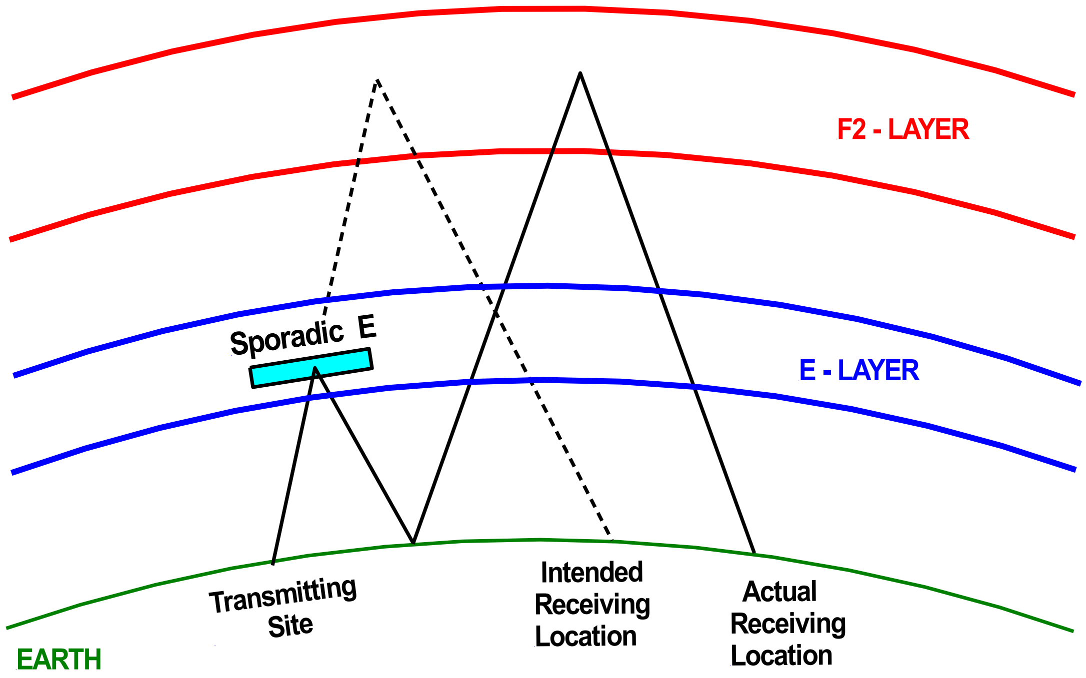
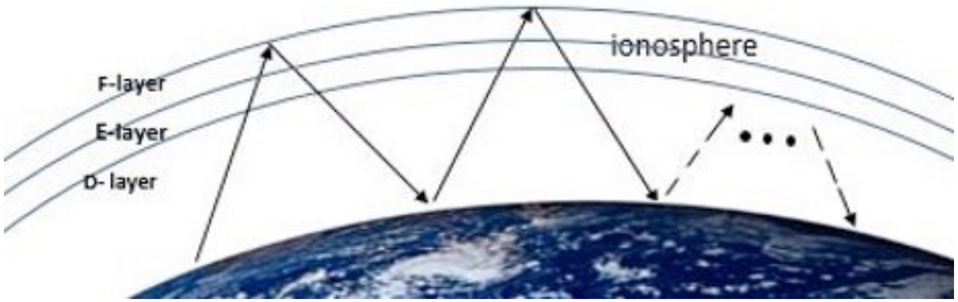
Propagation Modes



Ken Larson KJ6RZ
April 2024

www.skywave-radio.org

Long Distance Skywave Communications



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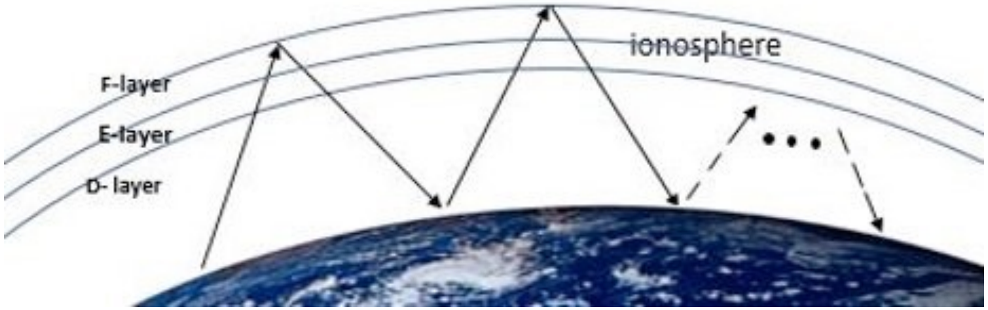
- Long distance communications consists of multiple hops through the ionosphere
- The strength of a signal decreases with each hop due to:
  - The energy lost (absorbed) in each pass through the D region, and
  - Ground losses with each reflection from the Earth's surface (~ 3db from poorly conducting ground and ~ 0.5 db for reflections from the ocean)
- 3 to 4 hops are typical for most long distance skywave communications
- Under ideal conditions, 5 to 6 hops may be possible particularly over the ocean
- Usually, however, more than 4 hops result in signals which are too weak to be received
- Long distance communications depends on each hop being as long as possible
- Enhanced by using high transmitting power and high gain directional antennas

Hop Distance



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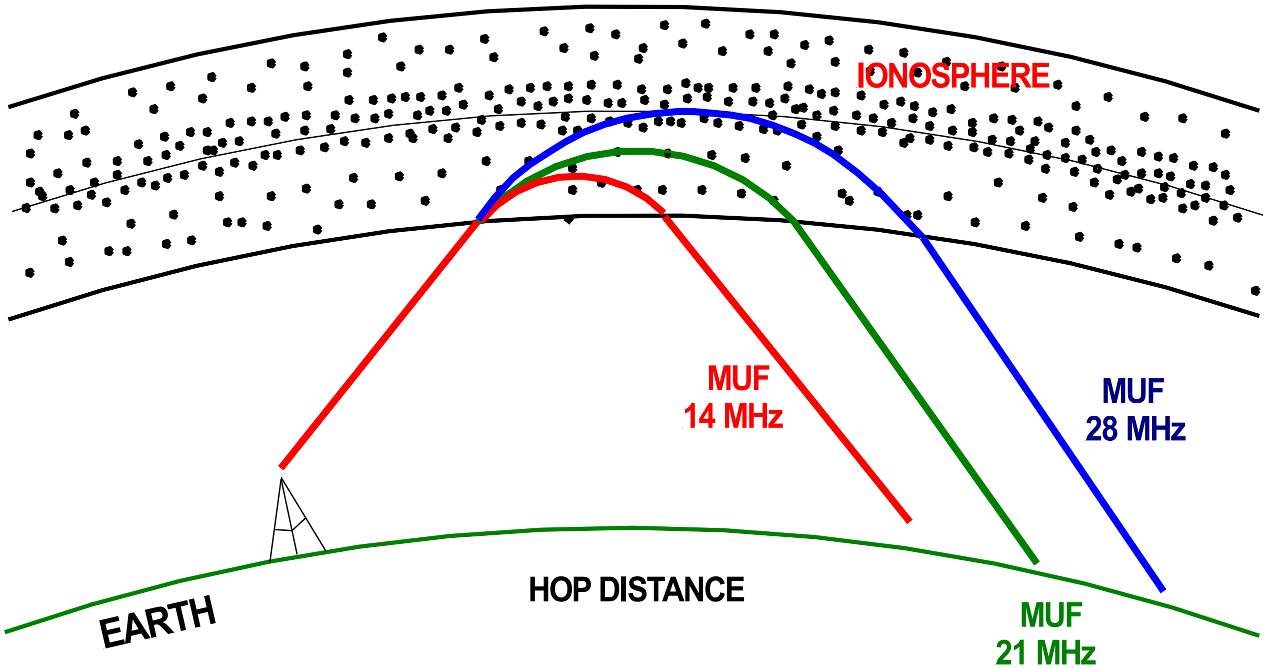
- The distance traveled on each hop depends on:
  - Operating frequency: operating at the Maximum Usable Frequency (MUF) produces the longest hops
  - The current critical frequency: MUF is determined in part by the current critical frequency, a high critical frequency results in a high MUF
  - The height of refraction: longer hops result from signals refracting back to Earth higher in the ionosphere
  - The elevation angle at which signals are transmitted: low angle signals travel further

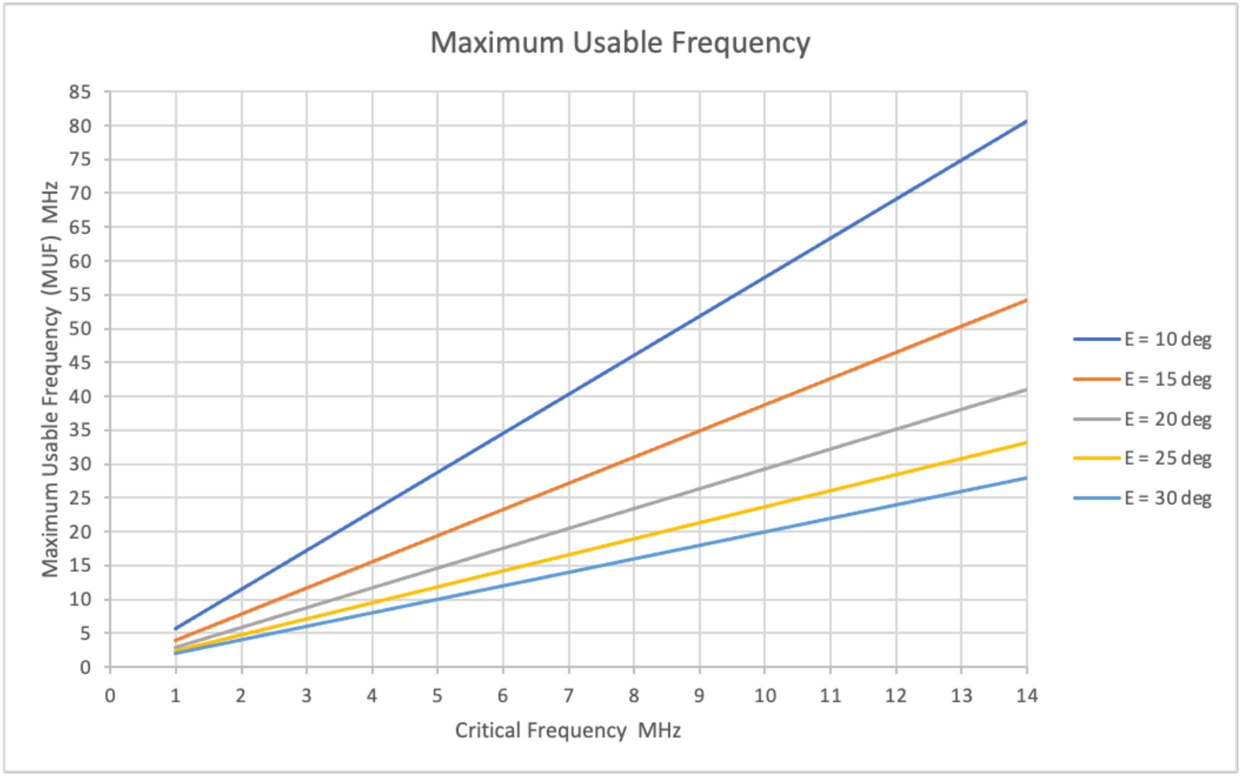
Operating Frequency



Author

- Signals travel progressively higher into the ionosphere as the MUF increases producing longer hop distances
- Example, the hop distance at a MUF of 28 MHz is longer than at a MUF of 14 MHz

Critical Frequency – Impact on MUF



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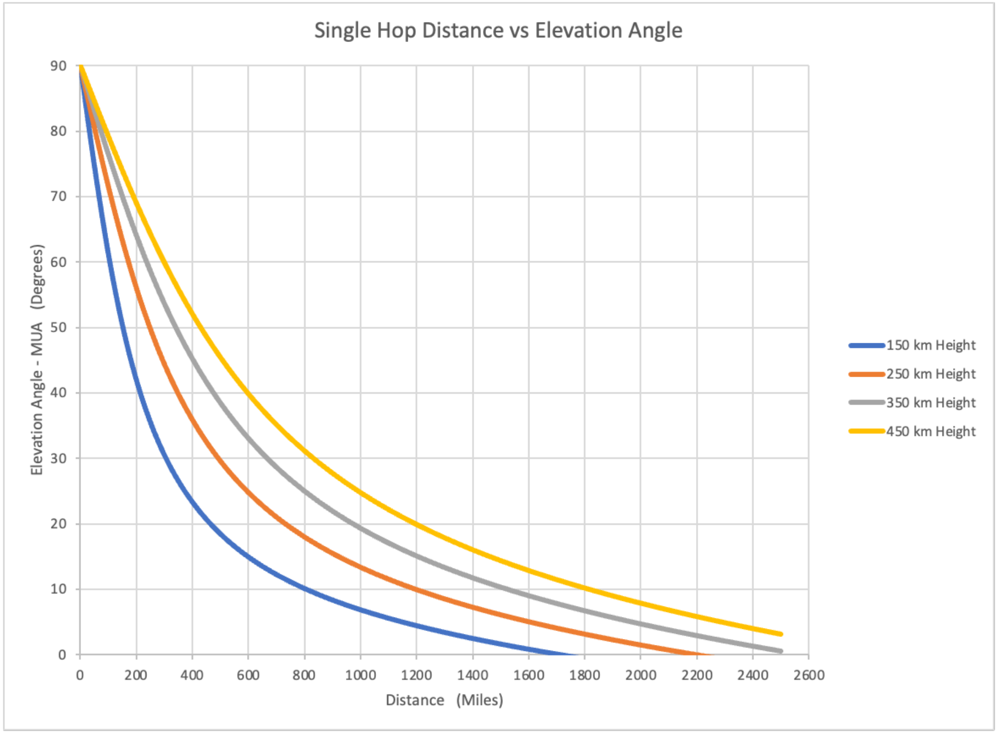
- A high MUF results from a high critical frequency and transmitting at a low elevation angle E
- For example, at a critical frequency of 8 MHz, the MUF is approximately 30 MHz when transmitting at an elevation angle of 15^{o} (red trace)
- At this MUF, the 20 through 10 meter frequency bands are open

Elevation Angle and Height of Refraction



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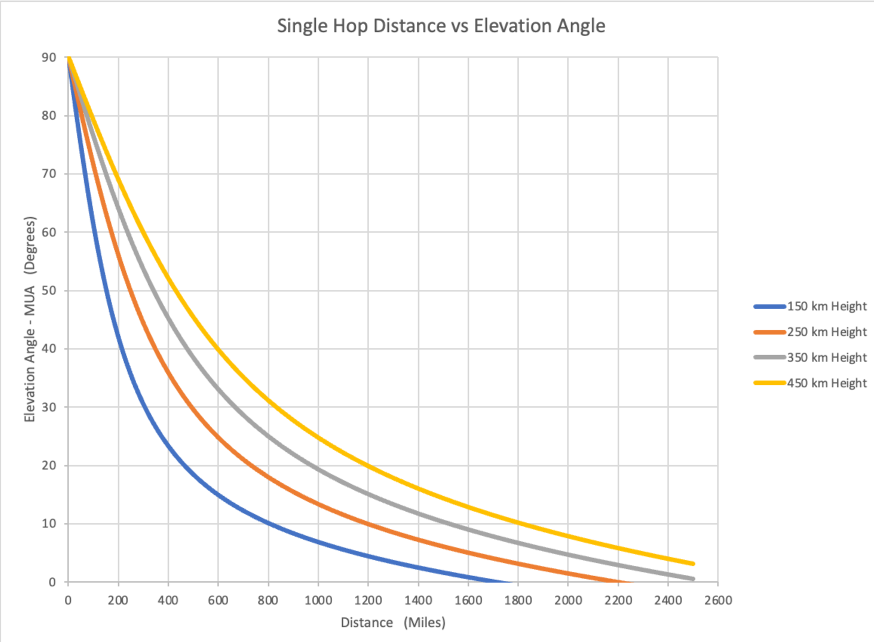
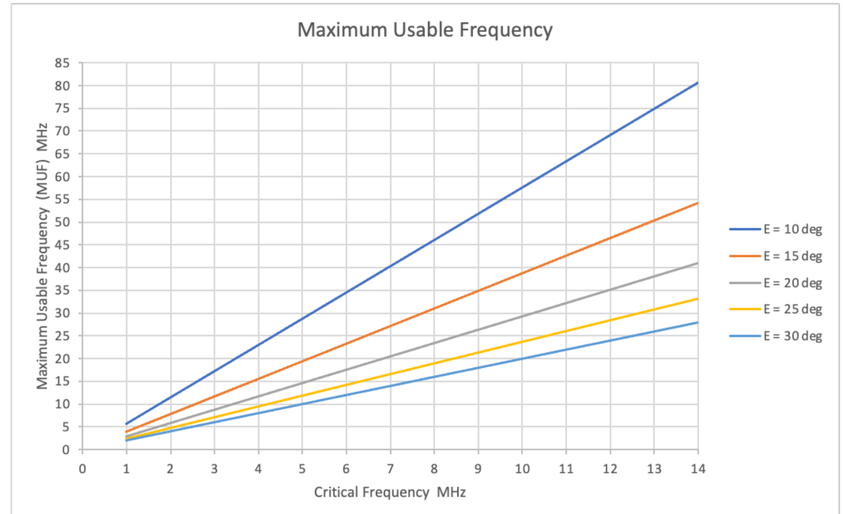
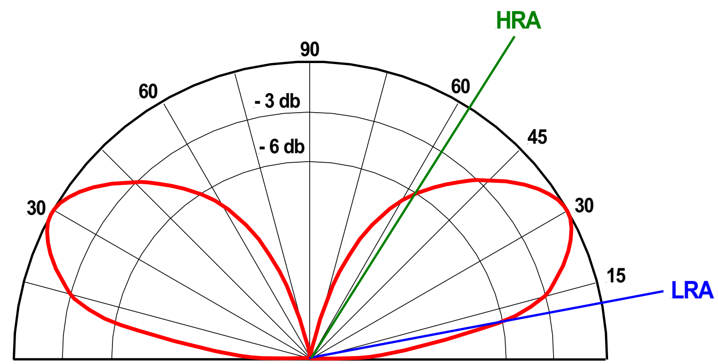
- Hop distance depends on the angle at which a signal is transmitted and the height at which the signal is refracted back to Earth
- For example, the hop distance of a signal transmitted at an elevation angle of 15^{o} will be approximately 1,200 miles when the refraction height is 350 km (gray trace)
- Note that the height at which a 10 meter signal refracts back to Earth is higher than that of a 20 meter signal resulting in the 10 meter signal having a longer hop distance

Your MUF and Hop Distance

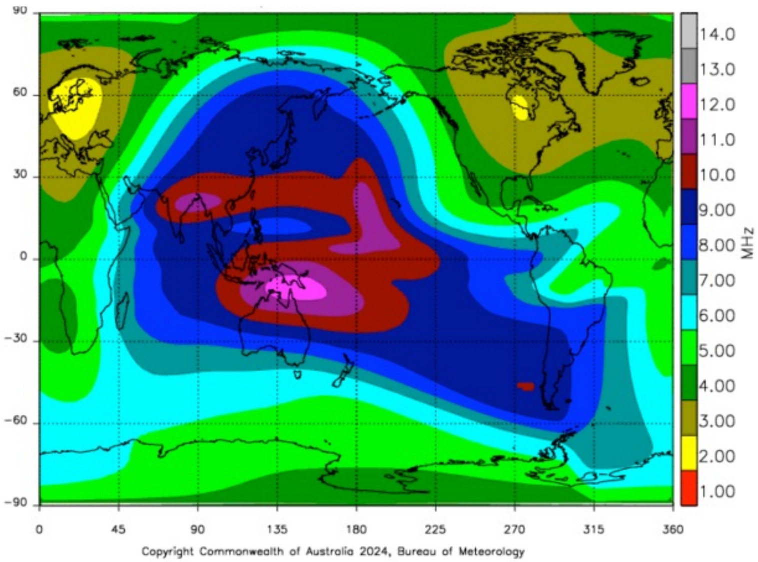




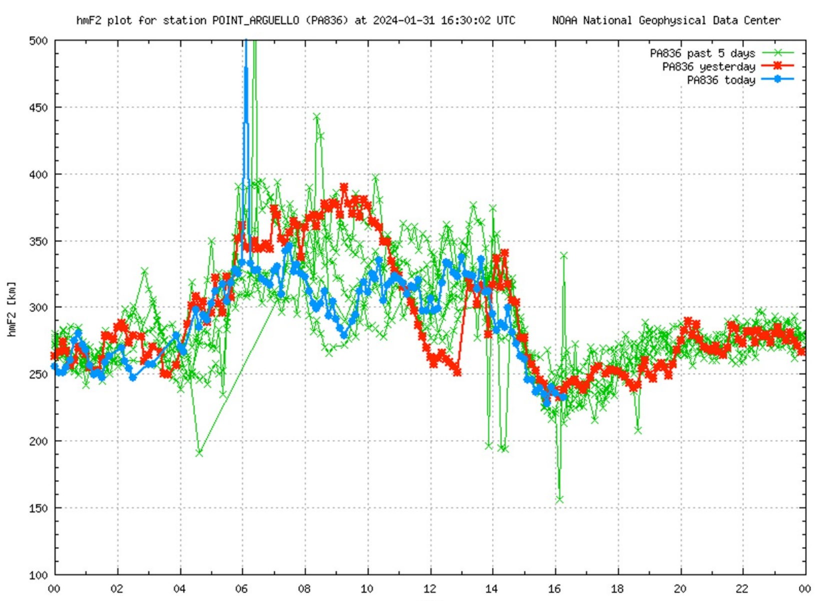


- YOUR maximum usable frequency and the hop distance that YOU achieve depends on the lowest angle at which YOUR antenna is capable of radiating a signal (LRA)
- MUF and hop distance are personal characteristics of YOUR radio station

Determining Critical Frequency and Height of Ionosphere



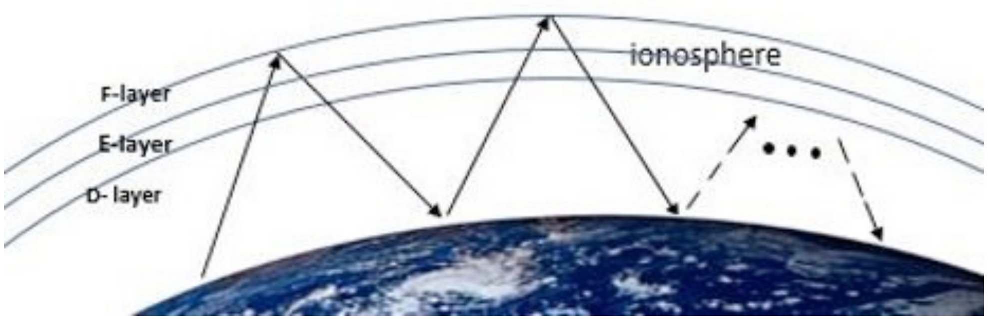
Critical Frequency



F2 Height

- Determining your MUF and hop distance depends on knowing the current critical frequency and height of the ionosphere's F2 region
- Current critical frequency is determined by clicking on Critical Frequency under the Current Conditions tab of the www.skywave-radio.org web site
- Example: the critical frequency over California was 4 MHz (dark green) at 02 UT (6 PM) on Jan 31, 2024
- Current height of the F2 region is determined by clicking on Ionograms under the Current Conditions tab
- Example: the F2 height over California (Point Arguello) was 250 km (blue trace) at 02 UT on January 31, 2024

Propagation Modes



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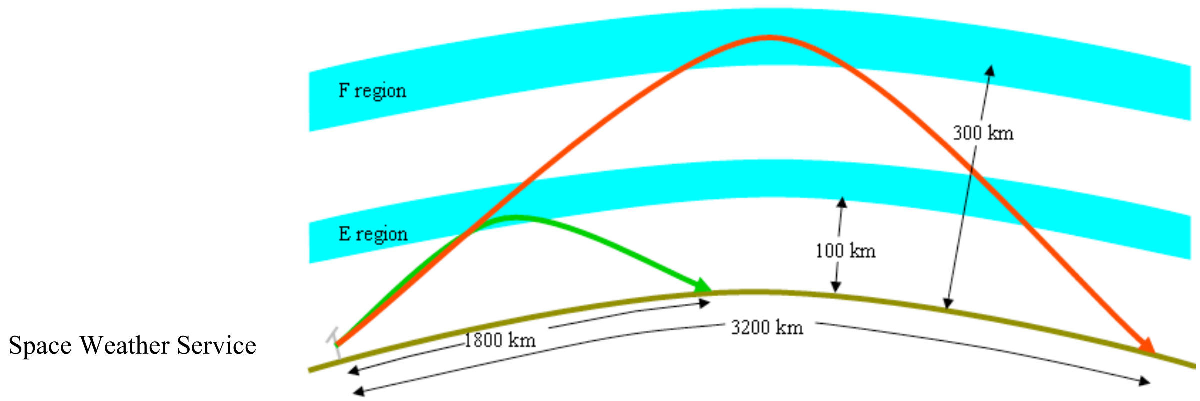
- We usually assume (as above) that skywave communications consists of multiple hops through the ionosphere's F region
- However, other propagation modes are also possible including:
- E mode propagation,
- Sporadic E propagation,
- Multi-path propagation,
- Backscatter,
- Great Circle propagation,
- Gray Line propagation,
- Equatorial Sporadic E propagation,
- Transequatorial Propagation (TEP),
- Ionospheric Ducting

E Mode Propagation

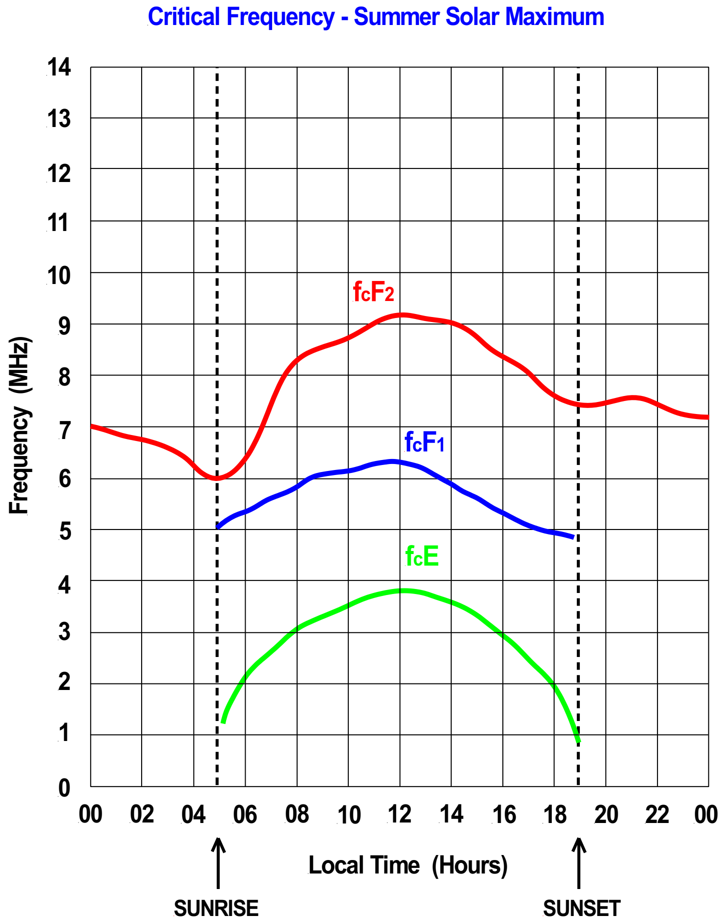


- Radio waves refract back to Earth from both the ionosphere's E and F regions
- E region hops are shorter than hops through the F layer
- A transmitted signal will bend back to Earth in the E region, preventing it from reaching the F layer, if the signal's elevation angle is below the E region Maximum Usable Angle (MUA_E)

$$MUA_E = \sin^{-1}\left[\frac{f_{cE}}{f_o}\right] \quad :: \quad f_{cE} = E\ region\ critical\ frequency, \quad f_o = \text{operating frequency}$$

- In that case, the E region acts like a shield preventing low angle signals from reaching the F region
- As a consequence the hop distances of low angle signals are dramatically shortened from their long hops through the F layer, adversely affecting long distance (DX) communications
- This typically occurs around noon time when the E region critical frequency is the highest

E Region Critical Frequency



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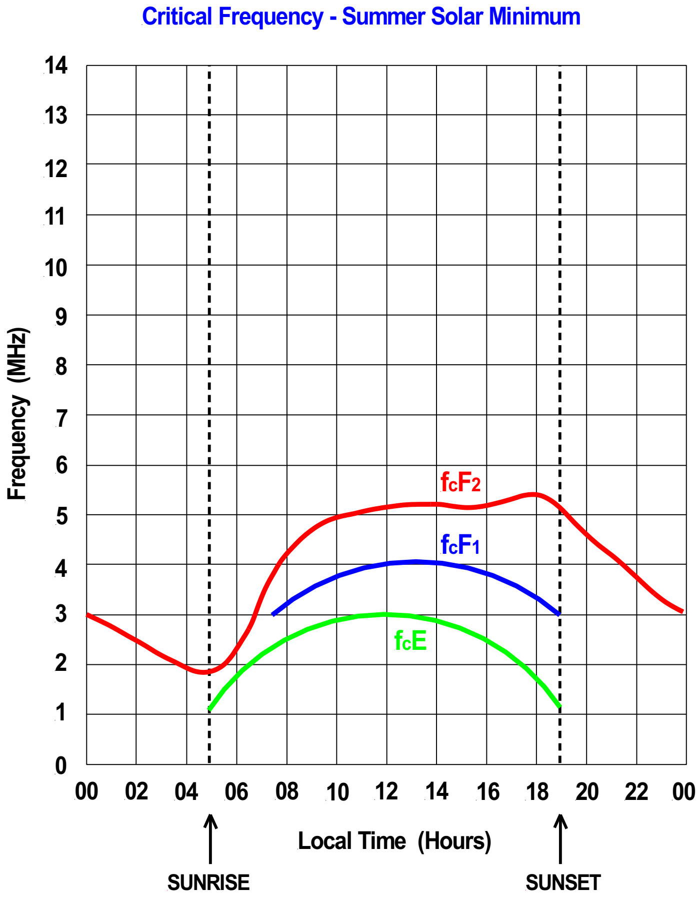
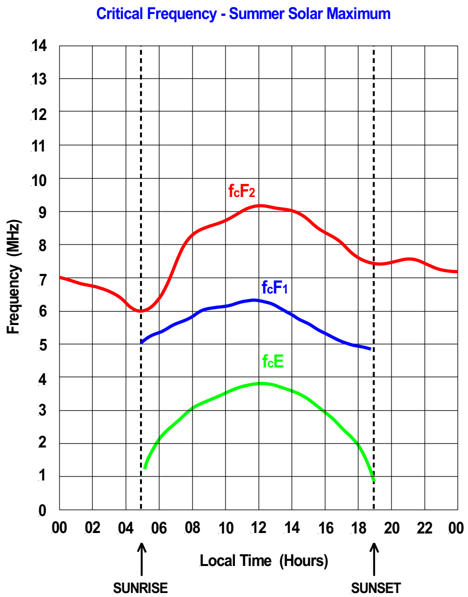
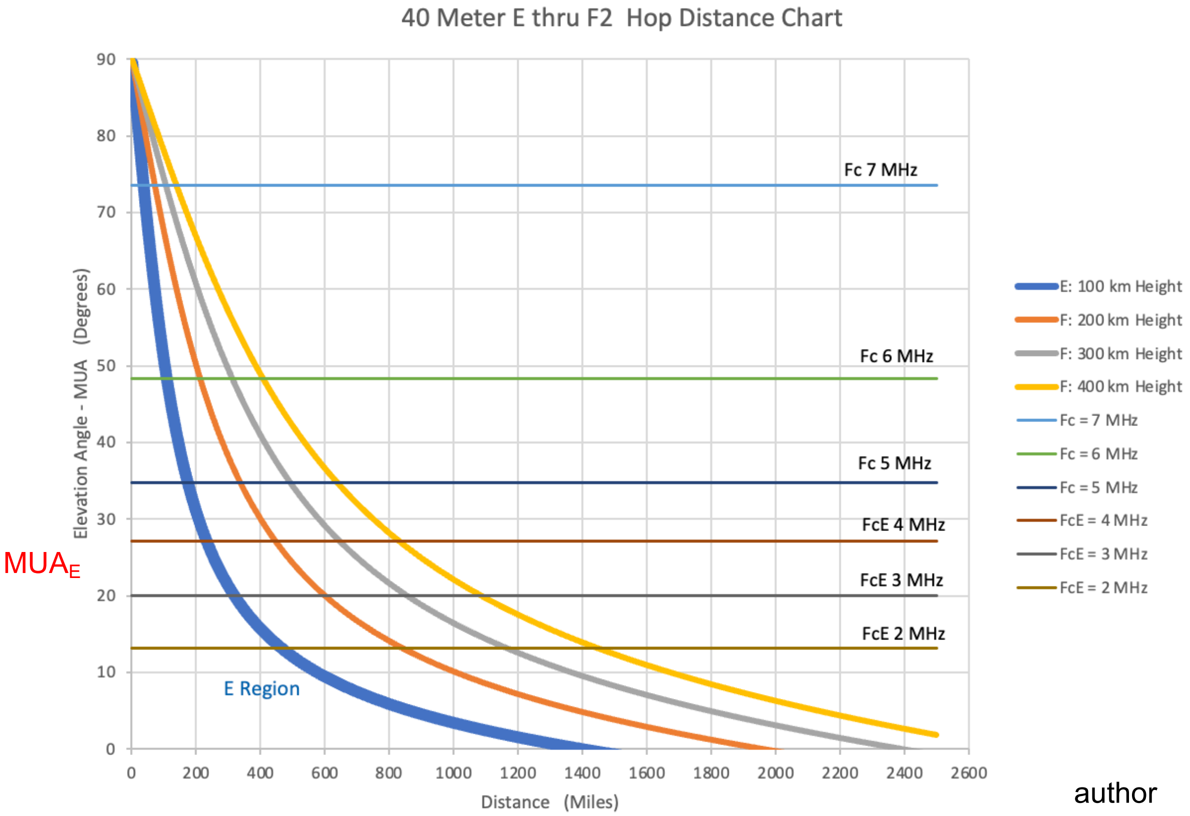


- The E region's noon time critical frequency f_{cE} during solar maximum is 3 to 4 MHz
- During solar minimum its noon time critical frequency is 2 to 3 MHz

E Region Screening

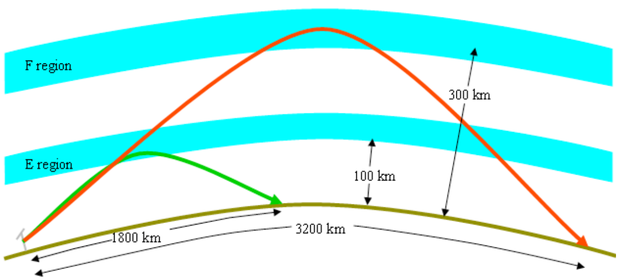


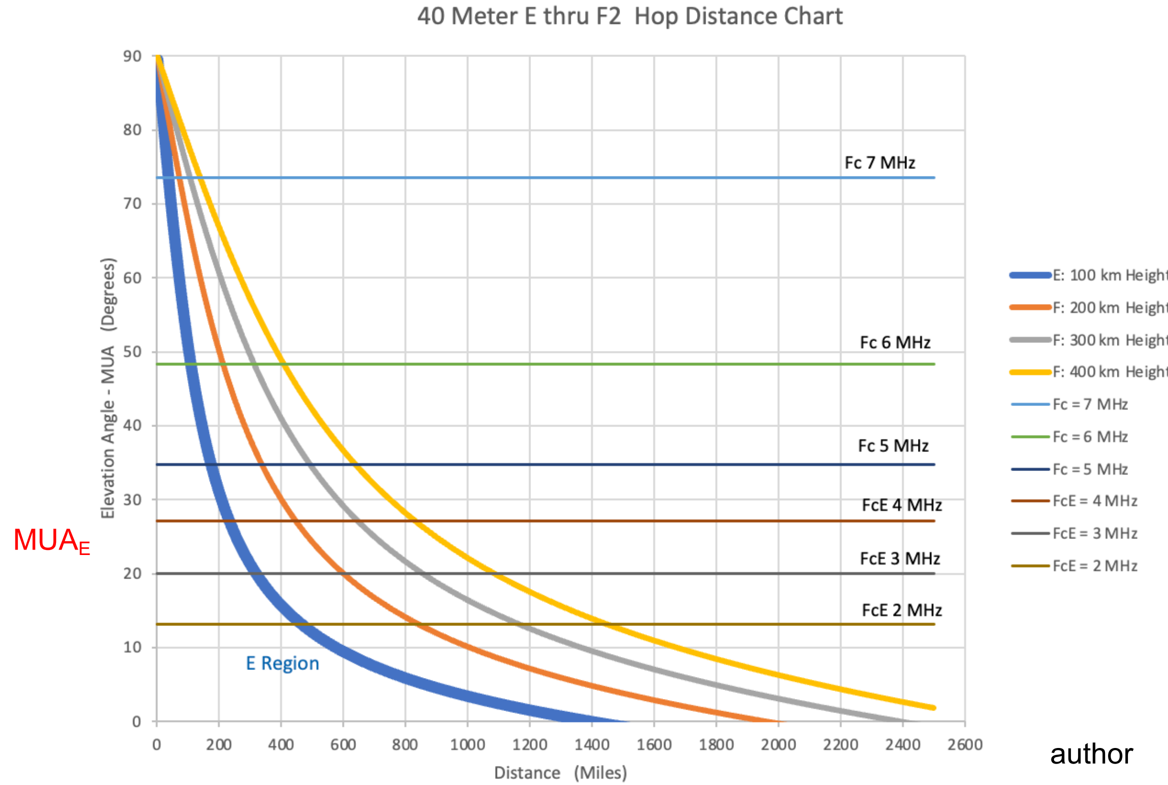


author

- At an F region height of 300 km (gray trace) 40m hop distances increase as the transmitted signal's elevation angle drops reaching a distance of 1,400 miles at an elevation angle of 10°
- However, the E region mid day critical frequency of f_{cE} = 3 to 4 MHz causes 40 meter signals transmitted at angles below the E region MUA_E of 20 to 28° to refract in the E region

E Region Screening continued

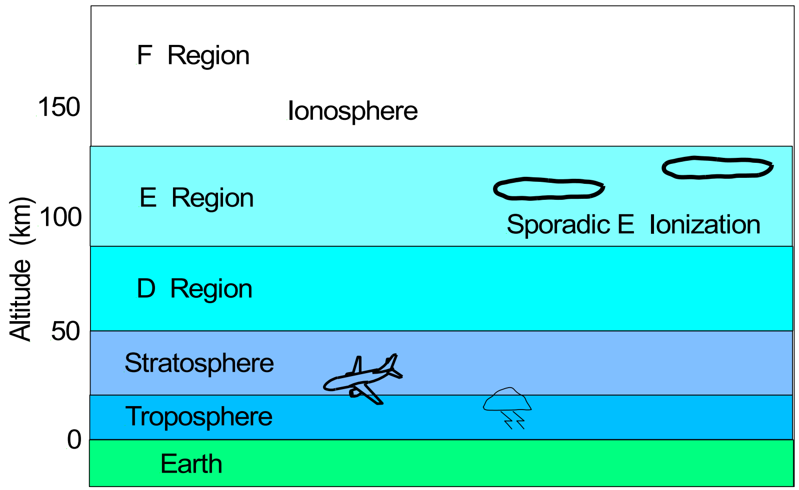




author

- Signals refracting in the E region are blocked from reaching the F layer
- Which in turn causes hop distance to drop from the F region 25° distance of 700 miles (gray curve) to the E region hop distance of only 250 miles
- E region screening has a more detrimental affect on 40, 30, and 20 meter mid day DX than D layer absorption

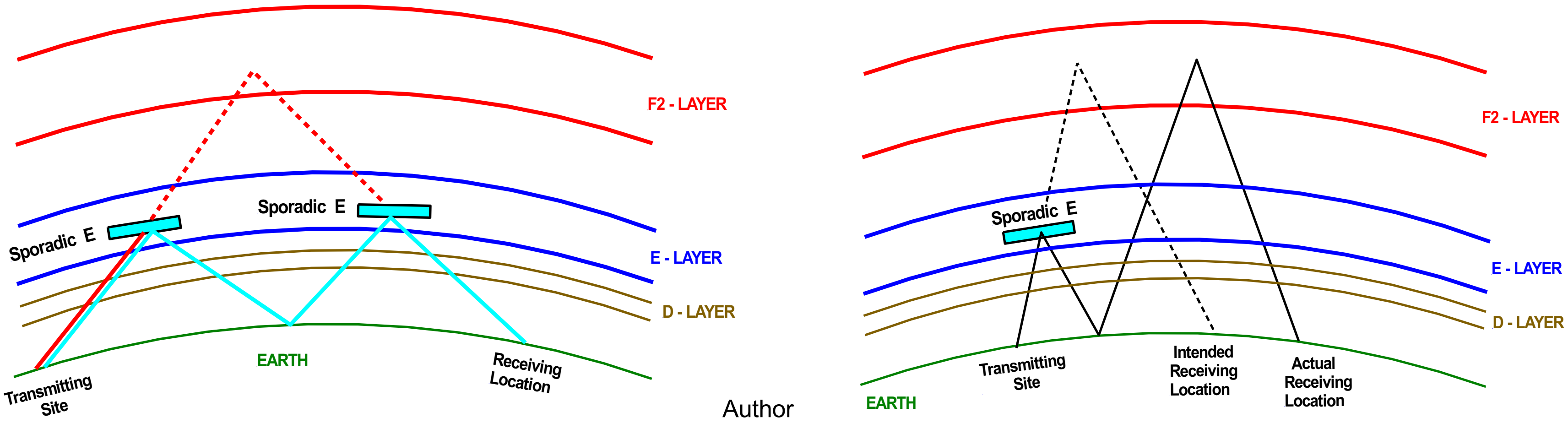
Sporadic E Propagation



author

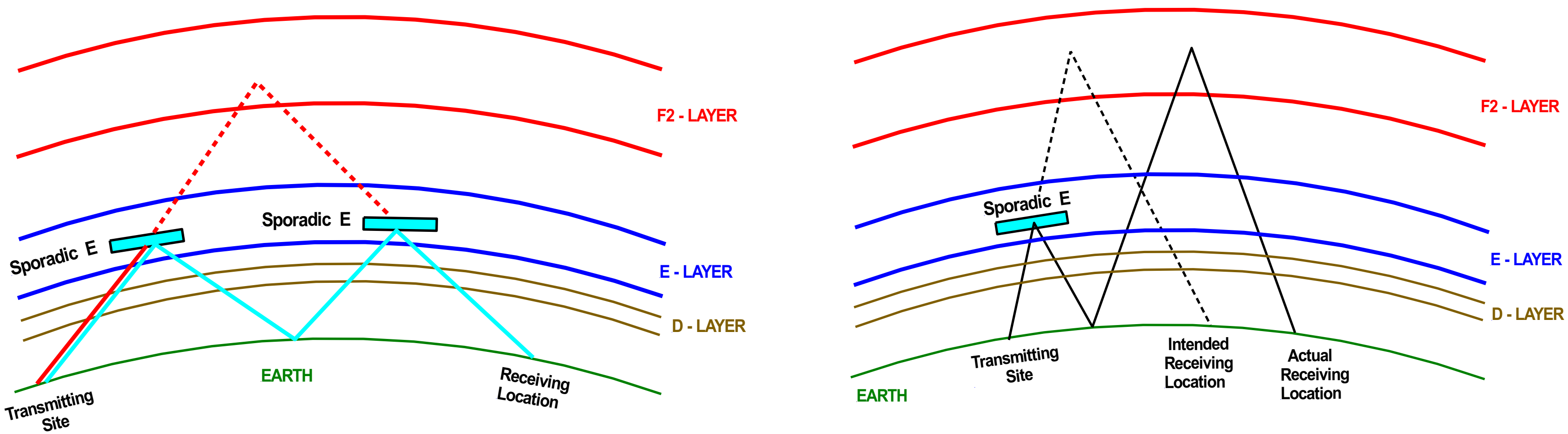
- Sporadic E (E_s) formations with abnormally high ionization levels often occur in the E region reflecting HF radio signals at frequencies up to 100 MHz
- They are called sporadic E because they randomly appear in various sizes and shapes, persist for minutes to hours, and occur from one day to the next with little predictability
- Sporadic E zones are relatively large structures about 2 kilometers thick with horizontal dimensions stretching hundreds of kilometers
- In general, sporadic E appearances seem to have little direct relationship to the ionization processes responsible for the E region itself

Sporadic E High Electron Densities



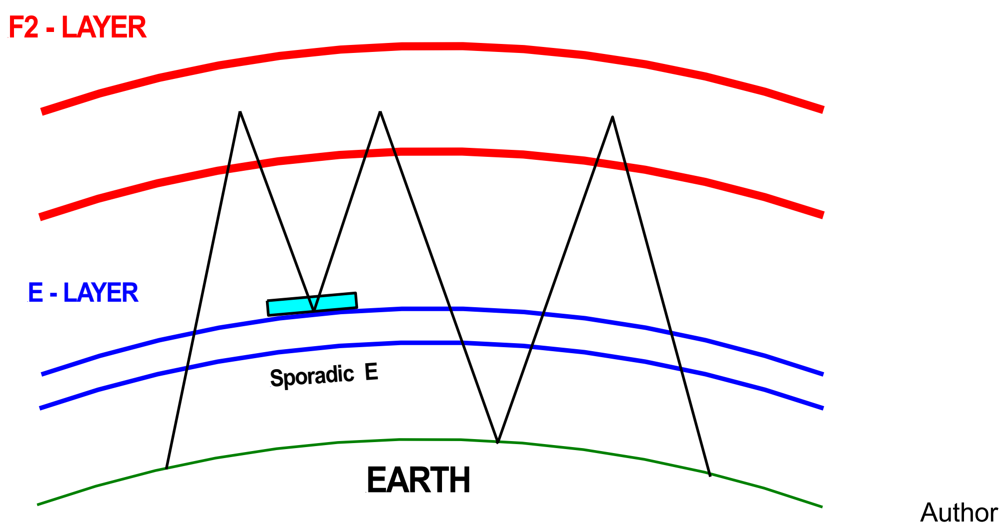
- Sporadic E zones often have electron densities:
  - Far greater than normal E region levels, and
  - At times even greater than in the F region
- High electron densities cause sporadic E patches to be opaque preventing radio signals from passing through to the F region

Sporadic E Can Seriously Impact HF Radio Circuits



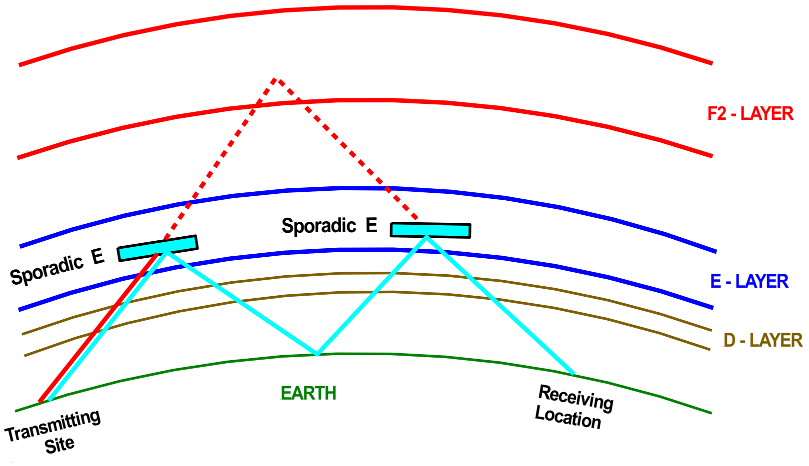
- Instead of allowing signals to pass through to the F layer, sporadic E patches reflect signals back to Earth forcing signals to follow multiple hop paths to the desired destination
- Multiple hops mean more ground reflections and more passes through the attenuating D region seriously degrading received signal levels
- Worse yet, the intended receiving location could be missed altogether
- Sometimes radio signals reach the F2 Layer through rapidly changing gaps between sporadic E patches causing the destination to receive weak or fluctuating signals
- Increasing operating frequency often does not avoid sporadic E propagation

Top Side Reflections



- It is important to note that
- Sporadic E reflections can occur on the top side of the E region as well

Low Latitude Sporadic E Zones



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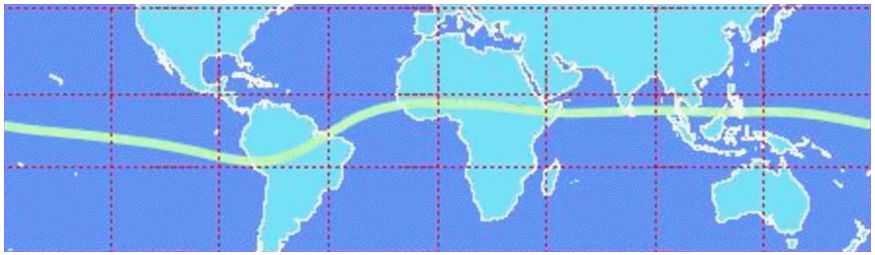
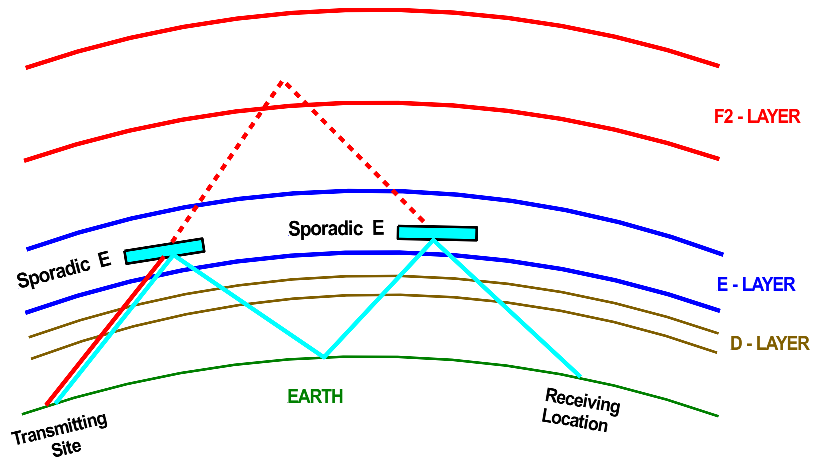


gfz-potsdam.de

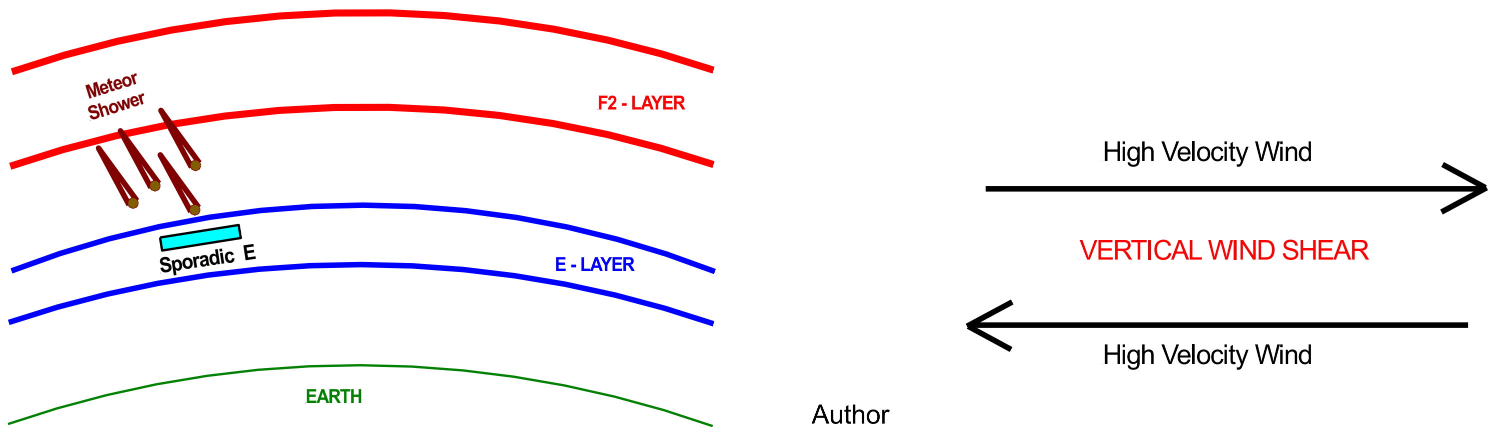
- Sporadic E zones are particularly strong in the low latitude equatorial region where they are essentially a daytime phenomenon with little seasonal variation
- It is believed that they are formed in this part of the world by instabilities in the equatorial electrojet

Mid Latitude Sporadic E Zones



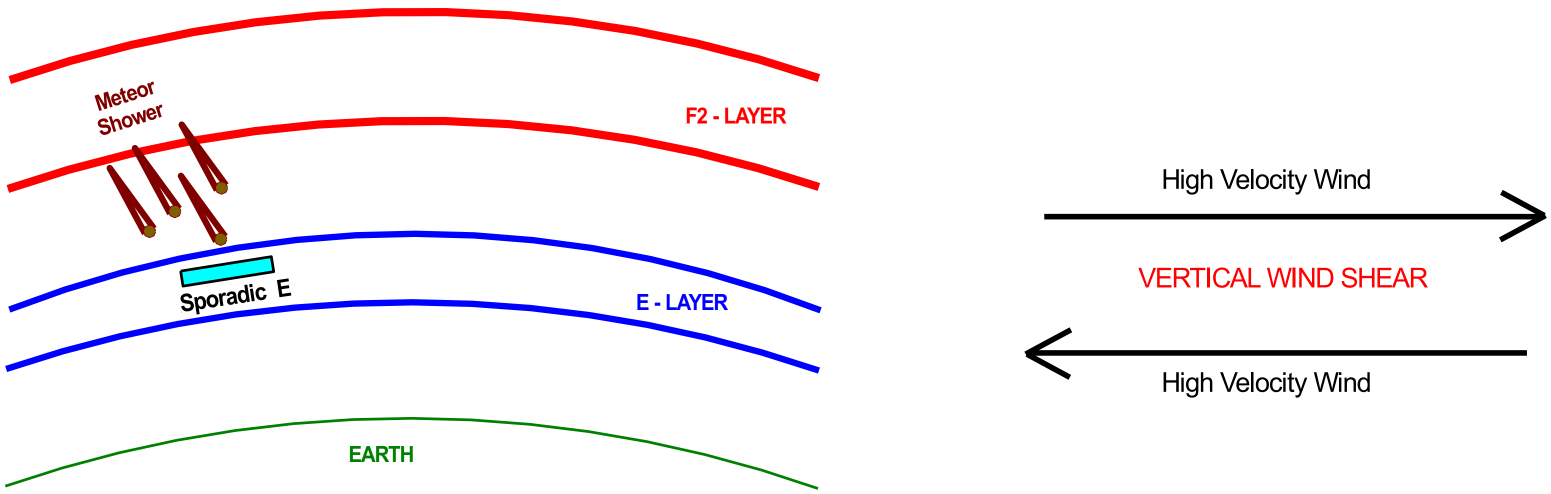
- At mid latitudes sporadic E zones tend to be weaker than in the equatorial and polar regions
  - Their occurrence is subject to diurnal and seasonal variations
  - They tend to be more prevalent during the summer than in winter
  - They tend to occur more during the day than at night, particularly in mid-morning and near sunset

Formation of Mid Latitude Sporadic E Zones



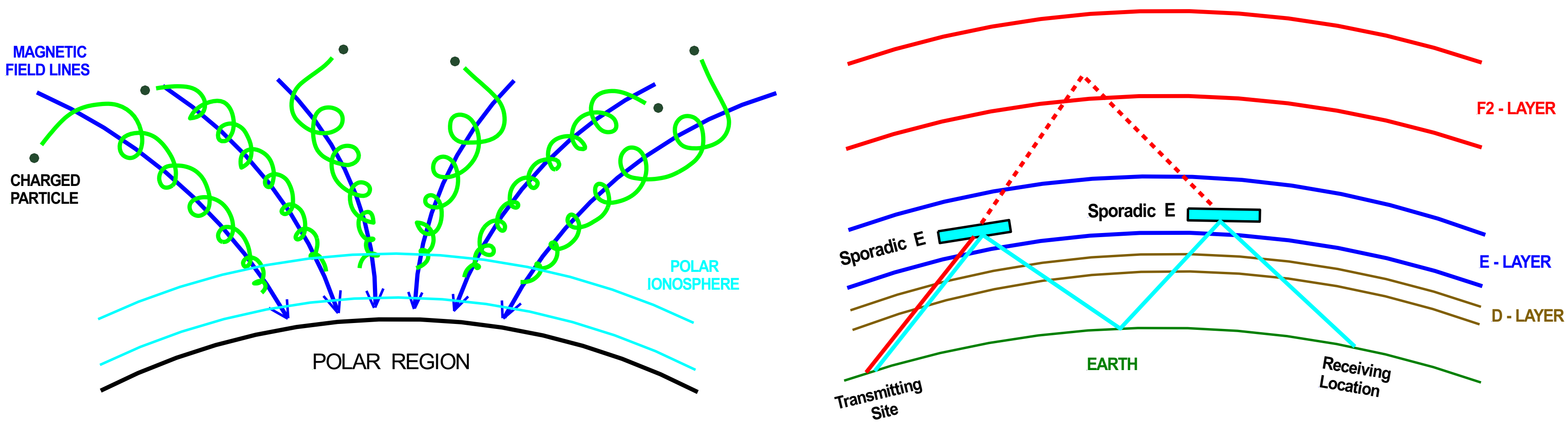
- It is believed that sporadic E patches at mid latitudes form as the result of wind shear in the upper atmosphere in combination with meteoric debris
- Enormous numbers of meteors burn up in the E region of the atmosphere
- The meteoric debris is largely monatomic metallic ions
- These ions become trapped between high velocity winds traveling in opposite directions within the E region

Formation of Mid Latitude Sporadic E Zones continued



- Metallic ions are much smaller than the molecular ions that make up most of the E region
- Because they are small, their rate of electron-ion recombination is low compared to molecular ions
- Resulting in high, sometimes much higher, concentrations of electrons in the sporadic E patches than in other parts of the E region

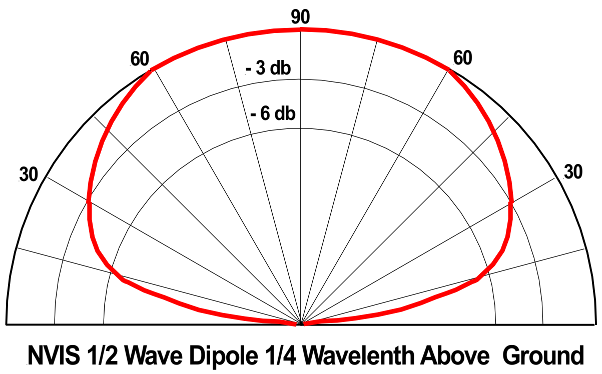
High Latitude Sporadic E



Author

- At high latitudes auroral sporadic E zones occur mainly at night with little seasonal variance
- They are attributed to ionization by incoming high energy charged particles entering the auroral region from the magnetosphere
- Clouds of auroral E_s drift westward in the evening and eastward in the early morning
- Sporadic E zones within the polar caps are different. They are weaker and extend across the polar caps in the form of ribbons in a roughly sunward direction

Multipath Propagation



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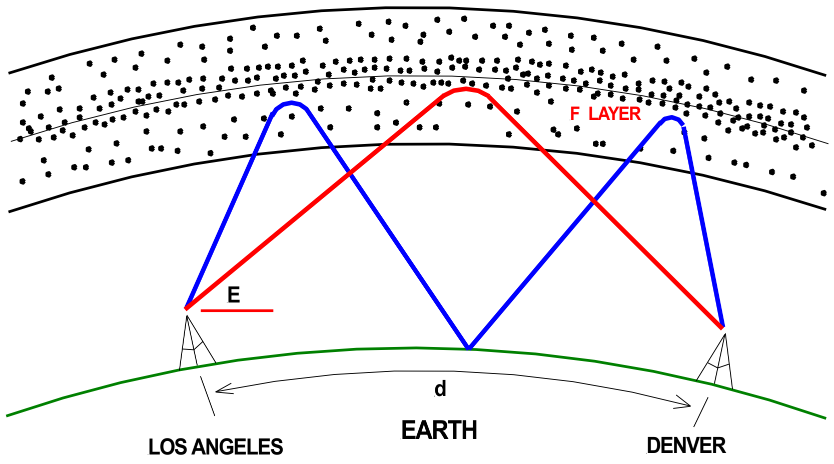
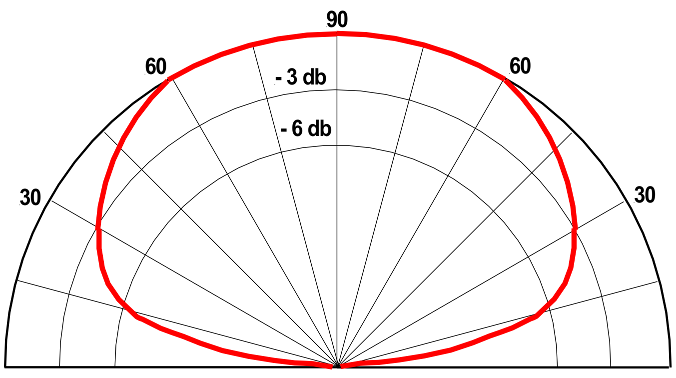
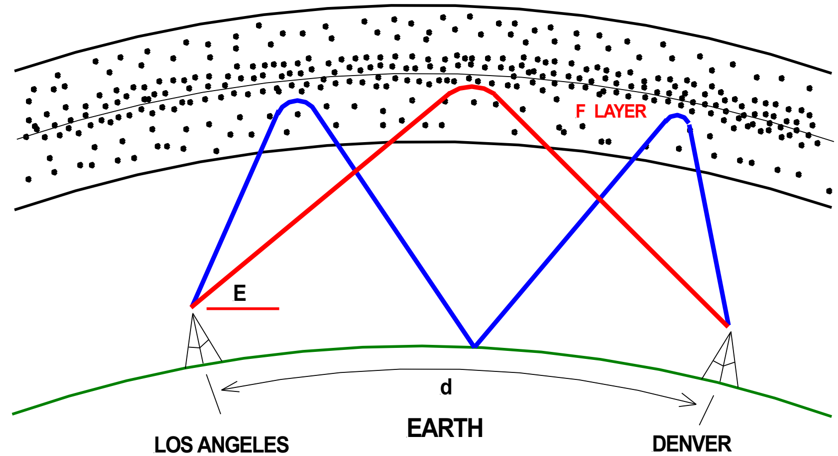


- Example: Communications between Los Angeles and Denver, a distance of 800 miles, can often occur on 40 meters in either one hop or in two hops
- We usually have little control over the elevation angle at which our antennas radiate
- A 40 meter NVIS half wavelength dipole radiates at all angles from 20 to 90^o
- Radiation from this antenna will reach Denver following both the single (20^o elevation angle) and double hop (38^o) propagation paths

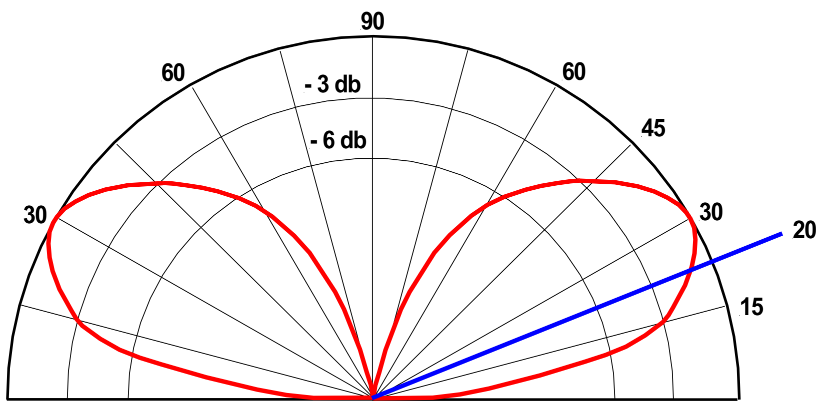
Multipath Propagation Interference





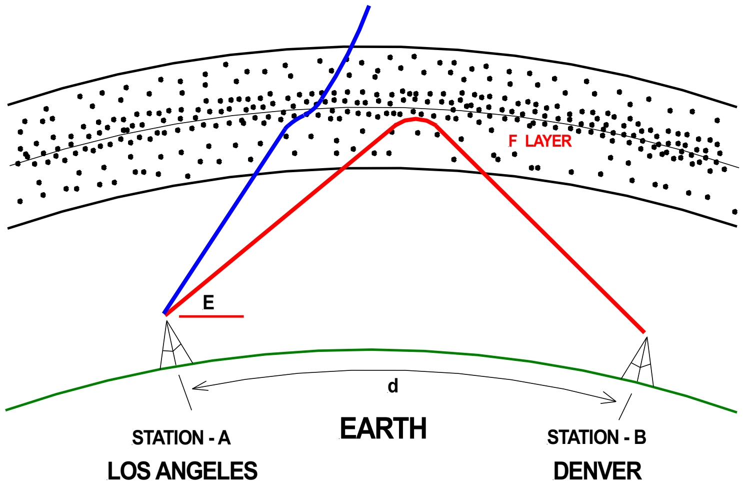
- The single and double hop signals will be out of phase when they arrive in Denver since the double hop signal has to travel a longer distance
- Consequently, the two signals will interfere with each other:
  - Reducing the strength of the received signal, in addition to
  - Producing distortion and fading

Solving The Multi-path Problem



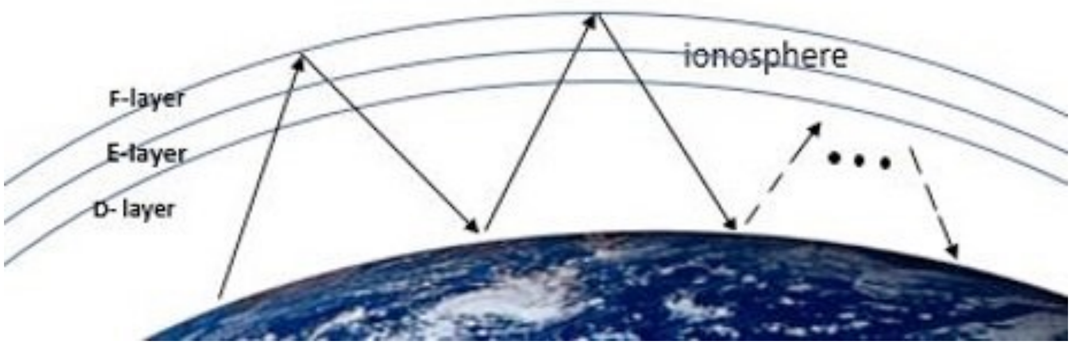
20 Meter 1/2 Wavelength Dipole Antenna At Optimum Height

Author



- Switching to a higher frequency (for example 20 meters) will force the double hop path to penetrate the ionosphere and disappear into outer space
- The lower angle single hop path is the only path remaining eliminating multi-path interference
- Consequently, operating at the highest possible frequency usually solves multi-path problems
- Note that a 20 meter antenna typically supports both the required 20° and 38° radiation angles, but the 38° signal is lost to outer space

Ground Reflection Elevation Angles



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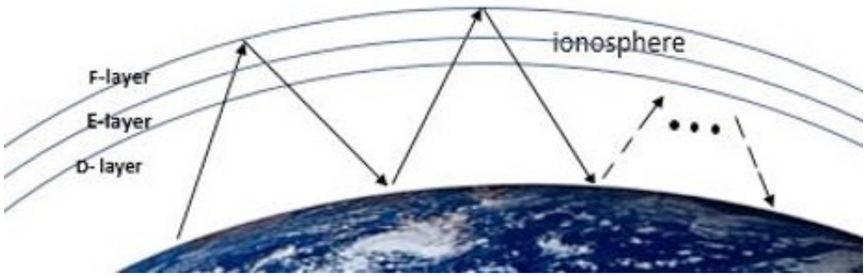
- We assume in our simple propagation diagrams that the elevation angle of our transmitted signal remains the same hop after hop as our signal makes multiple reflections from a flat, smooth, horizontal Earth
- This over simplification is usually not the case, consequently
- Ground reflection elevation angles are constantly changing as a signal propagates
- This affects hop distances
- Even worse, a high reflection angle could cause a signal to penetrate the ionosphere and be lost to outer space ---- preventing further propagation

Reflections From A Perfectly Smooth Surface



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- Our assumption of a smooth flat Earth is analogous in many ways to scenery perfectly reflecting from the surface of a very smooth lake
- In terms of reflection, the average depth of surface irregularities must be substantially less than the wavelength of the incident light, or radio wave, to be a perfectly smooth surface
- Radio waves do perfectly reflect from a smooth flat Earth traveling back and forth between the ionosphere and Earth's surface according to our simplistic propagation model
- But again, this is usually not the situation

Ground Scattering of Radio Waves

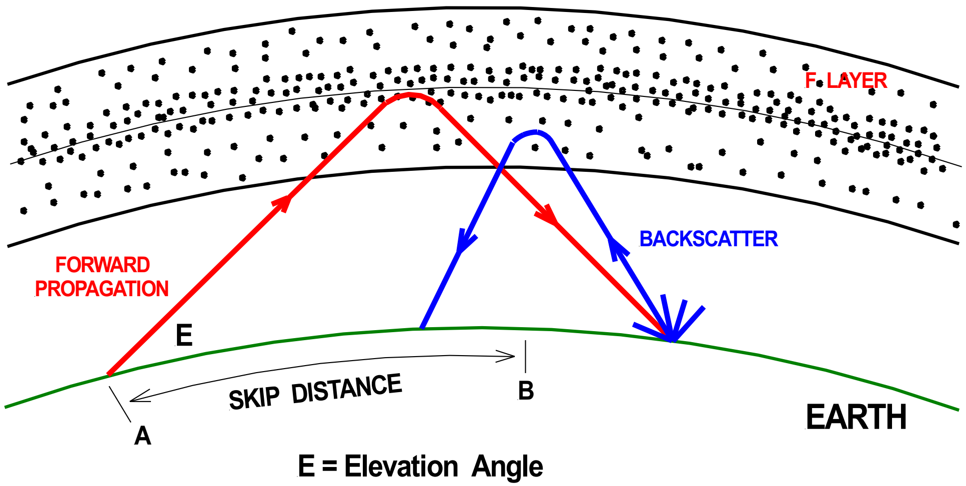
Smooth lake surface

Rough surface

olympus-lifescience.com

- If the surface of a lake is not perfectly smooth, reflected light will be scattered in all directions producing a blurry image
- The same is true of radio waves
- The depth of surface irregularities in hilly terrane is considerably larger than the wavelength of incident radio waves scattering the radio waves in multiple directions
- Some of the scattered radio waves will be reflected in the desired propagation direction
- Radio waves scattered in other directions will be lost resulting in ground scatter attenuation

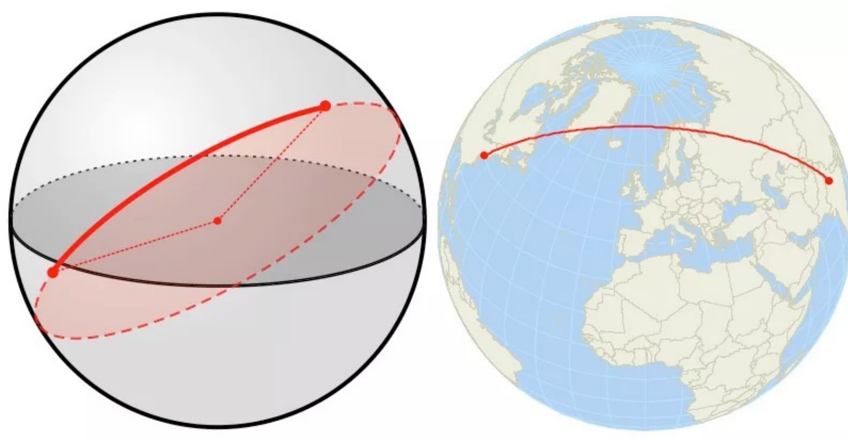
Backscatter



author

- Some of the scattered signal may travel back through the ionosphere toward the transmitting site
- This is known as backscatter
- It is not unusual for some of the backscattered signal to end up in the skip zone
- When this occurs, some of the stations in the skip zone may hear the transmitting station when normally they would not

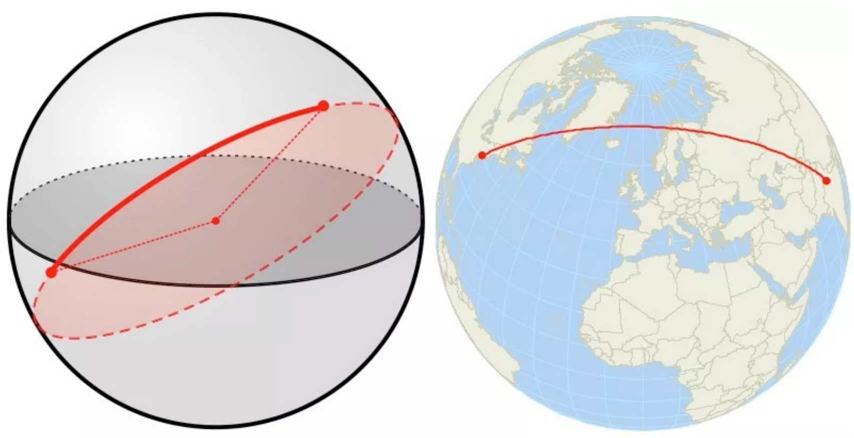
Great Circle Path



Caliper Corporation

- A great circle path is the shortest distance between any two locations on Earth’s surface
- A great circle is formed by a plane passing through the two points of interest and the center of the Earth
- A great circle always divides the Earth in half
- Thus, the equator and lines of longitude are great circles
- However, lines of latitude are not great circles since they do not cut the Earth in equal halves

Radio Wave Great Circle Propagation



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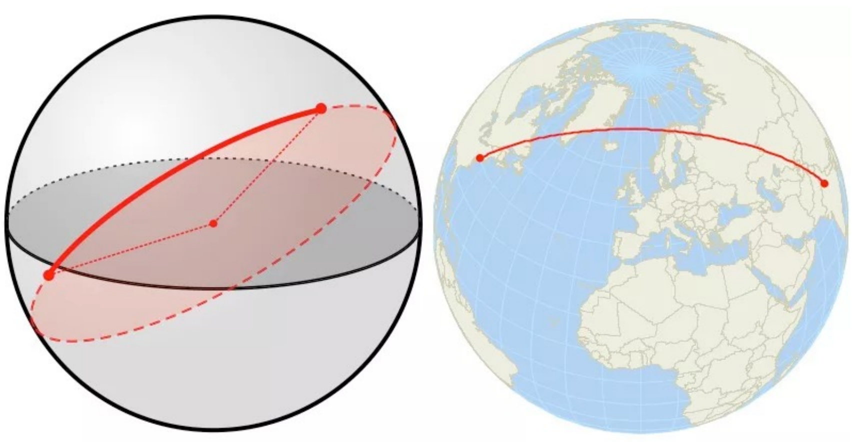
- Normally, radio waves follow great circle paths since a great circle is the shortest distance between the transmitting and receiving stations
- However, high latitude ionospheric irregularities including, ionospheric troughs, high latitude spread F, Traveling Ionospheric Disturbances etc. can seriously alter signal propagation paths
- In addition, diverging ordinary and extra ordinary radio waves complicate the problem further as they travel through the polar regions

Great Circle Propagation Example



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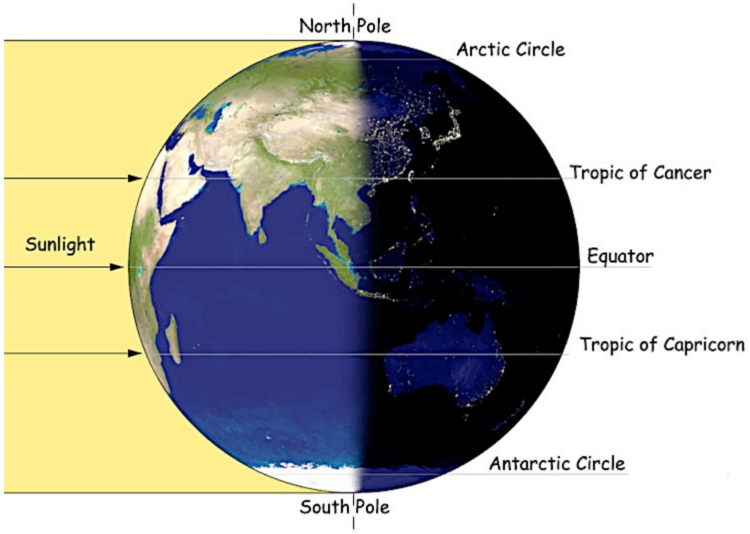
- For example, a signal intended to travel along the great circle path over the polar region from eastern United States to India
- Could instead end up in Egypt or perhaps Korea
- A signal transmitted from Los Angeles to Fairbanks, Alaska could end up in Hawaii
- In general, great circle paths become less meaningful for signals propagating through Earth's polar zones

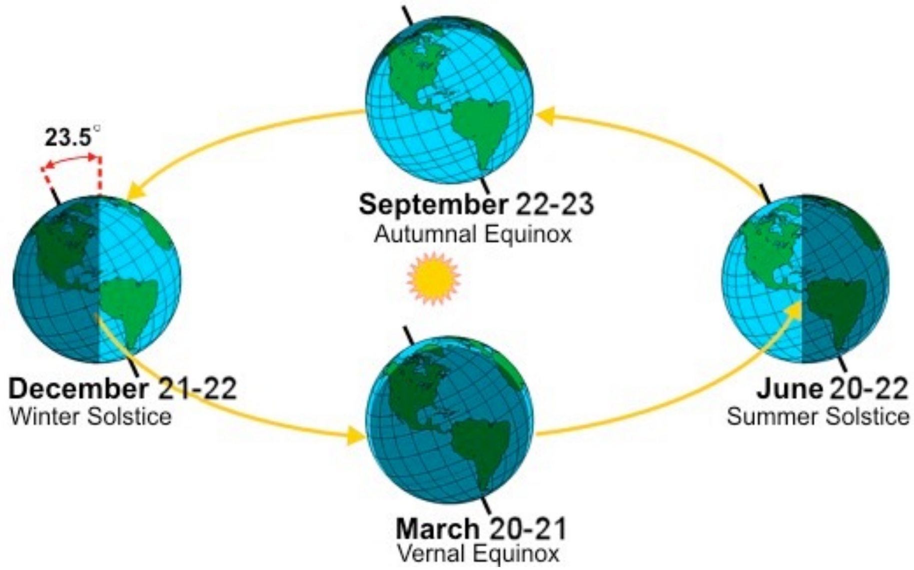
Earth's Terminator



cseligman.com

- The line dividing night and day is called the terminator
- It is also referred to as the gray line and twilight zone
- It is actually a fuzzy line due to the bending of sunlight in Earth's atmosphere
- Thus, a more appropriate term would be gray zone

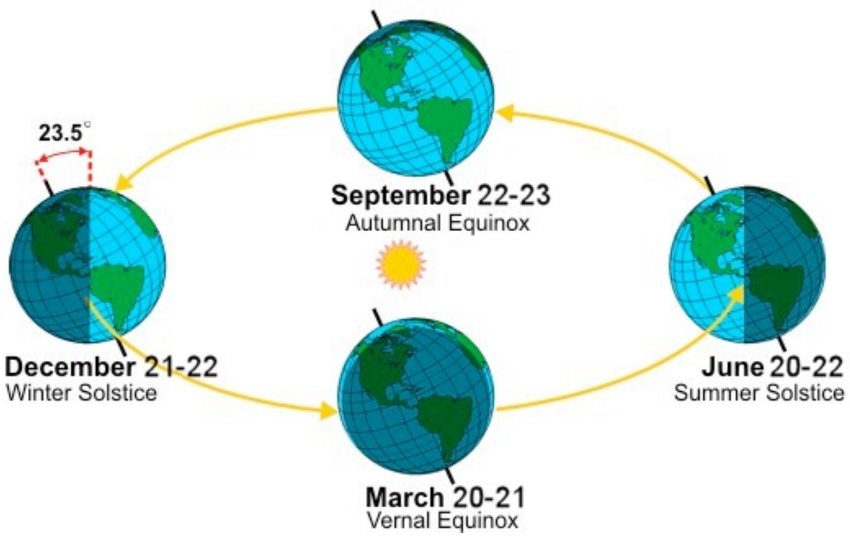
Position of Gray Line Constantly Changes



NOAA National Weather Service

- The position of the gray line is constantly changing as the Earth rotates throughout the day and orbits around the Sun during the year
- Earth's axis is always tilted 23.5^{o} with respect to its orbit
- The gray line runs north and south passing through the Earth's geographic poles during the March 21 and September 21 solar equinoxes
- During the December and June solstices (December 21 and June 21), the gray line is tilted 23.5^{o} with respect to Earth's axis

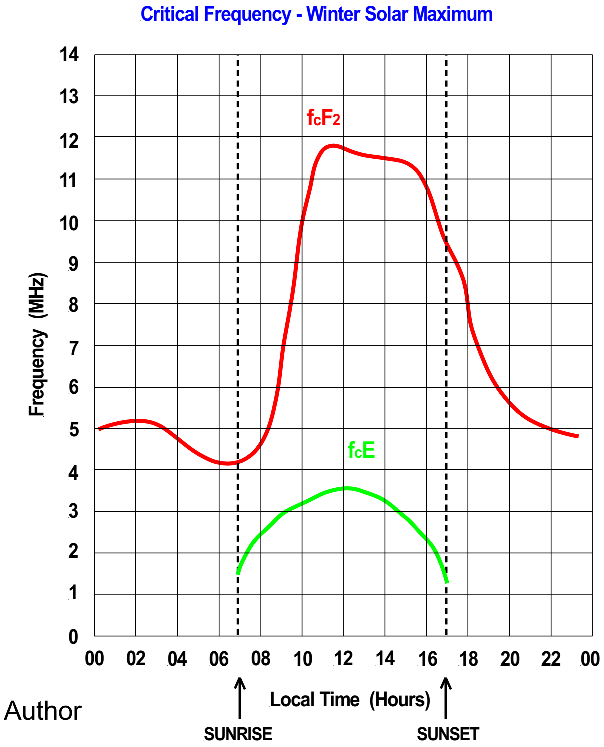
Gray Line Position Constantly Changing



NOAA National Weather Service

- During the course of a year, the gray line traverses a 47^{o} sector of the Earth north and south of the equator as the Earth orbits the Sun
- The width of the gray zone also varies
- The transition between night and day occurs quickly near the equator while in the polar zones it occurs more slowly
- Consequently, the gray zone is wider at high latitudes than at the equator

F and D Region Appearance



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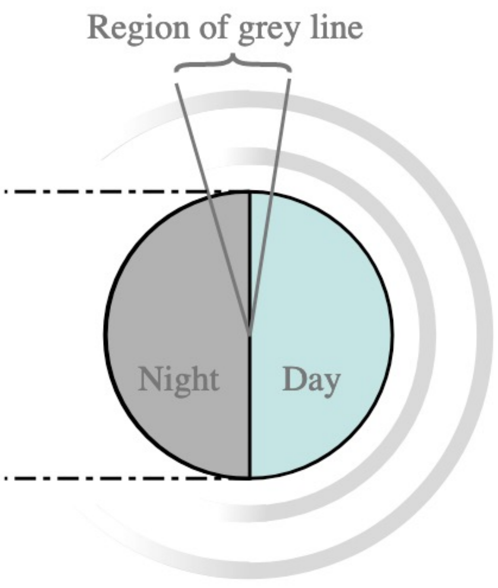
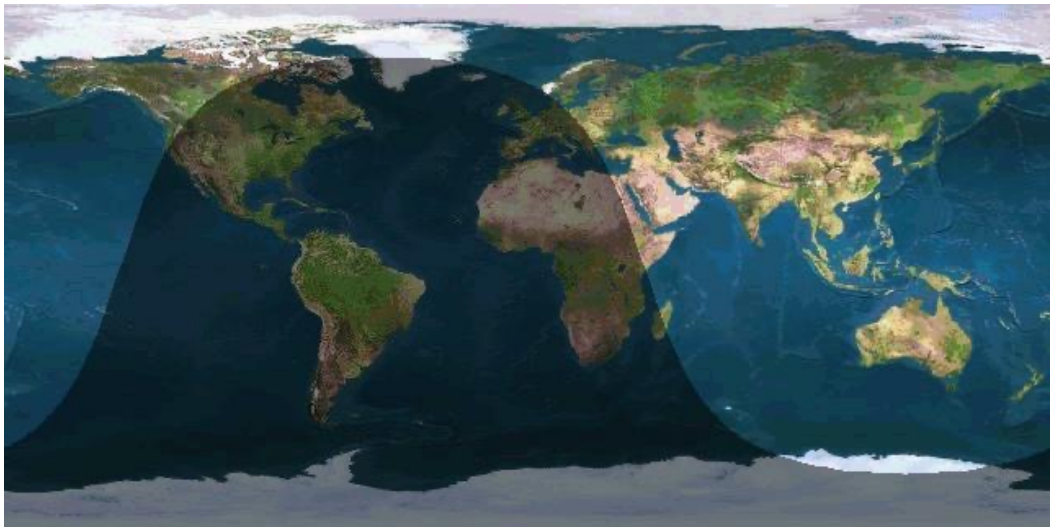
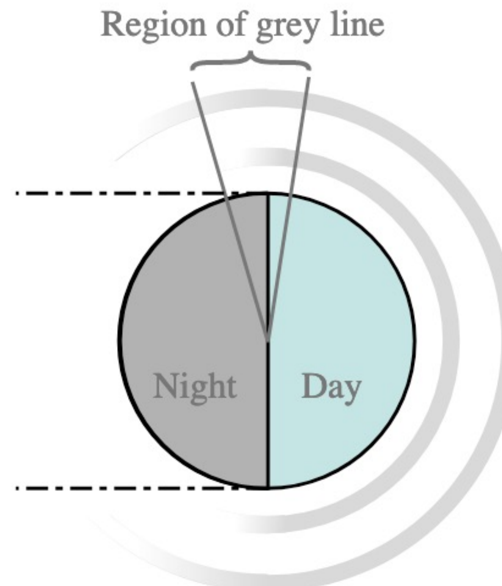


Electronics Notes

- The ionosphere changes significantly during sunrise and sunset
- At sunrise the F region builds rapidly as solar ionization resumes
- The D layer also reappears but more slowly
- The reverse occurs in the evening
- The D layer disappears soon after sunset while the F region slowly declines throughout the night

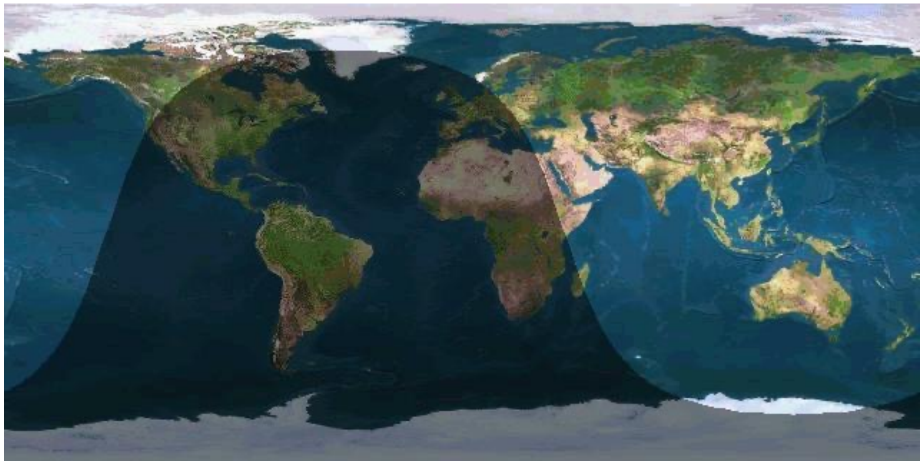
Periods of Enhanced Communications

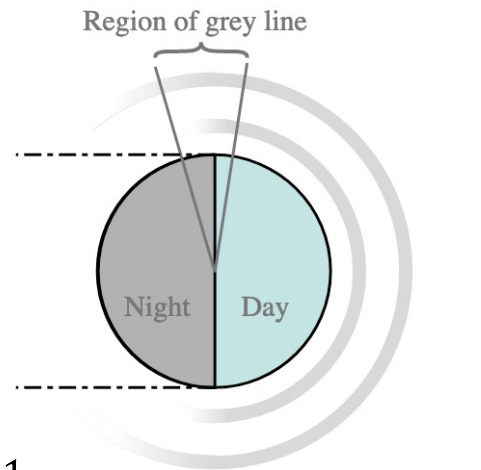




- The delay between the appearance and disappearance of the D region relative to the F layer provides a period of enhanced communications
- In the morning a strong F region permits excellent communications along the gray line before the signal absorbing D layer has a chance to develop
- In the evening the D layer disappears quickly again permitting a period of excellent communications while the F region is still strongly ionized

Gray Line Propagation Example

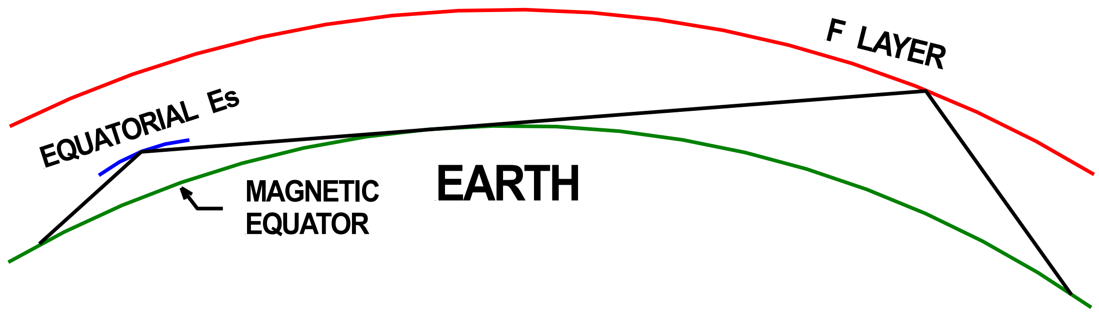




$$Absorption \propto \frac{1}{f^2}$$

- Excellent communications from northern Europe to eastern Africa occurs at sunrise
- In western Canada good communications into the south Pacific occurs at sunset
- Seasonal variations in gray line orientation provide optimum paths to slightly different parts of the world each day
- These periods of enhanced communications last for about 45 minutes to an hour
- Since D level absorption is inversely proportional to frequency squared, gray line propagation is very important for 80 meter and 40 meter DX, less so for 20 meters, and usually not relevant for 15 meters

Equatorial Sporadic E Propagation



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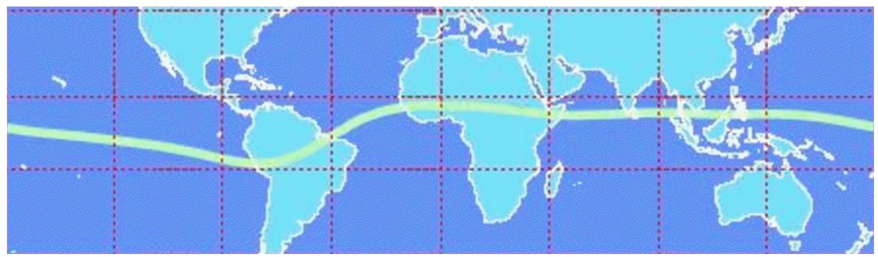

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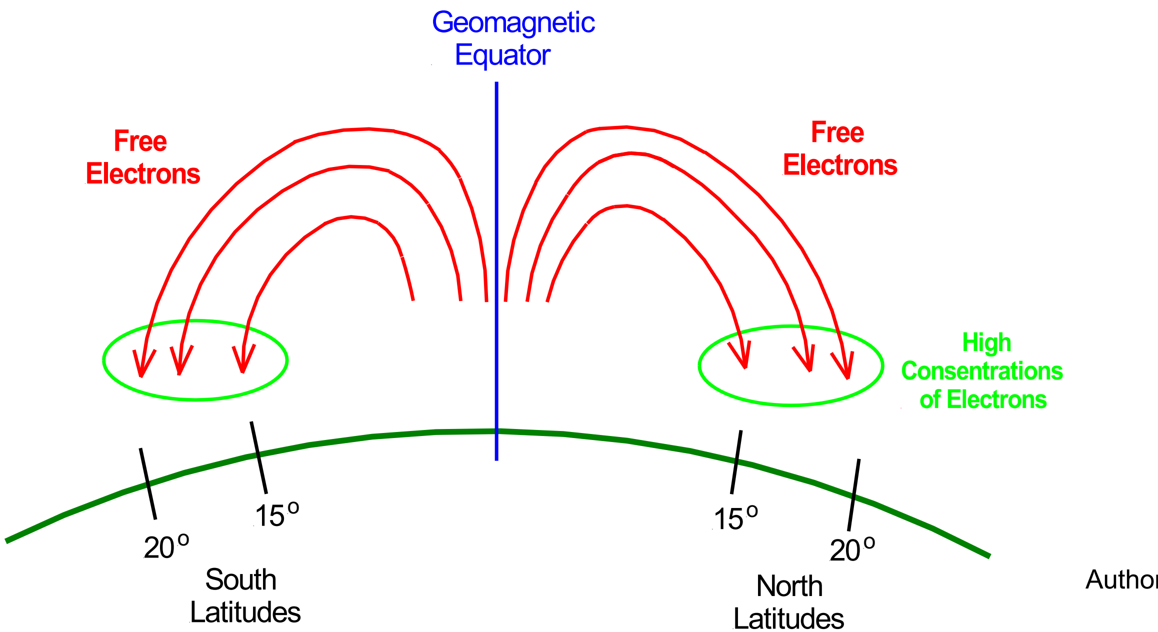
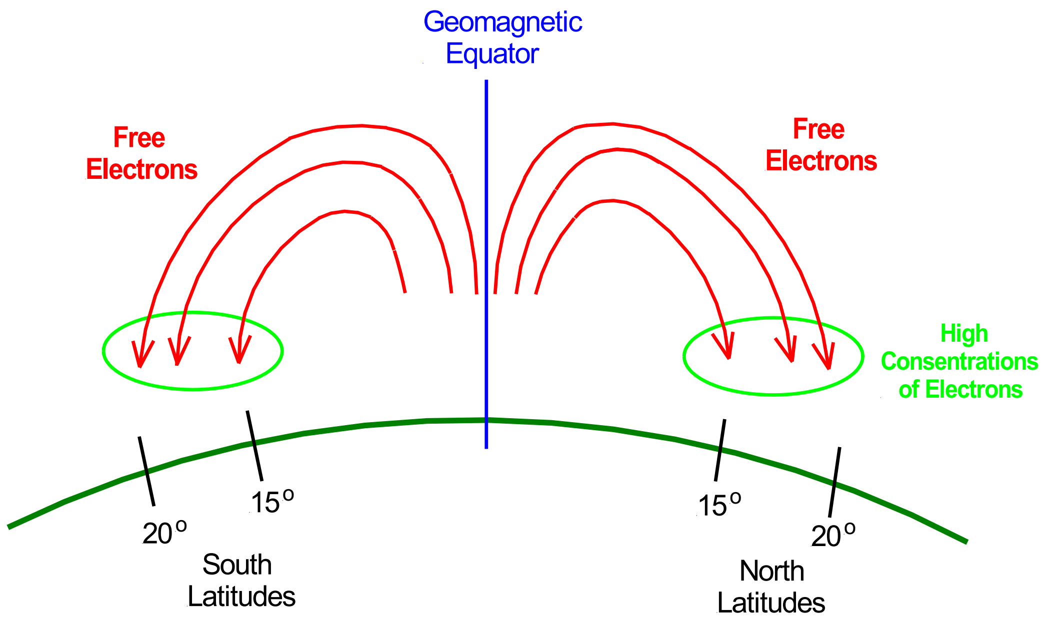
- At low latitudes, ionization irregularities resulting from the equatorial electrojet are believed to be responsible for creating sporadic E patches
- The patches appear daily in a band about 5° either side of the magnetic equator
- A signal transmitted at a low elevation angle can travel a considerable distance by reflecting from an equatorial sporadic E patch followed by a subsequent F layer refraction

Equatorial Fountain Effect



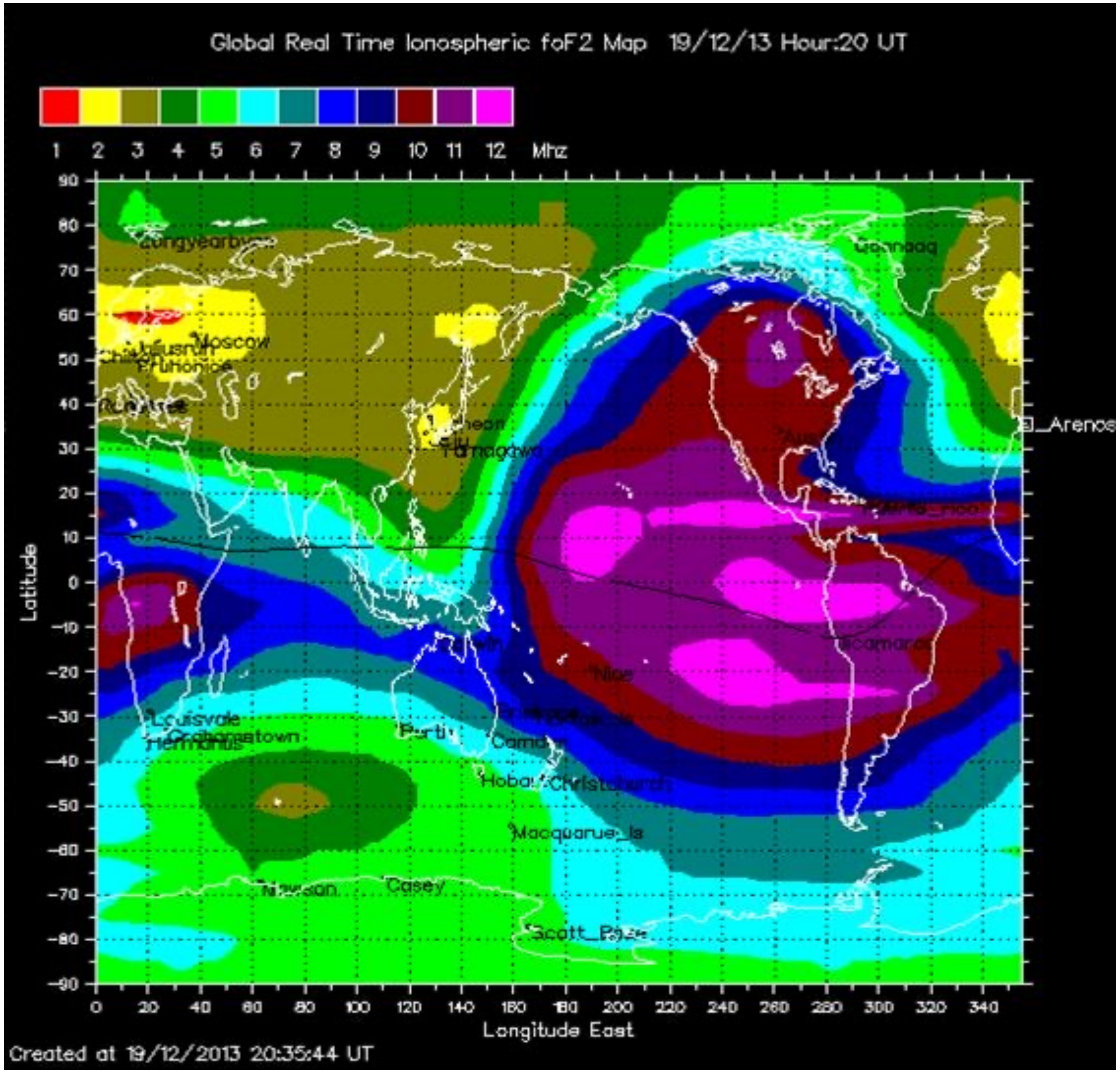
- During the day ions and electrons drift upward in the ionosphere due to the force exerted by perpendicular electric and magnetic fields along the geomagnetic equator
- Electric field gradually weakens and finally disappears at an altitude of around 800 km

Equatorial Fountain Effect continued



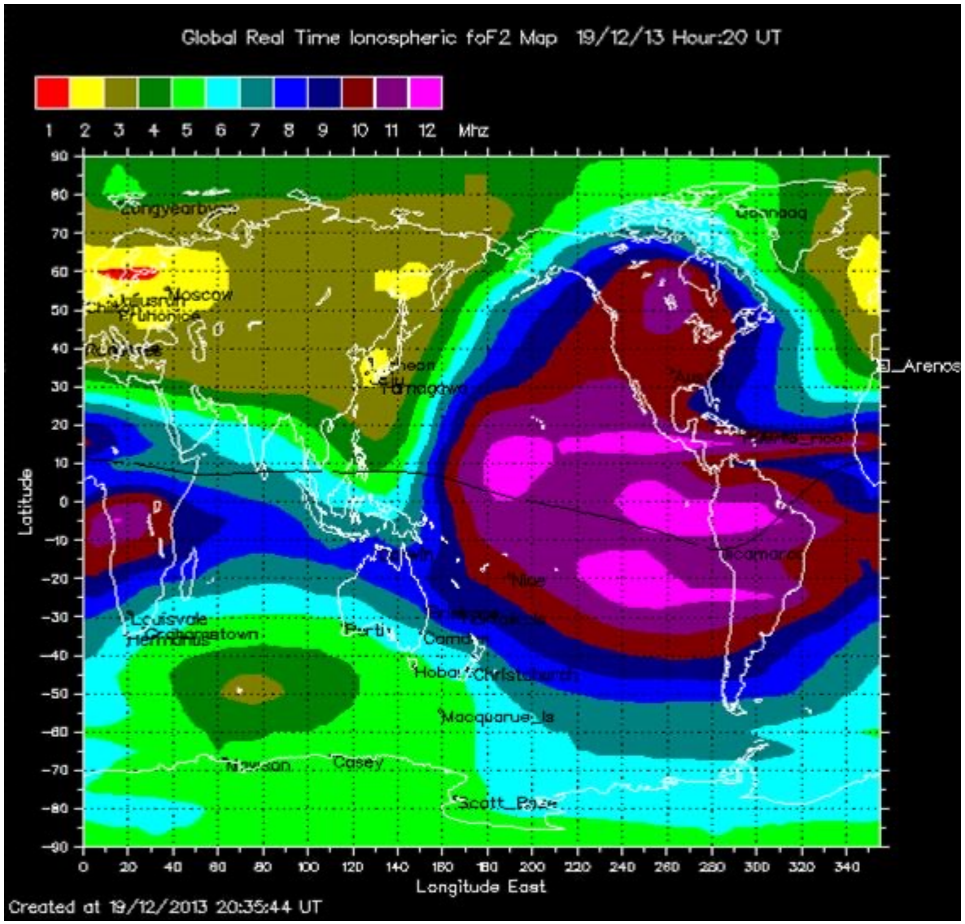
- With the electric field no longer present, charged particles (ions and electrons) travel along magnetic field lines that curve back to Earth 15 to 20° north and south of the equator
- The charged particles combine with those already in the region creating a peak or crest in electron concentrations
- While a trough, or deficiency of electrons, develops over the equator

Illustration Of Fountain Effect



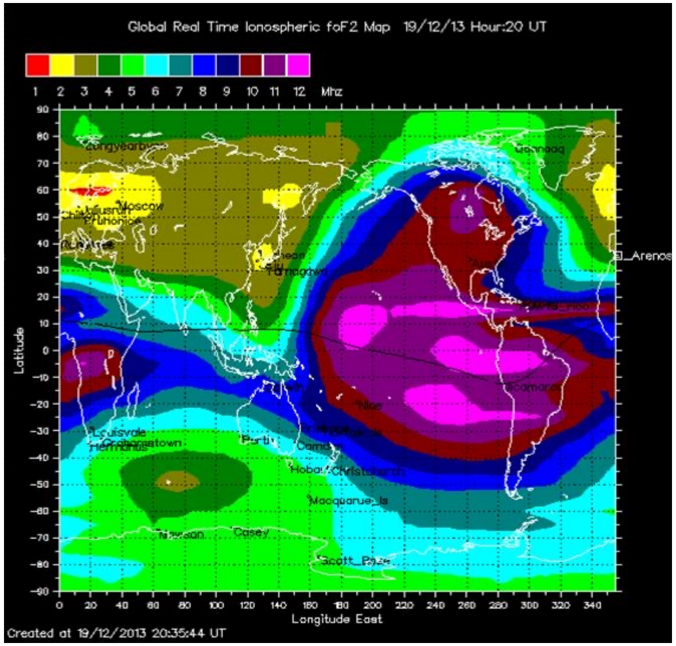
- The fountain effect is clearly visible in the winter (December) ionospheric map
- The black line sloping through South America is the magnetic dip equator
- The crests in electron concentrations are the bright pink zones on both sides of the magnetic equator

Fountain Effect Crests



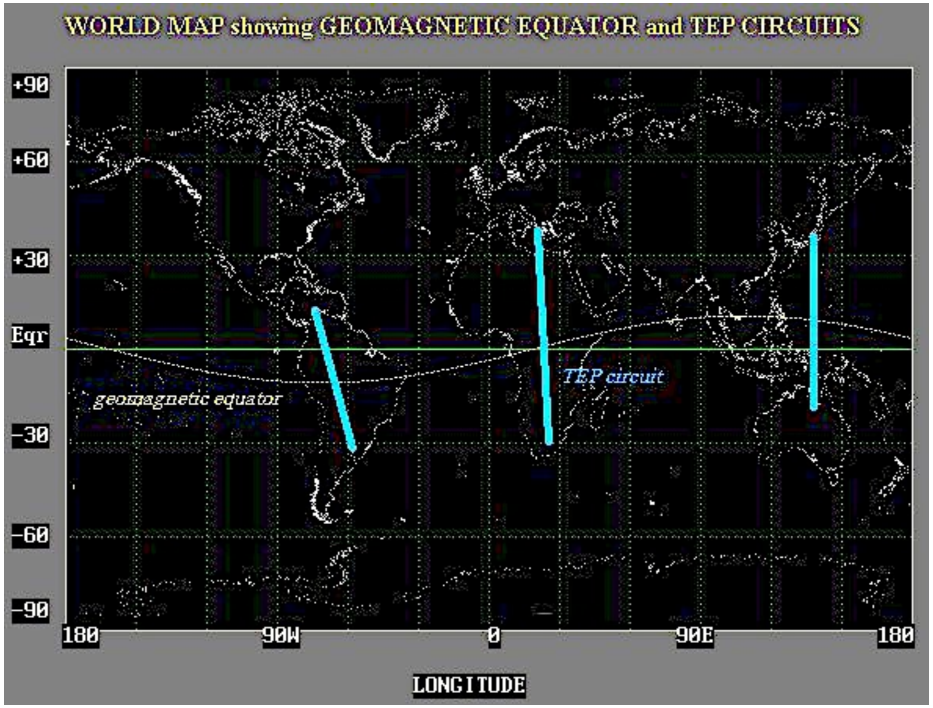
- The crests usually form in the late afternoon and early evening
- The crests vary from day-to-day and seasonally
- However, they are most pronounced during solar maximum
- The largest electron peaks (two of them in the figure) occur in the winter hemisphere
- The fountain effect and equatorial trough, cause critical frequencies along the magnetic equator to be less than in the crests

Fountain Effect MUF



- Within a crest critical frequencies can often reach 18 MHz or higher during solar maximum
- With Maximum Usable Frequencies (MUFs) extending up into the 6 meter band
- Example: the MUF at f_{cF2} = 18 MHz and an elevation angle E = 17° is
- $[MUF]_{17^\circ} = \frac{f_{cF2}}{\sin E} = \frac{18\ MHz}{\sin 17} = 61\ MHz$ with
- The frequency of optimum transmission
- $FOT = 0.85\ MUF = 0.85(61\ MHz) = 52.3\ MHz$
- Well within the 6 meter band

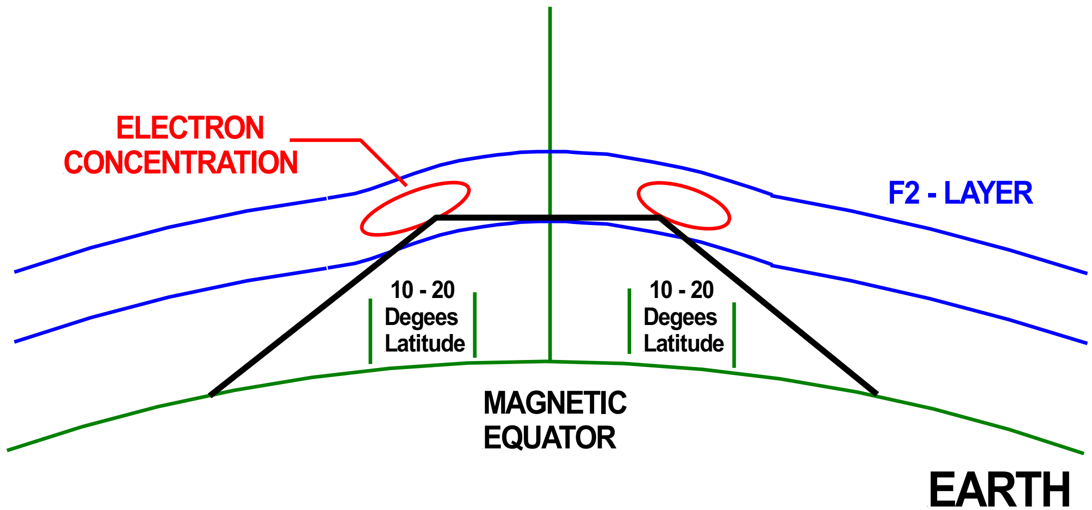
Transequatorial Propagation (TEP)



Australian Space Weather Services

- Transequatorial propagation, caused by the fountain effect, is primarily a long distance 6 meter propagation mode between:
  - Central America and South America,
  - The Mediterranean and South Africa, plus
  - Japan and northern Australia,

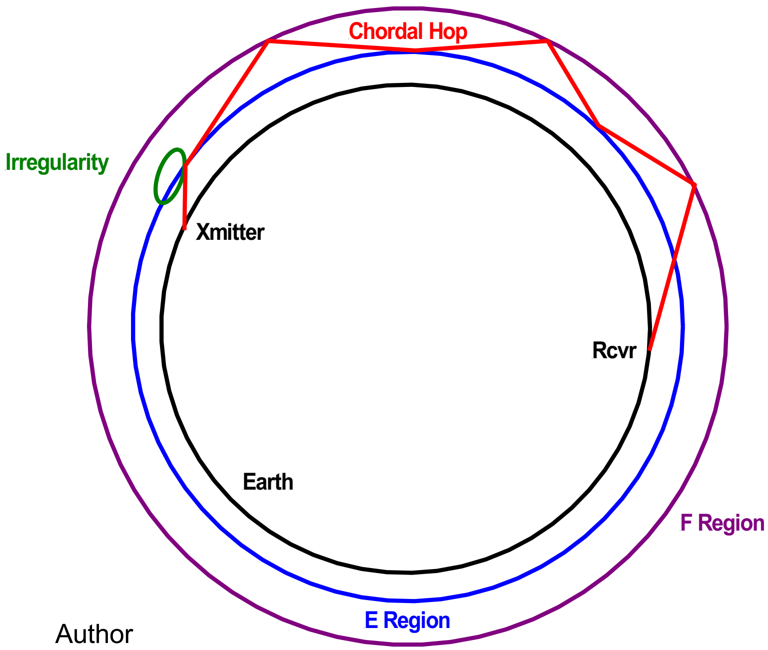
Transequatorial Propagation (TEP) continued



Author

- Typically, a radio signal transmitted from one hemisphere to the other requires multiple hops through the ionosphere to reach its destination, with signal attenuations occurring with each hop
- Transequatorial propagation allows a radio signal to travel the same distance in a single hop, greatly minimizing signal loss
- Transequatorial propagation occurs when a radio signal reflects off one fountain crest, travels across the equator to the second crest, and then reflects back to Earth

Ionospheric Ducting



- If a signal is injected into the ionosphere at just the right angle, and under the right conditions, it can become trapped between the F and E layers, reflecting off the bottom of the F and the top of the E layer
- This injection can sometimes occur when a signal reflects from ionospheric irregularities
- A signal traveling in an ionospheric duct avoids multiple passes through the energy absorbing D layer and reflections from the ground
- Consequently, the signal can travel a long distance with little signal loss
- When ducting is present, communications half way around the world can occur with the same signal strength, clarity, and stability as communicating locally on a 2 meter repeater

HF Non-skywave Propagation

Author

- In concluding this presentation, it is important to note that there are two non-skywave HF propagation modes, specifically:
  - Line of sight, and
  - Ground wave propagation
- Historically these two propagation modes were very important

HF Non-skywave Propagation continued

Author's 1962 amateur radio rig

- Prior to the mid 1960's the primary amateur radio bands were 160 through 10 meters
- While the VHF/UHF 2 meter, 220 MHz, and 440 MHz bands were assigned for amateur radio use, they were in general used only by experimenters
- The reason for this was that the vacuum tube transmitters and receivers of the day were physically too large to support communications at these VHF and UHF frequencies
- The wiring in these big radios was sufficiently long that it radiated at VHF/UHF frequencies making the technology impractical for VHF/UHF work
- For comparison, the small radio on the far left is the author's 1990 Kenwood TS-440 which far out performed the 1962 rig

VHF – UHF Bands

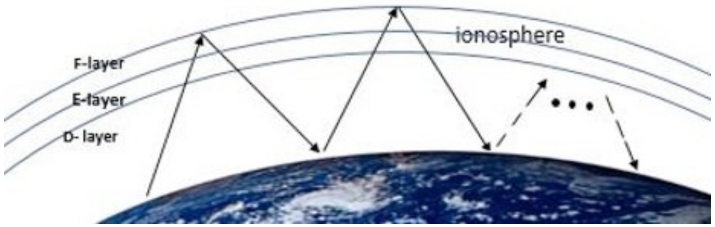
- Opening up the VHF and UHF bands for general amateur radio use had to wait for development of semiconductor technology and the subsequent tiny hand held and desk top VHF/UHF transceivers
- Today 2 meters is the most popular amateur radio band, being used primarily for local communications

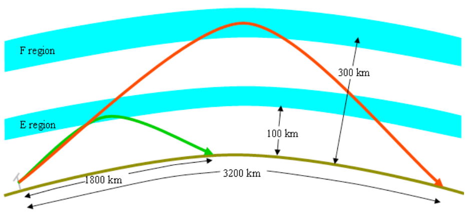
80 Meter Line of Sight & Ground Wave

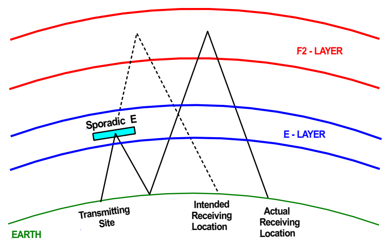
Frequency Band	Typical Ground Wave Distance
80 meters	68 miles
40 meters	50 miles
20 meters	30 miles

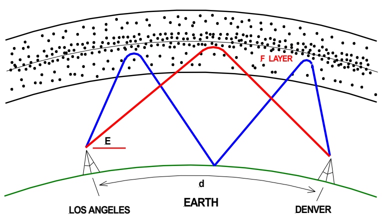
- Prior to semiconductors, 80 meters was used both day and night for local communications
- During the day 80 meter skywave communications is dead due to D layer absorption, **but not 80 meter line of sight and ground wave propagation**
- The distance covered by line of sight on 80 meters is essentially the same as line of sight 2 meter coverage
- The range of ground wave propagation increases with electrical conductivity
- It is greatest over sea water and smooth flat fertile ground
- The range of ground wave propagation is also proportional to signal wavelength
- Long wavelength signals travel further along the ground than short wavelength signals
- The problem with 80 meter local communications is the need for long antennas

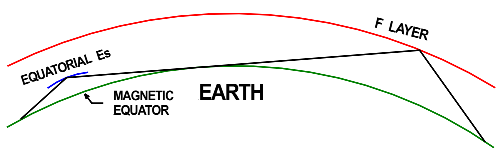
Propagation Mode Summary

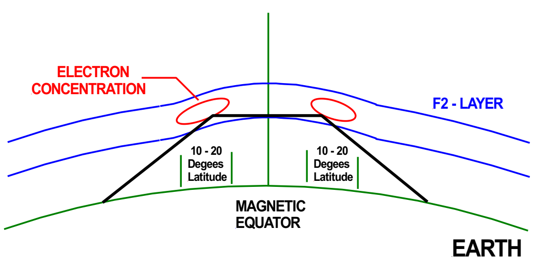


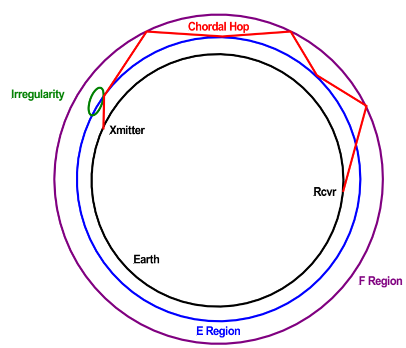












- There are many different skywave propagation modes, including
  - Multi-hop F layer propagation
  - E mode propagation,
  - Sporadic E propagation,
  - Multi-path propagation,
  - Backscatter,
  - Great Circle propagation,
  - Gray Line propagation,
  - Equatorial Sporadic E propagation,
  - Transequatorial Propagation (TEP), and
  - Ionospheric Ducting
- Which add to the challenges and fascination of HF skywave communications