The Rebirth of HF

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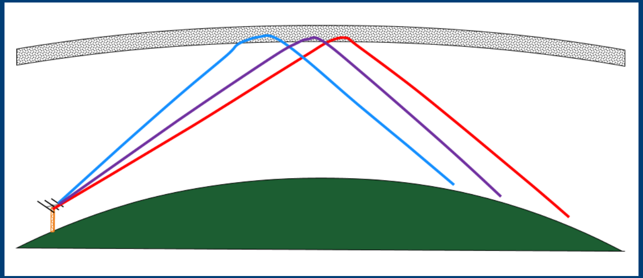
Make ideas real

Presentation outline

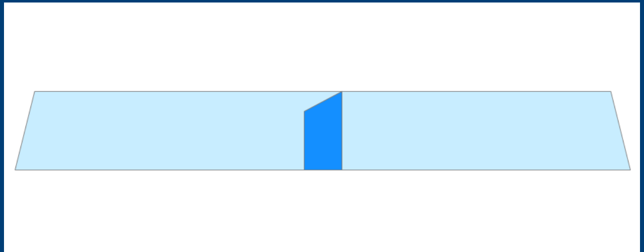
Introduction to HF Propagation

- Different propagation modes
- Skywave propagation
- Measuring the ionosphere



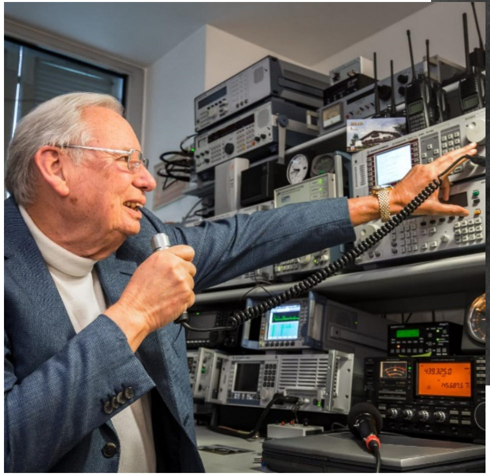
HF Communications

- Traditional HF applications
- The decline in HF
- The rebirth of HF



About HF

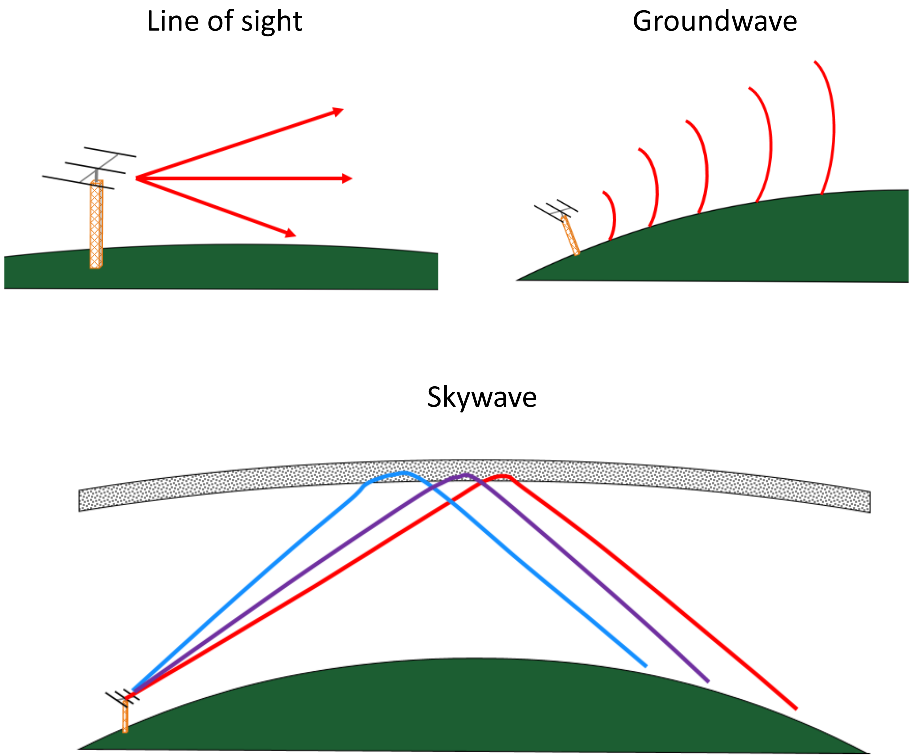
- HF = “high frequency”
  - Frequency range: 3 MHz to 30 MHz
  - Wavelengths: 100 meters to 10 meters
  - Sometimes referred to as “shortwave”
- Used primarily for worldwide communications
  - Broadcasters
  - Government / military
  - Amateur radio
- HF **propagation** enables global communication



Part 1 – Introduction to HF Propagation

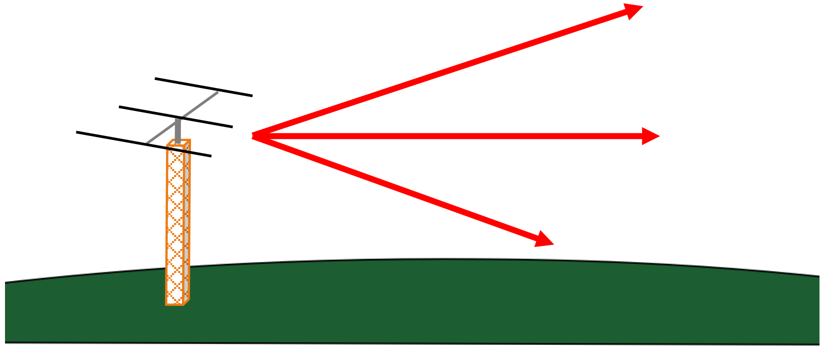
About HF propagation

- HF propagation can be highly variable compared to other frequencies
- Greatest challenge in HF: finding the optimum frequency for the intended destination and current propagation conditions
- Three main HF propagation modes:
  - Line of sight
  - Groundwave
  - Skywave



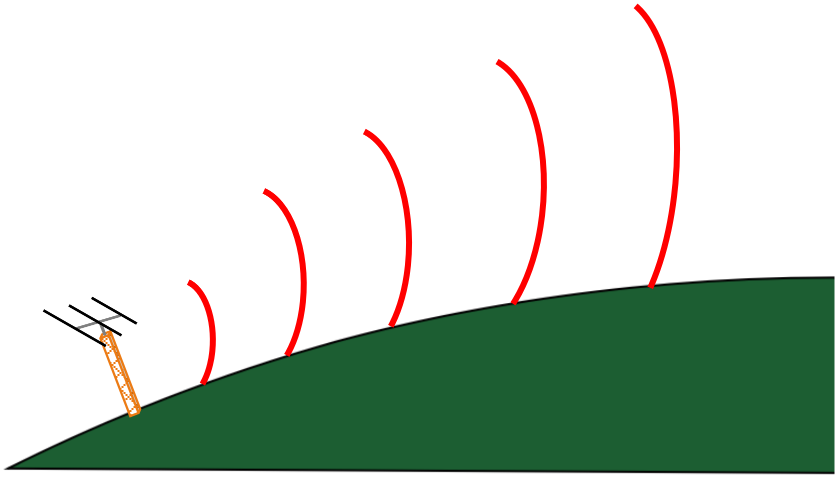
Line of sight

- Signals propagate in a straight line between transmitter and receiver
- LOS propagation is fairly consistent
- HF is often not a good choice for line of sight communications
  - Large antennas
  - Limited bandwidth
  - Higher noise



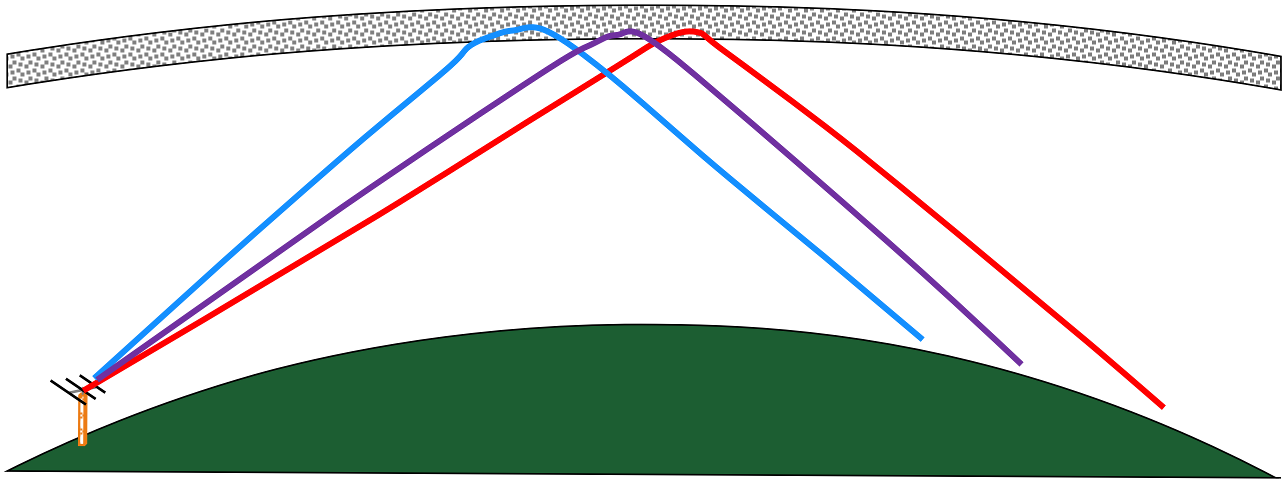
Groundwave

- Signals propagate along the Earth's surface
- Propagation highly dependent on:
  - surface conductivity
  - frequency
- Higher surface conductivity (e.g. salt water) yields better results (greater distances)
  - Good for ship-to-ship or ship-to-shore
- Lower frequencies yield better results
  - e.g. theoretical range with 150 W
    - @ 7 MHz: 35 km land, 250 km sea
    - @ 30 MHz: 13 km land, 107 km sea



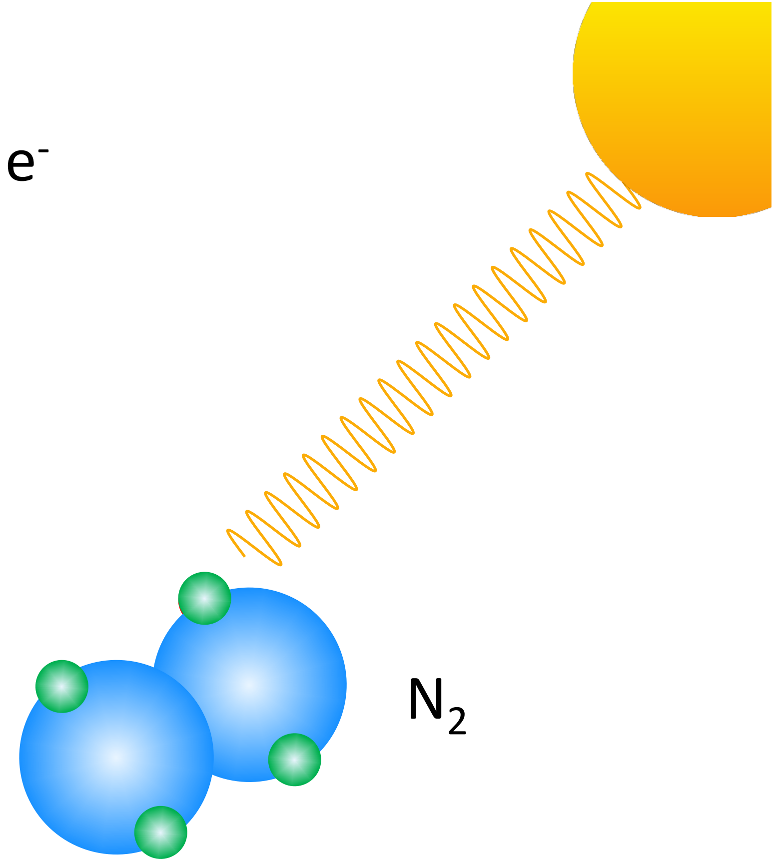
Skywave

- ► Enables beyond line of sight (BLOS) communications
- ► Signals are refracted by layers of ionized particles in the atmosphere
- ► Skywave propagation is a function of the state of the **ionosphere**



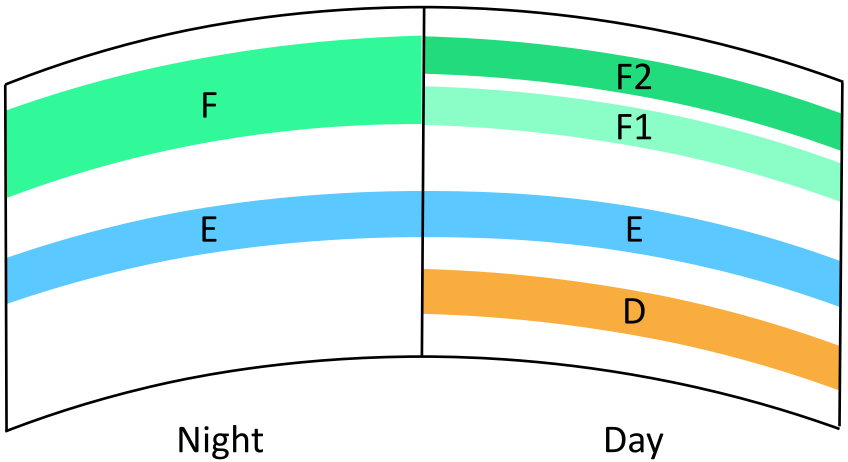
What is ionization?

- Solar ultraviolet energy can detach electrons from gaseous atoms or molecules
  - Results in a positive ion and free electron
  - The more sunlight, the higher the ionization
- When the external energy is removed, the ions **recombine**
  - Recombination is a slower process than ionization
  - Ionization increases rapidly at dawn, decreases less rapidly at dusk



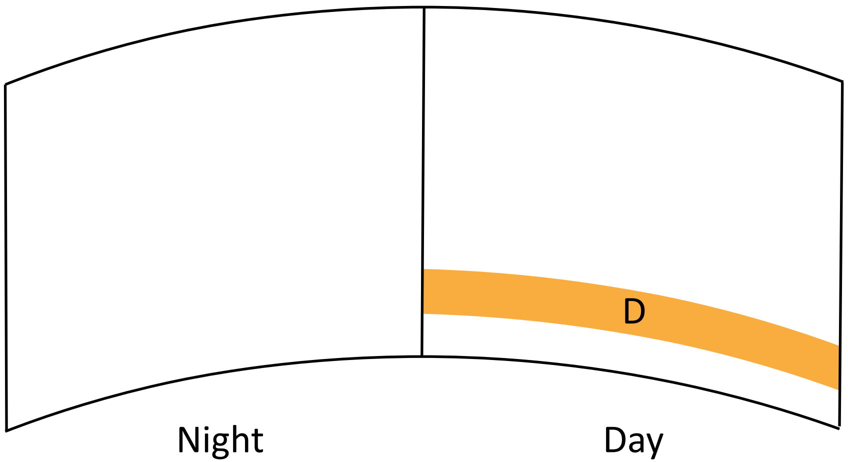
About the ionosphere

- The ionized region of the Earth's atmosphere is called the **ionosphere**
- Ionization varies by altitude
- Peaks in ionization levels are called layers or regions:
  - The D-layer (60 - 100 km)
  - The E-layer (100 - 125 km)
  - The F-layer (200 - 275 km)
- These differently-ionized layers refract (not reflect) and/or absorb HF signals in different ways



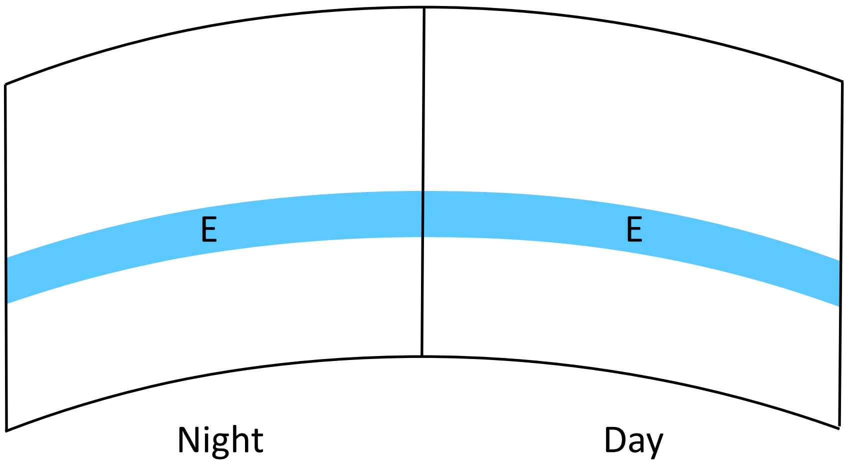
D-layer

- The D-layer only exists during daytime
  - Disappears at night
- Density of free electrons is too low to refract HF signals
- Primarily absorbs HF signals
  - Absorption is higher for lower frequency signals
  - Absorption highest at midday
- D-layer absorption causes higher frequencies to work better in daytime, lower frequencies to work better at night



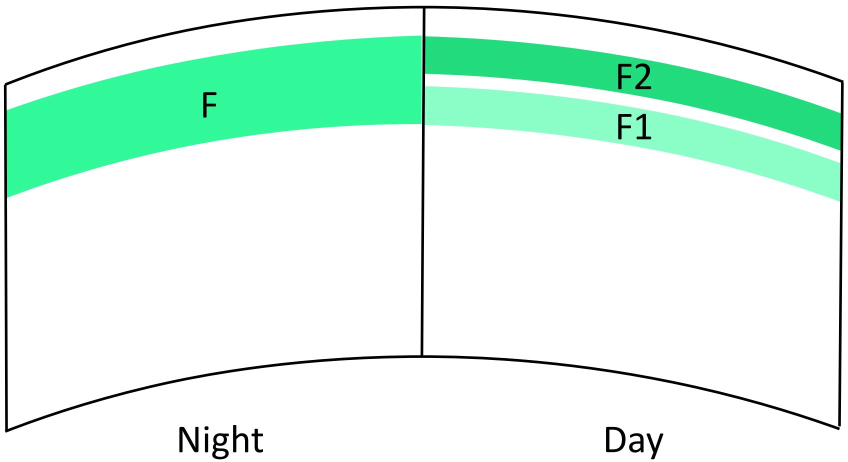
E-layer

- The E-layer is the first layer that can refract HF signals back towards the Earth
- Relatively thin layer (< 25 km)
- Denser (more highly ionized) during daylight hours, almost disappears at night
- Mostly used for short-range, daytime communication at HF
- The E-layer supports some rather exotic propagation modes (e.g. sporadic-E) that enable long-distance communications at VHF frequencies (up to ~150 MHz)



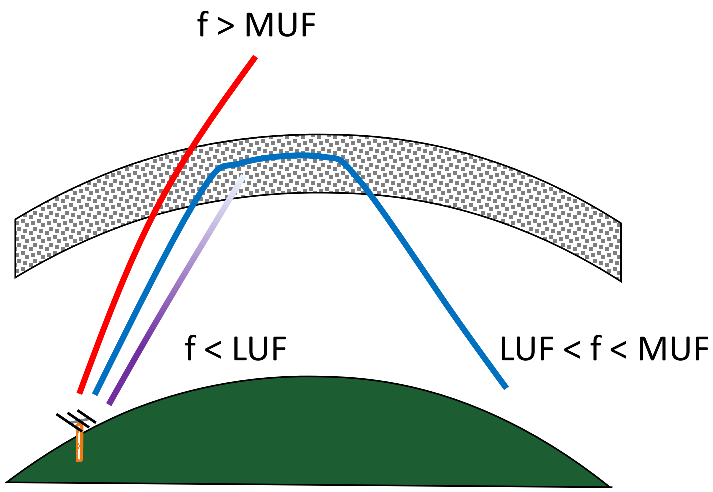
F-layer

- Most important layer for skywave
- During the day, the F-layer splits into two layers: F1 and F2
  - Height of these layers varies greatly
- F1-layer
  - supports daytime short- to medium-distance communications
- F2-layer
  - Highest altitude and ionization
  - Responsible for most long-distance HF communications



MUF and LUF

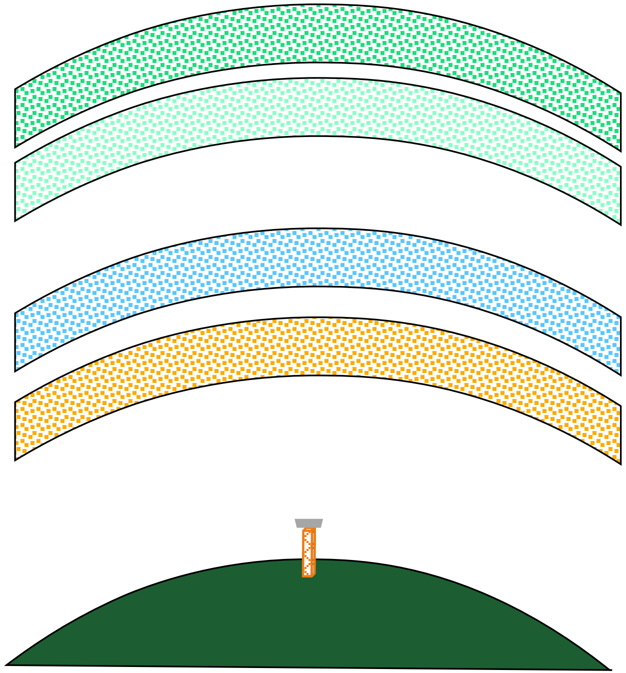
- Absorption / refraction is a function of signal frequency
- General rule for skywave: use the highest possible frequency for a given destination
  - This is the **maximum usable frequency** (MUF)
  - Signals > MUF are not refracted
  - As ionization increases, MUF usually increases
- Below the **lowest usable frequency** (LUF) communications become difficult or impossible
- LUF is (mostly) a function of noise (poor SNR)
- MUF is a function of the ionosphere
- When LUF > MUF, HF communication is not possible



Critical frequency

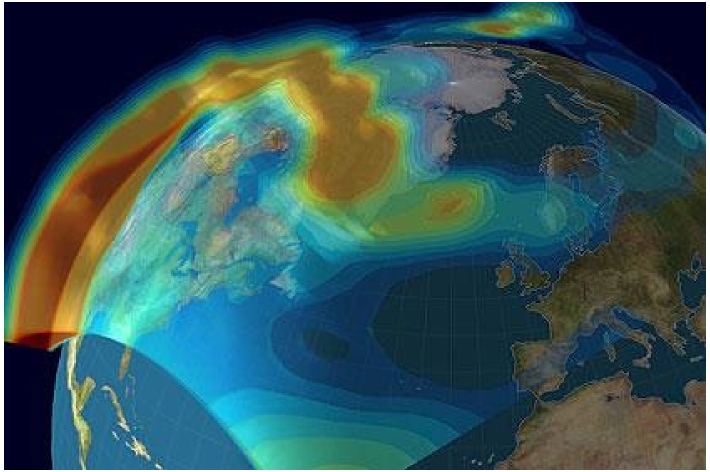
- Type equation here.The MUF is usually estimated from **critical frequency**
- Measuring critical frequency:
  - Transmit pulses vertically at different frequencies
  - Use return time to estimate layer heights
  - At the critical frequency, the pulse is not returned by the ionosphere (goes into space)
- Critical frequency (f_c) is a function of both the ionization level and the measurement location
- Estimated MUF ≈ 3 to 5 times critical frequency

$$MUF = \frac{f_c}{\cos\theta}$$



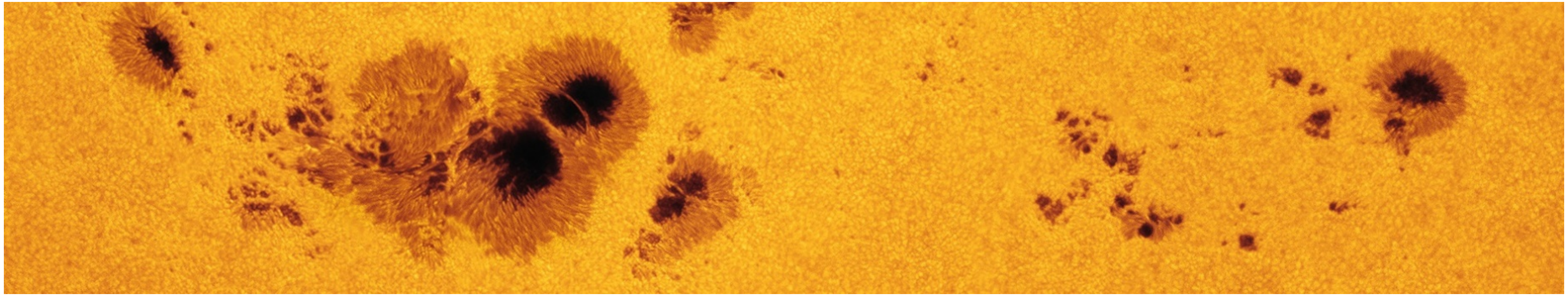
Quantifying the ionosphere

- Critical frequency is an **active** measurement
- Three passive methods for quantifying the state of the ionosphere:
  - Sunspot numbers: **predict** the level of ionization
  - Solar flux index: **measure** the level of ionization
  - Geomagnetic indices: indicate the impact of solar particles on the Earth's magnetic field
- Together these quantities provide a good indication of the current state of the ionosphere and can be used to predict HF propagation.



Sunspots

- ► Sunspots are (relatively) cooler surface regions of the Sun (3000 K vs. 6000 K)
  - – Last between a few days and a few months
- ► Associated with powerful magnetic fields
- ► The number of sunspots correlates with solar activity / radiation
  - – More sunspots generally means more atmospheric ionization and better HF propagation

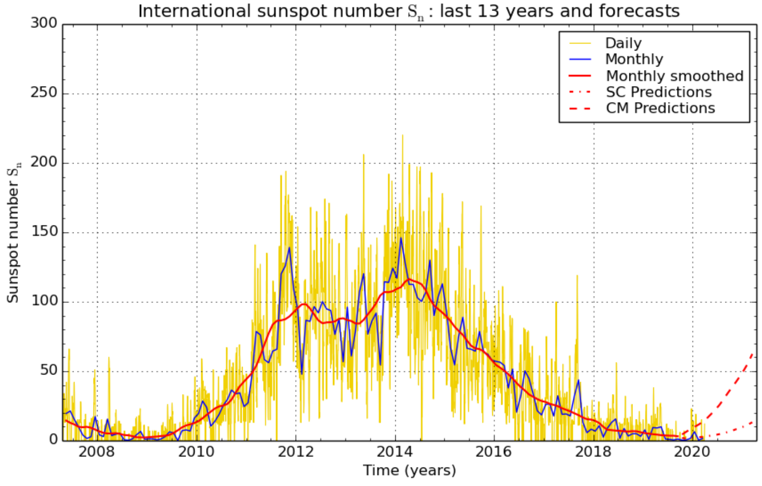


Sunspot number (SSN)

- Daily measurement of sunspots
  - Not a simple count: factors in size and groupings
- Recorded at solar observatories around the world
- Values range from zero to ~250 (max recorded)
- More sunspots → better HF propagation
- Sunspots have been counted and recorded for almost 400 years

Solar or sunspot cycle

- Sunspot activity follows a roughly 11 year cycle
- At the peak, SSN is ~150 and HF propagation is very good, even at higher frequencies
- At the bottom, SSN is ~0 and HF propagation is poor, especially at higher frequencies
- Sunspot cycle is generally good for long-term predictions of HF propagation
  - However, at several points in history (late 1600s and early 1800s), sunspot numbers stayed very low for several decades



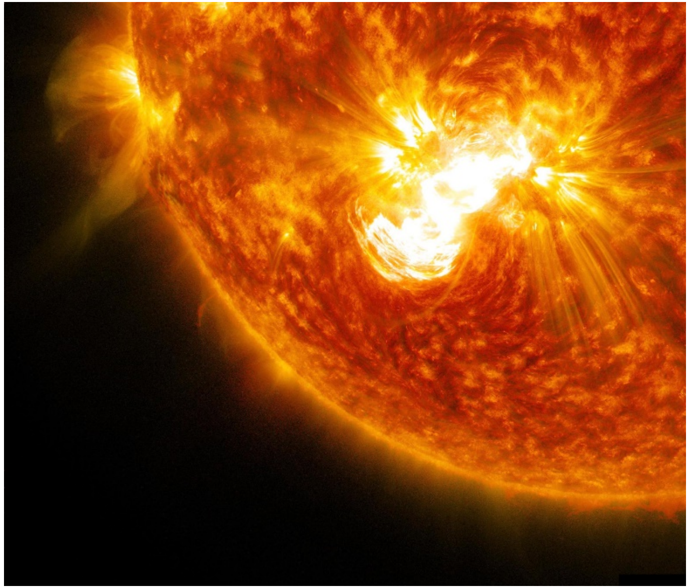
SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2020 April 2

Solar flux index (SFI)

- Solar activity can also be quantified by measuring the solar noise or flux at 2800 MHz (λ = 10.7 cm)
- Reported as the solar flux index (SFI)
  - Measured in solar flux units (sfu)
  - Measured values in the range 50 - 300
- Solar flux is a measurement, not an observation, so it is more consistent and reliable
  - But doesn't have a 400-year history of values
- Correlates quite well with SSN
  - SFI = 73.4 + 0.62 * SSN
- Higher SFI → higher MUF → better HF propagation

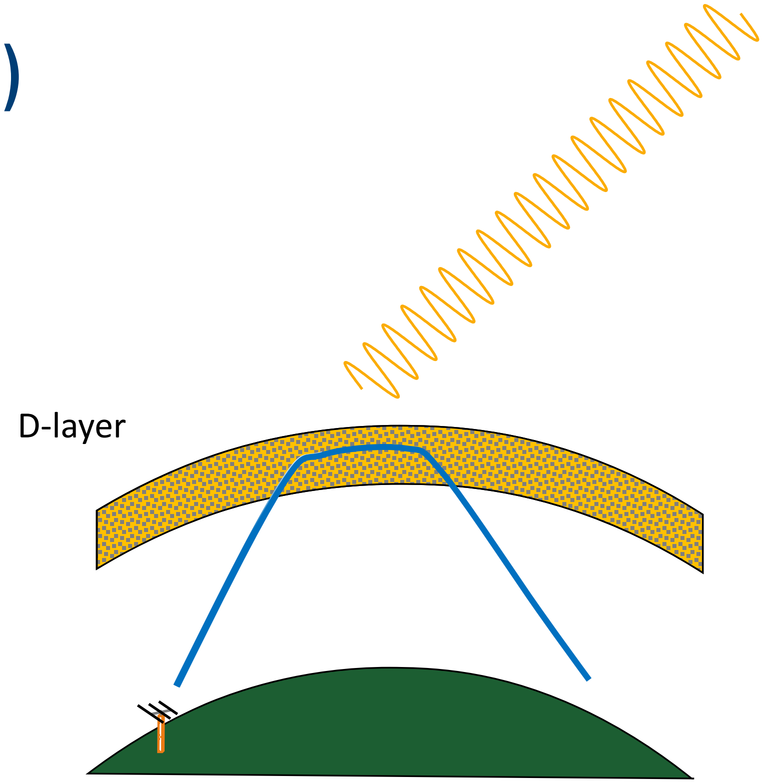
Solar flares

- The ionosphere is also affected by short-duration events occurring on the sun
- Most important of these are solar flares
  - Eruptions causing a rapid rise in radiation and ejection of low- and high-energy particles
- Unpredictable, but more common during peaks in the sunspot cycle
- Solar flares can lead to:
  - Sudden ionospheric disturbances
  - Polar cap absorption
  - Geomagnetic and ionospheric storms



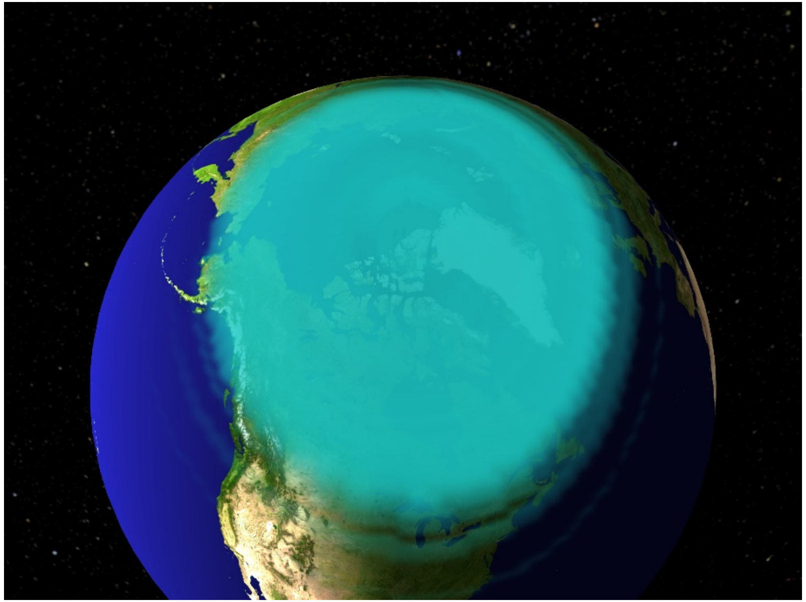
Sudden ionospheric disturbance (SID)

- About 8.5 minutes after a flare, radiation reaches the Earth
  - D layer ionization (and absorption) to increase rapidly, beginning with lower frequencies
  - Only impacts the sunlight hemisphere
  - Usually only lasts about an hour
  - Smaller flares can sometimes even enhance HF at higher frequencies



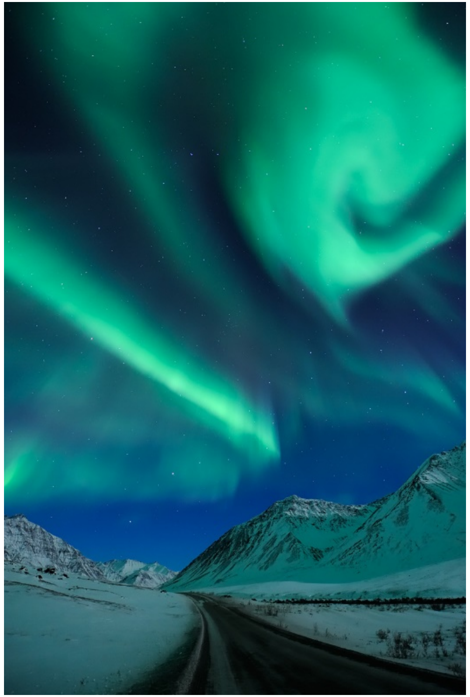
Polar cap absorption (PCA)

- Several hours after a flare, high energy particles reach the Earth
  - Enter the atmosphere near the poles
  - Increase D-layer absorption in the polar regions
  - Can last for several days
- Blocks HF traveling near the poles
  - Other paths may remain unaffected



Geomagnetic and ionospheric storms

- Lower energy particles arrive at 20-40 hours after a flare
- Low energy particles are also generated by a coronal mass ejection (CME)
- These particles can cause a **geomagnetic storm**
  - Create pretty aurora
  - Can interfere with GPS, satellites, power-distribution, etc.
  - Can lead to an **ionospheric storm**
    - lowers the MUF and degrades HF propagation
    - If MUF becomes ≤ LUF, a complete skywave blackout occurs



A and K indices

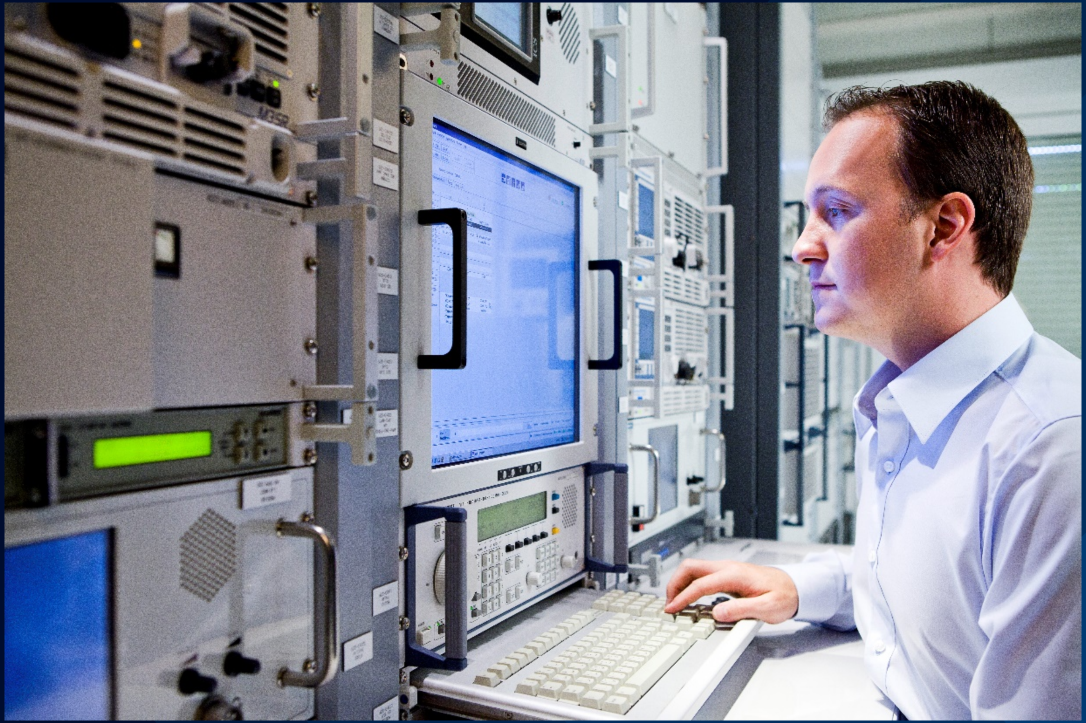
- A and K values measure **magnetic** fluctuations caused by ionospheric disturbances such as solar flares
  - Lower values → more stable ionosphere
- Measured at observatories around the planet
  - Local values of A and K can be averaged to product planetary values (Ap and Kp)
- A calculated daily, K measured every 3 hours
  - K indicates a current disturbance
  - A indicates how long the disturbance has been occurring

A	K	Conditions
0	0	Quiet
2-3	1	Quiet
4	1	Quiet / unsettled
7	2	Unsettled
15-27	3-4	Active
48	5	Minor storm
60	6	Major storm
132	7	Severe storm
208+	8+	Very severe storm

Summary of HF propagation

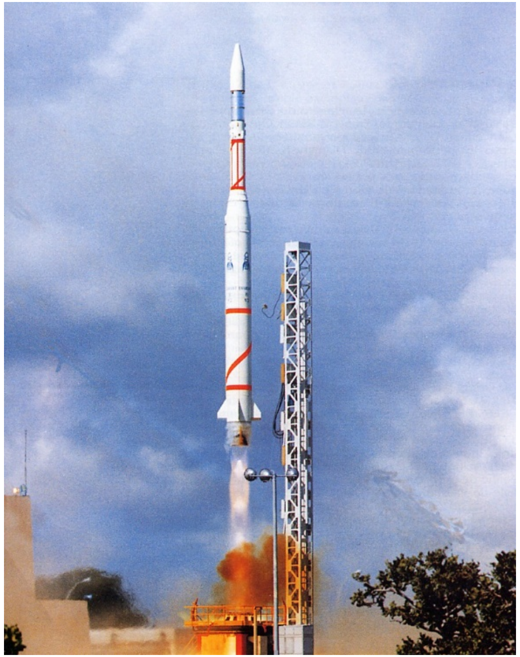
- ► Skywave is the mode used for global HF communications
- ► Signals are refracted / absorbed by the ionosphere
  - – Function of signal frequency and ionization
- ► Ionization increases
  - – During daylight hours
  - – As sunspots increase
- ► Solar events can unexpectedly disrupt the ionosphere
  - – Solar flares
  - – Coronal mass ejections
- ► SSN, SFI, and A/K indices are used to quantify the ionosphere

Part 2 – HF Communications



HF in decline

- Satellites began to replace HF in the late 1960s
  - Much higher data rates
  - Relatively immune from variable propagation
  - Did not require trained operators
- Internet changed expectations on connectivity
  - Higher data rates / instant communications
  - Always available
  - Globally available
- Decline in HF use / funding / mindshare lead to a decrease in development and knowledge of HF



Satellite vulnerabilities / weaknesses

- Anti-satellite (ASAT) technologies include:
  - Ground-based (e.g. lasers)
  - Air- or space-based “kill vehicles”
- Susceptible to jamming
  - Satellites not frequency-agile
- Solar storms or space weather
  - Flares and CMEs can disrupt / damage satellites
- Lack of polar coverage
  - Not all constellations cover the poles
- Terrain can block signals
  - Mountains, jungles, etc.

Rebirth of HF

- ► Global connectivity is mission-critical
  - Backup / redundancy is required
- ► Advantages of HF
  - Global coverage
  - Requires no “infrastructure”
  - Much, much cheaper than satellite
  - Robust against attacks
  - Robust against jamming

Enabling the rebirth of HF

Improved data performance

Improved audio quality

Improved availability

Improved operation

Improving availability and operation

- Availability and operation are closely related
- Which frequency should be used?
- Trained and experienced humans used do this
  - Propagation prediction tools (e.g. VOACAP)
- Principles of “Adaptive HF” (ITU-R F.1110-2 1)
  - Automatically select the frequency
  - Automatically establish the communication
  - Automatically adapt to congestion / propagation changes if needed
- Most common way to implement this is Automatic Link Establishment (ALE)

Automatic link establishment (ALE)

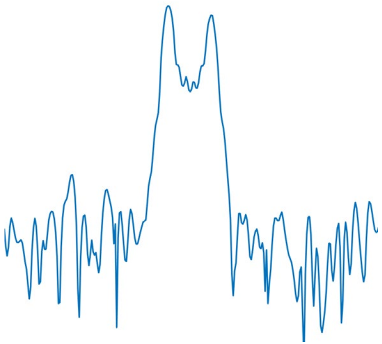
- Stations are assigned and are called by an address
  - If a station hears itself being called, it attempts to synchronize with the calling station
- Frequencies chosen using link quality analysis (LQA)
  - Stations periodically transmit a sounding signal and their address
  - Scanning stations measure and record the received signal
  - Database is used when selecting a channel for a given station
- Can listen to determine if a channel is in use and adapt if conditions change

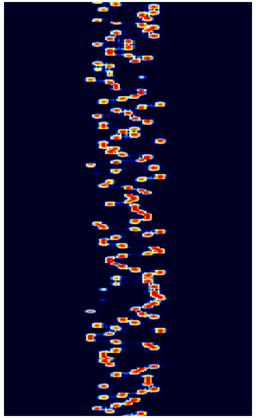
ALE generations

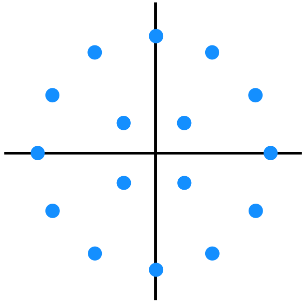
- First generation ALE schemes were proprietary
- 2G ALE (MIL-STD-188-141A) : standardized version
- 3G ALE (-141B / NATO STANAG 4538):
  - Faster link setup
  - Setup links under noisier conditions (lower SNR)
  - More efficient spectrum allocation
  - More scalable (more stations)

Legacy HF modulation

- Traditional HF uses 3 kHz “channels”
  - Standard bandwidth for SSB voice
- Modems used to send data over voice channels
- Modulation type has changed over time
  - Originally sent as FSK and PSK
  - M-ary modes (e.g. MFSK) later become popular
  - Newer types include QAM
  - Multicarrier systems like OFDM
- In modernized HF systems, voice is often sent digitally over data channels





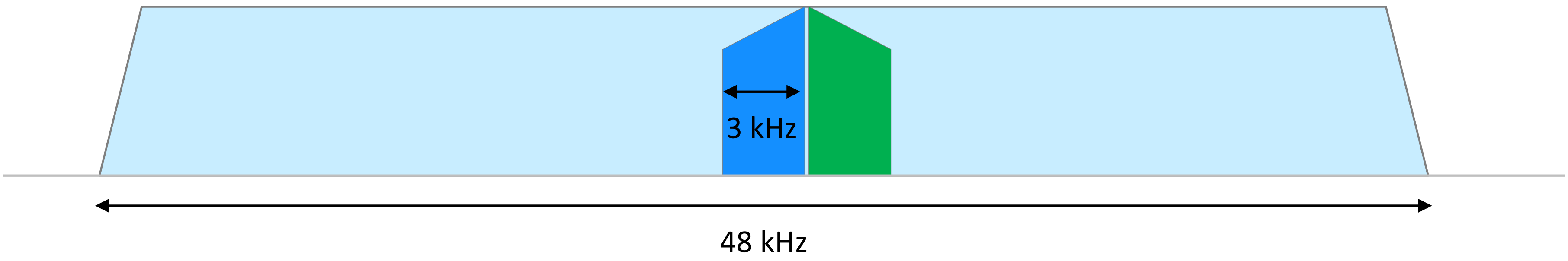


Improving HF bit error rate

- HF is a noisy, variable environment
- Burst errors are common in HF (many bits in a row corrupted)
- Not easy to detect / correct bit errors in legacy HF
  - Limited transmission speeds
- Methods of dealing with bit errors:
  - Interleaving reduces the effect of burst errors
  - Forward error correction (FEC) can detect and correct single bit errors
  - Automatic repeat request (ARQ) is used to request retransmission of errored packets

About wideband HF (WBHF)

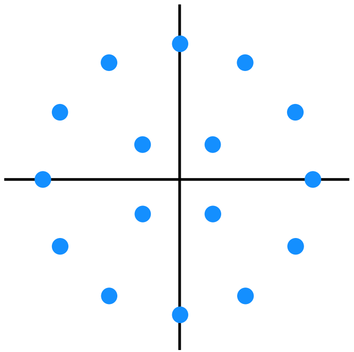
- A single larger channel provides better performance than multiple smaller channels
- Wideband HF (MIL-STD-188-110D)
  - Contiguous bandwidth up to 48 kHz in various steps
  - Data rates up to 240 kpbs on a 48 kHz channel
  - More robust in hostile environments
- Successfully used in numerous military trials



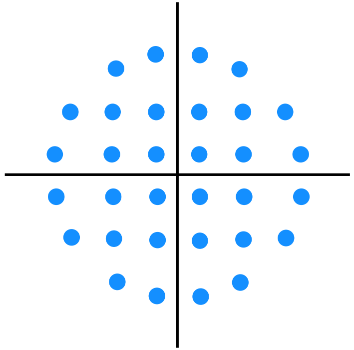
Modulation in wideband HF

- ► Wideband HF supports different modulation types and error reduction methods (FEC, interleaving, etc.)
- ► Wideband HF modulation types:
  - – Standard PSK
  - – Specially designed QAM
    - – Up to 256 QAM
    - – Higher order enables higher throughput
    - – Constellations are more circular than square in order to reduce peak to average ratio

16 QAM



32 QAM



4G ALE (wideband ALE)

- 4G ALE supports wideband HF
- Used to negotiate bandwidth, modulation type, error correction, number of subcarriers, etc.
- Supports more advanced spectrum sensing to determines optimal frequency and bandwidth
- Additional features for wideband and narrowband HF

Summary of HF communications

- Satellite largely replaced legacy HF for global communications
  - Higher throughput
  - Not propagation-sensitive
  - Easier to use
- Satellites are (much) higher cost and vulnerable
- Modernization of HF has reduced or eliminated many traditional shortcomings
  - Wideband HF and ALE