Understanding HF Skywave Propagation

A Guide for Radio Hams

by <u>Doron Tal</u> <u>⋈ 4X4XM</u>

This evolving guide leverages AI tools

to explore HF skywave propagation. It enhances amateur radio activities using tutorials on indices, diagrams, charts, online reports, nowcast conditions, and banners and includes a table of contents, shortcasts $\mathbf{\Phi}$, referencing sources $\mathbf{\pi}$, a glossary, a sitemap, and search capabilities.

For the best experience, please switch to landscape mode. Landscape

The PDF file is a static snapshot of the dynamic online HTML version. HTML page loading times may vary due to connectivity delays. -The symbol indicates a link to a reference-list.

Updated on 2025-April-30 10:54 UTC Use CTRL-F5 to refresh.

0:00 / 0:25

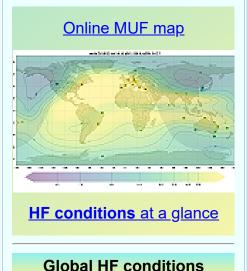
About this website | Other languages

1 Table of contents

Real-time Reports Global propagation: 17-10m band conditions. Now and 48 hours trend Real-time Watch of World Wide QSOs Regional conditions: QSOs on 11 HF Bands during the last 15 minutes.



Tracking digital modes using FT8—PSKReporter.



Tutorial Chapters

Introduction

A shortcast about this page

0:00 / 9:00



- 1. Basics of HF radio propagation
- 2. Monitoring HF band activity

<u>Band conditions</u> based on <u>DX charts</u>, <u>PSKR, WSPR, WebSDRs</u>, <u>Beacons</u>

3. Forecast HF bands conditions

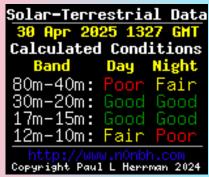
Skywave propagation basics

- 4. HF propagation modes
- 5. Impact of the sun (preface)
- 6. The ionosphere (preface)

Propagation Factors & Conditions

- 7. lonosphere's influence
 - 7.1 <u>Ionospheric regions & HF Skywaves</u>
 - 7.2 Long and mid range skywave
 - 7.3 Skywave multi-refractions
 - 7.4 Propagation indicators: foF2, MUF, OWF, LUF
 - 7.5 NVIS propagation
 - 7.6 Gray line propagation
 - 7.7 <u>lonospheric conditions</u>







Global HF fadeout

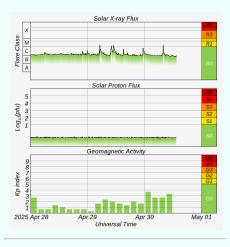


Current Kp

Current Solar Flare



Recent R-S-G reports



8. Regional HF conditions

- 8.1 <u>lonosondes</u>
- 8.2 lonogram
- 8.3 <u>Day-night—diurnal cycle</u>
- 8.4 Seasonal phenomena
- 8.5 Real-time propagation charts

9. lonosphere dynamics

- 9.1 Sporadic E (E_s)
- 9.2 lonospheric clouds-bubbles-spread F
- 9.3 <u>Ionospheric storms cause fadeouts</u> Ionospheric disturbances: <u>SID, TID, GRB</u>
- 10. Total Electron Content (TEC)

11. Global HF conditions

- 11.1 Banners & widgets
- 11.2 Solar indices: SSN, Solar Flux
- 11.3 Geomagnetic indices K, A, HPo
- 11.4 Propagation indices

The Sun and space weather

12 <u>Solar phenomena</u>

- 12.1 Quiet sun
- 12.2 Active sun
- 12.3 Sunspots and solar flux
- 12.4 Solar storms
- 12.5 The Solar cycle
- 12.6 Predicting solar flux
- 12.7 Live solar activity
- 12.8 Live solar alerts
- 12.9 Solar Radio Interference

Forecast

Forecast Proton Flux



Forecast Solar Flare



Geomagnetic Forecast

Band Conditions Forecast

Prediction

Predict solar flux ₽

Tools & Applications =

13. Space weather

- 13.1 Space weather scales
- 13.2 Solar wind
- 13.3 The magnetosphere
- 13.4 Geomagnetic activity
- 13.5 Geomagnetic storms
- 13.6 Space weather observations
- 13.7 Space weather reports
- 13.8 Geomagnetic forecast
- 13.9 Challenges in storm forecasting
- 14. Radio blackouts
- 15. **Summary**



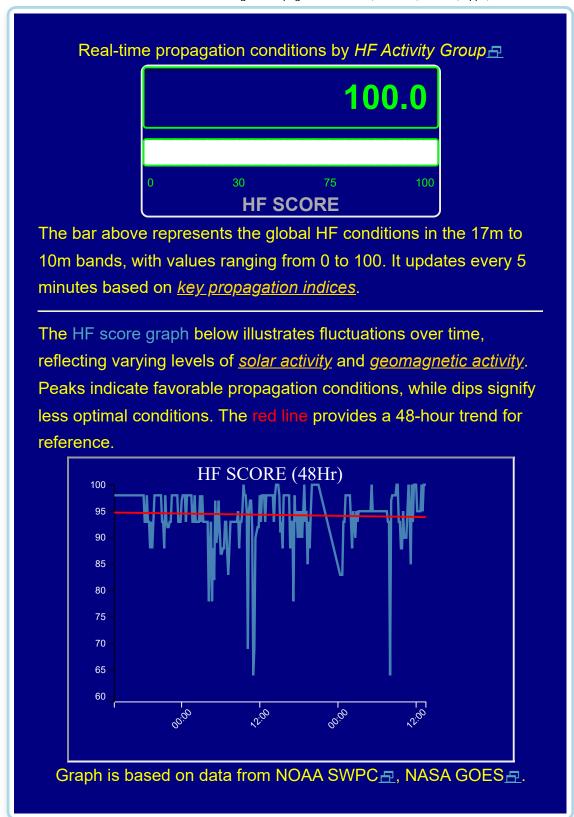
References * * FAQ * Sitemap * Languages * Visitors

- ► <u>A glossary—Index of Terms</u>
- ► <u>Search Terms for HF Radio propagation</u>.





* Rate this site



The following 15 chapters cover <u>regional and global online reports</u> <u>and tutorials</u> on various propagation topics.

Introduction

Topics covered:

- 1. What is radio?
- 2. What is an EM wave?
- 3. Radio propagation properties
- 4. Properties of electromagnetic waves
- 5. The electromagnetic spectrum
- 6. The radio spectrum
- 7. The rebirth of skywave HF radio
- 8. The HF bands assigned to radio amateurs
- 9. How does HF radio propagate?
- 10. What are HF band conditions?
- 11. Key Factors Affecting HF Propagation

What is Radio? — *Radio* is a type of electromagnetic (EM) energy that propagates as waves.

1 What is an electromagnetic (EM) wave?

An electromagnetic (EM) wave \blacksquare is a disturbance in electric field \blacksquare and magnetic field \blacksquare that may propagate through space at the speed of light (~3×10⁸ m/s in a vacuum). These waves are generated by accelerating charges or high-frequency currents and carry energy across distances.

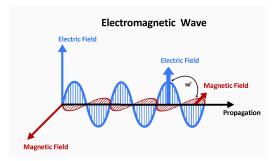


Figure 1.1: Electromagnetic Wave

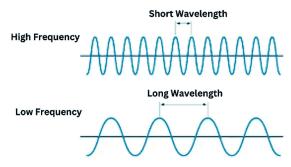


Figure 1.2: A wave characterized by frequency and wavelength

Frequency (f): Cycles per second (Hertz). **Wavelength** (λ): Distance between successive wave crests. Formula: $c = f*\lambda$, where c is light speed.

Radio signals, a type of electromagnetic radiation, typically travel in straight lines. Long-distance communication relies on waves reaching beyond the horizon. While non-linear propagation may seem complex, it can be understood with basic knowledge of electromagnetic principles, Earth's atmospheric layers, and solar-terrestrial interactions.

A comparison between Radio and Light propagation phenomena:



Figure 1.3: Radio wave propagation phenomena

Radio waves can travel in different ways between a transmitter and a receiver.

See here an overview of these five wave propagation phenomena.

<u>The difference between optical refraction</u> <u>vs. skywave refraction</u>.

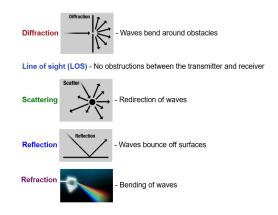


Figure 1.4: Light Wave propagation phenomena

The key difference between Radio and Light is that light waves are more easily affected by obstacles and atmospheric conditions due to their shorter wavelength.

û Properties of electromagnetic waves 🗗

- 1. *Absorption* ☐: The conversion of radio wave energy into heat and electromagnetic noise through interactions with matter.
- 2. Amplitude : The maximum extent of a vibration or oscillation, measured from the position of equilibrium.
- 3. Attenuation ☐ (Path Attenuation | Path Loss): The weakening of a signal as it travels over a distance.
- 4. <u>Diffraction</u>: Waves bend around obstacles, allowing them to spread behind them.
- 5. <u>Dispersion</u> : Separation of waves at different angles of refraction ☐ of different frequencies/wavelengths.
- 6. Fading / Shadowing :: Signal strength fluctuates due to obstacles and multipath propagation.

- 7. Electromagnetic Field | Electromagnetic Radiation : Electric and magnetic components that oscillate perpendicular to each other.
- 8. *Field Intensity*: The strength of the wave's electric or magnetic field, typically measured in (Volt/m) or (Ampere/m).
- 9. <u>Frequency</u> : The number of peaks per second.
- 10. *Interference* : Waves superpose to form a wave with different amplitudes, causing constructive or destructive interference.
- 11. *Polarization* ☐: The orientation of the electric field of the wave, which can be linear, circular, or elliptical.
- 12. Power Density ☐: The amount of power transmitted per unit area, typically measured in watts per square meter (W/m²).
- 13. *Ray* ☐: The direction of wave propagation, often conceptualized as a line along which the energy of the wave travels.
- 14. Signal-to-Noise Ratio (SNR). A measure comparing the level of a desired signal to the level of background noise, expressed in decibels (dB). A higher SNR indicates a clearer and more distinguishable signal from the noise.
- 15. <u>Reflection</u> →: Waves bounce off a surface, where the angle of incidence equals the angle of reflection.
- 16. <u>Refraction</u>: Waves bend as they pass from one medium to another due to a change in wave speed, governed by Snell's law.
- 17. <u>Scattering</u>: Waves spread out in different directions due to interaction with particles or rough surfaces, leading to the diffusion of the incident wave.
- 18. <u>Spectrum</u> →: The range of frequencies or wavelengths of electromagnetic waves, from radio waves to gamma rays.
- 19. Standing wave ☐: A wave that oscillates in time but whose peak amplitude profile does not move in space.
- 20. Wave interference: Combine coherent waves by adding their intensities or displacements, considering their phase difference.
- 21. Wavefront: A surface of constant phase of the wave, which can be thought of as the leading edge of the wave moving through space.
- 22. *Wavelength* ☐: The distance between consecutive peaks of a wave.

The electromagnetic spectrum: Radio waves are a subset of the electromagnetic spectrum that has unique applications based on frequency and wavelength. The following Figure 1.5 moves from long to short wavelengths, with radio waves on the left side.

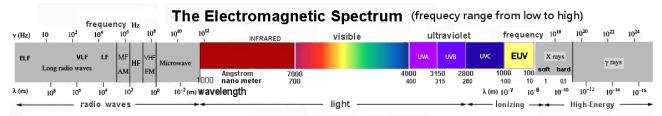


Figure 1.5: The electromagnetic spectrum

1 The radio spectrum shown below in Figure 1.6 goes from low to high frequency (long to short wavelength).

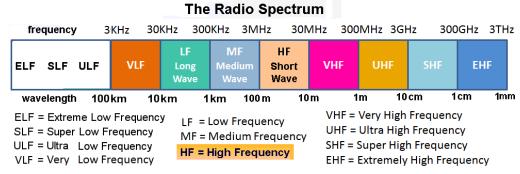


Figure 1.6: The radio spectrum divided into 11 bands, from 3 Hz to 3 THz.

The rebirth of skywave HF radio

<u>Skywave HF radio</u> declined in the 1960s due to <u>ever-changing</u> <u>lonosphere</u>, interference <u>r</u>, and bandwidth limits, leading to the rise of satellite technology.

Between 1965 and 2020, satellite system issues—high costs, outages, and complex infrastructure—revived interest in HF radio. Advances like digital voice, automatic link establishment (ALE), and spread-spectrum, have improved skywave reliability and affordability, making it popular again for long-distance and emergency communications.

Advantages of Skywave over Satellites:

- Remote Reach: Skywave covers areas without satellite access.
- Infrastructure-Free: No infrastructure needed; ideal for emergencies.
- Cost-Effective: <u>Long-range communication</u> with low-power transmitters.

Table 1.1: The MF and HF bands assigned to radio amateurs ₽

Band (Meters)	Frequency Range (MHz)	Features	Notes
160 m	1.800–2.000	Day-time ground wave Winter nights skip	Part of MF band
80 m	3.500–4.000	Winter night skip Low solar activity	Allocation varies by region
60 m	5.3305–5.3665	Regional—limited power Low solar activity	Limited availability
40 m	7.000–7.200	Daytime ~500 km Winter night skip Low solar activity	Regions 1&3 Up to 7.3 MHz in Region 2
30 m	10.100–10.150	Day/night all-year	WARC <u>₽</u> CW and digimodes <u>₽</u>
20 m	14.000–14.350	Day/night all-year	The optimal DX band
17 m	18.068–18.168	Peak daytime Solar maximum	WARC <u>#</u>
15 m	21.000–21.450	Peak daytime Solar maximum	Popular during solar max
12 m	24.890–24.990	Highly affected by solar activity	WARC <u>#</u>
10 m	28.000–29.700	Highly affected by solar activity	The widest HF band

1 How does HF radio propagate?

HF radio waves mainly propagate as <u>skywaves</u>, <u>refracing</u> off the <u>ionosphere</u>, enabling long-distance communication.

1 What are HF band conditions?

<u>HF band conditions</u> refer to the quality of HF signals propagating as <u>skywaves</u>, which are influenced by <u>ionospheric dynamics</u>.

1 Key Factors Affecting HF Propagation:

- 1. Space weather conditions impact skywaves by changing the ionosphere.
- 2. Each HF band has unique characteristics.
- 3. There is a "<u>window of usable frequencies</u>" for skywaves, which depends on <u>time</u> <u>of day</u>, <u>seasons</u>, <u>solar cycles</u>, and <u>geographic locations</u>.
- 4. The usable frequency range is between the <u>LUF</u> and the <u>MUF</u>. Signals within this range enable worldwide long-distance communication.
- 5. Different ionospheric regions affect HF waves and change dynamically.
- 6. <u>Solar Indices</u>—SSN and SFI: <u>Higher values suggest improved HF propagation conditions</u>, associated with higher values of <u>f_oF₂</u>, <u>MUF</u>, and <u>OWF</u>.
- 7. Higher <u>LUF</u> values indicate disruptions in lower HF band communications, thus closing the "window of usable frequencies."
- 8. Solar X-ray bursts, enhanced solar wind, and CMEs may cause radio blackouts.
- 9. <u>Geomagnetic indices</u> measure Earth's magnetic activity; higher values of <u>A and K</u> typically indicate propagation disturbances.

The following chapters discuss all of these concepts. Click on the links above to read about each of the variables affecting HF propagation.

Ham radio activity is a reliable indicator of current band conditions. Previously, manually scanning ham bands with analog receivers was time-consuming. Today, advanced tools enable efficient global assessment of various HF bands. By combining multiple methods and tools, you can enhance your understanding of the basics of HF band propagation conditions and ensure a more accurate assessment. The following table summarizes the proposed methods, applications and tools.

Table 2.1: Tools and Applications for Monitoring HF Band Conditions

Method	Applications	Tools
Watch Activity Charts	Real-time ham band activity of all modes	DXview DXMAPS DX clusters
	Tracking digital modes	FT8 WSPR
	Tracking Global Beacons	NCDXF
Listen & Compare Signals	Use various antennas at your station	Explanation & example
	<u>Utilize remote receivers</u>	WebSDR, KiwiSDR

Social Media and Forums: operators share current band conditions and experiences.

Tools like <u>DXView</u> and <u>DXMAPS</u> provide real-time visualizations of HF activity. <u>DX clusters</u> focuse on general band openings, while DXMAPS emphasizes specific QSOs and contests.

1 2.1.1 **DXView map** by <u>Jon Harder, NG0E, showing real-time ham activity</u> in the last 15 minutes on 11 <u>ham bands</u> (1.8–54 MHz).

The DXView map (Figure 2.1 below) shows real-time ham band activity. This visual aid helps identify open bands and communication modes ₱.

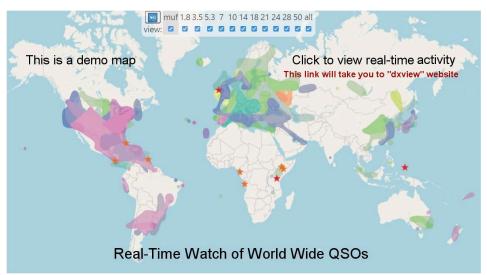


Figure 2.1: Real-time Ham Band Activity

The DXView map helps identify open bands and communication modes ♣ based on real-time activity from the last 15 minutes. It compiles data from online sources: <u>WSPRnet</u>, RBN♠ (CW, FT4, FT8), and <u>DX Cluster</u>. <u>Signal-to-Noise Ratio (SNR)</u>♣ data determines if a path supports SSB (SNR > 10 dB), CW (SNR > -1 dB), or only digital modes (decoding down to about -28 dB SNR). The DXView website provides a guide on interpreting the map and selecting band colors.

While DXView focuses on band openings, the next tool (DXMAPS) focuses on specific contacts, allows users to add their info, visualize propagation paths, and analyze contest performance.

1 2.1.2 DXMAPS by Gabriel Sampol, EA6VQ—real-time charts per band

DXMAPS provides real-time charts of reported QSOs (contacts) and SWLs (shortwave listeners) across amateur bands. Visualized propagation paths may help users analyze band conditions and contest performance effectively. Registered users can send formatted DX-Spots for easier identification. Propagation mode identification is available for high bands, above 28 MHz.



Figure 2.2: QSO/SWL real time information

1 2.1.3 **DX Clusters** are worldwide networked servers that collect messages from active radio amateurs and distribute them to all connected participants. Active radio amateurs or shortwave listeners use DX clusters to get timely information about activities on the amateur radio bands.



Figure 2.3: An illustration of DX Clusters by DALL-E Al Image Generator

Analysis of multiple DX cluster messages can be used as an indicator of <u>propagation</u> <u>conditions</u> and how they are changing. However, it's not a perfect predictor, and local factors matter.

û 2.2 Tracking digital modes🔁

FT8 is a popular *digital mode* that automatically decodes weak signals and provides real-time data on HF activity.

Tools:

- WSJT-X :: A computer program used for weak-signal radio communication between amateur radio operators.
- **PSKReporter**<u></u> : A global signal-reporting network that maps signal transmission and reception in near real time.

To monitor propagation conditions:

- 1. Use software like WSJT-X to decode FT8 signals.
- 2. Upload your reports to PSKReporter to visualize current band conditions.

Example:

A PSKReporter chart generated by WSJT-X software, illustrating global FT8 signal reception. The following map demonstrates a near real-time data display of band activity, propagation paths, and weak signal communication conditions.

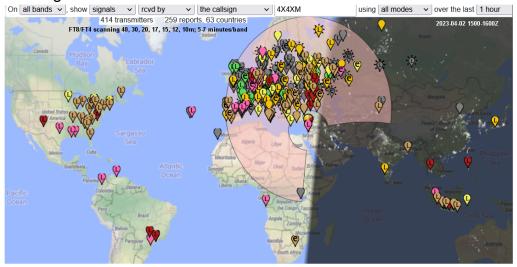


Figure 2.4: PSKReporter Chart of Signals Received

The Receiving station



Figure 2.5: **Malahite v1.3 DSP Receiver** connected to K-180WLA **Magnetic Loop antenna** (MLA)

WSPR ☐ (Weak Signal Propagation Reporter) is used to test propagation paths on the <u>ham</u> <u>bands</u>.

The following are useful links: WSPRnet, WSPR Rocks, WSPR Live.

Listening to the NCDXF Beacon Network is beneficial for DX station hunting. Eighteen **worldwide beacons** operate on five bands: 20, 17, 15, 12, and 10 meters.



Figure 2.6: **NCDXF beacons map**—These stations use standardized antennas and power levels.

The above is a map of the NCDXF Beacon Network, which operates on the frequencies: 14.100, 18.110, 21.150, 24.930, and 28.200 MHz. Receiving readable signals on these frequencies can indicate open bands.

Beacon IDs are callsigns in <u>CW</u>, followed by a carrier decreasing in four power levels: 100, 10, 1, and 0.1 Watts. If you can hear the weakest 0.1 Watts signal, it suggests good propagation or a low-noise location. The NCDXF website provides further details for operators.

Tune between 28.2 and 28.3 MHz for additional beacons operating full time.

1 2.4 Use various antennas at your station to assess HF propagation conditions

This activity requires hands-on experience and a basic understanding.

Using different antennas at your station helps assess HF propagation conditions by comparing received signal levels and signal-to-noise ratios. Switch between dipoles, verticals, and loop antennas to receive signals from beacons.

Observe variations in signal strength and clarity:

- 1. Monitor signal strength from various distant stations on different bands using different antennas (e.g., dipole, vertical, loop).
- 2. Compare reception: Note variations in signal strength across different antennas and bands.
- 3. Analyze signal quality: Observe signal quality (e.g., fading, noise levels) for each antenna.
- 4. Cross-reference data: Compare your observations with online propagation predictions and real-time propagation information.

Example:

If you consistently receive strong signals from Europe on 20 meters with a vertical antenna, but weak signals with a dipole, it might indicate favorable vertical wave propagation conditions. Conversely, if 40 meters performs better with the dipole, it could suggest better horizontal wave propagation on that band.

By systematically observing these factors, you can gain valuable insights into current HF propagation conditions and optimize your antenna choices for specific bands and destinations.

2.5 Monitor bands using remote receivers, WebSDR, and Kiwi SDR 2.5 Monitor bands using remote receivers.

WebSDR and Kiwi SDR offer online access to remote receivers. These platforms allow users to monitor global HF signals without local equipment. Both support multiple users and offer real-time spectrum and waterfall visualization. However, their user interfaces and functionalities differ, with each platform having unique advantages to suit various needs and preferences. The following example demonstrates the Wideband WebSDR at the University of Twente, Enschede, NLF. The visual spectrum and waterfall display enable users to monitor and analyze signals from remote locations.

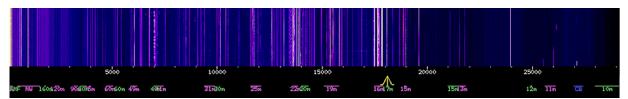


Figure 2.7: **Real-time waterfall display for a wide radio spectrum**, frequency range of 0-29 MHz, with the ability to resize the width down to 250 KHz.

Alternatively, choose a remote receiver from the following maps:



Figure 2.8: **WebSDR Global Map** showing locations worldwide Users can select a receiver to remotely monitor HF signals, access live waterfall displays, and tune into specific bands.



Figure 2.9: **Global map of Kiwi SDR receivers** showing locations worldwide Users can select stations to explore propagation conditions and compare band activity at different geographic locations.

- 1. Why Do We Need HF Propagation Forecasting?
- 2. Evolution of Forecasting Techniques
- 3. How to determine HF propagation conditions
- 4. Forecasting vs. Prediction
- 5. Forecasting and Prediction

1 Why Do We Need HF Propagation Forecasting?

HF propagation forecasting enables operators to select optimal frequencies and plan communication times. Key metrics such as <u>foF2</u> and <u>MUF</u> provide real-time insights into ionospheric conditions, essential for long-distance communication.

1 Evolution of Forecasting Techniques

Remarkable advancements in *space technology*, *software-defined radio* (*SDR*), and the internet have revolutionized our understanding of radio wave propagation. Before the 1990s, propagation charts and reports were often published in amateur radio magazines. Today, real-time solar indices and computer programs provide accurate, up-to-the-minute propagation data via *online tools*.

1 How to determine HF propagation conditions

The <u>MUF</u> , based on <u>ionograms</u> , plays a key role in determining *HF propagation* conditions.

1 Forecasting vs. Prediction

The terms *forecasting* and *prediction* differ primarily in their time frames and methodologies.

- **Forecasting**: Short-term estimations based on current data (e.g., "Conditions will improve in the next hour").
- **Prediction**: Long-term estimates based on trends (e.g., "Better 40-meter conditions expected next month").

1 Forecasting and Prediction

Utilizing real-time *propagation charts based on measured critical frequency* improves long-distance communication, reduces interference, and ensures efficient, reliable use of the *HF bands*.

The quickest methods to forecast HF propagation conditions over the next hour are:

- 1. Watch real-time DXView chart
- 2. Watch real-time propagation charts.

To understand propagation conditions fully, gather global physical parameters, such as real-time <u>solar flux (SFI)</u>, <u>solar X-ray flux (R)</u>, <u>proton solar flux (S)</u>, <u>and geomagnetic</u> <u>activity (Kp)</u>. Then, combining real-time data with mathematical models, allows accurate HF propagation forecasting for different bands, regions, and times.

Online and offline <u>applications and tools</u> can simulate the current <u>ionospheric condition</u> and its effect on <u>band conditions</u> by using mathematical models, recent solar activity data, <u>space weather reports</u>, and real-time <u>ionospheric sensing</u>.

Forecasting and Prediction Summary:

- Watch <u>ham activity charts</u>
- Analyze <u>real-time charts</u> to <u>forecast</u> potential propagation conditions.
- Utilize tools and software based on solar and geomagnetic data to <u>predict</u> band conditions.

Skywave propagation basics

↑ Chapter 4. HF Propagation Modes

This chapter reviews the primary modes of high frequency (HF) radio propagation.

There are three main modes of HF Radio Propagation: <u>LOS</u>, <u>Ground wave</u>, and <u>Skywave</u>.

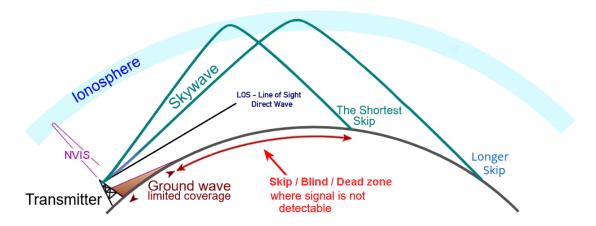


Figure 4.1: **Overview of HF Propagation Modes**In chapters 7-9, we explore the factors and conditions that influence skywave propagation.

- 1. <u>Line of Sight (LOS) propagation</u>: Short-range, direct-path communication above 30 MHz.
 - Line of Sight exists when radio signals pass directly between two stations with no
 obstacles in between. This mode works well for short-range transmission at higher
 frequencies, often within a few kilometers of the visual horizon. Signals cannot follow
 the curvature of the globe.
- 2. **Ground wave** or surface wave propagation: Effective below 2 MHz; influenced by terrain and conductivity.
 - AM radio stations use ground wave propagation during the day.
 - Vertically polarized surface waves travel parallel to the Earth's surface and can cross the horizon.

- Geologic features and RF absorption by the earth attenuate ground wave transmission.
- Ground waves are effective below 1 MHz over salty seawater or conductive ground but are ineffective above 2 MHz.
- 3. **Skywave** (or skip propagation): Long-distance propagation via *ionospheric refraction* (3–30 MHz).
 - Ionospheric Variability: Ionization density profiles vary in thickness and altitude.
 - Daytime Absorption: The lowest <u>D region absorbs</u> frequencies below 10 MHz, as discussed later, focusing on the <u>LUF</u>.
 - **Ducting effects**: Can occur occasionally.
 - The **Skip Distance** (*Figure 4.1*) is a dead zone with no reception between ground wave and skywave. It is calculated using the following formula:

$$D_{
m skip} = 2h\sqrt{\left(rac{
m f_{MUF}}{
m f_c}
ight)^2} - 1$$

where D_{skip} is Skip Distance, h is the height, f_{MUF} is maximum usable frequency, and f_c denotes the <u>critical frequency</u>.

- · Special cases:
 - Gray line (greyline): Utilizes the twilight zone around Earth separating daylight from darkness.
 - <u>NVIS</u>: Near Vertical Incidence Skywave operates at 2–8 MHz, using low horizontal antennas to address dead zones.
 - <u>Sporadic E</u>: In late spring or early fall, low VHF (30 to 150 MHz) signals can be unpredictably refracted back to Earth.

Note: Currently, this project does not cover the following propagation modes:

- Aurora → propagation
- Scatter Propagation
- Meteor Scatter propagation
- Backscatter propagation
- Moon Bounce (EME) propagation

Table 4.1: Summary of HF basic propagation modes

Mode	Distance Range	Key Features	Frequency Range
Line-of- Sight	Short (a few km)	Direct signal path with no obstructions	Above 30 MHz
Ground Wave	Up to 100 km	Follows Earth's surface; best over seawater	Below 2 MHz
Skywave	Global (1000+ km)	Refracted by the ionosphere; supports long-distance	3–30 MHz (<u>HF</u> <u>bands</u>)

Among these modes, skywave propagation is the most versatile for HF bands. The upcoming chapters detail the factors affecting skywaves.

Chapter 5. How does the sun affect radio communications?

The sun affects how radio waves travel. Figure 5.1 illustrates how the <u>solar EUV radiation</u> ionizes atoms in the upper atmosphere, creating <u>the ionosphere</u>—a dynamic <u>plasma region</u> that enables HF skywave communication.

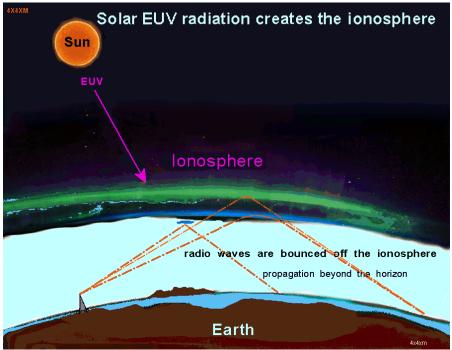


Figure 5.1: An illustration of ionosphere generation and its effect on radio waves

Knowing a bit about <u>solar activity</u> can help radio amateurs make better use of these effects to improve their experience or solve problems.

Highlights covered in the upcoming chapters:

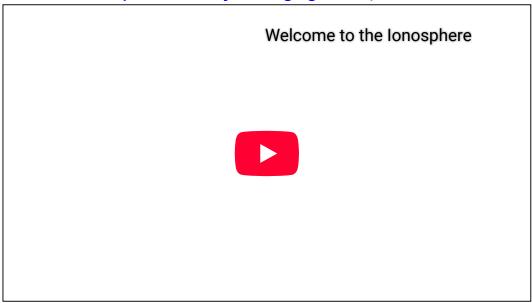
- 1. *The ionosphere* is a conducting region of <u>plasma</u> that <u>refracts</u> HF radio waves.
- 2. <u>Global and regional propagation conditions</u> depend on the sun's position and orientation, i.e., <u>time of day</u>, <u>season</u>, and <u>ionospheric state</u> above different <u>geographical locations</u>.
- 3. High <u>solar activity</u> increases <u>ionization</u> in the ionosphere, resulting in better <u>propagation</u> <u>conditions</u>, especially in higher HF bands.
- 4. The <u>sunspot number</u> and <u>solar flux</u> correlate with improved <u>global propagation conditions</u>.
- 5. Solar storms → may also disrupt global communications.

Chapter 6. The Ionosphere (preface)

This chapter serves as an introduction, laying the basis for a deeper study of the <u>ever-changing ionosphere's influence in HF radio communication</u>.

The term "ionosphere" refers to the active upper region of the atmosphere → that grows and shrinks with solar energy.





Video clip: The dance of radio waves within a vibrant airglow.

<u>Solar storms</u> intensify the ionosphere's beauty, while
Earth's weather below adds to the unique destination.

Earth's weather and the <u>space weather</u> both affect the ionosphere, a spectacle of charged particles—<u>ions and free electrons</u>.

"Ionospheric clouds" move at different speeds and directions, with irregularities in conductivity.

The ionosphere is a series of regions in the upper atmosphere

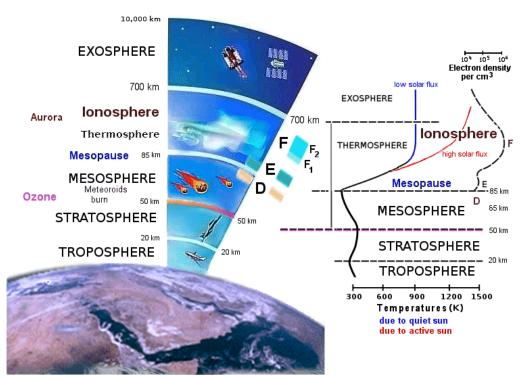


Figure 6.1: **The lonosphere (Thermosphere) is part Earth's Atmosphere**The Thermosphere is characterized by **very high temperatures** ranging from 550 to over 1300 degrees Kelvin, due to the <u>solar EUV</u>.

What is the cause of the high temperatures? —Solar radiation ionizes the ionosphere, resulting in free electrons, as illustrated here.

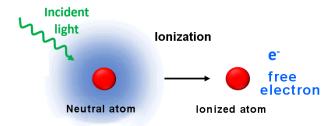


Figure 6.2: Ionization of atoms or molecules generates free electrons

HF radio waves transmitted from Earth to the ionosphere cause these free electrons to oscillate and re-radiate, resulting in <u>wave refractions</u>.

The ionospheric refractive index ☐ is analogous to that in geometrical optics ☐. Figure 6.3 illustrates light refraction in a glass prism.

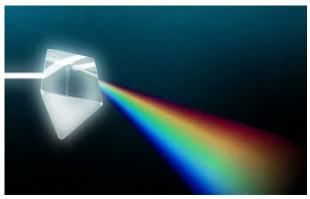


Figure 6.3: **A prism bends shorter wavelengths more**; this is an optical dispersion due to refraction **-**.

A prism bends blue light more than red, creating a rainbow. Glass prisms have a higher refractive index for blue light than red (typically 1.5–1.8).

In contrast, ionospheric plasma has a refractive index slightly less than one and bends low HF bands (3–10 MHz) more than high HF bands, as shown in Figure 6.4.

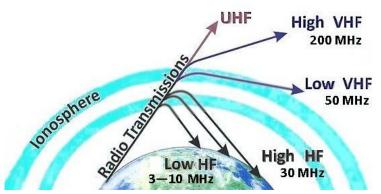


Figure 6.4: The ionosphere bends lower frequencies more; this is radio wave dispersion.

<u>The next chapter</u> extends the explanations on the ionospheric regions and their role in skywave HF propagation.

Propagation Factors and Conditions

1 Chapter 7: Ionospheric Influence

The ionosphere, composed of ions and electrons, plays a vital role in radio communication by <u>refracting skywave signals</u>.

Subchapters:

- 7.1 <u>Ionospheric Regions</u>
- 7.2 Long- and mid-range Skywave
- 7.3 Skywave Multi-refractions
- 7.4 Propagation Indicators
- 7.5 NVIS Propagation
- 7.6 Gray Line Propagation
- 7.7 <u>Ionospheric conditions</u>

1 7.1 Ionospheric Regions

Note: People commonly use the term layers, but **regions** more accurately describe the ionosphere's structure.

The D, E, and F regions form the <u>ionospheric structure</u>, although <u>ionization density varies</u> <u>with altitude and time</u> across the entire ionosphere.

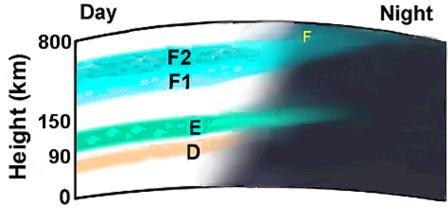


Figure 7.1: Ionospheric regions illustration

It's common to present the order of ionosphere regions affecting HF skywaves from the highest region downwards, as follows:

• The **F region**, located between 150 and 800 km above the Earth, enables longdistance HF communication in the 3.5 to 30 MHz bands.

This region consists of <u>ionized</u> hydrogen (\mathbf{H}^+) and helium (\mathbf{He}^{++}) with the highest <u>free-electron density</u> up to 10^{12} electrons per cubic meter excited by the **10–100** nano-meter <u>EUV</u>. It splits during the day into two sub-regions, $\mathbf{F_1}$ and $\mathbf{F_2}$, which merge and slowly dissipate after sunset.

• The **E region**, located between 90 and 150 km above the Earth, dissipates a couple of hours after sunset.

This region consists of ions such as O_2^+ , O^+ up to 10^{11} electrons per cubic meter excited by the **1–10** nano-meter EUV_{-} solar radiation.

During intense $Sporadic E_{(E_s)}$ events (particularly near the equator) it sporadically reflects frequencies in the SO-144 MHz bands.

• The **D region**, located 50–90 km above ground, is active during daytime and dissipates at sunset.

In this region, <u>UVC</u> at 121.6 nm excites nitric oxide ions (NO⁺), up to 10¹⁰ electrons per cubic meter. This causes radio frequencies to be <u>absorbed and</u> <u>blocked</u> during daylight hours, preventing frequencies lower than the <u>lowest usable</u> <u>frequency (LUF)</u> from reaching higher E and F regions (<u>Figure 7.9</u>).

Moreover, chaotic <u>solar flare bursts</u> ⊕ (X-rays with wavelengths of <u>0.1–1 nm</u>) significantly enhance ionization in this region, causing <u>blackouts</u> that can last from minutes to hours.

Additionally, enhanced <u>solar wind</u> and <u>CME</u>s may cause <u>Polar Cap Absorption (PCA)</u> events that can last up to 48 hours.

The F, E, and D regions differ in gas composition and <u>free electron density</u>. These regions are conceptual rather than rigidly defined. Sometimes there are <u>plasma clouds</u> rich in free electrons. The average electron density affects the <u>critical frequency</u> of each region. Their characteristics change <u>daily</u>, <u>seasonally</u>, and throughout the <u>solar cycle</u>.

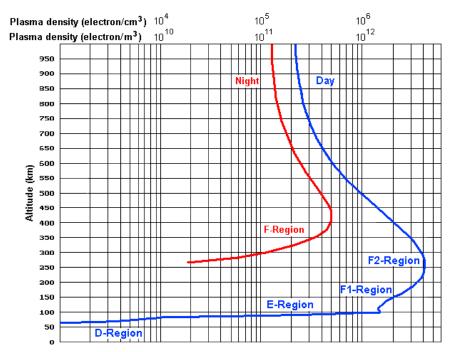


Figure 7.2 Typical Distributions of Free Electrons in the lonosphere

The above graph is based on a review from U.C.Berkeley by Bob Brown Ph.D, NM7M (SK)₽

<u>Free-electron densities</u> fluctuate throughout the <u>day and night</u>, across <u>seasons</u>, and are influenced by various factors such as <u>sunspots</u>, <u>solar cycle</u>, <u>geomagnetic storms</u>, and lightning storms, all of which can affect radio <u>propagation conditions</u>.

Why does the density of free electrons increase sharply with height between 50 km and 250 km?

The density of free electrons results from a balance between ionization (due to solar EUV) and recombination (ion-electron recombination events). The F region gets most of the UV radiation compared to the lower E and D regions, while the rate of electron-ion recombination is much faster in the lowest D region (due to the higher gas density). As a result, the *free-electron density* of the high-set F region (at noon) is significantly higher than that of the E and D regions. At most, only one thousandth (1/1000) of the neutral atmosphere is ionized.
☐

1 7.2 Long and Mid-Range Skywave

Figure 7.3 shows skywave *refractions* from the F and E ionospheric regions.

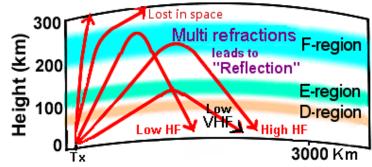


Figure 7.3: Multi refractions of radio waves in the ionosphere.

The F region refracts HF (3-30 MHz); <u>Figure 6.4</u> illustrates the difference between low and high HF bands refraction.

The E region sporadically refracts low VHF (50-150 MHz).

Long-range skywave propagation typically employs low transmission angles that correspond to high incident angles.

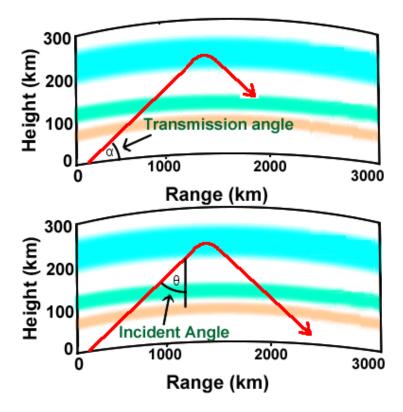


Figure 7.4: **Transmission** angle (α) and **incident** angle (θ)

A low transmission angle, which means the transmitted beam is nearly horizontal, enables refractions at higher frequencies and over longer distances. However, using real antennas at frequencies below 30 MHz to achieve low-angle radiation of less than 5 degrees can be extremely challenging.

7.3 Skywave Multi-refractions

The <u>ionosphere</u> refracts <u>skywaves</u> in complex multiple modes

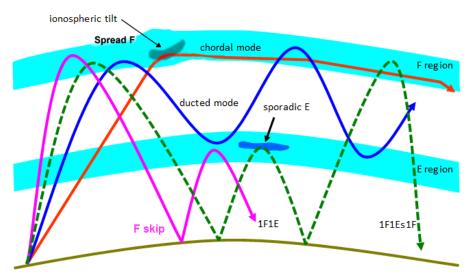


Figure 7.5: Complex skywave modes:

F Skip / ¹F¹E, E-F Ducted, F Chordal, E-F occasional and sporadic E[□].

This figure extends Fig.2.4 of ASWFC□.

The diagram illustrates various modes of radio wave propagation in the ionosphere, such as ionospheric tilt, chordal mode, ducted mode, sporadic E, F skip, 1F1E, and 1F1Es1F. It emphasizes how radio waves interact with the E and F regions, depicting their travel paths across long distances.

The <u>free electrons</u> in the ionosphere <u>refract</u> radio waves as they move through the ionospheric regions, where the <u>free-electron density</u> gradually varies; numerous refractions are what create the <u>frequency-dependent</u> refractions of ionosphere <u>skywaves</u>.

1 7.4 HF Propagation Indicators: Critical Frequencies

The refraction of radio waves in the ionosphere is characterized by their <u>critical</u> <u>frequency</u>. This is the highest frequency at which radio waves refract back to Earth. Higher frequencies escape into space.

The terms (frequencies) $\underline{f_0F_2}$, \underline{MUF} , \underline{OWF} , and \underline{LUF} serve as indicators for HF radio propagation conditions.

7.4.1 The **Critical Frequency** $rac{r}{r}$ (f_0F_2) is the highest frequency below which a radio wave is refracted by the <u>F2-region</u> at **vertical incidence**, independent of transmitting power.

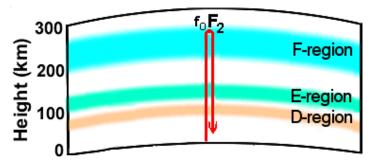


Figure 7.6: Vertical refraction from F₂ region

The critical frequency is dependent on the density of the *free-electrons*:

$$f_c = 9\sqrt{N_{
m max}}$$
 where $m f_c$ is the critical frequency and N $_{
m max}$ is the free electron density.

If the transmitted frequency is higher than the plasma frequency of the ionosphere, then the electrons cannot respond fast enough, and they are not able to re-radiate the signal.

<u>lonosondes</u> determine the critical frequency, which varies significantly based on location and time.

Statistically, between 2005 and 2007, the global average critical frequency (f_0F_2) varied from 1.8 MHz to 11 MHz, with an average of 7.5 MHz.

The critical frequency varies with several factors: <u>time of day</u>, <u>geographic latitude</u>, <u>season</u>, <u>solar activity</u>, and <u>geophysical conditions</u>.

<u>Day vs. Night</u> and <u>Geographical Locations</u>:

The critical frequency varies with latitude and the day due to increased ionization from solar radiation. At night, the MUF decreases.

The graph below shows how the critical frequency varies with latitude during the day and night.

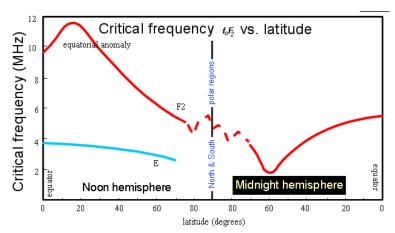


Figure 7.7: **Noon & Midnight** f_0F_2 **vs. Geographic Latitude**, based on Australian Space Weather Service publication.

- Day Hemisphere: The red curve (F2 region) peaks around 18 degrees latitude, forming an "equatorial anomaly."
 - The blue curve (E region) remains relatively flat.
- **Night Hemisphere**: The red curve shows a "mid-latitude trough" around 60 degrees latitude. Gradually growing towards the equator.
 - The E region dissipates at night.
- <u>Seasonal Variations</u>: The critical frquency is higher in summer due to the sun being directly overhead and lower in winter.
- Solar Activity: High solar activity can increase the MUF by enhancing ionospheric ionization.
- Geophysical conditions: Factors such as <u>geomagnetic activity</u> and atmospheric tides can also have an impact.

See links to <u>the online f_0F_2 </u> maps and <u>the recent f_0F_2 measurements at various locations</u> around Australia.

7.4.2 The **Maximum Usable Frequency** (**MUF**) , synonym: Highest Possible Frequency (HPF), is a fascinating concept in skywave propagation—an indicator for forecasting propagation conditions. It is the highest frequency you can use to send radio signals successfully. The MUF depends on the angle at which those signals are transmitted but is independent of the transmitting power.

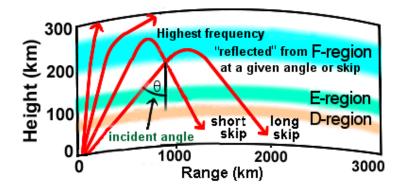


Figure 7.8: **MUF illustration**

The MUF is calculated using the formula:

 $MUF = \underline{f_0F_2} \times sec(\theta)$

- <u>f_oF₂</u>: Critical frequency of the F2 region.
- **0**: Angle of incidence relative to the vertical.
- As a rule of thumb, the MUF is approximately 3-4 times the <u>critical frequency</u>; i.e., incident angle $\theta = 70^{\circ}-75^{\circ}$; transmission angle $\alpha = 15^{\circ}-20^{\circ}$.

For vertical incidence ($\theta = 0$), MUF equals f_0F_2 . For oblique paths, MUF increases with $sec(\theta)$.

See the recent MUF charts.

7.4.3 The **Optimum Working Frequency** (**OWF**) is usually 85% of the MUF.

Synonym terms:

- Frequency of optimum traffic/transmission (FOT)
- Optimum traffic/transmission frequency (OTF)

7.4.4 The <u>Lowest Usable Frequency</u> (<u>LUF</u>) is the lowest viable frequency for communication limited by <u>daytime</u>, <u>D region absorption</u>.

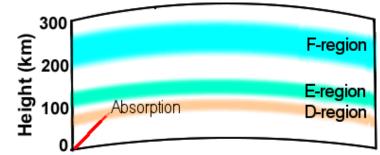


Figure 7.9: Daytime Low HF Absorption below 10 MHz

LUF, also known as the absorption-limited frequency (ALF), is a soft frequency limit, unlike the sharp cut-off of the MUF.

The <u>D region</u> absorbs frequencies below the LUF during the day. At night, the D region does not exist, so there is no low-frequency limit.

- During a solar flare, the LUF may rise swiftly.
- Strong solar flare process can cause blackouts lasting minutes to hours.
- See the LUF chart affected by the last M1+ solar flare.
- See the D-RAP model, which provides an online global LUF chart.

Understanding these variations is crucial for effective HF radio communication, as it helps select the optimal transmission frequency.

7.5 NVIS Propagation

NVIS - Near Vertical Incidence Skywave → is a unique communication mode using skywaves directed almost vertically.

NVIS provides the solution for the dead zone (between ground wave and skip). It is the only solution for communication coverage in hilly and/or jungle areas over short distances of a few hundred kilometers.

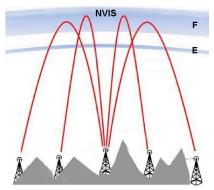


Figure 7.10: How NVIS provides communications within a hilly area.

- Typical operating frequencies are 2-4 MHz at night and 4-8 MHz during day.
- NVIS requires suitable antennas (like a low dipole at hight of 0.1-0.25 wavelengths) to improve vertical radiation and reduce lower-angle radiation, contrary to what is customary for long-range communication.
- NVIS offers enhanced resistance to fading (constant signal level), and minimal attenuation, making it suitable for low transmit power levels and omnidirectional coverage, allowing flexibility in setup and placement.
- To avoid skip zones on 40 m band use NVIS when f0F2 is higher than 8.5 MHz.
 Switch to 80 m if the day is on the downward slope. Optimize antenna radiation pattern for the desired takeoff angle. Optimum NVIS height for horizontal dipoles: 0.18–0.22λ for TX and 0.16λ for RX.

The <u>NVIS map</u> shows the recent global distribution of <u>critical frequency (foF2)</u>.

7.6 Gray line Propagation ☐

The "gray line" (US English) is the <u>twilight zone</u> around the Earth separating daylight from darkness. Propagation along this zone is highly efficient because the <u>D region, which</u> <u>absorbs HF signals during the day</u>, vanishes quickly on the sunset side and hasn't formed yet on the sunrise side. Ham radio operators and shortwave listeners can optimize long-distance communications by tracking this *twilight zone*.

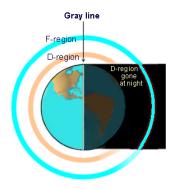


Figure 7.11: **lonospheric Regions and Gray Line**

The height of the <u>F and D regions</u> is exaggerated in comparison to Earth dimensions.

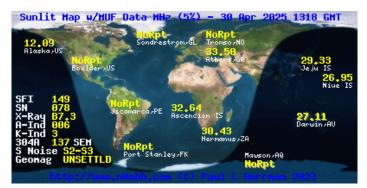


Figure 7.12: **Online gray line chart** For more information click on the map.

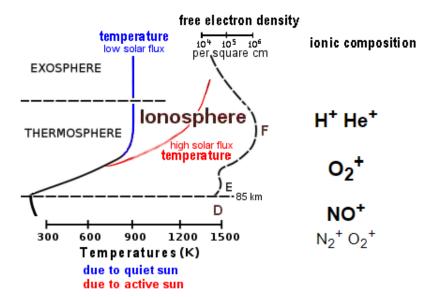
Some radio operators use specialized gray line map to predict when the gray line will pass over their location, as well as the best frequencies and modes of propagation to apply at that time. Overall, gray line propagation is a fascinating and useful phenomenon that has the potential to open up exciting opportunities for long-distance radio communication.

7.7 Ionospheric conditions

The ionospheric conditions vary in <u>geographical locations</u>, <u>24-hour cycles</u>, <u>seasonal</u> <u>changes</u>, and <u>solar activity</u>.

The following supplementary information is *not crucial* for understanding skywave propagation.

The <u>ionospheric physical conditions</u> are: temperature distribution, <u>free electron</u> <u>density</u>, pressure, density, gas compositions, chemical reactions, and transport phenomena (horizontal and vertical winds), as illustrated below.



Shown on the left figure:

- **Temperatures** distribution due to **low** or **high** solar flux
- Free electron density
- Ionic compositions.

Not shown on the left figure:

- Gas pressure and density
- Gas compositions
- · Chemical reactions
- Winds: horizontal and vertical

Figure 7.13: **lonospheric physical conditions**

The dynamics in the D region correspond to chemical reactions between the ions O^+ , N^+ , and NO^+ with N_2 , O_2 , and NO.

Nutshell: This chapter examines ionospheric regions, distributions of free electrons, critical frequencies, and specific propagation modes.

The following chapter discusses regional, diurnal, and seasonal propagation conditions, including online real-time charts.

Table 7.1: An overview of the ionospheric regions

lable 7.1: An overview of the ionospheric regions									
Region identifier	Effective height	Significant characteristic	Typical <u>MUF</u> MHz	When Present	Minimum Plasma density electrons/m3	Maximum Plasma density electrons/m3	<u>Plasma</u> characteristic	Affected by <mark>EUV</mark> wavelength	Main Ions
F	150– 800 km	<u>Super</u> <u>reflector</u> of high HF	15–30	Splits at daytime into F ₁ and F ₂	10 ¹¹	10 ¹²	collisionless	10–100 nm	H ⁺ He ⁺
E	90–150 km	low HF reflector Sporadic	7–10 50–	Negligible at night	10 ⁹	10 ¹¹	partly collision	<u>1–10 nm</u>	O ₂ +
		VHF reflector	150						
D	48–90 km	<u>Daytime</u> <u>attenuation</u>	<7 <u>LUF</u> >10	Daytime only	10 ⁸	10 ⁹	fraguant	<u>121.6 nm</u>	NO ⁺
		Chaotic blackout			10 ⁹	10 ¹⁰	frequent collisions	1–8Å X ray	N ₂ ⁺ O ₂ ⁺

Chapter 8. Regional HF Propagation Conditions

Regional <u>propagation conditions</u> offer a detailed view of what individual operators may experience, based on observed values of f_0F_2 , <u>MUF</u>, and <u>LUF</u> between two locations. Sub-chapters: 8.1 <u>lonosondes</u> » 8.2 <u>lonograms</u> » 8.3 <u>Day-night: Regular diurnal cycle</u> » 8.4 <u>Seasonal phenomena</u> » 8.5 <u>Online charts of MUF, f_0F_2 , and LUF</u>

û 8.1 Ionosonde🗗

The ionosonde, also known as the chirpsounder (developed in 1925), is an *HF radar* that sends short pulses of radio waves into the ionosphere to find the most optimal frequencies for HF communication. It calculates the time it takes for pulses to return and then plots the height (derived from the time delay) versus frequencies to produce an *ionogram*. An ionosonde sweeps the HF spectrum from 2 to 30 MHz, raising the transmitted frequency (Tx) by about 100 kHz per second and digitally modulating it in 25 kHz increments. Matching receivers (Rx) detect and analyze echo signals, as seen in the next figure.

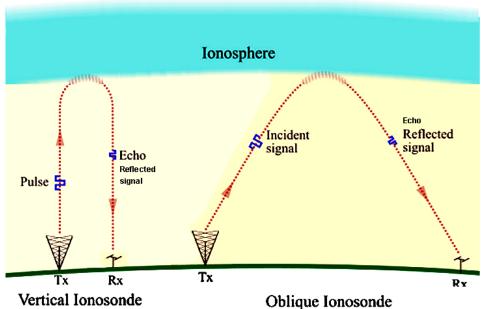


Figure 8.1: Basic ionosonde types are vertical and oblique sounding

Every 15 minutes, *ionosonde stations* around the world report real-time data via the internet.

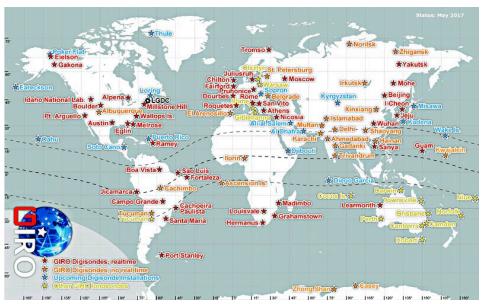


Figure 8.2: Global map of Giro digisondes as of 2017 -

Some stations aren't always active. Since 2021, real-time ionosonde data sharing has reduced in countries such as Russia, China, Japan, and others. Thus, significant regions of the globe are not yet covered with ionosonde stations, as shown on the above map.

Readings of <u>foF2</u> from several sites can be combined to build a <u>propagation map for foF2</u>.

û 8.2 lonogram 🗗

An ionogram is a visual representation of the height of the ionospheric refraction of a specific HF radio frequency. It shows the plasma density distribution in *ionospheric* regions at various altitudes (48–800 km).

lonograms typically display two key elements:

- 1. Horizontal Lines: These lines indicate the virtual height at which an amplitudemodulated pulse is echoed, varying with the operating frequency.
- 2. Vertical Curve: This curve represents the critical frequency.

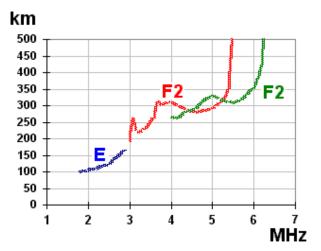


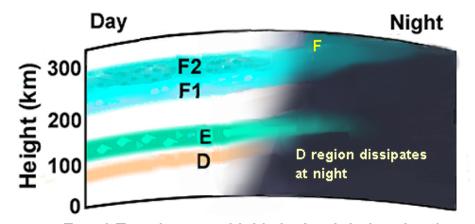
Figure 8.3: A typical ionogram

The ionogram above illustrates the ionospheric E and F2 regions. The red curve shows **ordinary refraction**, and the green curve shows **extraordinary refraction**, due to the ionosphere's anisotropic nature causing double refractions (birefringence). ☐.

While this provides a simplified explanation, the reality is that the ionosphere is neither uniform nor stable, perpetually changing over time. Consequently, researchers developed the <u>Digisonde Directogram</u> to identify ionospheric plasma irregularities.

1 8.3 Day-night: Regular diurnal cycle

The diurnal cycle on Earth occurs every 24 hours, with the sun affecting ionosphere characteristics. The figures below illustrate typical diurnal cycle: The E and F regions have larger electron densities during daylight, while the D region disappears at night. The <u>MUF</u> and <u>LUF</u> rise with the sun and diminish after sunset.



F and E regions are highly ionized during day time Figure 8.4: Diurnal cycle of ionospheric regions

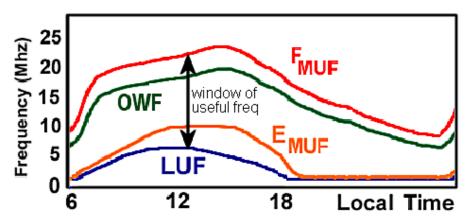


Figure 8.5: Typical diurnal cycle based on NPS training materials

F_{MUF}: F region maximum usable frequency

OWF: optimum working frequency

E_{MUF}: E region maximum usable frequency

LUF: The lowest usable frequency is due to D-region absorption, which limits the **window of useful frequencies** \$\(\frac{1}{2}\)

û 8.4 Seasonal phenomena—variations and anomalies 🔁

Seasonal variations

Intensified <u>solar EUV (Extreme Ultraviolet) radiation</u> leads to higher free-electron densities, especially during the summer months and more intensely near the equator compared to the poles.

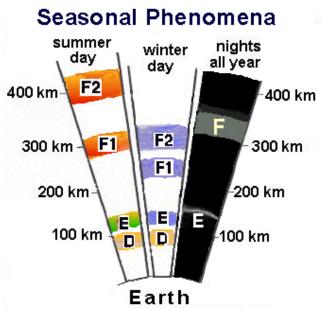


Figure 8.6: Ionospheric region dynamics at mid-latitudes

As a result, HF <u>propagation conditions</u> on the bands above 10 MHz are better in the summer and closer to the equator, whereas propagation conditions on the bands below 10 MHz are better in the winter and at mid-latitudes (30° to 60°).

Summer anomalies

Summer anomalies can cause plasma irregularities in the ionosphere's mid-latitude F region in both hemispheres. Seasonal changes significantly impact ionization, with summer frequently bringing instabilities known as *mid-latitude spread-F* due to increased solar radiation. The Arecibo Radio Observatory in Puerto Rico observed anomalous electron density irregularities during such an event, extending above the ionosphere's stable topside, as shown in the following figure:

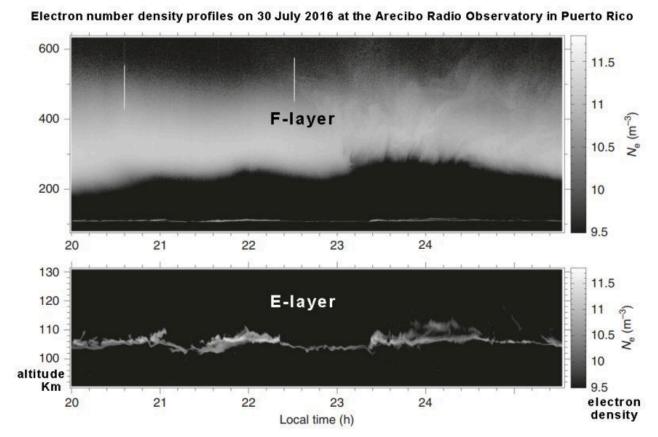


Figure 8.7: Electron density anomaly at mid-latitudes <u>₽</u>

The top figure shows both the E and F regions on the same scale and the bottom figure shows E region in an expanded scale

The following seven **online charts** show HF propagation conditions, all based on recent *ionosonde measurements*:

MUF

- 1. Online *gray line chart* ahows MUF at 13 stations with global *propagation indices* updated every 3 hours; Provided by NONBH
- 2. <u>MUF 3000 km map</u>: HF propagation conditions at a glance ^{updated every 15 minutes;} Provided by <u>KC2G</u>

There is also an <u>animated version</u> showing the last 24 hours.

foF2

3. Online <u>NVIS Map</u> shows wolrdwide distribution of <u>f</u>_O<u>F</u>₂ provided by <u>KC2G</u>, updated every 15 minutes

The following 3 **NVIS maps** are updated every 15 minutes by the Australian Space Weather Forecast Center (ASWFC)₽

- 4. Online chart of **NVIS** (f_oF₂) ASWFC
- 5. Online chart of *T index f*₀*F*₂ ASWFC
- 6. Online chart of *the recent f_oF₂ measurements* at various locations of Australia, New Zealand and East Antarctica ASWFC

LUF

- 7. Global online chart of <u>LUF calculated by D-RAP model</u> NOAA SWPC
- 8. Online chart of <u>LUF</u> updates only when it detects a <u>solar flare</u> of magnitude M1 or higher <u>ASWFC</u>.

Online *gray line chart* showing current <u>MUF</u> at 13 stations and <u>global propagation</u> <u>indices</u>; updated every 3 hours (by Paul L Herrman, N0NBH).

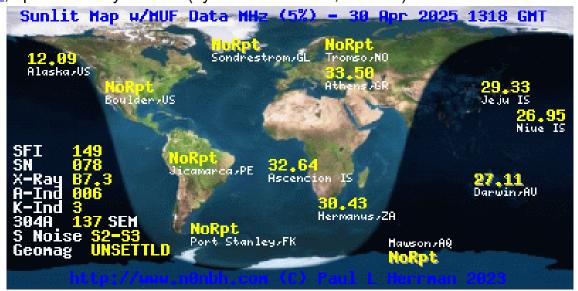


Figure 8.8: **Grayline map with MUF data and some propagation indices**The above figure shows day-night, 13 local <u>MUF</u> reports, and the <u>global indices</u>: <u>SFI</u>, <u>SN</u>中, <u>A&K</u>中, <u>304</u>Å中, <u>Geomag</u>, <u>Sig Noise</u>.

① Online MUF 3000 km propagation map □ updated every 15 minutes

This map may assist <u>radio amateurs</u> in finding the best times and frequencies for contacts by displaying <u>HF propagation conditions</u> at a glance.

- This online map shows the calculated *MUF* based on *ionograms*.
- A radio path of 3,000 km is being considered for unification.

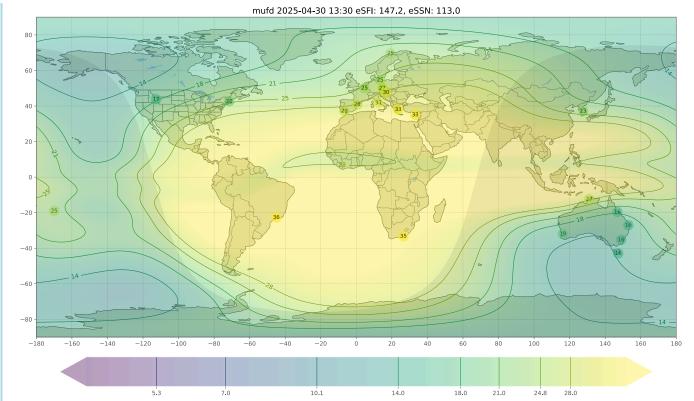


Figure 8.9: **Online MUF 3000 km propagation map**, by <u>Andrew, KC2G</u> *How to use this map* | *Notes* | *Animated map*

How to use this map?

The colored regions of this map, defined by iso-frequency contours, illustrate the <u>Maximum Usable Frequency</u> expected to refract off the <u>ionosphere</u> along a 3000 km path. The map also includes the position of <u>gray line</u>.

The <u>ham bands</u> are designated by iso-frequency contours: 5.3, 7, 10.1, 14, 18, 21, 24.8, and 28 Mhz.

For example, if a given area on the map is greenish and lies between the contours labeled "10" and "14," the *MUF* in that location is around 12 MHz.

The raw data is <u>MUF</u> calculated from data collected by <u>ionosondes</u>, which are represented by numbered colored discs that show their location.

A number inside a disc indicates the calculated 3000km MUF from the **critical ionospheric frequency**, f_oF2. The information from selected <u>stations</u> is compiled by **Mirrion 2** and GIRO , and processed by the International Reference Ionosphere (IRI) model (produced by a joint task group of COSPAR and URSI .

The <u>MUF</u> along a path between any two locations shows the possibility of long-hop DX between those points on a given band.

For example, if the MUF is 12MHz, then 30 meters band and longer will work, but 20 meters band and shorter won't.

For long multi-hop paths, the **worst MUF** anywhere on the path is what matters. For single-hop paths shorter than 3000 km, the usable frequency will be less than the *indicated MUF*. As one gets closer to vertical, i.e., <u>NV/S-T</u>, the usable frequency drops to the **Critical ionospheric frequency**. (f_oF2, as shown in the <u>next map</u>).

Notes:

- 1. The accuracy of the data is insufficient for commercial radio services due to several factors:
 - a. Uncertainty in predicting ionospheric state:
 - Vertical sounding data introduces uncertainty when predicting the ionosphere's state.
 - The limited coverage of monitoring radio stations results in reliance on data processing.
 - b. Challenges of data interpolation and extrapolation <u>→</u>:
 - The algorithm attempts to determine the MUF (or foF2) at scattered points globally.
 - Accuracy is compromised when extrapolating from sparse data points.
 - Predictions are more reliable near measurement stations but deteriorate for distant regions.
 - c. Issues with measurement stations:
 - Inconsistent or conflicting data from stations may lead to unusual results when aligning measurements.
 - Unexpected global model changes may occur due to stations going offline or reappearing, compounded by the limited initial data points.
 - d. Restricted sharing of real-time data:
 - Since 2021, real-time ionosonde data sharing has reduced in countries such as Russia, China, Japan, and others.
 - Some ionosondes are accessible solely via NOAA, and GIRO outages could cause map updates to cease.
 - e. Impact of geomagnetic storms and solar activity:
 - Events such as geomagnetic storms, elevated <u>X-ray flares</u>, and <u>solar wind</u> significantly affect the accuracy of MUF estimations derived from vertical sounding data.
 - While these disturbances are implicitly reflected in ionogram results, predicting band conditions remains challenging.

- The propagation model is overly simplistic. It does not capture all the variables, such as <u>blackouts</u> due to D-region absorption and <u>noise induced</u> by geomagnetic storms.
- f. Future Development: Efforts are underway to develop geospace dynamic models to mitigate these challenges.
- 2. The "MUF(3000km)" project is the result of research and development by Andrew D Rodland KC2G, which is based on an earlier work by Matt Smith AF7TI. WWROF financing and data from ionosonde operators all over the world, provided by GIRO and NOAA made it feasible.
- 3. See Acknowledgments.
- 4. Read more about this open source project<u>.</u> ■.
- 5. Read more about the open source software and models ₹.
- 6. Roland Gafner, HB9VQQ, extended *the static presentation* with an **animated map** showing the last 24 hours in 15-minute steps. **1**

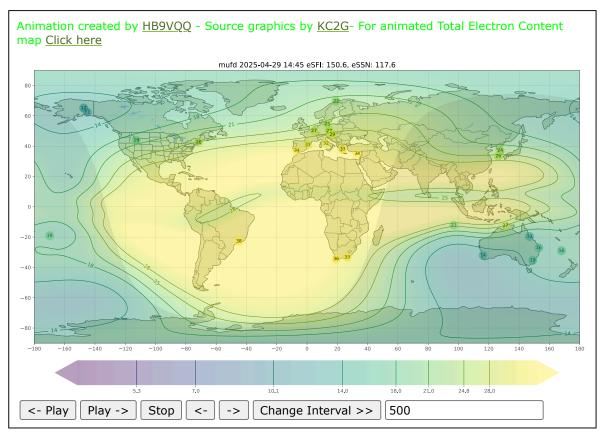


Figure 8.10: **Animated MUF 3000 km propagation map** in the last 24 hours courtesy of Roland Gafner, HB9VQQ

<u>NVIS</u> online live map for vertical refraction (critical frequency <u>foF2</u>) provided by <u>Andrew D Rodland, KC2G</u> updated every 15 minutes

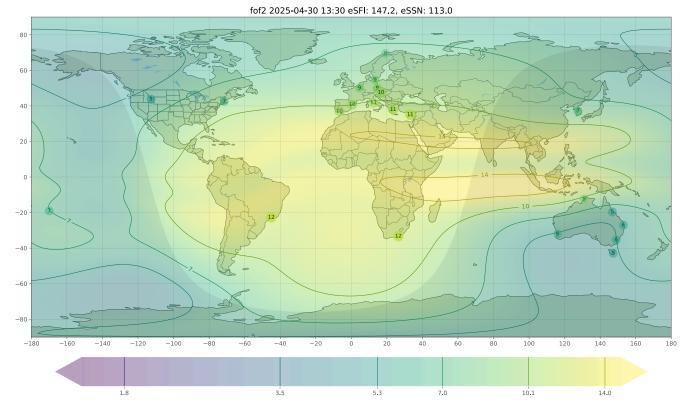


Figure 8.11: Online NVIS Map, by Andrew, KC2G

The map's colored regions, outlined by iso-frequency contours, show the <u>critical</u> <u>frequency</u> for near-vertical ionosphere refraction. Colored discs mark ionosonde stations, with numbers representing critical frequency (foF2)—the site's raw data source.

Another <u>NVIS</u> real-time map provided by the Australian Space Weather Service is updated every 15 minutes. It displays contours of the **critical ionospheric frequency** - $\mathbf{f_0F_2}$. There are a few differences between this map and the <u>KC2G map</u>, mainly due to the choice of frequencies for the contours. The KC2G map highlights ham bands. The following map, however, is designed for commercial use.

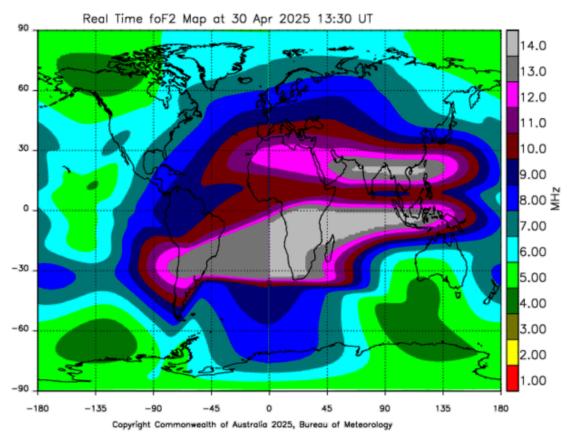


Figure 8.12: **Online NVIS map** courtesy of ASWFC Click on this online map to view the source page. There is further information.

Online T Index Map - $\underline{f_0F_2}$ is provided by Australian Government Space Wheather Services

The T-index forecasts high-frequency communication conditions and functions as an "equivalent <u>sunspot number</u>." Derived from f_0E_2 measurements, it accounts for anomalies like <u>geomagnetic storms</u> that may influence these readings. Typically ranging from -50 to 200, lower values indicate limited HF frequency usability (e.g., during solar minimum), while higher values correspond to optimal conditions for higher frequencies (e.g., near solar maximum).

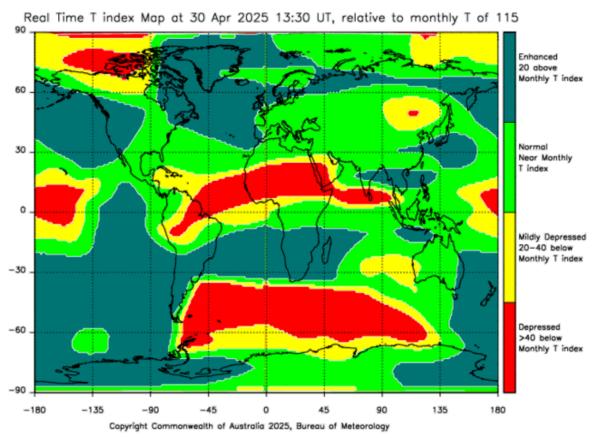


Figure 8.13: **Online T Index Map** courtesy of ASWFC

<u>T Index FAQ | T Index Map | Real-time T Indices | Forecast T indices</u>

1 The recent f₀F₂ measurements at various locations of Australia, New Zealand and East Antarctica

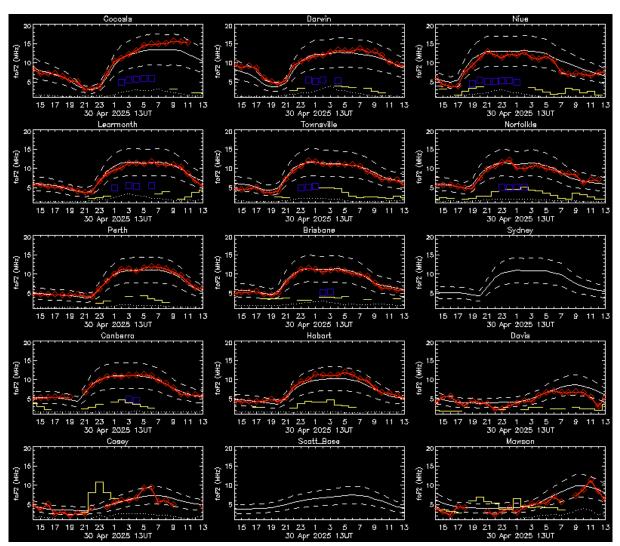


Figure 8.14: foF2 Plots courtesy of Australian Space Weather Forecasting Centre Click on this online chart to view the source page.

1 LUF (ALF) chart for the Pacific region, affected by the last M1+ solar flare

The lowest frequency at which two radio stations can connect is known as the <u>LUF</u>. It is dependent on ionospheric conditions due to <u>solar flares</u>, <u>solar wind</u>, and <u>geomagnetic activity</u>, as well as path factors (such as transmitting power and receiving SNR-). These variables collectively complicate mapping efforts. <u>Figure 14.3</u> illustrates the attenuation resulting from solar flares and <u>solar energetic particle (ISEP)</u>)events over the past eight hours.

The Australian Space Weather Alert System (ASWFC) provides LUF data for the recent M1+ solar flare:

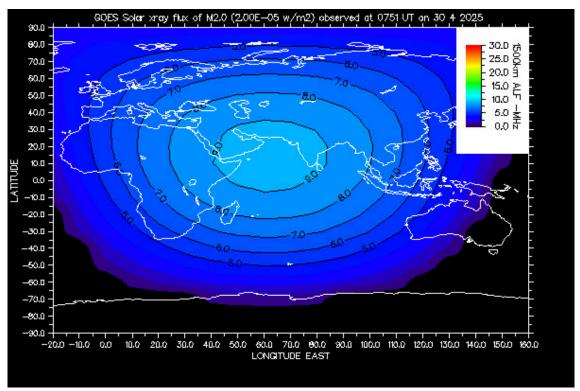


Figure 8.15: <u>LUF</u> (ALF) chart for the Pacific region by ASWFC<u>₹</u>

This chart relies on events and updates whenever a flare of magnitude M1 or greater occurs. The top line indicates the recent flare time. The chart illustrates the <u>LUF</u> affected by the recent significant <u>solar X-ray flare</u>. As shown by the color bar, the most significant impacts occur within the inner circle. The map reflects the LUF for standard 1500 km HF circuits, where communication below the LUF is uncommon, while communication above it is generally possible. Shorter circuits may exhibit higher LUF values, enabling the use of lower frequencies. Conversely, longer circuits might still experience <u>signal fading</u>, even at elevated frequencies.

1 Chapter 9. Ionosphere Dynamics

The ionosphere has a regular <u>daily cycle</u>, but dramatic events cause chaotic disruptions. The <u>atmosphere's different regions</u> interact like a team, <u>influencing one another in intricate ways</u>.

Weather patterns in the <u>troposphere</u> and activities from the Sun and <u>Earth's magnetic field</u> also play a role in this system. *Atmospheric waves*, such as gravity waves (ripples caused by air moving up and down) and planetary waves (large waves influenced by Earth's rotation and heat), along with <u>geomagnetic activity</u>, significantly impact the energy and dynamics in the <u>thermosphere</u>. This chapter delves into how these interactions affect the propagation of radio waves through the sky.

Sub-chapters:

- 9.1 Sporadic E
- 9.2 <u>Ionospheric clouds or bubbles spread F</u>
- 9.3 Ionospheric Storms cause fadeouts

Sporadic E (E_s) indicates occasional refractions from highly ionized <u>plasma clouds</u> in the lower E region.

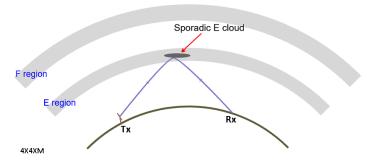


Figure 9.1: refraction from Sporadic E plasma cloud

Operators may use E_s for making mid-range contacts on the VHF amateur bands: 50 MHz (6 m), 70 MHz (4 m), and 144 MHz (2 m).

Sporadic E Propagation in 2 minutes courtesy of Andrew McColm, VK3FS.



Video clip: Equatorial *sporadic E*, occurring within ±10° of the geomagnetic equator, is a regular midday phenomenon. In polar latitudes, sporadic E, known as auroral E, can accompany auroras and disturbed magnetic conditions. At mid-latitudes, E_s propagation often supports occasional long-distance communication on VHF bands during the approximately six weeks centered on the summer solstice, which normally only propagate by line-of-sight.

û 9.2 Ionospheric Clouds (bubbles) — spread F

All the *ionospheric regions* consist of *plasma clouds* as illustrated below:

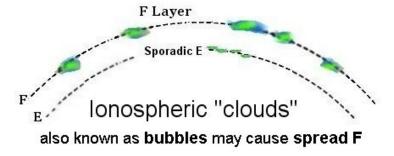


Figure 9.2: Ionospheric Clouds or Bubbles

The moving plasma clouds or bubbles are <u>traveling disturbances of electron density</u>. Ionospheric "plasma bubbles" or "clouds" are the physical cause to the observed *spread F phenomenon* .

How do "ionospheric clouds" affect HF propagation?

The dynamic ionosphere causes signal fading (QSB) over time. Small-scale irregularities in the ionosphere are observed at all levels, with periodic motions attributed to neutral *atmospheric waves* interacting with ionized components in the upper atmosphere. While understanding is limited, the research promises the ability to predict short-term changes.

Additionally the ionosphereic regions are disrupted by (1) The <u>chaotic solar activity</u> and (2) The **tropospheric weather** from far below.

What effect does tropospheric weather have on the ionosphere?

Troposphere storms, hurricanes, and strong wind patterns can all temporarily alter the <u>TEC</u> caused by *EUV solar radiation* →.

In other words, the ionosphere and troposphere are coupled py a variety of mechanisms.

For instance, a lightning storm can cause electrodynamic interaction.

The following figure illustrates **electrodynamical coupling** of the Troposphere with the lonosphere ::

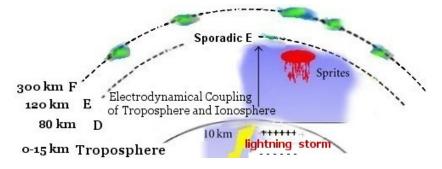
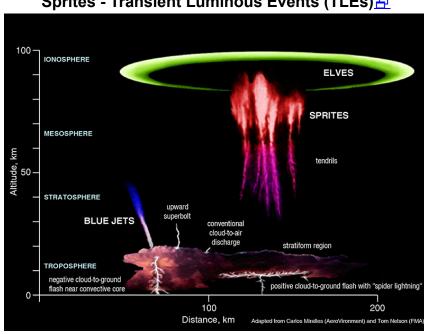


Figure 9.3: lonospheric clouds due to Troposphere-lonosphere coupling



Sprites - Transient Luminous Events (TLEs) -

Figure 9.4: The different forms of Transient Luminous Events Credit: NOAA

There are other complex mechanisms that couple the troposphere to the ionosphere. We won't go into detail at this point.

In conclusion, "Ionospheric clouds" → that develop as a result of the coupling → between the troposphere and ionosphere may affect skywave HF propagation.

How are ionospheric clouds or bubbles detected?

The **Digisonde Directogram** may detect ionospheric plasma irregularities.

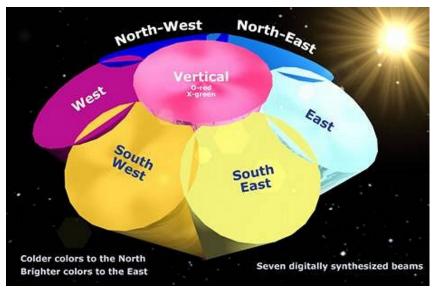


Figure 9.5: Digisonde Directogram

It consists of **multi-beam ionosondes**, which measure echoes coming from various locations. Seven ionosonde, beams (one vertically and six diagonally) are used to generate the ionograms.

The end result is an extended ionogram of *plasma clouds* as they drift over a Digisonde station ₽.

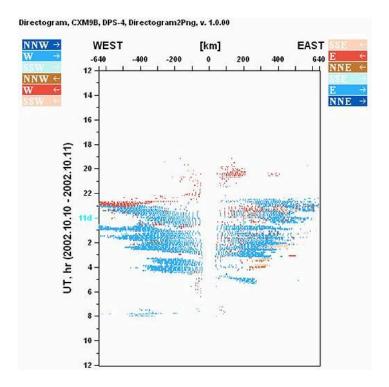


Figure 9.6: **Sample directogram** for Cachimbo station from 12 UT Oct 10 to 12 UT Oct 11, 2002. Blue color means ionospheric motion from west to east.

1 9.3 lonospheric Storms cause fadeouts

lonospheric storms involve a sudden change in the density of ionized particles, usually due to <u>solar flares</u>. However, <u>solar wind</u> and <u>tropospheric tides</u> can also influence these storms. Below, we explain the ionospheric disturbances: <u>SID</u>, <u>TID</u>, and <u>GRB</u>.

9.3.1 "Sudden lonospheric Disturbances" (SID) are any one of several ionospheric perturbations resulting from abnormally high ionization or plasma density in the <u>D-region</u> of the ionosphere and caused by <u>solar flares</u> and/or <u>solar particle events</u> (<u>SPE</u>). The SID affects HF skywave signal strengths, with lower frequencies being more heavily absorbed and resulting in a larger decrease in signal strength (see the next figure).

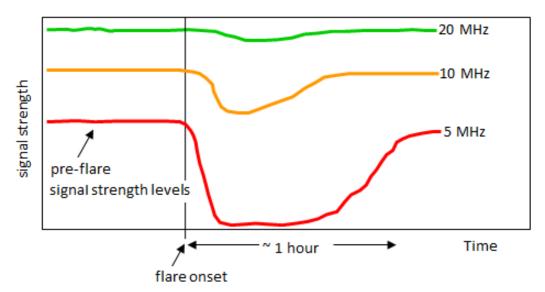


Figure 9.7: **Fadeout signal strength vs. time** courtesy of Australian Space Weather Service

During a strong SID, the <u>LUF</u> will increase to a frequency higher than the <u>MUF</u>, thus closing the usable frequency window, an event called a <u>fadeout or blackout</u>.

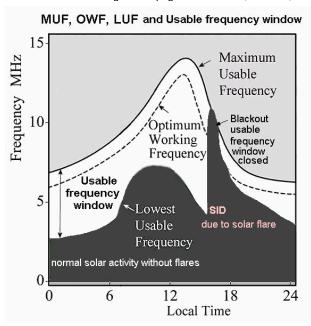


Figure 9.8: Normal solar activity vs. SID due to flares

The current short wave <u>fadeout</u>—SWF event (if any):

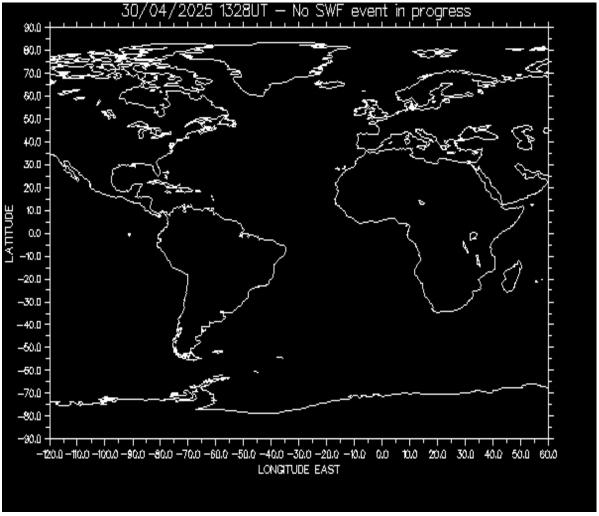


Figure 9.9: **Online SWF event** report courtesy of ASW Alert System

9.3.2 **Polar cap absorption (PCA)** events, driven by <u>solar wind</u>, involve high-energy protons reaching Earth's atmosphere near the magnetic poles, increasing ionization in the D and E regions. These events last from an hour to several days. <u>Coronal mass ejections (CMEs)</u> can also release energetic protons that enhance D-region absorption in polar areas.



Figure 9.10: Illustration of **Polar Cap Absorption (PCA)**: radio waves can't propagate over the north pole

Streams solar ejected protons increase ionization in the lower ionosphere, blocking all radio communications in polar zones. These PCA events last as long as proton energy exceeds ~10 MeV and 10 pfu at geosynchronous satellite altitudes. The resulting HF radio blackouts pose significant challenges for aviation in polar regions, especially above 82 degrees north latitude, where rerouting is necessary to maintain viable communications. See *the current fadeout report*.

9.3.3 **Traveling Ionospheric Disturbance** (TID) is a wave-like structure passing through the ionosphere that alters the altitude and angle of refraction of skywaves. TIDs travel horizontally at 5–10 km/minute, with varying phases, amplitudes, and angles of arrival. Some originate in auroral (polar) zones.

Probing traveling <u>F region</u> ionospheric disturbances

The Super Dual Auroral Radar Network (SuperDARN) is an international network of 35 HF radars (8 MHz–22 MHz) located in the northern and southern hemispheres.



Figure 9.11: SuperDARN site in Holmwood SDA, Saskatoon, Canada 🔁

The SuperDARN are designed to study <u>F region</u> ionospheric dynamics, instability, disturbances and storms. The research covers geospace phenomena, including field-aligned currents, magnetic reconnection, and mesospheric winds. It tests theories of polar cap expansion and contraction under changing <u>IMF</u> conditions, observing large-scale responses to substorms. The collaboration includes various institutions.

9.3.4 **Cosmic Gamma-ray Bursts** (GRB) → may also cause communications disturbances. Measurable effects are rarely observed.

On October 9, 2022, there was a cosmic gamma-ray burst that affected all ionospheric and stratospheric regions. These are intense explosions observed in distant galaxies, the brightest and most extreme events in the universe. NASA describes them as the most powerful class of explosions since the Big Bang. Afterglows are longer-lived and typically emitted at longer wavelengths.

Studies are being done on this phenomenon.

û Chapter 10. Total Electron Content (TEC)🔁

What is TEC?

TEC is the total number of free electrons present along a path between two points.

Why is TEC important for <u>HF propagation conditions</u>?

TEC correlates with the critical frequency, $\underline{f_0}\underline{F_2}\underline{r}$, and is therefore implemented in a variety of ionosphere models. Moreover, the total electron content can provide additional information about the structure and dynamics of the ionosphere. It can detect and monitor ionospheric disturbances, such as those caused by <u>solar flares</u> or <u>geomagnetic storms</u>.

Units: 1 TEC Unit (TECU) is the number of <u>free electrons</u> per square meter (x10¹⁶) for a shell height of 400 km directly above a certain point. Values in Earth's atmosphere can range from a few to several hundred TEC units.

How is TEC measured?

Data is gathered from GPS receivers worldwide, observing carrier phase delays in radio signals from satellites above the ionosphere, often using GPS satellites.

The effect of Tropospheric weather ☐

The troposphere and ionosphere are separate atmospheric layers with distinct functions. However, they do interact through various processes. Tropospheric lightning may induce changes in total electron content and consequently affect HF propagation conditions. Thunderstorms can also worsen the signal-to-noise ratio, in particular in the lower HF bands; i.e., tropospheric weather may affect these conditions, especially in tropical regions. Thus, monitoring and modeling TEC patterns and variations allows us to better understand and prepare for the *constantly changing atmospheric conditions*.

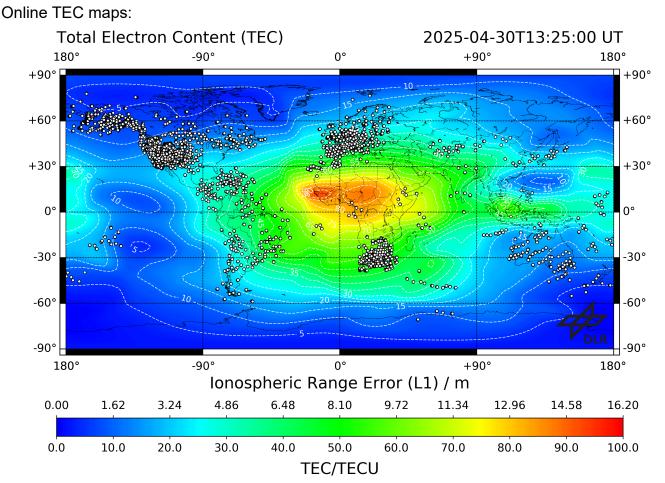
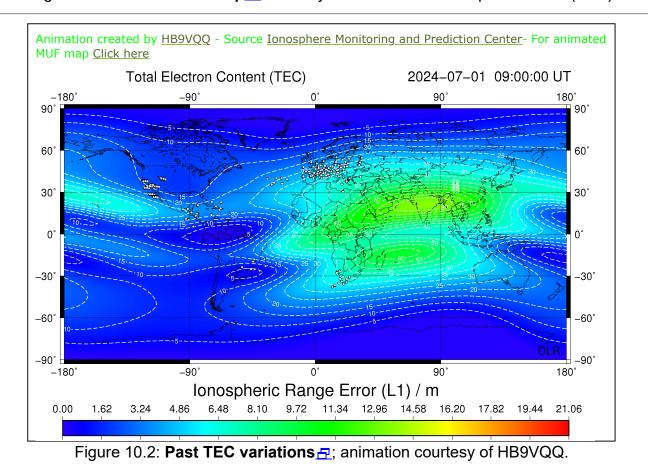


Figure 10.1: Online TEC map courtesy of the German Aerospace Center (DLR)



TEC conclusion:

<u>Solar EUV radiation</u>, <u>solar wind</u>, <u>CMEs</u>, and <u>atmospheric disturbances</u> all contribute to TEC fluctuations, which vary with time, location, seasons, <u>geomagnetic conditions</u>, troposphere conditions, and the <u>solar cycle</u>. Data analysis may reveal qualitative patterns for spring, fall, summer, and winter solstices.

<u>Solar activity</u>, ionospheric conditions, and global average <u>ionization levels in the F2 region</u> affect HF radio waves worldwide.

The <u>regional conditions</u>, as explained in Chapter 8, can be very different from the global averages described in this chapter.

Sub-chapters:

- 11.1 Banners & widgets—displaying global propagation conditions
- 11.2 Solar Indices
- 11.3 Geomagnetic Indices
- 11.4 Propagation Indices

û 11.1 Banners and Widgets

<u>Banners and widgets</u> are visual aids for displaying global propagation conditions using <u>propagation indices</u>. They help radio operators to quickly assess current world conditions and make informed judgments about their operations.

Paul L. Herrman (NONBH) developed the banners shown below.

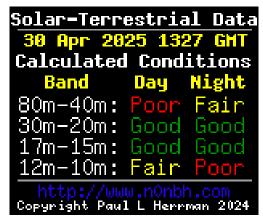


Figure 11.1: Global conditions



Figure 11.2: The Basic Solar indices ₽

SFI & SN correlate with <u>F2-region ionization</u>.
 <u>A and K</u> indicate geomagnetic instability.
 See the <u>interpretation of these indices</u>.

Solar-Terrestrial Apr 2025 1324 GHT HF Conditions Band Day 80n-40n 30n-20n 17n-15n Good Fair 12n-10n VHF Conditions Aur Lat Aurora 2n EsNA EHE Deg Solar Flare Prb HUF **X**5 Geomag Field UNSETTLD Sig Noise Lvl MUF US Boulder NoRpt Current Solar Image http://www.nOnbh.com Copyright Paul L Herrman 2023

NONBH Glossary

SFI: 10.7cm Solar Flux → SN: Sunspot Number

A-Index K-Index

X-Ray flare class that affects D region absorption

304Å: @SEM—Solar EUV Monitor on SOHO satellite.

Pf - Proton flux | Ef - Electron flux (solar wind)

Aurora → F region ionization → (polar zones)

B_z - Magnetic field ↑ to ecliptic plane →

SW - Solar Wind speed km/s

Aur Lat - The lowest Aurora Latitude Calculated by NOAA₽

ESEU - Sporadic E Europe every ½ hour **ESNA** - Sporadic E N. America every ½ hour **EME Deg** - Earth-Moon-Earth attenuation every ½ hour

MUF (MHz) every 15 min

MS—Meteor Scatter Activity every 15 min

GeoMag—calculated from <u>K-Index</u> every 3 hours. **Sig Noise IvI**—Background noise in S-units due to <u>geomagnetic activity</u>, calculated every ½ hour

Current Solar Image

Choose one of four EUV wavelengths,

each associated with a different color of the sun disc.

Figure 11.3: **Propagation conditions indices**

Propagation indices displayed with views of the Sun and Earth

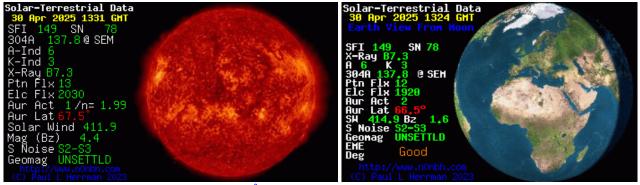


Figure 11.4: Solar image at <u>304Ångstrom</u>

Figure 11.5: Earth view from the Moon

û 11.2 Solar Indices🗗

Extreme Ultra Violet (EUV) radiation ☐ creates the ionosphere, especially the F2-region. Since EUV is fully absorbed by the ionosphere, it doesn't reach the ground, making direct measurement impossible for ground-based devices. Before the space age, scientists relied on two indirect markers to gauge the ionization levels of the F2-region. These are the "Solar Indices":

1. **SSN** - <u>Sunspot</u> Number is a count of the number of dark spots seen on the sun. Higher SSN values correlate with improved conditions on 14 MHz band and above:.

See the recent SSN values.

2. **SFI** - <u>Solar flux index</u> refers to the intensity of **solar radio emissions** at **10.7 cm** (2,800 MHz).

Higher flux correlates with increased *ionization levels* of the *E and F regions*, enhancing HF radio propagation conditions.

The current SFI: **Loading solar flux data...** (solar flux units; 1sfu=10⁻²² Watts per meter² per Hz).

- 3. **304Å Index** measures the solar radiation strength at <u>304 Ångstrom (30.4 nm) EUV</u>, emitted primarily by ionized helium in the sun's photosphere. This parameter has two measurements: one from the *EVE instrument* on the <u>Solar Dynamics Observatory</u> (<u>SDO</u>) and the other from SEM instrument on the <u>SOHO satellite</u> It accounts for about half of the ionization of the F region in the ionosphere and loosely correlates to the <u>SFI</u>. The background SFI level is typically around 134 at solar minimums and can exceed 200 or more at solar maxima. It is updated hourly.
- 4. **Solar X-ray flares** (1–8 Ångstrom) are measured by instruments onboard <u>GOES</u> satellites ₽.

Excessive X-ray flares can cause ionization at the D region, leading to communication disruptions and blackouts.

Understanding the Correlation between Sunspots and Solar Flux:

- Sunspot number records have been traced back to the 17th century but are often subject to interpretation. The solar flux at 10.7 cm wavelength (2,800 MHz) aligns closely with daily sunspot numbers, making both databases interchangeable.
- See <u>a comparison table between SSN and SFI</u>.
- The 10.7 cm Solar Flux data is more stable and reliable ☐ compared to the Sunspot Number (SSN).
- Radio telescopes in Ottawa (from February 14, 1947, to May 31, 1991) and Penticton, British Columbia (since June 1, 1991), report solar flux density at 2,800 MHz daily at local noon (1700 GMT in Ottawa and 2000 GMT in Penticton). Corrections are made for factors like antenna gain, air absorption, solar bursts in progress, and background sky temperature.
- Due to variations in solar radiation globally, even with corrections, consistent results are challenging. Thus, readings from the Penticton Radio Observatory in British Columbia, Canada, are used as a benchmark. These numbers are crucial for predicting ionospheric radio propagation.
- The 10.7 cm radio flux consists of contributions from the undisturbed solar surface, active regions, and transient enhancements above the daily level. Levels are determined and corrected within a few percent.

11.3 Geomagnetic Indices

Geomagnetic indices measure <u>disturbances</u> in <u>Earth's magnetic field</u>, which can disrupt HF propagation by increasing atmospheric noise and weakening radio signals. These indices are crucial for understanding the potential impacts on all communication systems, satellite operations, and even power grids.

K and A are local indices

K-index: This index represents short-term (3-hour) *geomagnetic activity* at a specific geomagnetic station. It quantifies disturbances in Earth's horizontal magnetic field by comparing geomagnetic fluctuations, measured by a magnetometer ♣, to a quiet day. The K-scale is logarithmic, allowing for a more manageable representation of the wide range of geomagnetic activity magnitudes.

A-index: This index averages K values to provide a linearized view of geomagnetic activity. It is important for predicting and understanding the effects of *geomagnetic storms* on HF communications.

Kp and Ap are global—planetary indices.

K and A indices measure local geomagnetic activity at a single observatory. A global average of these indices is calculated from 13 mid-latitude geomagnetic observatories, marked as $\mathbf{K_p}$ and $\mathbf{A_p}$:

- **K**_p: Average of K-indices from 13 observatories, indicating planetary geomagnetic activity.
- A_p: Daily planetary geomagnetic activity, derived from the Kp index.
- * A comparison table between K and A indices.
- * See the recent Kp and K indices.

The **HPo** (GFZ) indices are less commonly referenced.

This higher time resolution can be crucial for predicting and mitigating the impacts of geomagnetic storms on various technologies.

The half-hourly Hp30 and hourly Hp60, developed at GFZ (German Research Center for Geosciences), offer improved time resolutions compared to the three-hourly Kp. Together with the linear versions Ap30 and Ap60, they are collectively known as the HPo index, providing near-real-time data from about 13 geomagnetic observatories.

û 11.4 Skywave propagation indices🗗

HF propagation indices are essential tools for amateur radio operators to evaluate and predict radio wave propagation conditions. The key indicators include the Maximum Usable Frequency (<u>MUF</u>), Lowest Usable Frequency (<u>LUF</u>), and ionospheric noise levels. These indicators correlate with <u>solar indices</u> such as the Sun Spot Number (<u>SSN</u>), Solar Flux Index (<u>SFI</u>), <u>X-ray</u> <u>flares</u>, and <u>solar wind</u>, as well as <u>geomagnetic indices</u>. Understanding all these parameters is crucial for accurately estimating HF propagation conditions.

Interpretation of the propagation indices

Table 11.1: The correlation between HF band conditions and the good indices: MUF, SSN and SFI₽

Conditions	BAD		Low		Average		Good		Better	Best	
MUF (MHz)	<12	<15	> 21		> 24		> 28		> 5	60	
<u>SSN</u>	0	25	50	75	100	125	150	175	200	250	
SFI (sfu)	67	83	102	124	148	172	196	219	240	273	

Conclusion: High values of the **solar** indices **SSN and SFI** correlate with **good** <u>HF propagation</u> <u>conditions</u>.

Table 11.2: The correlation between HF band conditions and the geomagnetic K and A indices. ☐

HF band conditions			Best	t	A	veraç	erage		Poor		
Geomagnetic activity index (log-scale)	Κ	0	1	2	3	4	5	6	7	8	9
Geomagnetic activity index (linear)	Α	0	4	7	15	27	48	80	132	207	400

Conclusion: High values of K and A indicate disturbed HF propagation conditions.

Note: The <u>solar wind</u> significantly influences fluctuations in the geomagnetic indices. By examining <u>solar wind data—such as density and velocity</u>—we can understand both the "why" and "how fast" behind these changes, allowing us to predict variations ahead of the next 3-hour K update. If you're simply determining whether the HF band is usable tonight, the local K index may suffice. However, for optimizing a specific path or timing, incorporating solar wind data becomes essential.

Table 11.3: The correlation between HF band conditions and radio blackout scale, and solar flare class

Band conditions₽	Best			Average	Poor		BAD	
Radio-blackout scale ₽	R0			R1	R2	R3	R4	R5
Solar Flare Class₽	Α	В	С	М			X	



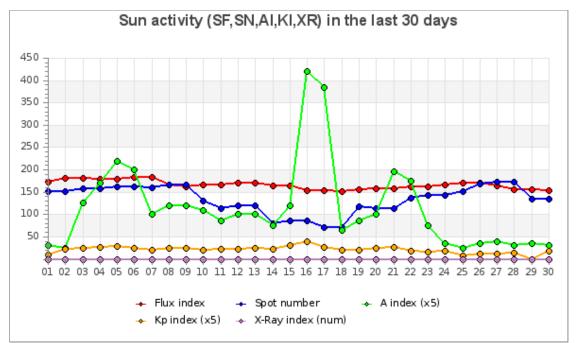


Figure 11.6: **The recorded propagation indices** over the last 30 days, provided by QRZCQ.

Please note the correlation between the acronyms in the title (**SF, SN, AI, KI, XR**) and the names of the relevant indices given below the graph:

SF:=**Flux index**; SN:=**Spot number**; Al:=**A index**; KI:=**Kp index**; and XR:=**X**-Ray index.

The Sun and Space Weather

🕆 Chapter 12. Solar phenomena 🔁

Solar irradiance quantifies sunlight power on a surface in watts per square meter (W/m²). On Earth, it fluctuates with location, time, and atmospheric conditions. Since 1978, space-based studies show the "solar constant" varies, influenced by cycles like the 11-year sunspot cycle. Quiet and active solar events affect space weather and HF skywave propagation.

Sub-chapters:

- 12.1 Quiet sun
- 12.2 Active Sun
- 12.3 Sunspots and Solar Flux
- 12.4 Solar storms (flares, particle events)
- 12.5 The Solar Cycle
- 12.6 Predict Solar Flux
- 12.7 Live Solar Activity Online
- 12.8 Live Solar Alerts Online (X-ray flares and solar wind protons)
- 12.9 Solar Radio Interference

12.1 Quiet sun

The sun emits electromagnetic radiation <u>radiation</u> across a wide spectrum <u>radiation</u> from Gama-rays to <u>ELF</u> (extreme long radio waves).

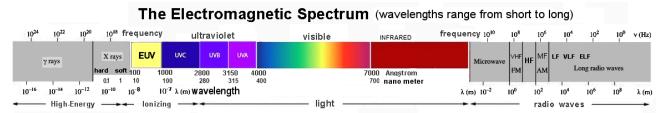


Figure 12.1: **The solar electromagnetic spectrum**, arranged left to right by wavelength from shortest to longest.

The Extreme Ultra Violet **EUV** generates the *ionosphere*.

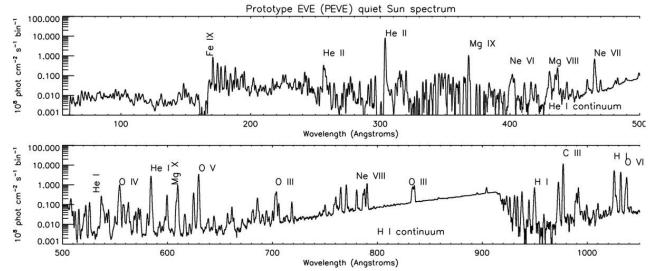


Figure 12.2: The EUV spectrum of the whole Sun

This EUV spectrum was measured by the prototype SDO/EVE instrument flown aboard a rocket on 2008 April 14, during solar minimum between cycles 23 and 24.

Ref<u>₽</u>: ibid. Solar UV and X-ray spectral diagnostics, Fig. 11 on page 25 of 278.

- Peak (He II) **EUV** radiation at a wavelength of **30.4 nm** is the most important solar emission contributing to half of the *lonospheric F region* ionization ₽.
- Lyman series-alpha Hydrogen-spectral-line at a wavelength of **121.6 nm** ionizes **Nitric Oxide** (NO) at the **D-region** causing mostly <u>absorption of HF bands below 10 MHz.</u>

12.2 Active Sun

Solar activity $\underline{\square}$ is driven by the eleven-year periodic reversal of the sun's magnetic field due to a chaotic dynamo near the surface $\underline{\square}$.

The main solar phenomena associated with HF radio propagation on Earth are:

- <u>Sunspots</u>: last from a few days to a few months; the number of spots varies in 11-year <u>solar cycle</u>: a deterministic chaos:
- Solar flux at 10.7 cm : a measurable indicator of solar activity that correlates with sunspots;
- Solar flares : radiation bursts that last from tens of seconds to several hours;
- Solar wind propels energetic particles propels. See classification chart for proton flux propels.
- Coronal mass ejections (CMEs)₽.

1 12.3 Sunspots ₽ and Solar Flux

- Sunspots are darker, cooler regions on the Sun's surface characterized by intense magnetic activity.
- There is a positive correlation between sunspot numbers and solar radiation intensity, including at the <u>10.7 cm wavelength</u>, known as solar flux.
- Higher sunspot numbers indicate elevated solar flux levels, enhancing ionization in Earth's upper atmosphere and improving high-frequency (HF) radio wave propagation.
 Conclusion: more sunspots → higher solar flux → better HF communication.
- Sunspots vary in shape, size, and duration, lasting from a few hours to several months.
- The average number of sunspots fluctuates throughout the <u>solar cycle</u>, an approximate 11-year cycle of solar activity.

Left: **Sunspots** in *visible light* Right **Extreme Ultra Violet** (EUV 30.4 nm)

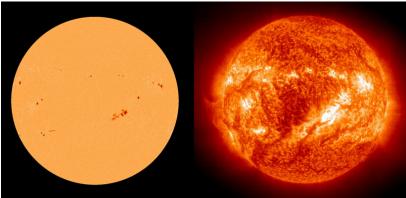


Figure 12.3: **Two images of the Sun** (February 3, 2002) by Solar and Heliospheric Observatory (SOHO) satellite courtesy of European Space Agency and NASA.

Q. What is the reason for analyzing sunspots in both *visible* and *ultraviolet light*?

A. Observing sunspots in visible light allows us to see them directly with our eyes or telescopes. Using ultraviolet (UV) light reveals magnetic disturbances that are invisible in regular light. Studying sunspots in both visible and UV light helps us understand their features and the activities occurring on the sun.

12.4 Solar storms (X-ray flares and particle events) 🗗

The Impact of Solar Storms on HF Communication

<u>Solar storms</u> can significantly disrupt high-frequency (HF) communication through radio fadeouts and blackouts, caused by solar flares and solar energetic particles (SEP).

- <u>Solar flares</u>: Primarily affect equatorial regions and may cause <u>short-term blackouts</u> lasting from minutes to hours.
- <u>SEP events</u>: Mainly cause <u>Polar Cap Absorption (PCA)</u>, leading to attenuation levels that can obstruct most transpolar HF radio transmissions. In severe cases, can result in <u>tens of decibels of attenuation</u>.

A PCA may commence as soon as a few minutes after the flare onset and persist up to ten days.

For centuries, people have been observing <u>sunspots</u> without knowing what they are. We now understand that these are symptoms of <u>solar storms</u>.

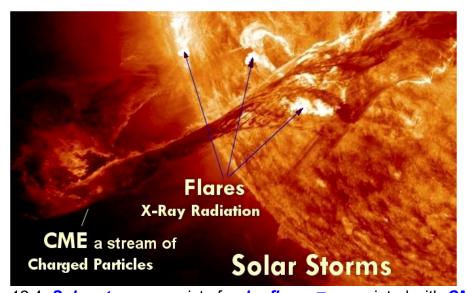


Figure 12.4: Solar storms consist of solar flares associated with CMEs ₽

Coronal Mass Ejections (CMEs) often appear as twisted ropes. <u>Figure 12.7</u> presents the model connecting solar flares with CMEs.

(A) The "solar flares" are bursts of (soft X-ray and EUV, 0.1–1 nm) radiation ₽.

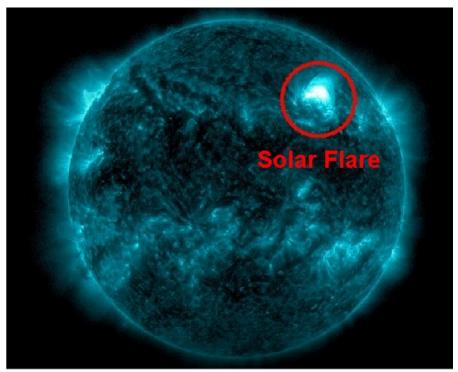


Figure 12.5: A Solar flare courtesy of NOAA, May 2023

- 1. Solar flares enhance the <u>ionization</u> of the ionosphere, specifically the <u>D-region</u> at 50-90 km altitude.
- 2. The <u>enhanced D region absorbs HF radio</u>, causing radio signals to fade out. These events are known as <u>blackouts</u>.
- 3. Solar flares <u>→</u> can last from tens of seconds to several hours.
- 4. Solar flares classification: <u>A, B, C, M, or X on a logarithmic scale</u> <u>-</u>.

Table 12.1: Solar flare classes

Flare Class	Peak Irradiation 1–8 Ångstroms								
В	< 10 ⁻⁶ W/m ²								
C	10 ⁻⁶ – 10 ⁻⁵ W/m ²								
M	10 ⁻⁵ – 10 ⁻⁴ W/m ²								
х	> 10 ⁻⁴ W/m ²								

- 5. The recent solar flares
- 6. The current solar flare 88.8
- 7. The *D region absorption model* is used as a guide to understand *fadeout events*.

(B) Solar Energetic Particle Events <u>₹</u> (CME, <u>SEP</u>, and <u>SPE</u>):

1. A coronal mass ejection (CME) is a significant ejection of plasma mass from the sun's corona into the heliosphere from the sun's solar flares. The magnetic fields of CMEs merge with the interplanetary magnetic field.

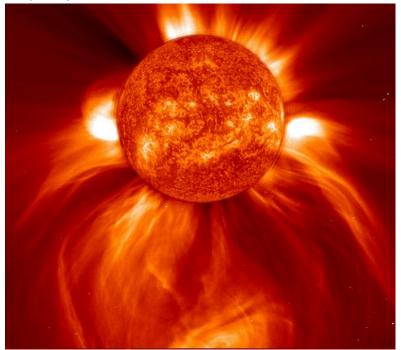


Figure 12.6: **LASCO C2 image**, taken 8-January-2002 shows coronal mass ejection (CME) captured by **SO**lar and **H**eliospheric **O**bservatory (SOHO). Credit: NASA / GSFC / <u>SOHO</u> / ESA

CMEs release large amounts of matter into the solar wind and interplanetary space, primarily consisting of electrons and protons.

Coronal Mass Ejections (CMEs) occur alongside <u>solar flares</u>. Pre-eruption structures require magnetic energy, while post-eruption structures form magnetic flux ropes and prominences.

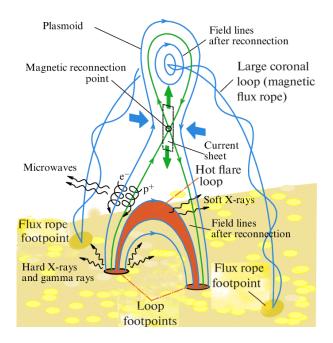


Figure 12.7: **Model of solar flares and CMEs**; enhanced diagram following Fig 1. of Shibata et al. ₽

Types of CMEs :

- * **Halo CMEs**: Appear as a halo around the Sun; often directed towards or away from Earth.
- * Partial Halo CMEs: CMEs: Cover part of the Sun; less impactful than full halos.
- * Narrow CMEs: Confined to a narrow width; less likely to impact Earth directly.
- * **Fast CMEs**: Travel faster than 500 km/s. They can cause significant geomagnetic storms.
- * **Slow CMEs**: Travel slower than 500 km/s. Generally have a lesser impact. Each type can affect <u>Earth's magnetosphere</u> differently, potentially causing geomagnetic storms.

Solar flares and CMEs spontaneously, disrupt the <u>solar wind</u> and damaging systems both near-Earth and on its surface.

The next chapter explains how <u>space weather observations</u> provide warnings of approaching CMEs.

2. **Solar energetic particles (SEPs)** are high-energy, charged particles from the solar atmosphere and part of the *solar wind*. They include electrons, protons, alpha particles, and heavy ions with energies from a few tens of keV to many GeV. Solar particle events (SPEs) accelerate solar energetic particles (SEPs) either at the sites of solar flares or through shock waves generated by coronal mass ejections (CMEs). Upon reaching Earth, these high-energy particles interact with the planet's magnetosphere, influencing space

weather conditions. <u>Earth's magnetic field</u> guides them to the magnetic poles, <u>causing</u> <u>auroras</u>. Scott Forbush first detected SEPs as ground-level enhancements in 1942.

- 3. Solar Proton Event (SPE) occurs when the Sun emits protons that accelerate to high energies during a solar flare or coronal mass ejection (CME). These protons travel towards Earth through the solar wind or CME and are guided by <u>interplanetary magnetic</u> <u>field lines</u>.
- 4. Online report of the current solar wind heading Earth.

Sunspots, unlike flares and CMEs, are statistically predicted.

<u>Sub-chapter 12.5</u> discusses the Solar Cycle.

<u>Sub-chapter 12.6</u> presents long term prediction for Radio Flux at 10.7 cm.

12.5 The Solar Cycle □

<u>Sunspots</u> change in eleven year cycles. There are many sunspots during solar maximum and few during solar minimum.

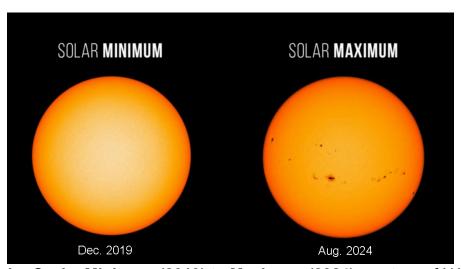


Figure 12.8: **Solar Cycle: Minimum (2019) to Maximum (2024)** courtesy of NASA's Goddard Space Flight Center.

Visible light images from NASA's Solar Dynamics Observatory showcase the Sun's appearance at solar minimum (left, Dec. 2019) and solar maximum (right, Aug. 2024). During solar minimum, the Sun often appears spotless. Sunspots, linked to solar activity, are used to track the solar cycle's progress.

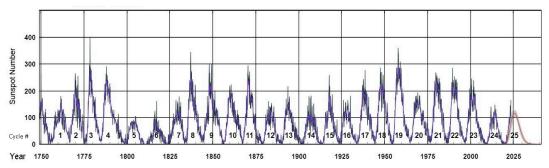
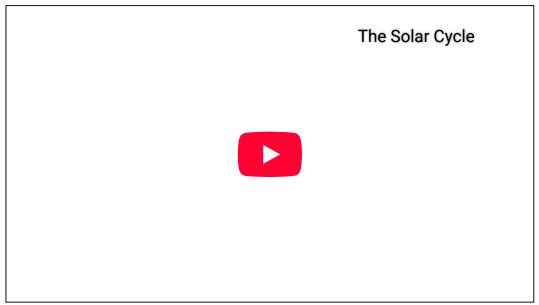


Figure 12.9: **Solar Cycle Sunspot Number Progression**Source: The International Space Environment Service (ISES)



Video clip: An animated overview of the Solar Cycle; published by NASA in May 2013

Solar magnetic flips are associated with solar maximum, when the number of sunspots is near its maximum, but it is often a gradual process that can take up to 18 months. The reversal will most likely take three to four months to complete.

The sunspot cycle begins when a sunspot appears on the sun's surface at roughly 30 degrees latitude. The formation zone then travels toward the equator. At its peak intensity, the sun's global magnetic field reverses its polar regions, as if the positive and negative ends of a magnet were flipped at each of the sun's poles.

There have been 24 (11-years) solar cycles since 1749. The magnetic field of the sun totally flipped every 11 years or so. In other words, the sun's north and south poles switched places. After two reversals (22 years), the solar magnetic field returns to its former orientation. This is known as "Hale cycle".

Understanding the complex interactions between solar magnetic fields, sunspots, and the solar cycle is crucial for comprehending the Sun's dynamic behavior and its impact on Earth, specifically HF propgation conditions.

The Current 25th Cycle began in 2020. The number of sunspots observed far exceeds predictions.

July 2024 marked the peak of Solar Cycle 25, with a monthly average sunspot number of 196.5, a new high. The last time this occurred was in December 2001. Despite predictions of a similar cycle size to previous cycles, Solar Cycle 25 exceeded these expectations.

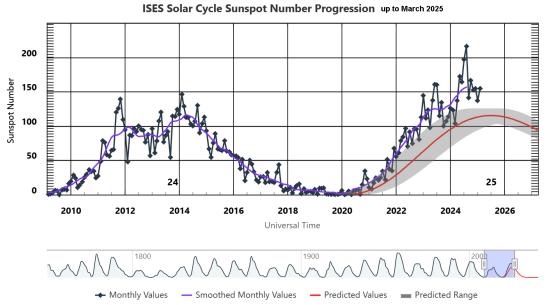


Figure 12.10: **Sunspot Number** progression during solar sycles 24 and 25 up to Mar 2025 Source: The International Space Environment Service (ISES)

Online chart of the recent 30-day sunspot numbers

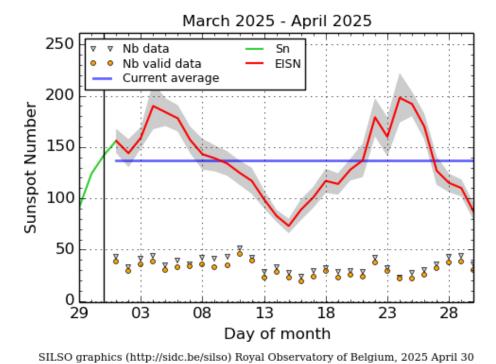


Figure 12.11: EISN - Estimated International Sunspot Number

Solar flux ☐ like sunspot number can be also used to show the observed and predicted Solar Cycle.

ISES Solar Cycle F10.7cm Radio Flux Progression

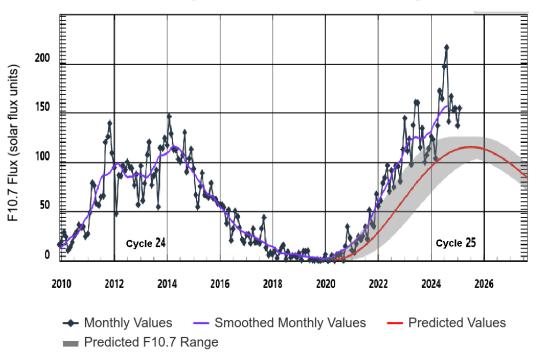
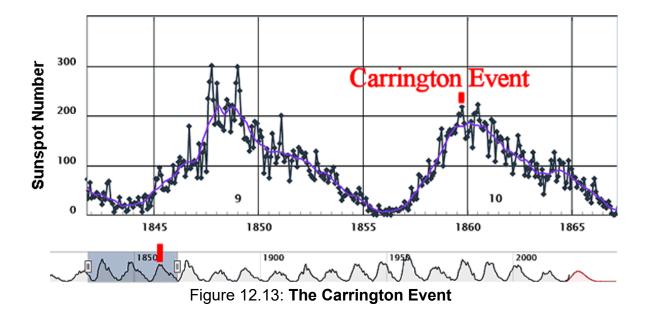


Figure 12.12: **Solar Flux** progression during solar sycle 25 up to Dec 2024 Source: The International Space Environment Service (ISES)

a. Solar Cycle Notable Events

More than 150 years ago, the most intense *geomagnetic storm* was recorded on 1-2 September 1859 during solar cycle 10.

This event is known as the **Carrington Event**<u></u>. ■.



b. Sunspot cycles can vary, meaning they are not identical.

Comparison of the recent <u>Solar Cycles</u> by Jan Alvestad<u></u>:

The current 25th solar cycle is significantly stronger than the previous 24th cycle, but weaker than the three preceding cycles (21st-23rd).

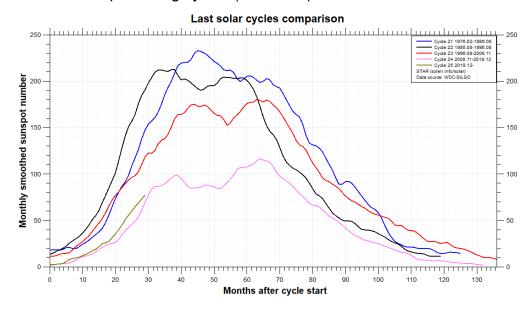


Figure 12.14: Comparison of the recent Solar Cycles

c. North-South Sunspot Asymmetries

Previous research has found north-south asymmetries for solar activity. These data point to some decoupling between the two hemispheres during the evolution of the solar cycle, which is consistent with dynamo theories. So yet, only little data are available for the two hemispheres independently for the most important solar activity metric, sunspot numbers. Below see an example:

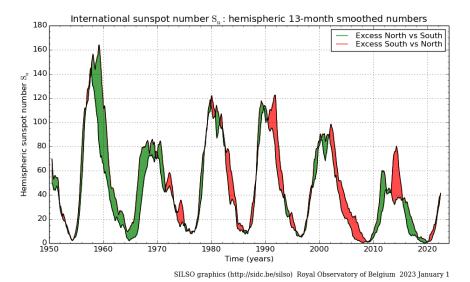


Figure 12.15: Sunspot Asymmetries

Hemispheric Sunsopt Number 1950-2021 provided by SIDC - Solar Influences Data Analysis

Center, Royal Observatory of Belgium

☐

12.6 Predicting Solar Flux and Sunspot Number

The NOAA Space Weather Prediction Center forecasts the monthly sunspot number and 10.7 cm radio flux. The sunspot number represents the count of visible sunspots on the solar surface, while the 10.7 cm radio flux measures solar radio emission at 2,800 MHz. These predictions use a blend of observational data, analytical methods, and AI techniques.

Here are three recommended reports:

- A multi-year (2022-2040) forecast ☐ of Sunspot number and 10.7 cm radio flux.
 The predicted values are based on the consensus of the Solar Cycle 24 Prediction Panel.
- 2. The **27-day Space Weather Outlook Table** offers numerical predictions for three important solar and geophysical measurements:
 - 2.1 10.7 cm Solar Radio Flux This is a measure of solar activity.
 - 2.2 Planetary A Index This indicates the level of geomagnetic activity.
 - 2.3 The **Largest Daily K Values** These reflect the highest levels of geomagnetic disturbances each day.
- 3. Three Day Geomagnetic and Aurora Forecast by SolarHam → that relays data and images from various sources.

12.7 Live Solar Activity Online -

<u>Near real-time views of the Sun</u> shown below were taken by <u>SOHO</u> telescope \blacksquare at four <u>EUV</u> wavelengths, each associated with a different color of the sun disc.

Brighter areas show higher levels of solar surface activity, i.e. higher Solar Flux Index.

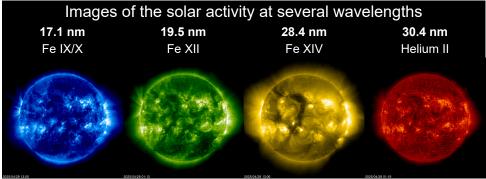


Figure 12.16: **Real-time SOHO** images at <u>EUV</u> by **EIT** (Extreme ultravioletImagingTelescope). Solar Images courtesy of NASA, Solar Data Analysis Center. Click on a thumbnail to view a larger image (opens a new window). Sometimes you may see cluttered images (<u>NASA CCD Bakeout explanation</u>).

The Extreme Ultraviolet Imaging Telescope (EIT) aboard the SOHO spacecraft captures high-resolution images of the solar corona. The EIT detects <u>EUV</u> at certain wavelengths: 17.1, 19.5, and 28.4 nm (from ionized iron in the solar corona), as well as 30.4 nm (from helium). These four wavelengths reveal the intensity distribution originating from the solar chromosphere and the transition region. The average and local EUV intensity changes over time scales ranging from days to months due to the <u>predictable solar rotation</u> and from years to decades due to the <u>predictable solar cycle</u>. However, <u>unpredictable X-ray flares</u> can vary by orders of magnitude over time scales ranging from minutes to hours, as discussed in the following subchapter.

12.8 Live Solar Alerts Online 7

The extreme solar events like X-ray flares and high energy protons may affect <u>space weather</u> and <u>HF radio propagation</u>.

Links to Online reports and alerts

12.9 Solar Radio Interference

A. Solar flares and CMEs emit radio waves at various frequencies.

- These emissions come in bursts.
- These bursts disrupt space weather and interfere with communication systems.
- The spectrum of radiation spans from a few kHz to several GHz.
- Different sunspot cycles can produce distinct radio burst distributions, especially at 245 MHz.
- Predicting future solar events is challenging due to gaps in data archives, leading to underestimated burst rates.
- The temporal variations in the maximum solar radiation intensity at different frequencies, particularly at 245 MHz, help estimate the flow velocity in the solar corona during coronal mass ejections.

B. Solar radio emissions may indicate complex processes.

Below, see multi-frequency (VHF-SHF) radio bursts superimposed on a persistent background characterizing solar flares:

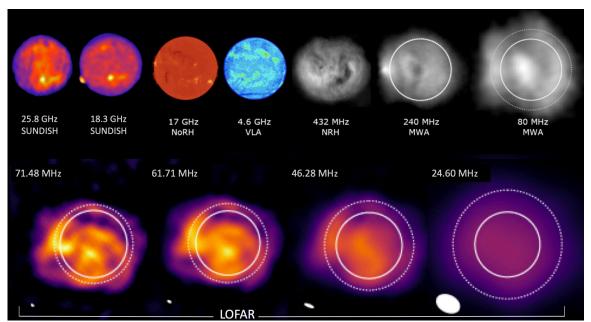


Figure 12.17: Multi-Radio-Frequency Observations of the Sun

Picture Source: Patrick McCauley Mccauley.pi, CC BY-SA 4.0; Author: Peijin Zhang 2022

û Chapter 13. Space Weather🔁

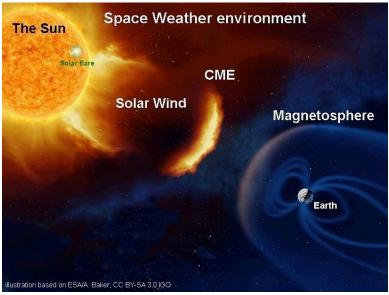


Figure 13.1: Space Weather Environment; illustration based on ESA/A. Baker, CC BY-SA 3.0 IGO.

Space weather refers to conditions and events in space, primarily caused by <u>solar activity</u> affecting Earth and its environment. These include <u>solar flare</u>, <u>solar wind</u>, <u>coronal mass ejection</u> (<u>CME</u>), and <u>geomagnetic storms</u>, impacting HF (3-30 MHz) radio communication.

Wikipedia describes space weather ☐ as "a branch of space physics ☐ and aeronomy ☐, or heliophysics ☐, concerned with time-varying conditions within the Solar System ☐, emphasizing space surrounding the Earth."

Sub-chapters:

- 13.1 Space Weather Scales
- 13.2 Solar Wind Impact on Earth and HF Propagation
- 13.3 Earth's Magnetic Field Governs The Magnetosphere
- 13.4 What is Geomagnetic Activity?
- 13.5 Geomagnetic Storms
- 13.6 Space Weather Observations
- 13.7 Space Weather Reports
- 13.8 Geomagnetic forecast
- 13.9 Challenges in Geomagnetic Storm Forecasting

û 13.1 Space Weather Scales 🔁

The NOAA R-S-G scales categorize three types of space weather events, assessing their severity and likely consequences with numbers (0–5):

Scales	Phenomena	Units	Propagation Result					
R ₀₋₅	Solar X-ray ₽	Flare Class	Radio blackouts⊟					
S ₀₋₅	Solar proton flux₽	pfu*	Polar Cap Absorption ₽					
G ₀₋₅	Geomagnetic Activity ₽	<u>Kp index</u>	Propagation disrtubances					

Table 13.1: **The NOAA R-S-G scales** *Proton flux unit (pfu) = protons/cm²/second/steradian

13.2 Solar Wind Impact on Earth and HF Propagation

The <u>solar wind</u> is the fundamental driver of space weather. It is a stream of charged particles are emitted by the <u>sun's corona</u> into outer space. These particles interact with <u>Earth's magnetosphere and magnetic field</u>, significantly affecting skywave propagation and triggering <u>auroras</u> around the Earth's poles.

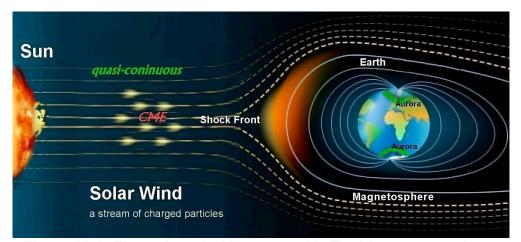


Figure 13.2: **The solar wind** interacts with <u>Earth's magnetosphere</u>.

The illustration above shows the solar wind reaching the magnetosphere, compressesing the magnetic field on the side facing the sun while elongating it on the opposite side.

The solar wind can vary greatly in <u>speed, density, temperature</u>, <u>composition of the charged particles</u>, and the <u>interplanetary magnetic field (IMF)</u>. These variations are influenced by solar activity, such as <u>coronal mass ejections (CMEs)</u> or coronal holes. Although predicting exact changes in the solar wind is challenging, there is some correlation with <u>sunspots</u> and <u>solar flares</u>. The solar wind can reach Earth within 20 to 30 minutes after a solar storm begins (relativistic electrons) and up to four days later (heavier charged particles).

The Interplanetary Magnetic Field (IMF) → extends the Sun's magnetic field into space, carried by the <u>solar wind</u>. It interacts with <u>Earth's magnetosphere</u>, affecting <u>geomagnetic</u> <u>storms</u> and <u>auroras</u> →.

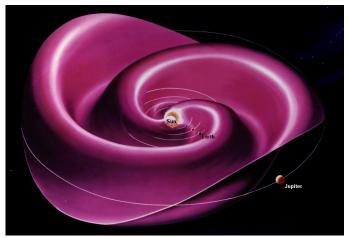


Figure 13.3: The Heliospheric Current Sheet (HCS)

The IMF originates from the Sun's corona, forming a three-dimensional plasma spiral due to the Sun's rotation, known as the Parker spiral . It has radial and azimuthal components and a sector structure where the magnetic field direction can switch. Figure 13.21 shows the current prediction of plasma density and radial velocity.

13.3 Earth's Magnetic Field Governs The Magnetosphere

Earth's magnetic field poverns the magnetosphere, the region enveloping our planet. This field protects us from the adverse effects of solar particles, X-ray flares, and cosmic radiation, all of which influence geomagnetic activity and, in turn, significantly impact skywave propagation. The strength of the magnetic field is measured in units of Gauss (G) or Tesla (T). □

Earth's magnetic field

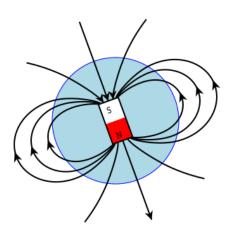


Figure 13.4: Earth's Magnetic field.—the geomagnetic field.

The orientation of Earth's magnetic field is composed of two variables:

- 1. Earth's axis is tilted 23.5° to the ecliptic plane ♣
- 2. Earth's magnetic field is tilted 11° relative to the Earth's axis.

Earth-Magnetosphere

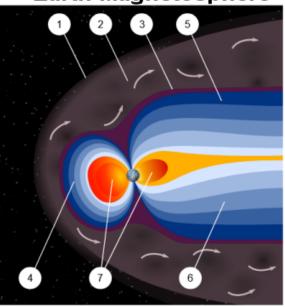


Figure 13.5: **The magnetosphere** is a "magnetic bubble" that surrounds Earth. Its shape depends on the *solar wind* and the orientation of the Earth's magnetic field. Click on the figure above for additional explanations.

13.4 Geomagnetic Activity

Geomagnetic activity refers to disturbances in <u>Earth's magnetic field</u> caused by the <u>solar wind</u> and other solar phenomena. There is a long term possitive correlation between <u>high solar</u> <u>activity</u> and geomagnetic activity. These disturbances can range from minor fluctuations to major <u>geomagnetic storms</u> , often associated with auroras . ■.

Auroras in polar zones result from interactions between charged solar wind particles and Earth's magnetic field, creating the glowing auroras. These interactions enhance ionization of the D-region, disrupting HF radio communications.

The following public domain images show auroras near the polar regions, known as the Northern Lights (Aurora Borealis) and Southern Lights (Aurora Australis).



Figure 13.6: Rare **Red Aurora** caused by oxygen at altitudes above 150 km.



Figure 13.7: Green Aurora caused by oxygen at altitudes of about 100 to 150 km.



Figure 13.8: A horizontal view of colorful auroras.

Purple and Blue caused by nitrogen molecules at lower altitudes of 90 to 100 km.

1 13.5 Geomagnetic Storms

Geomagnetic storms <u>race</u> are significant disturbances in <u>Earth's magnetosphere</u> caused by <u>solar wind</u> shock waves or <u>coronal mass ejections (CME)</u>.

- 1. Geomagnetic storms are more frequent during periods of high solar activity.
- 2. These storms occur one to four days after a CME, triggering <u>auroras</u> <u>A</u>.

What causes geomagnetic storms?

Solar magnetic storms trigger geomagnetic storms, as illustrated in figure 13.9 below.

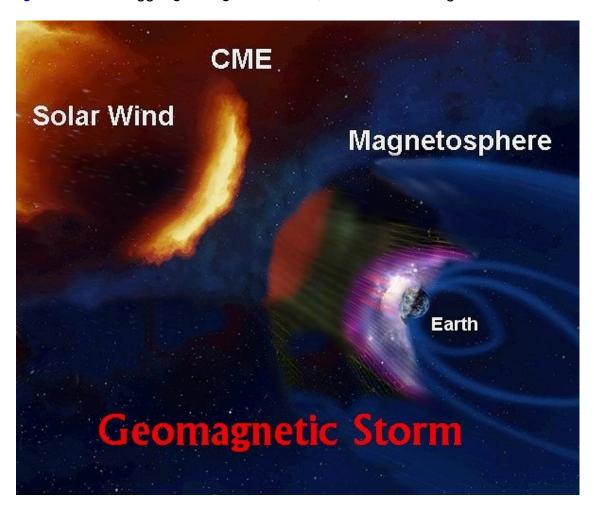


Figure 13.9: Interaction Between Earth's Magnetosphere and Solar Activity When a <u>CME</u> enters the <u>magnetosphere</u>, it causes a <u>Geomagnetic Storm</u>

The impact of geomagnetic storms on HF propagation

Table 13.2: The correlation between the global geomagnetic activity and HF propagation conditions

Geomagnetic activity	G ₀₋₅		G0				1	2	3	4	5
Disturbance (3-h log. scale) Kp		0	1	2	3	4	5	6	7	8	9
Disturbance (24-h linear scale)	Ар	0	4	7	15	27	48	80	132	207	400
HF Propagation conditions				t	A۱	/era	ge	Po	oor	BA	AD

- A geomagnetic storm induces high absorption levels in the lower HF bands near the equator, causing a complete <u>fadeout</u> of HF signals, due to the reduction of the <u>MUF</u> in equatorial regions, while increasing the <u>LUF</u>.
- 2. The MUF in **polar regions** grows dramatically, enabling low VHF contacts.

Geomagnetic Storm Dynamics

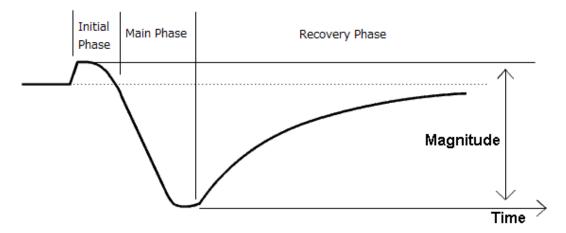


Figure 13.10: **Geomagnetic Storm Dynamics** based on Kakioka Magnetic Observatory, Japan

This is a typical morphology of sudden-commencement type magnetic storms (horizontal force variation).

13.6 Space Weather Observations

Monitoring space weather involves a combination of space observations, ground-based measurements, and computer models:

Space observatories: Satellites play a crucial role in predicting space weather and its impact on HF radio propagation:

- 1. **ACE** (Advanced Composition Explorer): Positioned at <u>L1 Lagrange point</u>, provides real-time data on <u>solar wind</u> and geomagnetic storms, giving up to an hour's advance warning of space weather events that can impact Earth.
- 2. **GOES** (Geostationary Operational Environmental Satellites): Tracks <u>solar flares</u> and other space weather phenomena, aiding in timely alerts and mitigating potential impacts on HF propagation and space technology.
- 3. **DSCOVR** (Deep Space Climate Observatory): Positioned at <u>L1 Lagrange point</u>, monitors real-time solar wind, providing early warnings for <u>geomagnetic storms</u>. Relevant Science Focus Areas: 1. Solar wind activity. 2. Reflected and emitted radiation from the entire sunlit face of the Earth. 3. Ozone and aerosol amounts, cloud height and phase, vegetation properties, hotspot land properties and UV radiation estimates at Earth's surface.
- 4. **SDO** ☐ (Solar Dynamics Observatory): Delivers detailed images of the sun divided into *four spectral bands*.
- 5. <u>SOHO</u> (Solar and Heliospheric Observatory): Positioned at <u>L1 Lagrange point</u>, monitors solar activity and space weather.
- 6. **STEREO** ☐ (Solar and Terrestrial Relations Observatory): Consists of STEREO-A (Ahead) and STEREO-B (Behind), which orbit the Sun near the stable *Lagrange Points L4 and L5*☐ to provide a 3D view of solar phenomena from multiple perspectives.
- 7. The **Parker Solar Probe** significantly contributes to the prediction of space weather. By flying closer to the Sun than any previous spacecraft, it collects unprecedented data on the solar wind and the Sun's corona.

**Note: The satellites SOHO, ACE, and DSCOVR, monitor the hazardous Coronal Mass Ejections (CMEs) at the <u>L1 Lagrange point</u>.

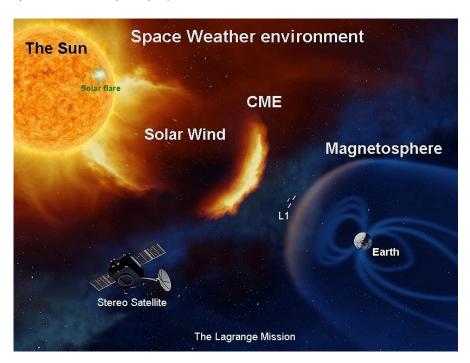


Figure 13.11: Monitoring Space Weather

The Lagrange Mission monitors hazardous <u>CME</u> headed toward Earth; A modified illustration based on ESA/A. Baker, CC BY-SA 3.0 IGO; AGU - Advanced Earth and Space Science

On the right side (of the above picture), you may see an illustration of the Magnetosphere=, which protects Earth from Solar Wind. The magnetosphere is a part of a dynamic, interconnected system that responds to solar, planetary, and interstellar conditions. It is disturbed when solar wind interacts with the space environment surrounding Earth. The Lagrange point L1 allows a satellite to maintain a constant line with Earth as it orbits the Sun.

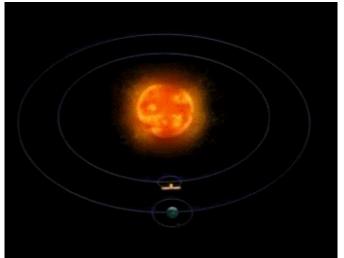


Figure 13.12: A satellite trapped at the L1 point of the Sun-Earth-Moon gravitational system.

Published by Space Weather Live

Ground-based observatories:

- 1. **lonosondes** measure the ionosphere's electron density profile by transmitting radio waves and analyzing the returned signals. They help determine the ionospheric regions' height and density, crucial for predicting HF radio wave propagation.
- 2. **Terrestrial magnetometers** measure geomagnetic fluctuations, providing data on the Earth's magnetic field. They help monitor geomagnetic storms and disturbances that can affect HF propagation by altering the ionosphere's structure. See examples of terrestrial magnetomeres.
- 3. <u>Radio telescopes</u> detect solar radio emissions, which can indicate solar flares and other disturbances. By monitoring these emissions, scientists can predict space weather events that might impact HF radio communication.

Ground-based observatories, combined with satellite data, provide a comprehensive picture of space weather conditions affecting HF propagation.

13.7 Space Weather Reports

For example see bellow seven online reports:

- 1. Space Weather Nowcast by Serge Y. Stroobandt, ON4AA, will open a new window
- 2. The **current** global / planetary <u>Kp index</u> Europen Space Weather Service
- 3. The recent 3 days of Space Waether R-S-G Scales NOAA SWPC services
- 4. The current K-index in Australia Austrlian Space Weather Service
- 5. The <u>recent 8-day UK K indices and the "global" Kp</u> British Geogolgical Survey
- 6. The <u>recent geomagnetic activity over the United States</u> NOAA
- 7. The current Solar Wind and Interplanetary Magnetic Field Rice Space Institute

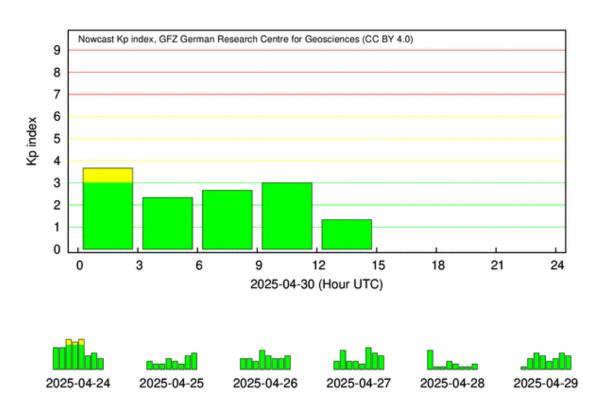


Figure 13.13: **Kp index online overview**

The **recent** 3 days of Space Waether **R-S-G** Scales provided by NOAA SWPC services:

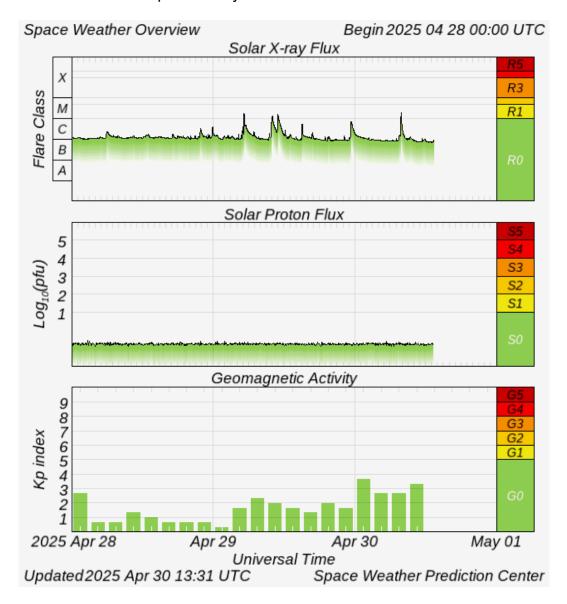


Figure 13.14: Space weather online overview

1

The K-index at different regions vs Kp 🔁

Real-time K index near Australia provided by ASWFC

Real-time Australia K index

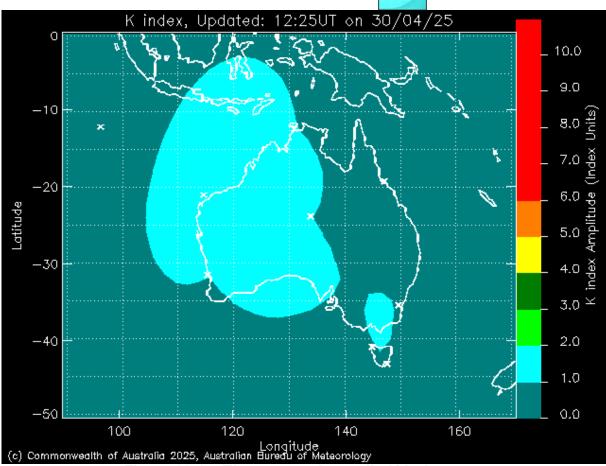


Figure 13.15: The current Australia K index map

The recent 8-day UK K indices and the "global" Kp provided online by British Geogolgical Survey

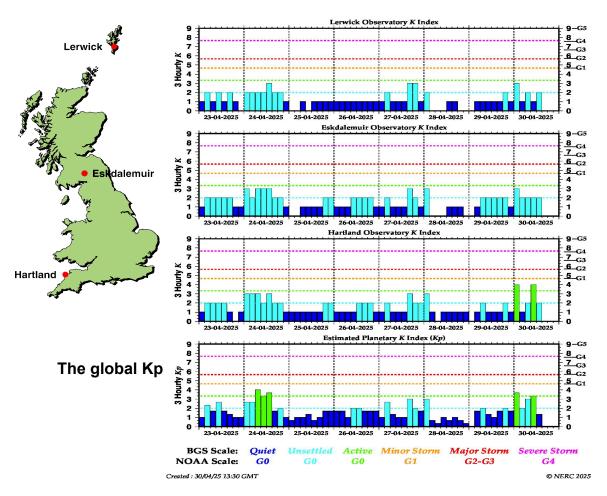


Figure 13.16: The recent K index map over the UK

1 The recent geomagnetic activity over the United States

K-indices and the "planetary" **K**_p provided online by NOAA, SWPC<u>₽₽</u> based on US Geomagnetic Observatories<u>₽</u>:

- 1. Boulder, Colorado
- 2. Fredericksburg, Maryland
- 3. College, Alaska

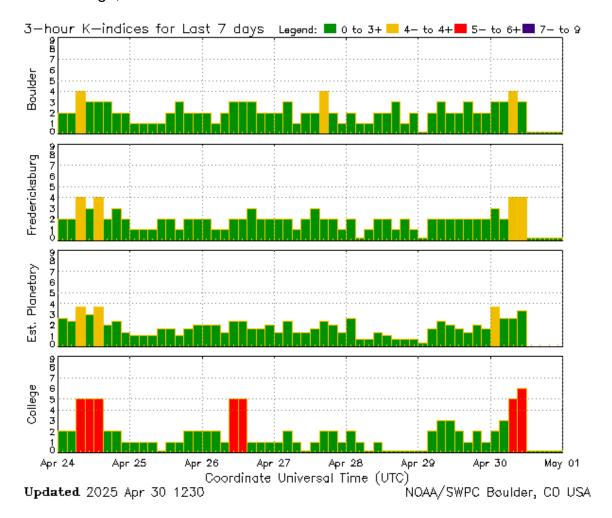


Figure 13.17: 3-hour K-indices for the last 7 days over the US

The last 30 days A-indices over the US provided online by NOAA

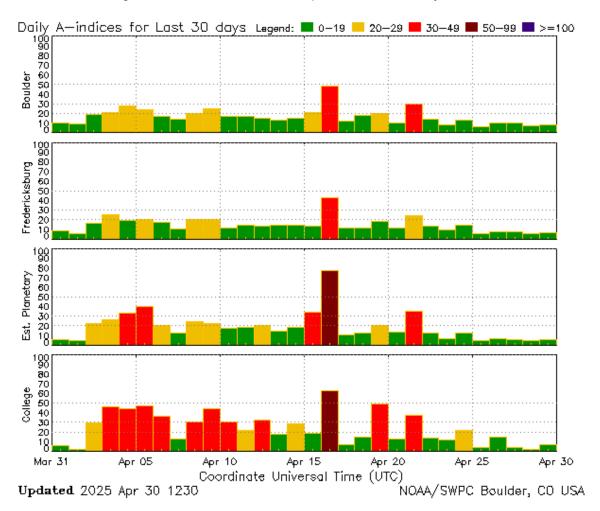
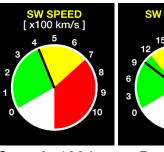


Figure 13.18: Daily A-indices for the last 30 days over the US

The Rice Space Institute's provides the current solar wind ☐ data and the *interplanetary magnetic field* as measured by *ACE*→.

Figure 13.19: Online report of the Solar wind



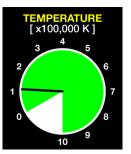
Speed x100 km per second



Density of charged energetic particles per unit required to stop volume



Pressure The force per unit area the solar wind flow; nP = nano pascals



Proton's **Temperature**

The background color reflects <u>magnetosphere</u> and <u>ionosphere</u>'s status: no disruptions, potential disruptions, and severe disruptions.

Figure 13.20: Online report of the *Interplanetary Magnetic Field* (IMF) → as measured by ACE → magnetometer →.



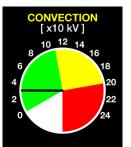
Nano Tesla



Potential danger Impact on to high altitude aircraft in the polar regions



Magnetosphere Interactions



Voltage Across the Polar Cap x10 Kv

13.8 Geomagnetic Forecast

Forecasting geomagnetic activity relies on solar and space weather observations. It is crucial for protecting power grids, communication systems, and satellites from solar storms. Knowing upcoming geomagnetic activity can help radio amateurs plan their operations effectively.

Geomagnetic Warnings and Alerts <a>-





provided online by ASWPC.

See below two products provided online by NOAA SWPC:

```
:Product: Geomagnetic Forecast
:Issued: 2025 Apr 29 2205 UTC
# Prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction
NOAA Ap Index Forecast
Observed Ap 28 Apr 005
Estimated Ap 29 Apr 007
Predicted Ap 30 Apr-02 May 005-005-012
NOAA Geomagnetic Activity Probabilities 30 Apr-02 May
Active
                    15/15/35
Minor storm
                    01/01/25
Moderate storm
                    01/01/05
Strong-Extreme storm 01/01/01
NOAA Kp index forecast 30 Apr - 02 May
           Apr 30
                     May 01
                              May 02
00-03UT
             1.67
                      1.33
                                3.00
03-06UT
             1.33
                      1.33
                                3.67
06-09UT
             1.33
                      1.33
                                2.67
09-12UT
            1.33
                      1.33
                                2.67
12-15UT
            1.33
                      1.67
                                1.67
15-18UT
            1.33
                      1.33
                                2.33
                       1.67
                                2.33
18-21UT
            1.67
             1.67
21-00UT
                       1.67
                                2.67
```

Geomagnetic Activity Forecast → provided online by NOAA SWPC →

Ap Index: Daily global geomagnetic activity, derived from the Kp index.

Geomagnetic Activity % probabilities:

Observed today | Estimated 24 hours | Predicted 48 hours

Kp Index Forecast: Predicts geomagnetic activity every 3 hours.

This product helps predict space weather impacts on Earth, such as disruptions to communication and navigation systems.

Prediction of Plasma Density and Radial Velocity

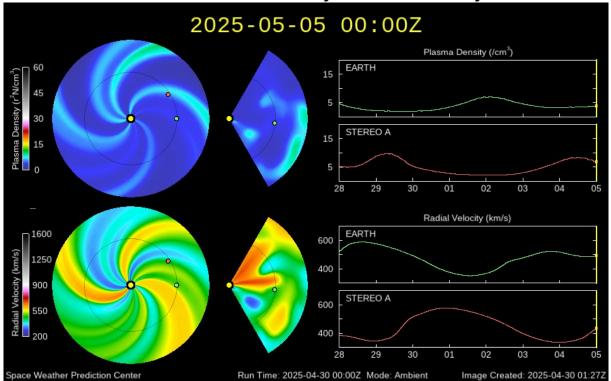


Figure 13.21: Two polar plots around the sun, provided online by NOAA SWPC: **Plasma density** (particles per cubic centimeter: r²×N/cm⁻³) and **Radial velocity** (km/s).

This illustration depicts NOAA's prediction of plasma density and radial velocity from a <u>CME</u> originating from the Sun.

The left panels (*ecliptic plane* and *meridional slice*) show spatial distribution, while the right panels show time series data for Earth and <u>STEREO A.T.</u>. It may help us understand the impact of space weather on Earth. The spatial distribution plot shows the Sun as a yellow dot, Earth as a green dot, and STEREO A as a red dot.

The *ecliptic plane* (left vane circle) is the imaginary flat surface along which the Earth and other planets orbit the Sun. It demonstrates the plasma spreading around the Sun over time, allowing us to estimate the consequences of space weather on Earth. The *meridional slice* (in the middle) that intersects the Earth provides a 'side' view of the solar wind structures as they approach the planet.

The Space Weather Forecast Center employs WSA-Enlil, a large-scale heliospheric model. It issues one-to-four-day warnings about solar wind structures and Earth-directed CMEs, which cause geomagnetic storms. Solar disturbances disrupt communications, harm geomagnetic systems, and jeopardize satellite operations.

13.9 Challenges in Geomagnetic Storm Forecasting

Geomagnetic storm predictions are often inaccurate because only about 12% of <u>coronal mass</u> <u>ejections (CMEs)</u> actually reach Earth, leading to frequent (~88%) false warnings of potential storms. Historical data shows that only a few solar storms, like the Quebec storm in 1989 and a series of storms in 2003, matched the intensity of the <u>Carrington Event</u>. In 2012, a powerful CME narrowly missed Earth.

Physics Girl highlighted a similar event in April 2022, where a solar storm missed Earth by just 9 days:



A video clip by Dianna Cowern "Physics Girl" 🗗

Some CMEs exhibit a consistent magnetic field direction, while most show changing field directions during their passage over Earth. Generally, CMEs impacting <u>Earth's magnetosphere</u> will have an <u>IMF</u> orientation that favors geomagnetic storm generation at some point.

The CME's ability to cause geomagnetic disruptions is determined by the magnetic structure of the embedded <u>flux rope</u>. However, existing forecasting capabilities are limited due to a scarcity of remote-sensing techniques for predicting CME deformation, rotation, and deflection.

🕆 Chapter 14. Radio blackouts or fadeouts 🔁

What are radio blackouts? A radio blackout or fadeout is a sudden signal loss induced by <u>solar</u> X-Ray flares, as explained <u>here</u>.



Figure 14.1: Current and predicted fadeouts as reported online by ASWFC.

During a blackout event, the drop in signal heavily affects the lower HF bands:

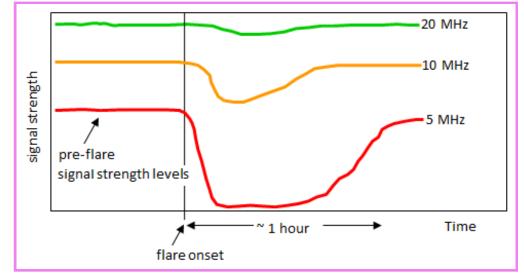


Figure 14.2: Typical Fadeout signal strength vs. time, courtesy of ASWS

The current solar flare: B8.8 relayed by ASWFCenter.

^{*} The last significant radio blackout occurred on October 3, 2024 | The latest significant solar flares

Global Fadeout Reports

The **D-RAP** (D Region Absorption Predictions) model uses empirical relationships to calculate HF absorption based on space weather parameters.

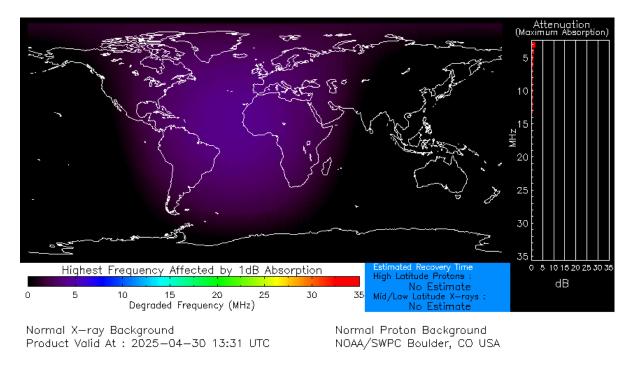


Figure 14.3: **The predicted** *LUF* attenuation of skywaves (from 3 to 35 MHz) due to <u>flares</u> and <u>SEP</u>

Click on the figure to view an animation over the last eight hours.

The *D-RAP model* helps understand HF radio fadeouts and blackouts by providing graphical and textual information on global HF propagation conditions. Electron density in the D region, which can vary within minutes, directly affects the <u>LUF</u>. At low latitudes, X-ray photons from <u>solar flares</u> lead to <u>rapid fadeouts and blackouts</u>. <u>Solar wind particles</u> cause longer-term <u>polar cap absorption (PCA) events</u> at high latitudes.

1 Chapter 15. Summary

Skywave propagation review

- Global skywave communication depends on the <u>ionosphere's ionization</u> and <u>operating</u> frequency.
- 2. Ionospheric phenomena may be well understood, but they are not fully predictable.
- 3. Chaotic solar activity may affect skywave propagation conditions.
- 4. Today's technology enables better predictions of skywave propagation conditions.

Forecasting HF radio propagation: practical techniques

- 1. Use weak signal <u>digital modes</u> (FT8, JT65, WSPR) to probe the communication conditions.
- 2. Utilize <u>PSKReporter</u> for real-time feedback and strategy adjustments.
- 3. Monitor <u>real-time MUF (Maximum Usable Frequency) charts</u> to achieve optimal communication.
- 4. Stay adaptable: switch bands or modes as conditions change.

Key concepts

- 1. <u>HF Radio Propagation Basics</u>: Understanding the core principles of HF radio waves and ionosphere interactions.
- 2. <u>Skywave Propagation</u>: How do radio waves refract off the ionosphere for long-distance communication?
- 3. <u>Critical Frequency</u>: The Maximum Usable Frequency (MUF) influences communication quality.
- 4. <u>Solar Effects</u>: <u>Solar phenomena</u> influence radio communications by altering ionosphere behavior.
- 5. Solar X-Ray Flares: Communication can be impacted when the sun is directly overhead.
- 6. <u>Solar Wind</u> and <u>Coronal Mass Ejections (CMEs)</u>: These events disturb communication conditions.
- 7. <u>Solar Storms</u>: These storms particularly affect the <u>D-region</u>, suddenly disrupting propagation.
- 8. <u>Space weather</u> and <u>Geomagnetic activity</u>: Geomagnetic storms and other space weather events alter communication reliability.
- 9. Radio Blackouts or Fadeouts: Sudden signal loss induced by solar flares.
- 10. Forecast Models <u>□</u>: Radio wave propagation relies on <u>solar indices (SSN, SF)</u>, <u>geomagnetic indices (K, A)</u>, <u>operating frequency</u>, <u>time of day</u>, and <u>season</u>.
- 11. Accuracy of Forecasting: Forecasting <u>solar flares</u> and <u>geomagnetic storms</u> often <u>lacks</u> <u>accuracy</u>.

- 12. Geospace Dynamic Models: These models are still being developed to forecast geomagnetic storms and blackouts, implicitly included in the results of ionograms.
- 13. <u>Real-time charts</u>: The most effective approach to quickly assess current propagation conditions, even though the <u>accuracy is insufficient for professional radio services</u>.

The essay ends prematurely, but the website updates daily.

1 Last but not least:

Since only a small number of amateurs operate in the SHF and higher frequencies, commercial users have begun accessing *radio amateur bands*. However, we have gained new narrow bands in the short, medium, and long wave ranges. While these additions may be limited, they provide new opportunities for enhancing communication without dependence on commercial infrastructure.

If you have comments, questions or requests please e-mail.

73 de Doron, 4X4XM

TREFERENCES Links to external sources automatically open in a new tab.

The list of sources below are organized by topic, as follows:

- 1. This page relays online data and images from the linked sites
- 2. Monitor Band Activity of Radio Amateurs Real-time watching of worldwide hams' activity
- 3. <u>Electromagnetic Waves Basics</u> ► <u>Radio propagation</u>
- 4. <u>Propagation via lonosphere</u> ► <u>Propagation</u> ► <u>lonospheric Intro & Model</u> ► <u>Regions</u> ► <u>MUF-OWF-LUF</u> ► <u>Seasonal & Anomalies</u> ► <u>Probing Ionosphere</u>
- 5. NVIS unique mode of a skywave
- 6. Gray line
- 7. Propagation Indices
- 8. Observations of Terrestrial magnetometers, The Sun, Space weather, TEC Total Electron Content, MUF from ionosondes. Propagation Charts
- 9. Solar Phenomena
- 10. Space Weather Phenomena Geomagnetic storms & Aurora-Impact on HF radio Propagation
- 11. Space Weather Agencies & Services
- 12. Forecasting and prediction
- 13. Tools and Applications for analyzing and forecasting HF propagation
- 14. Supplementary references
- 15. Misc. references

1. This page relays online data and images from the following websites:

- 1.1 <u>ASWFC Space Weather Service (SWS)</u> ↑ | <u>Australian Space Weather Alert System</u> ↑
- 1.2 British Geological Survey
- 1.3 DLR German Aerospace Center
- 1.4 ESA The European Space Agency Network
- 1.5 NASA Solar Data Analysis Center
- 1.6 NOAA Space Weather Prediction Center (SWPC)—index
- 1.7 Rice Univ. Space Institute
- 1.8 The Royal Observatory of Belgium
- 1.9 <u>hamgsl.com</u>, Paul L Herrman, <u>N0NBH</u>
- 1.10 hamwaves.com, Serge Stroobandt, ON4AA
- 1.11 HFQSO.com, HF Activity Group, Tom K5VWZ
- 1.12 prop.kc2g.com, Andrew D. Rodland, KC2G 1
- 1.13 hb9vqq.ch, Roland Gafner, HB9VQQ
- 1.15 grzcq.com, QRZCQ 1
- 1.16 solen.info, Jan Alvestad, retired from FMC Kongsberg Subsea AS, Norway

2. Monitor HF Band Activity of Radio Amateurs **Real-time watching of worldwide hams' activity.

Software-Defined Radio (SDR) is a technology where analog hardware components are replaced by software.

2.1 <u>SDR - Software Designed Radio</u> Wikipedia

SDR radios

- 2.2 <u>List of software-defined radios</u> wikipedia
- 2.3 <u>BEST Software Defined Radios (SDR's) to Buy</u> 17-Feb-2025 <u>Ham Radio DX</u>, VK7HH, Hayden P Honeywood
- 2.4 <u>Malakhite DSP portable SDR radio receiver</u> (Russian) Russian hamforum
- 2.5 <u>Malahit DSP1 and DSP2 clone receivers</u>: ▶ A YouTube playlist featuring demonstrations and explanations Doron, 4X4XM
- 2.6 <u>BELKA SDR Pocket RX 10 KHz 31 MHz</u>: A YouTube playlist featuring demonstrations and explanations Doron, 4X4XM

WebSDR and KiwiSDR are two worldwide networks of remote public SDR receivers:

- 2.7 <u>List of public **WebSDR** stations</u>
 - Wideband WebSDR at the University of Twente, Enschede, NL
 - WebSDR.org background information
 - FAQ about the WebSDR project
- 2.8 Map of public Kiwi SDR stations
 - List of public Kiwi SDR stations
 - Introduction to using the KiwiSDR
 - KiwiSDR design review

Activity Charts and DX Clusters

- 2.9 <u>Curation of 51 DX clusters nodes @DXZone</u> Amateur Radio Internet Guide DXZone
- 2.10 DXMAPS Gabriel Sampol, EA6VQ
 - A video demo of DXMaps OfficialSWLchannel,

This website displays maps and lists of recent QSOs on various ham bands (from LF to UHF) that may indicate real-time propagation conditions.

- 2.11 DXWatch custom DX filter Spot Search and Create Your Filter DXWatch—Felipe, PY1NB
- 2.12 <u>Live DX Spot Reports</u> (auto-refreshes every 60 seconds) QRZ Ham Radio

- 2.13 The Holy Cluster Israeli Association of Radio Communication, the IARC
- 2.14 Real-time Ham Band Activity Map Jon Harder, NG0E
- 2.15 <u>Sites for Checking Signal Propagation and Band Activity</u> South Pasadena Amateur Radio Club (W6SPR)
- 2.16 HamDXMap: MUF, foF2, live radio frequencies weather Christian Furst, F5UII
- 2.17 Real-time propagation and band conditions QRZ online
- 2.18 <u>F5LEN Webcluster</u> Pascal Grandjean, F5LEN
- 2.19 HA8TKS DXcluster HA8TKS
- 2.20 <u>SK6AW DXcluster</u> | <u>Condex</u> SK6AW

Reporters of digital modes

- 2.21 <u>Display Reception Reports</u> PSKReporter
- 2.22 <u>Using PSK Reporter Website as a Propagation Tool</u> eHam.net
- 2.23 <u>HF Signal Propagation Reporter, PSK/JT65/FT-8/CW/JT9</u> HamRadioConcepts KJ4YZI

APRS-IS —Automatic Packet Reporting System-Internet Service

- 2.24 <u>Find Real-time Contacts, DX Cluster, Spotter Network, APRS</u> ► HamRadioConcepts K.I4YZI
- 2.25 <u>VHF Propagation Map APRS-IS</u> real-time radio propagation from stations operated near 144 MHz

WSPR - Weak Signal Communication 1

2.26 <u>Weak Signal Communication Software</u> Joe Taylor, K1JT

WSPR - Weak Signal Propagation Reporter

- 2.27 <u>Weak Signal Propagation Reporter</u> Wikipedia
- 2.28 <u>WSPR An Introduction for Beginners | WSJT-X Ham Radio</u> ► Ham Radio DX, 7-Jan-2022
- 2.29 <u>WSPR Explained: How to Get Started With One-Way Ham Radio</u> ExtremeTech
- 2.30 <u>Weak Signal Propagation Reporter (WSPR)</u> | <u>Stats</u> WSPRNet
- 2.31 WSPR Rocks —An alternative map VK7JJ
- 2.32 WSPR Live: Tools for the analysis of WSPR spot data.
- 2.33 Average propagation conditions: <u>The recent WSPR reports on 80–10m Ham</u>
 Bands up to 60 days <u>WSPR Rocks</u>

Beacons

				_
234	NODVED	KI C. C. C. C.	see ahove	ш
2.07	NCDXF Beacon	Network	occ above	_

- 2.35 International Beacon Project NCDXF
- 2.36 Beacons IARU
- 2.37 <u>International Beacon Project</u> (IBP) Wikipedia
- 2.38 Worldwide List of Beacons (1.8–28 MHz) RSGB
- 2.39 <u>High Frequency Beacons and Propagation</u> VU2AWC
- 2.40 Amateur Radio Propagation Beacon Wikipedia
- 2.41 Ham Radio Beacon List Google
- 2.42 Radio beacon | Radio propagation using beacons HF Underground
- 2.43 <u>Beacon monitoring programs</u> DXZone

Detect Changes in Propagation Conditions using RBN, WSPR, PSKR etc.

- 2.44 Reverse Beacon Network (RBN) | History | Online Activity
- 2.45 Reverse Beacon Network on graph online HA8TKS
- 2.46 Ham Radio Reporting Networks. HamSCI
- 2.47 <u>Using the WSPR Mode for Antenna Performance Evaluation and Propagation</u>

 <u>Assessment on the 160-m Band</u> 2022 ^{Jurgen Vanhamel et al.}
- 2.48 <u>Ionospheric Sounding Using Real-time Amateur Radio Reporting Networks</u> (2014) Nathaniel A. Frissell, W2NAF et al.
- 2.49 Reverse Beacon Networks PSK Reporter And WSPR 2013 Fred Kemmerer, AB10C
- 2.50 <u>Interpreting WSPR Data for Other Communication Modes</u> 2013 ^{Dr. Carol F. Milazzo,} KP4MD

3. Electromagnetic Waves Basics ► Radio Propagation

Basic EM wave properties

- 3.1 Absorption Wikipedia
- 3.2 Amplitude Wikipedia
- 3.3 Attenuation Wikipedia
- 3.4 Diffraction Wikipedia
- 3.5 <u>Dispersion</u> Wikipedia | <u>Dispersion</u> Param Himalaya
- 3.6 Fading / Shadowing Wikipedia
- 3.7 Electric field ₽

- 3.8 <u>Electromagnetic field</u> Wikipedia
 3.9 <u>Electromagnetic radiation</u> Wikipedia
- 3.10 Field intensity | Field strength Wikipedia | Signal strength in telecommunications Wikipedia
- 3.11 Frequency Wikipedia
- 3.12 Path Attenuation—Path Loss Wikipedia
- 3.13 Polarization Wikipedia
- 3.14 Power Density Wikipedia
- 3.15 Radio Propagation ₽ (see below)
- 3.16 Ray (optics) Wikipedia
- 3.17 Reflection of EM waves Wikipedia
- 3.18 Refraction | Refractive index Wikipedia
- 3.19 <u>Scattering</u> Wikipedia
- 3.20 Spectrum -
- 3.21 Standing wave Wikipedia
- 3.22 <u>Wave interference</u> | <u>Electromagnetic interference</u> | <u>Interference (communication)</u> Wikipedia
- 3.23 Wave Behaviors NASA Science
- 3.24 Wavefront Wikipedia
- 3.25 Wavelength Wikipedia

Electromagnetic Spectrum

- 3.26 The <u>Electromagnetic Spectrum</u> spans from 3 Hz (<u>Radio Waves</u>) to 3x10²⁴ Hz (<u>Gama rays</u>) Wikipedia
- 3.27 The entire <u>radio spectrum</u> spans from 3 Hz to 3x10¹² Hz (100,000 km to 1 mm) Wikipedia
- 3.28 <u>High Frequency</u> (HF) 3–30 megahertz (MHz) ^{Wikipedia} | The <u>shortwave radio</u> spans from 3 MHz to 30 MHz (100 m to 10 m) ^{Wikipedia}

Radio Propagation

- 3.29 <u>Basic Radio Wave Propagation</u> (PPt Presentation) Nor Hadzfizah Mohd Radi
- 3.30 Introduction to RF Propagation John S. Seybold
- 3.31 Radio EM Wave Reflection Electronics-Notes, Ian Poole

- 3.32 Radio Propagation Tutorial Basics Electronics-Notes, lan Poole
- 3.33 Radio Propagation from Extremely Low Frequency (ELF) to Far infrared (FIR) Wikipedia
- 3.34 Radio Wave Propagation Fundamentals Chapter 2 KIT.edu

Propagation Modes

- 3.35 <u>Line-of-sight propagation</u> (LOS) Wikipedia
- 3.36 Non line-of-sight propagation Wikipedia

Ground Wave

- 3.37 Ground Wave Propagation Wikipedia
- 3.38 Ground Wave Propagation Tutorial Electronics-Notes, Ian Poole
- 3.39 <u>Ground wave MF and HF propagation</u> ASWFC Part of key topics within ionospheric HF propagation
- 3.40 Ground Wave Propagation (Tutorial) BYJU'S Tuition Center
- 3.41 Skip zone Wikipedia

Skywave / Skip

- 3.42 Skywave or Skip Propagation Wikipedia
- 3.43 <u>Skywaves & Skip Zone</u> Electronics-Notes, lan Poole Key topics within ionospheric HF propagation
- 3.44 Path length and hop length for HF sky wave and transmitting angle ASWFC

Skywave Propagation Tutorials

- 3.45 <u>HF Propagation Tutorials & Plates</u> Hamwaves Serge Stroobandt, ON4AA
- 3.46 Critical frequency Wikipedia
- 3.47 <u>Ionospheric Radio Propagation</u> A youtube playlist ^{Doron, 4X4XM}

Skywave Propagation Overviews

- 3.48 The Rebirth of HF Rohde & Schwarz
- 3.49 Course Overview: <u>Atmospheric Effects on Electromagnetic Systems</u> Naval Postgraduate School

- 3.50 All-In-One Overview: <u>There is nothing magic about propagation</u> José Nunes CT1BOH (2021)
- 3.51 Overview: <u>Understanding HF / VHF / UHF / SHF Propagation</u> (PDF) Paul L Herrman N0NBH
- 3.52 <u>High Frequency Communications An Introductory Overview Who, What, and Why?</u> Bill Foose at HIARC meeting
- 3.53 Propagation of Radio Waves Basu, VU2NSB principles and methods

Complex Propagation modes

- 3.54 <u>Complex propagation modes of HF sky wave</u> <u>ASWFC</u>
- 3.55 Atmospheric Ducting Wikipedia
- 3.56 <u>Tropospheric Ducting</u> Wikipedia

4. Propagation via the ionosphere 🖈

<u>Propagation</u> ► <u>Refractive Index</u> ► <u>Ionospheric Intro</u> ► <u>Model</u> ► <u>Regions</u> ► <u>MUF-OWF-LUF</u> ► <u>Seasonal & Anomalies</u> ► <u>Ionosphere Probing</u>

Ionospheric Propagation

- 4.1 An introduction to HF propagation (2022) Sean D. Gilbert Mipre, G4UCJ
- 4.2 <u>An Introduction to HF propagation and the Ionosphere</u> (1999 2009) ^{Murray} Greenman, ZL1BPU
- 4.3 <u>HF Progagation: The Basics</u> QST, December 1983 Denis J. Lusis, W1JL/DL
- 4.4 <u>lonization</u> (basics) Wikipedia
- 4.5 <u>Ionosphere & Radiowave Propagation</u> Electronics-Notes, Ian Poole
- 4.6 Introduction to <u>Ionospheric HF Radio Propagation ASWFC</u>
- 4.7 <u>Ionospheric propagation Ba</u>sics Electronics-Notes, Ian Poole
- 4.8 <u>Introduction to HF Propagation</u> (2018) Rick Fletcher, W7YP
- 4.9 <u>Ionospheric Propagation</u> University of Toronto
- 4.10 <u>Is HF propagation reciprocal?</u> (2006) Tomas Hood, NW7US, HFRadio.org
- 4.11 Propagation of radio waves explained Jean-Paul Suijs, PA9X
- 4.12 <u>Radio Propagation 101</u> Why should you be interested in propagation? ▶ Dan Vanevenhoven
- 4.13 Regional and Long Distance Skywave Communications Ken Larson, KJ6RZ
- 4.14 The HF Bands for Newcomers (An Overview), ARRL (2007) Gary Wescom, N0GW
- 4.16 The Ionosphere Part 2 ► (E region is critical to 50–144 MHz) Aug 2024 Andrew McColm, VK3FS
- 4.17 <u>The Ionosphere, Shortwave Radio, and Propagation</u> MIT Film & Video Production club
- 4.18 <u>The Effects Of The Ionosphere On Radio Wave Propagation</u> An Excellent Presentation made more than 86 years ago!!! Art Bodger
- 4.19 <u>Transequatorial Radio Propagation</u> CO8TW
- 4.21 <u>Understanding HF Propagation</u> Steve Nicols, G0KYA, RSGB
- 4.22 <u>Ward Silver On Radio Wave Propagation</u> Ham Radio Crash Course

Ionospheric Research

- 4.23 Welcome to the lonosphere NASA Goddard
- 4.24 <u>Ten Things to Know About the Ionosphere NASA</u>

Ionospheric Refractions

- 4.25 Refractive index (Optics) Wikipedia The refractive index of the ionosphere
- 4.26 Refractive Index of Ionosphere Calculator Calculator A to Z
- 4.27 <u>Birefringence</u> (Optics) Wikipedia Double refraction due to unisotropic ionosphere 1.
- 4.28 The refractive index and the absorption index of the ionosphere Research notes
- 4.29 <u>Ionosphere and Radio Communication</u> Saradi Bora, Kamalabaria College, North Lakhimpur, Assam, India

The ionospheric refractive index P.126

- 4.30 Refractive index of ionosphere Plasma Physics
- 4.31 <u>Ionospheric Radio Wave Propagation</u> Richard Fitzpatrick, University of Texas at Austin
- 4.32 <u>The Complex Refractive Index of the Earth's Atmosphere and Ionosphere</u> Ernest K. Smith, University of Colorado

Ionospheric Plasma

- 4.33 Plasma (basics) Wikipedia
- 4.34 Collisionless Plasmas Science Direct
- 4.35 Plasma recombination Wikipedia

Basic Ionospheric model

4.36 <u>lonosphere</u> (overview) Wikipedia

The section titled "<u>Layers of ionization</u>" should be replaced with "Regions of ionization" and it needs additional citations for verification, as explained <u>here</u>.

- 4.37 Introduction to the ionosphere Anita Aikio. Dept. Physics, University of Oulu, Finland
- 4.38 <u>Ionospheric Radio</u> (book 1990) ^{Kenneth Davies}

Additional lonospheric models

ITU, URSI, Google search | IRI model | Neural network model | ITM Processes | Advanced Ionospheric Models

Ionospheric Regions

- 4.39 A clarification: Region vs. Layer: Earth's Atmosphere and Ionosphere
- 4.40 <u>The lonosphere</u> 2014 ^{UCAR}
- 4.41 Mesopause Wikipedia
- 4.42 <u>Distribution of ionospheric free-electrons</u> Bob Brown, NM7M (<u>SK</u>), Ph.D.
- 4.43 The Ionosphere and the Sun Naval Postgraduate School

- 4.44 <u>Ionospheric D, E, F, F₁, F₂ Regions</u> Electronics-Notes, Ian Poole
- 4.45 Ionospheric D-region Britannica
- 4.46 Sporadic E propagation Wikipedia
- 4.47 <u>Sporadic E Propagation in 2 minutes</u> ► Andrew McColm, VK3FS
- 4.48 Sporadic E Propagation ► Andrew McColm, VK3FS
- 4.49 <u>Sporadic E propagation (E_s)</u> Andrew McColm, VK3FS
- 4.50 <u>Understanding Sporadic E Propagation for VHF DX</u> Ham Radio DX
- 4.51 <u>Understanding Sporadic E</u> Rohde Schwarz

MUF, OWF, and LUF - Explanation of the concepts; see below How is MUF determined?

- 4.52 <u>HF Radiation Choosing the Right Frequency</u> Naval Postgraduate School (NPS)
- 4.53 <u>MUF Maximum usable frequency Wikipedia</u>
- 4.54 FOT Frequency of optimum transmission Wikipedia
- 4.55 <u>LUF</u> Lowest usable high frequency Wikipedia
- 4.56 <u>Critical frequency, MUF, OWF, and LUF</u> Electronics-Notes, Ian Poole
- 4.57 How to use Ionospheric Propagation? Electronics-Notes, Ian Poole

Ionospheric variations

- 4.58 <u>Sunspot Number and critical frequencies and Time</u> (Years and Seasons) <u>ASWFC</u>
- 4.59 <u>Season Rollover Why do shortwave frequencies have to change?</u> Neale Bateman, BBC
- 4.60 The Seasonal Behavior of the Refractive Index of the Ionosphere over the Equatorial Region Turkish Journal of Science & Technology

Ionospheric anomalies

- 4.61 Persistent anomalies to the idealized ionospheric model Wikipedia
- 4.62 <u>Effect of Seasonal Anomaly or Winter on The Refractive Index of in Height of The</u>

 <u>lonospheric F2-Peak</u> International Journal of Basic & Applied Sciences
- 4.63 <u>Major upwelling and overturning in the mid-latitude F region ionosphere</u> David Hysell et all, Nature

See complementary references on plasma bubbles/clouds and Spread F of skywaves.

Ionospheric Disturbances 1

- 4.64 <u>Sudden Ionospheric Disturbance</u> (SID) Wikipedia
- 4.65 <u>Sudden Ionospheric Disturbance (SID)</u> Draft: WFD (23 March 2014) William Denig, National Centers for Environmental Information-NOAA
- 4.66 <u>Sudden Ionospheric Disturbances</u> An overview National Centers for Environmental Information-NOAA
- 4.67 Sudden Ionospheric Disturbances (SIDs)
- 4.68 <u>Travelling Ionospheric Disturbances</u> (TIDs), <u>ASWFC</u>
- 4.69 <u>Ionospheric Density Irregularities, Turbulence, and Wave Disturbances during the</u>
 <u>Solar Eclipse</u> (2017) Rezy Pradipta, Endawoke Yizengaw, and Patricia H. Doherty
- 4.70 <u>Modeling Amateur Radio Soundings of the Ionospheric Response to the 2017</u>

 <u>Great American Eclipse</u> Nathaniel A. Frissell, W2NAF et al.

Ionospheric Storms 1

4.71 Ionospheric storm Wikipedia

Polar Cap Absorption

- 4.72 Polar Cap Absorption (PCA) events Explanation ASWFC
- 4.73 Polar Cap Absorption Report ASWFC
- 4.74 <u>Polar Cap Absorption Events Massive Short Wave Communications Blackouts</u>
 Windows 2 Universe
- 4.75 What is a Polar Cap Absorption event and what signals are affected by this Official SWL channel
- 4.76 <u>Detailed explanation of modelling absorption due to polar cap absorption and</u> <u>shortwave fadeout</u> (2020, Geological Survey of Canada) R.A.D. Fiori
- 4.77 Effects of polar cap absorption events on geostationary satellite VHF communications systems (1970, NOAA) Pope, Joseph Horace, Leinbach, H.
- 4.78 The Polar Cap Absorption Effects (1962, SAO NASA) D.C. Rose, Syed Ziauddin

Ionosphere Probing Basics

- 4.79 Radio Techniques for Probing the Terrestrial Ionosphere (book 1989) R.D. Hunsucker
- 4.80 <u>Introduction To Ionospheric Sounding</u> (2006) Bruce Keevers, National Geophysical Data Center, NOAA

Applied Ionospheric Probing Techniques <u>lonosondes</u> | <u>lonograms</u> | <u>Stations</u> | <u>Charts</u>

4.81 <u>Chirp</u>ing Explained - <u>Passive Ionospheric Sounding and Ranging</u> Peter Martinez, G3PLX

- 4.82 Chirp reception and interpretation (2013) Pieter-Tjerk de Boer, PA3FWM
- 4.83 <u>Software-Defined Radio Ionospheric Chirpsounder For Hf Propagation Analysis</u> (2010) Nagaraju, Melodia (NYSU); Koski (Harris Corporation)
- 4.84 <u>Small Form Factor Ionosonde Antenna Development</u> (2014) Tyler Erjavec, The Ohio State University

Ionosondes 1

- 4.85 <u>Ionosonde</u> Wikipedia
- 4.86 <u>Introduction to Ionospheric Sounding for Hams</u> Dr. Terry Bullett. W0ASP University of Colorado
- 4.87 Ionosonde HF Underground

Ionograms 1

- 4.88 <u>Ionogram</u> Wikipedia
- 4.89 <u>Understanding HF Propagation and Reading Ionograms</u> Description Bootstrap Workbench
- 4.90 <u>Ionogram Information</u> Hamwaves Serge Stroobandt, ON4AA
- 4.91 <u>Digisonde Directogram UMass Lowell Space Science Lab website, MA, US</u>
- 4.92 Mirrion 2 Real Time Ionosonde Data Mirror NCEI, NOAA
- 4.93 Ionogram Data Info GIRO, UML
- 4.94 <u>The Defence Science and Technology Group High-Fidelity, Multichannel Oblique</u> <u>Incidence Ionosonde</u> (2018) DOI AGU

Global Ionosphere Radio Observatory (GIRO)

- 4.95 <u>Station map</u> | <u>Station list</u> | <u>Fast Station List</u> | <u>Calendar list</u> | <u>Ionogram-Scaled</u> Characteristics GIRO
- 4.96 <u>Station Map: Global Digisonde Stations</u> Lowell Digisonde International (LDI)
- 4.97 DIGISONDE®: Simultaneous Ionospheric Observations Around The Globe LDI

Probing ionospheric disturbances by Auroral Radar Network 1

- 4.98 Super Dual Auroral Radar Network (SuperDARN) Wikipedia
- 4.99 Super Dual Auroral Radar Network (SuperDARN) JHU/APL
- 4.100 <u>First Observations of LSTID Using Automated Amateur Radio Receiving Networks</u> (2022) Nathaniel A. Frissell, W2NAF et al.

- 5. **NVIS** a unique mode of a skywave: real-time map **1**, explanation **1**
 - 5.1 <u>Understanding NVIS</u> Rohde Schwarz
 - 5.2 HF NVIS Military HF Radio
 - 5.3 NVIS Wikipedia
 - 5.4 <u>NVIS Propagation: Near Vertical Incidence Sky</u>wave Electronics-Notes, Ian Poole
 - 5.5 <u>Near-Vertical Incidence Sky-Wave Propagation</u> 36 pages Presentation for radio hams Gerald Schuler, DU1GS / DL3KGS
 - 5.6 Near Vertical Incidence Skywave (NVIS) W8BYH, Fayette ARES
 - 5.7 Near Vertical incidence Skywave Propagation NVIS Antennas ▶ 80, 60, 40m bands KB9VBR Antennas
 - 5.8 NVIS Overview David Casler, KE0OG
 - 5.9 <u>Ham Radio NVIS for Regional Communications</u> ▶ Radio Prepper
 - 5.10 NVIS Near Vertical Incidence Skywave What is it? advantages; antennas; links Jim Glover, KX0U (ex WB5UDE)
 - 5.11 Near Vertical Incidence Skywave (NVIS) Ham Radio School, WØSTU
 - 5.12 NVIS propagation Dave Lawrence, VA3ORP (2007)
 - 5.13 NVIS explained part 1, part 2, part 3 NCSCOUT —NVIS explained citing these 3-parts publication AmrRON
 - 5.14 NVIS Antennas Dale Hunt, WB6BYU

NVIS Extended Research Papers

- 5.15 <u>Radio communication via NVIS propagation: an overview</u> Telecom Sys (2017) DOI, Ben A. Witvliet, Rosa Ma Alsina-Pagès
- 5.16 <u>Analysis of the Ordinary and Extraordinary Ionospheric Modes for NVIS Digital</u>
 <u>Communications Channels</u> Sensors (Basel)
- 5.17 NVIS HF signal propagation in ionosphere using calculus of variations Geodesy and Geodynamics, Umut Sezen, Feza Arikan, Orhan Arikan

- 6.1 An introduction to gray-line DXing Rob Kalmeije
- 6.2 <u>Grey Line HF Radio Propagation</u> Electronic Notes
- 6.3 Grey line Map Doug Brandon, N6RT @ DX QSL Net
- 6.4 Gray line Map DXFUN
- 6.5 Gray line Propagation GOKYA
- 6.6 <u>Gray-line Propagation Explained</u> Padio Hobbyist

6.7 <u>Identifying Gray-Line Propagation Openings DXLab</u>

7. Propagation Indices (Indexes) include Solar Indices and Geomagnetic Indices

They are used as indicators of Global Propagation Conditions

- 7.1 <u>Beginner's Guide for Radio Propagation Indexes</u> May 2024 ^{Greg Lane, N4KGL}
- 7.2 <u>Beginners Guide to Propagation Forecasting</u> Ed Poccia, KC2LM
- 7.3 <u>Circular of Basic Indices for Ionospheric Propagation ITU</u>
- 7.4 Global Indices Glossary of Terms HamQSL, Paul L Herrman, N0NBH
- 7.5 Making sense of Solar Indices Andrew McColm, VK3FS
- 7.6 Quick Guide to HF Propagation Using Solar Indices W2VTM; N2LVI

 Quick Guide to HF Propagation Using Solar Indices Kingsport amateur Radio Club 2020
- 7.7 <u>Understanding HF propagation reports</u> Amateur Radio views and reviews for Beginners Rich, VE2XIP
- 7.8 What are Solar Flux, Ap, and Kp Indices? Andrew McColm, VK3FS
- 7.9 What exactly are the key Indicies? Andrew McColm, VK3FS

Focus on Solar Indices

- 7.10 Solar Index and Propagation Made Easy HF Ham Radio Jan 2021 TheSmokinApe, Steve E McGrane, KT0ADS, Luck WI
- 7.11 Solar induced indices: SFI, SN, A, K, Kp Electronics-Notes, Ian Poole
- 7.12 The history of the 10.7 cm solar flux Government of Canada
- 7.13 The 10.7 cm solar radio flux K. F. Tapping, AGU
- 7.14 Penticton/Ottawa 2,800 MHz Solar Flux NOAA

Focus on Geomagnetic Indices

- 7.15 Planetary K-index NOAA / NWS Space Weather Prediction Center
- 7.16 K-index Definition & Detailed Explanation Sentinel Mission
- 7.17 K-index Wikipedia
- 7.18 <u>Hp30 and Hp60 vs. Kp index</u> GFZ (German Research Center for Geosciences)

<u>Terrestrial</u> | <u>Solar</u> ► <u>Space weather</u> ► <u>TEC</u> ► <u>MUF</u> ► <u>Propagation Charts</u>

Current Geomagnetic Activity measured by terrestrial magnetometer stations

- 8.1 <u>US Geomagnetic Observatories</u> U.S. Geological Survey (USGS)
- 8.2 <u>Current Global Geomagnetic Activity</u> British Geological Survey
- 8.3 Recent 7 days: K and A indices by station NOAA
- 8.4 <u>K-index distribution —low, middle and high latitude</u> Space Weather Live
- 8.5 The Kp index Space Weather Live

Earth Observations

- 8.6 <u>Deep Space Climate Observatory Wikipedia</u>
- 8.7 DSCOVR: Deep Space Climate Observatory NOAA
- 8.8 Deep Space Climate Observatory (DSCOVR) NASA
- 8.9 <u>DSCOVR: Earth Polychromatic Imaging Camera (EPIC)</u> NASA

Solar Observations

- 8.10 Views of the Sun taken by SOHO at EUV wavelengths
- 8.11 Solar Flare Activity Explained ASWFC
- 8.12 Solar Flare Forecast ASWAS: Australian Space Weather Alert System
- 8.13 <u>CME Corona Mass Ejection</u>, monitored by <u>LASCO Chronograph</u> <u>NOAA SWPC</u>
- 8.14 <u>Current Solar Images</u> Solar Data Analysis Center (SDAC), NASA Goddard Space Flight Center
- 8.15 <u>Current Sunspot Regions</u> Space Weather Live Belgium
- 8.16 <u>Solar Data Analysis Center</u> serves Solar Images, Solar News, Solar Data, and Solar Research NASA
- 8.17 <u>Solar Resource Page</u> Mark A. Downing, WM7D
- 8.18 Yohkoh Soft X-Ray Telescope (1991-2001) Wikipedia

SDO

- 8.19 SDO Mission NASA The Solar Dynamics Observatory
- 8.20 SDO guide NASA
- 8.21 Highlights From SDO's 10 Years of Solar Observation NASA
- 8.22 The Active Sun from SDO: 30.4 nm NASA The Solar Dynamics Observatory

- 8.23 <u>Solar Demon Flare Detection</u> running in real time on SDO/AIA Royal Observatory of Belgium
- 8.24 Sun In Time AIA (Atmospheric Imaging Assembly), relays SDO images courtesy of NASA
- 8.25 <u>EVE Overview</u> Solar Phys. The Solar Dynamics Observatory
 The EVE project (real-time high-resolution EUV measurements) was designed to improve understanding of the evolution of solar flares and extend the related mathematical models. used to analyze solar flare events.
- 8.26 <u>Solar UV and X-ray spectral diagnostics</u> Giulio Del Zanna, Helen E. Mason Living Reviews in Solar Physics (2018) 15:5

Solar storms and space weather

8.27 **Dr. Tamitha Skov - Space Weather Woman**; <u>Wikipedia</u>, <u>Youtube channel</u>, facebook, Homesite

Dr. Tamitha Skov is a space weather physicist that reviews solar storms and anlyzes how they affect spacewetaher. She specializes in forecasting and analyzing space weather processes in the heliosphere and exosphere. Her work extends to both traditional media and social platforms. As a credentialed space weather forecaster, she helps the public understand the effects of space weather.

8.28 Monitor Solar Active Regions - search by date Peter Thomas Gallagher, Irland

Space Weather Observations

- 8.29 <u>Current Space Weather Parameters</u> Online report updated every 2 minutes ^{Solar}
 Terrestrial Dispatch
 Solar Wind, X-ray flares, Auroral Storm Potential, Current Magnetic Indices
- 8.30 R6 Army MARS: Consolidated Solar Weather—Real-time Terrestrial indices (D-Rap, Kp and GOES)—Online report Region 6 Army MARS
- 8.31 ACE Solar Wind in the last 24 hours—Online report ACE-NOAA SWPC

Solar wind (particles reaching Earth measured by ACE and GOES)

- 8.32 GOES: Geostationary Operational Environmental Satellite Wikipedia
- 8.33 GOES: Geostationary Operational Environmental Satellite Network NASA
- 8.34 Solar Proton Flux from 6 hours to 7 days GOES—NOAA SWPC
- 8.35 Near-Earth solar wind forecast (EUHFORIA) provided by ESA
- 8.36 Real-time forecast of Solar Energetic Proton Events Prof. Dr. Marlon Núñez (Universidad de Málaga, Spain)
- 8.37 <u>Forecasting Solar Energetic Proton events (E > 10 MeV)</u> Prof. Dr. Marlon Núñez (Universidad de Málaga, Spain)

Solar wind Magnetospheric Multiscale (MMS)

Four Magnetospheric Multiscale (MMS) spacecraft, flying in a tetrahedral formation, detect charged particles and magnetic fields in space, helping scientists understand how the solar wind interacts with Earth's magnetosphere. This mission, involving Rice University, studies magnetic reconnection, acceleration, and turbulence in space.

- 8.38 <u>Magnetospheric Multi Scale (MMS)</u> See also the <u>index of /spw/realtime</u> Rice University
- 8.39 Magnetic reconnection Wikipedia
- 8.40 <u>Magnetospheric Multiscale (MMS) Mission</u> National Aeronautics and Space Administration (NASA), Goddard Space Flight Center
- 8.41 <u>Magnetospheric Multiscale Mission</u> Wikipedia

Index of NOAA images

8.42 <u>Space weather prediction center: index of images</u> NOAA

Recent Days Geomagnetic Indices

- 8.43 Recent 3 days: X-ray, proton flux, and geomagnetic activity NOAA
- 8.44 <u>Latest events</u> (recent Solar Watch) GOES ^{Lockheed Martin Solar & Astrophysics Laboratory (LMSAL)}

X-Ray flares—EM Radiation

- 8.45 Space Weather Alerts, Watches and Warnings SWPC, NOAA
- 8.46 Recent GOES X-ray Flux up to 3 days GOES, NOAA SWPC
- 8.47 Recent flare @ 13.1 nm wavelength NOAA SWPC
- 8.48 Solar and Heliospheric Observatory SOHO ESA & NASA
- 8.49 Extreme ultraviolet Imaging Telescope (EIT) aboard SOHO Wikipedia
- 8.50 <u>X-Ray Flares</u> review of the last 3 days from SDO, SOHO, GOES, and STEREO Relayed by Spaceweather-live, Belgium

Recent month solar observations

- 8.51 Recent Month Sunspot Number SILSO, Royal Observatory of Belgium
- 8.52 Recent Month <u>Daily Sunspot Number</u> MET Malaysia
- 8.53 Recent Month Solar Activity Plot Australian Space Weather Service
- 8.54 Recent month <u>Solar and geomagnetic data</u>—Table copied from Institute of Ionosphere, Kazakhstan ^{Solen-Jan Alvestad}

Reviews and comparisons of past Solar observations

- 8.55 May 2024 Solar storms Wikipedia
- 8.56 Geomagnetic storms May 2024 Duckduckgo
- 8.57 Solar Terrestrial Activity Reports Solen-Jan Alvestad
- 8.58 What does the sun's X-ray flux tell us? Earthsky
- 8.59 The aurora and solar activity archive (select month and year) Space Weather Live
- 8.60 RHESSI: The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is a retired project that watched solar flares daily from 2002 to 2023. NASA
- 8.61 Notable "List of solar storms" Wikipedia

Real-time **TEC** - Total Electron Content (calculated)

- 8.62 Total Electron Content (TEC) Wikipedia
- 8.63 TEC Recent theories, methods and models
- 8.64 Near-real-time TEC maps ESA Europen Space Weather Service
- 8.65 Animated TEC maps Roland Gafner, HB9VQQ
- 8.66 TEC at Ionosphere Monitoring and Prediction Center ESA
- 8.67 <u>One-hour Forecast Global TEC Map</u> DLR (ESA)
- 8.68 Station list DLR (ESA)
- 8.69 Archive of TEC DLR (ESA)
- 8.70 North American TEC NOAA
- 8.71 Near real-time global TEC Map ASWFC
- 8.72 Global Ionosphere Map (GIM) SpringerLink

Real-time lonograms

- 8.73 Recent ionograms (Cyprus) University of Twente, Enschede, Netherlands
- 8.74 Animated ionograms Latest 24-Hour GIRO
- 8.75 <u>lonosonde stations connected to NOAA</u> NGDC, NOAA
- 8.76 Real-time ionogram near your location Hamwaves Serge Stroobandt, ON4AA

Real-time MUF estimations using ionograms at different locations

8.77 <u>Ionosonde station list</u> UML - University of Massachusetts Lowell

- 8.78 GIRO Instrumentaion GIRO, UML
- 8.79 About GIRO UML, Center for Atmospheric Research
- 8.80 Real-time foF2 Plots for Today, Yesterday and the past 5 days (more than 100 links to Inonosonde stations) NOAA

HF Propagation Charts from Critical Frequency Data

- 8.81 <u>Current foF2 (NVIS) Propagation Map</u>, updated every 15 minutes <u>Andrew D Rodland</u>, <u>KC2G</u>
- 8.82 <u>Current MUF 3000 km propagation map</u>, updated every 15 minutes <u>Andrew D</u> Rodland, KC2G
- 8.83 <u>Ionospheric Maps Current foF2 Plots</u> (Global) ASWFC
- 8.84 <u>Hourly Area Predictions (HAP)</u> Charts of selected regions <u>ASWFC</u>
- 8.85 <u>Current f_oF2 Plots</u> (Asia & Australia) <u>ASWFC</u>
- 8.86 <u>Amateur Radio Usable HF Frequencies & Forecast</u> refreshed every 20 minutes Remarkable Technologies, Inc.
- 8.87 Global HF Propagation Andy Smith, G7IZU

9. 🖺 Solar Phenomena 🛊

Solar Radiation

- 9.1 Sunlight Wikipedia
- 9.2 <u>Extreme Ultraviolet</u> (EUV) Wikipedia
- 9.3 Solar irradiance Wikipedia

Solar Physics

- 9.4 Solar Physics (Heliophysics) Youtube playlist
- 9.5 <u>Heliophysics</u> Wikipedia
- 9.6 Heliophysics NASA
- 9.7 <u>Heliophysics and amateur radio: citizen science collaborations . . .</u> Nathaniel A. Frissell, W2NAF et al.
- 9.8 <u>Heliosphere</u> Wikipedia
- 9.9 Exosphere Wikipedia
- 9.10 Chromosphere Wikipedia
- 9.11 Solar transition region Wikipedia
- 9.12 Transition region NASA

Solar Wind

- 9.13 <u>Solar Wind Phenomena</u> NOAA
- 9.14 Solar Wind Wikipedia

Active Sun

- 9.15 Overview of <u>Solar phenomena</u> Wikipedia Sunspots (Solar Cycle), flux (SF), solar wind, particle events, flares, CME
- 9.16 Links to types of Solar storms Wikipedia

Sunspots 1

- 9.17 Sunspots Wikipedia
- 9.18 Sunspot Number ASWFC
- 9.19 The Lifetime of a Sunspot Group ASWFC
- 9.20 <u>Effective sunspot number: A tool for ionospheric mapping and modelling</u> URSI General Assembly 2008

Coronal Holes

- 9.21 <u>Coronal hol</u>e Wikipedia
- 9.22 Coronal Holes NOAA
- 9.23 What is a Coronal Hole? ASWFC

Solar Cycle 1

- 9.24 <u>Carrington Event Wikipedia</u>
- 9.25 Solar Cycle Wikipedia
- 9.26 Solar Cycle ASWFC
- 9.27 <u>Solar Cycle Progression</u> NOAA
- 9.28 Solar maximum Wikipedia
- 9.29 Solar minimum Wikipedia
- 9.30 Progression of solar cycle 25 Helio4Cast
- 9.31 <u>Sunspot number series: latest update</u> SILSO, Royal Observatory of Belgium
- 9.32 <u>The Sun Has Reached the Solar Maximum Period</u> October 15, 2024 NASA's Goddard Space Flight Center
- 9.33 North-South Asymetry of Monthly Hemispheric Sunspot Numbers SILSO, Royal Observatory of Belgium
- 9.34 <u>Understanding the Magnetic Sun NASA</u>

The Solar Dynamo

- 9.35 <u>The solar dynamo begins near the surface</u> 22 May 2024 Nature by Geoffrey M. Vasil et al
- 9.36 Evolution of Solar and Stellar Dynamo Theory. Paul Charbonneau & Dmitry Sokoloff @ Space Science Reviews, Springer 2023
- 9.37 An overlooked piece of the solar dynamo puzzle 2019 HZDR
- 9.38 The Solar Dynamo: The Physical Basis of the Solar Cycle and the Sun's Magnetic Field 2017 Credible Hulk
- 9.39 The Solar Dynamo: Toroidal and Radial Magnetic Fields 2008 NASA
- 9.40 The Solar Dynamo: Plasma Flows Tom Bridgman @ NASA, August 19, 2008
- 9.41 The Sun as a Dynamo High Altitude Observatory @ NCAR (2001-2008)

Solar Radiation Storms 1

Solar X-ray Flares 1

9.42 <u>Classification of X-ray solar flares</u> or solar flare alphabet soup Spaceweather.Com

- 9.43 Radio blackouts R-scale NOAA
- 9.44 Flare class table ASWFC
- 9.45 Solar flare Wikipedia
- 9.46 Solar flares (radio blackouts) NOAA SWPC
- 9.47 Solar Radiation Storm NOAA SWPC
- 9.48 Solar Radiation Storm Space Weather Live
- 9.49 <u>Understanding how solar flares affect radio communications</u>

 Barrett Communications,

 Australia
- 9.50 <u>Hot-plasma ejections associated with compact-loop solar flares</u> Kazunari Shibata et al. Astrophys. J. Lett. 451 L83 (1995)
- 9.51 <u>X-ray and gamma-ray emission of solar flares</u> 2019 ^{Alexandra Lysenko, Dmitry} Frederiks, Rafail L. Aptekar

Solar Particle Events

- 9.52 Solar Particle Event (SPE) Wikipedia
- 9.53 Solar energetic particles (SEP) Wikipedia
- 9.54 Solar Radiation Stroms S-scale NOAA
- 9.55 <u>Solar Proton Events Affecting the Earth Environment</u>: Historical list, 1976 present NASA
- 9.56 Next-Generation Solar Proton Monitors for Space Weather Eos
- 9.57 The Difference Between CMEs and solar flares NASA

CME 1

- 9.58 What is Coronal Mass Ejection Wikipedia
- 9.59 Coronal Mass Ejections CME NOAA
- 9.60 Coronal mass ejection orientation Google search

Particle Precipitation

- 9.61 Particle Precipitation ScienceDirect
- 9.62 <u>Particle Precipitation in the Earth and Other Planetary Systems: Sources and Impacts Frontiers</u>
- 9.63 <u>Energetic particle precipitation</u> Laboratory for Atmospheric and Space Physics, Univ. of Colorado

Solar Radio Emissions

- 9.64 Solar radio Wikipedia
- 9.65 Radio bursts from the Sun Wikipedia
- 9.66 The Effect of Solar Radio Bursts on GNSS Signals (2022) Xinan Yue et al., Science Direct
- 9.67 <u>Solar radio emission as a disturbance of radio mobile networks</u> at 2.6GHz (June 2022) Giuliano Muratore, Teresa Giannini & Davide Micheli
- 9.68 Solar Radio Burst Statistics and Implications for Space Weather Effects at 8 frequencies:
 - <u>245; 410; 610; 1,415; 2,696; 4,995; 8,800; and 15,400 MHz</u> (2017) O. D. Giersch, J. Kennewell, M. Lynch
- 9.69 Radio 'screams' from the Sun (below 10 MHz) warn of radiation storms (2007) Bill Steigerwald, NASA; Bernhard Fleck; ESA
- 9.70 <u>Distributions of Radio emissions at 245 MHz during flares</u> (2005) Yury Yasyukevich, Researchgate
- 9.71 <u>Multi-wavelength analysis of CME-driven shock and Type II solar radio burst band-</u> <u>splitting</u> (2001) Shirsh Lata Soni, et al
- 9.72 <u>An analysis of solar noise outbursts and their application to space communication</u>
 (1971) Marion Francis Moen

10. Space weather phenomena 1

<u>Definition & concepts | Impact on HF radio Propagation | Geomagnetic storms & Aurora | Prediction</u>

| SID TID | Space Weather Agencies & Services

Space Weather Definition and Concepts

- 10.1 Space Weather Wikipedia
- 10.2 Five Questions About Space Weather and Its Effects on Earth, Answered NASA
- 10.3 What Is Space Weather? NOAA
- 10.4 What is Space Weather? ASWFC
- 10.5 <u>Solar-terrestrial science</u> <u>Canadian Space Agency</u>
- 10.6 <u>Definition of Space Weather</u> Instituto Nacional de Pesquisas Espaciais (INPE), Brazil
- 10.7 Answering five key questions about space weather NASA
- 10.8 Space Weather Naval Postgraduate School
- 10.9 Space Weather Highlights AGU
- 10.10 Space Weather Scales Explanation | PDF format NOAA
- 10.11 The Space Weather Forecast Explained British Geological Survey
- 10.12 <u>Solar storms: a new challenge on the horizon?</u> November 2023 ^{Counsel of the} European Union
- 10.13 A Media Primer for the Solar Cycle and Space Weather NESDIS

The Impact of Space Weather on Radio Communication

- 10.14 Space Weather Indices * Comparison tables * ASWFC
- 10.15 How does Space Weather impact HF radio communication? NOAA
- 10.16 Space Weather and Radio Communications ASWFC
- 10.17 <u>Ionospheric conditions Space Weather</u> Space Weather Canada
- 10.18 <u>Mastering HF Communication: Decoding Space Weather Data</u> August 2023 ^{Chris,} N6CTA

The article explains how radio amateurs can use real-time space weather data to optimize HF communication

- 10.19 The Sun and HF radio propagation Electronic Notes
- 10.20 Space Weather and Propagation (A presentation 2019) Martin Buehring, KB4MG
- 10.21 <u>Solar Activity and HF Propagation</u> (A presentation) Paul Harden, NA5N © QRP-ARCI 2005
- 10.22 <u>Ionospheric Disturbances and Their Impacts on HF Radio Wave Propagation</u> URSI
- 10.23 <u>Effect of magnetic storms (substorms) on HF propagation: A review D. V.</u>
 Blagoveshchenskii

Geomagnetic storms

- 10.24 Geomagnetic storms Wikipedia
- 10.25 Geomagnetic storms NOAA

The Impact of Geomagnetic storms on Radio Communication

- 10.26 Geomagnetic storm G-scale NOAA
- 10.27 Geomagnetic storms Maine Emergency Management Agency
- 10.28 A presentation: Solar Activity and HF Propagation Paul Harden, NA5N © QRP-ARCI 2005

Pages 85-88 focus on the impact of geomagnetic storms on HF propagation

- 10.29 The impact of geomagnetic storms on HF propagation Bing Search
- 10.30 <u>Space weather impact on radio wave propagation</u> Feb 2023 Norbert Jakowski, German Aerospace Center (DLR), Institute for Solar-Terrestrial Physics
- 10.31 <u>Monitoring and forecasting of ionospheric space weather effects of geomagnetic</u> storms 2002 J. Lastovicka, Institute of Atmospheric Physics, Czech Republic
- 10.32 <u>Effect of magnetic storms (substorms) on HF propagation: A review</u> D. V. Blagoveshchenskii, Geomagnetism<u>₽</u> and Aeronomy volume 53, pages 409–423 (July 2013)
- 10.33 Effect of Weak Magnetic Storms on the Propagation of HF Radio Waves Kurkin, V. I. ; Polekh, N. M. ; Zolotukhina, N. A. (Feb 2022)
- 10.34 <u>HF Propagation during geomagnetic storms at a low latitude station</u> Physics & Astronomy International Journal 2020

10.35 <u>Enhanced Trans-Equatorial Propagation following Geomagnetic storms</u> Oliver P. Ferrell, Nature volume 167, pages 811–812 (1951)

Geomagnetic storms dynamics

- 10.36 The Disturbance Storm Time (Dst) Index NOAA
- 10.37 Geomagnetic storm overview Kakioka Magnetic Observatory, Japan
- 10.38 Geomagnetically Induced Currents (GICs) in Equatorial Region Jusoh M. Huzaimy
- 10.39 <u>Evolution and Consequences of Coronal Mass Ejections in the Heliosphere</u> (April 2022) Wageesh Mishra, Insia
 - 9 Different phases of a typical geomagnetic storm are shown. The sudden commencement, initial, main and recovery phases are characterized by a sudden rise, constant, fast decrease, and slow recovery in the horizontal components of Earth's magnetic field, respectively.
- 10.40 <u>Compare Geomagnetic storms during solar maximum vs. solar minimum</u> Finn Soraas
- 10.41 <u>Classifying and bounding geomagnetic storms based on the SYM-H and ASY-H indices</u> (2024) Armando Collado-Villaverde, Pablo Muñoz & Consuelo Cid
- 10.42 <u>Distribution and Recovery Phase of Geomagnetic Storms During Solar Cycles 23</u> and 24 Wageesh Mishra et al
- 10.43 <u>Geomagnetic storm main phase effect on the equatorial ionosphere over Ile–Ife as measured from GPS observations</u> (2020) Ayomide O. Olabode, Emmanuel A. Ariyibi
- 10.44 Book: Ring Current Investigations The Quest for Space Weather Prediction (2020)
 Vania K. Jordanova, Raluca Ilie, Margaret W. Chen

Notable geomagnetic storms

- 10.45 5 geomagnetic storms that reshaped society USGS.gov
- 10.46 <u>High-Frequency Communications Response to Solar Activity in September 2017</u>
 as Observed by Amateur Radio Networks ^{AGU}
- 10.47 <u>Influence of 31 August 1 September, 2019 ionospheric storm on HF 2 radio</u>
 wave propagation Yiyang Luo et al
- 10.48 <u>Strong geomagnetic storm reaches Earth, continues through weekend</u> May 2024 NOAA

Aurora

- 10.49 Aurora Wikipedia
- 10.50 Astronomy Picture of the Day Search Results for "aurora" NASA
- 10.51 Aurora NOAA SWPC
- 10.52 The Science, Beauty, and Mystery of Auroras NOAA SWPC

- 10.53 The Auroral E-region is a Source for Ionospheric Scintillation EOS
- 10.54 <u>Diffuse Auroral Electron and Ion Precipitation Effects on RCM-E Comparisons</u>
 With Satellite Data During the 17 March 2013 Storm
 JGR Space Physics 2019 Chen,
 Lemon, Hecht, Sazykin, Wolf, Boyd, Valek
- 10.55 <u>Impacts of Auroral Precipitation on HF Propagation: A Hypothetical Over-the-Horizon Radar Case Study</u> Joshua J. Ruck, David R. Themens
- 10.56 Auroral Propagation RSGB
- 10.57 Radio Auroras Ham Radio Engineering: GM8JBJ
- 10.58 Aurora Event Propagation Gregory A Sarratt, W4DGH
- 10.59 Using Auroral Propagation for Ham Radio Electronics notes
- 10.60 Auroras & Radio Propagation including Auroral Backscatter Electronics notes
- 10.61 Aurora Prediction North Pole NOAA
- 10.62 Aurora Prediction South Pole NOAA
- 10.63 Tonights Static Viewline Forecast Aurora Prediction North Pole NOAA
- 10.64 Tomorrow Static Viewline Forecast Aurora Prediction North Pole NOAA
- 10.65 3 Day Geomagnetic and Aurora Forecast SolarHam, Kevin, VE3EN
- 10.66 At what Kp index can I see aurora? Doron, 4X4XM
- 10.67 The Magnetosphere Wikipedia
- 10.68 The Magnetosphere Illustration Hamwaves Serge Stroobandt, ON4AA
- 10.69 Magnetospheres NASA

Interplanetary magnetic field

- 10.70 Interplanetary magnetic field IMF Wikipedia
- 10.71 <u>The Interplanetary Magnetic Field (IMF)</u> Sun's magnetic field, B(t)x,y,z, Earth's magnetosphere Space Weather Live
- 10.72 <u>Dynamics of the Interplanetary Gas and Magnetic Fields</u> (1958) Parker, E. N
- 10.73 Relating 27-Day Averages of Solar, Interplanetary Medium Parameters, and Geomagnetic Activity Proxies in Solar Cycle 24 2021
- 10.74 Do Intrinsic Magnetic Fields Protect Planetary Atmospheres from Stellar Winds?
- 10.75 <u>Investigation of the relationship between geomagnetic activity and solar wind</u> parameters based on a novel neural network (potential learning)
- 10.76 <u>Artist's Conception of the Heliospheric Current Sheet</u> (HCS) 1969-1980 ^{Schatten,} Wilcox, Ness, Svalgaard, Hoeksema, and Scherrer
- 10.77 The 3-D Shape of the HCS (1978) Smith, Tsurutani, and Rosenberg
- 10.78 <u>Analysis of the heliospheric current sheet's local structure based on a magnetic model</u> 2022 D. Arrazola, J. J. Blanco and M. A. Hidalgo

10.79 The Schatten current sheet October 2024 Kalman Knizhnik

- 10.80 Gamma-ray burst Wikipedia
 - Gamma-ray bursts are the most intense explosions in the universe, observed in distant galaxies, with longer-lived afterglows and longer wavelengths emitted.
- 10.81 Evidence of an upper ionospheric electric field perturbation correlated with a gamma ray burst (GRB), Mirko Piersanti et al, November 2023

 Analyzing the October 9, 2022, gamma-ray burst (GRB221009A).
- 10.82 <u>Disturbance of Geophysical Fields and the Ionosphere during a Strong</u>

 <u>Geomagnetic Storm on April 23, 2023</u> V. V. Adushkin, A. A. Spivak et al

Correlation between Cosmic rays ₽ and sunspot numbers

- 10.83 Periodic Variations of Cosmic Ray Intensity and Solar Wind Speed to Sunspot

 Numbers (2020) Hindawi Collaborative work
- 10.84 Cosmic Ray Showers (2016) NOAA
- 10.85 Cosmic Rays and the Solar Cycle (2005) University of Delaware

11. 📳 Space weather agencies and their services

Only national agencies that provide worldwide services in English are included.

- 11.1 World Meteorological Organiztion WMO
- 11.2 ISES: The International Space Environment Service; ISES 23 members
- 11.3 A list of 14 International Service Providers NOAA
- 11.4 European Space Agency Space Weather Service (ESA)
- 11.5 **NOAA** Space Weather Prediction Center (SWPC) services:
 - Real-time <u>Space Weather Conditions</u> R-S-G, EUV<u>F</u>, CME, Aurora, <u>GOES</u> Flux (X-Ray, Proton), K-index
 - Index of NOAA SWPC services: products, experimental, images, text data format, and ison data format
 - Solar Wind predicted, 3-hours to 7-days
 - 3 day forecast R, S, G Space Weather Scales
 - Space weather products and data NOAA, SWPC
 - Geophysical Alert Message The next 24 hours based on recent indices; WWV.txt NOAA Alrets
 - National Centers for Environmental Information (NCEI) NOAA
- 11.6 <u>Space Weather Prediction Center</u> (SWPC) Wikipedia
- 11.7 <u>American Commercial Space Weather Association</u> of 19 companies ACSWA
- 11.8 Australian Space Weather Forecasting Centre ASWFC | Alert System 2022
- 11.9 Belgium: Solar Influence Data Analysis Center (SIDC) Royal Observatory of Belgium
- 11.10 Brazil: The Embrace Program Instituto Nacional de Pesquisas Espaciais (INPE), Brazil
- 11.11 Britain: (BGS; MOSWOC; UKMO) Meteorological Office | Geological Survey
- 11.12 Canada: Space Agency (CSA) | Space Weather (SWC)
- 11.13 Chaina: <u>Space Environment Prediction Center</u> (SEPC)—National Space Science Center (NSSC)
- 11.14 Germany: The GFZ German Research Centre for Geosciences GFZ
- 11.15 Japan: <u>Space Weather Forecast</u> National Institute of Information and Communications Technology NICT, ISES, RWC
- 11.16 Korea: Space Weather Center RRA/KSWC
- 11.17 South Africa: National Space Agency (SANSA) SANSA
- 11.18 Taiwan: Space Weather Operational Office Central Weather Administration (CWA)

12. Forecasting and prediction

Forecasting and Prediction of Solar Activity

- 12.1 Predicted long term sunspot number and Radio Flux at 10.7 cm NOAA / NWS Space
 Weather Prediction Center
- 12.2 27-Day Outlook of 10.7 cm Sun Radio Flux and the Earth Geomagnetic Indices
- 12.3 Solar Flare Forecast ASWFC
- 12.4 Solar flare probabilities SolarHam, Kevin, VE3EN
- 12.5 Solar Synoptic Map NOAA
- 12.6 Weekly Highlights and Forecasts of Solar and Geomagnetic Activity NOAA
- 12.7 <u>Sun news activity, Solar flare, CME, Aurora EarthSky</u>
- 12.8 Flashes on the Sun Could Help Scientists Predict Solar Flares Jan 17, 2023 NASA
- 12.9 <u>We can now predict dangerous solar flares a day before they happen</u> 30 July 2020 Jonathan O'Callaghan, Newscientist
- 12.10 <u>A tech-destroying solar flare could hit Earth within 100 years</u> 16 October 2017 ^{Leah}
 Crane, Newscientist

Space Weather Prediction

12.11 Space weather: What is it and how is it predicted? SpaceCom

Space Weather Forecasting

- 12.12 Space weather forecast NOAA
- 12.13 Radio Communications Dashboard SWPC NOAA
- 12.14 Past, Current, and 3-day forecast of R-S-G ASWFC
- 12.15 Space Weather Forecast Discussion SWPC NOAA
- 12.16 How to Improve Space Weather Forecasting (2020) Eos, AGU
- 12.17 How to Assess the Quality of Space Weather Forecasts? (2021) Eos, AGU
- 12.18 HF Radio & Space Weather Dashboard Ismael PELLEJERO IBAÑEZ, EA4FSI

Forecast Geomagnetic Activity

12.19 3-Day Geomagnetic Forecast (text) NOAA

12.20 <u>Importance and challenges of geomagnetic storm forecasting</u> Frontiers in Astronomy and Space Sciences

Geomagnetic Warnings and Alerts

- 12.21 Geomagnetic Warning ASWFC
- 12.22 Geomagnetic Alert ASWFC

Low-accuracy Geomagnetic Storm Predictions

- 12.23 Is a solar flare the same thing as a CME? EarthSky
- 12.24 The Difference Between CMEs and solar flares NASA
- 12.25 Solar Storms: Odds, Fractions and Percentages NASA
- 12.26 Near Miss: The Solar Superstorm of July 2012 NASA
- 12.27 <u>It missed us by 9 days</u> 2022 April, 18 Dianna Cowern known as "Physics Girl"
- 12.28 Coronal Mass Ejections: Models and Their Observational Basis P. F. Chen

Blackout and SID

- 12.29 Communications blackout Wikipedia
- 12.30 Radio blackouta R-scale NOAA
- 12.31 The **D-RAP model** | Global D-Region Absorption Prediction Documentation SWPC NOAA
- 12.32 <u>A dynamic collection of propagation information gathered from many different sources</u> <u>Doug Brandon, N6RT</u>
- 12.33 Propagation Links eHam.net Team

Tools and Applications for <u>analysis</u>, <u>prediction</u>, and <u>forecasting</u> HF propagation

Apps Categories: <u>Real-time Activity / Band Monitoring, real-time maps & Charts,</u>
<u>Prediction Software, Mathematical models</u>, etc.

Online tools

Online Activity and Band Monitoring

Gathering information of real-time activity on the <u>ham bands</u>₽

- 13.1 Real-time Ham Band Activity Map Jon Harder, NG0E
- 13.2 <u>Analyzing Propagation From Active DX Stations</u> Band Activity by (1) Time of Day,
 (2) Continent ^{DXLab}
- 13.3 <u>Radio Propagation Maps</u> Based on established contacts; Choose a propagation map from the menu ^{Andy Smith, G7IZU}

Online tools, charts and raw data

- 13.4 Propagation Data and Tools HF Underground
- 13.5 When is the best time to make an HF contact? Propagation Prediction tools

 Ria's Ham Shack, 7 April 2022 Ria Jairam, N2RJ

Real-time HF Propagation Tools

- 13.6 <u>HF-START HF Simulator Targeting of All-users, Regional Telecommunications NICT, Japan</u>
 - HF-START High Frequency Simulator Targeting for All-users' Regional Telecommunications is HF propagation simulator that is developed to meet the needs of space weather users for, but not limit to telecommunications: <u>real-time info</u>, <u>web tools</u>, <u>about</u>
- 13.7 <u>HF Propagation Tools</u> Hamwaves Serge Stroobandt, ON4AA

 Real-time online dashboard of solar activity influencing HF propagation on Earth.
- 13.8 Real-time HF propagation space weather Hamwaves Serge Stroobandt, ON4AA Real-time online dashboard of solar activity influencing HF propagation on Earth.

Propagation Banners

13.9 Add Solar-Terrestrial Data to your Website HamQSL, Paul L Herrman, N0NBH

Real-time Maps & Charts -

- 13.10 MUF 3000 km map based on Real-time measurements Andrew D Rodland, KC2G
 - * Read more about the MUF (3000 km) project
 - * Read a review titled: "<u>Developing an Open-Source HF Propagation Prediction Tool</u>".

Roland Gafner, HB9VQQ, provides an animated map view of the last 24 hours in 15-minute steps.

13.11 HamDXMap for the DXer, radio propagation concepts Christian Furst, F5UII

Forecasting and Prediction Software

Forecasting Software

13.12 <u>An Open-Source IRI-based Nowcasting Tool for Ionospheric Electron Density and HF Propagation Andrew D Rodland (2022 Harvard Abstracts)</u>

An overview of the software and the models behind prop.kc2g.com, a website using the IRI-2016 model, conditioned on near-real-time ionosonde data, to provide global maps of MUF(3000) and foF2. While primarily designed for radio amateur use, this system is useful for nowcasting of F region ionospheric density and mesoscale low elevation HF propagation characteristics.

13.13 The Advanced Stand Alone Prediction System (ASAPS) ASWFC

Australian Space Weather Forecasting Centre offer three software products to predict HF propagation:

- 1. GWPS designed for HF operators working in defence and emergency services
- 2. ASAPS Kernel The Advanced Stand Alone Prediction System designed for government, defence and emergency services
- 3. Consultancies designed for industry, defence and emergency services
- 13.14 S/N HF Propagation Forecast Calculator for the current month DL0NOT

Prediction Software

"Proppy"

- 13.15 Proppy Online HF Propagation Prediction James Watson, M0DNS
- 13.16 Proppy HF Circuit Prediction: NCDXF/IARU Beacons James Watson, M0DNS
- 13.17 <u>Proppy HF Circuit Prediction: RadCom's monthly propagation predictions</u> James Watson, M0DNS

"DR2W"

13.18 <u>DR2W - Predict Propagation Conditions</u> DK9IP (Winfried), DH3WO (Wolfgang), DJ2BQ (Ewald), ZS1AO/DJ2HD (Mathew)

A Long-term forecasting cannot take into account unpredicted ionospheric and magnetic disturbances or anomalies.

"VOACAP"

- 13.19 VOACAP Primer James (Jim) Coleman, KA6A
- 13.20 <u>VOACAP Online Application for Ham Radio</u> <u>Jari Perkiömäki, OH6BG</u> / OG6G

VOACAP forecasts monthly average of the expected reliability with diurnal and seasonal variations.

A Long-term forecasting cannot take into account unpredicted ionospheric and magnetic disturbances or anomalies.

- 13.21 VOACAP Quick Guide Jari Perkiömäki, OH6BG / OG6G
- 13.22 **VOACAP Shortwave Prediction Software** Rob Wagner VK3BVW
- 13.23 How to use VOACAP Part 1: Overview, Part 2, Part 3 Jari OH6BG & OH7BG Raisa
- 13.24 VOACAP DX Charts VOACAP
- 13.25 VOACAP Charts for RadCom VOACAP
- 13.26 RadCom online Propagation Prediction Tools RSGB

"IOCAP"

- 13.27 <u>Ionospheric Characterisation Analysis and Prediction tool (IOCAP)</u> SANSA
- 13.28 IOCAP Application Introduction Video SANSA

The South African National Space Agency (SANSA) created i/o cap Primary Work Surface, an operational HF communication solution.

It's a modern, user-friendly HF frequency prediction tool that's simple to use and accurate. In a software program, it blends space weather research and practical HF experience.

Misc.

13.29 DX Toolbox - Shortwave / Ham Radio / HF Radio Propagation Black Cat Systems

This is a software application that provides a range of tools for HF radio operators, including propagation forecast based on the Solar Terrestrial Dispatch (STL) model. It also includes a real-time solar data display and a gray line map.

- 13.30 HF Propagation (Microsoft Apps) Stefan Heesch, HB9TWS
- 13.31 PROPHF v1.8, HF Propagation predictions Christian, F6GQK
- 13.32 W6ELProp (2002) Sheldon C. Shallon, W6EL

Predicts skywave propagation between any two locations on the earth on frequencies between 3 and 30 MHz

- 13.33 <u>HamCAP</u> (<u>VOACAP</u> interface) by Alex Shovkoplyas, VE3NEA. Rated 8.93 by DxZone
- 13.34 The Propagation Software Pages A collection of links AC6V

HF Propagation Software Review

- 13.35 Review of HF Propagation analysis & prediction programs Research Oriented Luxorion, LX4SKY
 - Amateur propagation programs, accessible via the internet, provide graphical solutions and simulate ionospheric effects using near-real-time data or well-known functions, achieving high accuracy.
- 13.36 <u>Review of Propagation prediction programs VOACAP-based</u> Luxorion, LX4SKY <u>VOACAP</u>, a US government-funded HF propagation prediction engine, has been continuously improved over since the 1980s.
- 13.37 Predicting and Monitoring Propagation DXLab
 - * Solar terminator display and prediction shows gray line at any specified date and time.
 - * Propagation prediction provides a graphical view of openings by frequency and time using your choice of the included <u>VOACAP</u>, <u>ICEPAC</u>, and IONCAP forecasting engines.
- 13.38 PropView DXLab
 - PropView forecasts LUF and MUF between two locations over a 24-hour period using <u>VOACAP</u>, <u>ICEPAC</u>, and IONCAP engines. It can specify locations via latitude/longitude entry or DXCC prefix entry. PropView can build schedules for the IARU/HF beacon network and monitor the NCDXF/IARU International Beacon Network. It interoperates with Commander and DXView for automatic monitoring and location display.
- 13.39 <u>RF prop, Radio Propagation & Diffraction Calculator, W6ELProp, PropView,</u>
 HamCAP DxZone
- 13.40 Radio Propagation Forecasting (2019) Basu, VU2NSB Beacons, VOACAP, CCIR and URSI Models

HFTA - High Frequency Terrain Assessment

- 13.41 <u>Introduction to HFTA High Frequency Terrain Assessment</u> Nashua Area Radio Society, N1FD
- 13.42 Operating Instructions for HFTA, Version 1.04 (2013) ARRL
- 13.43 HF Terrain Analysis Using HFTA (2015) Stan Gibbs, KORV
- 13.44 HFTA and Take Off Angles ~ 01/20/2021 RATPAC Amateur Radio
- 13.45 Maximizing Performance of HF Antennas with Irregular Terrain Jim Breakall, WA3FET
- 13.46 <u>Introduction to HFTA high frequency terrain assessment and more | Request an Azimuthal Map Tom, NS6T</u>

Space weather models

- 13.47 Mathematical Models of Space Weather NASA
- 13.48 Space Weather Modeling Framework (SWMF)

Ionospheric models

13.49 <u>Ionosphere modeling</u> Google Search

- 13.50 HF radio wave propagation ionosphere models Google Search
- 13.51 Semi-Empirical ionosphere models Google Search
- 13.52 Full Wave ionosphere models HF propagation Google Search
- 13.53 Solar activity ionosphere models Google Search
- 13.54 International Reference Ionosphere model (2020) ^{IRI}

 IRI, an international project, established a Working Group in the late 1960s to create an empirical standard model of the ionosphere. It is sponsored by the Committee on Space Research COSPAR and the International Union of Radio Science URSI
- 13.55 <u>The radio refractive index: its formula and refractivity data</u>—including maps (updated May 2016) ITU
- 13.56 <u>Ionospheric Characteristics And Methods Of Basic MUF, Operational MUF AND</u>

 <u>Ray-Path Prediction</u> updated 25 Feb 2004 Recommendation ITU-R P.434-6
- 13.57 <u>HF propagation prediction method</u> updated 11 July 2001 ITU-R P.533 model
- 13.58 <u>Propagation Factors Affecting Frequency Sharing In HF Terrestrial Systems</u> updated 12 Mar 2001 ITU
- 13.59 Global Assimilation of Ionospheric Measurements (GAIM) model
- 13.60 Advanced D region Ionosphere Prediction System (ADIPS)
- 13.61 What can we expect from a HF propagation model? Luxorion, LX4SKY

 Mathematical models and numerical procedures simulate dynamic processes in HF radio propagation, considering interactions between the Sun's and Earth's surfaces, sun, space weather, ionosphere, and atmosphere.

Validation of models

- 13.62 ITU-R Directory (2025) ITU
 - Software, Data and Validation examples for ionospheric and tropospheric radio wave propagation and radio noise
- 13.63 <u>HF Propagation modeling validation for Earth to space transmission by multiple</u>
 bounces links 2021 S. Rougerie et al
- 13.64 <u>Comparison of observed and predicted MUF(3000)F2 in the polar cap region</u> Radio Science AGU (2015)
 - Comparison of ICEPAC, VOACAP, and REC533 models reveal diurnal and seasonal variations. Summer diurnal variation is not represented by the VOACAP or ICEPAC models. REC533 surpasses VOACAP during the winter and equinox months. ICEPAC performs poorly during periods of low solar activity.
- 13.65 <u>Validation of High Frequency (HF) Propagation Prediction Models in the Arctic region</u> 2014 Athieno, R., Jayachandran, P. T.
- 13.66 Evaluation of ICEPAC model for HF propagation prediction 2016 SANSA Space Science

- 13.67 <u>An attempt to validate HF propagation prediction conditions over Sub-Saharan</u>

 <u>Africa</u> 2011 Mpho Tshisaphungo et al
- 13.68 Experimental verification of a generalized multivariate propagation model for ionospheric HF signals 1996 Y. Abramovicht et al

Ray-tracing models

- 13.69 Ray Tracing ionosphere models HF propagation Google Search
- 13.70 <u>VOACAP</u>—Voice of America Coverage Analysis Program is a professional hf system performance prediction tool
 VOACAP predicts monthly average expected reliability, considering diurnal and seasonal variations, but does not account for unpredicted ionospheric and magnetic disturbances or
- 13.71 <u>General information on the ICEPAC propagation prediction model</u> ^{Jari Perkiömäki}, OH6BG
- 13.72 ITUR HF Prop

anomalies.

Prediction of HF circuits based on Recommendation ITU-R P.533 model - an improved (2017) point-to-point propagation prediction tool, based on an ITU engine, developed by Gwyn Williams, G4FKH.

lonospheric models that simulate a neural network

13.73 Neural Network Ionospheric Model (NNIM)

Hybrid ionospheric models

13.74 <u>Application of Machine Learning Techniques to HF Propagation Prediction</u> Richard Buckley, William N. Furman - Rochester, NY

14. Supplementary references

Our hobby

14.1 Amateur Radio Wikipedia

Amateur Radio, also known as *Ham Radio*, is a hobby involving non-commercial communication, wireless experimentation, self-training, private recreation, radiosport, contesting, and emergency communications. This activity utilizes radio transmitters and receivers.

14.2 Radio Amateur Wikipedia

Radio Amateur or Radio Ham is **the person** usually a licensed operator who communicates with other radio amateurs on amateur radio frequencies.

- 14.3 <u>Amateur radio station</u> Wikipedia Read about different types of stations used by amateur radio operators.
- 14.4 <u>History of Amateur Radio</u> Wikipedia
- 14.5 Etymology of ham radio Wikipedia
- 14.6 Why is it called ham radio? Field Radio
- 14.7 <u>Status Summary of Radio Amateurs & Amateur Stations of The World 2000</u> IARU (archived)
- 14.8 Number of radio amateurs by country from 2000 to 2022 ► Ham Radio DX, VK7HH,

 Hayden P Honeywood

 The IARU officially reported worldwide figures for hams in 2000. The statistics for 2022 are an estimate based on a prior pattern of growth.
- 14.9 Shortwave listening (SWL) Wikipedia

The Bands assigned for Radio Amateurs

- 14.10 Nomenclature of the frequency and wavelength bands used in telecommunications (2022) ITU Radiocommunication Bureau
- 14.11 Amateur radio frequency allocations Wikipedia
- 14.12 WARC bands Wikipedia
- 14.13 Authorized frequency bands ARRL
- 14.14 HF bands RSGB
- 14.15 Ham Radio Frequencies The DXZone
- 14.16 Amateur Radio Band Characteristics N4UJW, Ham Universe

Ham radio propagation websites

- 14.17 Historical charts of past events <u>e**SFI** (Solar-flux-index) and e**SSN**(Sunspotnumber) courtesy of Andrew D Rodland, KC2G.</u>
- 14.18 Live Ionospheric Data Paul L. Herrman, N0NBH presented by Meteorscan.com
- 14.19 Current global HF Score HF Activity Group, Tom K5VWZ—Palmetto Tech Network LLC
- 14.20 <u>Sun data and propagation—The last 36 hours—The last 30 days—WSPEnet—DxCluster</u> QRZCQ
- 14.21 Solar Conditions & Ham Radio Propagation (indices) W5MMW
- 14.22 <u>SolarHam—Real-time Space Weather</u>—Latest Solar Imagery and Alerts <u>SolarHam</u>, Kevin, VE3EN
- 14.23 Live Solar Events—Radio Reflection Detection Andy Smith, G7IZU

14.24 <u>The Basics of Radio Wave Propagation</u> Edwin C. Jones, MD, PhD (AE4TM) Knoxville, TN That page provides an overview of radio wave transmission processes, including a glossary of solar and propagation terms.

Communication Modes and Techniques

14.25 List of amateur radio modes Wikipedia

Signal Processing and Communication

- 14.26 Analog transmission Wikipedia
- 14.27 Analog to digital converter Wikipedia
- 14.28 Data communication Wikipedia
- 14.29 <u>Digital to analog converter</u> Wikipedia
- 14.30 Modulation Wikipedia
- 14.31 Radio Wikipedia
- 14.32 Signal transmission Wikipedia

FT8

- 14.33 FT8 Wikipedia
- 14.34 <u>FT8 Frequency Chart: Navigating the Digital Mode Landscape</u> Thehamshack, Jerry L Withers, <u>KD7OKK</u>

Digital Voice (DV)

- 14.35 <u>Digital Voice the Easy Way</u> 2023 QST
- 14.36 FreeDV: Open Source Amateur Digital Voice 2023 FreeDV
- 14.37 A Guide to Digital Voice on Amateur Radio → April 2021 Andrew McColm, VK3FS
- 14.38 <u>How to Use FreeDV Digital Voice Over HF Ham Radio</u> Dec 2020 Ham Radio Crash Course
- 14.39 Using FreeDV To Talk On Digital HF 80M Oct 2019 Tech Minds
- 14.40 RSGB 2018 Convention lecture: FreeDV Digital Voice for HF and other low SNR channels ▶ Sept 2019 RSGB
- 14.41 Digital Voice on HF 2013 GAILO
- 14.42 Will digital voice (on HF) ever be a thing? 2018 Dan, KB6NU

- 14.43 <u>International Digital Audio Broadcasting Standards: Voice Coding and Amateur</u>
 Radio Applications 2003 QEX
- 14.44 Practical HF Digital Voice June 2000 G4GUO, G4JNT, QEX

Automatic link establishment (ALE)

Automatic Link Establishment (ALE) is a feature that enables a radio station to select the best frequency to establish a connection with another HF radio station or network of stations. It replaces traditional prediction techniques and reliance on trained operators.

- 14.45 Automatic link establishment (ALE) Wikipedia
- 14.46 Youtube clips about ALE:
 - ALE overview 14-June-2021 Sal, 9K2GV

 - ALE SCS P4Dragon Modem Promo 5-Oct-2021 Commsprepper
- 14.47 Free and paid software for ALE:
 - ALE 2G Intelligent Standards-Based HF Communications Software 2023
 ION2G
 - PC-ALE / PCALE support site Nov 2020 Steve Hajducek, N2CKH
 - PC-ALE 1.602; Latest version Feb 22, 2012. Only trial is free!
- 14.48 Automatic Link Establishment Overview 2018 COMMS Working Group
- 14.49 HF Automatic Link Establishment (ALE) 2009 Kingston Amateur Radio Club
- 14.50 ALE HF Network Ham Radio Amateur Radio 2007 Bonnie Crystal, KQ6XA, HFLINK
- 14.51 <u>ALE The coming of Automatic Link Establishment</u>, QST 1995 ^{Ronald E. Menold}, AD4TB

Spread Spectrum

Spread Spectrum Wikipedia

Frequency-hopping spread spectrum Wikipedia

Technological concepts

- 14.52 Satellite Wikipedia
- 14.53 <u>Lagrange points</u> (Google Search)
- 14.54 The Lagrange Mission Wikipedia

Scientific answers to radio amateurs' questions:

- 14.55 Ham Radio Science Citizen Investigation HamSCI
 - HamSCI promotes collaboration between researchers and radio operators, supports the development of standards and agreements, and advances projects with the following goals: * Advance scientific research through amateur radio. * Encourage the development of new technologies. * Provide educational opportunities for amateurs and the public.
- 14.56 <u>High-frequency Active Auroral Research Program HAARP Wikipedia</u>
- 14.57 Benefits of the HAARP Project for Radio Hams
- 14.58 Study of HF Radio Propagation Using HAARP and the Ham WSPR Network

 (2018) Citizen Space Science, Fallen
- 14.59 <u>HAARP (The High Frequency Active Auroral Research Program)</u> DARA Hamvention

HF Propagation Research 1958-1990

- 14.60 <u>Basic Radio Propagation Predictions</u> for September 1958, Three Months in Advance National Bureau Of Standards
- 14.61 <u>An Introduction to Ionosphere and Magnetosphere</u> 1972 isbn: 9780521083416 <u>J. A. Ratcliffe</u>
 - * Abstract IAEA * Selected pages Google books * Borrowing From The Lending Library
- 14.62 <u>Solar-Terrestrial Prediction Proceedings | Solar-Terrestrial Prediction Proceedings</u>

 1979 Richard F. Donnelly, Space Environment Lab, NOAA
- 14.63 <u>The Earth's Ionosphere</u> (book 1989) Plasma Physics and Electrodynamics Michael
 C. Kelley

Special articles by Bob Brown, NM7M (SK), Ph.D. U.C.Berkeley

- 14.65 The Little Pistol's Guide to HF Propagation (1996) Bob Brown
- 14.66 The Big Gun's Guide to Low-Band Propagation | text format (2002) Bob Brown
- 14.67 HF Propagation Tutorial Bob Brown (SK), NM7M

The AI tools used to improve the presentation of this website

- 14.68 Quillbot, since September 2022
- 14.69 <u>Initial chats with ChatGPT 3.5</u>, since April 2023
- 14.70 ChatGTP 4o, since May 2024

- 14.71 Copilot Microsoft, since June 2024
- 14.72 Gemini Google, since November 2024
- 14.73 Grok 3 (X), since December 2024

15. Misc. References

Physical concepts

- 15.1 Physics Wikipedia
- 15.2 Physical quantity Wikipedia
- 15.3 <u>Dimensional analysis</u> Wikipedia
- 15.4 Field (physics) Wikipedia
- 15.5 Electric field Wikipedia
- 15.6 Magnetic field Wikipedia
- 15.7 Radio Waves NASA
- 15.8 <u>Signal-to-noise ratio</u> (SNR or S/N) Wikipedia
- 15.9 Flux Wikipedia
- 15.10 Storm What are storms? Wikipedia
- 15.11 Physical Coupling Wikipedia
- 15.12 Collision frequency Wikipedia
- 15.13 Collision frequency Physical Chemistry
- 15.14 Spectroscopy Wikipedia
- 15.15 <u>Spectroscopy</u>: A YouTube playlist featuring demonstrations and explanations Doron, 4X4XM
- 15.16 <u>Lyman series-alpha hydrogen radiation at a wavelength of 121.6 nm</u> [nm = nanometer 10⁻⁹meter] Wikipedia

Mathematical and numerical concepts

- 15.17 Interpolation Wikipedia
- 15.18 Extrapolation Wikipedia

Geophysical concepts

- 15.19 The atmosphere of Earth Wikipedia
- 15.20 Definition of Aeronomy UMich
- 15.21 Earth's magnetic field Wikipedia Gauss (unit) Wikipedia Tesla (unit) Wikipedia

Geomagnetism: All the aspects of the Earth's magnetic field that surrounds Earth in the form of the magnetosphere.

- 15.22 Origin of Earth's Magnetic Field Earth.com
- 15.23 Geomagnetism an overview Science Direct
- 15.24 Global-GMDs: The global map of geomagnetic disturbances Hongyi Hu, Zhonghua Xu
- 15.25 Sustaining Earth's magnetic dynamo Nature
- 15.26 <u>Understand Earth's geomagnetic field through the dynamo effect principle</u> (video)

 Britanica
- 15.27 Magnetometer Wikipedia
- 15.28 Magnetometers A Comprehensive Guide
- 15.29 Magnetometry D. Waller & B. E. Strauss

Astromonomical concepts

15.30 The Solar System Wikipedia

Geometrical concepts

- 15.31 Ecplictic Plane | Plane of the Solar System Wikipedia
- 15.32 Geometrical Optics Wikipedia
- 15.33 Secant Trigonometry term Wikipedia 1

Deterministic Chaos

- 15.34 <u>Deterministic Chaos</u> The Exploratorium, 1996
- 15.35 <u>Deterministic Chaos</u> Principia Cybernetica 2000
- 15.36 Concepts: Chaos New England Complex Systems Institute

HF Propagation - Novel Research and Analysis

- 15.37 <u>Short and long term prediction of ionospheric HF radio propagation</u> J. Mielich und J. Bremer (2010)
- 15.38 <u>Spread-F occurrences and relationships with foF2 and h'F at low and mid-latitudes</u>
 in China (2018) Wang, Guo, Zhao, Ding & Lin (Chaina)
- 15.39 Long-Term Changes in Ionospheric Climate in Terms of foF2 Jan Lastovicka (2022)
- 15.40 <u>Ionospheric Monitoring and Modeling Applicable to Coastal and Marine</u>
 <u>Environments</u> Ljiljana R. Cander and Bruno Zolesi (2019)
- 15.41 <u>Statistically analyzing the ionospheric irregularity effect on radio occultation</u> M. Li and X. Yue, <u>Atmos. Meas. Tech., 14, 3003–3013, 2021</u>
- 15.42 <u>Analysis of Ionospheric Disturbance Response to the Heavy Rain Event</u> <u>Jian Kong</u>, <u>Lulu Shan, Xiao Yan, Youkun Wang Remote Sens. 2022, 14(3), 510</u>
- 15.43 <u>A simplified HF radio channel forecasting model</u> E.V. Moskaleva, N.Y. Zaalov, Advances in Space Research
- 15.44 Ionospheric current Upper Atmospheric Science Division of the British Antarctic Survey
- 15.45 <u>Radio Propagation Prediction for HF Communications</u> (2018) Dept. of Appl/ Physics & Tel., Midlands State Univ., Gweru, Zimbabwe
- 15.46 The influence of high latitude off-great circle propagation effects on HF

 communication systems and radiolocation M. Warrington, A.J. Stocker, N. Zaalov (2002)
- 15.47 Analyzing the current ionospheric conditions Google search

Recent Theories, Methods and Models

- 15.48 <u>Develop ionosphere computer models to enhance HF radio propagation</u> Military
 Aerospace 2022
- 15.49 <u>Investigation of Two Prediction Models of Maximum Usable Frequency for HF</u>
 Communication
 - Based on Oblique- and Vertical-Incidence Sounding Data (2022) atmosphere MDPI

ITM Processes

General explanation, physical phenomena (plasma bubbles or clouds), Spread F of skywaves

- 15.50 <u>Terrestrial Atmosphere ITM (Ionosphere, Thermosphere, Mesosphere) Processes</u>
 NASA Visualization (2018)
- 15.51 <u>Ionosonde Data</u> 19-7-2020 Larisa Goncharenko Stratosphere-to-ionosphere couplings; Pole-to-pole Observations; Sudden Stratospheric Warming induce global disturbances

Ionospheric clouds or bubbles

- 15.52 <u>Detection of Rapidly Moving Ionospheric Clouds</u> H. Wells, J. M. Watts, D. George (1946)
- 15.53 <u>Three-dimensional simulation study of ionospheric plasma clouds</u> S. Zalesak, J. Drake, J. Huba (1990)
- 15.54 Nonlinear 3-D Simulations of the Gradient Drift and Secondary Kelvin–Helmholtz

 Instabilities in Ionospheric Plasma Clouds 2003 Almarhabi et al)
- 15.55 Articles about "Ionospheric Plasma Bubbles" Google search
- 15.56 Articles about "lonospheric Plasma Clouds" Google search

Spread F phenomenon

- 15.57 Speard-F Definition 2024 Ametsoc.org
- 15.58 Spread F Radio Propagation Ian Poole, Electronics Notes
- 15.59 <u>Automatic classification of spread-F types in ionogram images using support</u>

 <u>vector machine and convolutional neural network April 2024</u> Earth, Planets and Space
- 15.60 Resolution of the equatorial spread F problem: Revisited 2023 J. D. Huba
- 15.61 <u>Ionosonde Observations of Spread F and Spread Es at Low and Middle Latitudes</u>
 <u>during the Recovery Phase of the 7–9 September 2017 Geomagnetic Storm</u> 2021

 Lehui Wei et al
- 15.62 <u>Spread F an overview | ScienceDirect Topics</u> Book 2020, The Dynamical Ionosphere ^{ScienceDirect}
- 15.63 <u>Multi-station investigation of spread F over Europe during low to high solar activity</u>

 J. Space Weather Space Clim. 2018 Krishnendu Sekhar Paul et al
- 15.64 <u>A theoretical analysis of global characteristics of spread-F</u> 2001 ^{Zuo Xiao & Tianhua} Zhang
- 15.65 A Review of Equatorial Spread F 1999 Rick McDaniel
- 15.66 Spread-F theories—a review 1985 Journal of Atmospheric and Terrestrial Physics
- 15.67 Equatorial Spread F 1962 Wynne Calvert
- 15.68 A Survey of Spread F 1960 F.N. Glover

Vertical Coupling (Troposphere - Ionosphere)

15.69 Sprite (lightning) Wikipedia

- 15.70 ICON Ionospheric Connection Explorer Wikipedia
- 15.71 Upper-atmospheric lightning Wikipedia
- 15.72 Transient Luminous Events: Lightning above our atmosphere AccuWeather
- 15.73 NASA ScienceCasts: Observing Lightning from the International Space Station
 NASA
- 15.74 Severe Weather 101: Lightning Types NOAA
- 15.75 Transient Luminous Events (TLEs) SKYbrary
- 15.76 <u>Investigations of the Transient Luminous Events with the small satellites, balloons</u>
 and ground-based instruments
 Safura Mirzayeva 2022 Master Thesis
- 15.77 <u>Solar cycle changes to planetary wave propagation and their influence on the middle atmosphere circulation</u> (1997) Arnold & Robinson
- 15.78 <u>Electrodynamical Coupling of Earth's Atmosphere and Ionosphere: An Overview</u>
 (2011) A. K. Singh, Devendraa Siingh, R. P. Singh, Sandhya Mishra
- 15.79 <u>A review of vertical coupling in the Atmosphere-Ionosphere system:</u>

 <u>Effects of waves, sudden stratospheric warmings, space weather, and of solar activity</u> (2015) Erdal Yiğit, Petra Koucká Knížová, Katya Georgieva, William Ward
- 15.80 <u>Electrodynamical Coupling of Earth's Atmosphere and Ionosphere: An Overview</u>
 (2020) Prof. Ashok K. Singh et al, University of Lucknow
- 15.81 <u>A Review of Low Frequency Electromagnetic Wave Phenomena Related to</u>

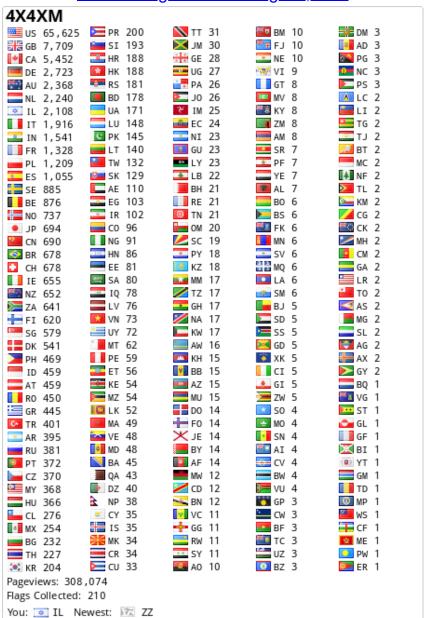
 <u>Tropospheric-Ionospheric Coupling Mechanisms</u> (2012) NASA
- 15.82 <u>TEC variations detected over southern Africa due to lightning storms</u> M M Amin, Inggs, P J Cilliers; South African National Space Agency

Advanced Ionospheric Models

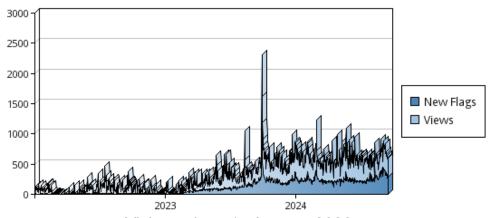
- 15.83 NET vs. IRI ionospheric models April 2025 Review on this website
- 15.84 <u>3-D Characterization of Global Ionospheric Disturbances During the 15 January</u>

 <u>2022 Tonga Volcanic Eruption</u> January 2025 ^{Changzhi Zhai et al}
- 15.85 Next-decade needs for 3-D ionosphere imaging May 2023 Frontiers
- 15.86 <u>In-space measurements could enhance high-frequency radio capabilities</u> April 2022 DARPA

Visitor's flags since 17 August ,2022



Visitor numbers peak during HF propagation disruptions.



Visitors since 17 August ,2022