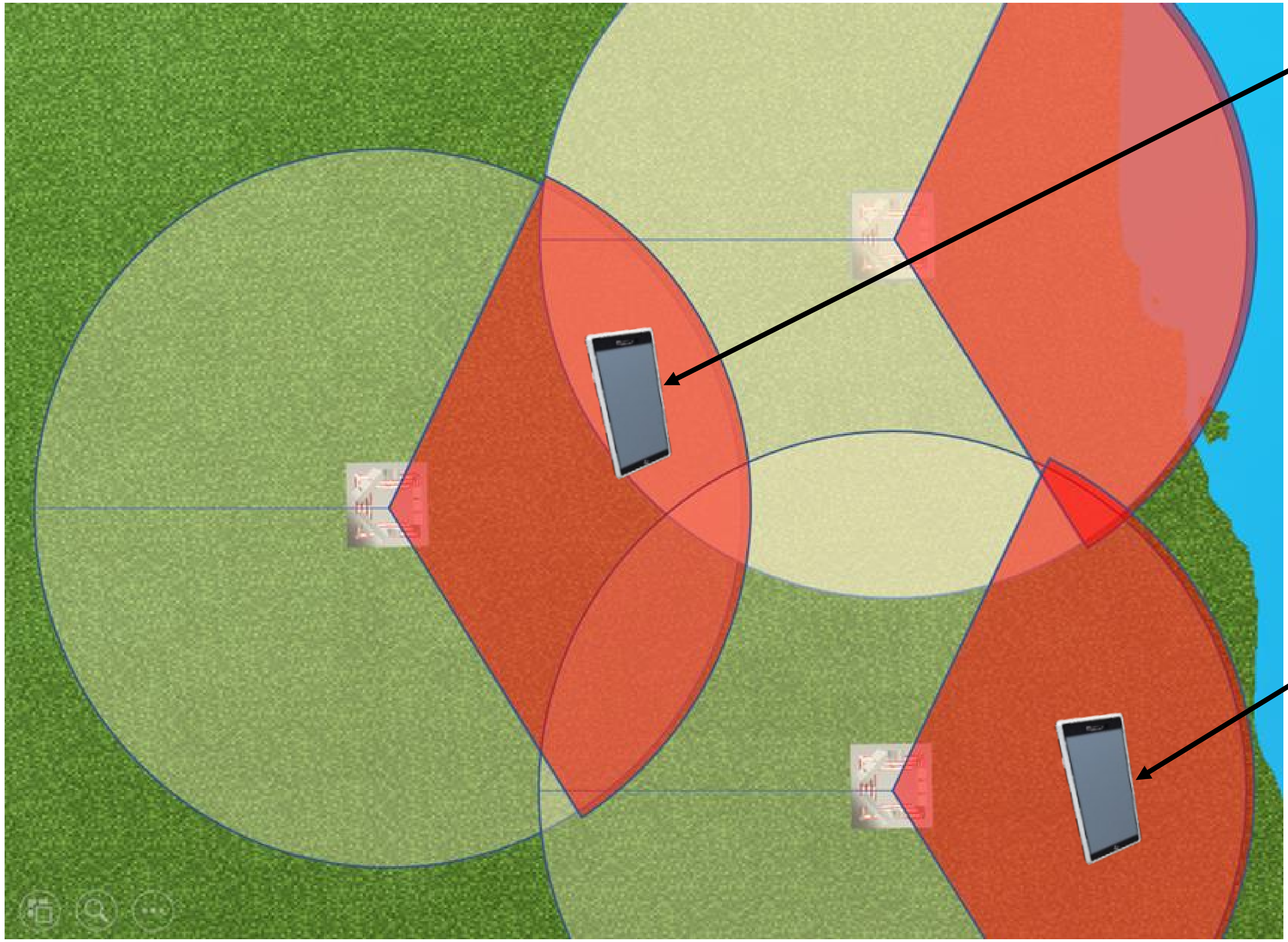
Omnidirectional antennas likely not impacted — unless transmitting and receiving antennas are on a direct line of sight with the Sun when a SRB occurs.



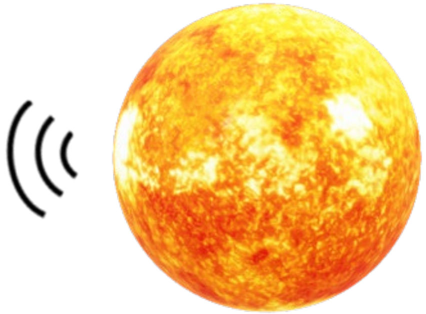
Solar Radio Bursts (Continued)

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.

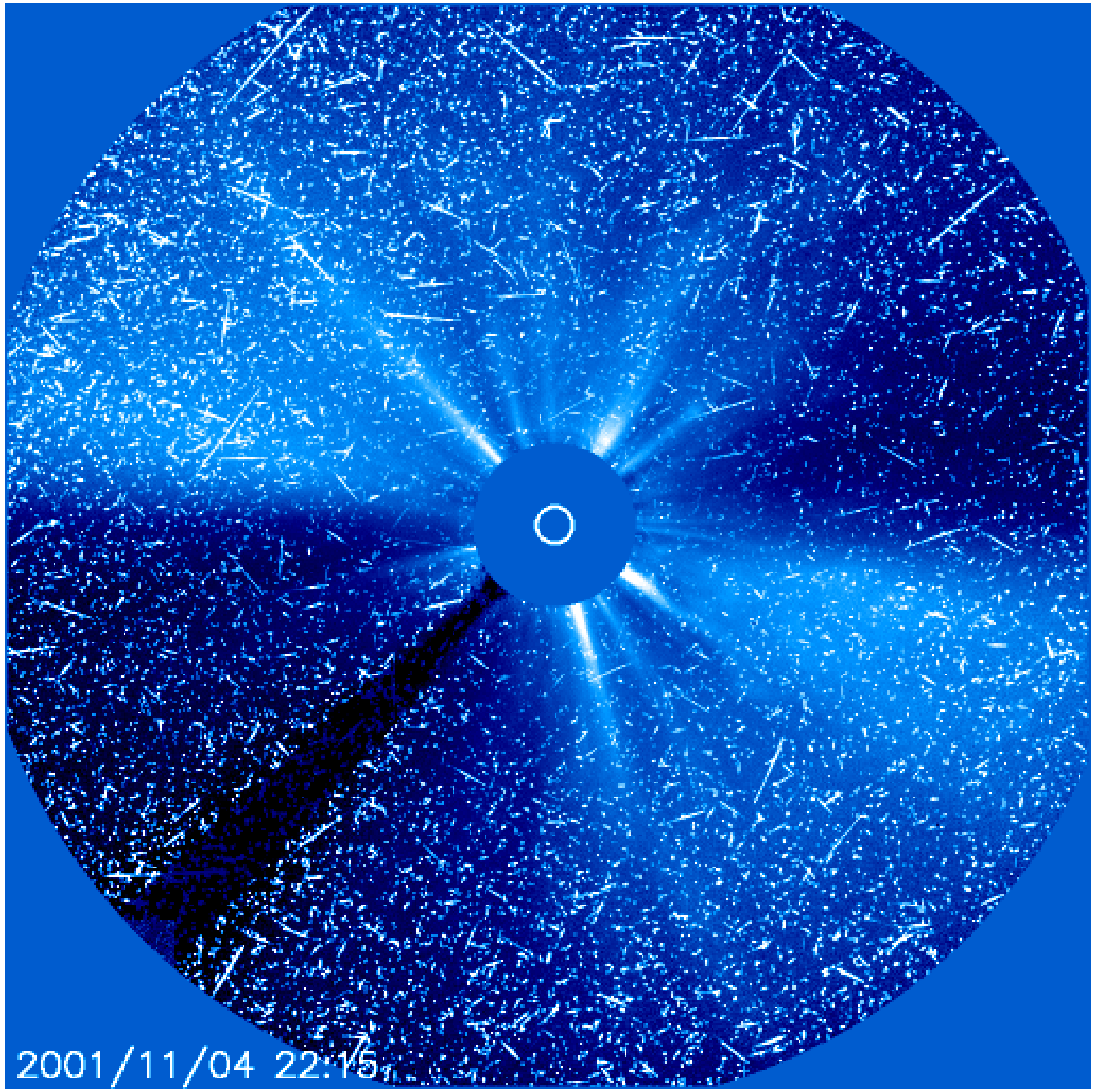


If sun facing antenna impacted, devices in the coverage area of a non-sun-facing antenna may not be impacted.

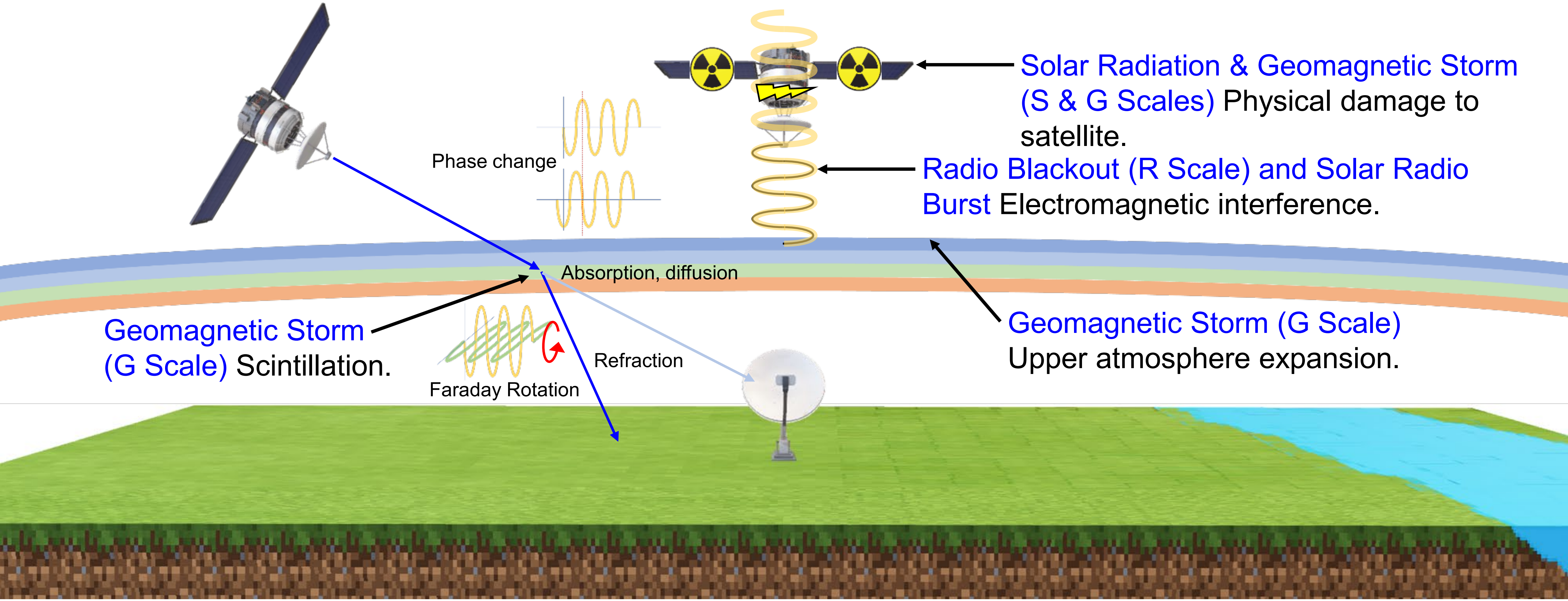


Outages impacting a subset of customers for less than 20 minutes are not considered significant outages.

Satellite Communications



SW Effects on Satellite Communications



Satellite Physical Effects (and Mitigations)

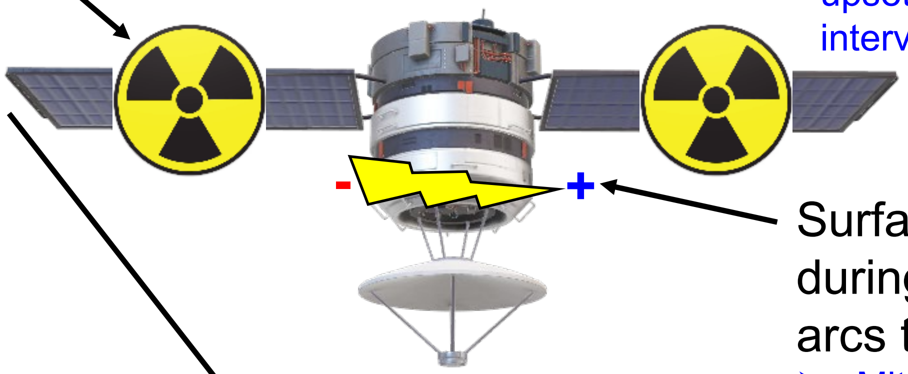
Solar Energetic Particle damage to solar panels shortens useful life.

- 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

01001101
00001101



Single Event Upset creates command or memory errors, usually temporary.

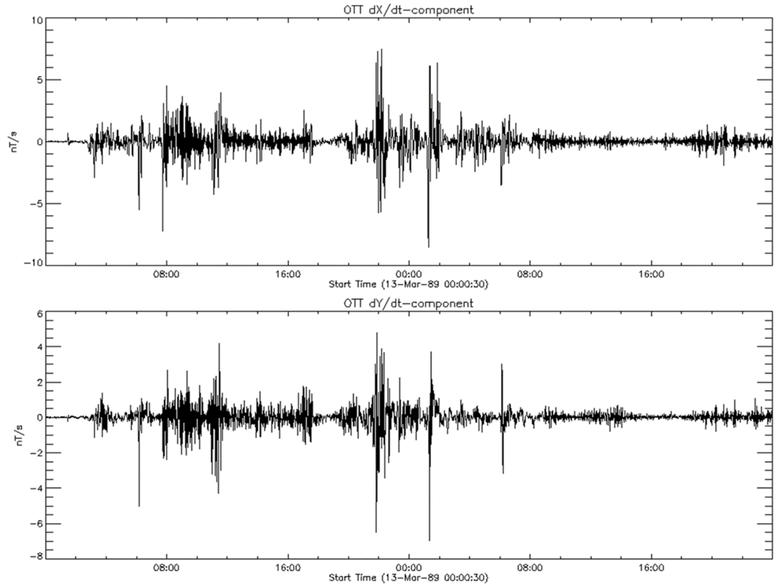
- New artificial intelligence can diagnose and fix upsets on the satellite with little or no human intervention

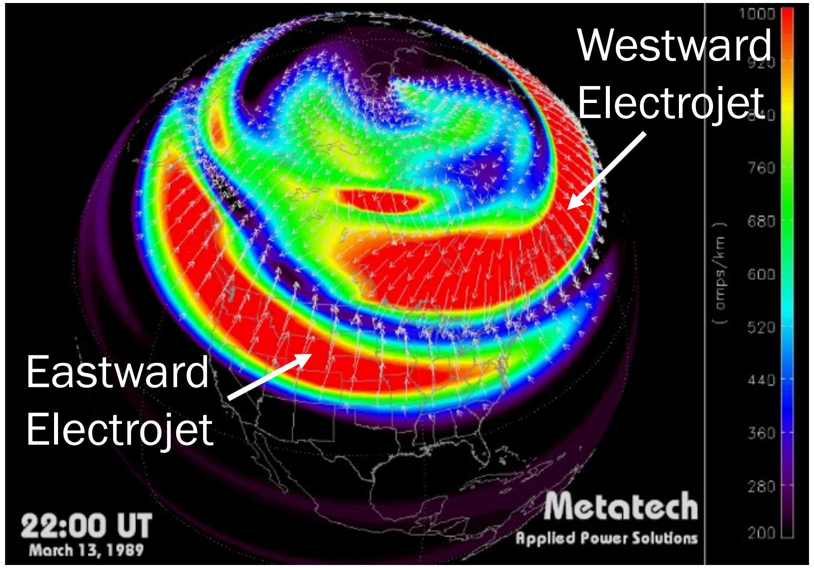
Surface and Deep Dielectric charging during geomagnetic storms causes arcs that can damage electronics.

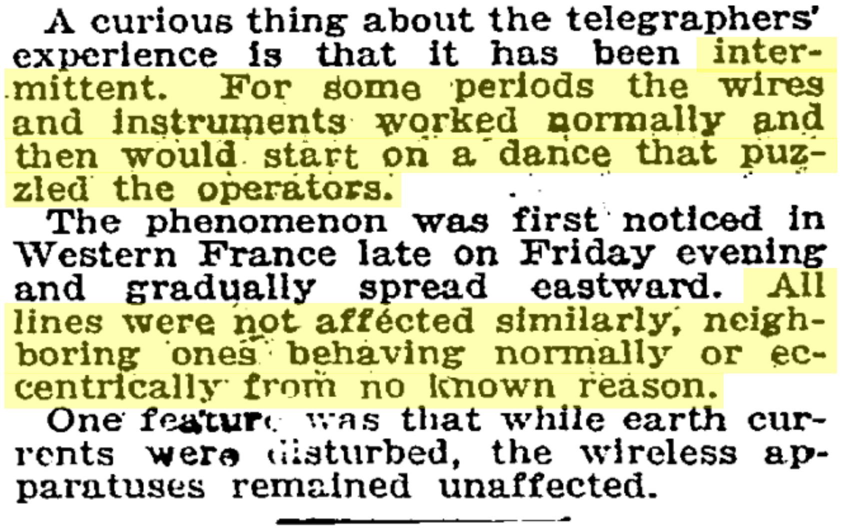
- Mitigated by proper design and quality control

Scintillation and Frequency

VHF	UHF	L Band	S Band	C Band	X Band	Ku Band	K Band	Ka Band	V Band
70-150 MHz	200-400 MHz	1-2 GHz	2-4 GHz	4-8 GHz	8-12 GHz	12-18 GHz	18-27 GHz	27-40 GHz	40-75 GHz






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.

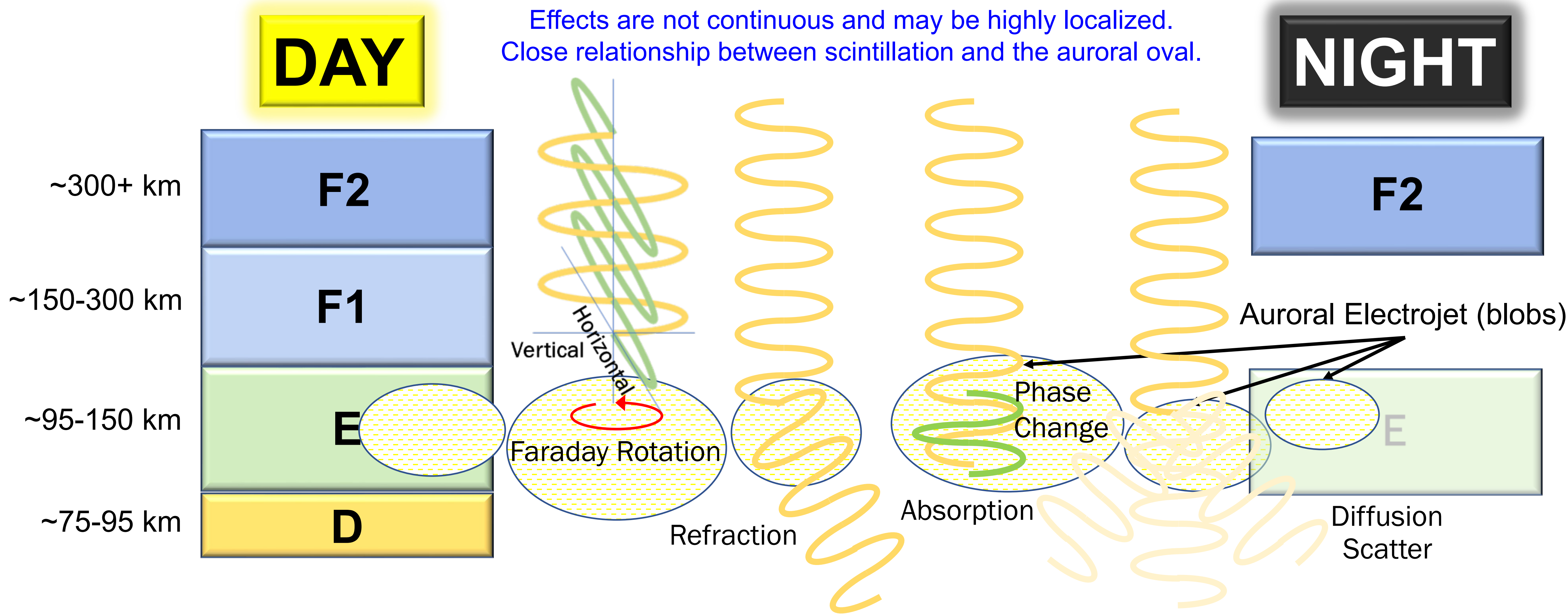
One feature was that while earth currents were disturbed, the wireless apparatuses remained unaffected.

The New York Times

Published: May 18, 1921

Scintillation Effects on SATCOM

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



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

Cost →

➢ Satellite Dependency	Single Satellite Single Orbit	Multiple Satellites Single Orbit	Multiple Satellites Multiple Orbits
➢ Satellite Service(s)	Single Provider Single Sat/GEP	Single Provider Multiple Sat/GEP	Multiple Providers Multiple Sat/GEP
➢ Frequency	VHF – L Band	S Band – C Band	X Band – V Band
➢ Receivers	Single Receiver Single Band	Multiple Receivers Single Band	Multiple Receivers Multiple Bands
➢ Disruption Tolerance	< 5 minutes	5 – 30 minutes	> 30 minutes
➢ Low vs. Higher Skill	Low Skill	Medium Skill	High Skill

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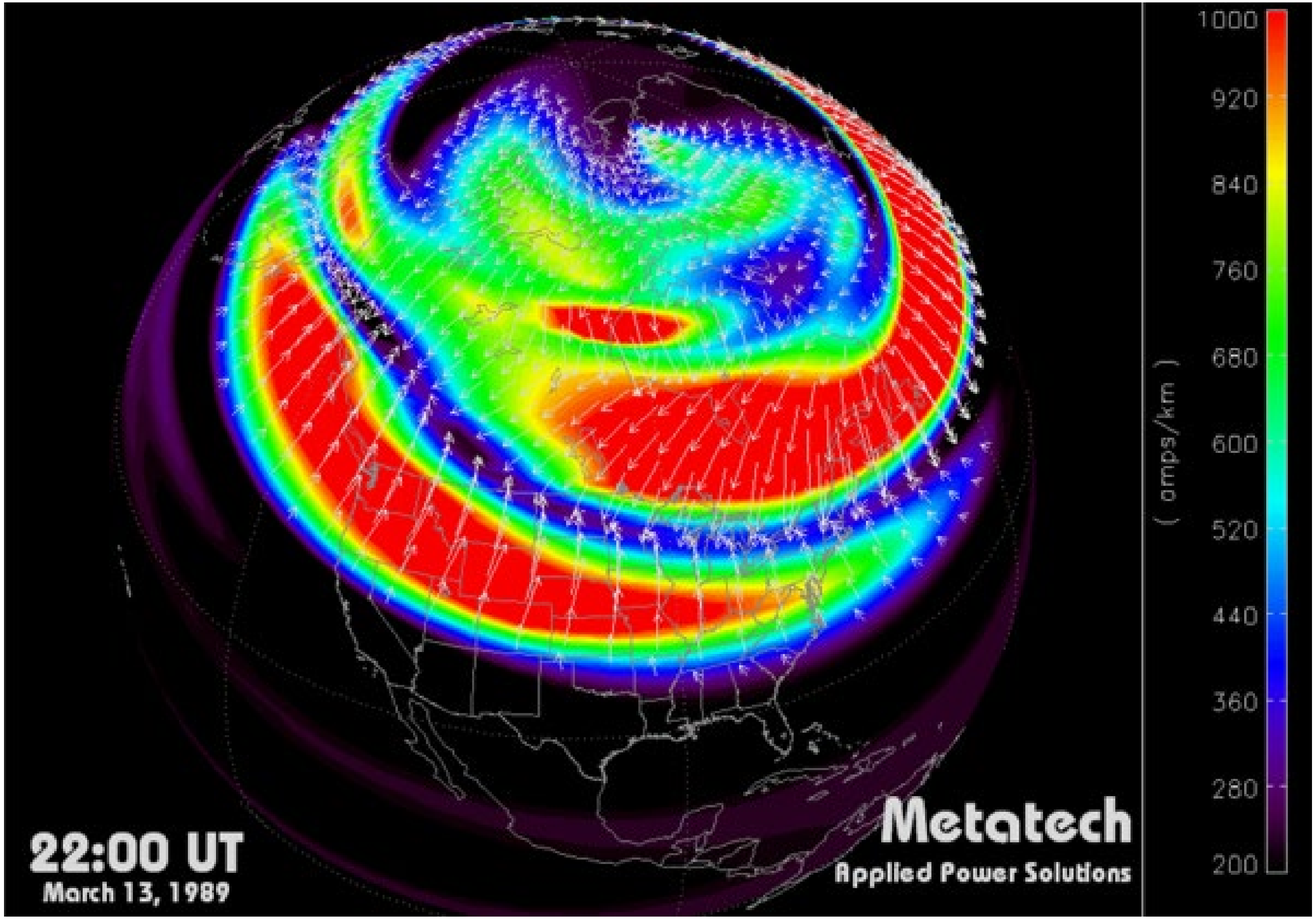
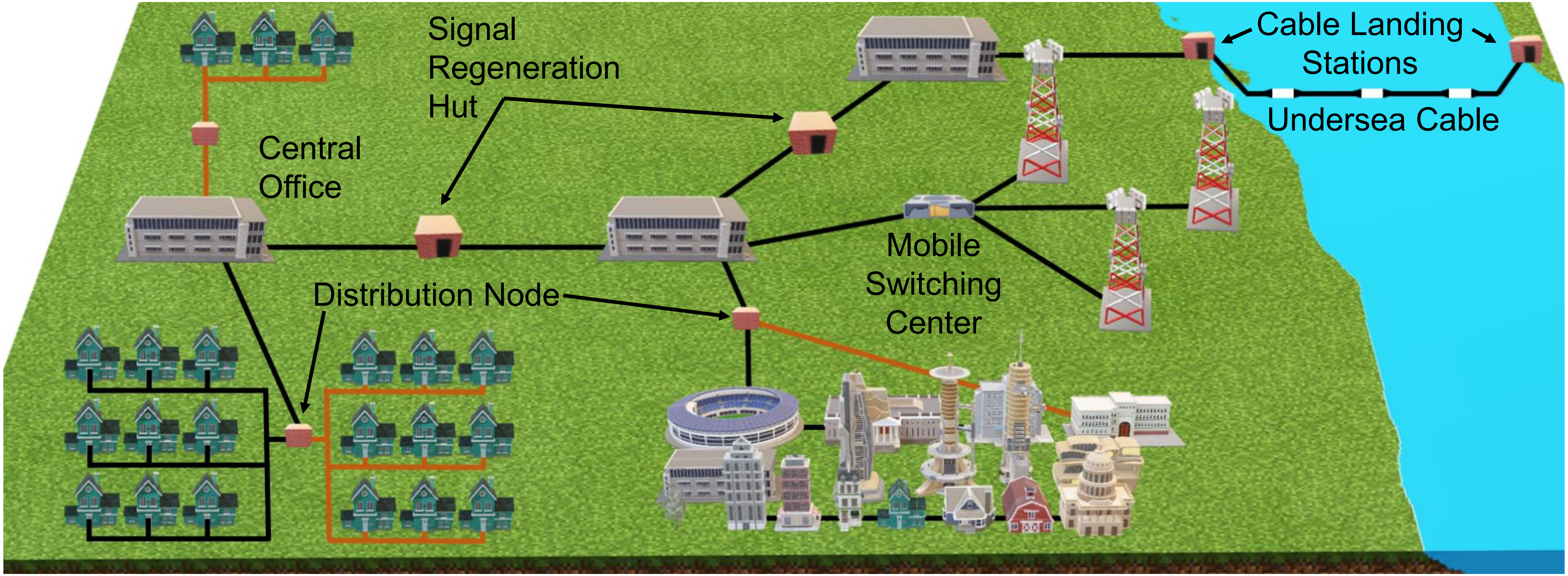
Wireline Communications



Terrestriel Wireline Basics - US

Fiber Optic Cable
Copper Cable

- Long haul cable ~88%-90% fiber optic
- Rural and “last mile” may still be ~40%-45% copper



- 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)

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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)

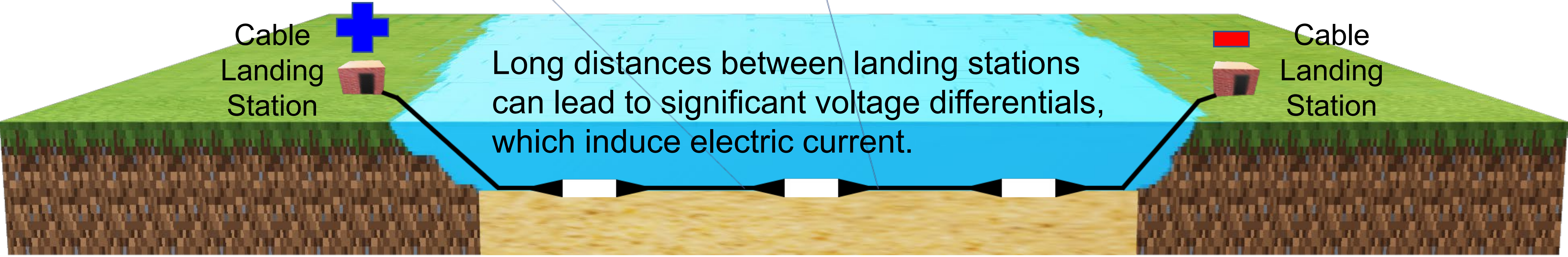
- Other cables in the area remained operational

GIC and Undersea Cables

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



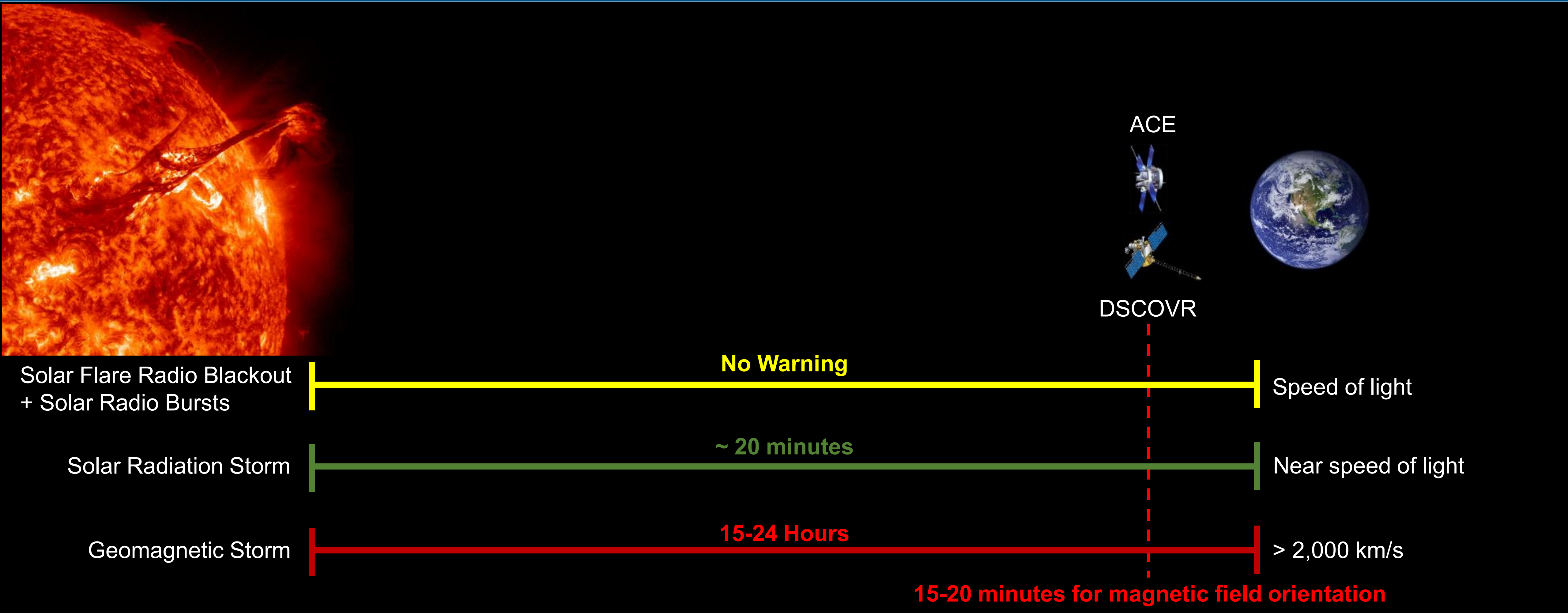
* Risk currently unknown

Putting It All Together – Scenario

Day 0 | Day 1 | Day 2 | Day 3

- 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



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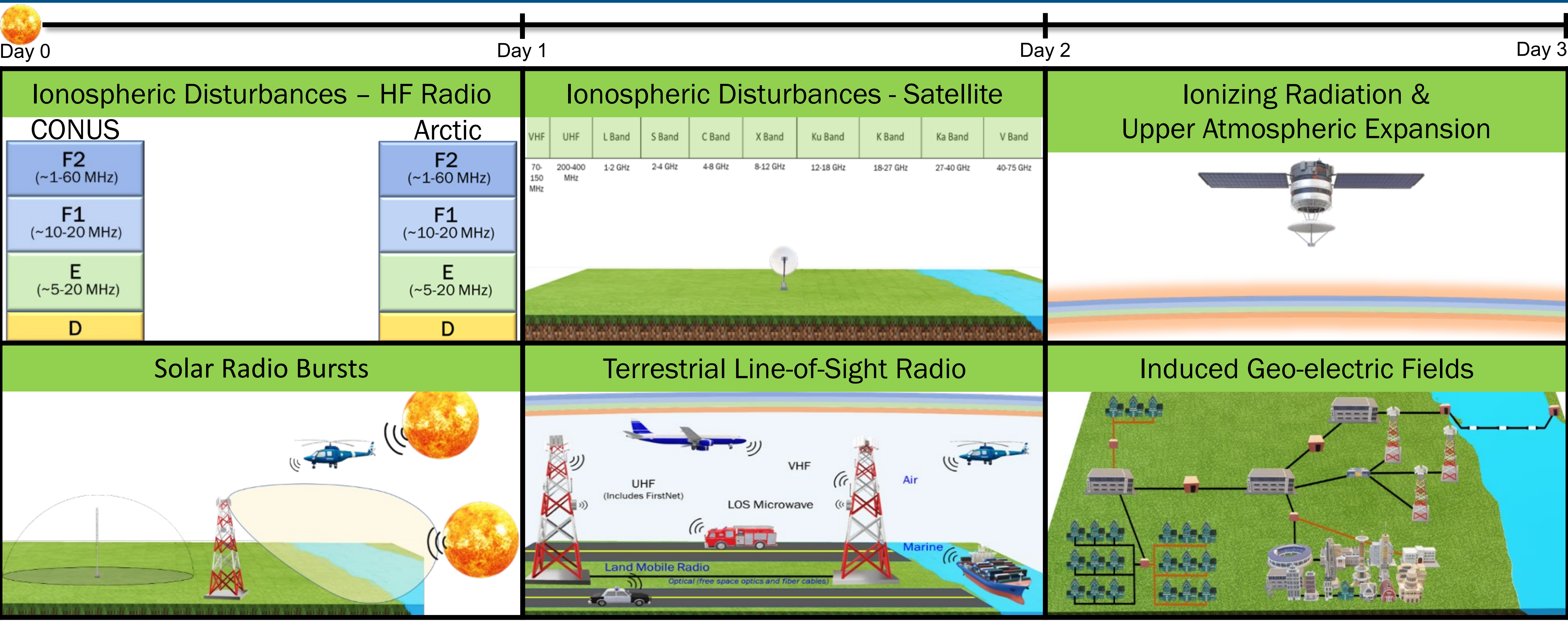
June 17, 2020

Baseline Representation



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.

06:30 ET – Start (R5 + SRB)

Day 0 | Day 1 | Day 2 | Day 3

Ionospheric Disturbances – HF Radio

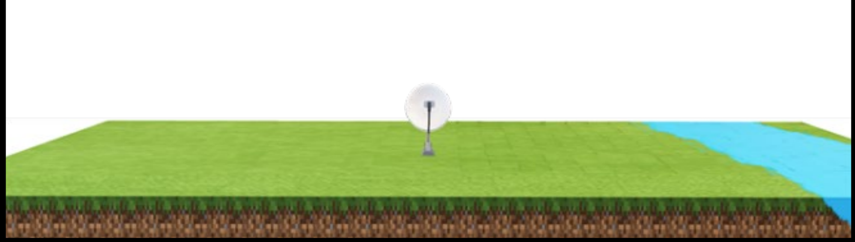
CONUS		Arctic
F2 (~1-60 MHz)	Skywave	F2 (~1-60 MHz)
F1 (~10-20 MHz)	Groundwave	F1 (~10-20 MHz)
E (~5-20 MHz)	Relay	E (~5-20 MHz)
D	Networked	D

Day side only

Higher freqs impacted last and recover first

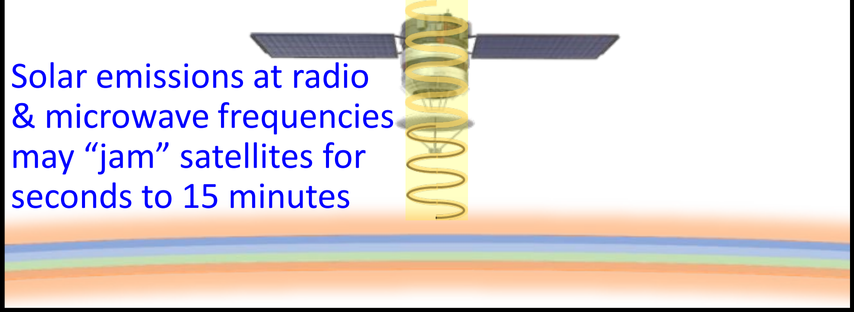
Ionospheric Disturbances - Satellite

VHF	UHF	L Band	S Band	C Band	X Band	Ku Band	K Band	Ka Band	V Band
70-150 MHz	200-400 MHz	1-2 GHz	2-4 GHz	4-8 GHz	8-12 GHz	12-18 GHz	18-27 GHz	27-40 GHz	40-75 GHz



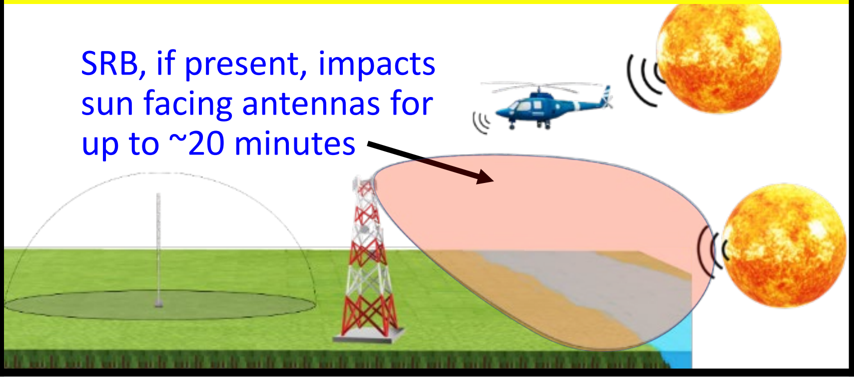
Ionizing Radiation & Upper Atmospheric Expansion

Solar emissions at radio & microwave frequencies may "jam" satellites for seconds to 15 minutes

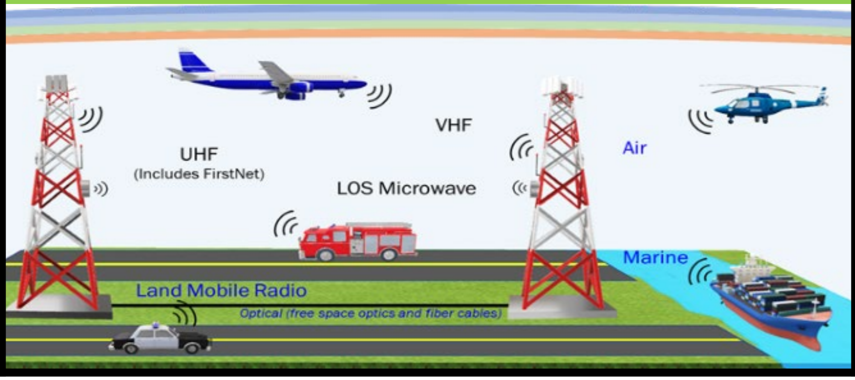


Solar Radio Bursts

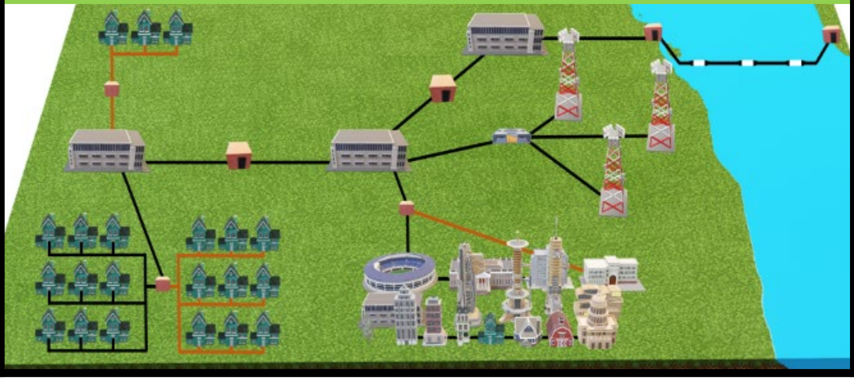
SRB, if present, impacts sun facing antennas for up to ~20 minutes



Terrestrial Line-of-Sight Radio



Induced Geo-electric Fields



Carrington Scale Solar Flare Radio Blackout (R5 – Extreme) arrives with forecasted probability but no operational warning.

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June 17, 2020

06:42 ET – 12 Minutes (R5 + SRB + > S1)

Ionospheric Disturbances – HF Radio

CONUS

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

Skywave
Groundwave
Relay
Networked

Day side only
Higher freqs impacted last and recover first

Arctic

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

Ionospheric Disturbances - Satellite

VHF	UHF	L Band	S Band	C Band	X Band	Ku Band	K Band	Ka Band	V Band
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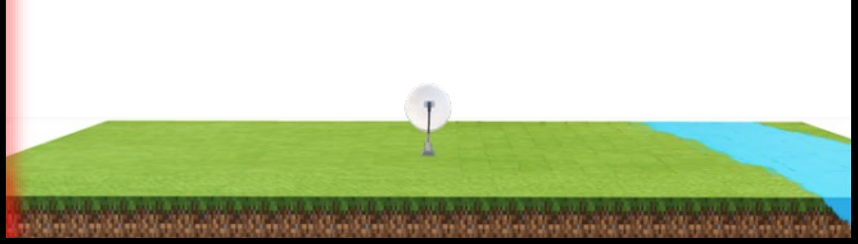
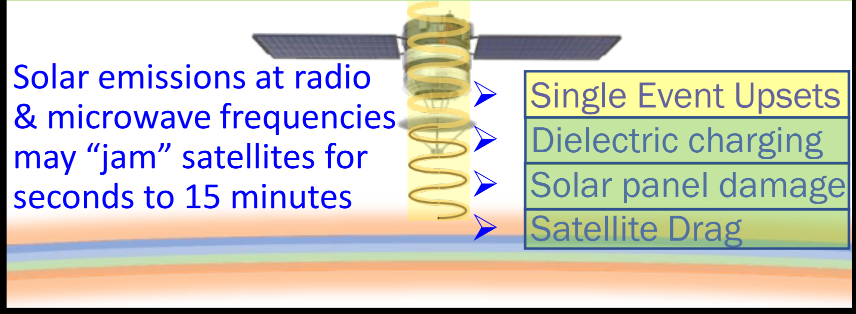


Ionizing Radiation & Upper Atmospheric Expansion

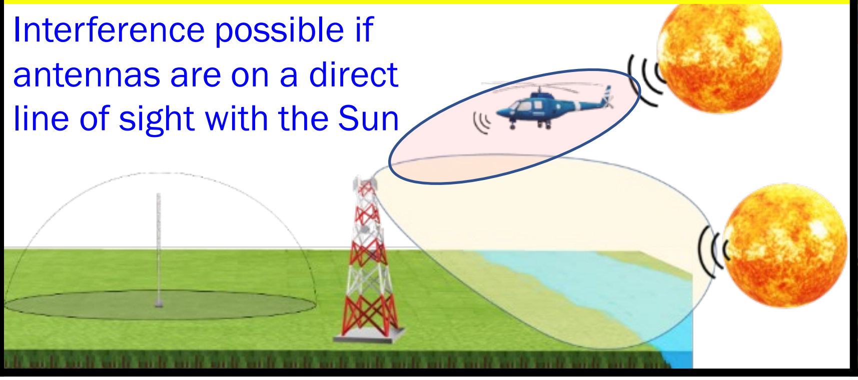


Solar emissions at radio & microwave frequencies may "jam" satellites for seconds to 15 minutes

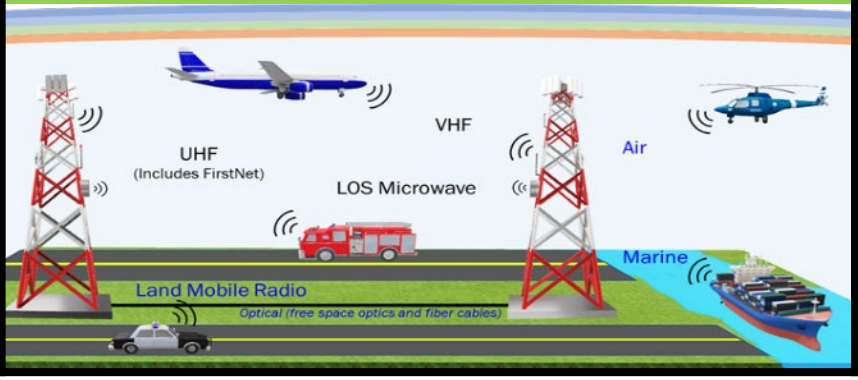
- Single Event Upsets
- Dielectric charging
- Solar panel damage
- Satellite Drag

Solar Radio Bursts

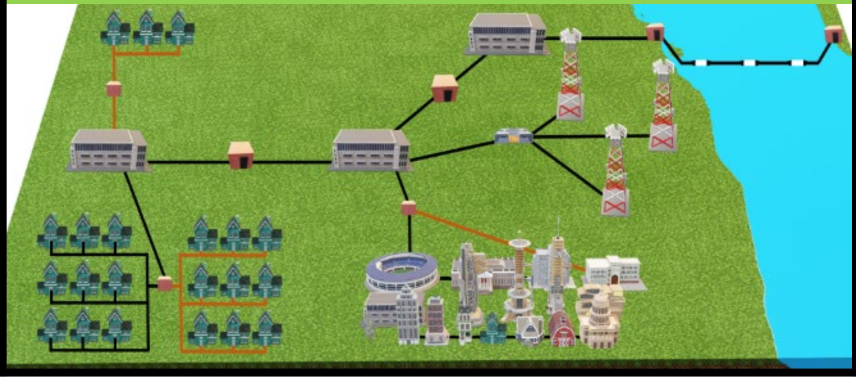
Interference possible if antennas are on a direct line of sight with the Sun



Terrestrial Line-of-Sight Radio



Induced Geo-electric Fields



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

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June 17, 2020

08:30 ET – 2 Hours (R5 + S5)

Ionospheric Disturbances – HF Radio

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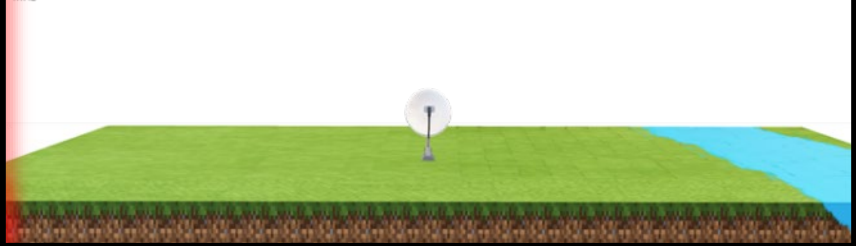
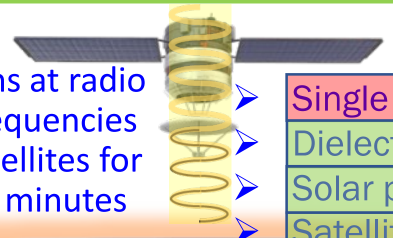


Ionizing Radiation & Upper Atmospheric Expansion

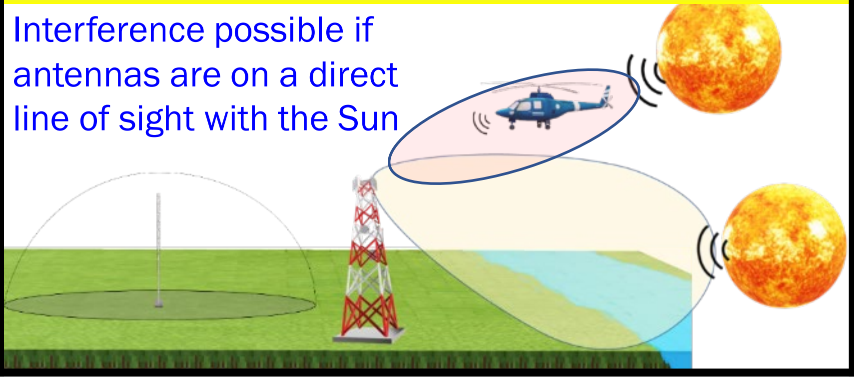
Solar emissions at radio microwave frequencies may "jam" satellites for seconds to 15 minutes



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

Solar Radio Bursts

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



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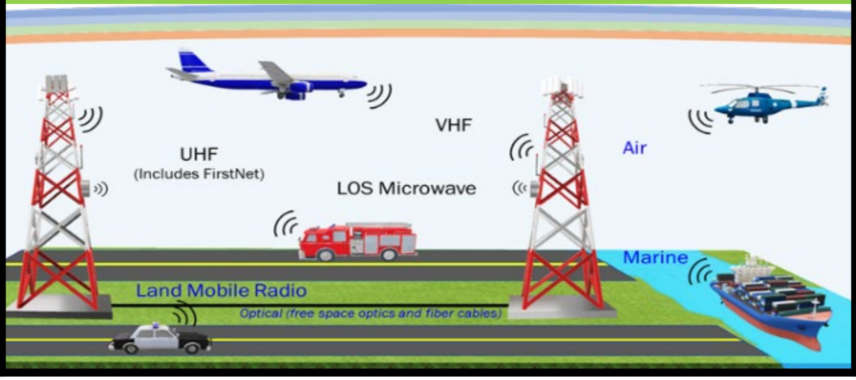
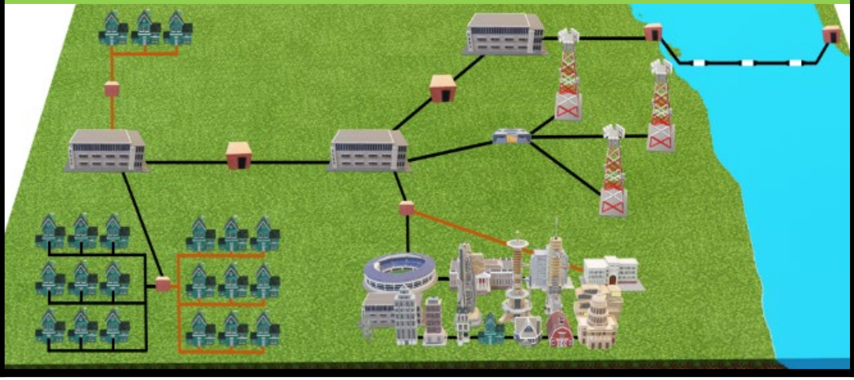


Induced Geo-electric Fields



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

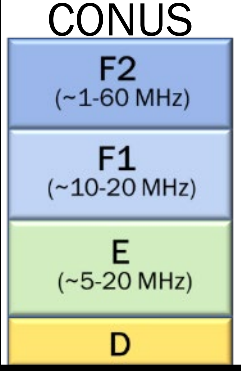
Mark MacAlester
Communications Liaison

June 17, 2020

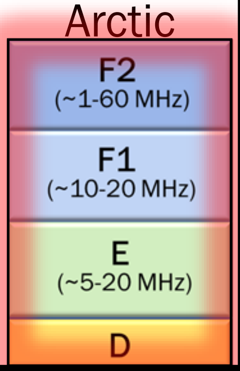
09:30 ET – 3 Hours (S5)

Day 0 | Day 1 | Day 2 | Day 3

Ionospheric Disturbances – HF Radio

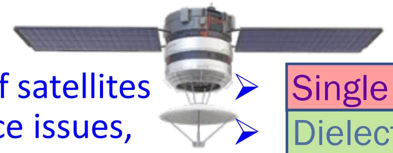


- CONUS HF recovers. If UV present, may enhance F Layer ionization.
- Artic HF severely impacted from S5



Ionospheric Disturbances - Satellite

Ionizing Radiation & Upper Atmospheric Expansion

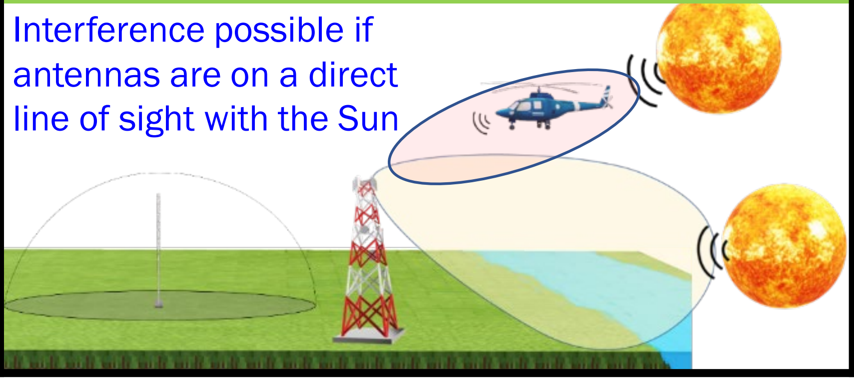


Up to ~ 10% of satellites may experience issues, most of them temporary

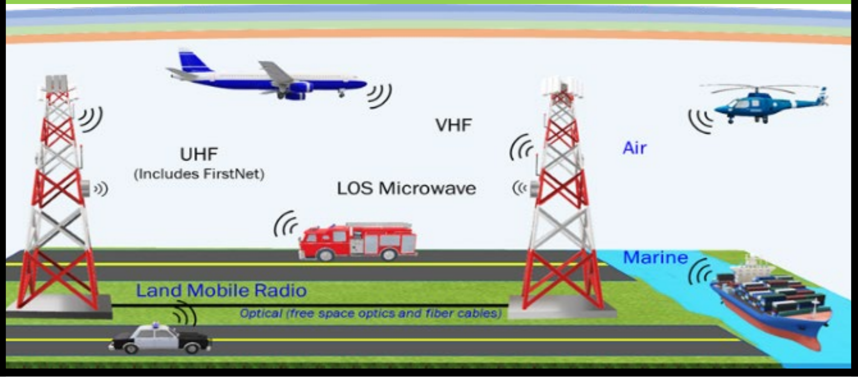
- Single Event Upsets
- Dielectric charging
- Solar panel damage
- Satellite Drag

Solar Radio Bursts

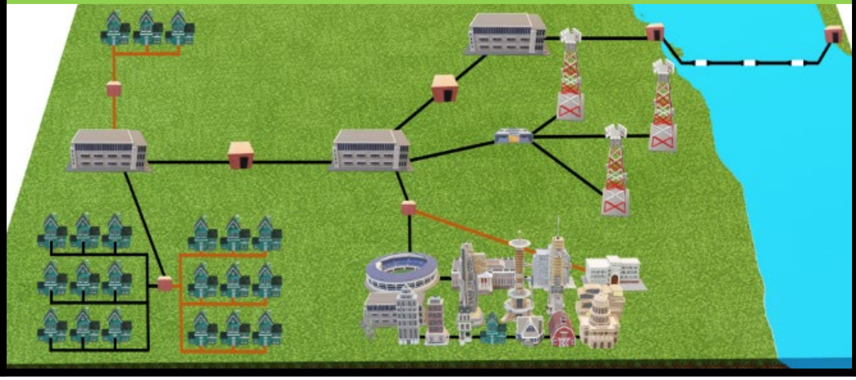
Interference possible if antennas are on a direct line of sight with the Sun



Terrestrial Line-of-Sight Radio



Induced Geo-electric Fields



Solar Flare Radio Blackout ends. Solar Radiation Storm (S5 – Extreme).

Mark MacAlester
Communications Liaison
June 17, 2020

23:30 ET – 17 Hours (S5)

Day 0 | Day 1 | Day 2 | Day 3

Ionospheric Disturbances – HF Radio

CONUS

F2
(~1-60 MHz)

- Artic HF severely impacted from S5 absorption

Arctic

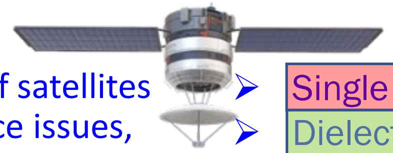
F2
(~1-60 MHz)

E
(~5-20 MHz)

Ionospheric Disturbances - Satellite

VHF	UHF	L Band	S Band	C Band	X Band	Ku Band	K Band	Ka Band	V Band
70-150 MHz	200-400 MHz	1-2 GHz	2-4 GHz	4-8 GHz	8-12 GHz	12-18 GHz	18-27 GHz	27-40 GHz	40-75 GHz

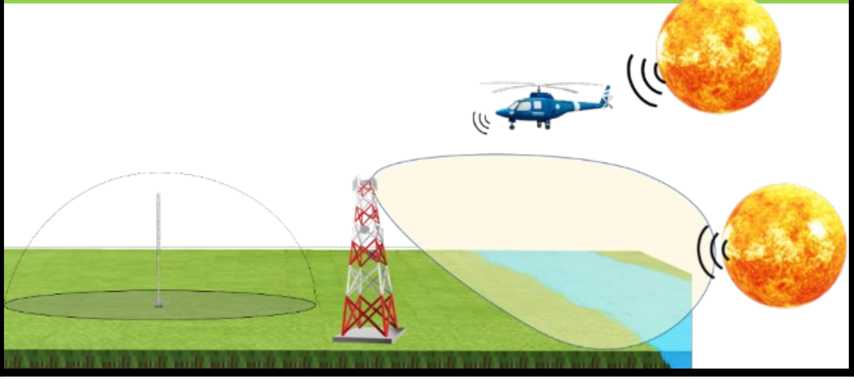
Ionizing Radiation & Upper Atmospheric Expansion



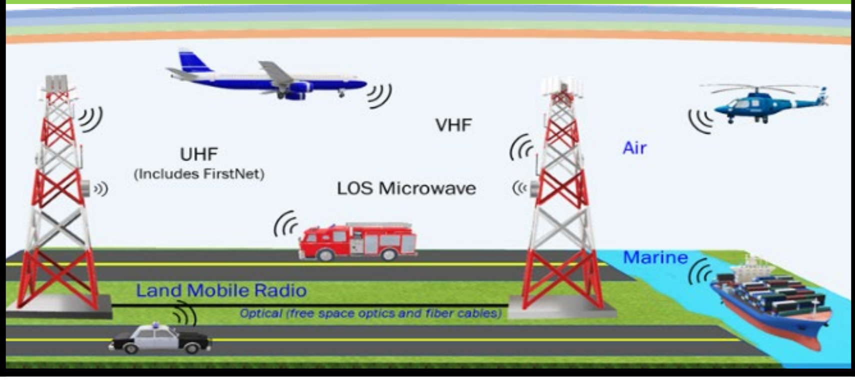
Up to ~ 10% of satellites may experience issues, most of them temporary

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

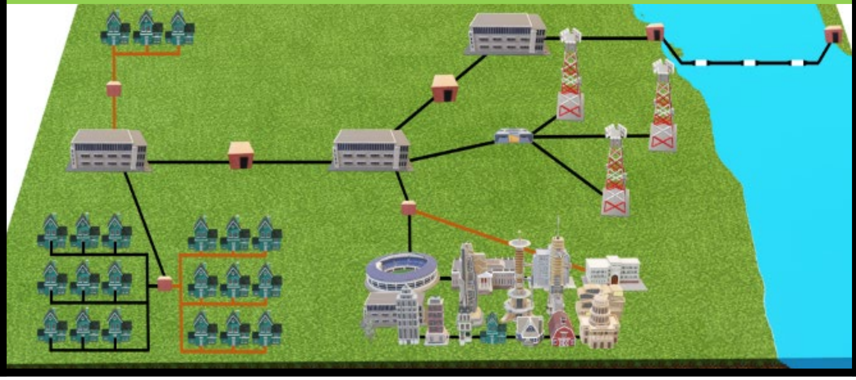
Solar Radio Bursts



Terrestrial Line-of-Sight Radio



Induced Geo-electric Fields



Solar Radiation Storm (S5 – Extreme). Coronal Mass Ejection arrives at Lagrange 1 (NASA's ACE & DSCOVR) – Geoeffective.

23:45 ET – 17.25 Hours (S5 + G5)

Ionospheric Disturbances – HF Radio

CONUS

F2 (~1-60 MHz)

E (~5-20 MHz)

- Electron depletion at F Layer
- HF enhanced equatorward of aurora for ~2 hr?
- "Auroral E"
- Artic severely impacted from G5 and S5

Arctic

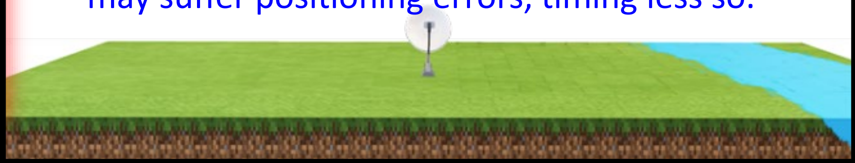
F2 (~1-60 MHz)

E (~5-20 MHz)

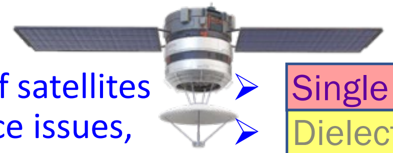
Ionospheric Disturbances - Satellite

VHF	UHF	L Band	S Band	C Band	X Band	Ku Band	K Band	Ka Band	V Band
70-150 MHz	200-400 MHz	1-2 GHz	2-4 GHz	4-8 GHz	8-12 GHz	12-18 GHz	18-27 GHz	27-40 GHz	40-75 GHz

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



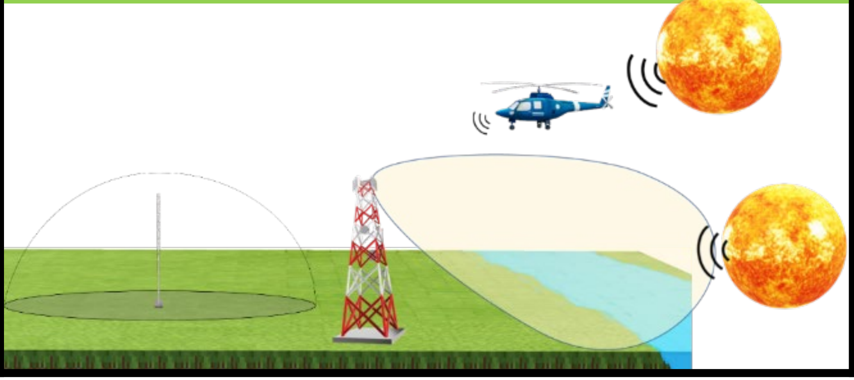
Ionizing Radiation & Upper Atmospheric Expansion



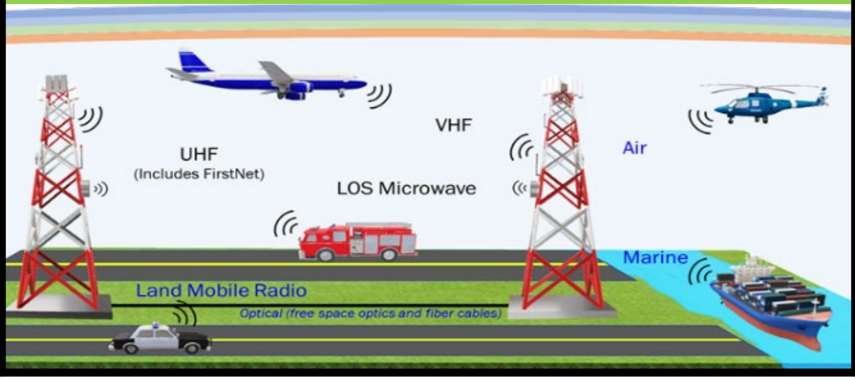
Up to ~ 10% of satellites may experience issues, most of them temporary

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

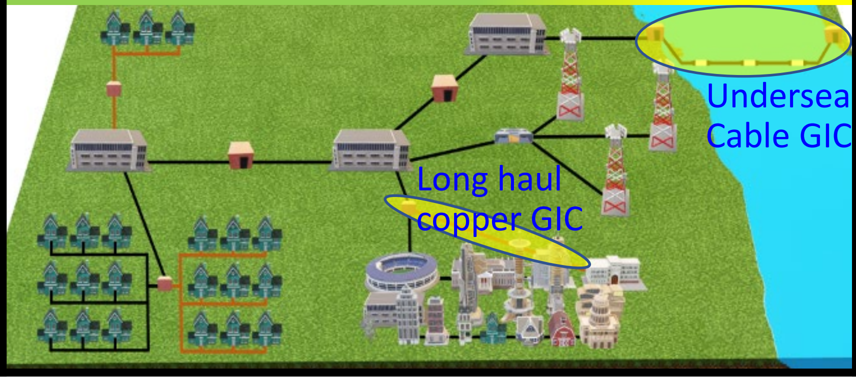
Solar Radio Bursts



Terrestrial Line-of-Sight Radio



Induced Geo-electric Fields



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

06:30 ET – 24 Hours (S5 + G5)

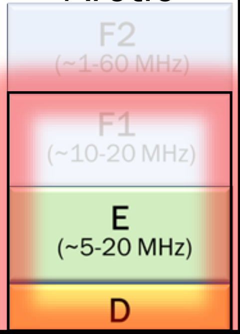
Day 0 | Day 1 | Day 2 | Day 3

Ionospheric Disturbances – HF Radio

CONUS

- Electron depletion at F Layer
- "Auroral E"
- Artic severely impacted from G5 and S5
- D layer may be usable

Arctic

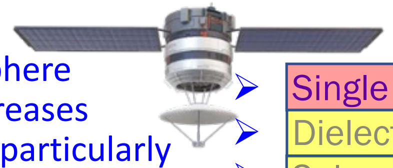


Ionospheric Disturbances - Satellite

VHF	UHF	L Band	S Band	C Band	X Band	Ku Band	K Band	Ka Band	V Band
70-150 MHz	200-400 MHz	1-2 GHz	2-4 GHz	4-8 GHz	8-12 GHz	12-18 GHz	18-27 GHz	27-40 GHz	40-75 GHz

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

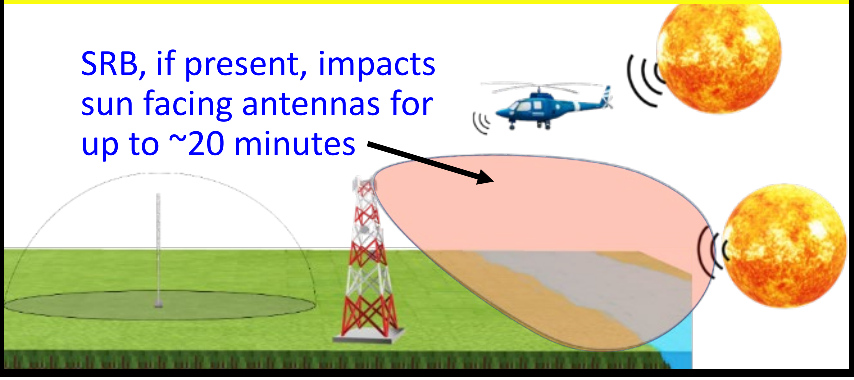


Upper atmosphere expansion increases satellite drag, particularly below 400 km

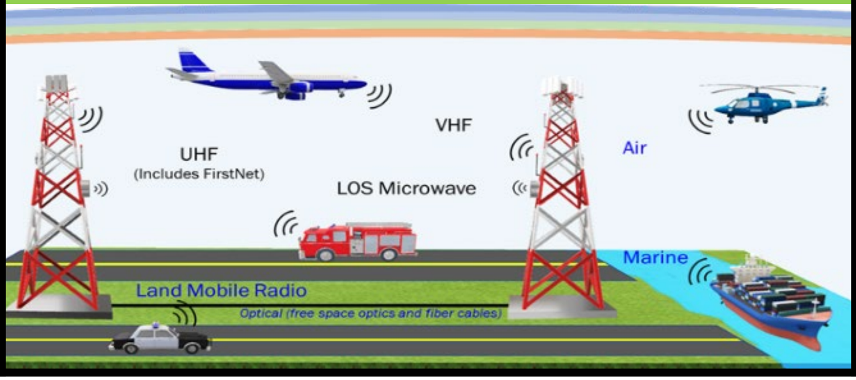
- Single Event Upsets
- Dielectric charging
- Solar panel damage
- Satellite Drag

Solar Radio Bursts

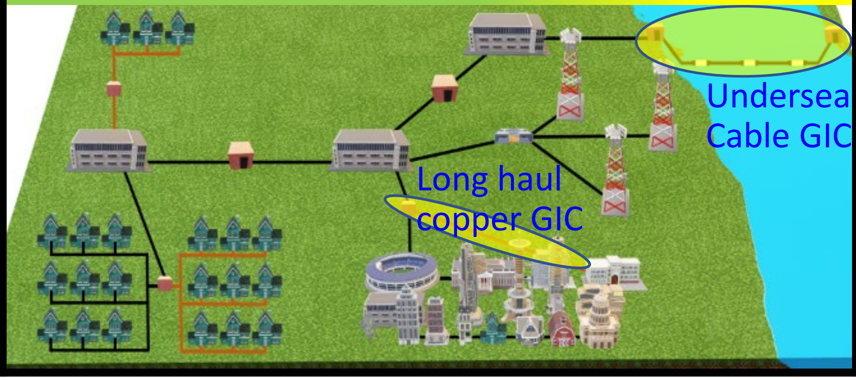
SRB, if present, impacts sun facing antennas for up to ~20 minutes



Terrestrial Line-of-Sight Radio



Induced Geo-electric Fields

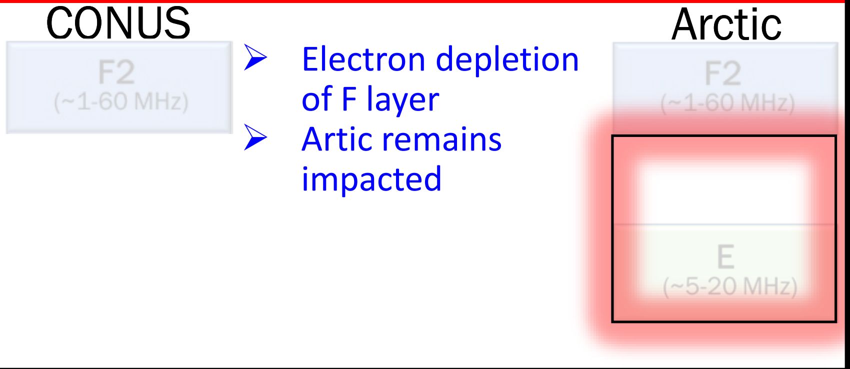


Geoeffective Geomagnetic Storm (G5 – Extreme) and Solar Radiation Storm (S5 – Extreme).

00:30 ET – 42 Hours (< S5)

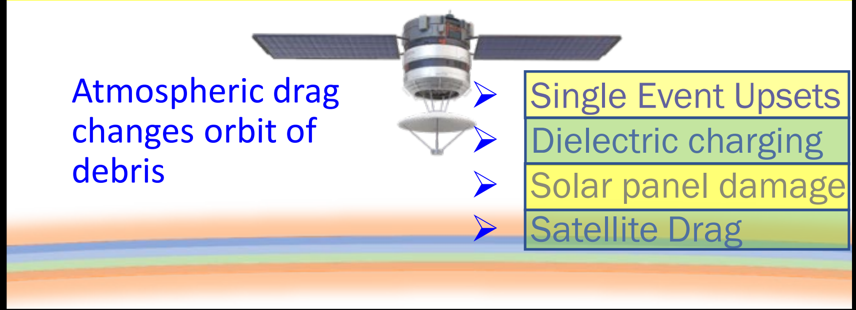
Day 0 | Day 1 | Day 2 | Day 3

Ionospheric Disturbances – HF Radio

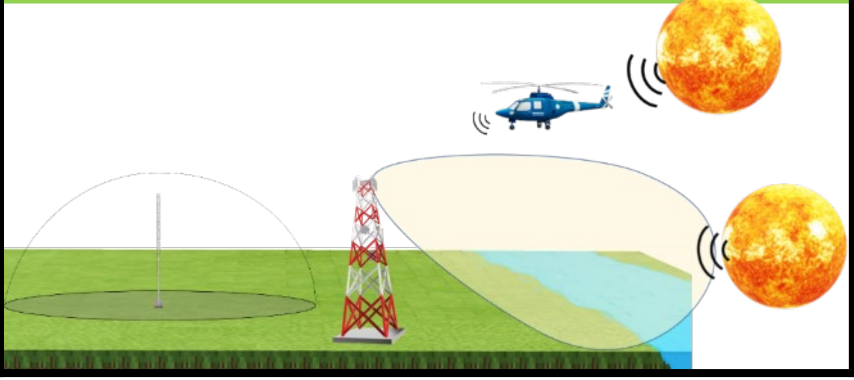


Ionospheric Disturbances - Satellite

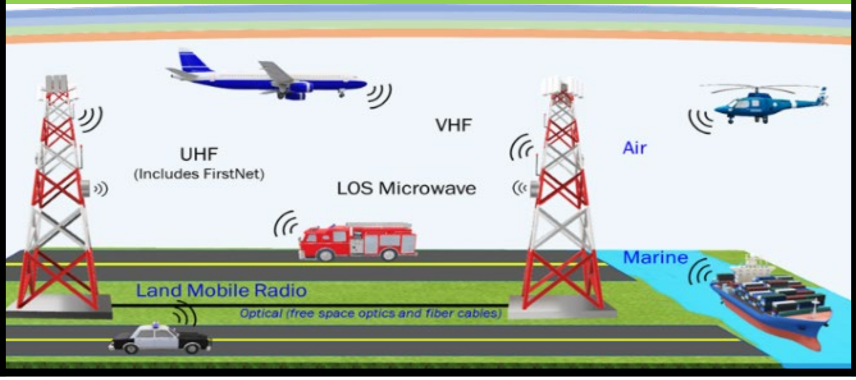
Ionizing Radiation & Upper Atmospheric Expansion



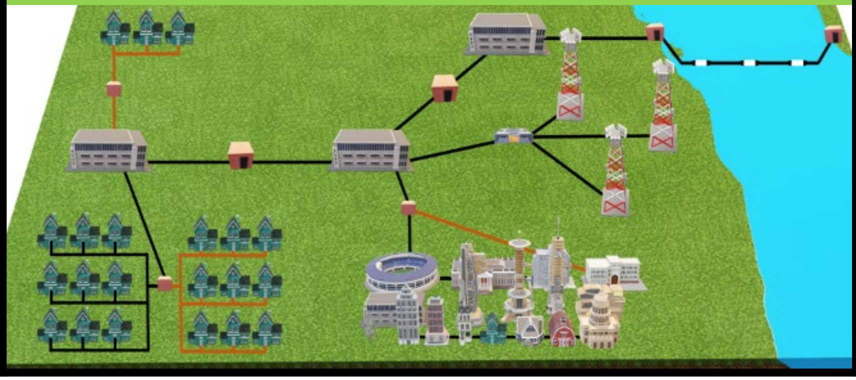
Solar Radio Bursts



Terrestrial Line-of-Sight Radio



Induced Geo-electric Fields



Geomagnetic storm ends.
Solar Radiation Storm diminishes over time.

06:30 ET – 3 Days

Day 0 | Day 1 | Day 2 | Day 3

Ionospheric Disturbances – HF Radio

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

- Artic takes an additional 1-2 days to recover

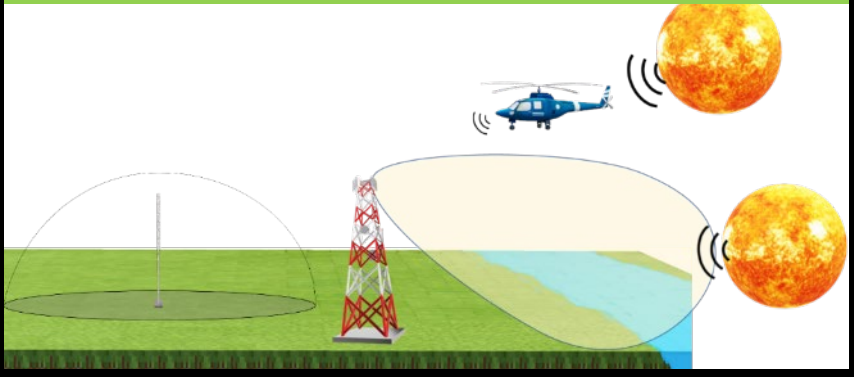
Ionospheric Disturbances - Satellite

Ionizing Radiation & Upper Atmospheric Expansion

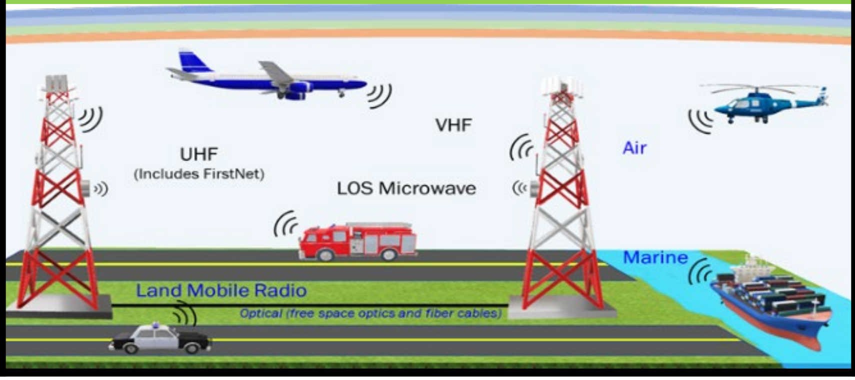
Atmospheric drag changes orbit of debris

Increased fuel use for station keeping may shorten satellite life

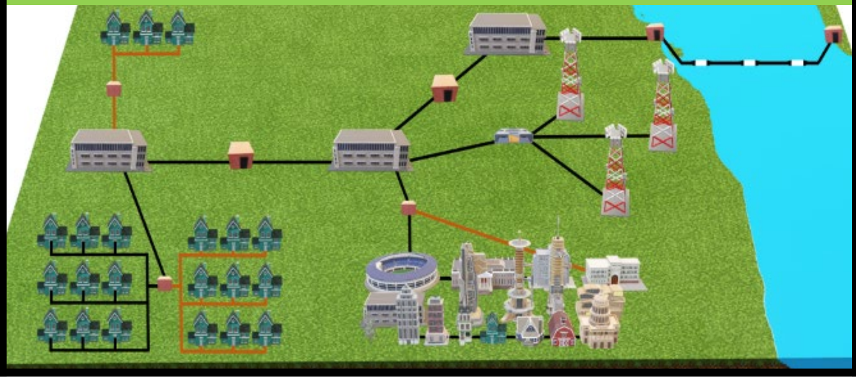
Solar Radio Bursts



Terrestrial Line-of-Sight Radio



Induced Geo-electric Fields



Artic takes 1-2 days longer to recover.
Longer storms may take longer to recover.

Extreme Events Can Bring Friends

TABLE.

Day.	Magnetic Range in Minutes of Arc. Dn.	H.	V.	Character.	Sun-Spots. Mean Daily Disc-area.	Mean Co-ordinates. Centre of Group. Lat.	Long.	Heliographic Co-ordinates. Centre Sun's Disc. D.	L.	Angular Distance. Spot from Central Meridian.
May 12	21	34	5	2	14·9	+0°·8	2°·7	−2°·9	32°·2	29°·5
13	40	40	>67	2	15·6	,,	,,	−2·8	19·0	16·3
14	50	64	56	2	16·5	,,	,,	−2·7	5·7	3·0
15	>129	...	>75	2	14·3	,,	,,	−2·5	352·5	10·2
16	47	70	>64	2	13·0	,,	,,	−2·4	339·3	23·4
17	21	29	8	2	11·3	,,	,,	−2·3	326·0	36·7
18	11	19	2	1	7·4	,,	,,	−2·2	312·8	49·9
19	58	30	21	2	...	,,	,,	−2·1	299·6	63·1
20	26	61	27	2	1·6	,,	,,	−2·0	286·4	76·3
21	26	20	11	2	0·3	,,	,,	−1·8	273·1	89·6

In the three columns giving the ranges of the magnetic elements, these ranges, Dn, H, V, are expressed in minutes of arc, in order the more easily to compare the magnitudes of the movements as measured on the curves. To reduce the numbers in the columns under H and V to units of force, γ, where $1\gamma \equiv 10^{-5}$ C.G.S. unit, the factors are 4·7 for H, and 6·4 for V. The values for V are very notably high. The international character figures for magnetic disturbances are 0 (quiet), 1 (disturbed), 2 (highly disturbed). Every day except one, May 18, is marked by the figure 2. This storm is remarkable for the number of days over which it extended. To find a parallel we must go back to the protracted storm, 1882 November 11–21, which also accompanied the passage of a great spot across the sun's disc. That storm was the greatest recorded up to that date at the Stonyhurst Observatory, where the photographic magnetographs had then been in constant action for fourteen years.*

In the columns concerned with solar data, the first gives the

* *Stonyhurst Observatory Report*, 1882, pp. 64–65.

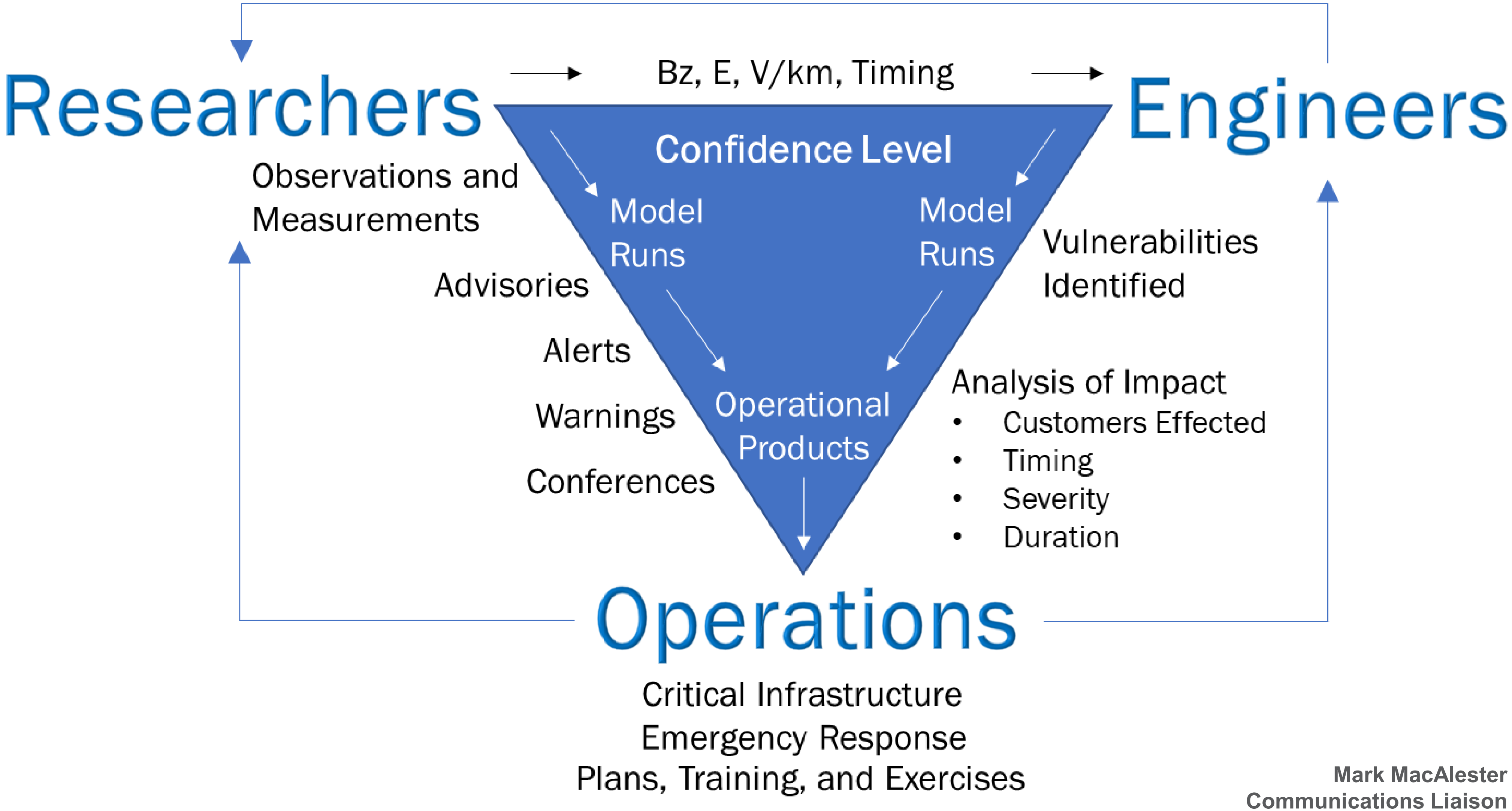
The "Great Storm" of 1921 was the largest of several storms over a period of almost two weeks.

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



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

The author would like to thank:

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- Mike Hapgood at RAL Space
- The Communications Information Sharing and Analysis Center
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- Mark Jenson and the J6 team at NORAD and USNORTHCOM
- Stephen White at the Air Force Research Laboratory
- And many others -- Thank you!

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

U.S. DEPARTMENT OF HOMELAND SECURITY

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