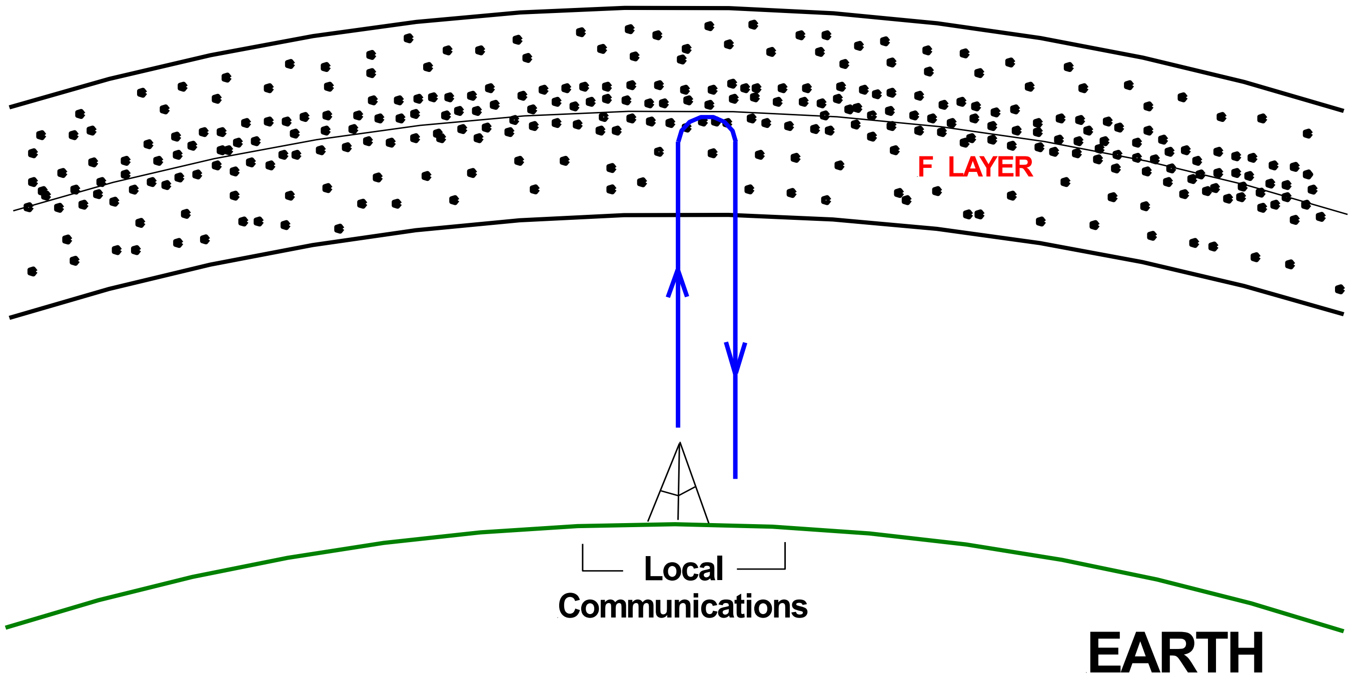
Critical Frequency

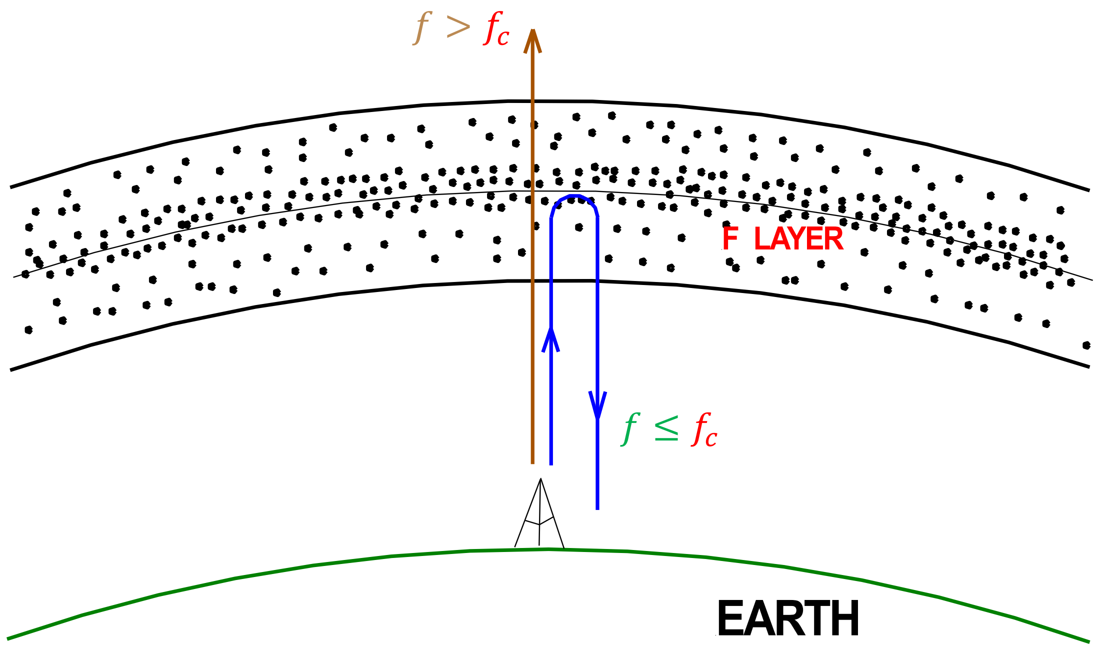


Ken Larson KJ6RZ

March 2024

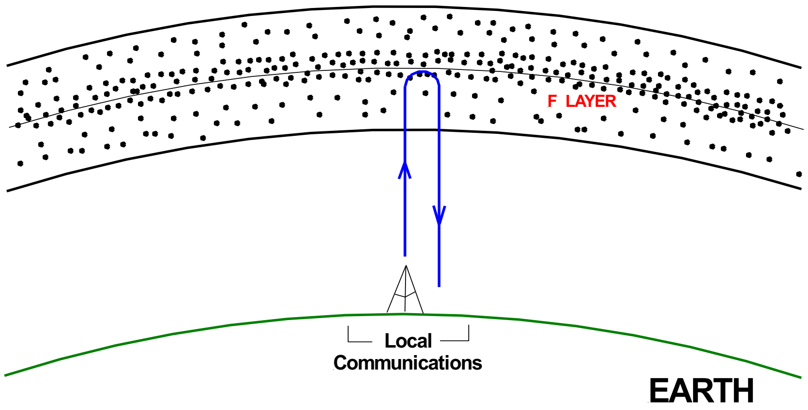
www.skywave-radio.org

What is Critical Frequency ?



- Critical Frequency $\mathbf{f_c}$ is the **highest** frequency signal that can be transmitted straight up and reflected back down to Earth.
- All signals lower in frequency than $\mathbf{f_c}$ will also be reflected back to Earth
- But, signals higher in frequency transmitted straight up will penetrate the ionosphere and be lost to outer space

Importance of Critical Frequency



- Critical frequency is one of the most important HF radio communication parameters
- Critical frequency determines:
  - What frequency bands are open and when,
  - The maximum usable frequency (MUF) for communicating with other stations
  - Whether a skip zone exists, and if so how large it is
  - Whether Near Vertical Incident Skywave (NVIS) propagation is possible or not
  - The performance of Regional and Local HF nets, specifically what stations can be reached, which can not, and the strategy for positioning net control stations
  - The stations reachable with your particular type of antenna

Plasma Frequency

- Free electrons and ions are not stationary, instead they are in constant motion
- In addition, electrostatic forces between the positive ions and negative electrons cause electrons to oscillate back and forth in simple harmonic motion around ions
- Ions are too massive to oscillate back and forth. Ions are 20,000 times more massive than electrons
- The frequency of oscillation, called the plasma frequency, is

$$\omega^2 = \frac{N(h) \cdot e^2}{\varepsilon_0 \, m}$$

ω = angular frequency (radians per second)

$N(h)$ = electron density per cm^3 at an altitude h above Earth's surface

e = charge on an electron

ε_o = permittivity of free space

m = mass of an electron

Plasma Frequency continued

Converting from radians per second to hertz

$$f = \frac{\omega}{2\pi}$$

and substituting in the values for $e, \varepsilon_o,$ and m plus converting to MHz gives

$$\text{Plasma Freq} = f \approx 9\left(10^{-3}\right)\sqrt{N\left(h\right)} \quad \text{MHz}$$

Plasma Frequency is roughly equivalent to the Ionosphere's resonant frequency

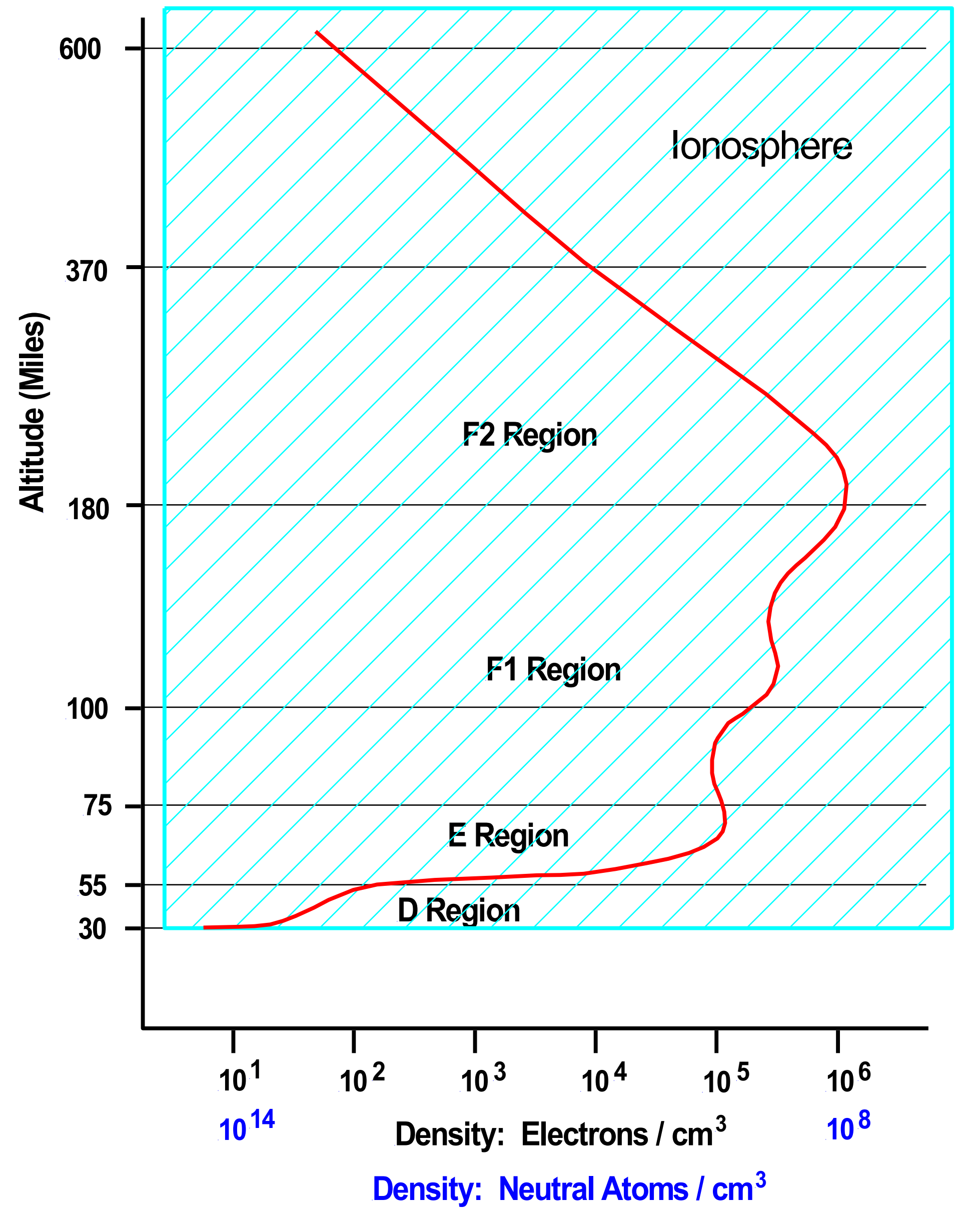
Plasma & Critical Frequency

- Each region of the ionosphere has its own critical frequency
  - F2 Layer → f_{cF2}
  - F1 Layer → f_{cF1}
  - E Layer → f_{cE}
- Critical frequency is determined by the maximum electron density in each region

Example:

$$f_{cF2} = 9(10^{-3})\sqrt{N_{F2}(h)} = 9 \text{ MHz}$$

N(h) = electron density per cm^3 at an altitude of h above Earth's surface



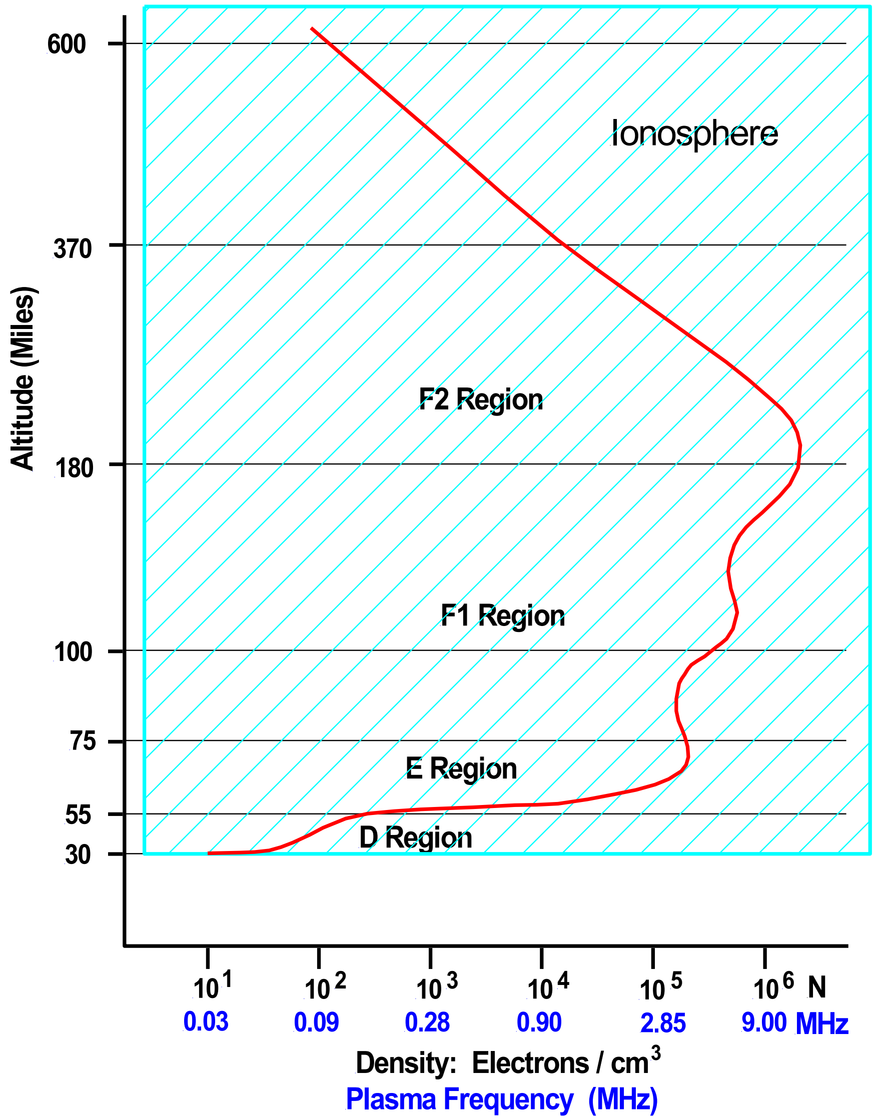
Critical Frequency continued

$$f_c = 9 \cdot (10^{-3}) \cdot \sqrt{N_{max}}\ \ MHz$$

- If the max electron densities for the various regions of the ionosphere are

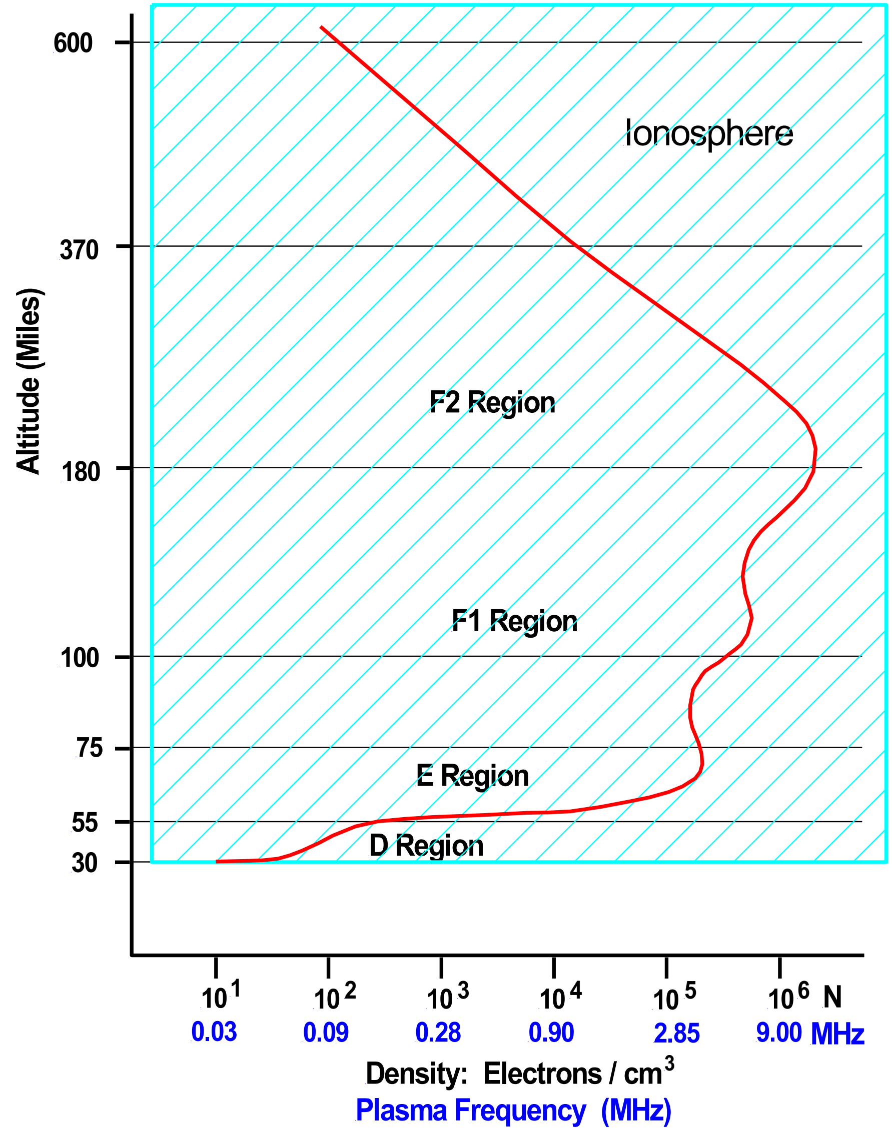
$N_{F2} = 1 \cdot 10^6, \cdots N_{F1} = 5 \cdot 10^5, \cdots N_E = 2 \cdot 10^3$

- Then the critical frequencies are
  - $f_{cF2} = 9$ MHz
  - $f_{cF1} = 6.6$ MHz
  - $f_{cE} = 4$ MHz

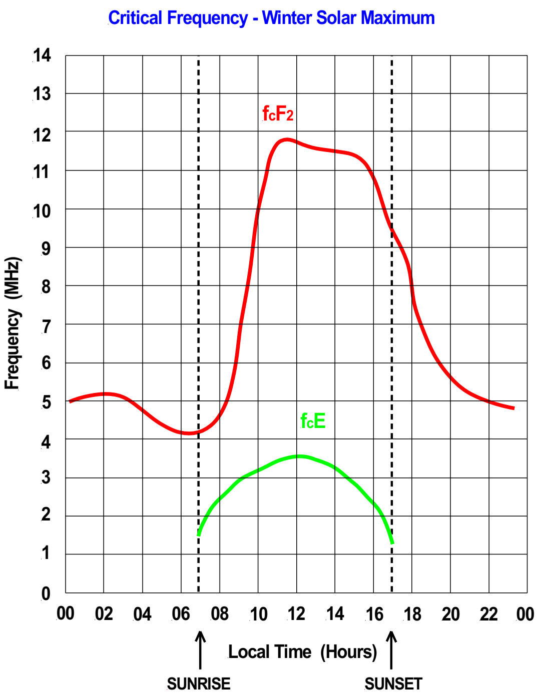


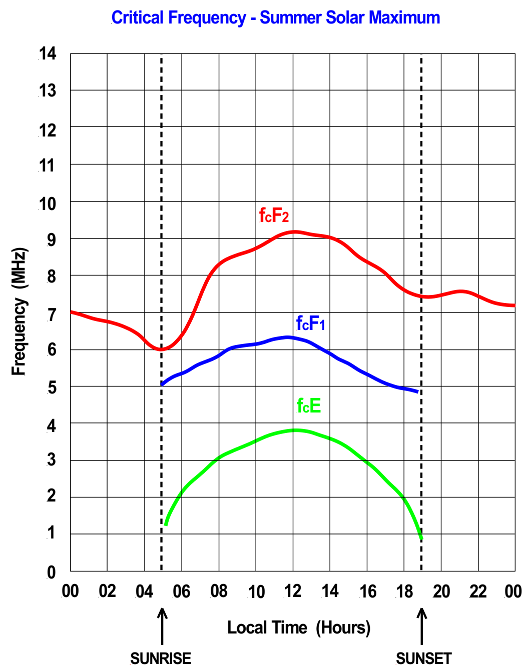
Critical Frequency continued

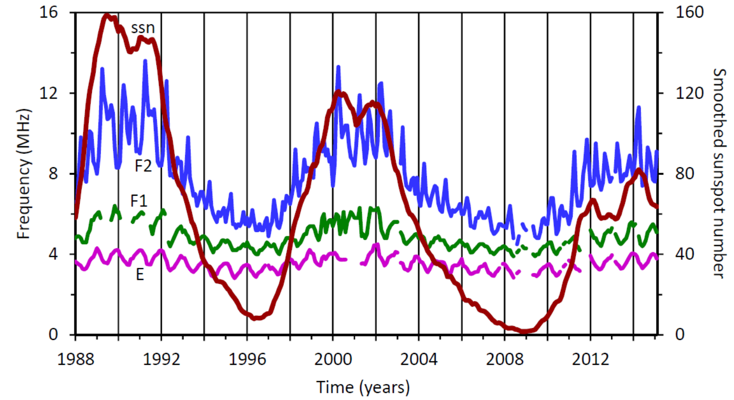
- For these critical frequencies
  - $f_{cF2} = 9$ MHz
  - $f_{cF1} = 6.6$ MHz
  - $f_{cE} = 4$ MHz
- A vertical 4 MHz signal will be reflected back to Earth by the E region
- A 6.6 MHz signal will pass thru E being reflected back to Earth by the F1 level
- A 9 MHz signal will pass thru E & F1 and reflect back in the F2 Region
- A 10 MHz signal will pass through the ionosphere and be lost to outer space



Critical Frequency Varies

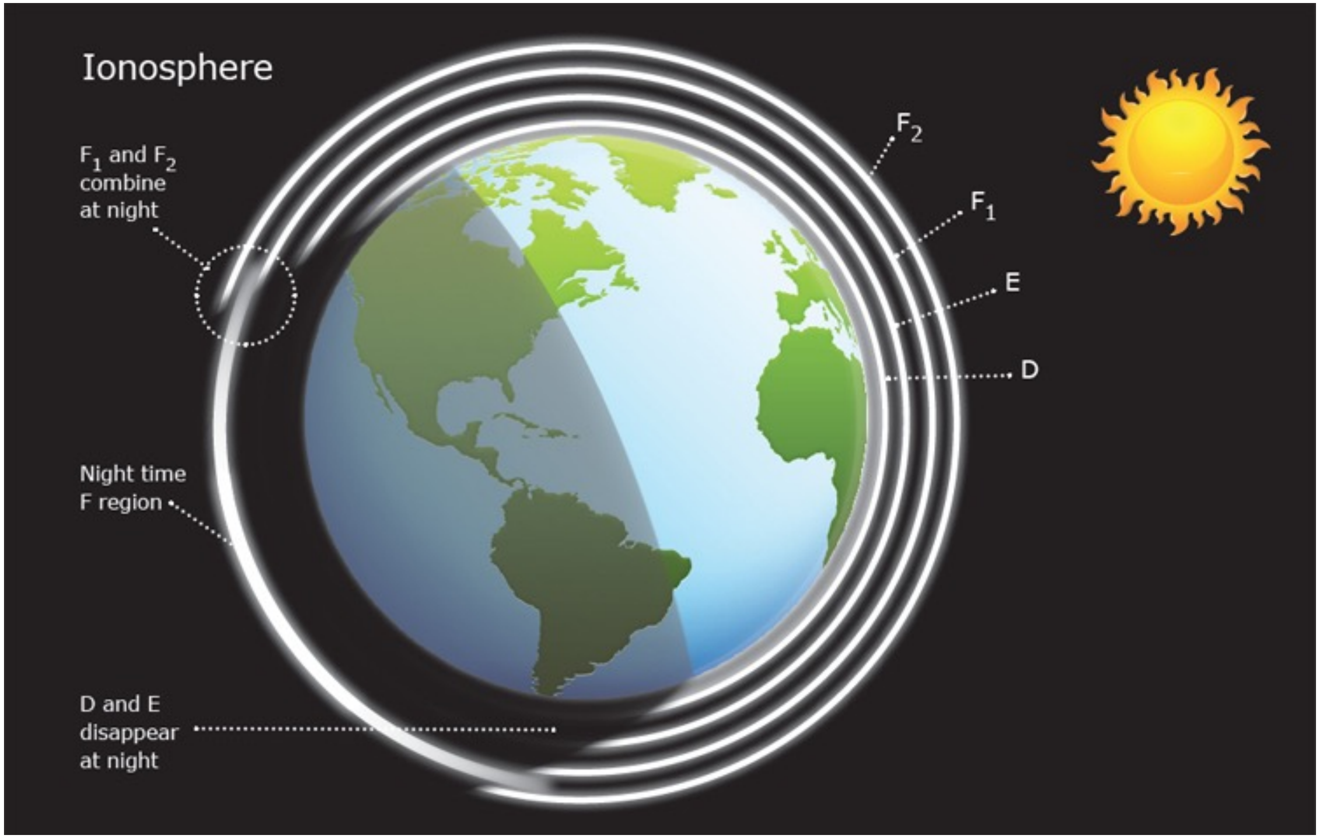






- Critical Frequency varies:
  - Throughout the day as the Earth rotates,
  - Seasonally as the Earth's upper atmosphere changes, and
  - With the 11 year solar cycle as Extreme Ultra-Violate (EUV) & X-ray radiation from the Sun changes

Ionosphere Diurnal Characteristics

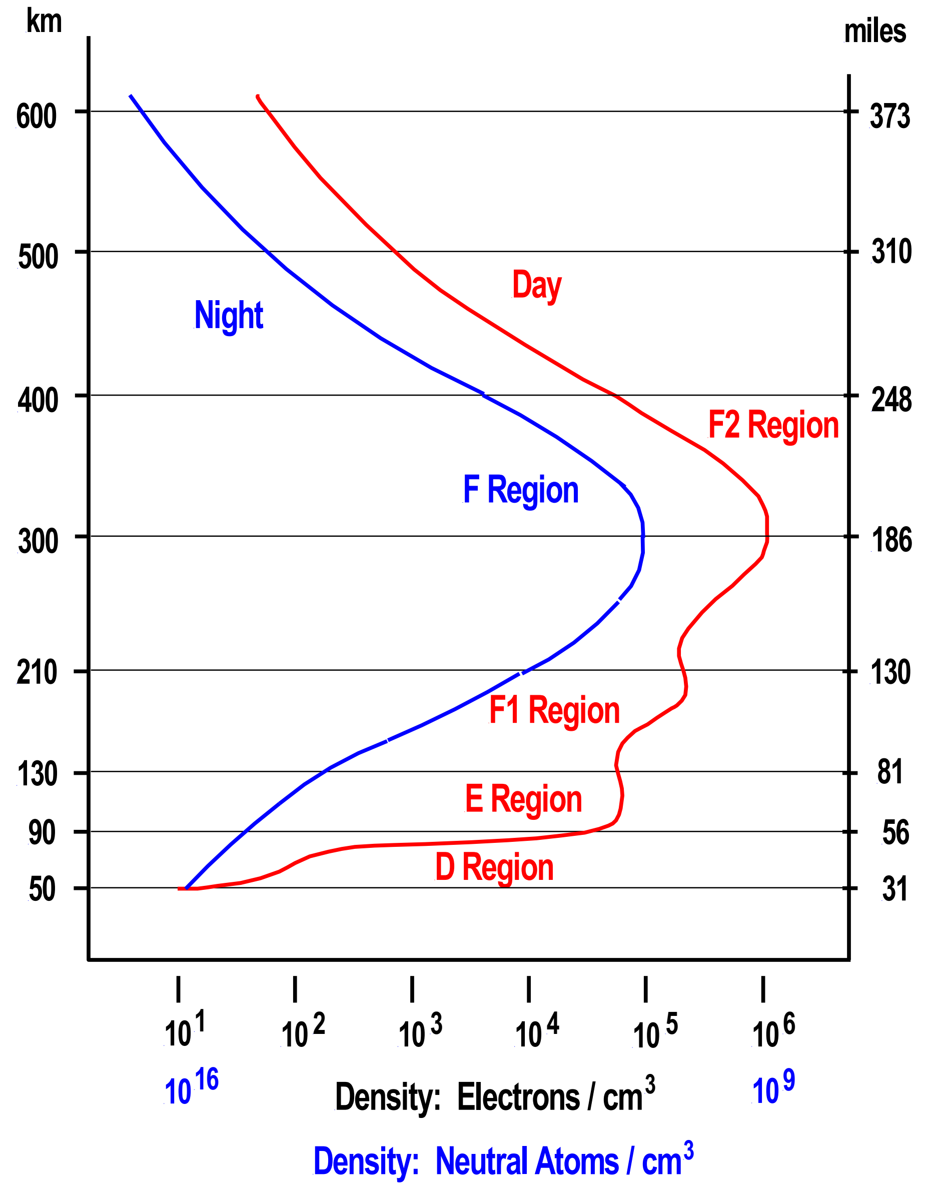


Source: University of Waikato, www.sciencelearn.org.nz

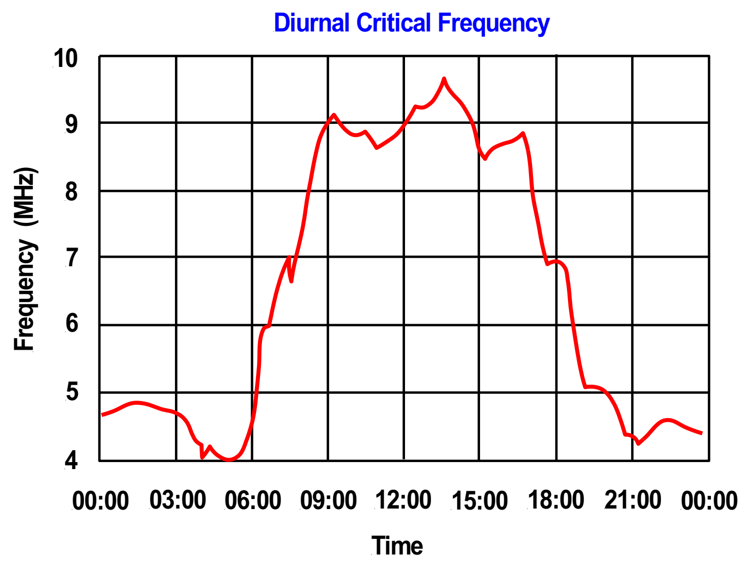
- During the day the F2, F1, E and D regions form as the result of photo-ionization
- At night there is no photo-ionization
- Consequently, the D and E regions disappear while the F1 and F2 combine into a weak F region as electrons and ions continue to recombine

Day vs Night Electron Densities

- The diurnal variations in the ionosphere are clearly visible in its electron density profile.
- During the day ionization levels quickly increase forming discrete F2, F1, E and D regions.
- However, at night electron-ion recombination cause the D region to disappear.
- For most practical purposes, the E region also disappears.
- The F1 and F2 regions merge forming a weak night time F region.



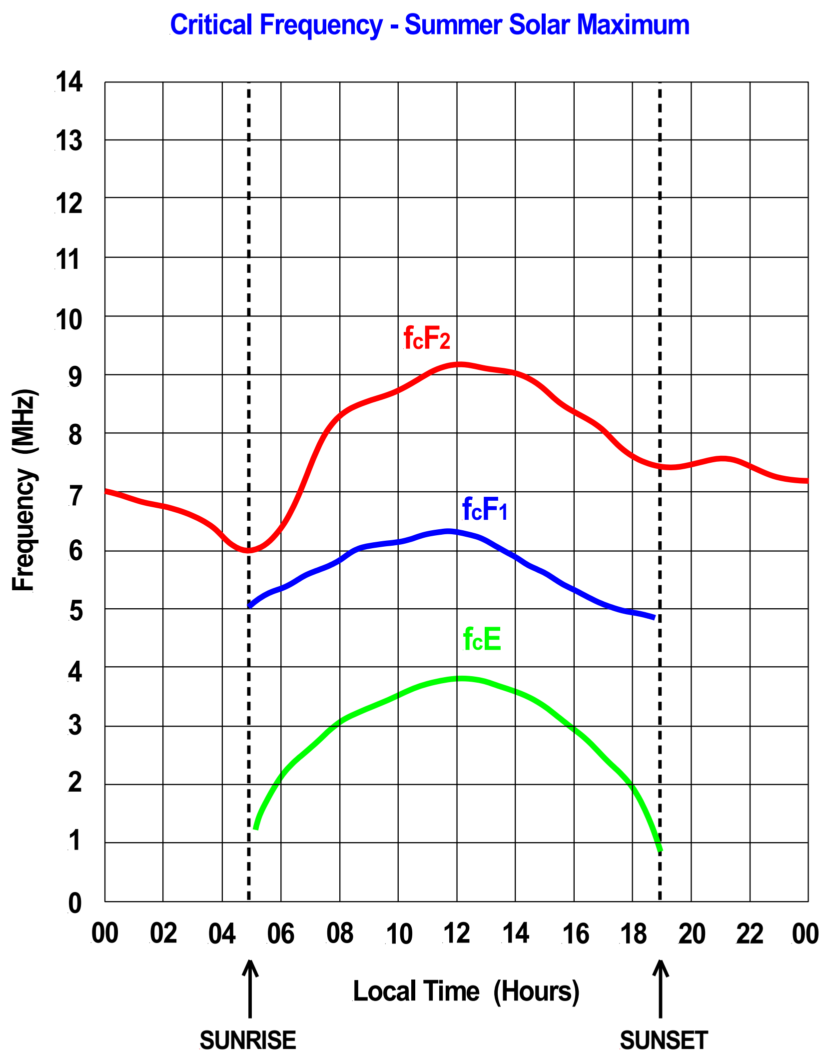
Typical F2 Layer Diurnal Critical Frequency



- The F2 Layer critical frequency varies throughout the day
- It is at its lowest level just before sunrise
- It increases quickly following sunrise as the result of photo-ionization
- Reaches a maximum from noon to about 2 PM (1400 hours)
- Then declines in the late afternoon and throughout the evening
- Night time f_cF2 values typically range between 2 – 3 MHz during solar minimum and 4 – 6 MHz during solar maximum.

E and F1 Diurnal Variations in Critical Frequencies

- During the day the F1 and E critical frequencies behave in a similar manner to the F2 region
- The F1 and E critical frequencies both peak at local noon
- At night, the F1 region disappears, merging with the F2 region
- The E region does not completely disappear at night.
- At night F_cE ~ 0.6 MHz, a value which is too low to have any significant affect on HF communications
- Thus for practical purposes we assume that the E region also disappears at night



E and F1 Critical Frequencies Vary With The Zenith Angle

- The critical frequency for the E region, at a particular latitude and time of day, is approximately given by the equation

$$f_cE = 0.9\ [\ (180 + 1.44\ R)\ \cos Z\ ]^{1/4}\ \text{MHz}$$

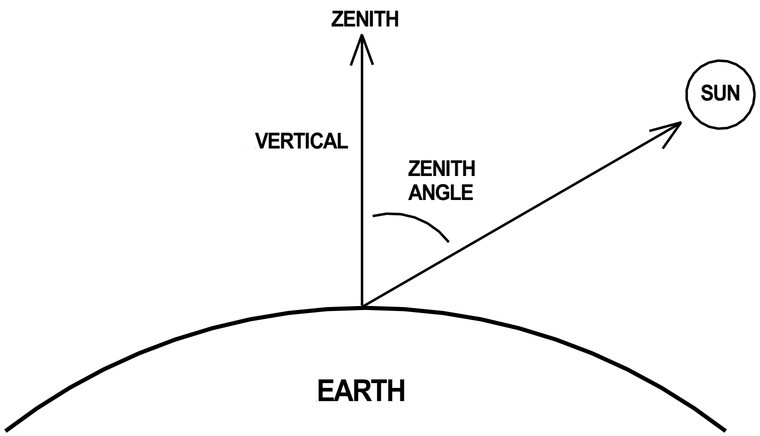
- Similarly, the critical frequency for the F1 region, at a particular latitude and time of day, is given approximately by the equation

$$f_cF1 = (4.3 + 0.01\ R)(\cos Z\ )^{0.2}\ \ \text{MHz}$$

where R is the current smoothed sunspot number (SSN) and Z is zenith angle at the latitude and time of day of interest

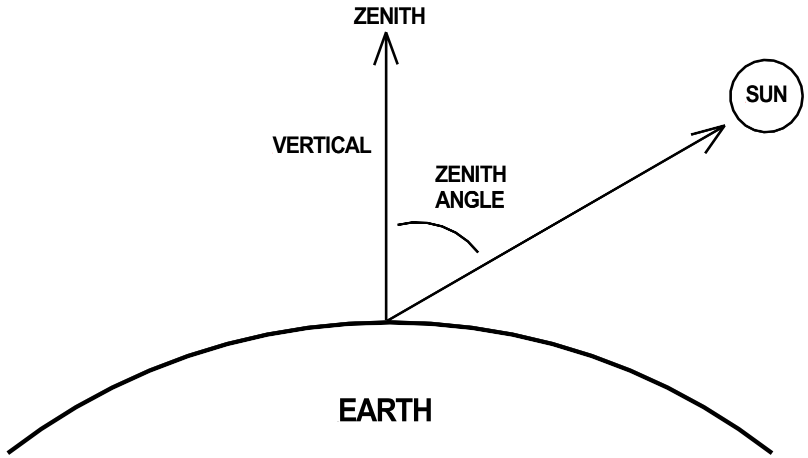
- The current smoothed sunspot number (R = SSN) is shown under "Current Conditions > Space Weather Conditions" on the website www.skywave-radio.org
- cos Z is found under "Tools > Solar Position Calculator" on the website

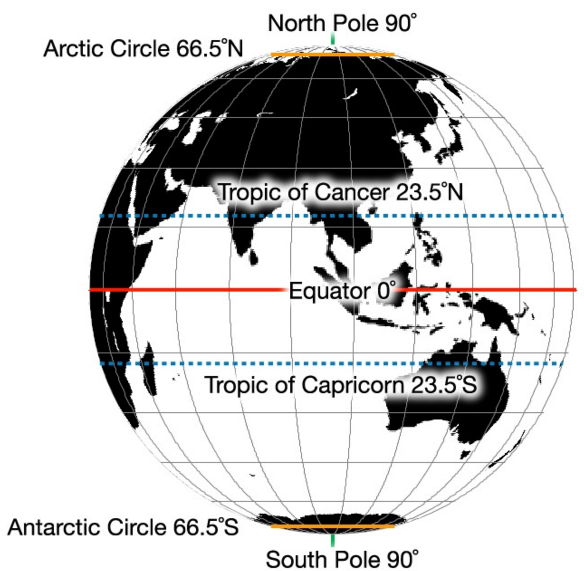
More on the Zenith Angle



- Zenith angle is the angle of the Sun relative to vertical at a particular time of day and location on the Earth's surface
- The zenith angle is 0^o when the Sun is directly over head
- At sunrise and sunset the zenith angle is near 90^o
- Local noon is defined as the time of day when the zenith angle is at a minimum

Zenith Angle and the Equinoxes

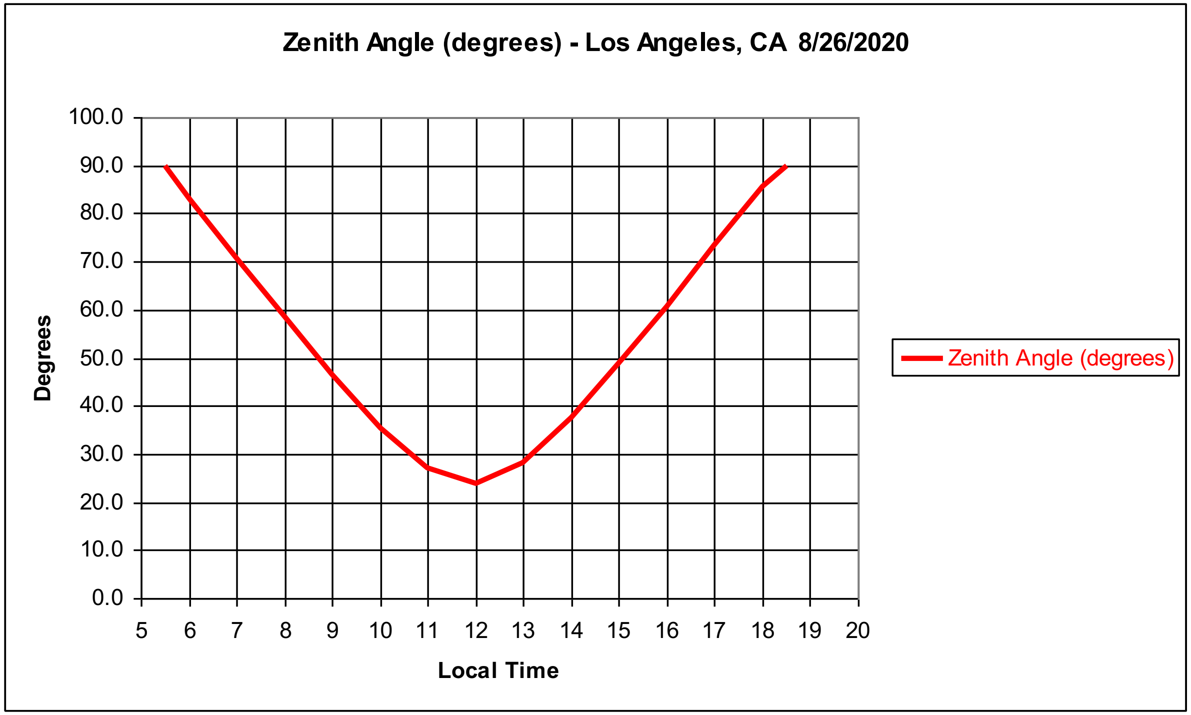




ICSM

- At local noon on September 23 and March 21 (the equinoxes) the Sun is directly overhead at the equator. At noon on these two days the zenith angle at the equator is 0^o
- At noon on December 21 the zenith angle is 0^o at the Tropic of Capricorn
- Similarly, at noon on June 21 the zenith angle is 0^o on the Tropic of Cancer
- Outside of the tropics (bounded by the Tropic of Cancer and the Tropic of Capricorn) the noon zenith angle can never be 0^o. The noon time zenith angle must always be greater than 0^o in the mid and polar latitudes

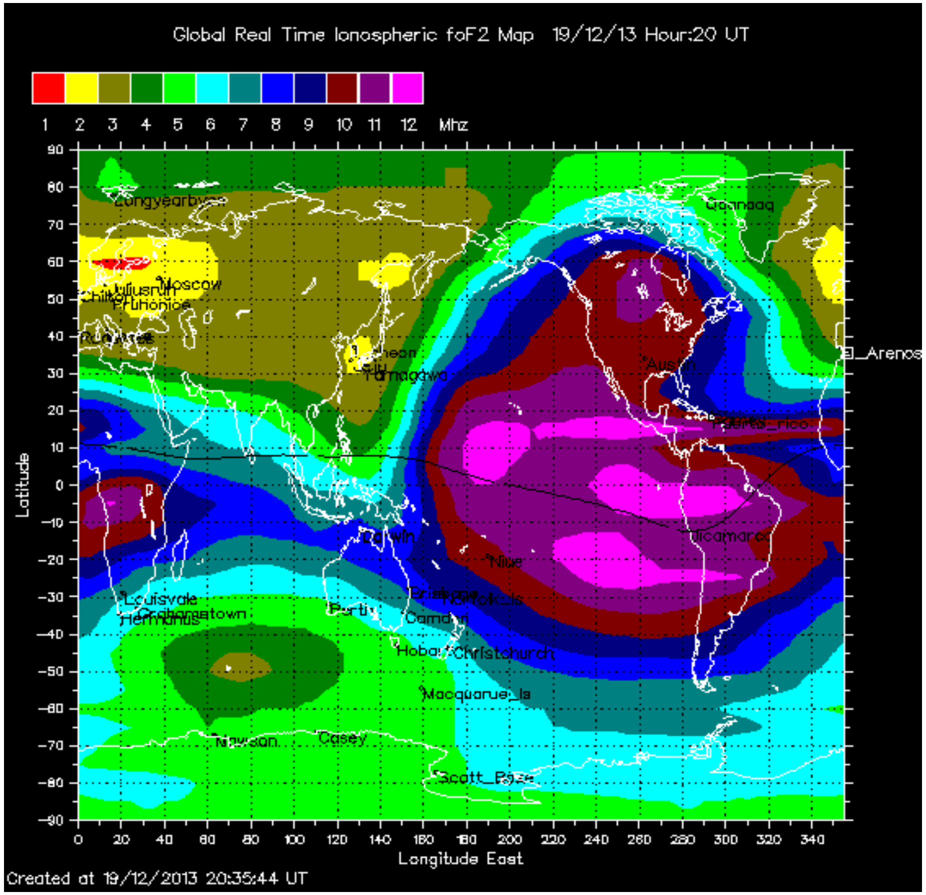
Zenith Angle Example



Local Time (hour)	Zenith Angle (degrees)
5.5	90.0
6	83.1
7	70.8
8	58.5
9	46.5
10	35.5
11	27.1
12	24.0
13	28.3
14	37.4
15	48.7
16	60.8
17	73.2
18	85.4
18.5	90.0

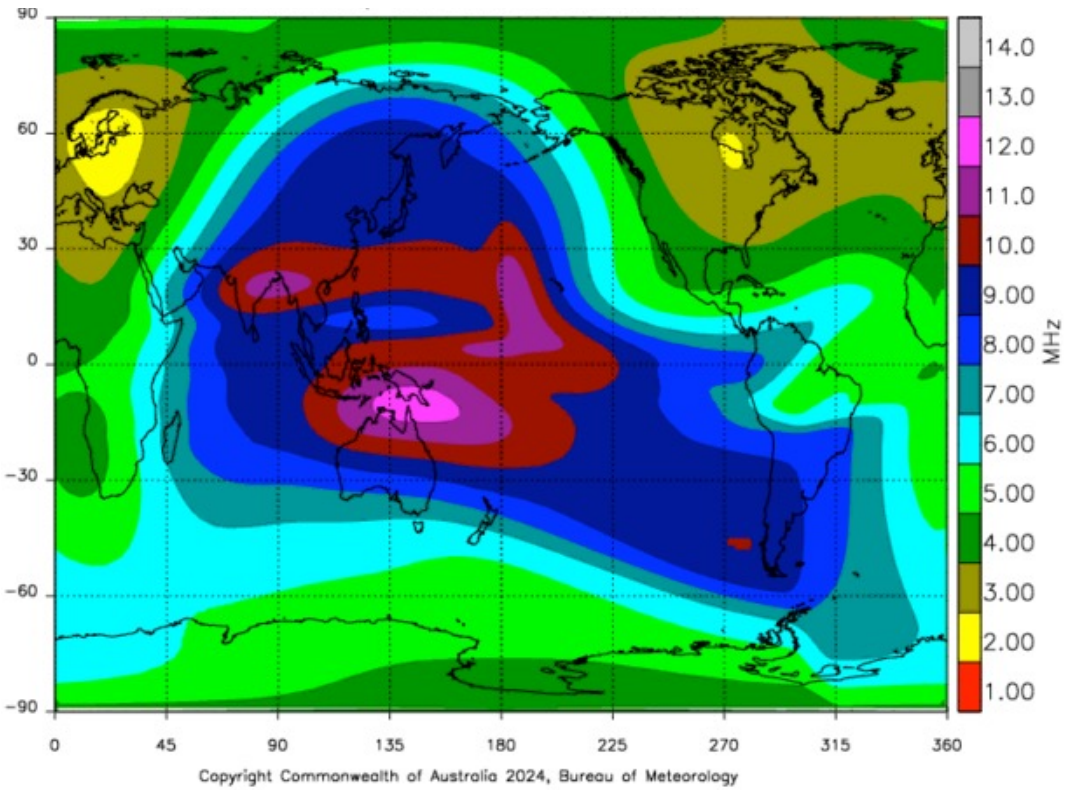
- The zenith angles for Los Angeles, CA through out the day on August 26, 2020 is shown above, note that the zenith angle is lowest a noon (24.0^{o})
- The Latitude for Los Angeles is N 34 degrees
- On this particular day sunrise occurred at 05:23
- And sunset occurred at 18:26

F2 Region Critical Frequencies



- Critical frequencies for the F2 region are far more complex than that for the E and F1 regions
- The best way to determine the F2 critical frequency is graphically

Determining Current F2 Critical Frequency



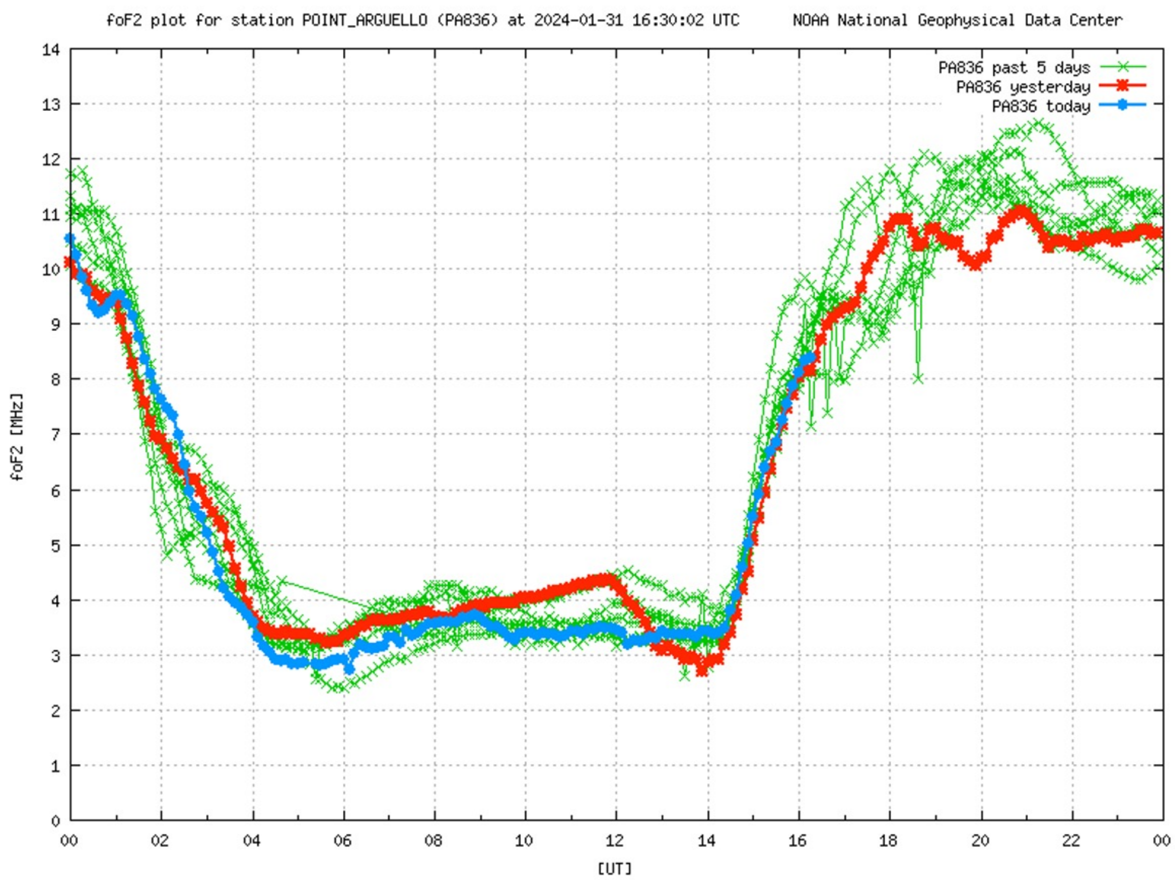
This chart shows the Critical Frequency for January 31, 2024 at 03:00 UT

Over California the Critical Frequency was between 4 to 5 MHz

Critical frequency in Northern Europe was 2 MHz

- The Australian Government produces a global F2 critical frequency map that is available on the www.skywave-radio.org website
- The critical frequency map is updated every 15 minutes
- The map is created automatically from reports received from ionosonde monitoring stations around the world
- **Seasonal Variation**: The shape of fc profiles are different in N. Hemisphere (winter) than in S. Hemisphere (summer)

Ionosonde F2 Critical Frequency Data

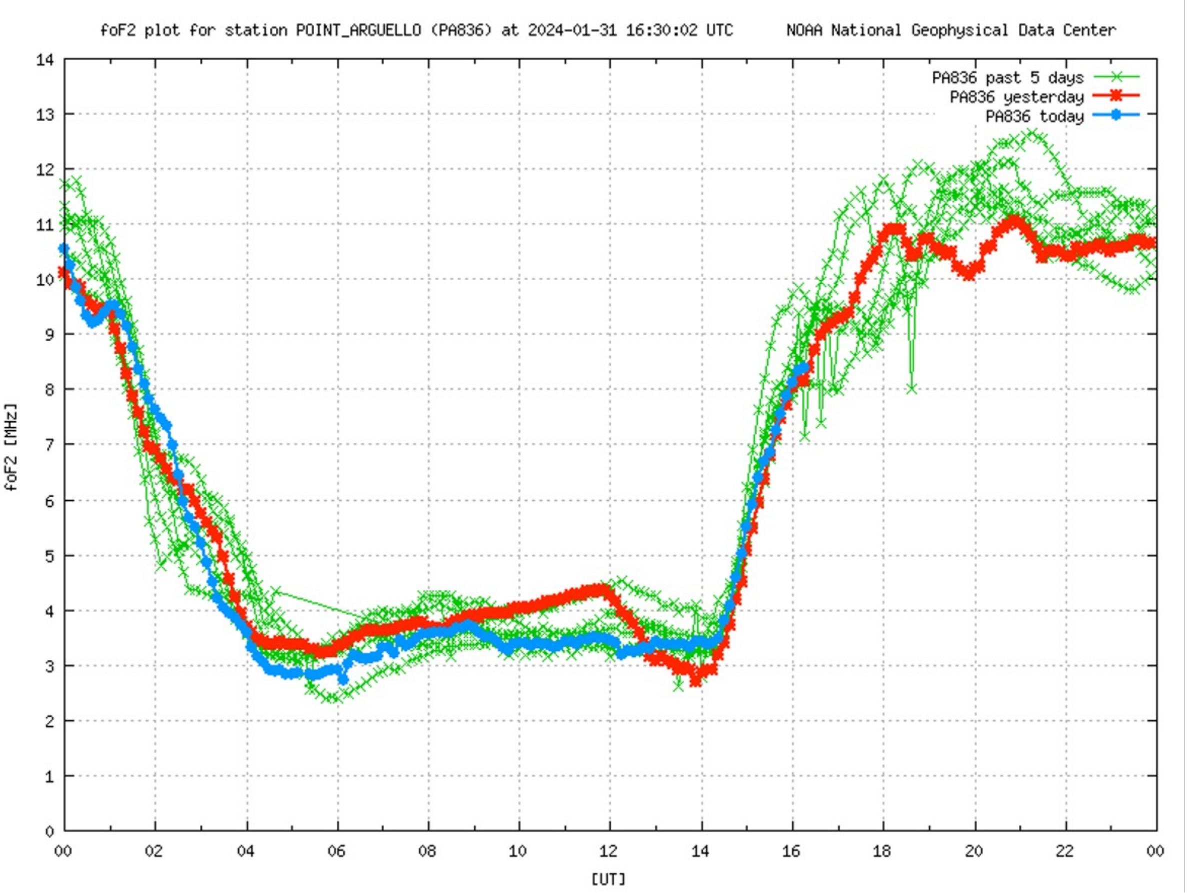


- Detailed regional critical frequency data is available on the www.skywave-radio.org website by clicking on Ionosonde under the Current Conditions tab
- Data from a large number of ionosonde sites is available
- For California the regional critical frequency data is obtained by clicking on Point Arguello, CA FoF2

This chart shows foF2 for the past 5 days, yesterday, and today in UT time

At the time of this chart (Jan 31, 2024 @ 03:00 UT) foF2 Blue Trace was 5 MHz

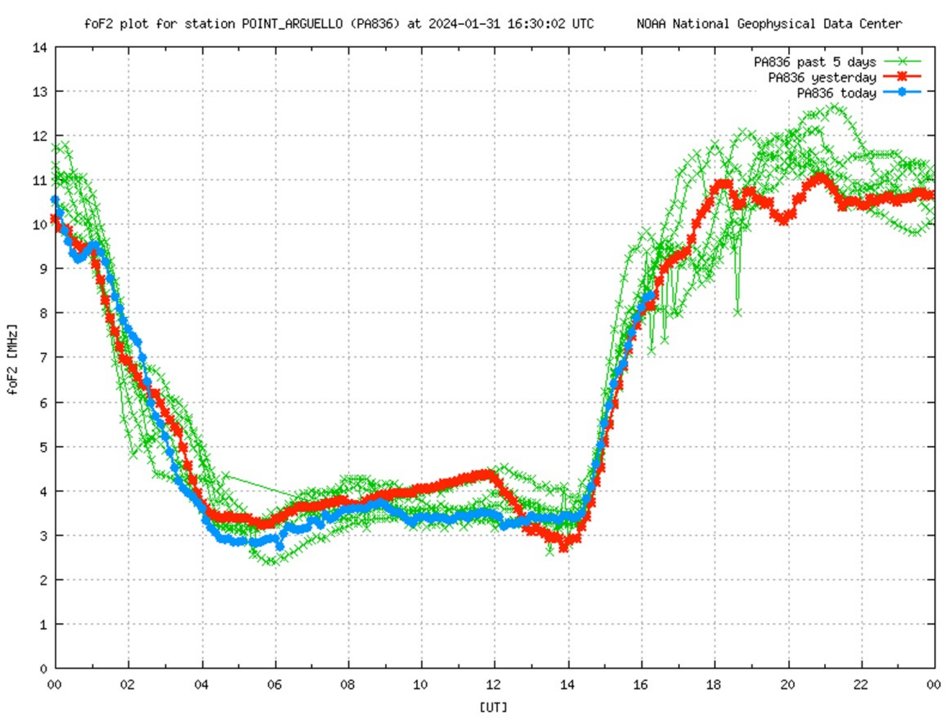
Day to Day Variations in Critical Frequencies



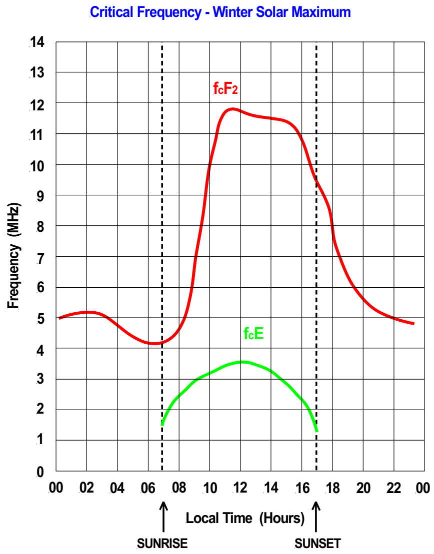
- As illustrated above, critical frequencies change from one day to the next
- The critical frequencies experienced today could well be different from those observed tomorrow

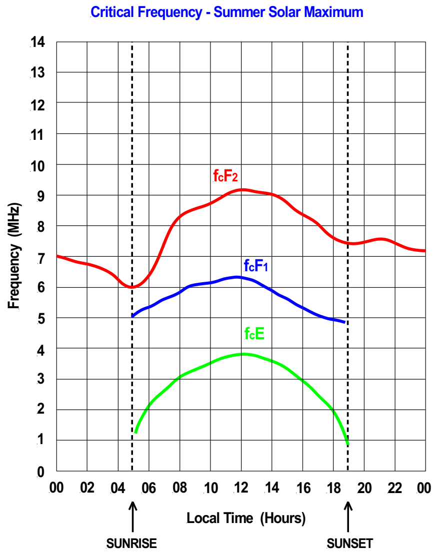
Day to Day Variations in Critical Frequencies

- The changes in critical frequencies from one day to the next are attributed in part to:
  - Daily changes in EUV radiation being received from the Sun
  - Occurrence of ionospheric storms caused by activity on the Sun
  - Changes in winds blowing in the upper atmosphere
  - Changes in electrical currents flowing in the ionosphere



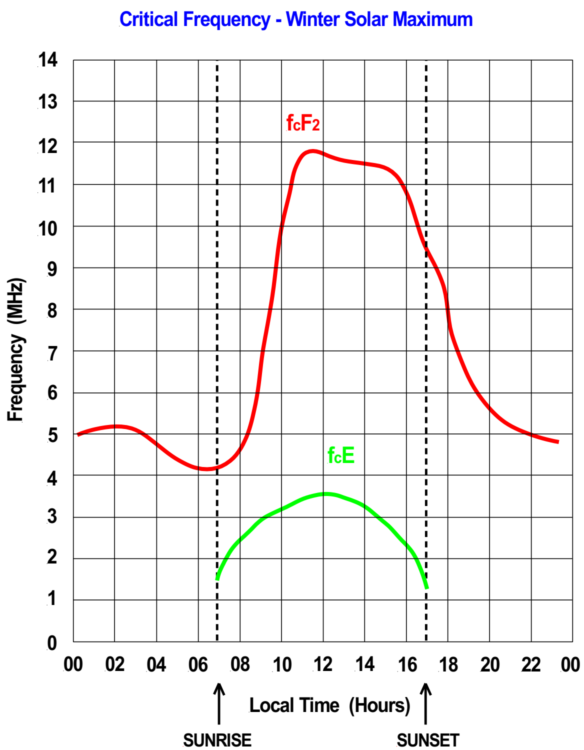
Seasonal Variations in Critical Frequencies

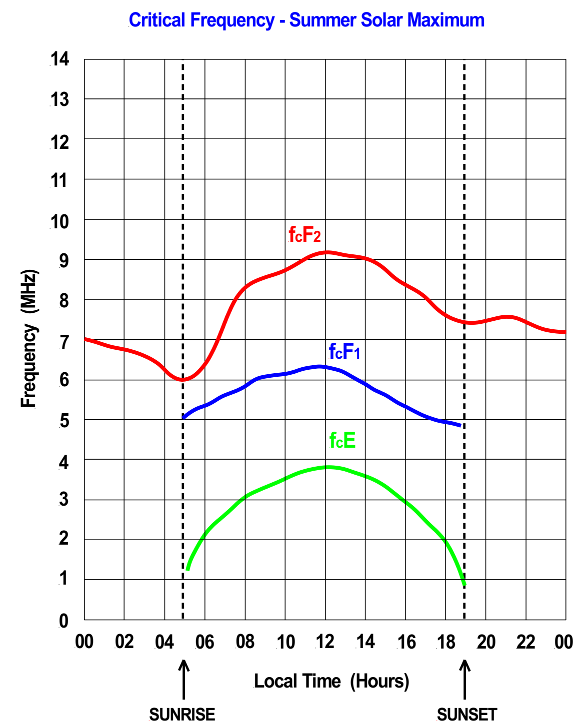




- Seasonal changes in critical frequencies are due primarily to:
  - Seasonal changes in zenith angles, and
  - Seasonal changes in the Earth's upper atmosphere
- Noon time zenith angles are always less in the summer (the Sun is more overhead) than in the winter
- We would thus expect critical frequencies to be higher during the summer than winter
- And they are for the E and F1 regions, but not so for the F2 region

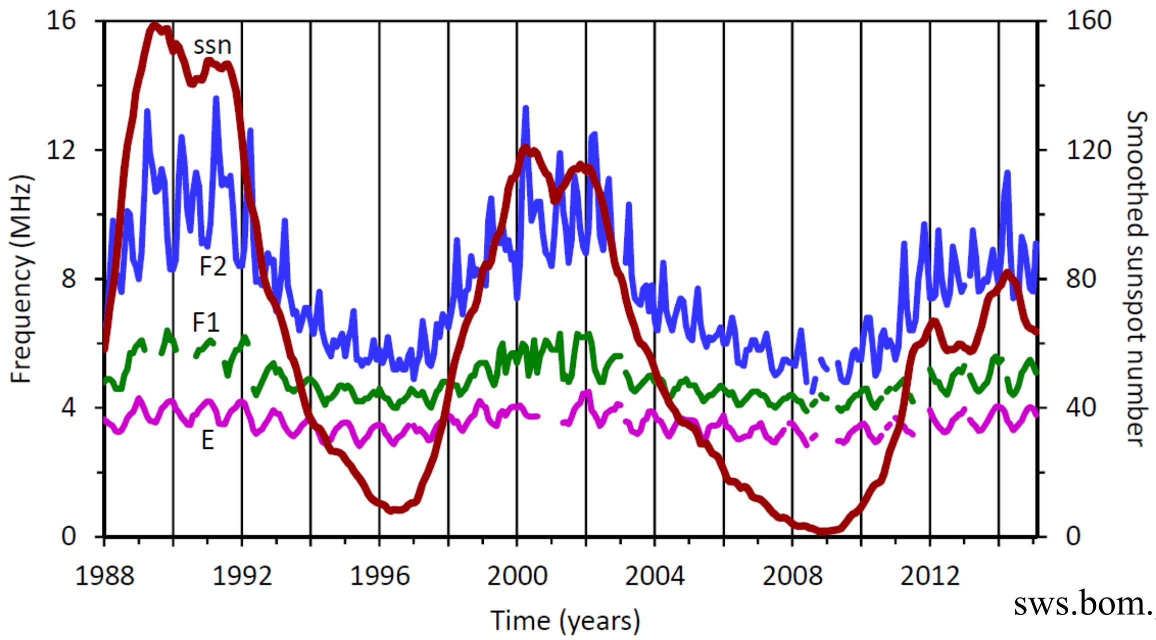
Seasonal Variations in Critical Frequencies





- Contrary to what would be expected, F2 critical frequencies during the winter are higher than during the summer, despite the fact that the Sun is lower in the sky during winter
- This is know as the seasonal anomaly
- In the winter cooler temperatures in the upper atmosphere retard electron – ion recombination resulting in higher electron densities and critical frequency than expected
- The F1 region disappears in the winter during solar maximum

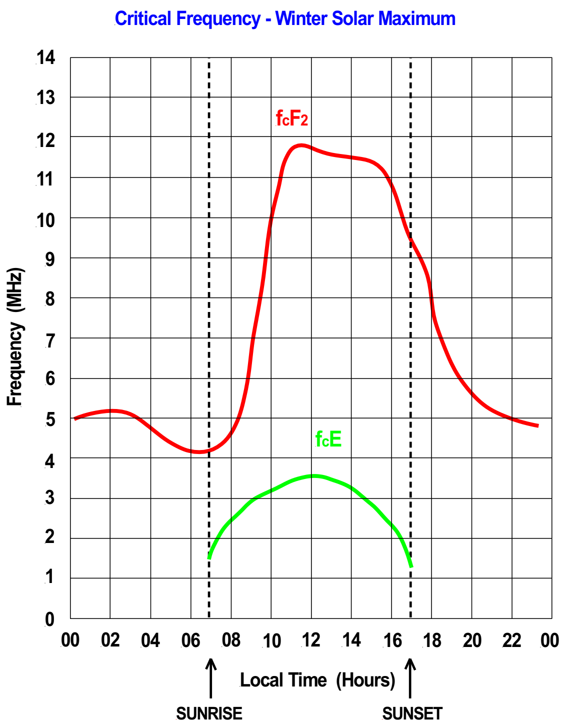
Critical Frequency Variation With Solar Cycle

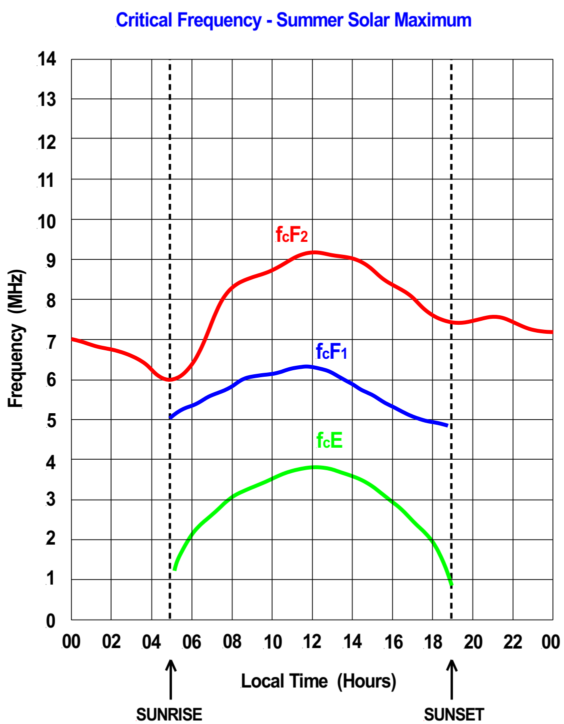


sws.bom.gov.au

- Since the EUV energy from the Sun varies with the 11 year solar cycle, the level of ionization in the ionosphere also varies with the solar cycle
- This variation is particularly evident in the variation of the **F2 critical frequency**
- As can be seen in the above figure, **fcF2** tracks the solar cycle very closely (solar cycle represented by the smoothed sunspot number - ssn)
- F1 & E critical frequencies also track the solar cycle, but not as dramatically

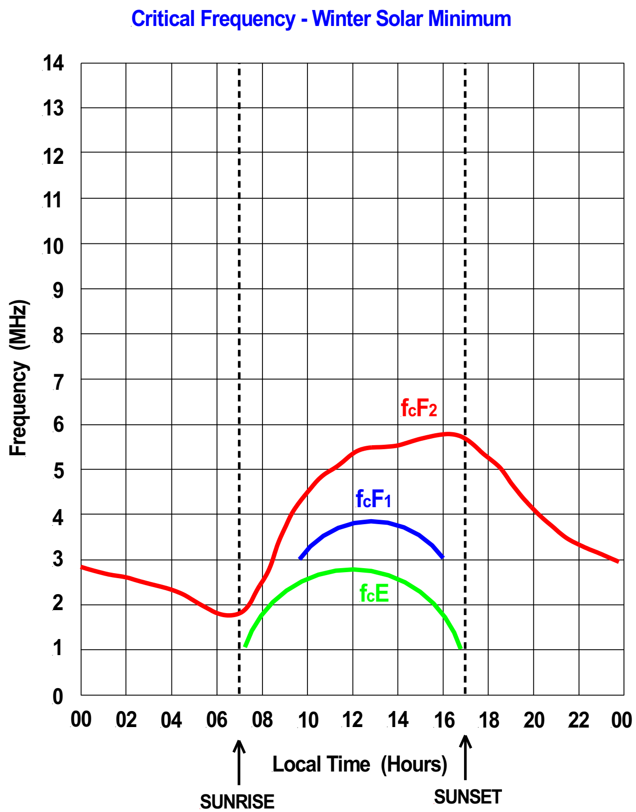
Critical Frequencies During Solar Maximum

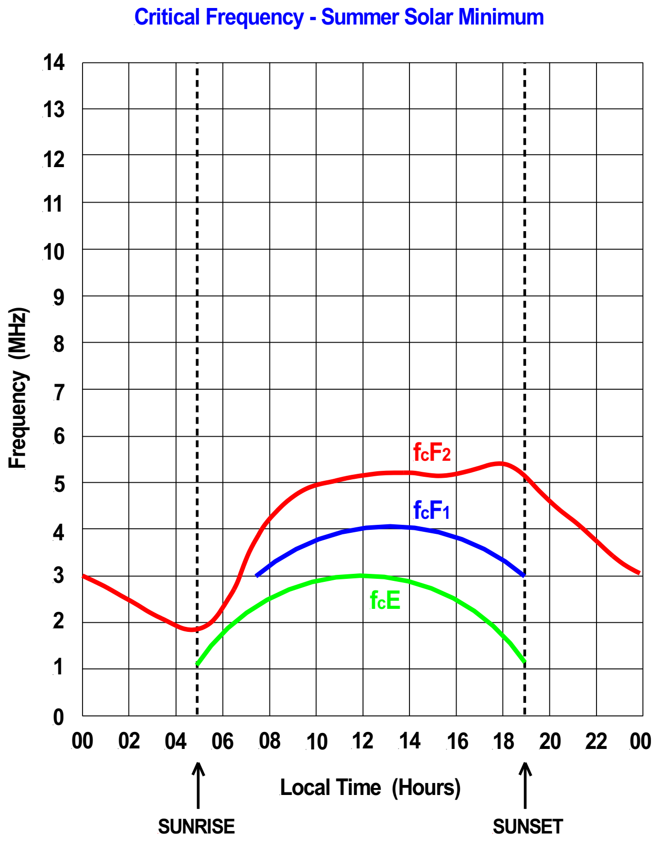




- Critical frequencies are at their highest levels during solar maximum, as expected
- Critical frequencies during the winter are typically 11 to 12 MHz during the day and 4 to 5 MHz at night, providing excellent long distance DX opportunities on 20 through 10 meters
- During the summer critical frequencies peak around 9 MHz and typically remain above 6 MHz during the night
- The relatively high night critical frequencies during solar maximum provides excellent 80 meter communications throughout the night

Solar Minimum Critical Frequencies



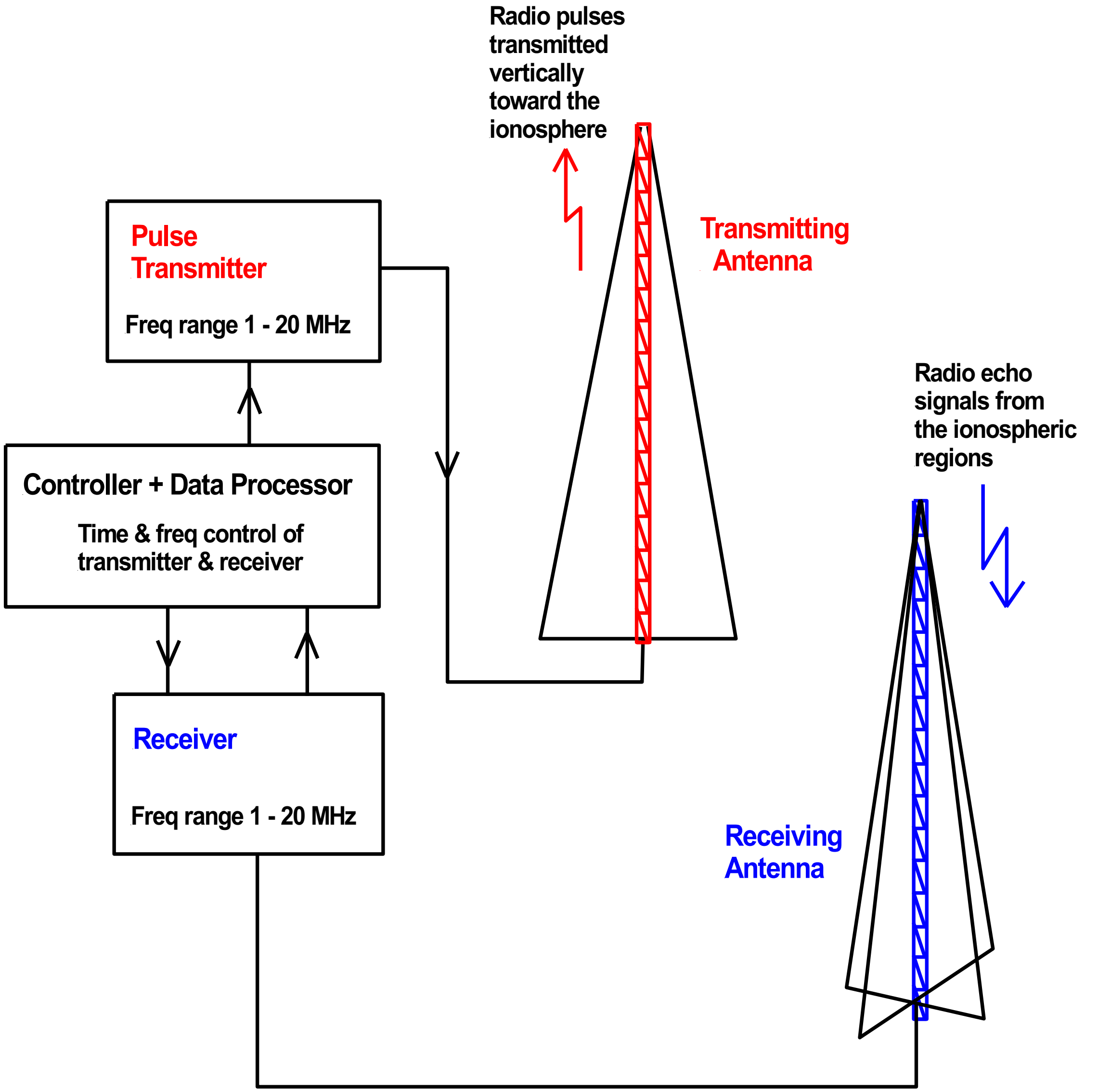


- Critical frequencies are lower during solar minimum adversely affecting all frequency bands
- The F2 critical frequency tends to peak in the late afternoon during solar minimum instead of around noon time
- Night critical frequencies are generally below 3 MHz creating problems for night time 80 meter operations

Observing the Ionosphere

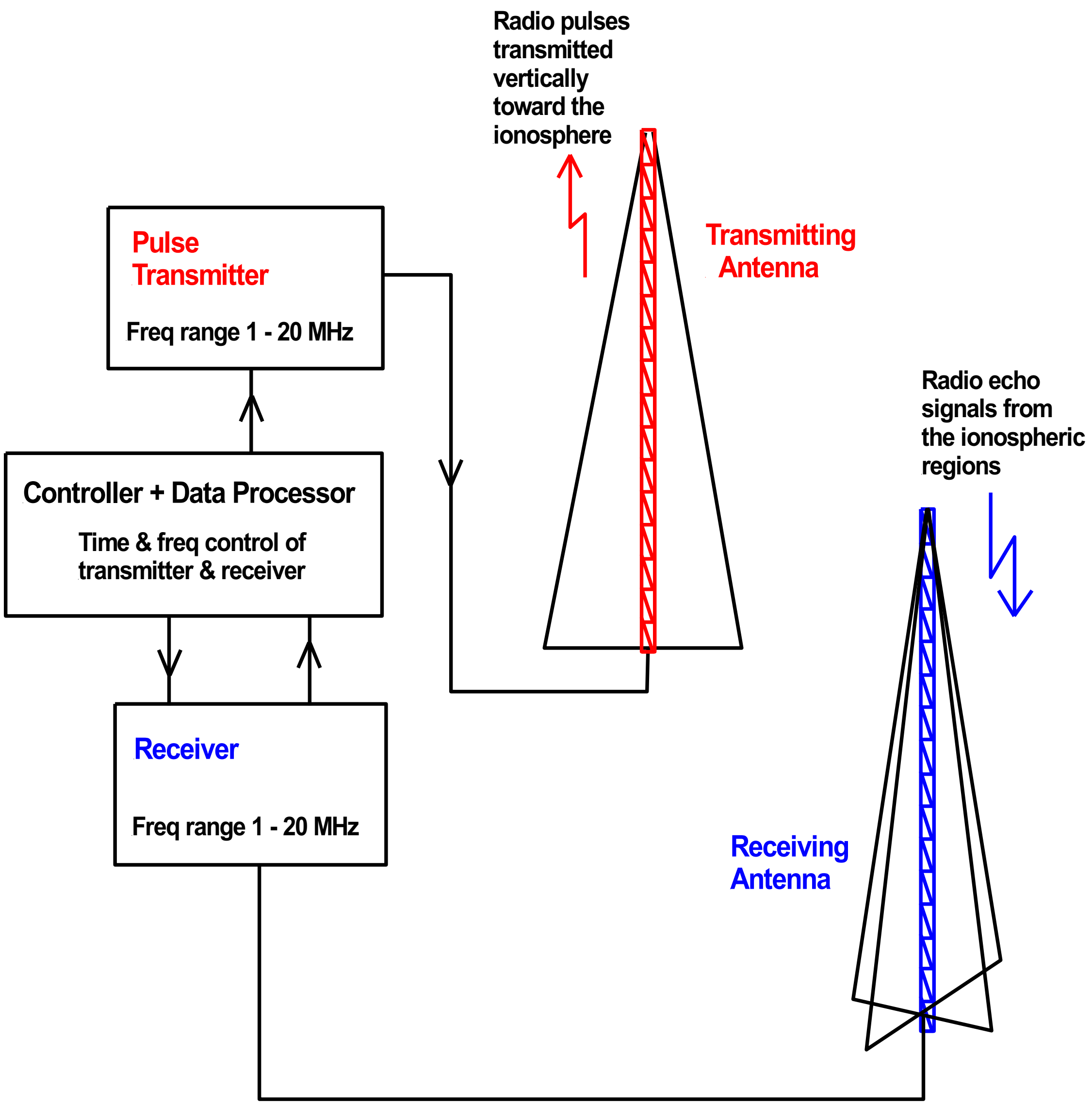
- Ground based sounders, known as ionosondes, have been used since the early days of radio to probe the ionosphere.
- They have provided the bulk of our current information on ionospheric structure

Ionosonde controller & data processor



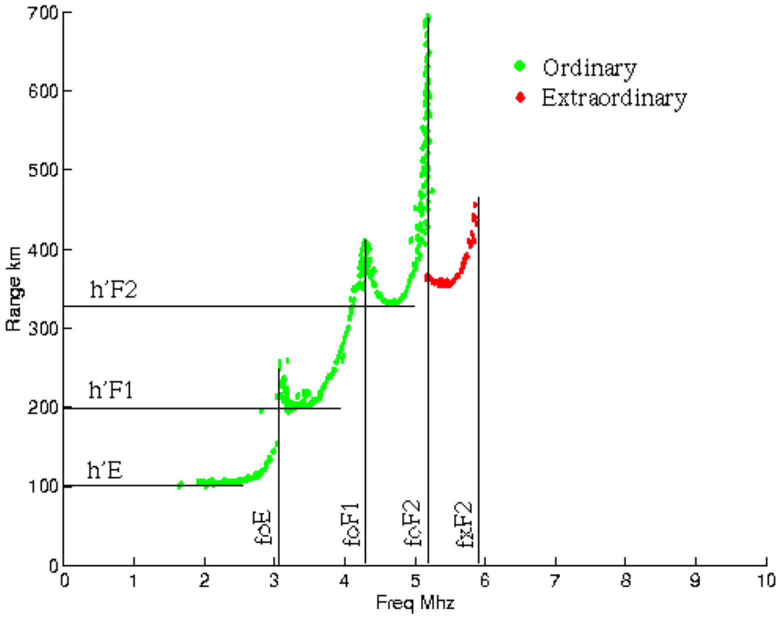
spaceacademy.net.au

Ionosonde



- An ionosonde transmits a pulsed signal at a high angle into the atmosphere and receives the echo, or reflection, of the signal back from the ionosphere
- The conditions of the echoed signal, whether it was reflected or not, the width and frequency of the reflected pulse, and the time between transmission and reception provides information on the current condition of the ionosphere
- The time between transmission and reception of a pulse indicates the height at which the signal was reflected

Ionogram



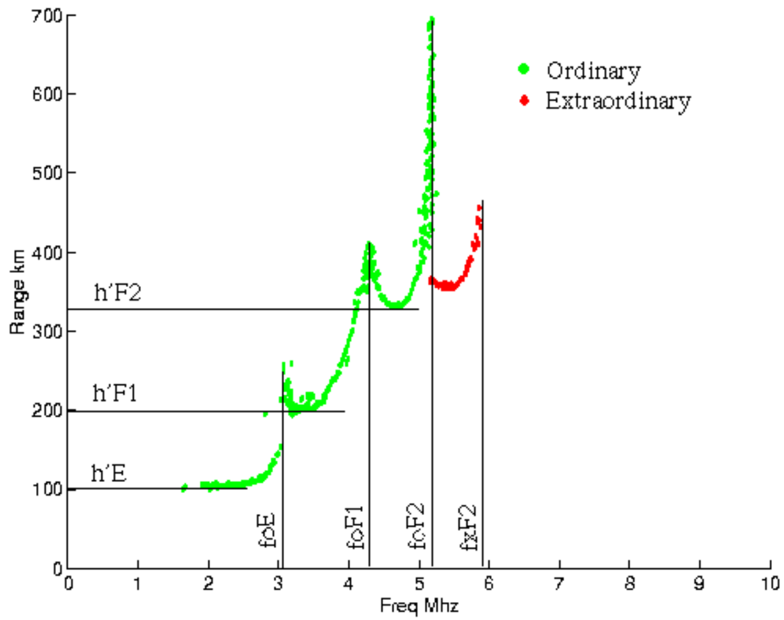
ukssddc.ac.uk

- An ionosonde converts the received echo into a graphical display of echo delay vs frequency known as an ionogram
- On the ionogram, echo delay is converted to altitude of the reflection point (Range km) using the equation

$$km = (1/2)cT$$

- km = kilometers, c = speed of light, T = time
- An ionosonde utilizes a sweep frequency transmitter
- The transmitter sends a long series of pulses, each at a slightly different frequency over a frequency range of typically 0.5 – 25 MHz.

Ionogram continued



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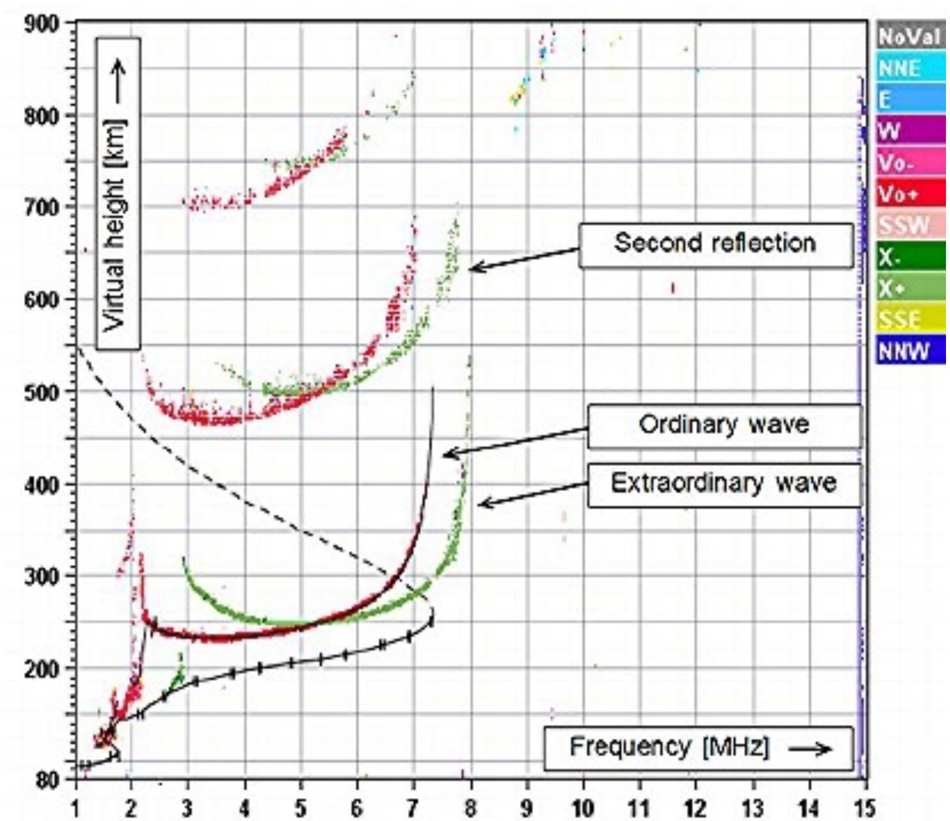
- A radio signal transmitted upward will penetrate the ionosphere until it reaches an altitude at which its frequency equals the ionosphere plasma frequency
- At that point it is reflected back to ground. All signals lower in frequency will also be reflected back
- For example, in the ionogram shown, a signal reflected at a frequency of ~ 3 MHz indicates the presence of an E region. A 4.2 MHz signal passes through the E region and is reflected in the F1 layer, identified by the longer time between transmission and reception of the pulse. A 5.1 MHz signal passes through both the E and F1 layers before being reflected in the F2 region, represented by a still longer delay. In this example a 7 MHz pulse passes through all 3 layers without being reflected at all. It is lost to outer space

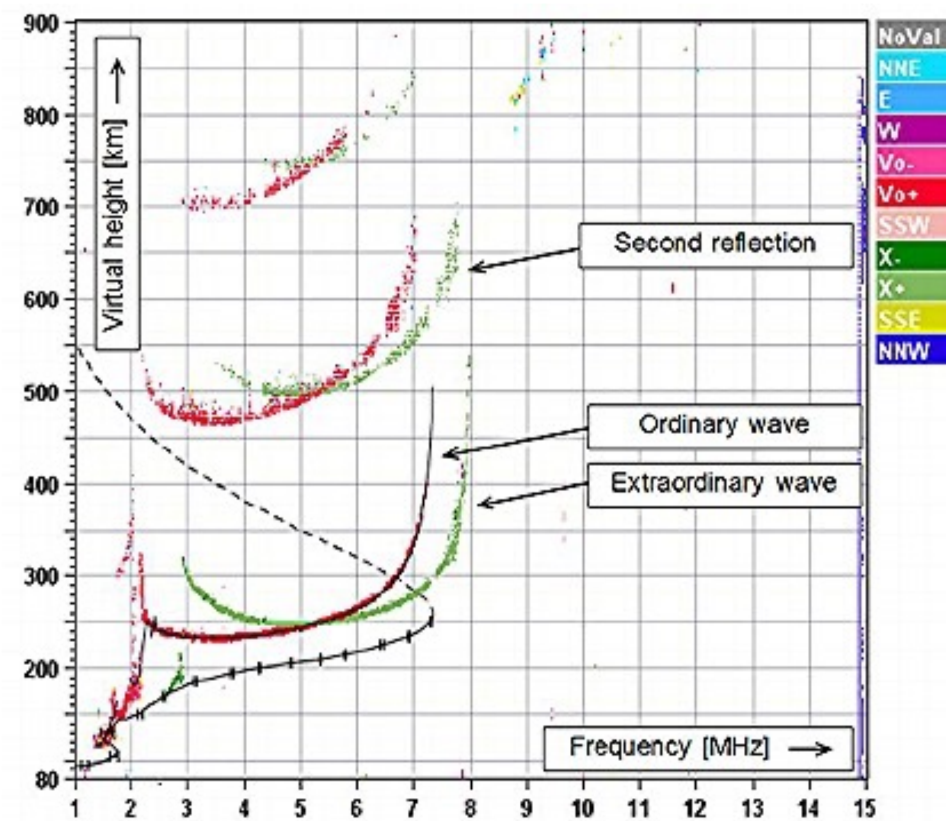
Ordinary & Extraordinary Modes



ResearchGate

- Earth's geomagnetic field causes an HF radio signal to split into two different signals each with a slightly different mode of propagation through the ionosphere (slightly different indices of refraction resulting in slightly different velocities and direction of travel)
- One propagation mode is termed the ordinary or o - mode
- The other is called the extraordinary mode, or x – mode. In this case the term extraordinary does not mean something special about this second propagation mode. It simply means an extra or additional mode

Ordinary & Extraordinary Modes continued



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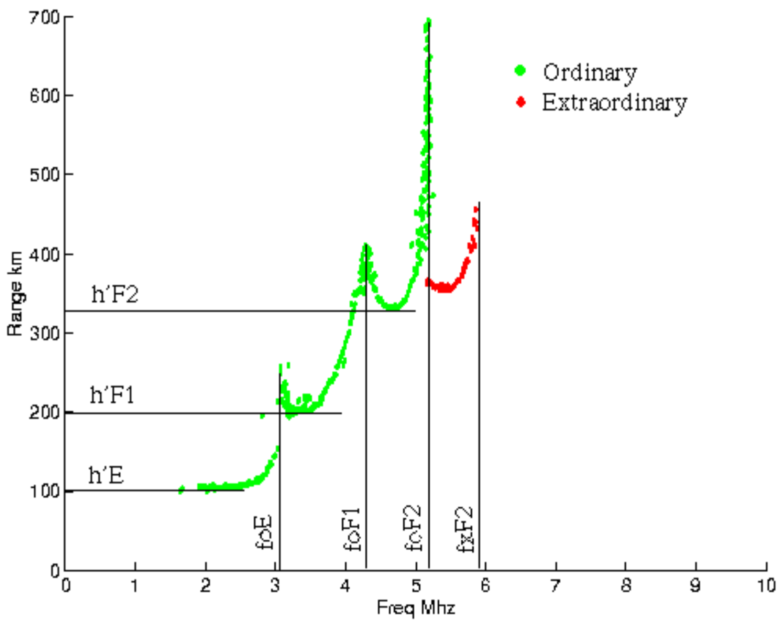
- Consequently, each ionogram consists of two traces, one corresponding to the o – mode and the other to the x – mode
- The x – mode is generally the higher frequency trace
- That is, the x – mode reflects from the ionosphere at a higher frequency than the o - mode

Reading an Ionogram



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h'F2 is the height (altitude) of the F2 maximum electron density.

f_oF2 is the F2 o–mode critical freq

f_xF2 is the F2 x-mode critical freq.

- By convention the o-mode trace is used in determining critical frequencies and maximum electron densities at the points of signal reflection

- The o-mode (f_o) critical frequency f_oF2 is,

$$f_oF2 = 9(10^{-3})\sqrt{N_{max}}$$

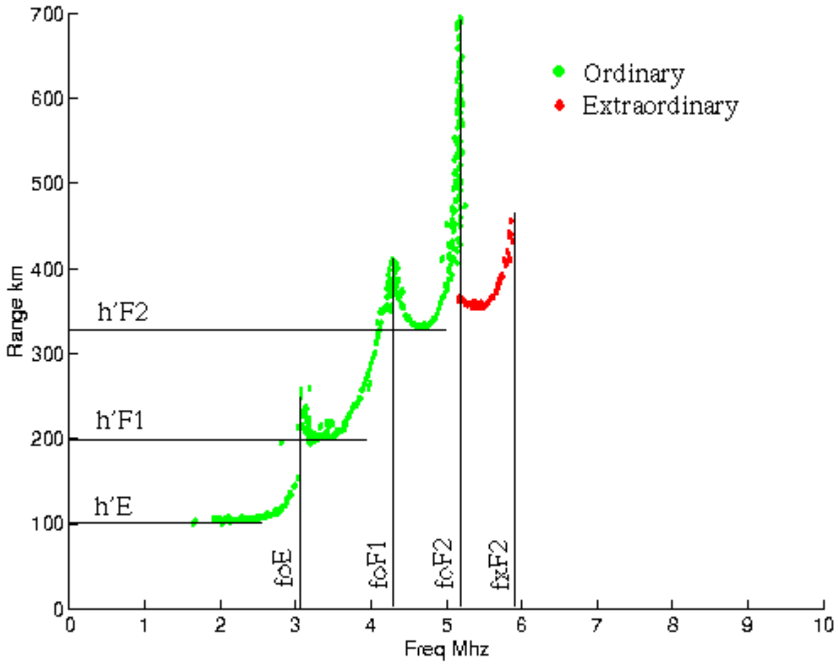
where N_{max} is the maximum electron density

- f_oF2 is read from the ionogram

- From that information, the maximum electron density N_{max} in the F2 region can be calculated from

$$N_{max} = \left[\frac{f_oF2}{9\left(10^{-3}\right)}\right]^2$$

Spikes in Ionogram Curves



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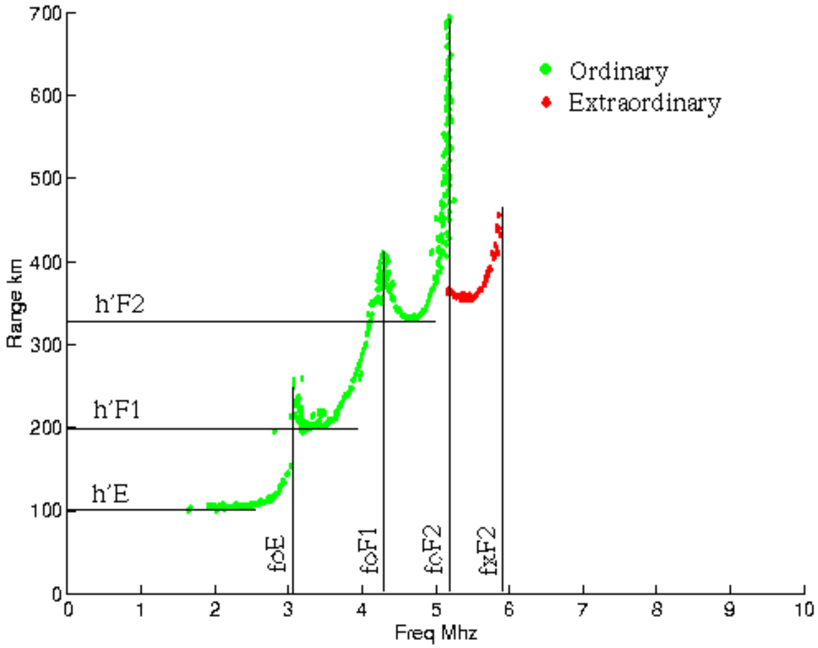
- The transmitted signal is assumed to travel at the speed of light c
- However, this is not really the case. The speed is actually less than c and in addition varies as the signal propagates through the ionosphere
- The speed decreases significantly as the sweep frequency of the transmitter approach a critical frequency point, considerably increasing the reflection time T at those points

Spikes in Ionogram Curves continued



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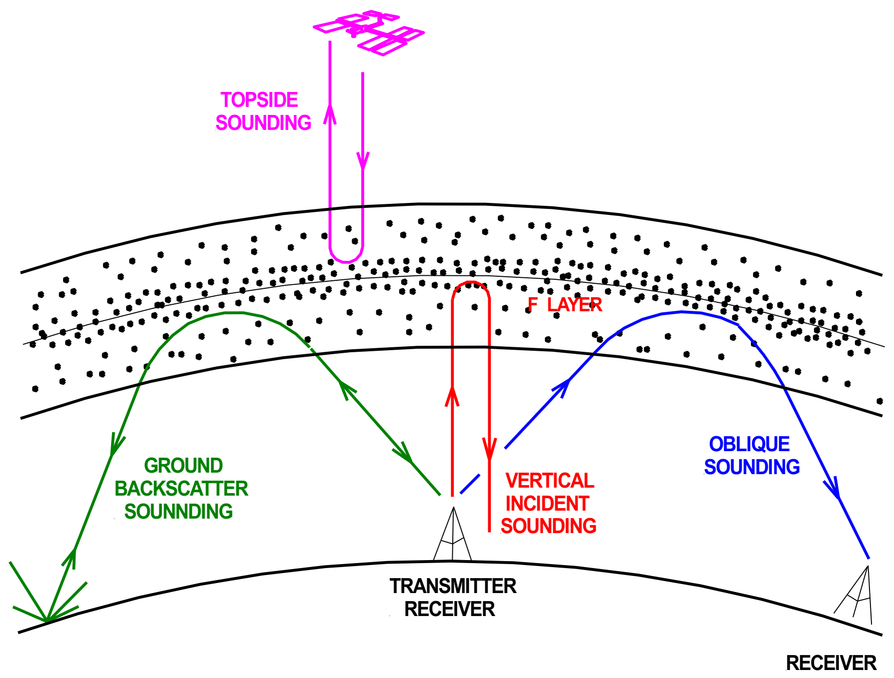
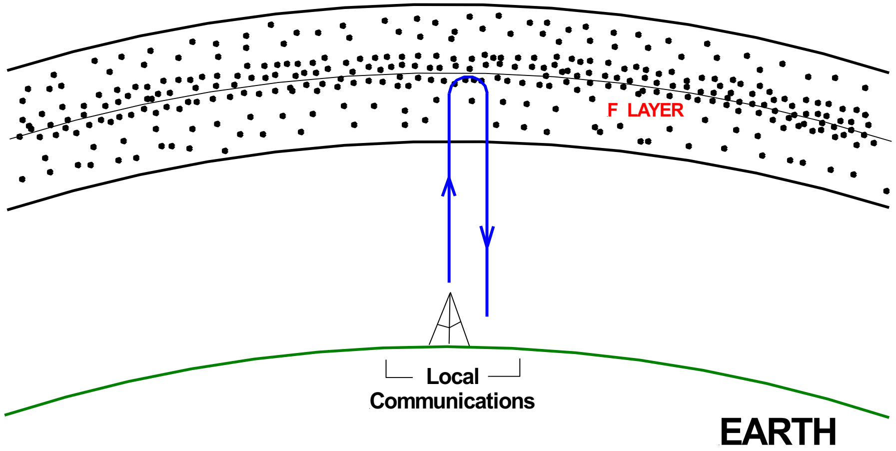
- On an ionogram, the increase in T appears as a spike in the height at which critical frequency reflection occurs
- This is an artifact
- The reflection heights are actually h'E, h'F1, and h'F2 as shown
- However, the spikes make it easy to determine the critical frequency points.

Types of Ionosondes



- Several types of ionosonde sounders (also known as HF radar) are currently in use:
  - Vertical incident sounders (VIS)
  - Oblique sounders
  - Direct and ground backscatter radar
  - Topside sounding using Earth satellites

Vertical Incident Sounders



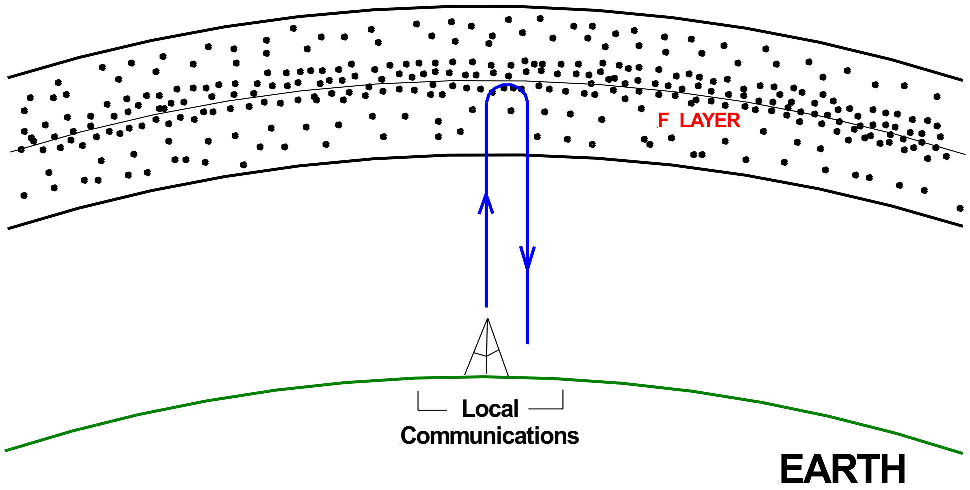
- Vertical incident sounding (VIS) transmits a sweep frequency HF signal vertically into the atmosphere and receives the echoes, or reflections, from the ionosphere on a co-located receiver

- Vertical incident sounding was the earliest method used for investigating the ionosphere and over the years has provided a very complete picture of ionospheric structure

- It remains the primary method of determining current ionospheric conditions in the E, F1, and F2 regions

- Signal absorption in the D region is a problem. Special methods are needed to determine electron densities in this region

Vertical Incident Sounders continued

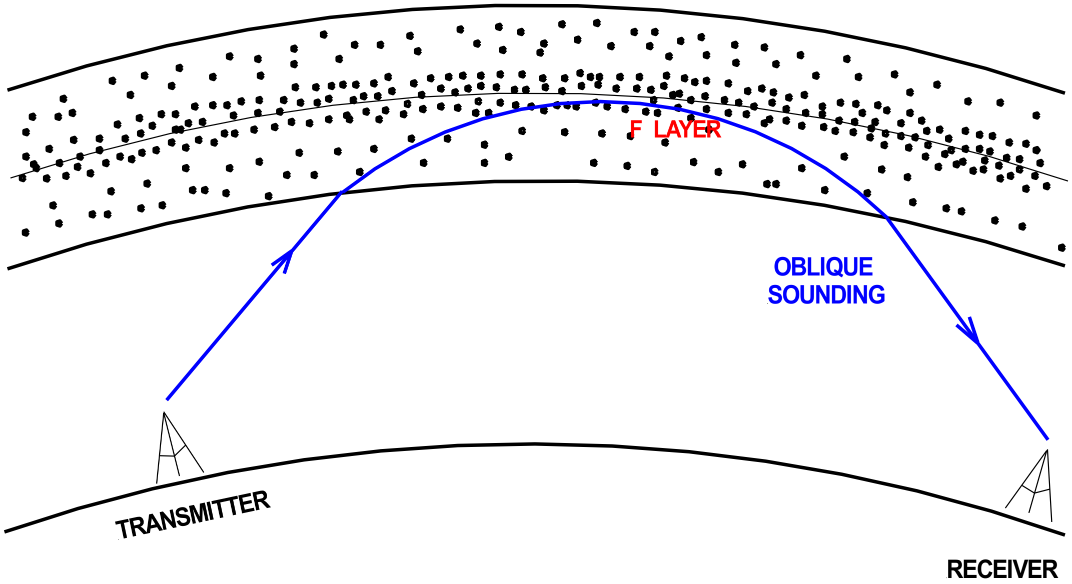


- Much of the current ionospheric nomenclature has evolved from the early VIS investigations.

- Typical VIS Specifications:

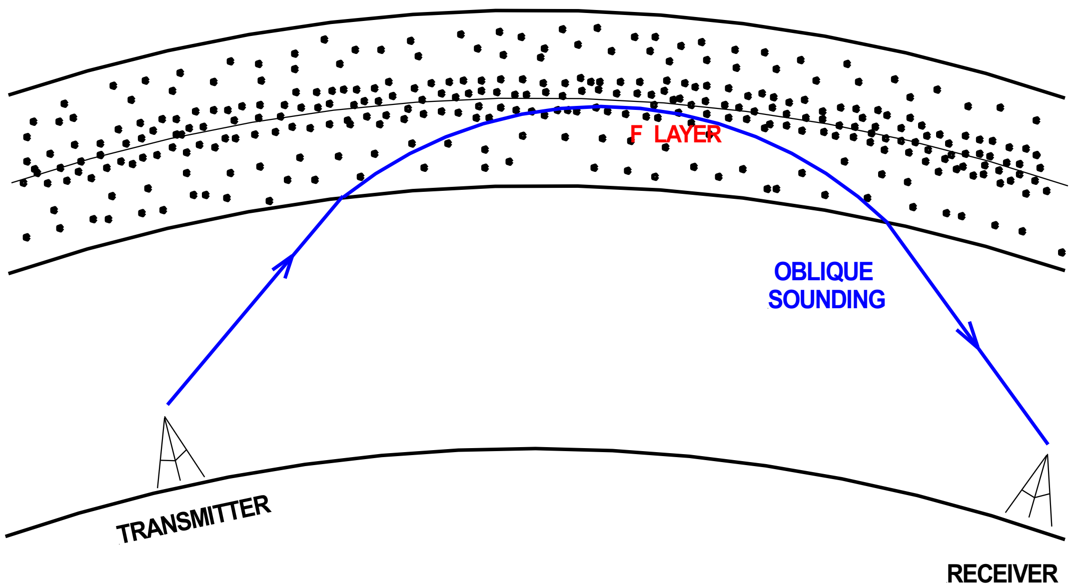
Frequency	0.5 to 25 MHz
Power	300 W to 10 KW
Sweep Cycle	30 sec – 5 min.
Pulse Rate	50 per sec
Pulse Width	30 microsec

Oblique Sounding



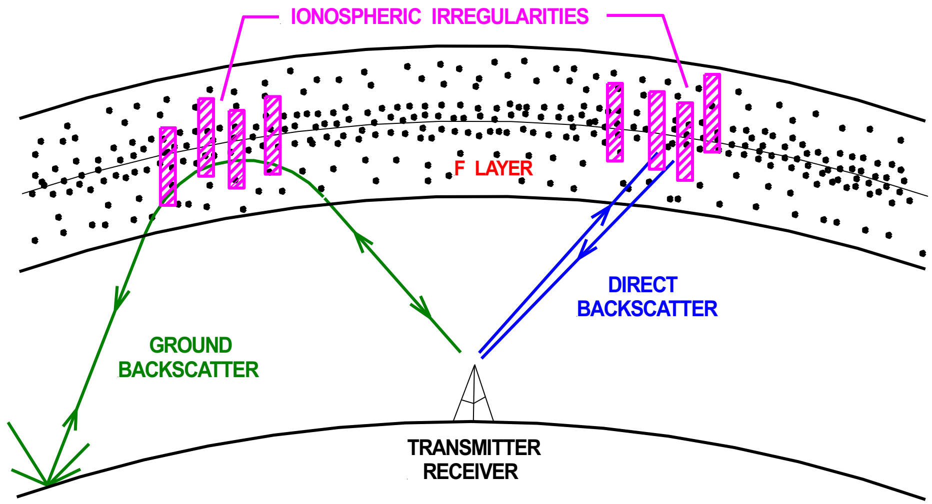
- Oblique sounding monitors propagation conditions on an HF communications circuit between two locations
- This is done by transmitting pulses of radio energy obliquely through the ionosphere from a sweep frequency transmitter to a distant receiver
- The transmitter and receiver must be synchronized in order to produce an oblique ionogram

Oblique Sounding continued



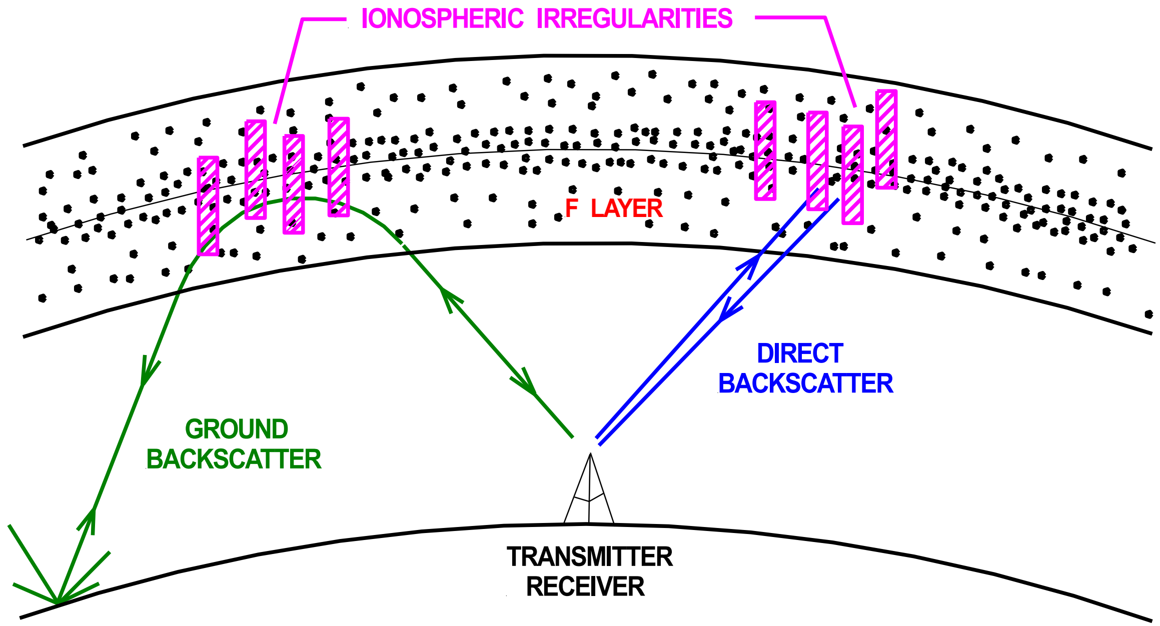
- Oblique sounding is very important for real time radio frequency management
- It is used to determine which frequencies and propagation modes are available over a particular communications circuit at the time of operation
- It is also very important for testing propagation predictions and validating ionospheric models

Backscatter HF Radar



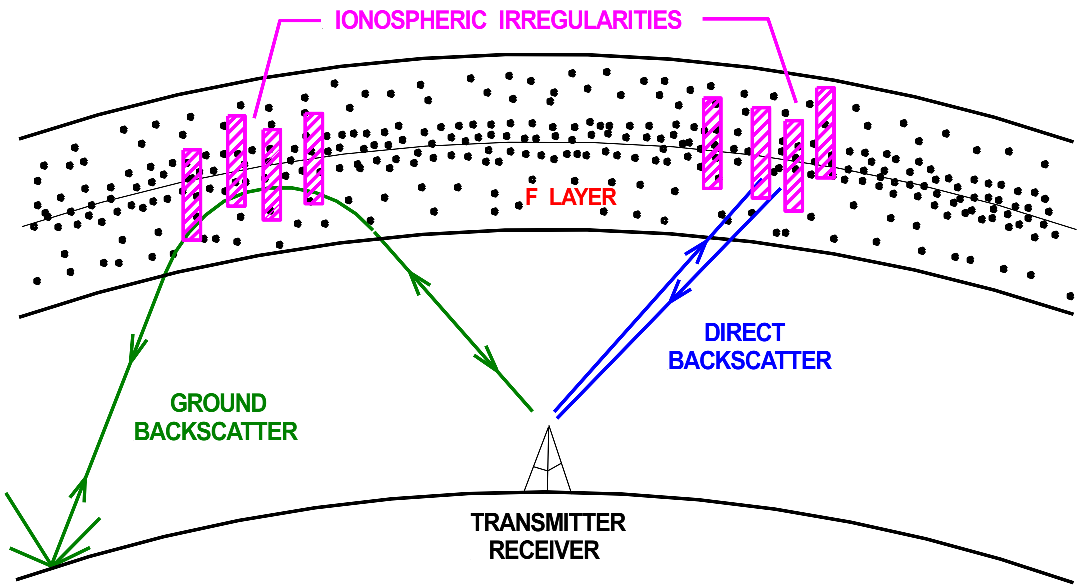
- Two types of backscatter HF radar systems are in use. They are:
  - Direct Backscatter Radar
  - Ground Backscatter Radar
- Both types are used to study ionospheric irregularities.
- Backscatter HF Radars are typically expensive complex systems frequently utilizing large arrays of up to 16 log-periodic antennas.
- Interpretation of backscatter data is often complex.

Direct Backscatter HF Radar



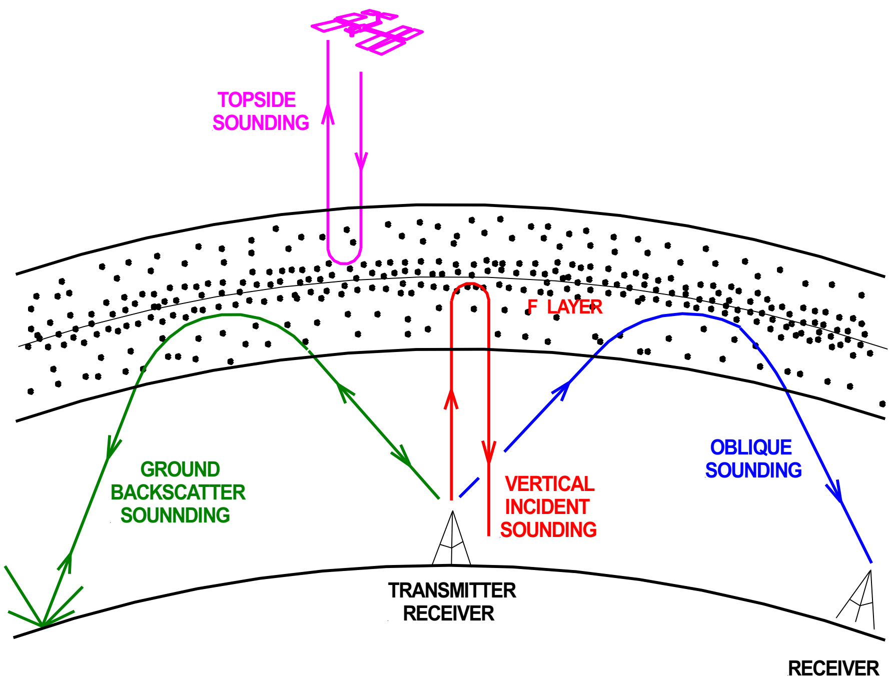
- Signals transmitted into the ionosphere are often scattered by ionospheric irregularities
- Some of the scattered signal is received back at the transmitting site
- Direct backscatter HF radar are systems designed to make use of this phenomena to study ionospheric irregularities by analyzing the received backscattered signal
- Networks of direct backscatter systems are used to study the ionosphere at high latitude
- All of the north polar region is covered and part of the south polar region

Ground Backscatter HF Radar



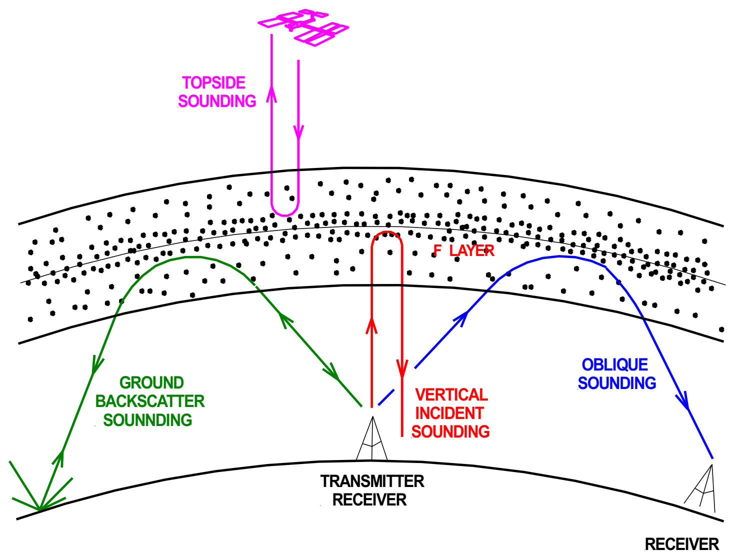
- All signals that are transmitted into the atmosphere and refracted back to Earth by the ionosphere, scatter when they hit the ground
- A small amount of scattered energy travels back through the ionosphere to the transmitting site
- The returning signal (ground echo) is often distorted by ionospheric irregularities
- These irregularities are studied by analyzing the distorted ground echo
- Ground backscatter signals are orders of magnitude weaker than direct backscatter

Top Side Sounding



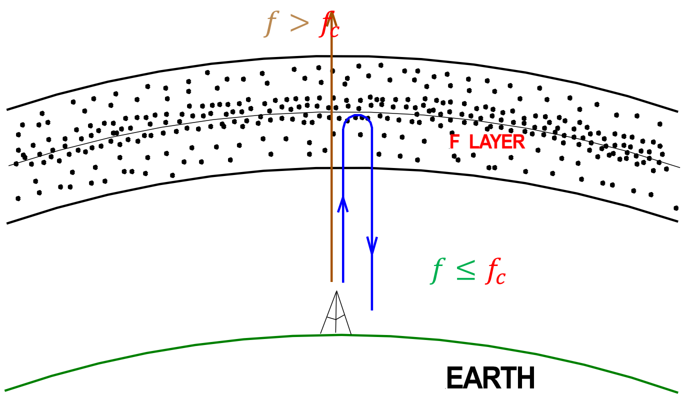
- Top side sounding utilizes Earth satellites to probe the upper part of the ionosphere
- Ground based ionosondes can only "see" the bottom of the ionosphere, up to the F2 maximum ionization level, by transmitting at frequencies at and below the F2 critical frequency f_oF2
- Higher frequency vertical signals pass through the ionosphere without being reflected back to Earth, and thus provide no information

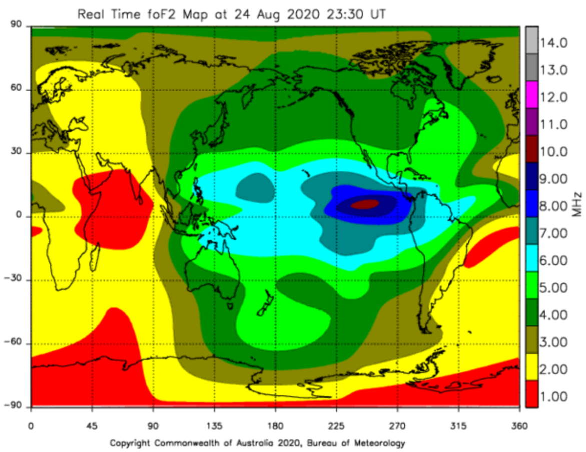
Top Side Sounding continued



- Top side sounding from an Earth satellite is very similar to ground based VIS except it probes down into the ionosphere from above
- The F2 maximum ionization level is the furthest that a top side sounder can see down into the ionosphere, again by transmitting at frequencies at and below the F2 critical frequency f_oF2
- Transmitting at a higher frequency will cause the signal to pass through the ionosphere to the Earth instead of being reflected back to the satellite
- Consequently, top side sounders explore the ionosphere from the F2 maximum ionization level to an altitudes of 1,000 km or more

Critical Frequency Summary





- Critical Frequency $\mathbf{f_c}$ is the **highest** frequency signal that can be transmitted straight up and reflected back down to Earth.
- All signals lower in frequency than $\mathbf{f_c}$ will also be reflected back to Earth
- But, signals higher in frequency transmitted straight up will penetrate the ionosphere and be lost to outer space
- Critical Frequency varies throughout the day as the Earth rotates, seasonally as Earth's upper atmosphere plus the elevation angle of the Sun changes, and with the 11 year solar cycle as EUV & X-ray radiation changes.
- Critical frequency determines band openings, maximum usable frequency, whether skip zones are present, the availability of NVIS propagation, performance of local and regional nets, etc
- Current critical frequency determined using the global F2 critical frequency map