Operationally Significant Phenomena and Impacts for Ground Operations

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On behalf of Chris Stubenrauch

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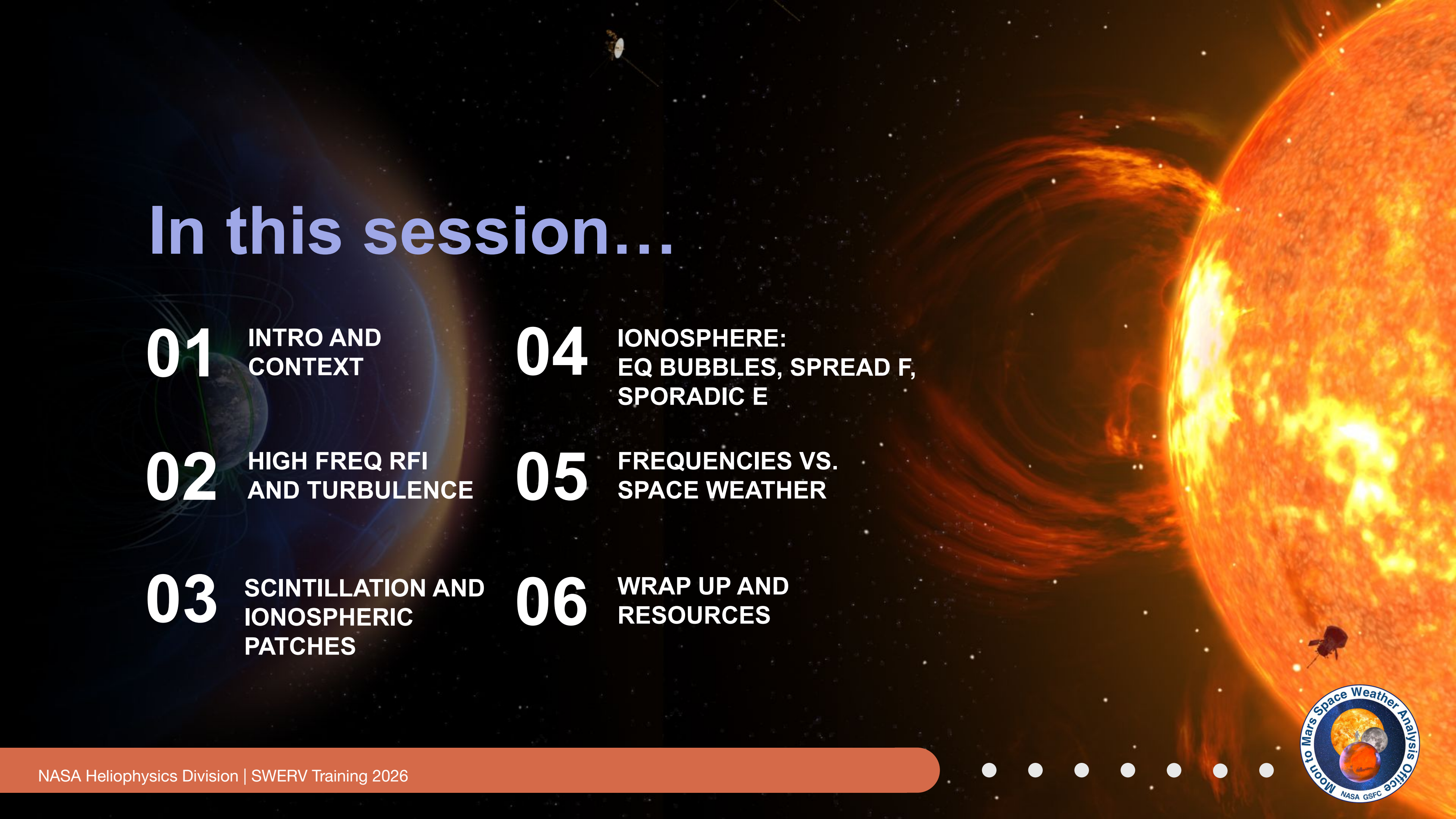

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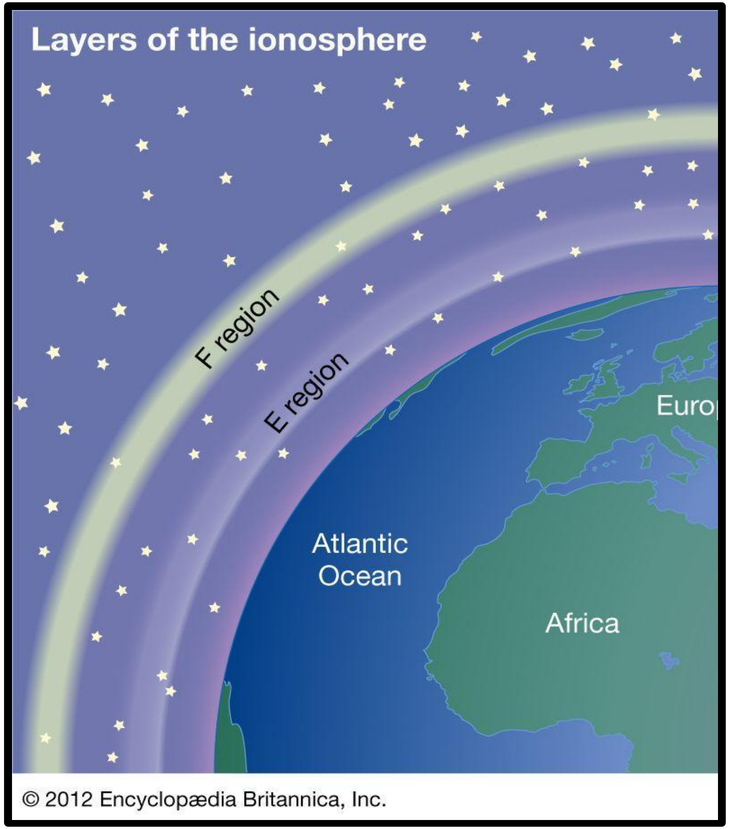
Overview of Ionospheric Phenomena Affecting Ground Operations

- This session focuses on how the ionosphere influences ground-based communications and navigation systems, particularly under disturbed space weather conditions.

- We'll explore the key ionospheric phenomena that cause signal disruptions, positioning errors, and degraded communications, especially in military and mission-critical environments.

- Topics include Geomagnetically Induced Currents (GICs) and infrastructure impacts, HF radio interference, GNSS/GPS signal degradation, ionospheric irregularities, and the impact of solar radio bursts across VHF/UHF/SHF bands



Why the Ionosphere Matters for Ops

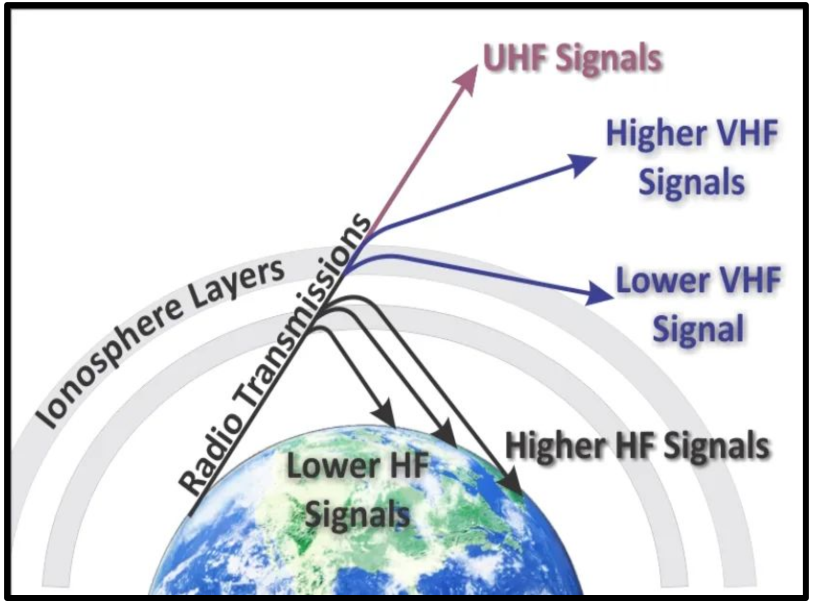
- The ionosphere is a layer of the upper atmosphere, extending from roughly 50 to 1,000 kilometers altitude, where solar radiation ionizes atmospheric gases.
- This region directly affects radio wave propagation and GPS signal paths, making it crucial for ground-based communication and navigation systems.
- Ionospheric conditions can change rapidly due to solar flares, geomagnetic storms, and daily/seasonal cycles, often without visible warning.

How HF Comms Work

- High Frequency (HF) signals (3–30 MHz) rely on the ionosphere to “bounce” signals beyond line of sight — critical for maritime, aviation, and polar comms.

- Different layers of the ionosphere (D, E, F) affect signal reflection height and strength; the F-layer is key for long-range communication.

- A stable ionosphere allows predictable communication paths — but when disturbed, signal quality and reach can degrade significantly.



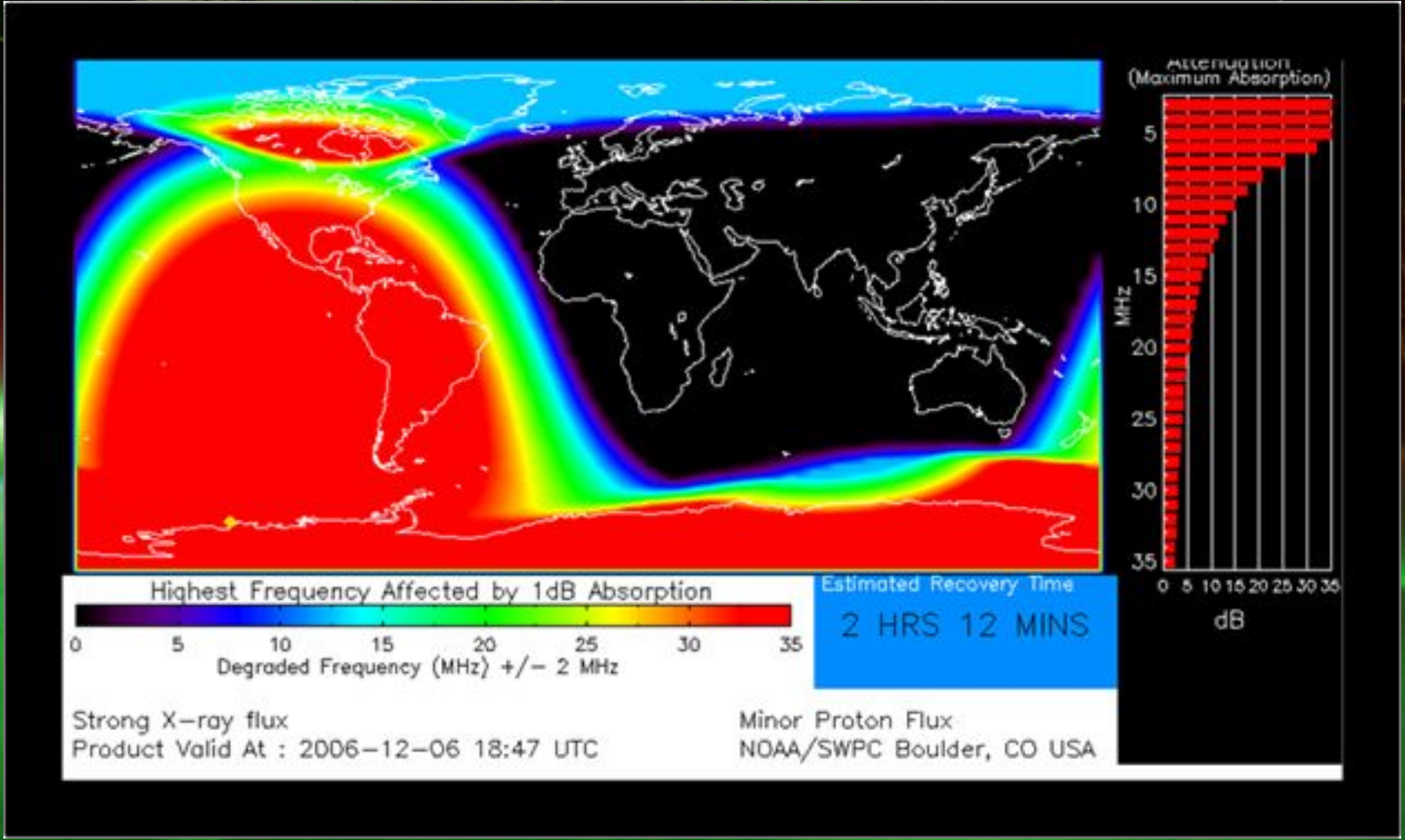
Causes of HF Interference

- Solar activity can significantly disrupt the ionosphere, especially the lower D-layer, which plays a critical role in how HF radio signals travel through the atmosphere.

- Solar flares, particularly those producing X-rays and extreme ultraviolet radiation, rapidly increase ionization in the D-layer. This results in increased absorption of HF radio signals, a phenomenon known as D-region absorption. During a solar flare, the D-layer becomes so ionized that it effectively "soaks up" HF energy, preventing signals from reaching higher layers where they would normally reflect.

- Geomagnetic storms, triggered by coronal mass ejections (CMEs), disturb the structure and density of the entire ionosphere — including the F-layer, which is most important for long-distance HF communications. These changes can cause signal path unpredictability, frequency fading, and total communication dropouts.

- At high latitudes, Polar Cap Absorption (PCA) events occur when high-energy protons from solar storms reach the polar ionosphere. These events result in prolonged HF blackouts lasting several hours to days, especially impacting aviation routes over the poles



Estimated Recovery Time
2 HRS 12 MINS

Strong X−ray flux
Product Valid At : 2006−12−06 18:47 UTC

Minor Proton Flux
NOAA/SWPC Boulder, CO USA

HF Operational Impacts

- HF radio is a backbone for long-range communications in areas with limited or denied satellite coverage — such as polar regions, mid-ocean, or austere operational environments.

- When the ionosphere becomes disturbed due to space weather events, HF signals can fade, reflect unpredictably, or be completely absorbed. This compromises command and control, air traffic communications, and ISR platforms that depend on long-haul comms.

- For aviation, this can result in loss of ATC contact over oceanic routes. For maritime operations, ships may be unable to maintain contact with headquarters. In denied environments or SATCOM-contested zones, this reduces operational resilience and increases mission risk.

Ionospheric Scintillation

Clear reception for a ship but disturbed reception due to the prescence of an equatorial plasma bubble for a tractor

- GNSS systems, including GPS, GLONASS, Galileo, and BeiDou, rely on signals transmitted from satellites in medium Earth orbit (MEO). These signals travel through the ionosphere before reaching receivers on the ground.

- When the ionosphere is disturbed by space weather, it can create small-scale, rapidly changing irregularities in electron density. As GNSS signals pass through these irregularities, they experience scintillation — rapid fluctuations in amplitude (signal strength) and phase (timing).

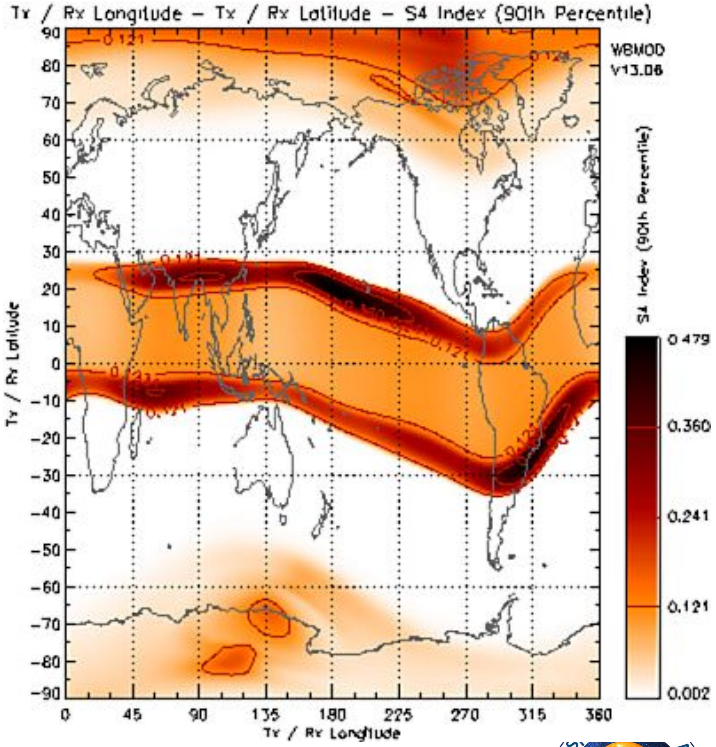
- Scintillation reduces receiver sensitivity, delays signal acquisition, and can cause complete loss of lock. It is most pronounced near the magnetic equator and polar regions, especially during geomagnetic storms or post-sunset hours

Ionospheric Scintillation (continued)

- There are two main types of GNSS scintillation that affect signal integrity:
    - Amplitude scintillation, measured by the S4 index, describes rapid variations in signal strength. It leads to degraded signal quality and potential loss of lock.
    - Phase scintillation, describes fluctuations in the phase of the signal, impacting timing and positioning accuracy.

- Both forms can occur simultaneously and are typically worse during geomagnetic storms, particularly at night. Scintillation is especially severe near the equatorial “anomaly” zones and auroral regions.

- Operational systems dependent on accurate position, navigation, and timing (PNT) may be affected without warning.



Equatorial Plasma Bubbles

- Equatorial Plasma Bubbles (EPBs) are large-scale depletions of plasma in the nighttime equatorial ionosphere.
- After sunset, rapid recombination of ionized particles leads to rising plumes of low-density plasma. These "bubbles" can extend upward into the F-layer and beyond, creating highly turbulent regions that interfere with radio wave propagation.
- EPBs are a primary source of intense GNSS scintillation and HF disruption in low-latitude regions, especially during equinox months and periods of elevated solar activity.

- EPBs can severely degrade or completely block GNSS signals for aircraft, ground forces, and maritime units operating near the magnetic equator.
- These events are most common in regions such as South America, Central Africa, and Southeast Asia. They typically occur post-sunset and can last 30 to 90 minutes per event.
- For night missions relying on GNSS-based navigation, targeting, or ISR, EPBs introduce unanticipated errors, signal drops, and operational delays.

Climatological Plasma Bubble Rate from GUVI imaging (Comberiate and Paxton 2009)

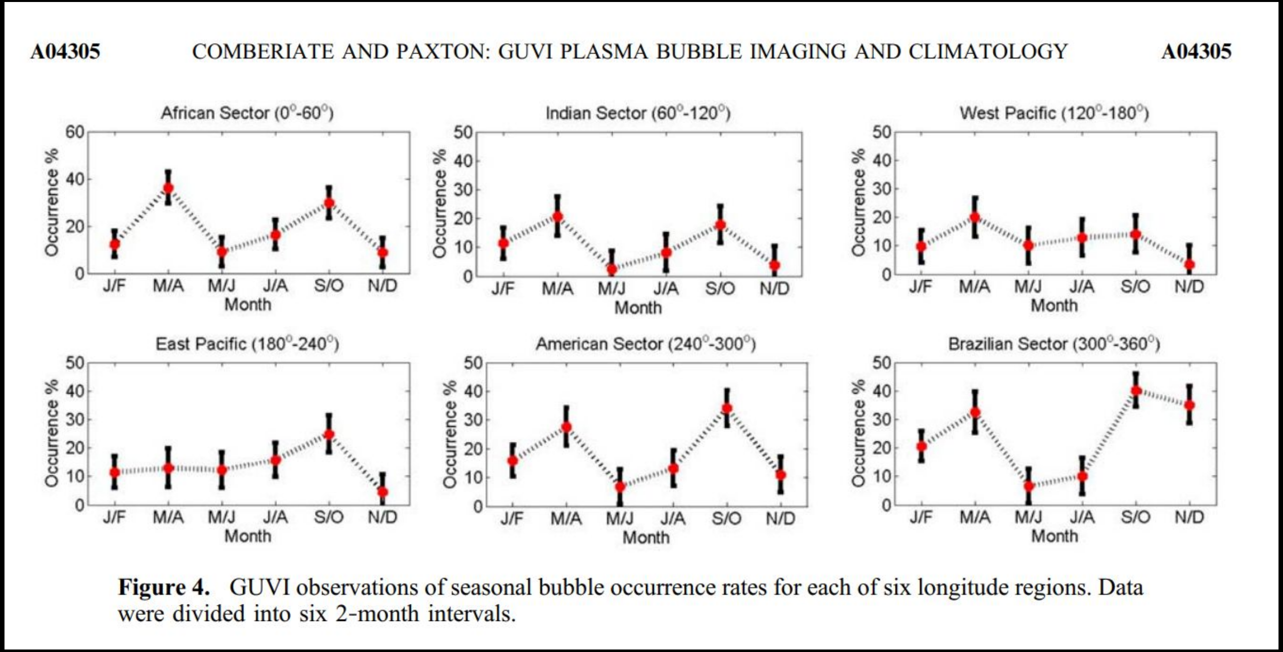


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Figure 4. GUVI observations of seasonal bubble occurrence rates for each of six longitude regions. Data were divided into six 2-month intervals.

Daytime vs Nighttime Ionosphere

The ionosphere changes dramatically between day and night due to the presence or absence of solar radiation. These variations drive many operational phenomena such as plasma bubbles and radio wave propagation anomalies.

Daytime Ionosphere:

- Solar UV and X-ray radiation strongly ionize atmospheric gases.
- Multiple distinct layers form (D, E, F1, F2), with high electron density.
- HF signals reflect predictably off the F-layer; GNSS signals generally remain stable.
- D-layer absorption can degrade low-frequency (HF) signals, especially below 10 MHz.

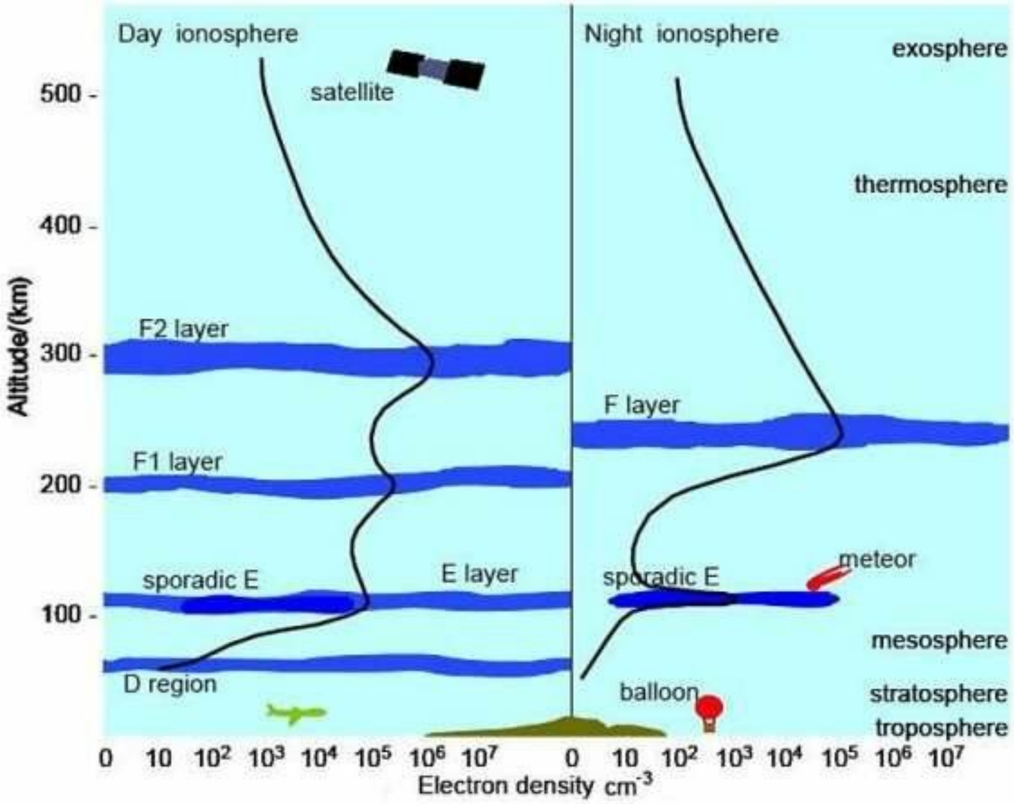
Nighttime Ionosphere:

- Solar ionization ceases; rapid recombination reduces electron density, especially in the lower layers.
- D and E layers collapse; F1 and F2 layers merge into a single, weaker F-layer.
- Reduced density and vertical gradients can lead to plasma instabilities (e.g., EPBs, Spread-F).
- HF propagation conditions change, sometimes improving long-distance comms but increasing risk of signal fading or scattering.

Why It Matters:

- Most GNSS disruptions, HF signal fading, and plasma instabilities occur at night, especially in equatorial regions.
- Mission planners should expect greater variability and turbulence in comms and navigation systems during nighttim operations.

Daytime vs Nighttime Ionosphere

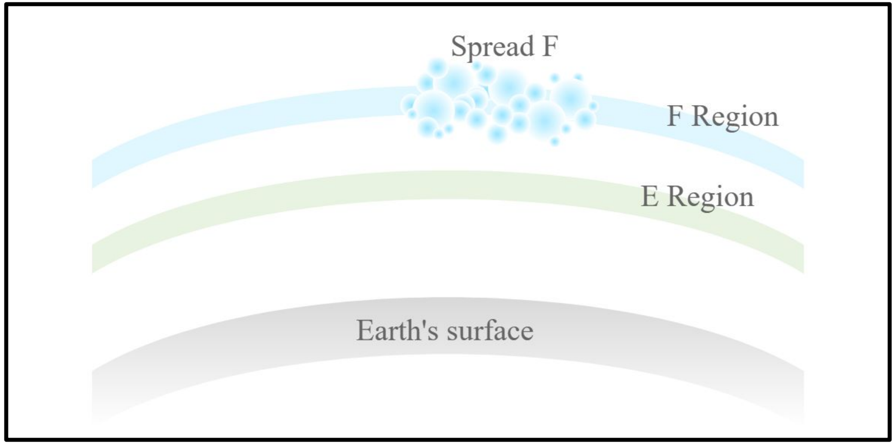


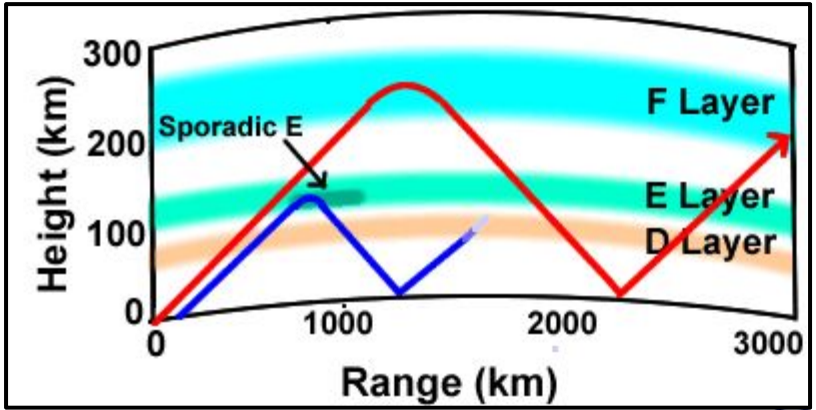
Spread F/Sporadic E

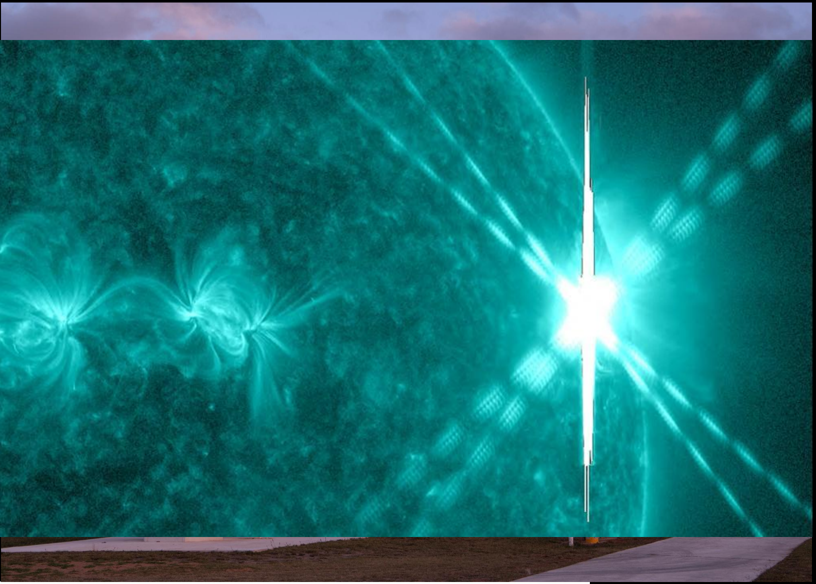
- Spread-F is an ionospheric phenomenon observed primarily at night, in which irregularities in the F-layer plasma density cause radar and radio waves to scatter.
- Instead of bouncing predictably off a smooth ionospheric layer, the signals are scattered in multiple directions, leading to weak, fading, or distorted reception. On ionograms, this appears as smeared or "spread" traces rather than clean reflections.
- Spread-F is closely related to plasma instabilities and often occurs alongside EPBs in equatorial regions.

- Spread-F conditions reduce the reliability of HF communications and certain over-the-horizon radar systems. In affected areas, operators may experience fading, multipath distortion, and signal dropouts that come and go unpredictably. This challenges frequency selection, message reliability, and timing-critical coordination.
- Frequency changes or switching to alternate comms bands may be necessary to maintain connectivity. However, without space weather awareness, these impacts can appear as unexplained equipment failure

Spread F/Sporadic E







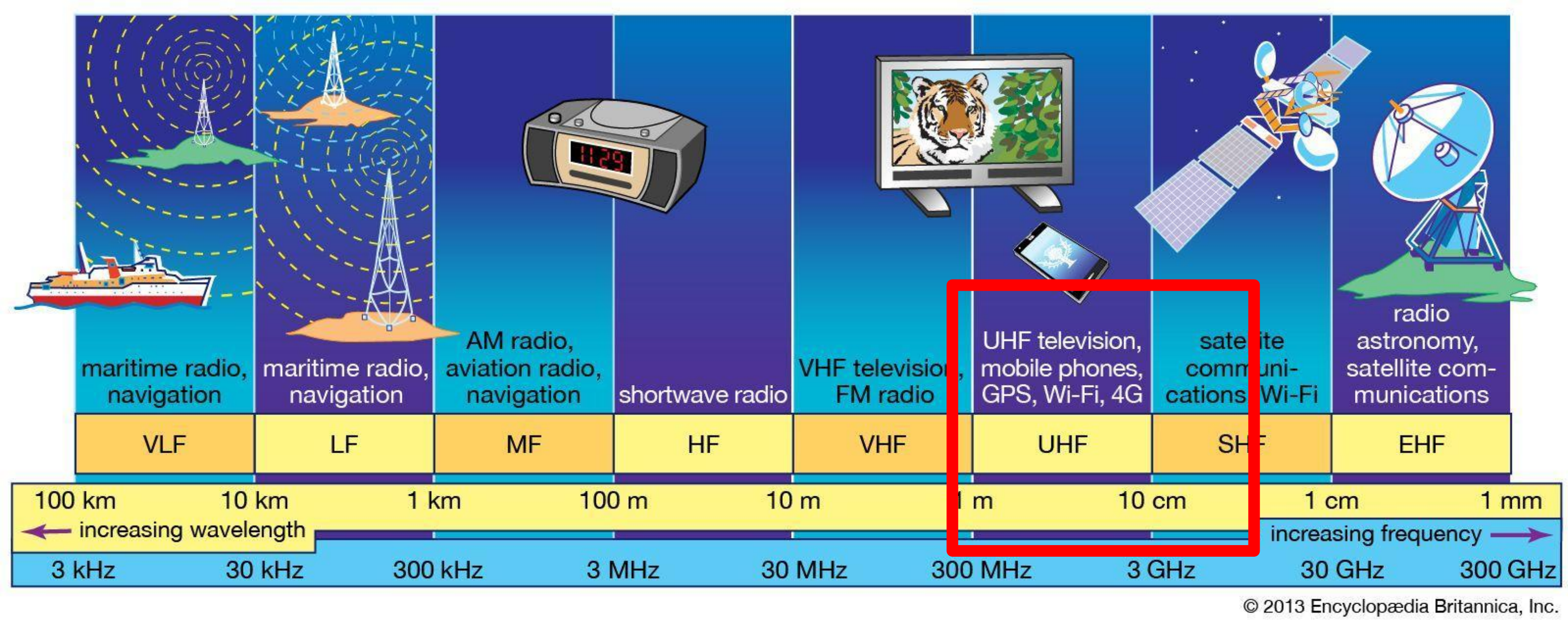
Solar Radio Bursts and Disruptions in UHF/SHF

- Solar radio bursts are intense emissions of radio energy generated during solar flares. These bursts can directly interfere with radio receivers operating in the Super High Frequency (SHF) band — including SATCOM, missile warning radars, and tracking systems.

- Unlike scintillation or absorption, which alter how signals travel, solar radio bursts overwhelm the receiver with strong background noise. The effect is similar to a local jamming event, except it originates from the Sun.

- These disruptions can last from several minutes to over an hour, depending on the flare's size and intensity. They are most dangerous when the Sun is in the line-of-sight of the satellite-receiver pair — typically during mid-morning or mid-afternoon local time.

Solar Radio Bursts and Disruptions in UHF/SHF



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Space Weather-Related Anomalies

Communications

Frequency	Impact	Source
High Frequency (3-30 MHz)	Signal fading, radio blackout, increased noise	Geomagnetic storms, solar flares, solar energetic particles
Very High-Frequency (30-300 MHz)	Signal fading and distortion in the VHF band	Ionospheric scintillation and solar radio interference (245 MHz)
Ultra High-Frequency/GPS (300 MHz - 3 GHz)	Signal degradation and inaccurate positioning	Radio bursts, ionospheric scintillation
Super High-Frequency (3-30 GHz)	Unreliable links for SHF/satellite communications	Rain attenuation (can be influenced by SWx like increased cloud coverage)
Extremely High-Frequency (30-300 GHz)	Unable to perform advanced satellite communications	Various atmospheric effects, including rain attenuation, and solar radio frequency interference

Space Weather-Related Anomalies

Communications

DECREASING SPACE WEATHER EFFECTS, INCREASING TERRESTRIAL WEATHER EFFECTS

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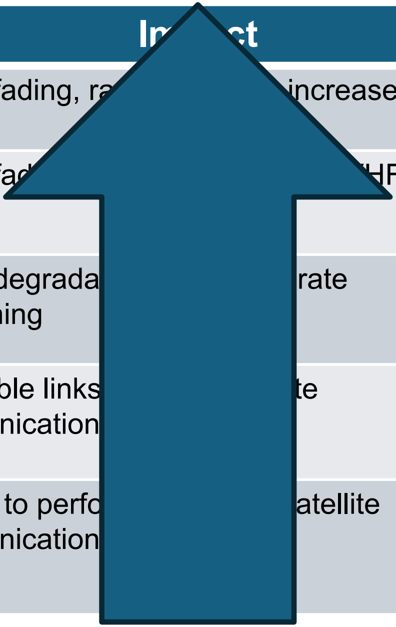

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Mitigation and Awareness Strategies

Space weather effects cannot be prevented, but their operational impacts can be anticipated, mitigated, and adapted to through training, technology, and planning.

- Monitor space weather forecasts from trusted sources like 2 WS/SpaceWOC, CSPOC, NOAA SWPC, NASA M2M, and NATO space weather centers.
  - **2 WS/SpaceWOC has specific forecasts and products tailored for DoD equipment and band-specific forecasts on multiple classification enclaves**
- Use frequency agility: train operators to shift HF bands or adjust frequencies based on real-time conditions.
- Equip systems with multi-band or hybrid comms capabilities (e.g., HF + SATCOM + LOS radio).
- Harden GNSS-dependent platforms with anti-jam technologies and alternative navigation methods (e.g., inertial navigation).
- Include space weather effects in pre-mission briefs, and ensure communication redundancy in contested environments.