

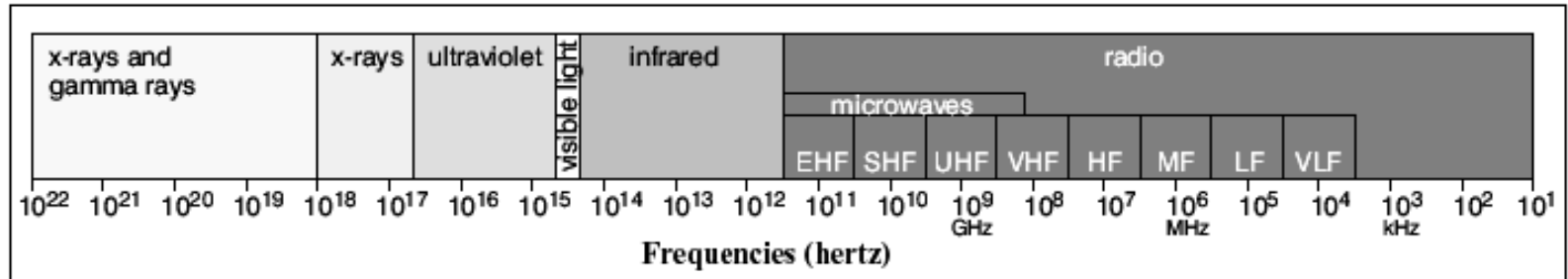
Why is Study of the Ionosphere Important?

- It affects all aspects of radio wave propagation on earth, and any planet with an atmosphere
- Knowledge of how radio waves propagate in plasmas is essential for understanding what's being received on an AWESOME setup
- It is an important tool in understanding how the sun affects the earth's environment

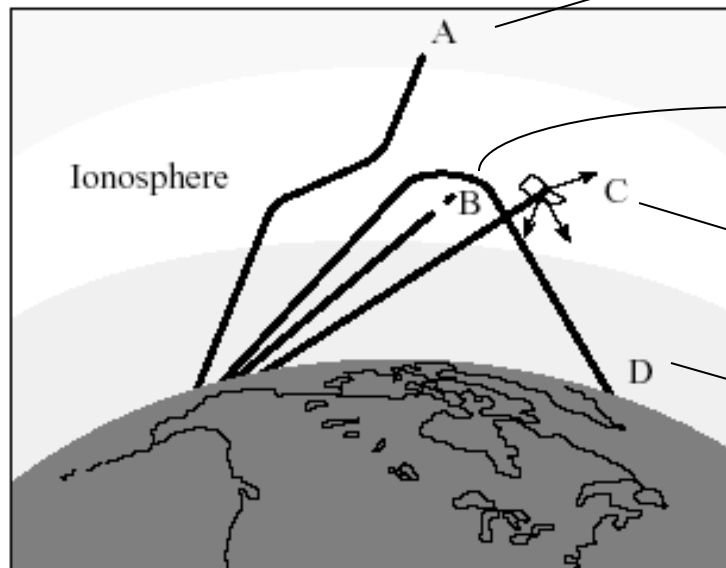
Radio Waves in the Ionosphere

- Radio wave is altered during its passage through the ionosphere
 - Propagation direction changes: refracted, reflected
 - Intensity changes: attenuated, absorbed

SOLAR AND IONOSPHERIC EFFECTS ON RADIO-WAVE SYSTEMS (Communications, Tracking, Navigation, etc.)



Fate of a Radio Wave



A. Wave penetrates the ionospheric layer

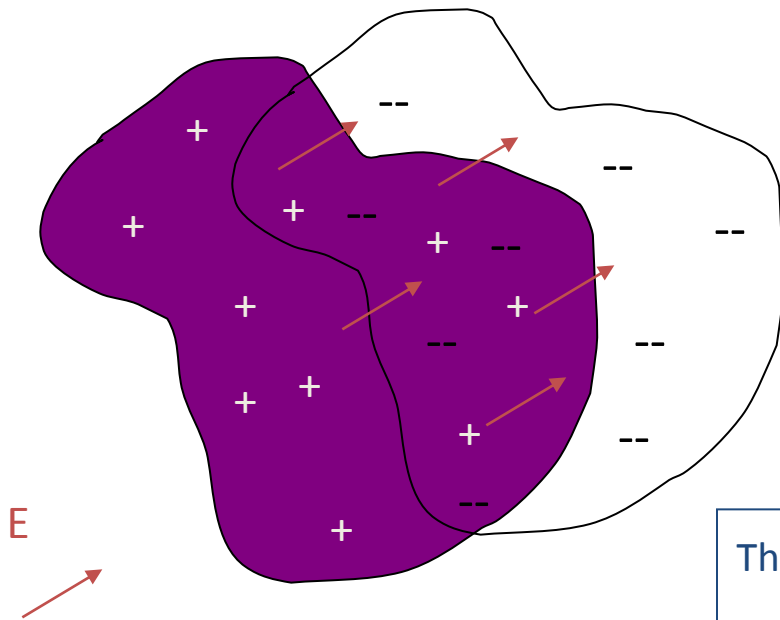
B. Wave is absorbed within the ionosphere

C. Wave is scattered in random directions by plasma irregularities

D. Wave is reflected normally by the ionosphere

Ionospheric Plasma

A **plasma** is a gaseous mixture of electrons, ions, and neutral particles. The ionosphere is a weakly ionized plasma.



If, by some mechanism, electrons are displaced from ions in a plasma the resulting separation of charge sets up an electric field which attempts to restore equilibrium. Due to their momentum, the electrons will overshoot the equilibrium point, and accelerate back. **This sets up an oscillation.**

The frequency of this oscillation is called the

$$\text{plasma frequency: } \omega_p = 2\pi f = (4\pi N_e e^2 / m_e)^{1/2}$$

which depends upon the properties of the particular plasma under study

Natural Oscillation in a Plasma: Plasma Frequency

$$nm_e \frac{d^2(\Delta x)}{dt^2} = -\frac{e^2 n^2}{\epsilon_0} \Delta x$$

$$\Delta x = (\Delta x)_0 \sin(\omega_p t)$$

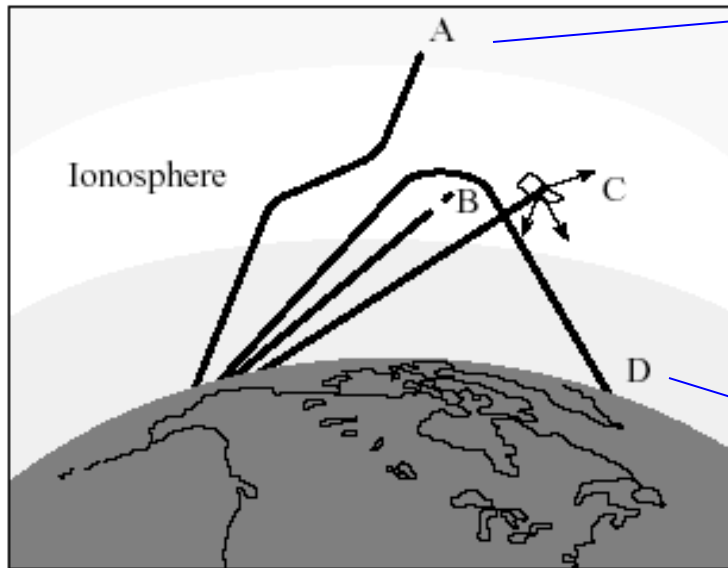
$$\omega_p = \sqrt{\frac{e^2 n}{\epsilon_0 m_e}}$$

$$\omega_p [\text{rads}^{-1}] \approx 56.4 \sqrt{n [\text{m}^{-3}]}$$

$$fp [\text{Hz}] \approx \omega_p / 2\pi = 9 \sqrt{n [\text{m}^{-3}]}$$

Radio Waves in an Ionospheric Plasma

A radio wave consists of oscillating electric and magnetic fields. When a **low-frequency radio wave** (i.e., frequency less than the plasma frequency) impinges upon a plasma, the local charged particles have sufficient time to rearrange themselves so as to “cancel out” the oscillating electric field and thereby “screen” the rest of the plasma from the oscillating E-field.



For a **high frequency** wave (i.e., frequency greater than the plasma frequency), the particles do not have time to adjust themselves to produce this screening effect, and the wave passes through (A).

This **low frequency** radio wave cannot penetrate the plasma, and is reflected (D).

The critical frequency of the ionosphere (**foF2**) represents the minimum radio frequency capable of passing completely through the ionosphere.

Interactions with a radio wave

- This radio wave (**low frequency**) cannot penetrate the plasma, and **is reflected**.

- For a **high frequency wave** (i.e., frequency greater than the plasma frequency), the particles do not have time adjust themselves to produce this screening effect, and **the wave passes through**.

- The **critical frequency** of the ionosphere (**foF2**) represents the minimum radio frequency capable of passing completely through the ionosphere.

$$N(\text{cm}^{-3}) = 1.24 \times 10^4 f^2 (\text{MHz})$$

- When collisions between oscillating electrons and ions and **neutral particles** becomes sufficiently frequent (as in the D-region, 60 – 90 km), these collisions “absorb” energy from the radio wave leading to what is called **radio wave absorption**.

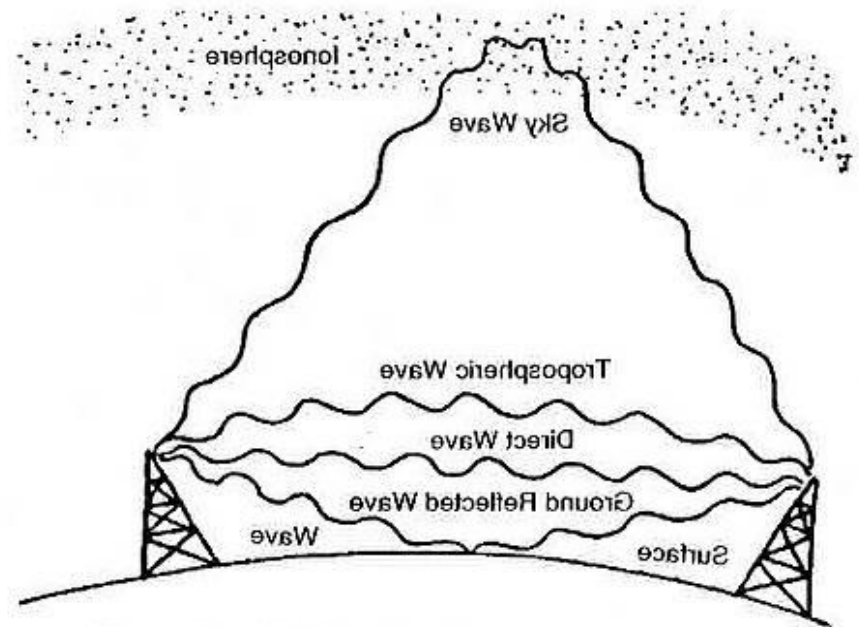
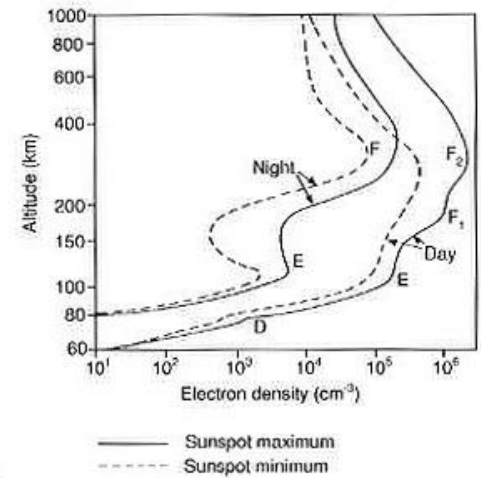
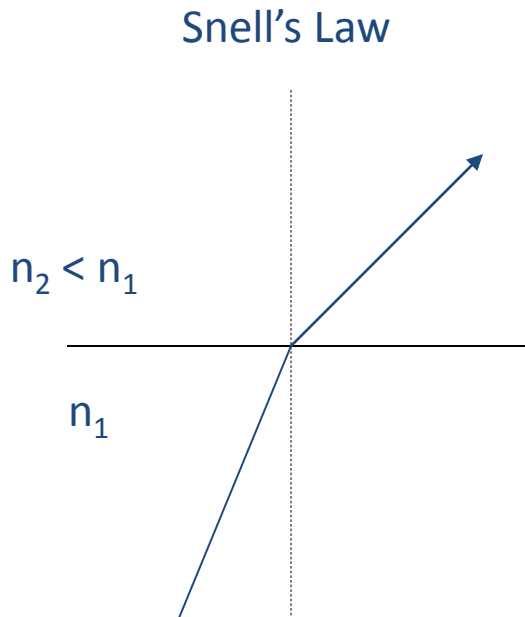


Figure 9.6 Various types of propagation modes available for radio waves. The exact mode of propagation will depend on signal frequency and atmospheric conditions (in particular ionospheric conditions) (after Forshaw, 1980).

Index of Refraction

Mathematically, the behavior of a radio wave in a plasma can be viewed in terms of an **index of refraction**.

As a radio wave propagates up into an ionosphere with increasing N_e , n decreases and the ray bends as shown:



The **index of refraction** for a radio wave in a plasma is given by

$$n = \sqrt{1 - \frac{8.1 \times 10^{-5} N_e}{\nu^2}}$$

Here N_e is the electron density in cm^{-3} and ν is the wave frequency in MHz.

For a given N_e , a high-frequency wave will suffer less refraction than a lower frequency wave, since n is closer to 1 for a high-frequency wave.

The above expression for refractive index becomes imaginary for certain values of N_e / ν , implying **reflection** of the radio wave. **For a vertically-propagating wave**, this occurs at the critical value (where $n = 0$):

$$\nu_c = 9 \times 10^{-3} \sqrt{N_{ec}}$$

Using our previous notations, then, the lowest frequency radio wave capable of penetrating the ionosphere is

$$foF2 = 9 \times 10^{-3} \sqrt{NmF2}$$

Neutral Particle Density, Temperature, Scale Height

- One of the most important features of the atmosphere is the vertical profile of density and pressure. The altitude variation of these quantities is described by assumption of hydrostatic equilibrium.

- From the momentum equation: $dp/dz = -mng$ or $dp/dz = -(mg/kT)p = -(1/H)p$, where the *scale height*, $H = kT/mg$, is introduced. H is a slowly varying function of location and it can be considered locally constant. In this case, we have the well-known *barometric altitude formula*: $p(z) = p_0 \exp[-(z-z_0)/H]$.

- H is a linear function of the gas temperature, T , supposing that T is also slowly varying, we obtain a similar barometric altitude formula for the gas density: $\rho(z) = \rho_0 \exp[-(z-z_0)/H]$.

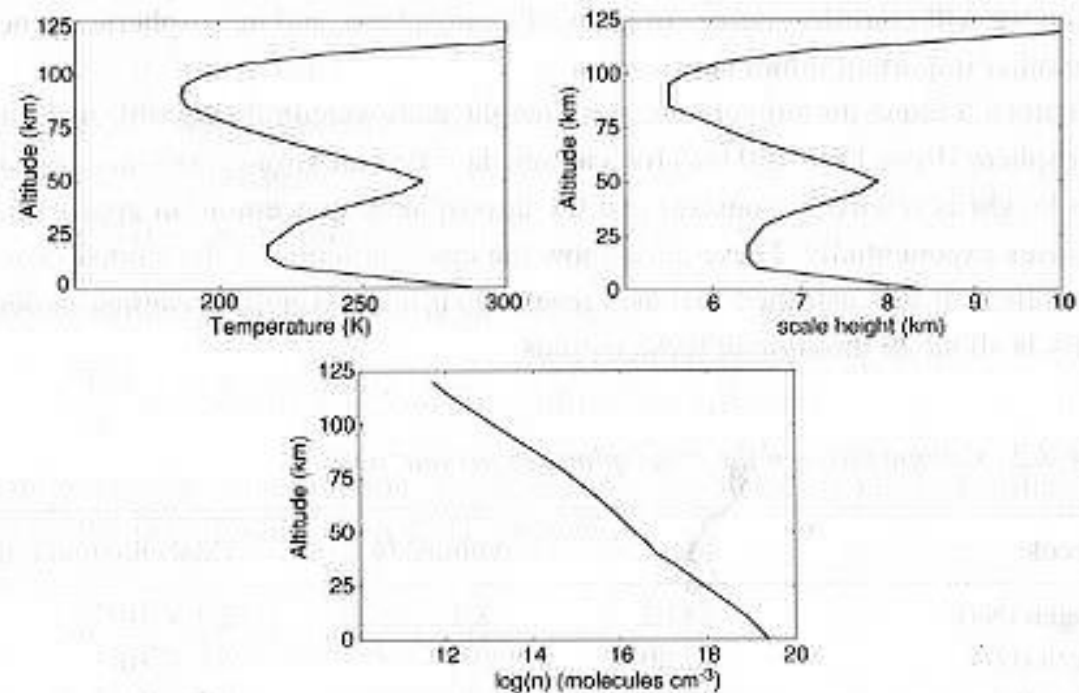


Figure 8.5 Temperature, scale height, and concentration profiles in the homosphere.

For average dayside conditions

Ionospheric Disturbances

- Ionospheric disturbances occur when a region of the Earth's ionosphere (50 – 500 km altitude) experiences a temporary fluctuation in degree of ionization.
- This variation can result from **geomagnetic activity** (and the influences of the neutral atmosphere), or it can be the direct result of X-rays and EUV produced by a **solar flare**.
- **Sudden Ionospheric Disturbances (SIDs)** are a category of disturbance which occurs almost simultaneously with a flare's X-ray emission (so SIDs are generally constrained in dayside).

Table 9.1 Radio wave bands

| Frequency Range | Wavelength Range | | Common Name |
|-----------------|---------------------|-------|------------------------------|
| 20 Hz–3 kHz | Greater than 100 km | (ELF) | Extremely Low Frequency |
| 3 kHz–30 kHz | 100 km–10 km | (VLF) | Very Low Frequency |
| 30 kHz–300 kHz | 10 km–1 km | (LF) | Low Frequency/Long Wave |
| 300 kHz–3 MHz | 1 km–100 m | (MF) | Medium Frequency/Medium Wave |
| 3 MHz–30 MHz | 100 m–10 m | (HF) | High Frequency/Short Wave |
| 30 MHz–300 MHz | 10 m–1 m | (VHF) | Very High Frequency |
| 300 MHz–3 GHz | 1 m–10 cm | (UHF) | Ultra High Frequency |
| 3 GHz–30 GHz | 10 cm–1 cm | (SHF) | Super High Frequency |
| 30 GHz–300 GHz | 1 cm–1 mm | (EHF) | Extremely High Frequency |

Ionospheric Disturbances

- **Short Wave Fade (SWF)** is a particular type of SID that can severely hamper HF radio users (up to 20 – 30 MHz) by causing increased signal absorption which may last for up to 1-2 hours.
- Geomagnetic storms may profoundly alter ionospheric electron densities over large segments of the middle and high latitudes. Ionospheric storms may occur in the absence of a discernable geomagnetic storm, but they are generally similar in their effects on HF systems regardless of the origin and association. The origin of a purely ionospheric storm is uncertain.
- For a given path, the workable frequency bands lies between the maximum usable frequency (MUF) capable of be reflected by the ionosphere and lowest usable frequency (LUF) still maintaining connectivity along the same path. In the Figure, ray path 1 is associated with the LUF and ray path 3 corresponds to the MUF path.

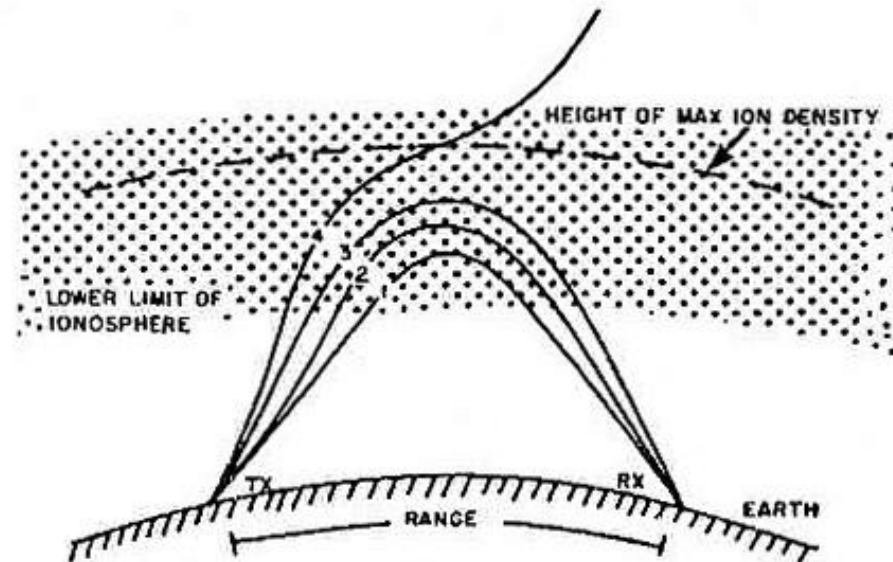
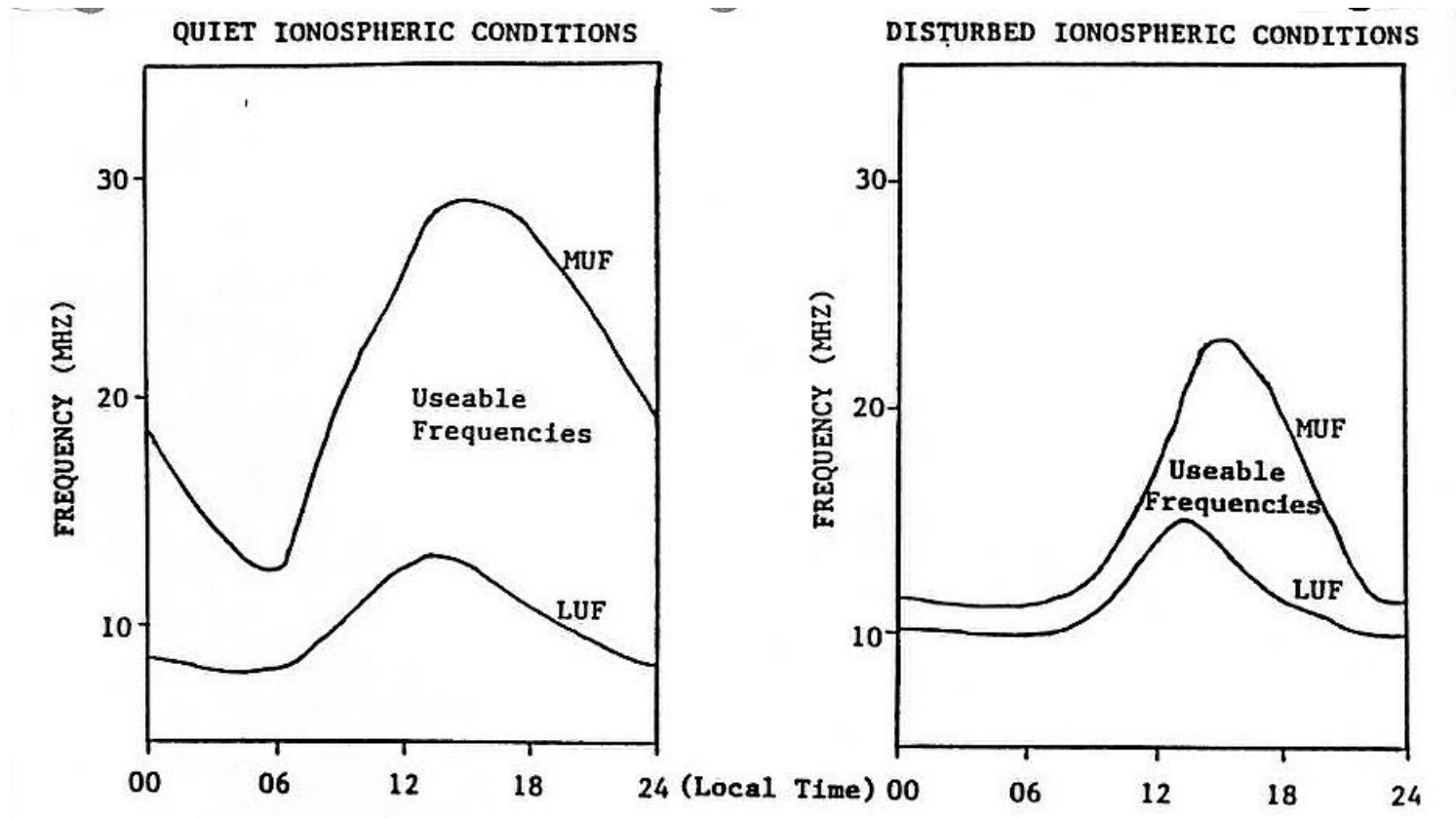


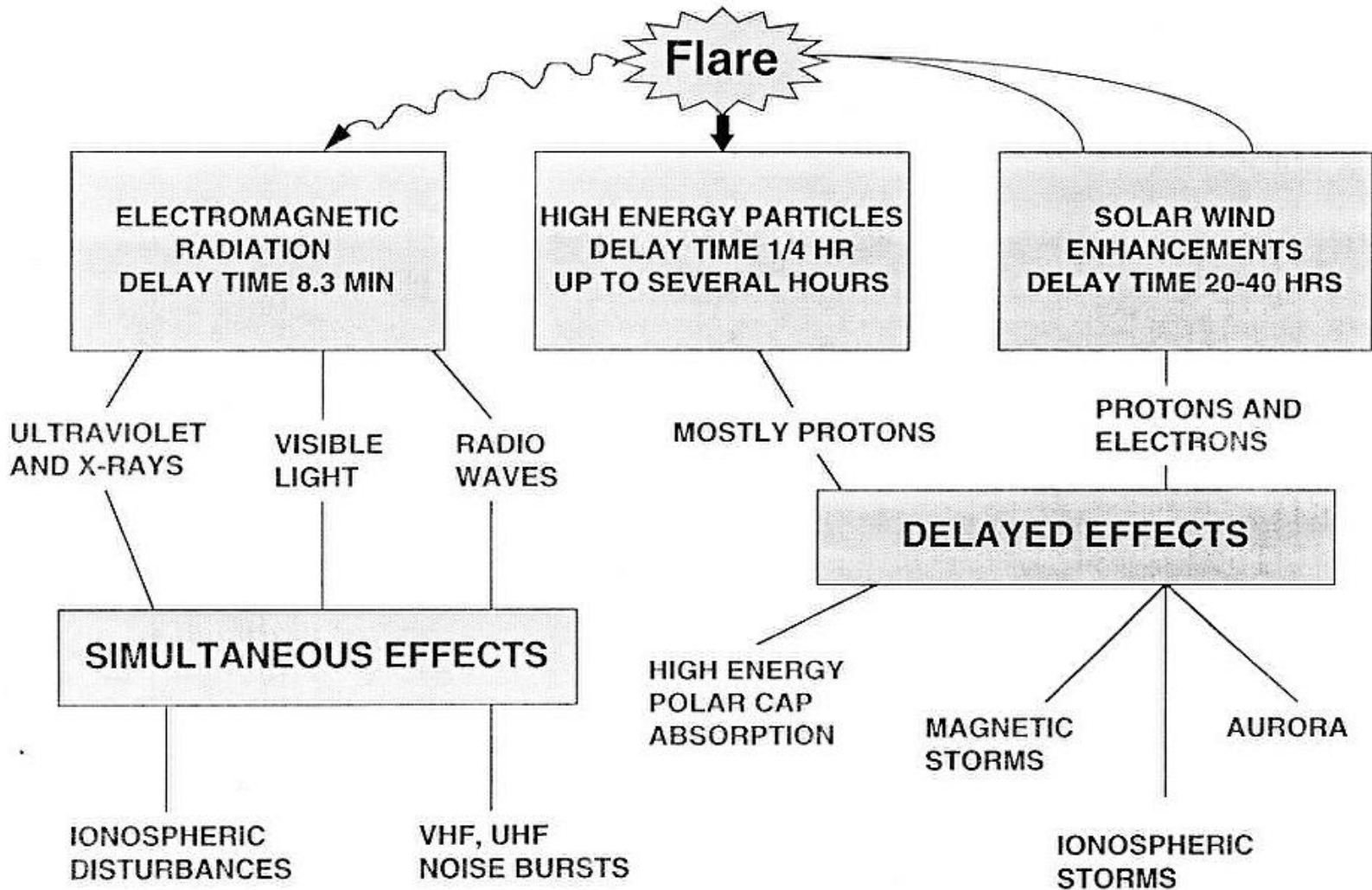
Figure 9.3 Diagram showing the effect different frequencies have on several ray paths for a fixed distance between transmitter (TX) and receiver (RX). As the frequency increases, the ray penetrates deeper into the ionosphere until it eventually escapes (after McNamara, 1985).

Comparisons MUF/LUF between Quiet and Disturbed Condition

- Impact of ionospheric conditions on HF propagation. The range of useable frequencies, between the MUF and LUF, is reduced during disturbed periods.



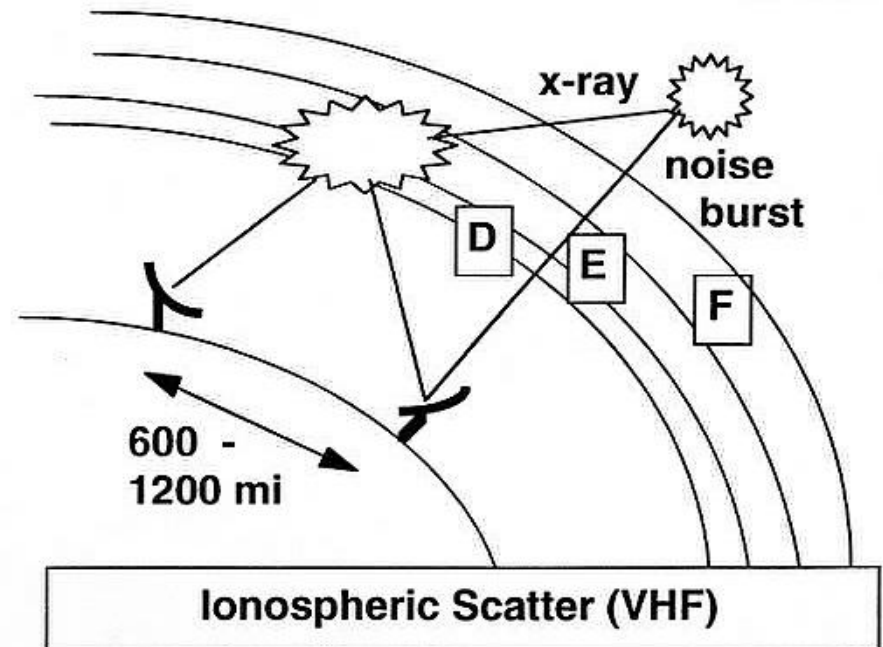
EFFECTS OF SOLAR FLARES



Solar Effects on Radio Waves

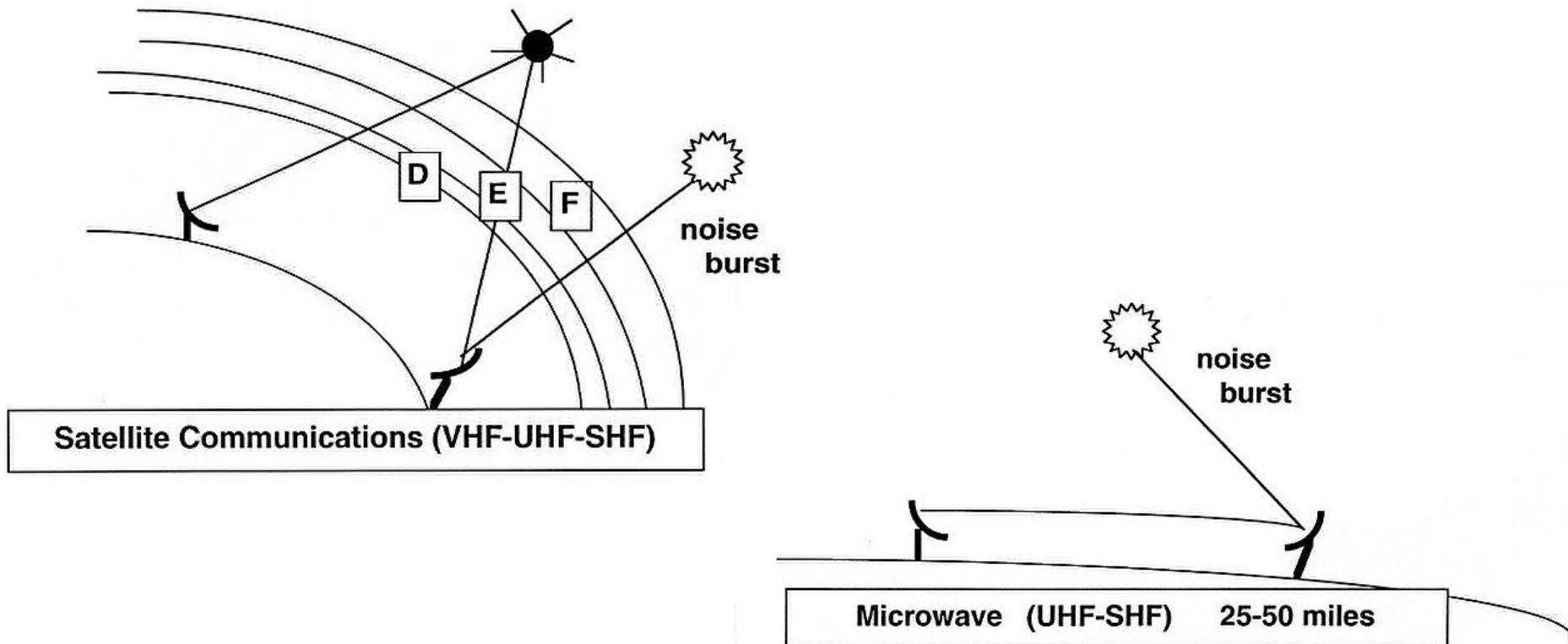
- **Radio Noise Storms.** Sometimes an active region on the Sun can produce increased noise levels, primarily at frequencies below 400 MHz. This noise may persist for days, occasionally interfering with communication systems using an affected frequency.
- **Solar Wind Recurrence.** The Sun rotates once approximately every 27 days. There is a tendency for long lasting solar wind anomalies, such as those originating from coronal holes, to pass the Earth every 27 days. These solar wind anomalies can cause recurring geomagnetic disturbances.

- **Solar Radio Bursts.** Radio wavelength energy is constantly emitted from the Sun; however, the amount of radio energy may increase significantly during a solar flare. These bursts may interfere with radar, HF (3 – 30 MHz) and VHF (30 – 300 MHz) radio, or satellite communication systems. Radio burst data are also important in helping to predict whether we will experience the delayed effects of solar particle emissions.



Solar Effects on Radio Waves

- Systems in the VHF through SHF range (30 MHz to 30 GHz) are susceptible to interference from solar radio noise. If the Sun is in the reception field of the receiving antenna, solar radio bursts may cause Radio Frequency Interference (RFI) in the receiver, as depicted below.



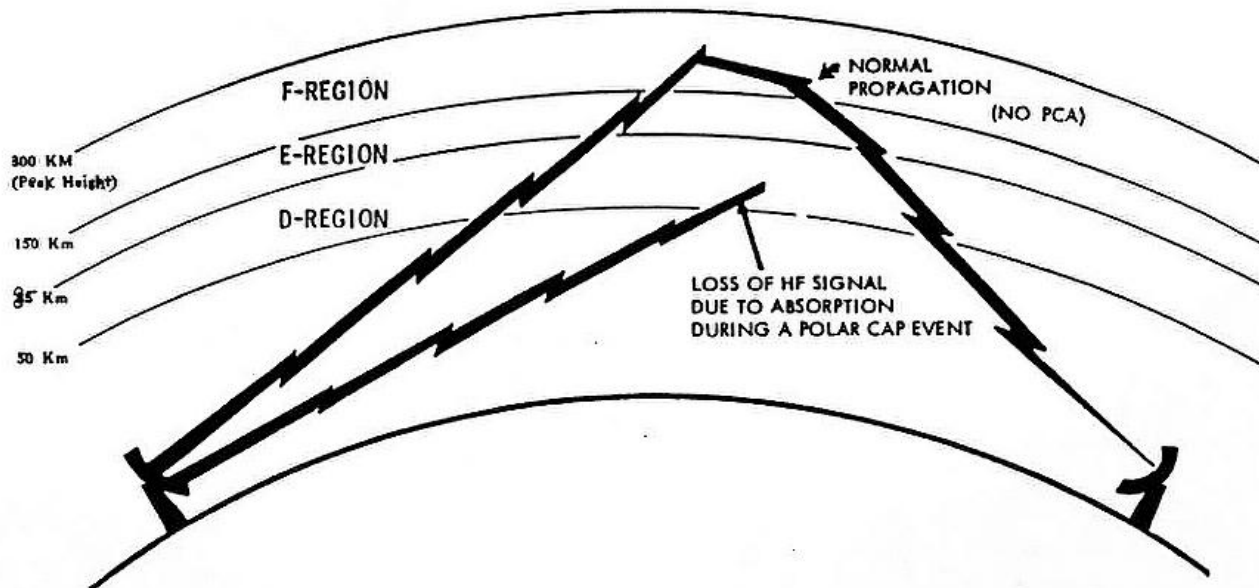
Solar Particle Events and Polar Cap Absorption

- Part of the energy released in solar flares are in the form of accelerating particles (mostly proton and electrons) to high energies and released into space.
- The energetic charged particles emitted will be guided by the IMF (not to be confused with solar wind, which guides the IMF).
- The intensity of the particle event will depend upon the size of the solar flare, the relative position of the Earth and the flare on the Sun, and the structure of the IMF.
- The major impacts of a solar particle event are spacecraft anomalies (charging, single event upsets, optical sensor disorientation, etc.) and **Polar Cap Absorption (PCA)**
- PCA events occur when high energy protons spiral along the Earth's magnetic field lines towards the polar ionosphere's D-region (50 – 90 km altitude).
- These particles cause significant increased ionization levels, resulting in **severe absorption of HF radio waves** used for communication and some radar system.
- This phenomenon, sometimes referred to as “polar cap blackout”, is often accompanied by widespread geomagnetic and ionospheric disturbances.

PCA

- In addition, LF and VLF systems may experience phase advances when operating in or through the polar cap during a PCA event due to changes in the Earth-ionosphere waveguide.

POLAR CAP ABSORPTION (PCA)



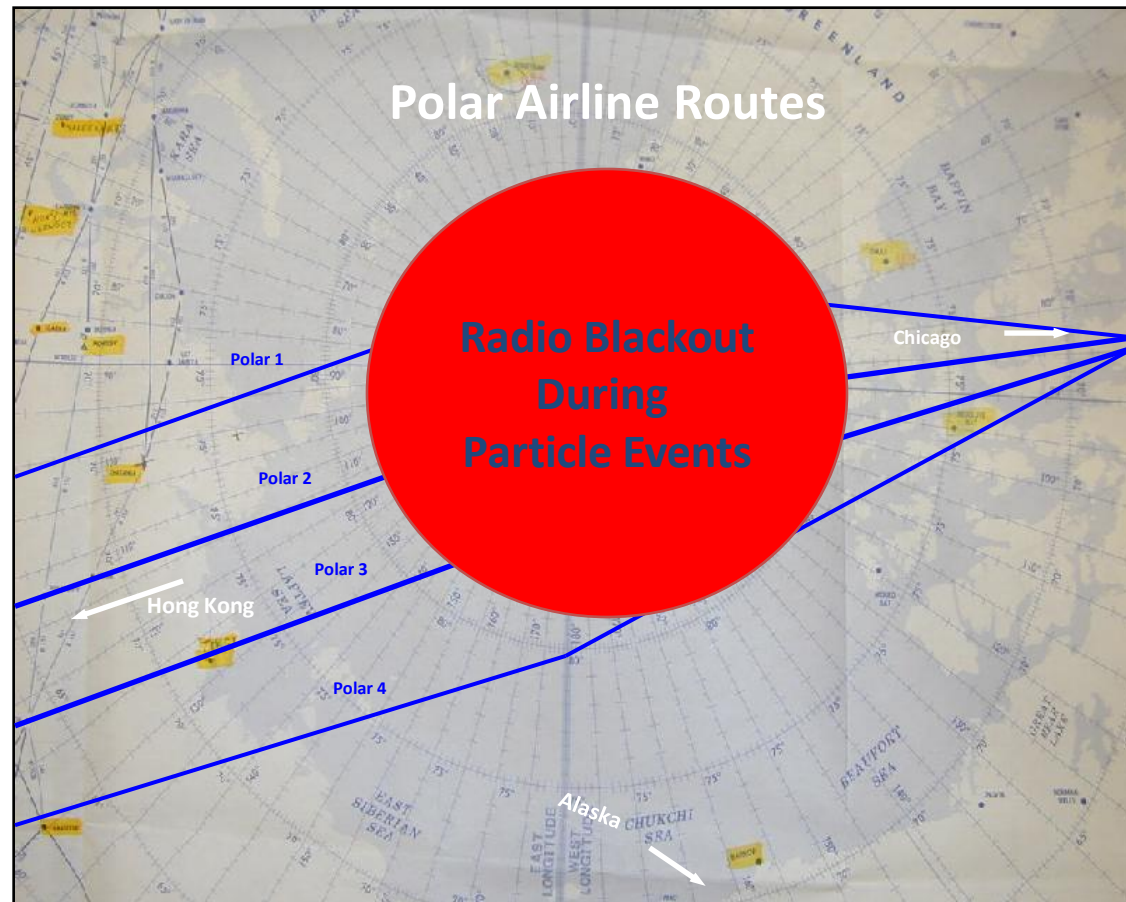
Energetic Particle Effects on High Latitude HF Communications

Polar airline routes loose ground communications

- Alternate routes required
- Uses more fuel
- Flight delays

Sample of Flights Affected:

- 10/26/00: Lost of HF prior to 75N, re- route off Polar route with Tokyo fuel stop. 15:00 flight now 20:30
- 11/10/00: Due to poor HF, ORD to HKG flown non-polar at 47 minute penalty
- 3/30/01-4/21/01: 25 flights operated on less than optimum polar routes due to HF disturbances resulting in time penalties ranging from 6 to 48 minutes
- 11/25/00: Polar flight re-route at 75N due to Solar Radiation, needed Tokyo fuel stop
- 11/26/00: Operated non-polar at 37 minute penalty due to solar radiation
- 11/27/00: Operated non polar at 32 minute penalty due to solar radiation.
- 11/28/00: Operated non-polar at 35 minute penalty due to solar radiation



Time Scale for Solar Flare Effects

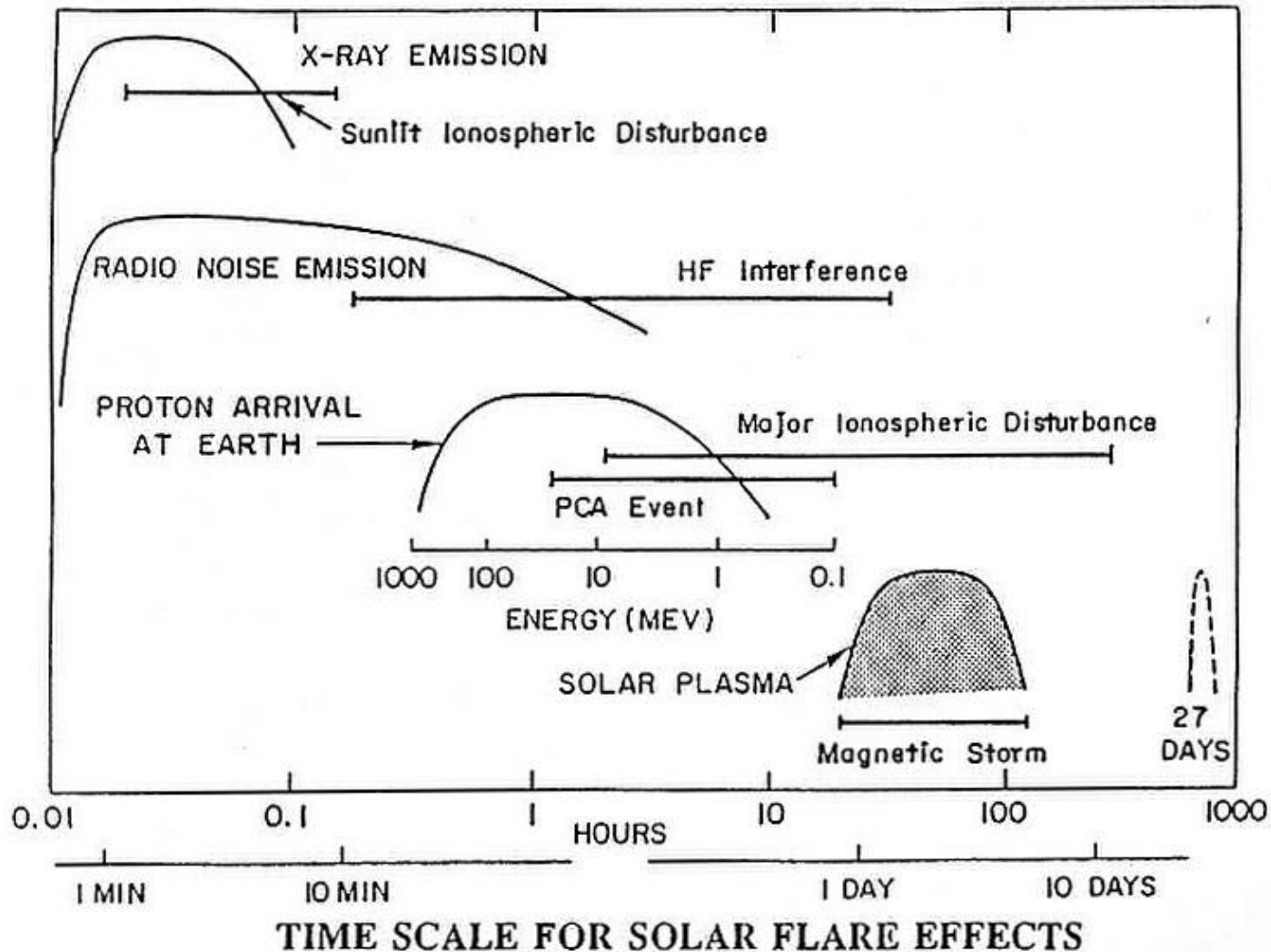
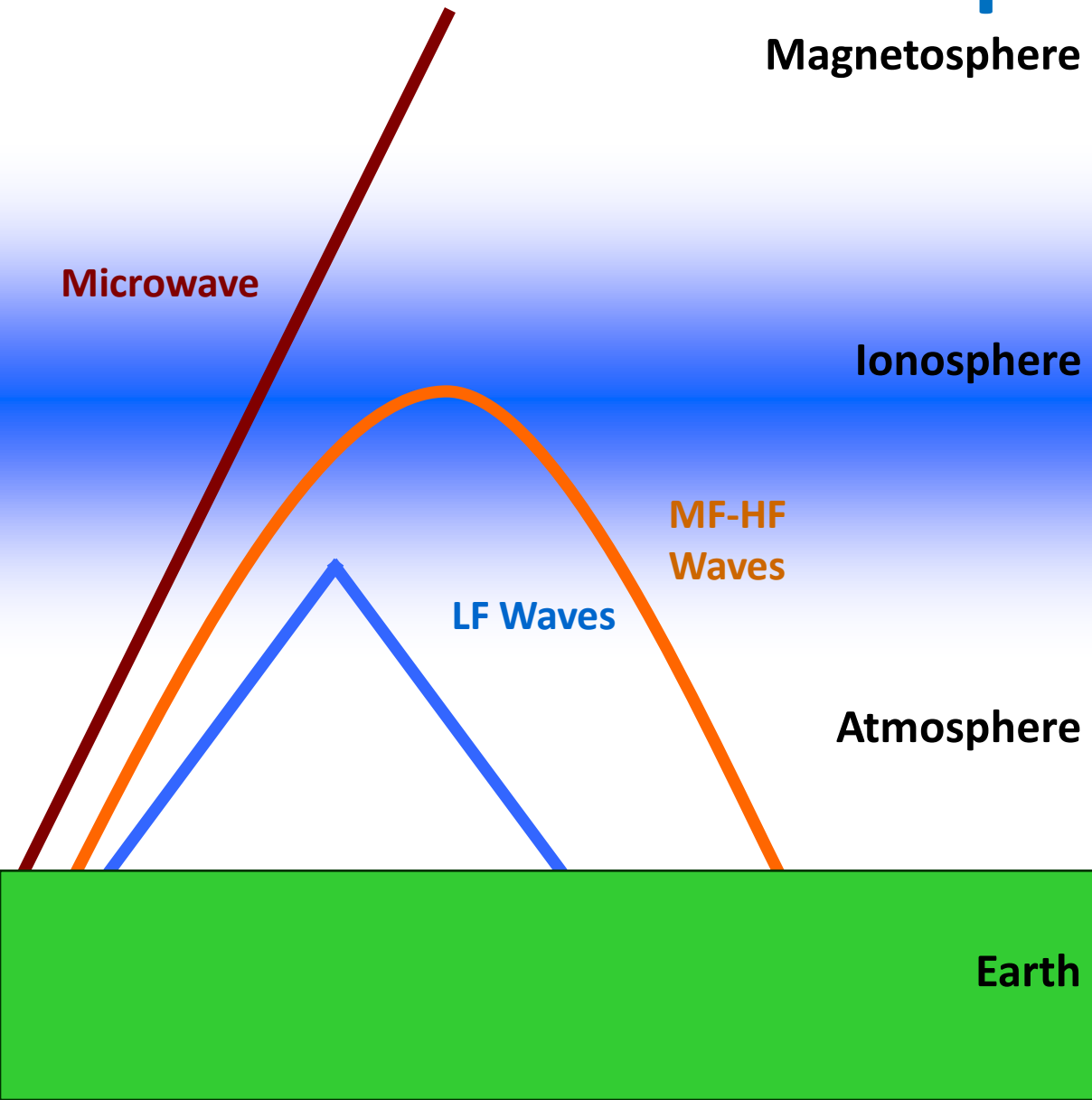


Fig. 14. Schematic plot of the relative variations in time of the amplitudes of the X-ray, radio noise, high energy particle, and solar plasma fluxes for a "typical" large solar flare.

Critical Frequency



Magnetosphere

Ionosphere

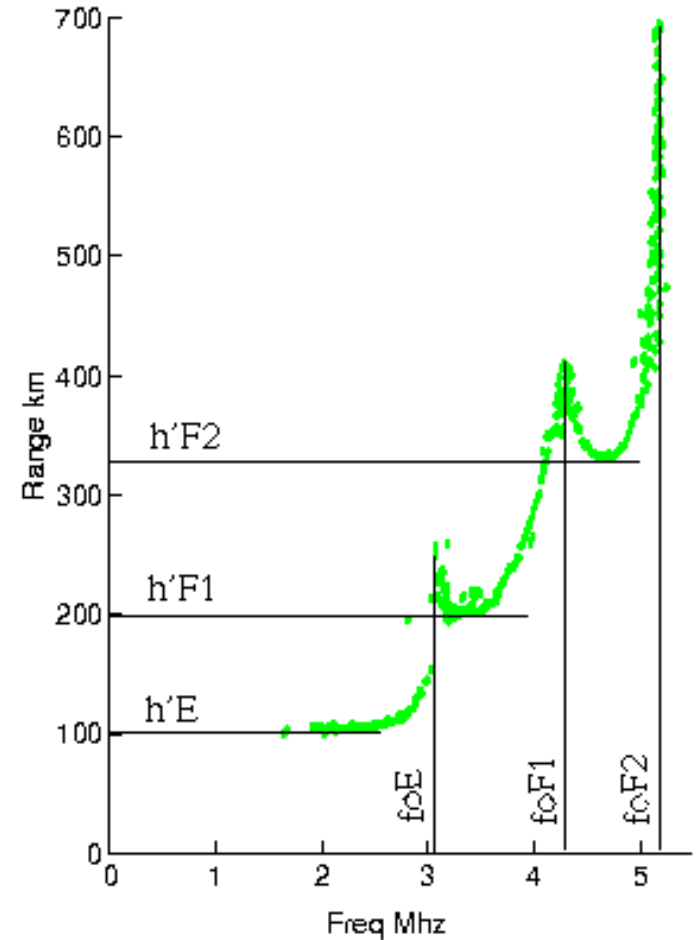
Atmosphere

Earth

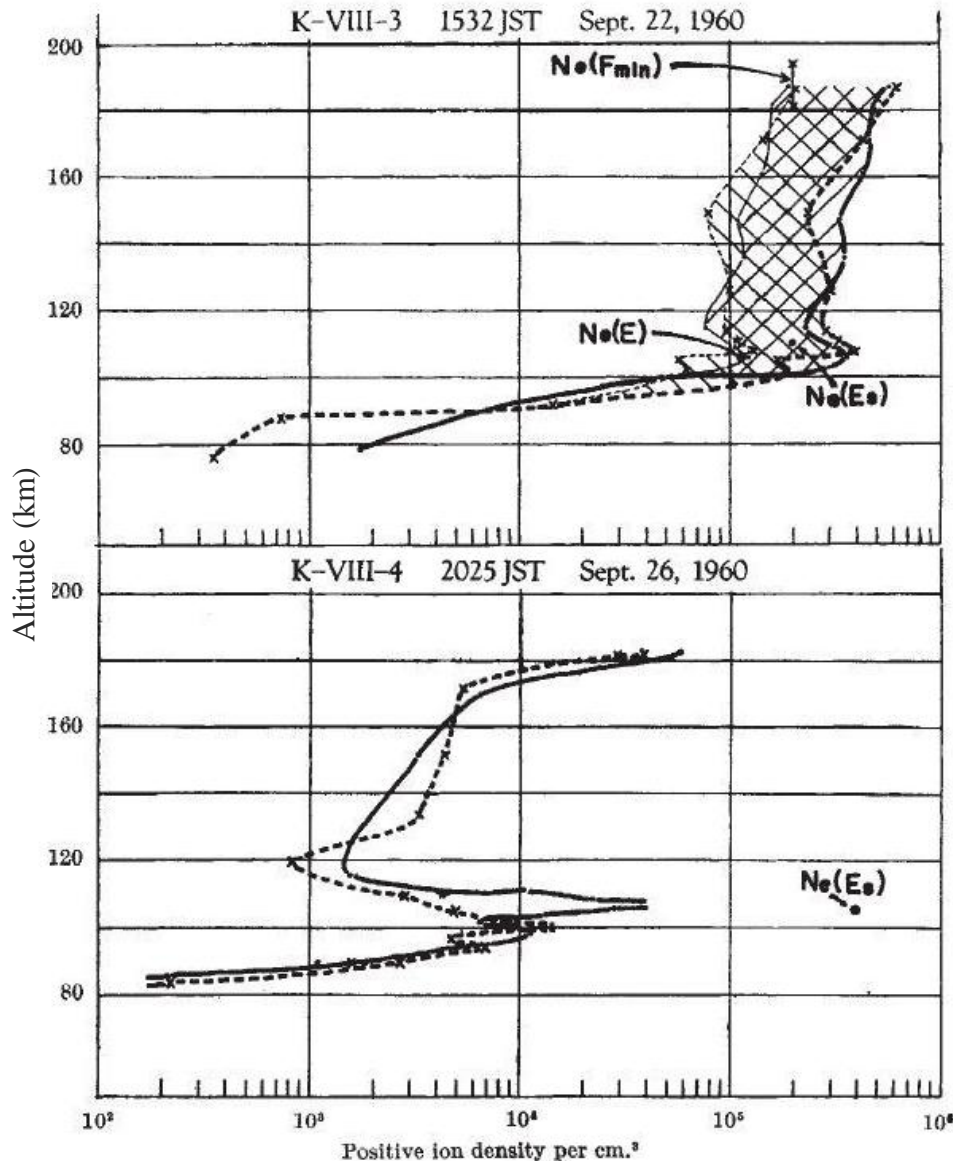
- Height at which radio waves reflect is dependent on maximum electron density of a layer
- Critical frequency defined as highest frequency reflected for normal incidence
- Maximum electron density related to critical frequency by
 - $n_e = 1.24 * 10^4 * f^2$
 - n_e in cm^{-3}
 - f in MHz

Ionograms

- Ionograms are a plot of the virtual height of the ionosphere vs. frequency (shown here in km vs. Mhz)
 - Show altitude and critical frequency at which electromagnetic waves at normal incidence reflect
 - Produced by ionosondes, which sweep from $\sim 0.1 - 30$ Mhz, transmitting vertically up into the atmosphere
- Get real time ionograms online
 - <http://137.229.36.56/>

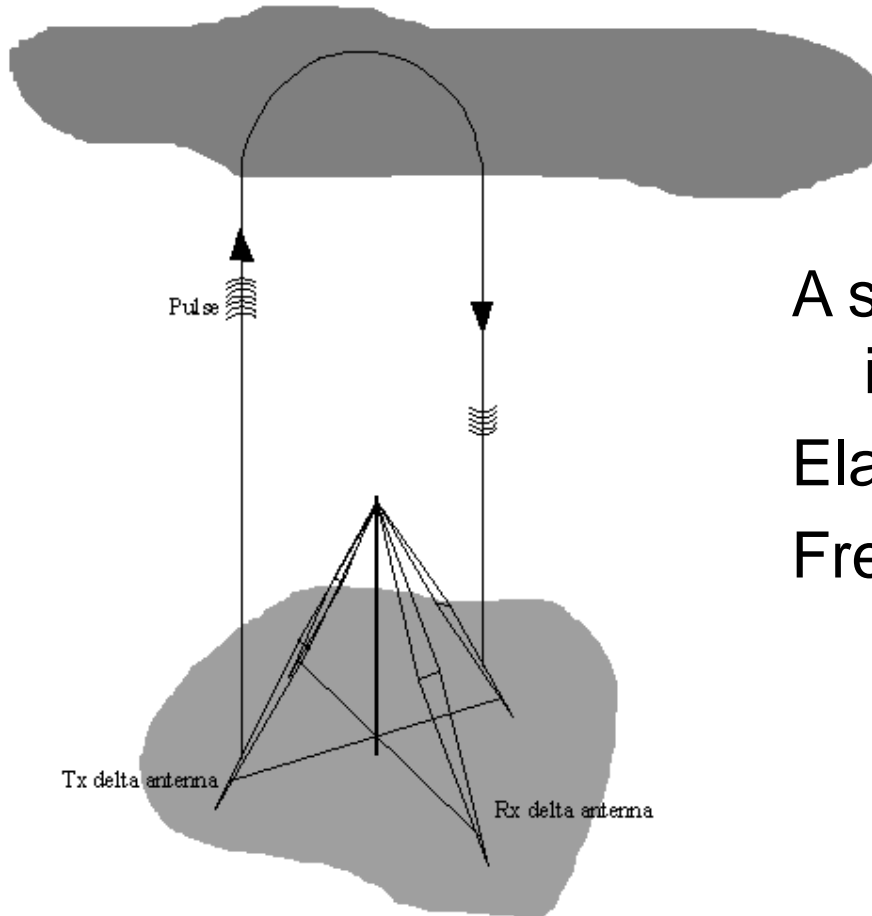


Rockets and the Ionosphere



- Launch rocket with instrument
- Record ascent and descent data
- Advantage: good height resolution
- Disadvantage: one-shot deal

Ionosonde



A special radar to examine
ionosphere from ionogram:
Elapsed time \rightarrow height
Frequency \rightarrow electron density

ionosonde

Radio Wave

