Radio Wave Propagation in the Ionosphere

1. Radio Wave Propagation

The electromagnetic radiation of the Sun is continuum, it spans radio waves through the infrared, visible, ultraviolet, x-ray, and beyond, as shown in Figure (1).

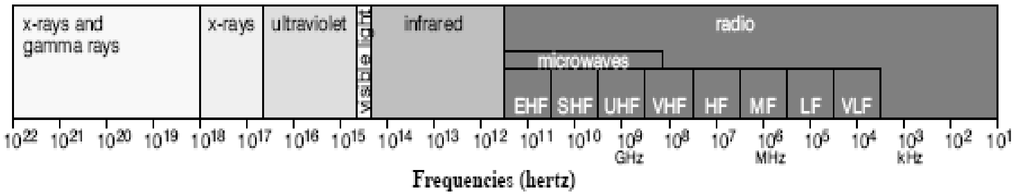


Figure (1) The Electromagnetic Spectrum.

The continuum of the electromagnetic frequency spectrum useful for communications extends from the extremely low frequency (ELF) (designated 30-300 Hz) to the extremely high frequency (EHF) (designated 30-300 GHz). Table (1) below specifies the designated nomenclature for those frequencies used in communications.

Table (1) Electromagnetic Spectrum Nomenclature.

Frequency Rang	Designation	Classification
30-300 Hz	ELF	Extreme Low Frequency
3-30 KHz	VLF	Very Low Frequency
30-300 KHz	LF	Low Frequency
0.3-3 MHz	MF	Medium Frequency
3-30 MHz	HF	High Frequency
30-300 MHz	VHF	Very High Frequency
0.3-3 GHz	UHF	Ultra High Frequency
3-30 GHz	SHF	Super High Frequency
30-300 GHz	EHF	Extremely High Frequency

Since the surface of the Earth is approximately spherical and because the electromagnetic waves in a uniform atmosphere travel in straight lines, long distance radio communication is made possible by the reflection of radio waves from the Ionosphere (i.e., the upper part of the Earth). The Ionosphere affects radio signals in different ways depending on their frequencies. Radio waves with frequencies above 30 MHz like VHF, UHF, SHF, or EHF usually penetrate the Ionosphere and, therefore, are usually for ground to space communications. While radio waves with frequencies below 30 MHz are designated as high frequencies (HF), the Ionosphere may act as an efficient reflector, allowing radio communication to distances of many thousands of kilometers.

The high frequency (HF) band is usually defined, as being between 3 to 30 MHz. it is an extremely cost effective (inexpensive widely available technology) radio frequency for implementing long-range communications. Figure (2) shows various types of frequencies are used for the communications.

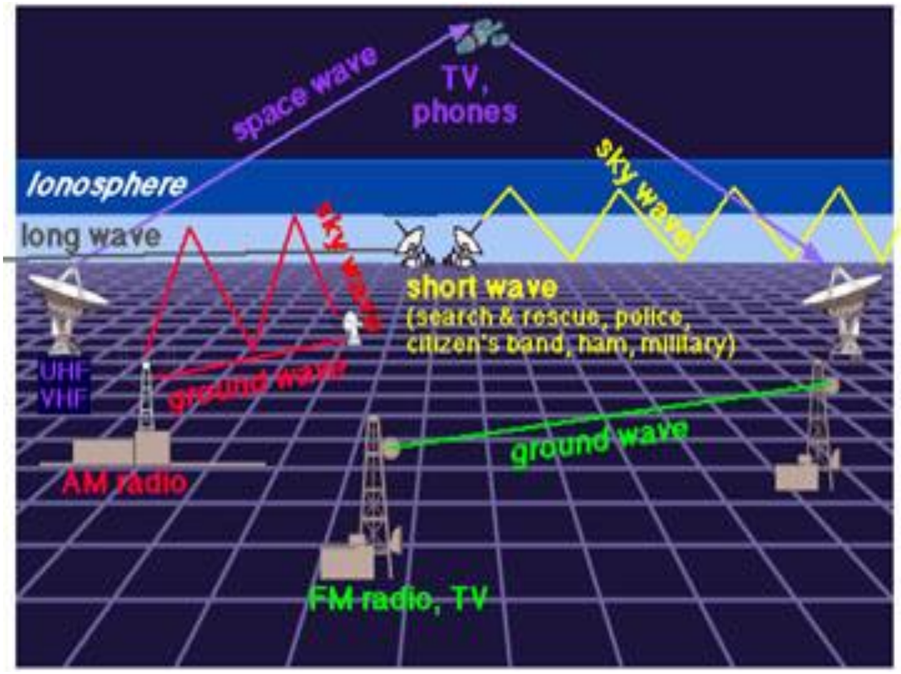


Figure (2) Various Types of Radio waves used for communication.

Heinrich Hertz was the first who had successfully send and receive radio waves. James Clerk Maxwell had mathematically predicted their existence in 1864. Between 1885 and 1889, he produced the electromagnetic waves in the laboratory and measured their wavelength and velocity. He showed that the nature of their reflection and refraction was same as those of light, confirming that light waves are electromagnetic radiation obeying Maxwell equations.

It was not until the last decade of the 19th century that an Italian scientist named Guglielmo Marconi (who is often called the Father of the wireless) converted the electromagnetic radiation theory and laboratory experiments into the first practical wireless telegraph system, due to this scientist achievement he was granted a British patent. In 1899, Marconi tested his wireless communication technique across the English Channel.

In a landmark experiment on December 12, 1901, Marconi, had demonstrated transatlantic communication by receiving a signal in St. John's Newfoundland that had been sent from Cornwall, England.

Marconi's famous experiment showed the way toward world wide communication, but it also raised a serious scientific dilemma. Up to this point, it had been assumed that electromagnetic radiation traveled in straight lines in a manner similar to light waves. If this were true, the maximum possible communication distance would be determined by the geometry of the path as shown in Figure (3).

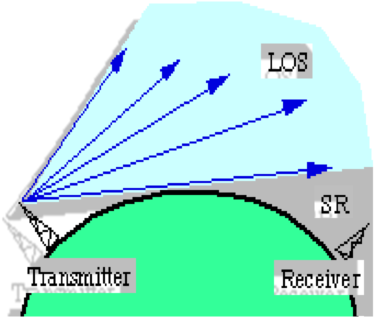


Figure (3) Areas in the light blue region are within the radio "Line of Sight" (LOS). The receiving antenna is in the shadow region (SR) and cannot receive a signal directly from the transmitter.

The radio signal would be heard up to the point where some intervening object blocked it. If there were no objects in the path, the maximum distance would be determined by the transmitter and receiver antenna heights and by the bulge (or curvature) of the earth. Drawing from light as an analogy, this distance ioften called the "Line-of-Sight" (LOS) distance. In Marconi's transatlantic demonstration, something different was happening to cause the radio waves to apparently bend around the Earth's curvature so that the communication signals from England could be heard over such an large distance.

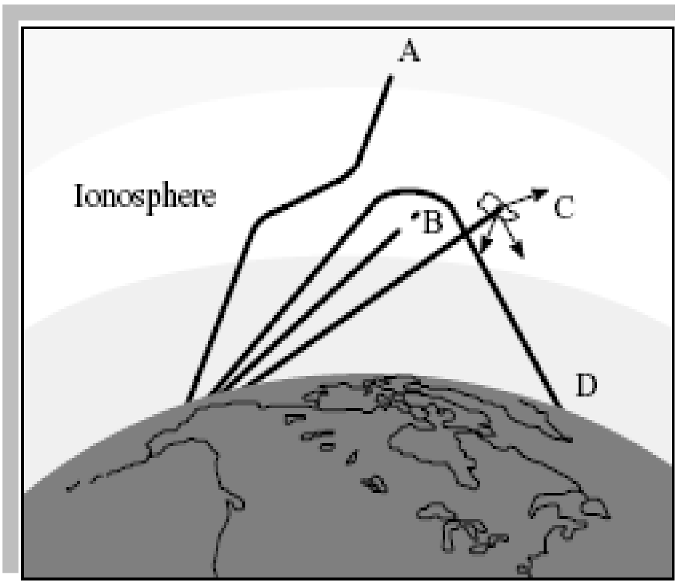
In 1902, Oliver Heaviside and Arthur Kennelly each independently proposed that a conducting layer existed in the upper atmosphere that would allow a transmitted EM signal to be reflected back toward the Earth. Up to this time, there was no direct evidence of such a region and little was known about the physical or electrical properties of the Earth's upper atmosphere. If such a dramatic extension of conductive layer existed, it would permit extension of "line-of-Sight" limitation to radio communication as shown in Figure (4).

Figure (4) A conductive region at high altitude would "reflect" radio signals that reached it and return them to Earth

During the mid-1920's, the invention of the Ionosonde allowed direct observation of the ionosphere and permitted the first scientific study of its characteristics and variability and its effect on radio waves. The excitement of Marconi's transatlantic demonstration inspired numerous private and commercial experiments to determine the ultimate capabilities of this newly discovered resource, the Ionosphere. Among the most important early experiments were those conducted by radio amateurs who showed the value of the so-called high frequencies above 2 MHz for long distance propagation using the ionosphere.

Ionospheric Disturbances

The Ionosphere occasionally becomes disturbed as it reacts to certain types of solar activity. Solar flares are an example, these disturbances can affect radio communication in all latitudes. Frequencies between 2 MHz and 30 MHz are adversely affected by increased absorption, whereas on higher frequencies (e.g.,30-100MHz) unexpected radio reflection can result in radio interference. Scattering of radio power by ionospheric irregularities produces fluctuating signals (Scintillation), and propagation may take unexpected paths. Figure (7) illustrates various ionospheric radio wave propagation effects.



A. Wave penetrates the ionospheric layer
B. Wave is absorbed by the layer
C. Wave is scattered in random directions by irregularities in the layer
D. Wave is reflected normally by the layer

Figure (1.7) The radio waves that reach the ionosphere [12]

Among the important types of ionospheric disturbances are the following:

1. *Solar Cycle and Sunspot Numbers*

Solar characteristics vary cyclically. The most familiar cycle is typically 11 years in duration, although cycles of different length and amplitude are not uncommon. The solar cycle has many properties of the solar activity, it is most evident with the appearance of the Sunspot on the solar disk. Figure (8) shows sample of the variation of solar sunspot number.

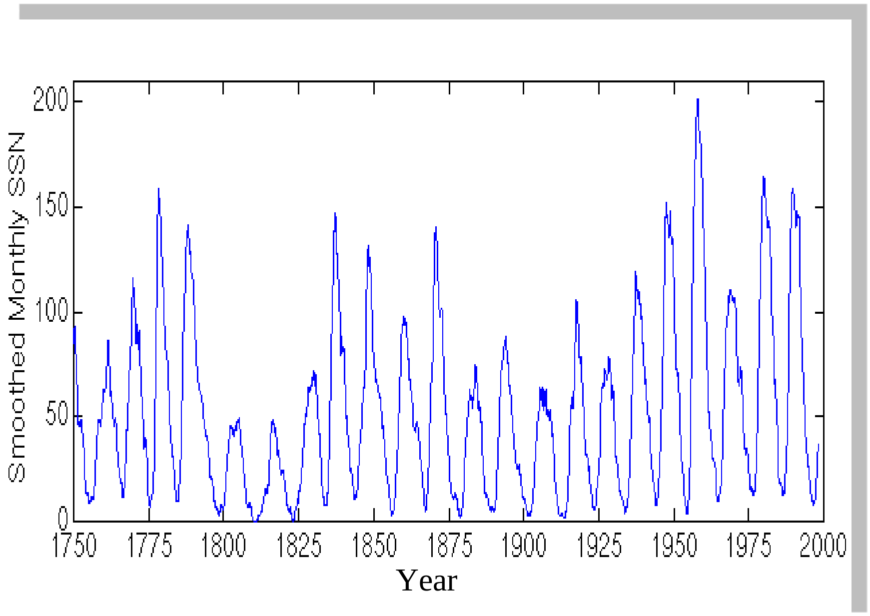


Figure (8) The Solar Cycle for 1750-1998

Sunspots are regions of strong magnetic field and appear optically darker than the surrounding surface, as shown in Figure (9).

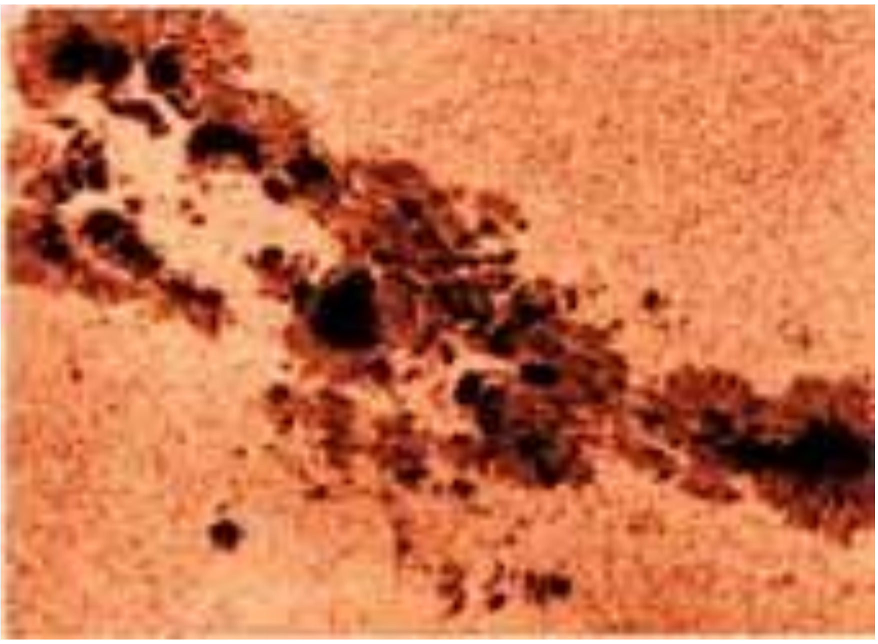


Figure (9) The Sunspots

At times, sunspots are rare and the Sun appears almost without defect (solar minimum). As solar activity increases, sunspots become more common and it is normal to see many groups of spots on the face of the Sun. The traditional measure of the solar cycle is the number of sunspots, statistically smooth, over a period of 12 months. The peak sunspot number of historical cycles varies greatly but five of the last six cycles have been large in amplitude. According the conventional numbering system that used to represent the solar cycles, cycle 19 (the peak sunspot number was 201, in 1957) was the largest cycle on record, cycle 21 (peak sunspot number was 165, in 1979) is the second largest cycle, and cycle 22 (peak was 159, in 1989) is the third largest cycle. The present cycle (number 23) is a moderately large cycle in terms of sunspot number (the peak sunspot number is 121, in 2000). The outside appearance for the Sun for two cases of the Solar activity (Minimum and Maximum Solar Activity) are shown by figure (9).

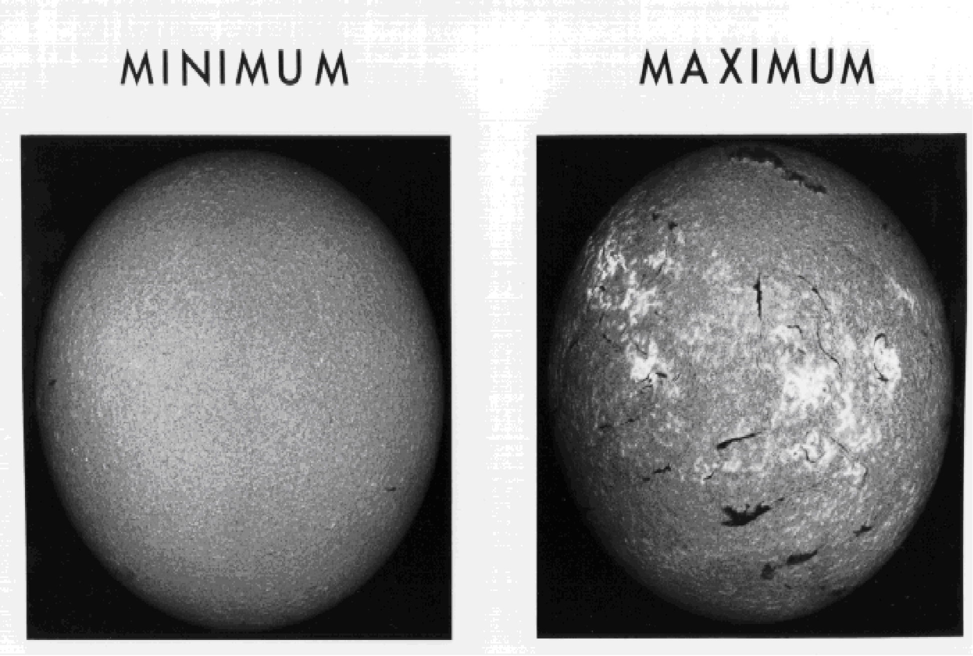


Figure (10) Two different solar activities

The daily sunspot number has little, if any, relationship to ionospheric variability. However, the most widely used Ionospheric Index, R12, is derived from the daily sunspot numbers. The R12 index is a twelve-month smoothed relative sunspot number.

2. Solar Flares

Solar flare is a violent explosion in the Sun's atmosphere releasing up to a total energy of 6×10^{25} Joules. Solar flares take place in the solar corona and chromosphere, heating plasma to tens of millions f Kelvin's and accelerating electrons, protons and heavier ions to near the speed of light.

They produce electromagnetic radiation across the electromagnetic spectrum at all wavelengths from long-wave radio to the shortest wavelength gamma rays. Most flares occur in active regions around sunspots, where intense magnetic fields emerge from the Sun's surface into the corona. Flares are powered by the sudden (timescales of minutes to tens of minutes) release of magnetic energy stored in the corona. X-rays and UV radiation emitted by solar flares can affect Earth's ionosphere and disrupt long-range radio communications. Direct radio emission at decimetric wavelengths may disturb operation of radars and other devices operating at these frequencies. Solar flares were first observed on the Sun in 1859 as localized brightening in a Sunspot group. The frequency of occurrence of Solar Flares varies, from several per day when the Sun is particularly active to less than one each week when the Sun is quiet. Large flares are less frequent than smaller ones. Solar activity varies with an 11-year cycle (the Solar Cycle). At the peak of the cycle there are typically more sunspots on the Sun, and hence more solar flares.

3. Sudden Ionospheric Disturbances

A Sudden Ionospheric Disturbance (SID) is an abnormally high plasma density in the ionosphere caused by an occasional sudden solar flare, which often interrupts or interferes with telecommunications systems. When a solar flare occurs on the Sun a blast of ultraviolet and x-ray radiation hits the dayside of the Earth after 8 minutes. This high energy radiation is absorbed by atmospheric particles raising them to excited states and knocking electrons to be free in the process of photoionization. The low altitude ionospheric layers (D and E regions) immediately increase in density over the entire dayside. Short radio waves (in the HF range) are absorbed by the increased particles in the low altitude ionosphere causing a complete blackout of radio communications. This is called a Short Wave Fadeout. These fadeouts last for a few minutes to a few hours and are most severe in the equatorial regions where the Sun is most directly overhead. The Ionospheric Disturbance enhances long wave (VLF) radio propagation.

4.Geomagnetic Storm Effects

Sufficiently large or long-lived solar flares and disappearing filaments (DSF) are sometimes accompanied by the ejection of large clouds of Plasma (ionized gas) into interplanetary space. These plasma clouds are called Coronal Mass Ejection (CME). A CME travels through the solar wind in interplanetary space and sometimes reaches the Earth as shown in Figure (11).

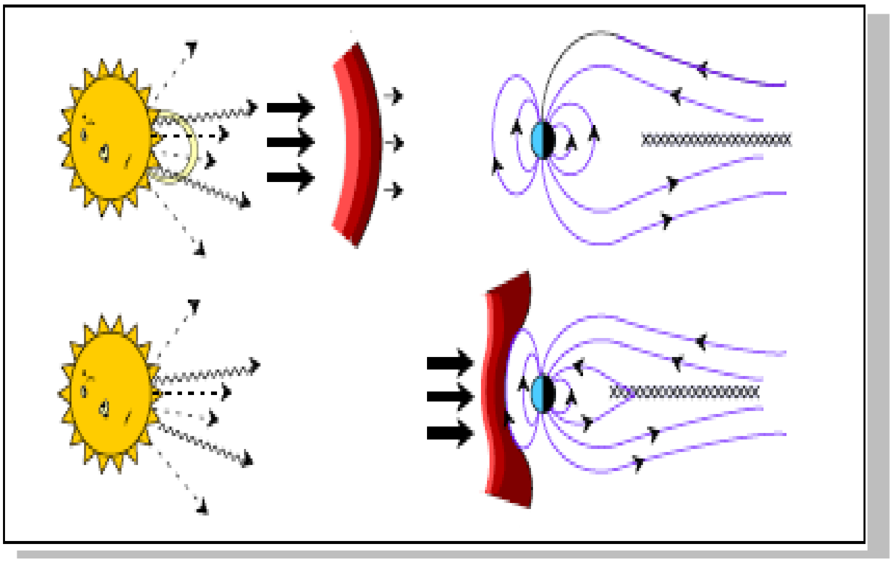


Figure (11) An ejection from the Sun distorts the Earth's magnetic field

This results in a world wide disturbance of the Earth's magnetic field, called a Geomagnetic Storm. Geomagnetic storms may be accompanied by ionospheric disturbances. These ionospheric disturbances can have adverse effects on radio signals over the entire frequency spectrum, especially in auroral latitudes. In particular, HF radio operators attempting to communicate through the auroral zones (the regions of visible aurora, or northern lights) during storms a rapid and deep signal fading will occur due to the ionospheric irregularities, which scatter radio signal. Geomagnetic Storms may last several days.

5. Energetic Particle Effects

On rare occasions a Solar flares may accompanied by a stream of energetic particles (mostly proton and electrons). The more energetic protons travel at speeds approaching that of light, they can reach the Earth in as little as 30 minutes. These protons reach the upper atmosphere near the magnetic poles as shown in Figure (12):

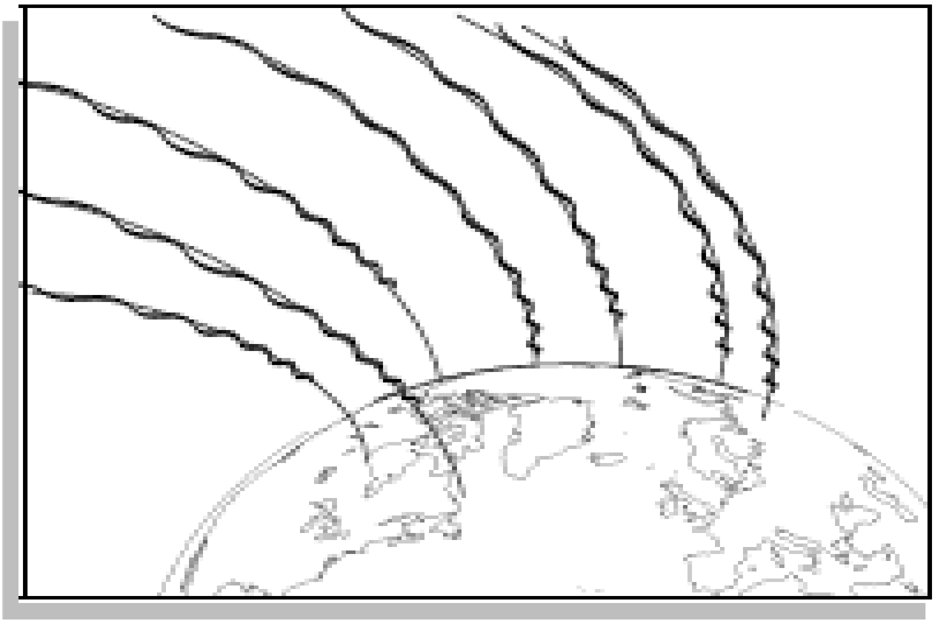


Figure (12) Solar energetic particles following The Earth's magnetic field lines they can penetrate the upper Atmosphere near the magnetic poles

Then the lower regions of the polar ionosphere become heavily ionized, and a severe HF and VHF signal absorption may occur. This is called a Polar Cap Absorption (PCA) event. PCA events may last from days to weeks, depending upon the size of the flare and how well the flare site is magnetically connected to the Earth. Polar HF radio propagation often becomes impossible during these events.

2. Ionospheric Variation

The ionosphere is not a stable medium, this will not allow the use of single radio frequency over the year, or even over 24 hours to setup a successful communication link. The ionosphere varies with the solar cycle, the seasons, the geographical location and during any given day. Therefore, a frequency, which may provide successful propagation now, may not do so at an hour later [19].

Among the important ionospheric variations, which affect the properties of the ionosphere and its capable for communication between two locations on the Earth's surface are the following:

1. *Solar Cycle Variations*

The Sun goes through a periodic rise and fall in activity which affects HF communications; Solar cycles vary in length from 9 to 14 years. At solar minimum activity, only the lower frequencies of the HF band will be supported by the ionosphere, while at solar maximum activity the higher frequencies will successfully propagate. This is because there is more radiation being emitted from the Sun at solar maximum activity period, the radiation produces more electrons in the ionosphere which allows the use of higher frequencies.

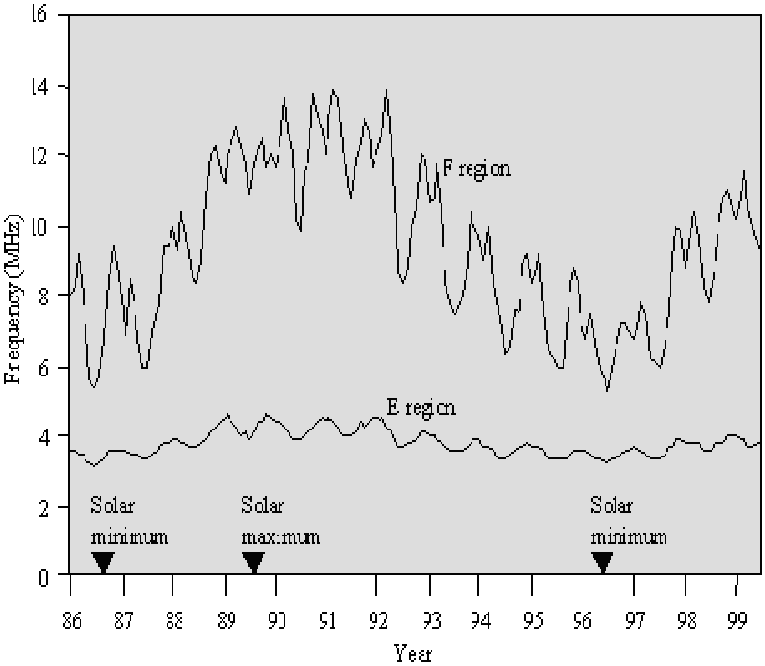


Figure (13) Solar cycle dependence of E and F region frequencies

2. *Seasonal Variations*

The plasma frequencies are greater in summer than winter for E- region. The variation in F-region frequencies is more complicated. In both hemispheres, the frequency value of F-region at noon show general peak around the equinoxes (March and September). Around solar minimum activity the summer noon frequencies are generally greater than those in winter, but around solar maximum, winter frequencies at certain locations, can be higher than those in summer. In addition, frequencies around the equinoxes are higher than those in summer or winter for both solar maximum and minimum. The observation of noon, winter frequencies often being greater than those in summer is called the seasonal anomaly.

3. Variations due to the Latitude

Figure (14) indicates the variations in E-region and F-region frequencies at noon and midnight from the poles to the geomagnetic equator. During the day and with increasing latitude, solar radiation strikes the atmosphere more obliquely, so the intensity of radiation and the electron density production decreases towards the poles.

The day time F-region frequencies have peak not at the magnetic equator, but around 15-20 degrees north and south of it. This is called the equatorial anomaly. At night, the plasma frequency reach a minimum around 60 degrees latitude north and south of the geomagnetic equator. This is called mid- latitude trough.

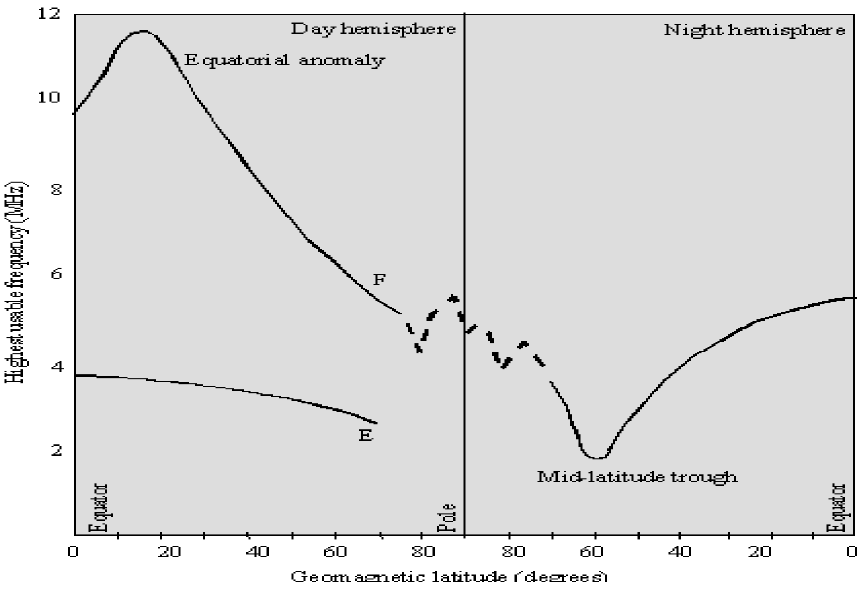


Figure (14) Representation of latitudinal variations

4. Diurnal Variations

Operating frequencies are normally higher during the day and lower at night. With dawn, solar radiation causes electrons to be produced in the ionosphere and frequencies increase reaching their maximum around noon.

During the afternoon, frequencies being decreasing due to electron loss and with evening, the D, E and F regions become insignificant. Therefore, the HF sky wave communication during the night is due to the F-region and absorption of radio waves decreases because of the lack of the D- region.

Through the night, plasma frequencies decreases reaching their minimum just before dawn. The typical diurnal variation is illustrated in Figure (15).