INTRODUCTION TO RADIOWAVE PROPAGATION

ECE 523E – ANTENNA & RADIOWAVE PROPAGATION

Tuesday, September 15, 2026

WHY STUDY RADIO WAVE PROPAGATION

1. **Every wireless system depends on it**
   - Cellular (2G–5G), Wi-Fi, Bluetooth, satellite, broadcast TV/Radio, radar, IoT, GPS.
2. **It shapes network design**
   - Base station placement, antenna height, frequency selection, and handover thresholds.
3. **It determines system performance**
   - Coverage range, data rate, link budget, interference, and reliability all trace back to propagation.
4. **It is a major source of impairment**
   - Path loss, shadowing, and multipath fading must be characterized and mitigated.

ELECTROMAGNETIC WAVES-RECAP

- **Radio waves are electromagnetic waves:** oscillating electric (E) and magnetic (H) fields perpendicular to each other and to the direction of travel.

$$c = f \cdot \lambda \quad \Rightarrow \quad \lambda = c / f \quad (c \approx 3 \times 10^8 \text{ m/s})$$

BAND	FREQUENCY	EXAMPLE USE
HF	3–30 MHz	Shortwave radio, amateur radio
VHF	30–300 MHz	FM broadcast, TV, air traffic
UHF	300 MHz–3 GHz	TV, cellular, GPS, Wi-Fi (2.4 GHz)
SHF	3–30 GHz	5G, Wi-Fi 6, satellite, radar

FREQUENCY Vs WAVELENGTH - RECAP

APPLICATION	FREQUENCY	WAVELENGTH (Λ = C/F)
FM radio	100 MHz	3 m
GSM / cellular	900 MHz	0.33 m (33 cm)
Wi-Fi	2.4 GHz	12.5 cm
5G / radar	28 GHz	1.07 cm

Higher frequency → shorter wavelength → smaller antennas but higher propagation loss and poorer obstacle penetration.

Example: Antenna size ≈ λ/2 (e.g., at 900 MHz → ~16.5 cm)

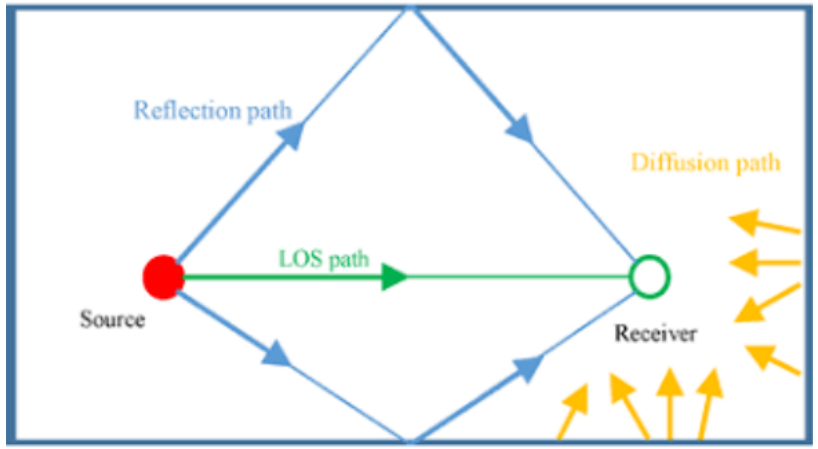
LINE-OF-SIGHT (LOS) VS. NON-LOS (NLOS) - RECAP

1. LOS — Direct Path

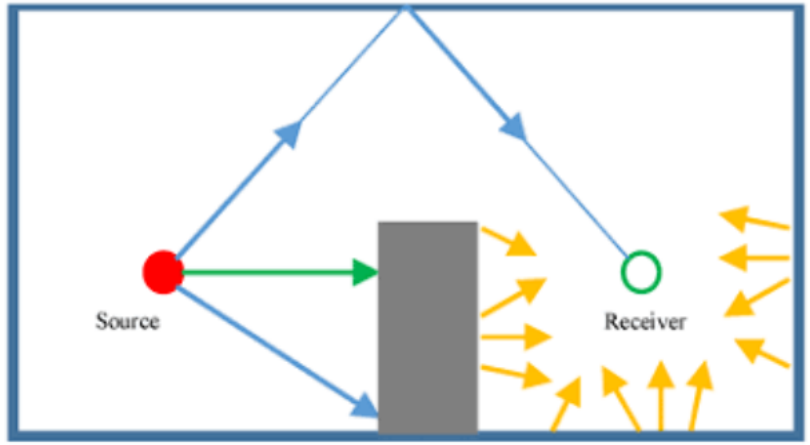
- A clear, unobstructed path between transmitter (Tx) and receiver (Rx). Dominant in satellite links, microwave point-to-point links, and mmWave 5G. Signal follows essentially one path — simplest to analyze.

2. NLOS — Obstructed Path

- Buildings, terrain, foliage, and indoor walls block the direct ray. The signal arrives via reflected, diffracted, and scattered paths — typical of urban and indoor cellular/Wi-Fi environments.



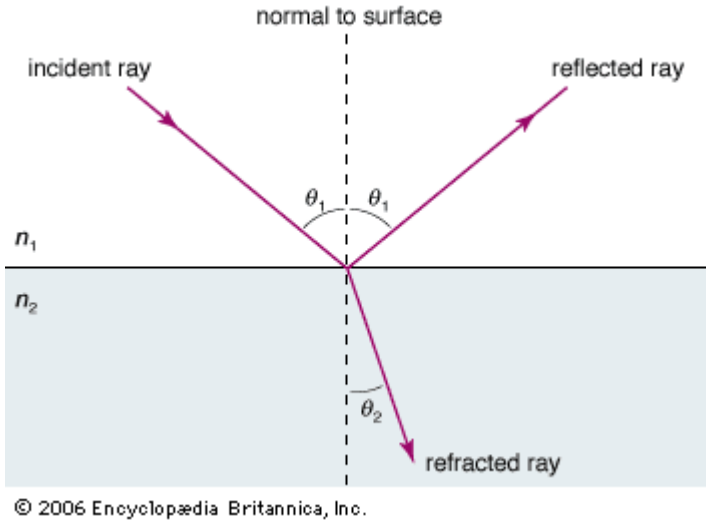
(a) LOS scenario



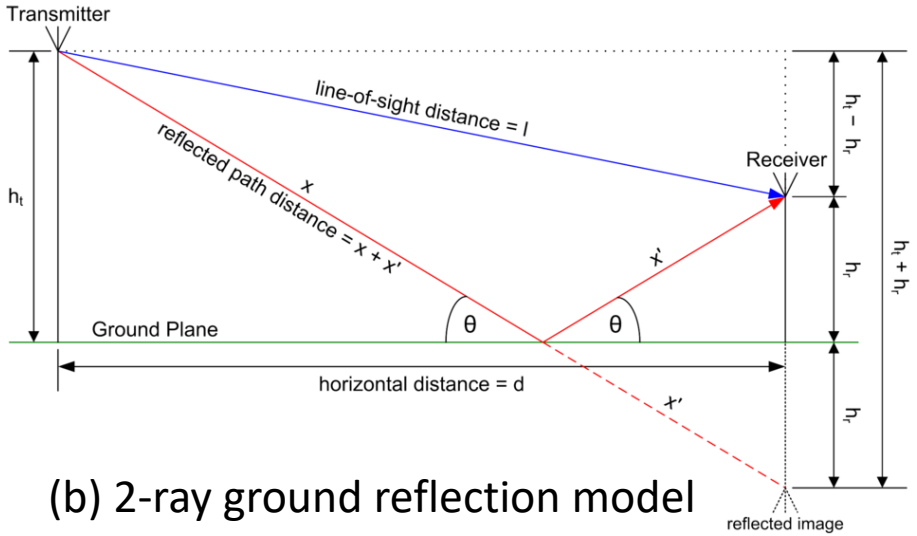
(b) NLOS scenario

REFLECTION IN RADIOWAVE PROPAGATION - RECAP

1. When a radio wave hits a surface that is **large compared to its wavelength** (buildings, walls, the ground), part of the energy bounces off, like light off a mirror.
2. Governed by **Snell's law**: angle of incidence = angle of reflection
3. **Reflection coefficient** depends on the surface material, polarization, and incidence angle
4. Good conductors and large dielectric surfaces reflect strongly
5. The **two-ray ground reflection model** — direct ray + ground-reflected ray — explains why received power often falls as $1/d^4$ instead of $1/d^2$



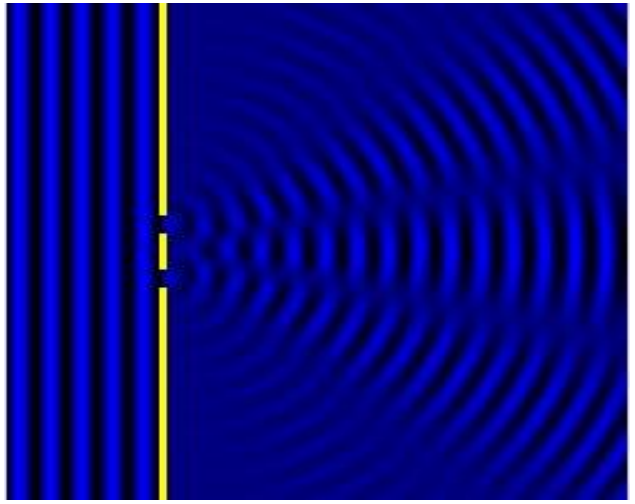
(a) Snell's Law



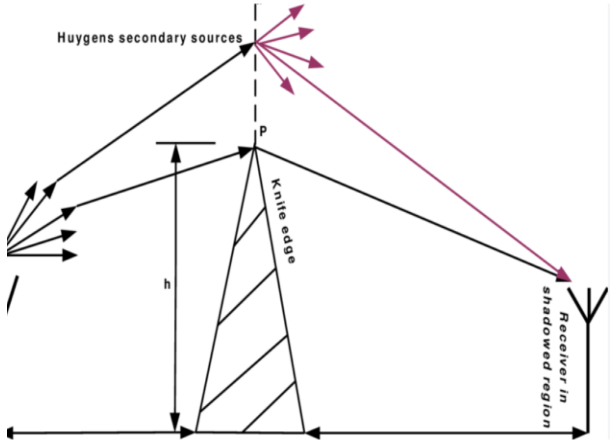
(b) 2-ray ground reflection model

DIFRACTION OF RADIO WAVES - RECAP

1. When the path is blocked by an edge or obstacle whose dimensions are **comparable to or larger than λ**, the wave "bends" around it — this is diffraction.
2. Explained by **Huygens' principle**: every point on a wavefront acts as a secondary source
3. Described quantitatively by the **knife-edge diffraction model**
4. Depends on the **Fresnel diffraction parameter v** (normalized obstruction height)
5. Allows signals to reach behind buildings and hills — vital for NLOS coverage
6. Higher frequencies (shorter λ) diffract less → more shadowing loss



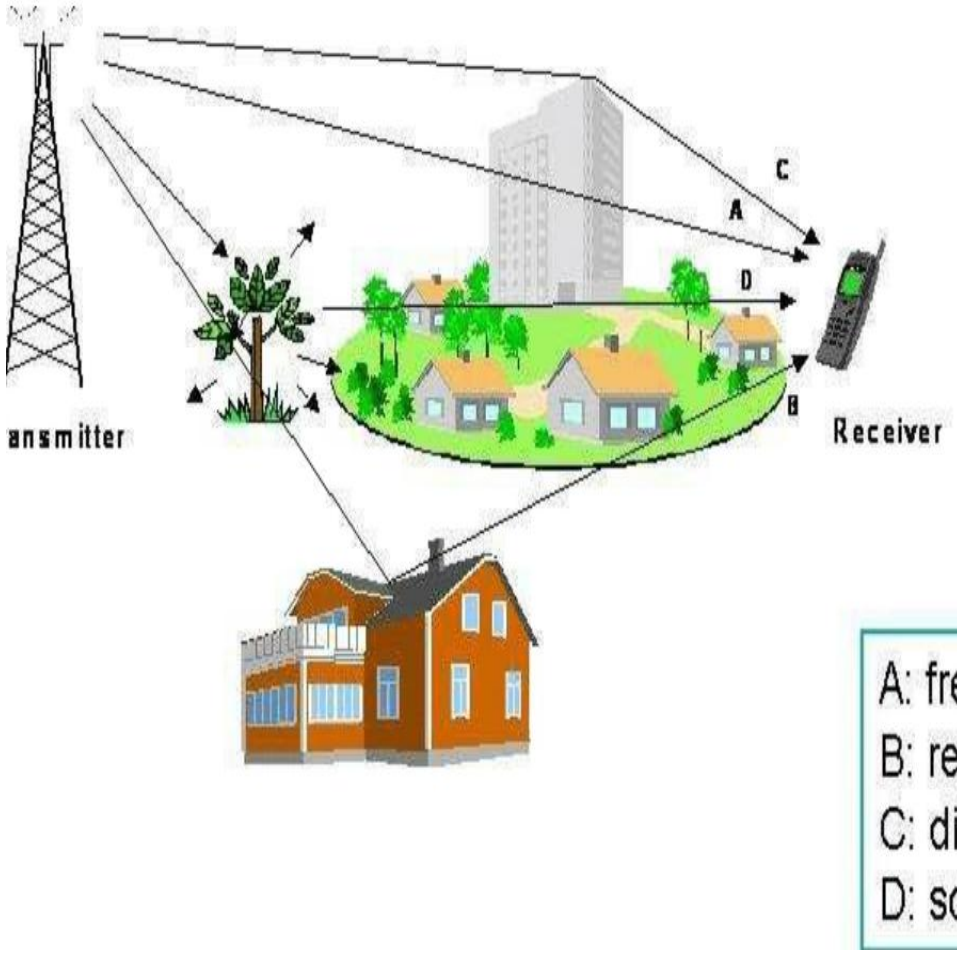
(a) two-slot diffraction



(b) Knife-edge diffraction

SCATTERING OF RADIO WAVES - RECAP

1. When the wave encounters **objects smaller than or comparable to λ** (street signs, lamp posts, foliage, rough surfaces), energy is radiated in many directions.
2. Roughness judged by the **Rayleigh criterion**: a surface is rough if height variations > $\lambda/(8 \cdot \sin\theta)$
3. Converts a single ray into many weaker rays → energy "leaks" into shadowed regions
4. Leaves and branches scatter strongly at microwave frequencies
5. Scattered rays are a key ingredient of rich **multipath**
6. Roughness factor $\propto \lambda$ | shorter λ → more scattering



FREE-SPACE PATH LOSS (FSPL)

1. The simplest model: Tx and Rx in empty space, with isotropic antennas.

$$P_r = P_t G_t G_r (\lambda / 4\pi d)^2$$

$$FSPL(dB) = 20 \log_{10}(4\pi d/\lambda) = 20 \log_{10}(d_{km}) + 20 \log_{10}(f_{MHz}) + 32.44$$

2. Power decays with **$1/d^2$** — the "inverse square law" for EM waves
3. FSPL increases with **20 dB per decade** of distance
4. Increases with frequency: $20 \log_{10}(f)$ → doubling f adds ~6 dB loss
5. Reference point for all other path-loss models

TYPES OF RADIO WAVE PROPAGATION

TYPE	FREQUENCY RANGE	CHARACTERISTICS
Ground wave	< 2 MHz (MF/LF)	Follows Earth's curvature; AM broadcast, submarines
Sky wave	3–30 MHz (HF)	Reflects off ionosphere; long-distance shortwave
Line-of-sight	> 30 MHz (VHF+)	Direct + reflected paths; cellular, TV, satellite, Wi-Fi

Above ~30 MHz the ionosphere becomes transparent, so communication relies on direct and terrain-interacting paths — the regime of most modern wireless systems.

OKUMURA–HATA MODEL

Because real environments are complex, engineers use **empirical models** derived from extensive field measurements.

- **Okumura (1968):** measurements around Tokyo; charts of median path loss vs. distance, frequency, antenna height
- **Hata (1980):** fitted Okumura's data into closed-form equations:

$$PL(dB) = A + B \cdot \log_{10}(d) + C$$

where

A includes frequency and base-station height;

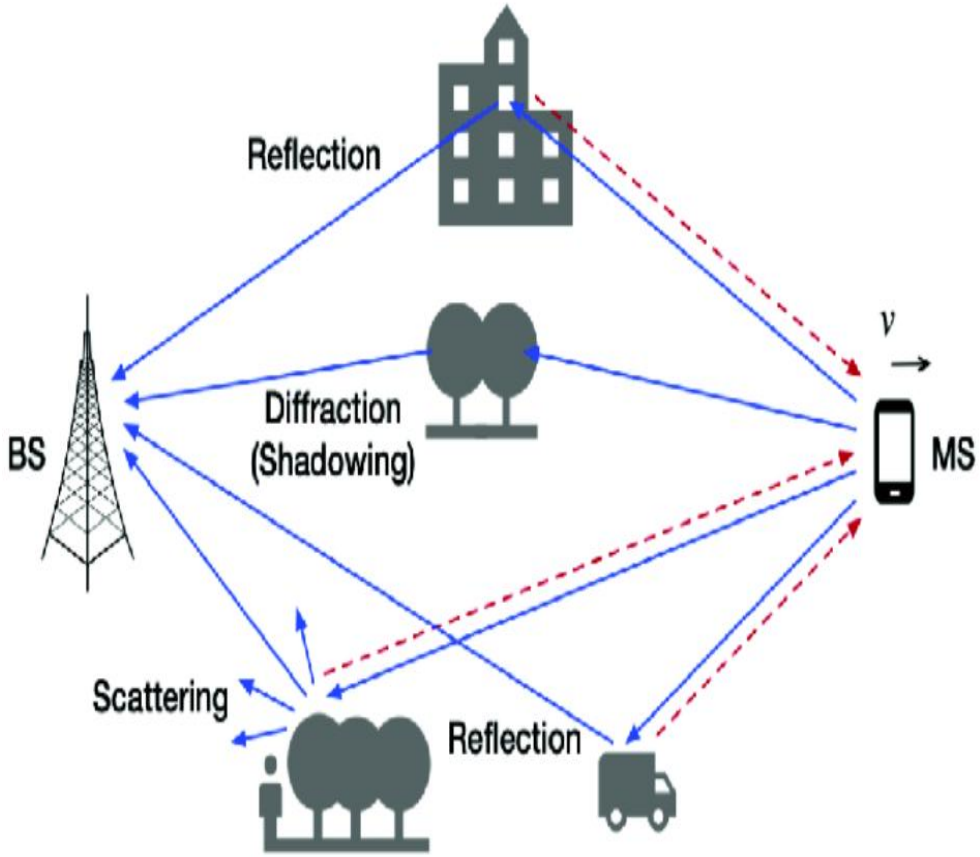
B is the distance slope (~44.9 at 900 MHz)

- Corrections exist for suburban and open/rural areas
- Still widely used for cellular link budgets and network planning

MULTIPATH PROPAGATION

1. In NLOS environments, the transmitted signal reaches the receiver over **many paths with different delays, amplitudes, and phases**.
2. The received signal is the **superposition** of all path contributions
3. Paths add **constructively or destructively** depending on relative phase → rapid signal variation with position or frequency
4. Described by the **power delay profile (PDP)**: delay spread τ_{rms} and excess delay

$$r(t) = \Sigma_i a_i \cdot s(t - \tau_i)$$



SMALL-SCALE VS. LARGE-SCALE FADING

	LARGE-SCALE FADING	**SMALL-SCALE FADING**
Cause	Path loss + shadowing by large obstacles	Multipath interference
Variation scale	Many wavelengths (meters to km)	Fractions of a wavelength (cm)
Distribution	Log-normal (shadowing, $\sigma \approx 4–12$ dB)	Rayleigh (NLOS) / Rician (LOS)
Mitigation	Higher power, taller antennas, repeaters	Diversity, equalization, OFDM, MIMO

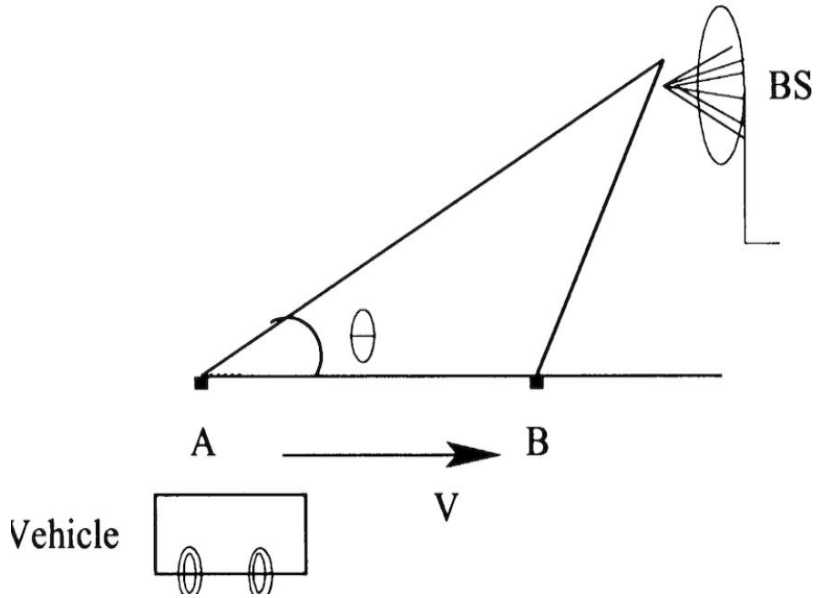
DOPPLER EFFECT IN RADIOWAVE PROPAGATION

1. Relative motion between Tx and Rx shifts the received frequency:

$$f_d = (v / c) \cdot f_c \cdot \cos\theta = (v / \lambda) \cdot \cos\theta$$

   Maximum shift when moving directly toward/away from the source ($\theta = 0°$ or $180°$)

2. Example: at 900 MHz, v = 100 km/h → $f_{d,max}$ ≈ **83 Hz**; at 28 GHz (5G) ≈ **2.6 kHz**
3. Multipath + motion → a **spread of Doppler shifts** (Doppler spread), which limits the channel coherence time
4. Quantified by the channel's **coherence time T_c ≈ $1/f_{d,max}$** — the time over which the channel stays roughly constant



KEY TAKE AWAYS

1. Radio waves propagate via **reflection, diffraction, and scattering** — the dominant mechanisms depend on wavelength vs. obstacle size.
2. Free-space loss decays as $\mathbf{1/d^2}$; ground-reflection (two-ray) as $\mathbf{1/d^4}$; empirical models (Okumura–Hata, Cost-231) capture real terrain.
3. Multipath causes **small-scale fading** (Rayleigh/Rician); large obstacles cause **shadowing** (log-normal).
4. Mobility introduces **Doppler shift and spread**, limiting coherence time.
5. Propagation knowledge is essential for link budgets, coverage planning, and choosing mitigation techniques: diversity, equalization, OFDM, MIMO.

HF COMMUNICATION

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Monday, September 14, 2026

HF RADIO WAVE PROPAGATION

1. HF radio wave propagation is the most commonly used terrestrial radio communication system capable of intercontinental communication.
2. As a result, it is the most commonly studied radio propagation band.

3. HF band spans 3 to 30 MHz.

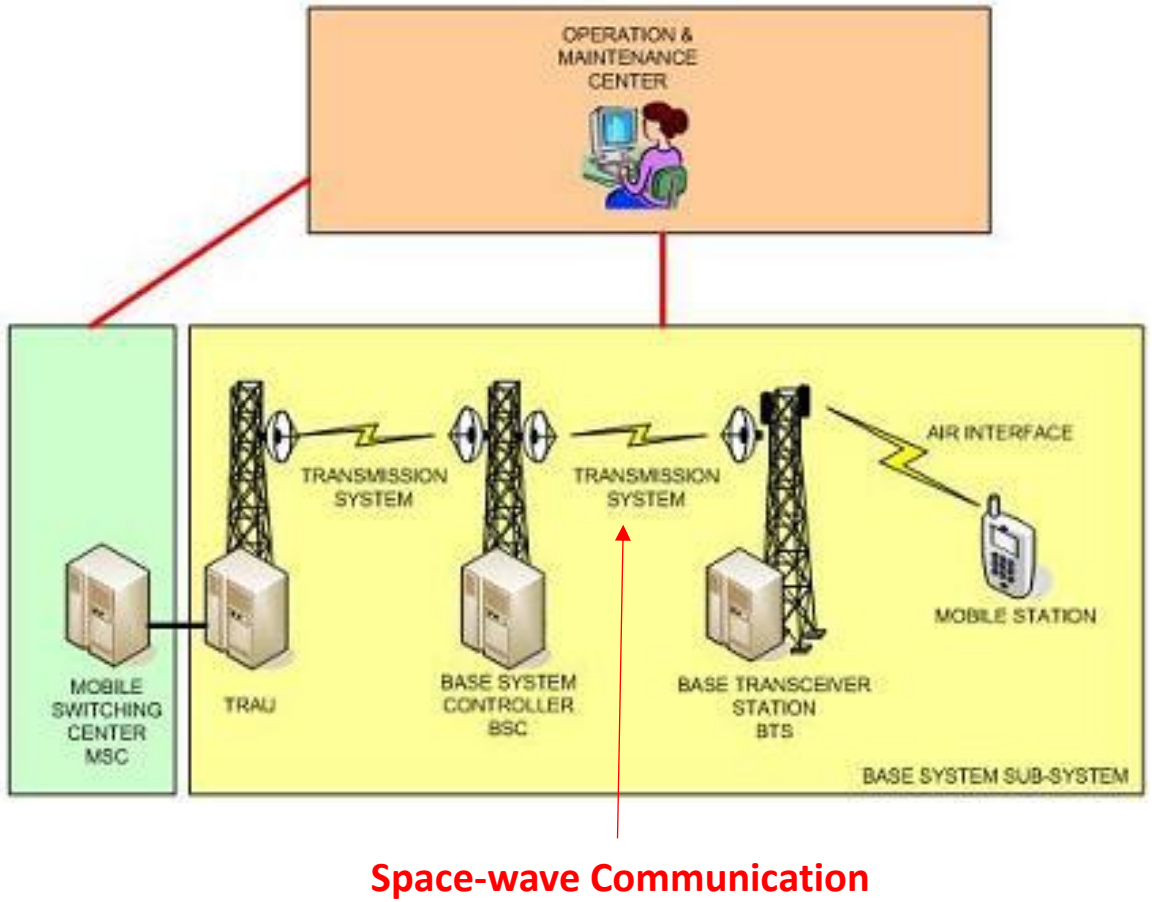
4. HF wavelength extends from 30m to 300m.

CHARACTERISTICS OF HF RADIO PROPAGATION

1. Propagation is possible over thousands of kilometres.
2. Propagation is highly variable. It has daily and seasonal variation, as well as a much longer 11 year cycle.
3. HF radio waves may travel by any of the following modes:
   a) Ground Wave
   b) Sky Wave
   c) Space Wave (line-of-sight)

SPACE WAVE

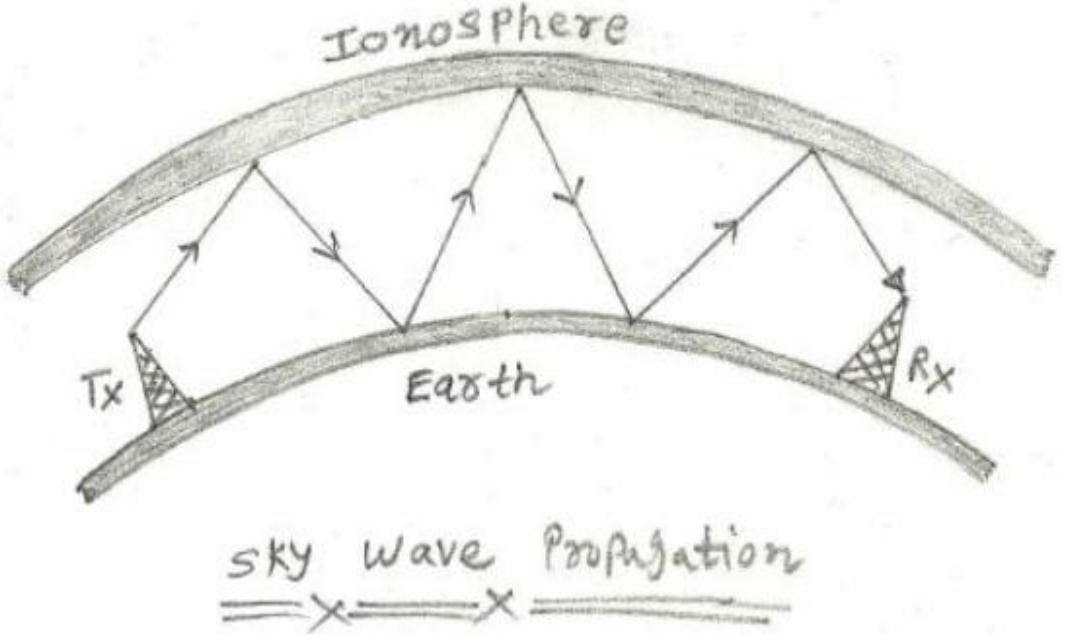
1. **Space wave** follow the line-of-sight path between transmitter and receiver. In order for direct wave communication to occur, antennas at both ends of the path have to have low beam-width.
2. This is difficult to do on the lower HF frequencies, and as a result, direct wave communication is normally used in UHF and microwave frequency bands.
3. Its range is determined by the height of both antennas and generally less than 40 Kms.



SKY WAVES

1. **Sky waves** are waves that leave the transmitting antenna in a straight line and are returned to the earth at a considerable distance by an electrically charged layer known as the ionosphere.

2. Communication is possible throughout much of the day to almost anywhere in the world via sky wave.



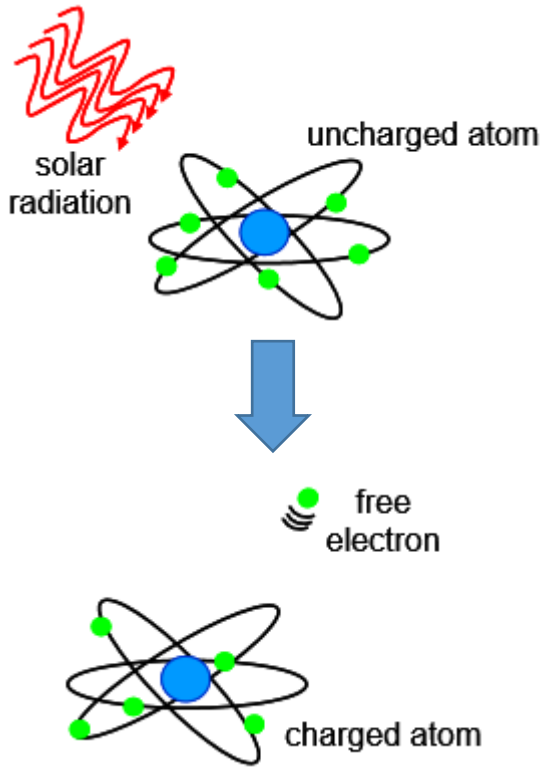
THE IONOSPHERE

1. **The Ionosphere** extends from a height of about 50 km to over 500 km. Most of the molecules of this part of the atmosphere are ionised by radiation from the Sun.
2. Ionisation is the process in which electrons, which are negatively charged, are removed from neutral atoms or molecules to leave positively charged ions and free electrons.
3. It is the ions that give their name to the ionosphere, **but it is the much lighter and more freely moving electrons which are important in terms of HF (high frequency) radio propagation.**
4. **The free electrons in the ionosphere cause HF radio waves to be refracted (bent) and eventually reflected back to earth**.
5. The greater the density of electrons, the higher the frequencies that can be reflected.

PRODUCTION/LOSS OF ELECTRONS IN THE IONOSPHERE

1. **Electrons are produced** when solar radiation collides with uncharged atoms and molecules. Since this process requires solar radiation, production of electrons only occurs in the daylight hemisphere of the ionosphere.

2. Loss of free-electrons in the ionosphere occurs when a free electron combines with a charged ion to form a neutral particle. Loss of electrons occurs continually, both day and night.



THE IONOSPHERE (2)

1. Though created by solar radiation, it does not completely disappear shortly after sunset.
2. The D and E layers disappear very quickly after sunset due to increased loss of electrons.
3. The F1 and F2 layers do not disappear, but merge into a single F layer.
4. Ions recombine much faster at lower altitudes.

THE D-LAYER

1. **D-layer** is created at sunrise, reaches maximum density at noon, and disappears by sunset.
2. The D layer plays only a negative role in HF communications.
3. It acts as an attenuator, absorbing the radio signals, rather than returning them to earth.
4. The absorption is inversely proportional to the square of the frequency, severely restricting communications on the lower HF bands during daylight.

THE E-LAYER

1. The E-layer is created at sunrise, reaches maximum density at noon, and disappears by sunset.

2. It can return lower HF frequencies to the Earth, resulting in daytime short skip on the lower HF bands.

3. It has very little effect on higher frequency HF radio waves, other than to change slightly their direction of travel.

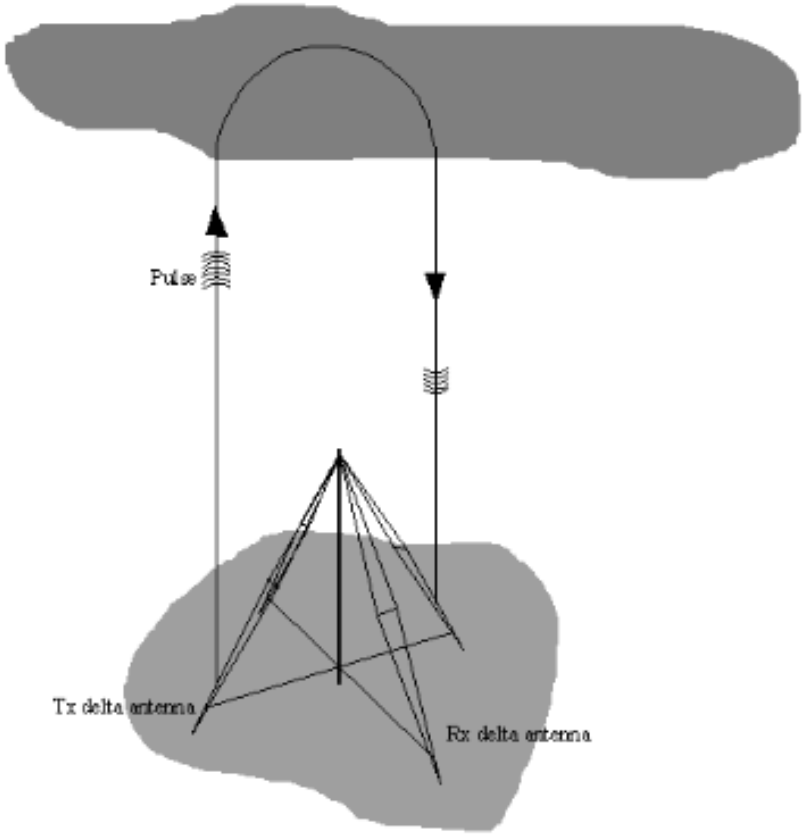
THE F-LAYER

1. The F layers are primarily responsible for long-haul HF communications.

2. Because there is only F layer ionization throughout the hours of darkness, it is carries almost all night-time communications over intercontinental distances.

OBSERVING THE IONOSPHERE

1. Various methods have been used to investigate the ionosphere, and the most widely used instrument for this purpose is the **ionosonde.**
2. I**onosonde** is a high frequency radar which sends very short pulses of radio energy vertically into the ionosphere. If the radio frequency is not too high, the pulses are reflected back towards the ground.
3. **The ionosonde** records the time delay between transmission and reception of the pulses over a range of different frequencies.
4. Echoes appear first from the lower E region and subsequently, with greater time delay, from the F1 and F2 regions.
5. At night echoes are returned only from the F region since the E region is not present.



CRITICAL FREQUENCY

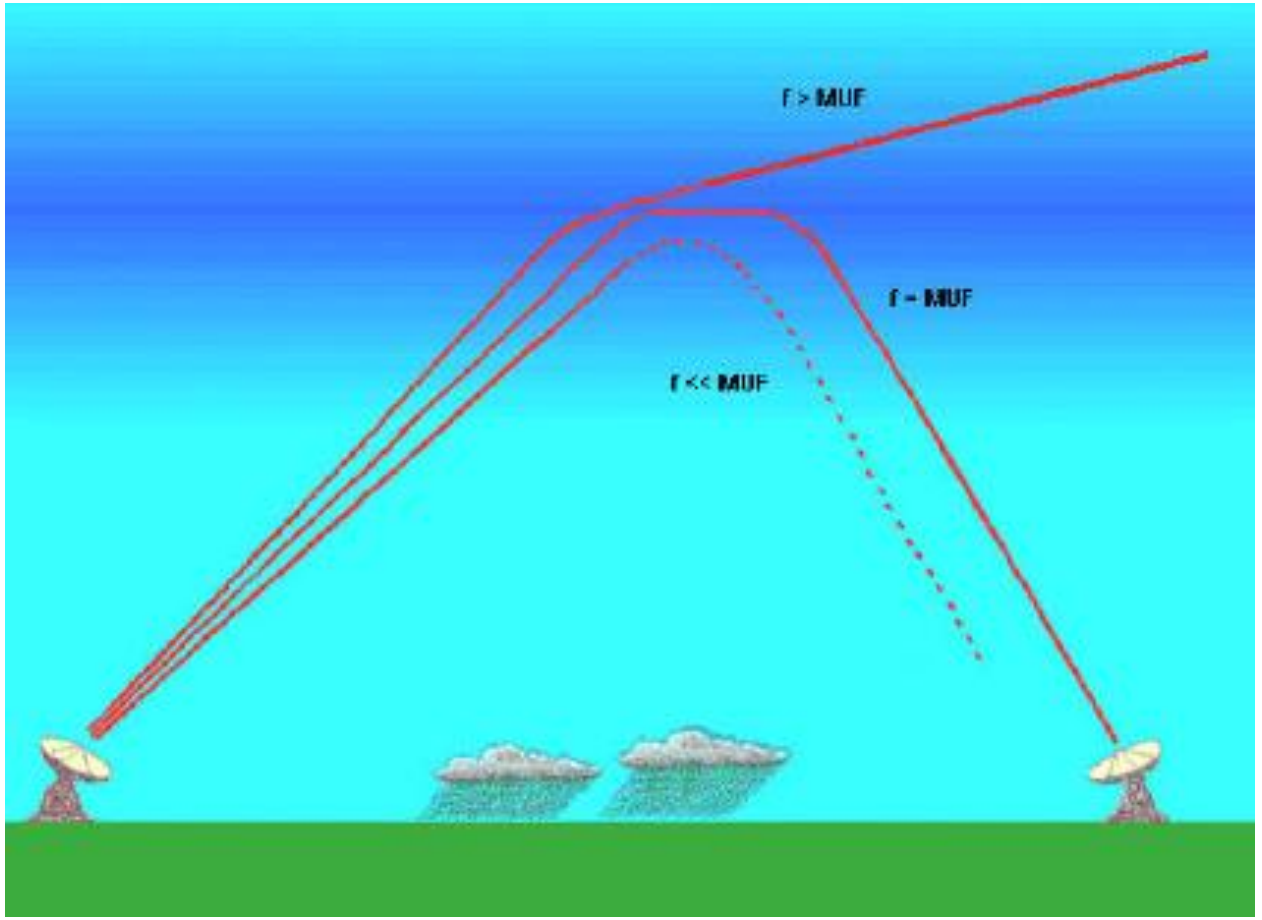
1. When radio waves are transmitted straight up towards the ionosphere (vertical incidence), the radio wave will be returned to earth at all frequencies below the critical frequency, (f_c) .

2. The critical frequency depends on the degree of ionization of the ionosphere, as shown in the following equation:

$$f_{cr} = \sqrt{\frac{N_e}{1.24 * 10^{10}}}$$

MAXIMUM USABLE FREQUENCY (MUF)

- **The Maximum Usable Frequency (MUF)** is the highest radio frequency that can be used for transmission between two points via reflection from the ionosphere (sky wave or "skip" propagation) at a specified time, independent of transmitter power.

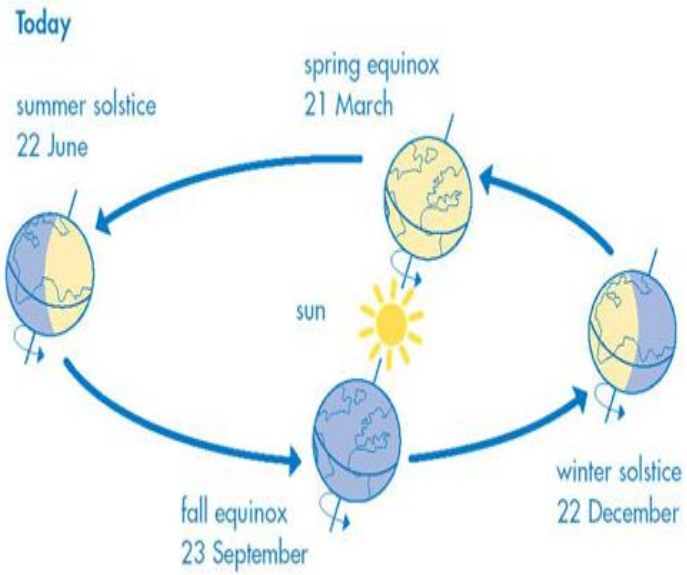


DAILY PROPAGATION EFFECTS

1. Shortly after sunrise, the D and E layers are formed and the F layer splits into two parts.
   - The D layer acts as a selective absorber, attenuating low frequency signals, making frequencies below 5 or 6 MHz useless during the day for transmission.
2. The E and F1 layers increase steadily in intensity from sunrise to noon and then decreases thereafter.
   - Short skip propagation via the E or F1 layers when the local time at the ionospheric refraction point is approximately noon.
   - The MUF's for the E and F1 layers are about 5 and 10 MHz respectively.
3. The F2 layer is sufficiently ionized to HF radio waves and return them to earth.
   - For MUF's is above 5 - 6 MHz, long distance communications are possible.
   - For MUF's below 5 MHz, the frequencies that can be returned by the F layer are completely attenuated by the D layer.

SEASONAL PROPAGATION EFFECTS

1. **During the Northern Hemisphere** winter months, the atmosphere is colder and denser.
2. The ionosphere moves closer to the earth increasing the electron density.
3. In summer, the earth makes its closest approach to the sun, which increases the intensity of the UV radiation striking the ionosphere.
4. Electron density can rises to 5 times greater than summer's.
5. Winter MUF's are approximately double summer's.

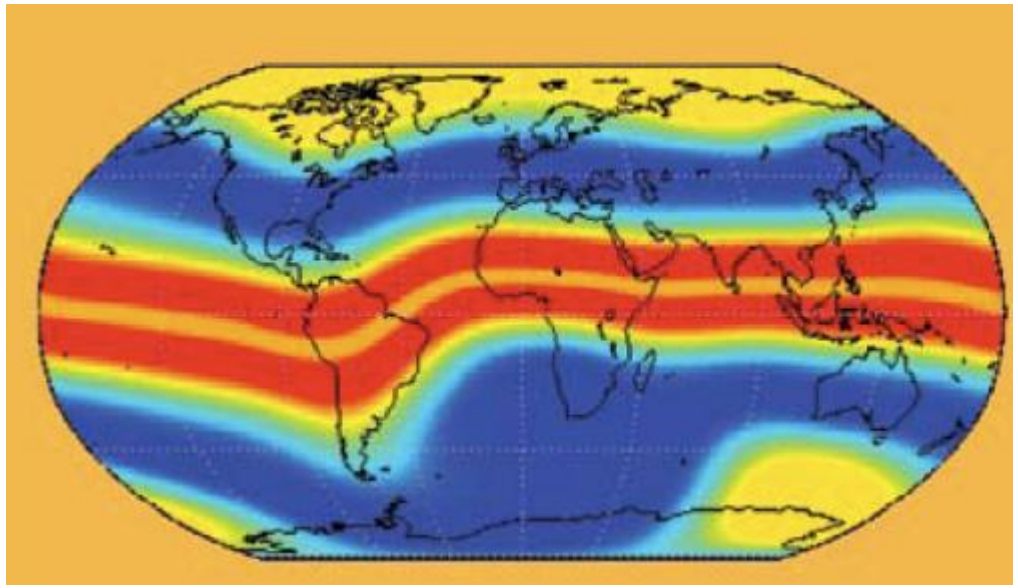


GEOGRAPHICAL VARIATION OF MUFs

1. The sun's ionizing radiation is most intense in the equatorial regions and least intense in the polar regions.

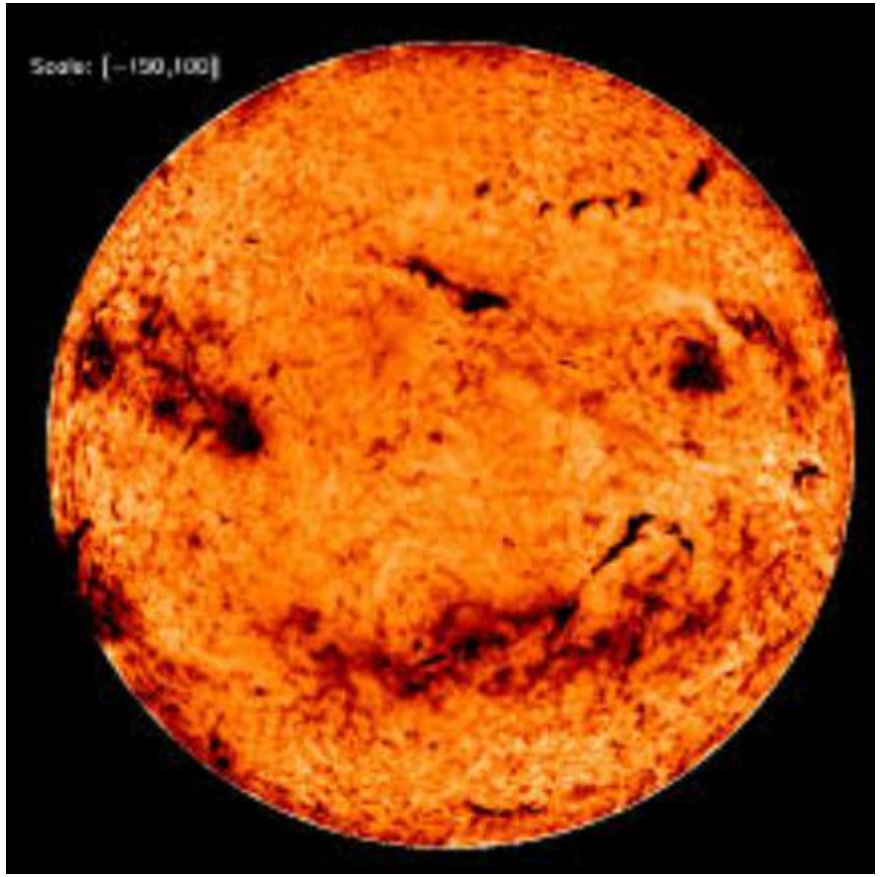
2. Daytime MUF of the E and F1 layers is highest in the tropics.

3. Polar region MUF's for these layers can be three times lower.



EFFECTS OF SUNSPORTS

1. **A SUNSPOT** is an area of intense magnetic activity on the surface of the sun which is cooler than the rest of the sun's surface. Because it is cooler, a sunspot is darker and therefore visible against the hotter, brighter background.
2. **The number of sunspots observed on the sun's surface follows an 11 year cycle.**
3. Sunspots have intense magnetic fields. These fields energize a region of the sun known as the chromosphere, which lies just above the sun's surface. More ultraviolet radiation is emitted, which increases the electron density in the earth's atmosphere.
4. The additional radiation affects primarily the F2 layer.
5. During sunspot maxima, the highly ionized F2 layer acts like a mirror, refracting the higher HF frequencies with almost no loss. MUF can rise to more than 50 MHz.



SOLAR FLARE

1. A solar flare is a plume of very hot gas ejected from the sun's surface.
2. It rises through the chromosphere into the corona.
3. X-ray emission from the corona increase and reach the earth in less than 9 minutes.
4. If X-rays are intense enough, the ionosphere will become so dense that all HF signals are absorbed by it and worldwide HF communications are blacked out.

