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High-frequency radio wave absorption in the D-region

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High-frequency Radio Wave Absorption

A research report presented by

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Game Plan

Radio Wave Propagation

- Sky Waves
- Properties of Ionosphere
- Geometric Optics

High-frequency Radio Wave Absorption

- Basic Absorption Equation
- Types of Absorption
- Absorption Coefficient
- Absorption Equation
- Special Cases

Electron Density

Collision Frequency

Conclusions/Discussion

Questions

Essential Points

Absorption is **frequency-dependent**

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Most HF absorption takes place within the **D-region**

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Within the D-region **non-deviative** absorption dominates
(Assuming HF)

Essential Points

Absorption is frequency-dependent

Most HF absorption takes place within the D-region

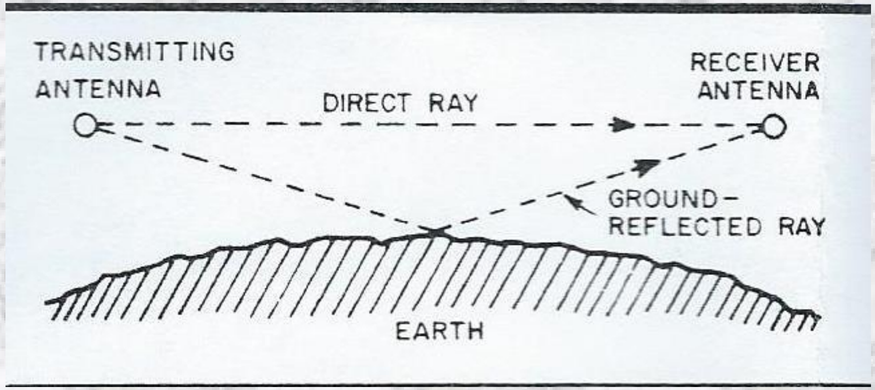
Within the D-region non-deviative absorption dominates
(Assuming HF)

Electron density is critical

Propagation via Sky Wave

Ground Wave vs. Sky Wave

Ground Wave

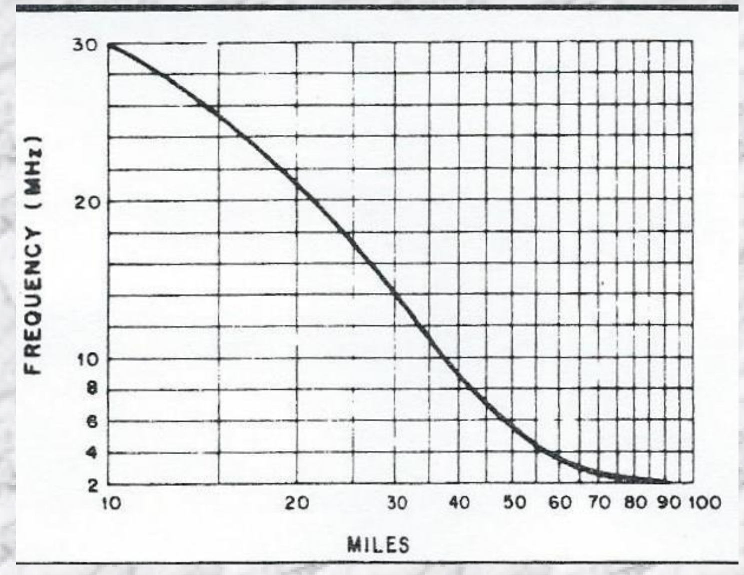


Direct ray and ground-reflected ray combine to form space wave

- Stays close to the earth
- Doesn't leave lower atmosphere

- AM broadcast band has range of about 160 km (100 miles)

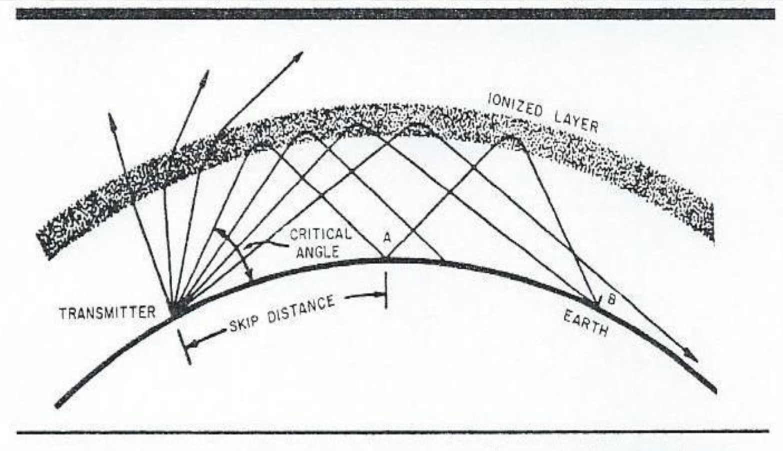
- **Generally ineffective for long-range communications**



Typical HF ground-wave range

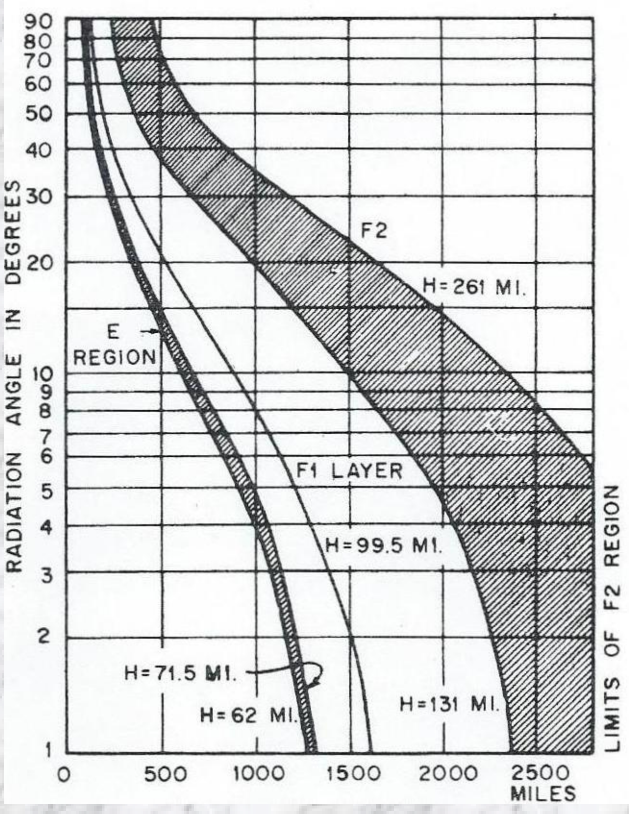
Images courtesy of ARRL Antenna Book, p 23-4

Sky Wave



Radio waves entering ionosphere at angles above critical angle go off into space

- Leaves lower atmosphere
- Passes through ionized region
- Refracted according to geometric optics

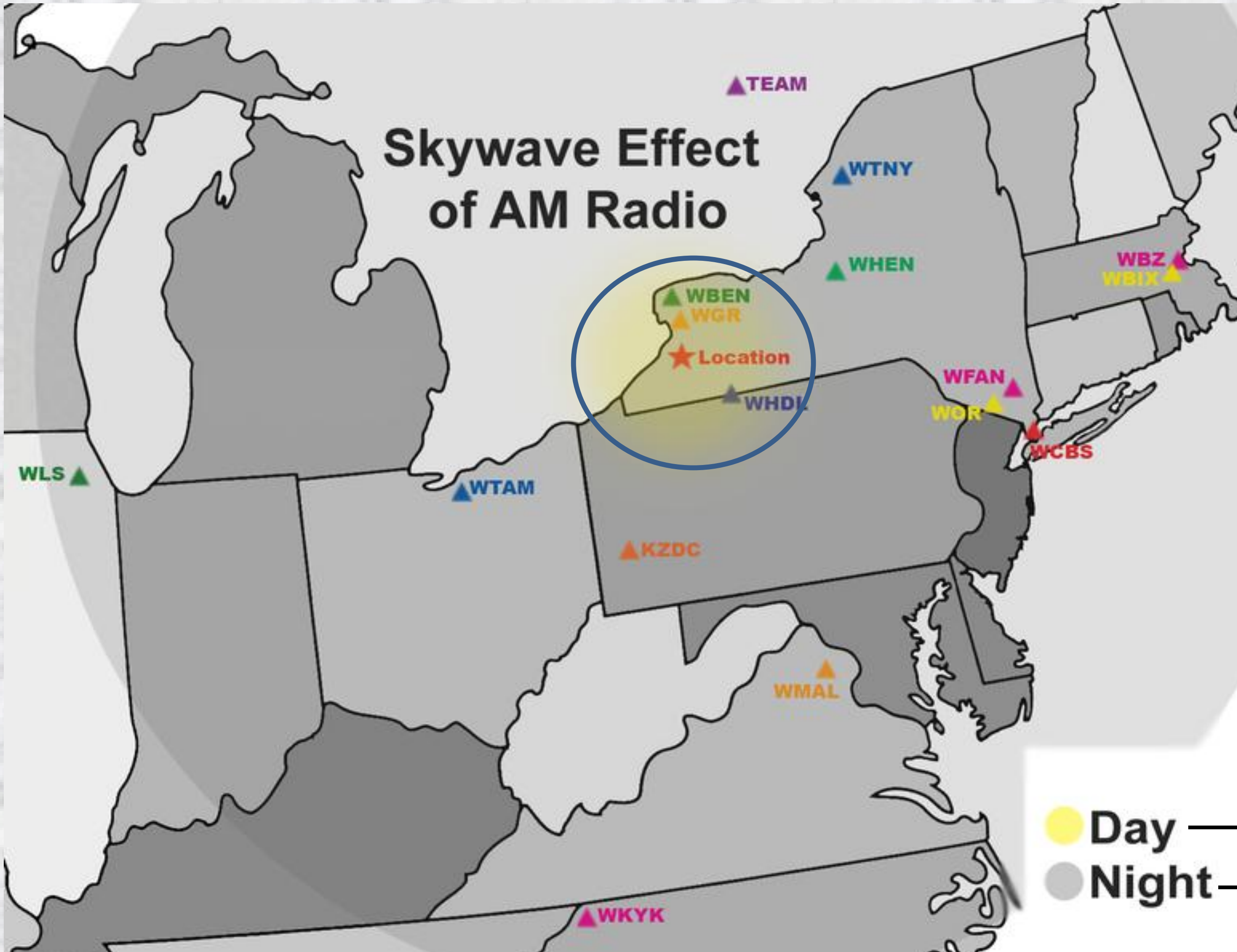


Distance vs. wave angle for one-hop transmission

- Range up to 4000 km (2500 miles) per hop
- **Efficient long-range communication**
- ***Subject to various atmospheric conditions***

Images courtesy of ARRL Antenna Book, pp 23-13, 23-16

Ground Wave vs. Sky Wave



→ Ground Wave

→ Sky Wave

Definitions

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IEEE Standard Definitions of Terms for Radio Wave Propagation," in *IEEE Std 211-1997* , vol., no., pp.i-, 1998 doi: 10.1109/IEEESTD.1998.87897

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High-frequency Spectrum: 3.0 MHz-30 MHz

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Ionospheric Properties

Ionosphere

The ionosphere is considered a weakly-ionized plasma

For a **fully-ionized** plasma the ratio of charged particles to neutral particles is about 1

Within the ionized region of the atmosphere this ratio is always much less than 1.

Hence the ionosphere is a weakly-ionized plasma

D-region

Height: About 90 km

Thickness: About 40 km

Significant diurnal variations

Typical daytime electron density

$\sim 10^9 - 10^{11}\ m^{-3}$

E-region

Height: About 150 km

Thickness: About 60 km

Diurnal variations though not as pronounced as D-region

Typical daytime electron density:

$$\sim 1 \times 10^{11} - 4 \times 10^{11}\ m^{-3}$$

F1-region

Height: About 350 km

Thickness: About 200 km

Diurnal variations

Typical daytime electron density:

$$\sim 4 \times 10^{11} - 2 \times 10^{12}\ m^{-3}$$

F2-region

Height: About 1000 km

Thickness: About 750 km

Diurnal variations, though not as pronounced

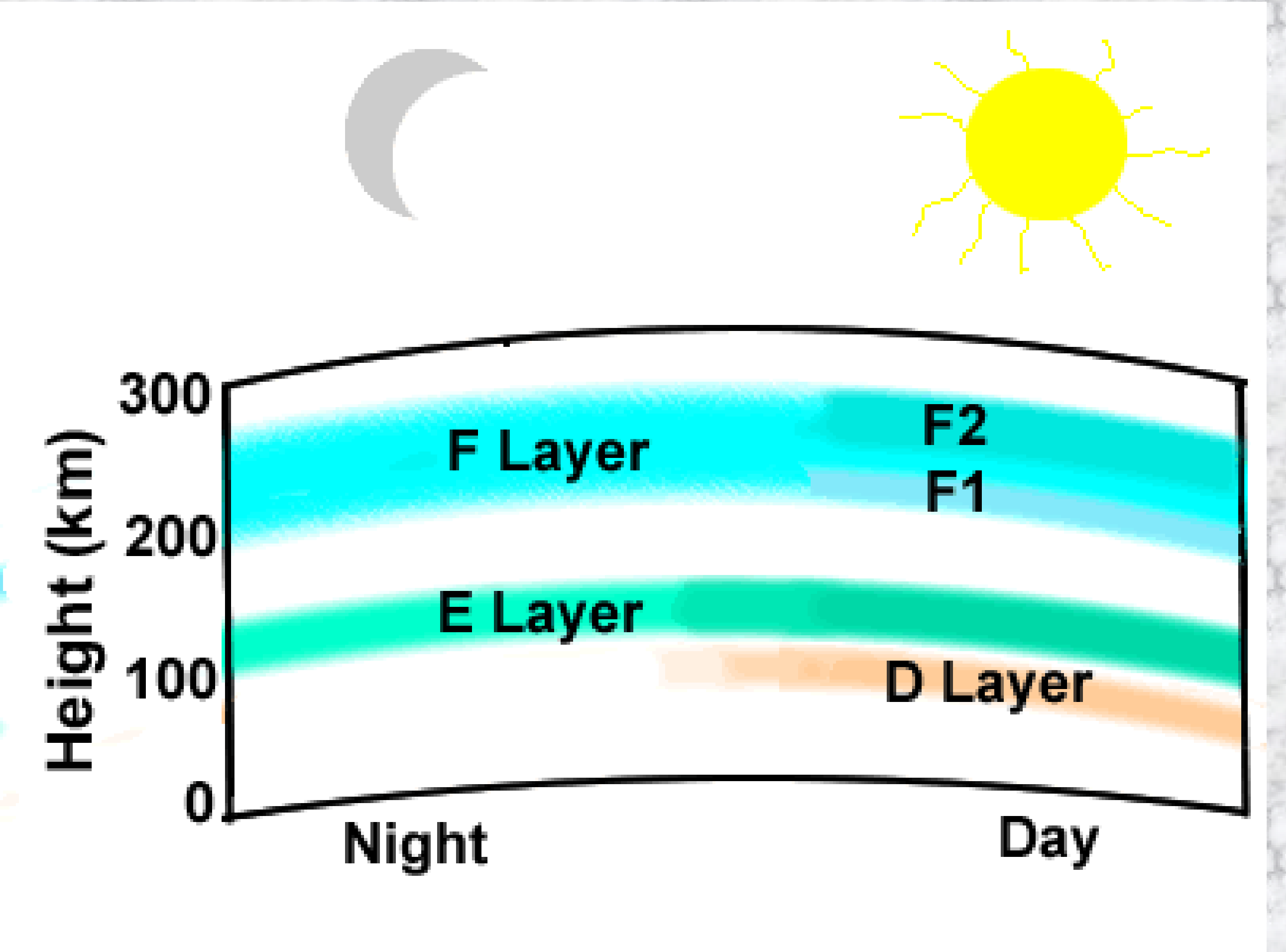
Electron Density:

$$\sim 8 \times 10^{10} - 2 \times 10^{12} \; m^{-3}$$

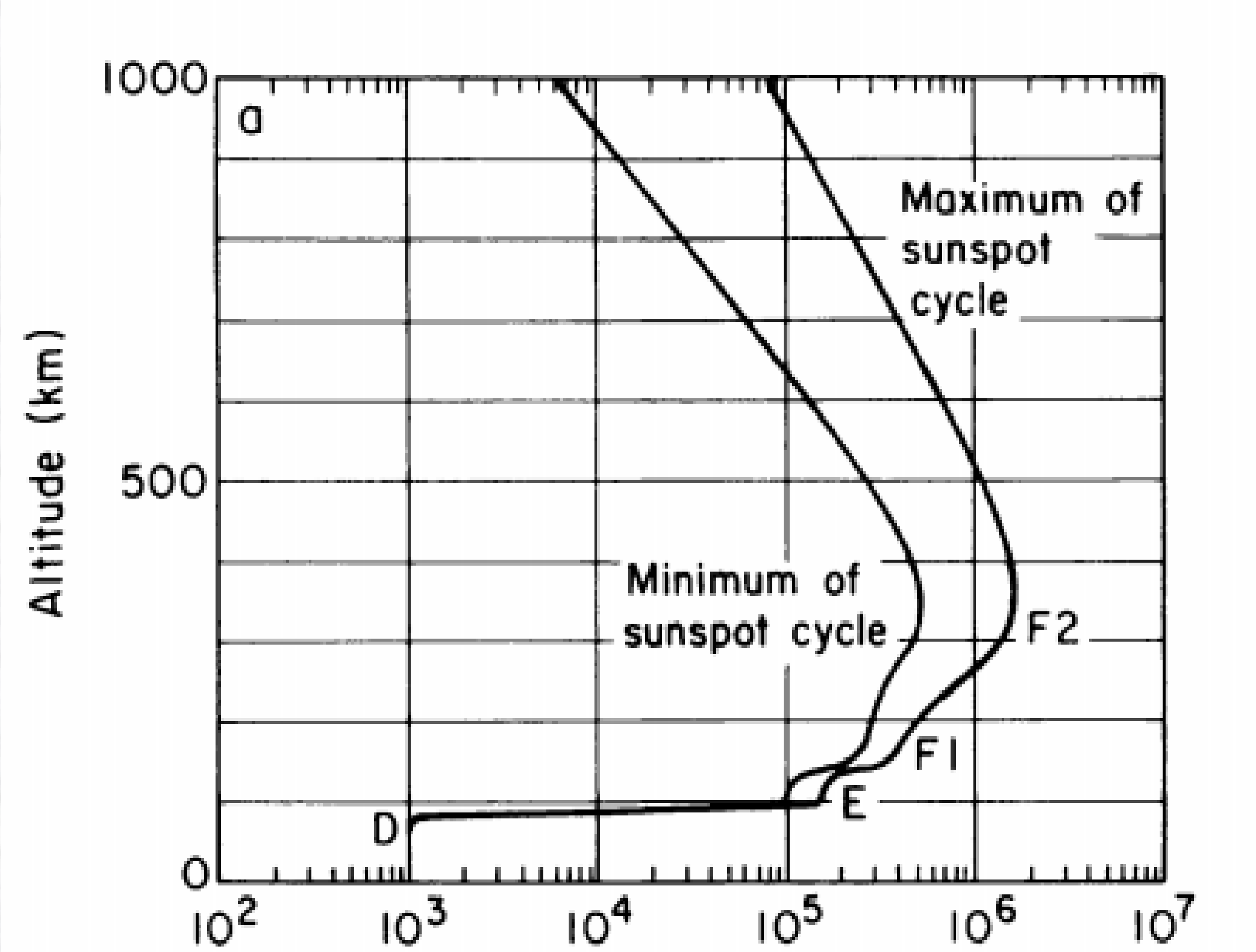
Unlike previous regions, F2 electron density decreases with height

Important note: F2 becomes the F-region after sunset.

Ionospheric Properties



Electron Density: Function of Height

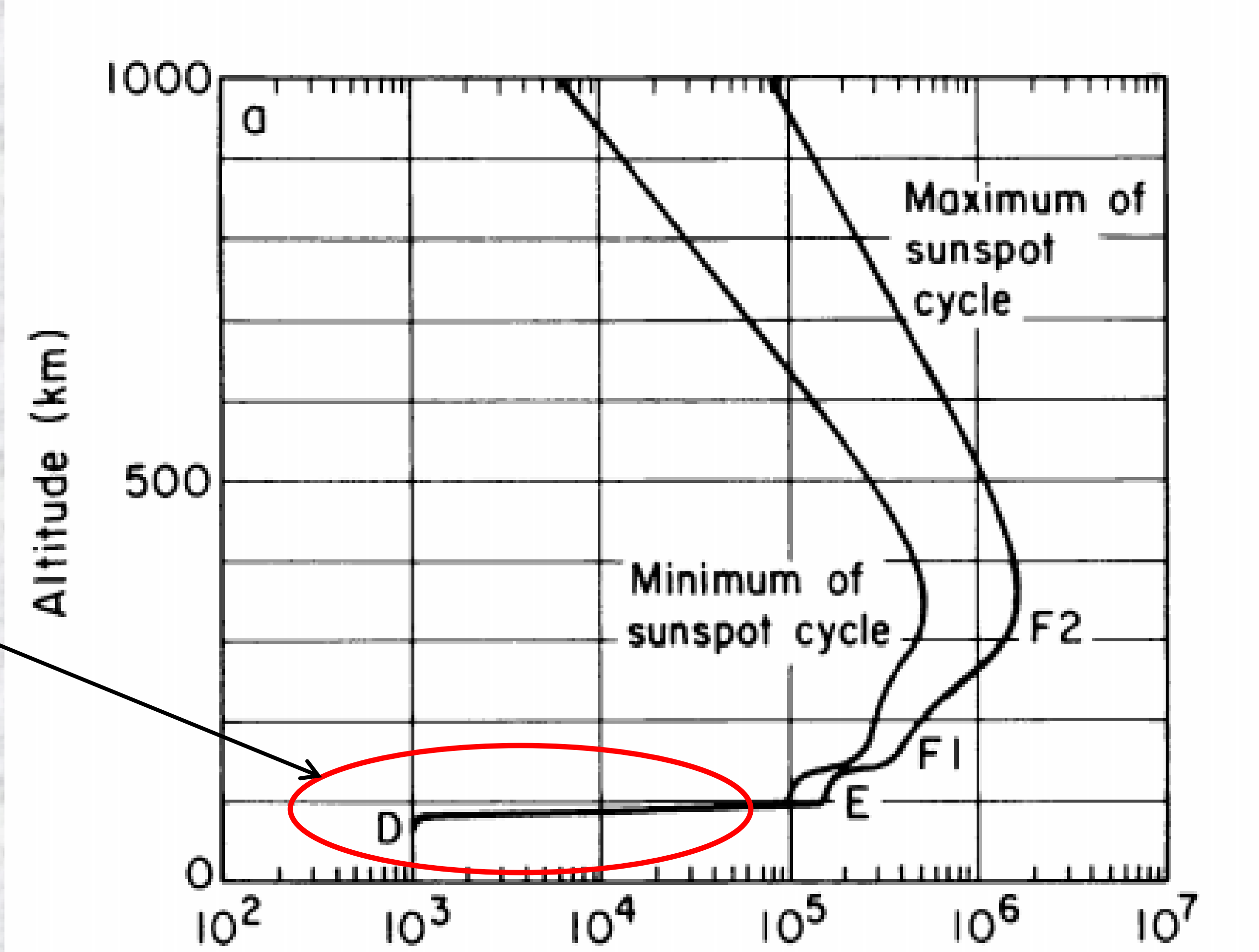


Electron concentration per cubic centimeter (Daytime)

Image from Kelley p 460

Electron Density: Function of Height

Maybe doesn't seem interesting but lots going on…



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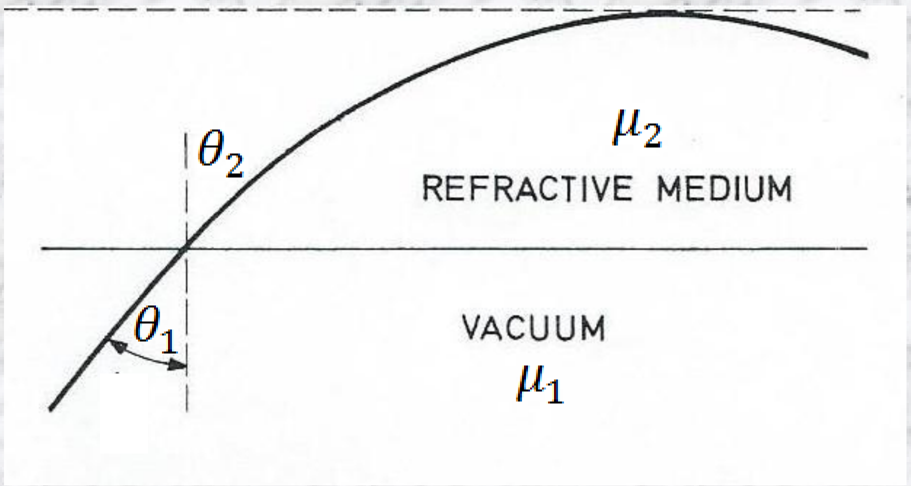
Geometric Approach

Geometric Approach



Ray path in a continuously varying medium (Ionosphere)
(Lied p 4)

When $\mu_2 < \mu_1 \Rightarrow \theta_1 < \theta_2$ ⟶ "**Bends away from the normal**"

Geometric Approach

Snell's Law:

$$\mu_1 \sin(\theta_1) = \mu_2 \sin(\theta_2)$$

Geometric Approach

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$\mu_1 \sin(\theta_1) = \mu_2 \sin(\theta_2)$ ⟶ Index of Refraction: $\mu = \dfrac{c}{v_{phase}}$

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$$\mu_1 \sin(\theta_1) = \mu_2 \sin(\theta_2)$$

→

Index of Refraction: $\mu = \dfrac{c}{v_{phase}}$

↓

$$\mu = \sqrt{\epsilon_r}$$

Geometric Approach

Snell's Law:

$$\mu_1 \sin(\theta_1) = \mu_2 \sin(\theta_2)$$ →

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Dielectric Constant of Weakly-Ionized Gas

$$\epsilon_r = 1 - \frac{\omega_p^2}{\omega^2}$$ ←

$$\mu = \sqrt{\epsilon_r}$$

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Dielectric Constant of Weakly-Ionized Gas

$$\epsilon_r = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\omega_p^2 \equiv \frac{n_e e^2}{\epsilon_0 m_e}$$

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$$\mu = \sqrt{1 - \frac{n_e e^2}{\epsilon_0 m_e \omega^2}}$$

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← Dielectric Constant of Weakly-Ionized Gas

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↓

$$\omega_p^2 \equiv \frac{n_e e^2}{\epsilon_0 m_e}$$

→

$$\mu = \sqrt{1 - \frac{n_e e^2}{\epsilon_0 m_e \omega^2}}$$

$$\omega = 2\pi f$$

→

$$\mu = \sqrt{1 - \frac{n_e e^2}{4\pi^2 \epsilon_0 m f^2}}$$

Note dependence on **electron density**

Geometric Approach

$$\mu = \sqrt{1 - \frac{n_e e^2}{4\pi^2 \epsilon_0 m f^2}}$$

Within a dispersive media such as the ionosphere:

Geometric Approach

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For a given frequency, as **electron density increases** index of refraction **decreases**

Geometric Approach

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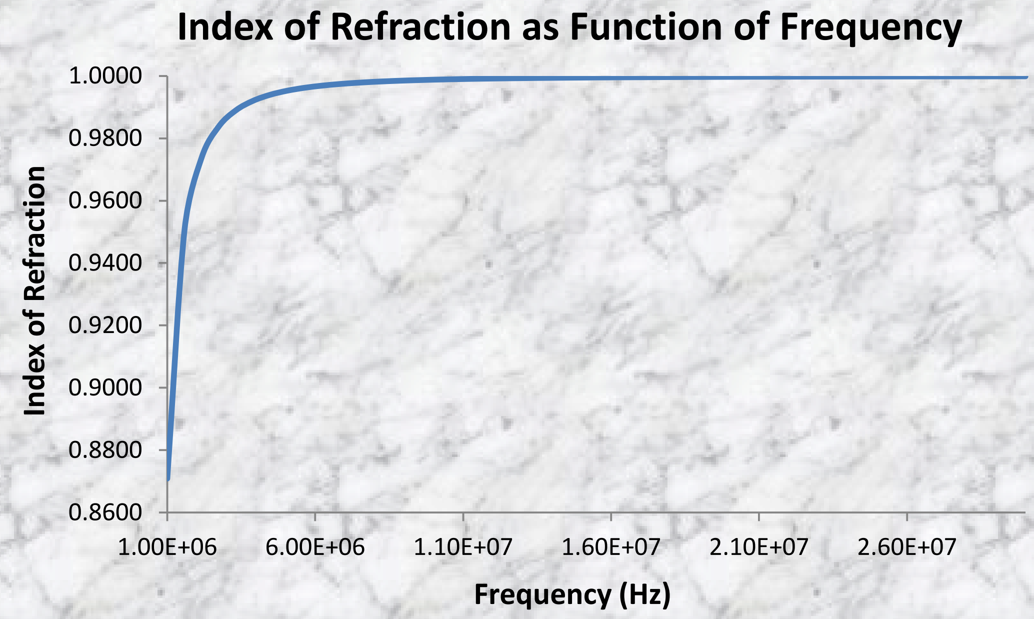
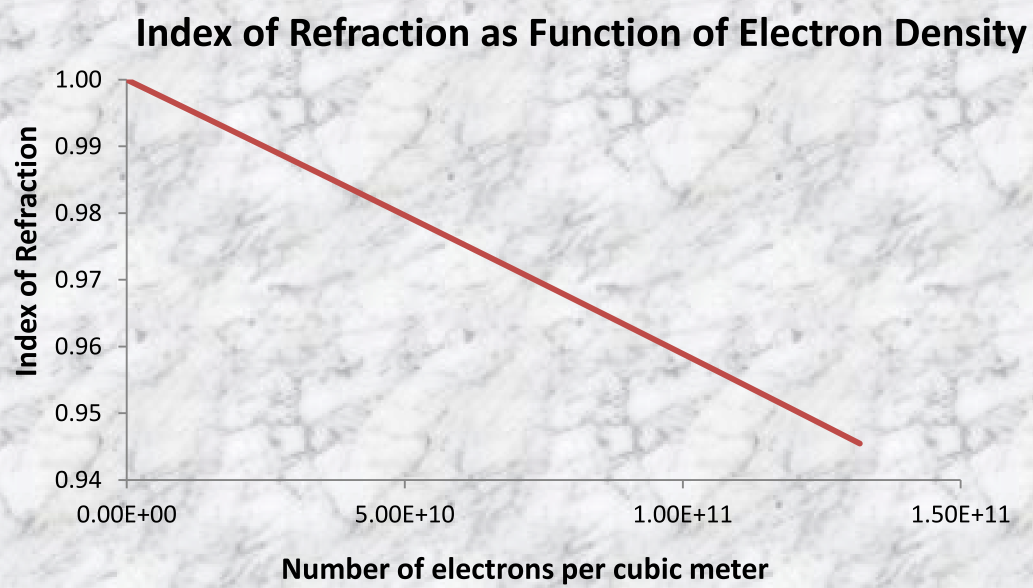
Within a dispersive media such as the ionosphere:

For a given frequency, as **electron density increases** index of refraction **decreases**

For a given electron density as **frequency increases** index of refraction approaches **unity**


Index of Refraction as Function of Frequency
Index of Refraction
1.0000
0.9800
0.9600
0.9400
0.9200
0.9000
0.8800
0.8600
1.00E+06
6.00E+06
1.10E+07
1.60E+07
2.10E+07
2.60E+07
Frequency (Hz)


Index of Refraction as Function of Electron Density
Index of Refraction
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.00E+00
5.00E+10
1.00E+11
1.50E+11
Number of electrons per cubic meter

Geometric Approach

$$\mu = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

Three Cases:

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$$\omega > \omega_p \Rightarrow \mu < 1 \Rightarrow \text{Refraction}$$

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Three Cases:

$$\omega > \omega_p \Rightarrow \mu < 1 \Rightarrow \text{Refraction}$$

$$\omega \leq \omega_p \Rightarrow \mu \to 0 \Rightarrow \text{Reflection point}$$

$$\omega \gg \omega_p \Rightarrow \mu \sim 1 \Rightarrow \text{Continues through ionosphere}$$

The Basic Absorption Equation

Basic Absorption Equation

Equation for total system loss

$$L_s = L_{ta} + L_{tp} - G_t + L_p + L_{rp} - G_r + L_{ra}$$

Note: Each term is a base-10 log. Hence, we add them

Basic Absorption Equation

Equation for total system loss

Transmitting | Receiving

$$L_s = L_{ta} + L_{tp} - G_t + L_p + L_{rp} - G_r + L_{ra}$$

What goes on in between

Critical term is path loss

Note: Each term is a base-10 log. Hence, we add them

Basic Absorption Equation

Equation for path loss

$$L_p = L_d + L_a + L_f$$

Basic Absorption Equation

Equation for path loss

$$L_p = L_d + L_a + L_f$$

Critical term is absorption.

Hence, we focus on the absorption term

Basic Absorption Equation

Equation for absorption

$$L_a = 10 \log\left(\frac{P_r}{P_u}\right)$$

$P_r \equiv$ Actual power received

$P_u \equiv$ Power received without absorption

Basic Absorption Equation

Equation for absorption

$$L_a = 20\log(\rho)$$

$$\rho \equiv \text{Apparent Reflection Coefficient}$$

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$$\text{Let } \rho \equiv \frac{I}{I_0'} \Rightarrow \rho = \exp\left[-\int \kappa \, ds\right]$$

Basic Absorption Equation

$$\Rightarrow \ln(\rho) = -\int \kappa \, ds$$

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***Kappa* has units of *nepers per unit length*. Hence, the above equation has units of nepers**

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From the rules of logarithms, $\log(x) = \dfrac{\ln(x)}{\ln(10)} \Rightarrow \log(\rho) = \dfrac{\ln(\rho)}{\ln(10)}$

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Since there are roughly 8.69 dB per neper the ***absorption equation*** has units of ***dB per unit length***

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Deviative absorption **uncommon in D-region**

Types of Absorption

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Type of absorption depends on relationship between **radio wave frequency** and **plasma frequency**

Type two: Radio wave frequency greater than plasma frequency

$$f > f_p$$

$$\Rightarrow \mu \approx 1$$

$$v_{phase} = \frac{c}{\mu} \approx c \text{ and } v_{group} = c\mu \approx c$$

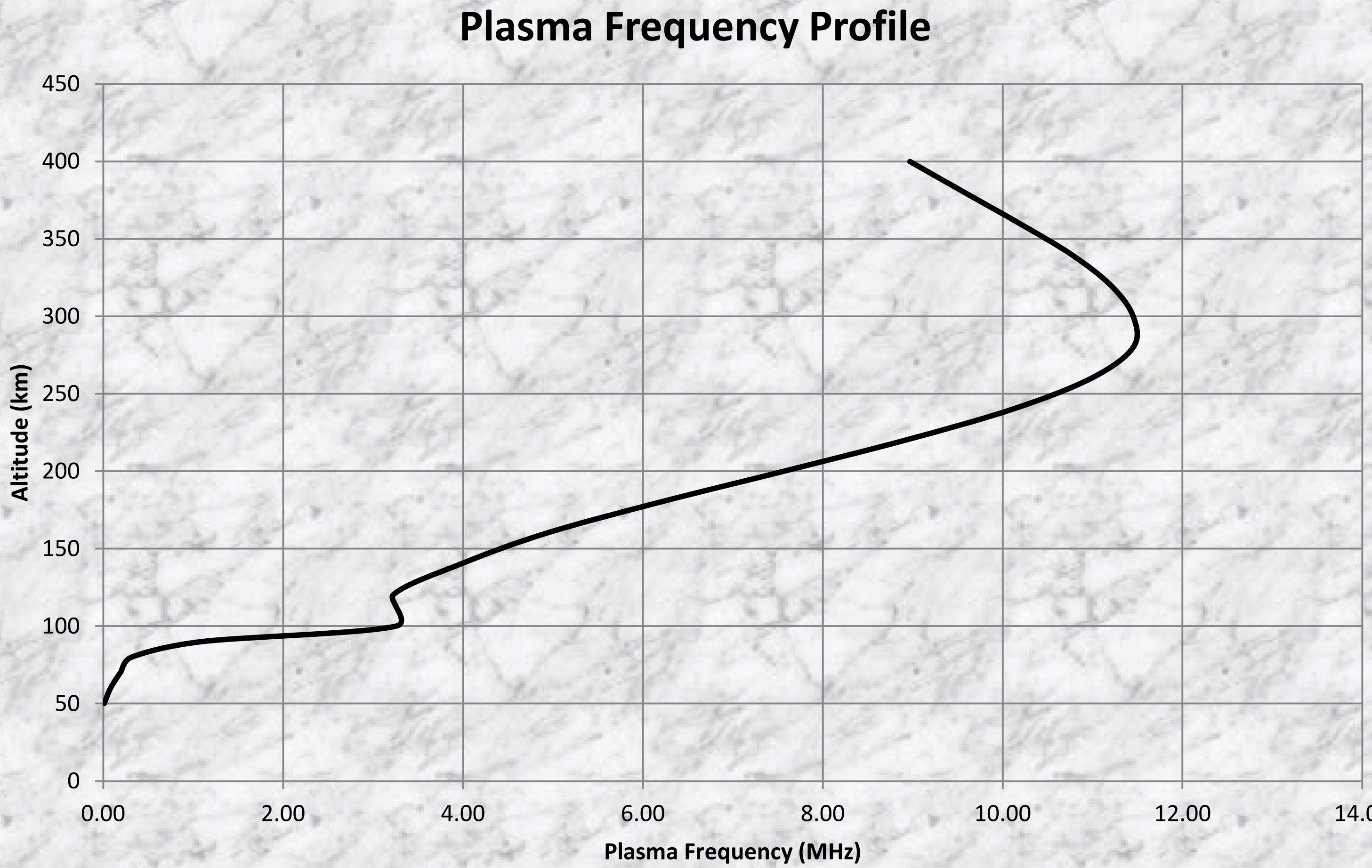
Hence, wave propagates at about speed of light

This is called **non-deviative absorption**

Very common in D-region

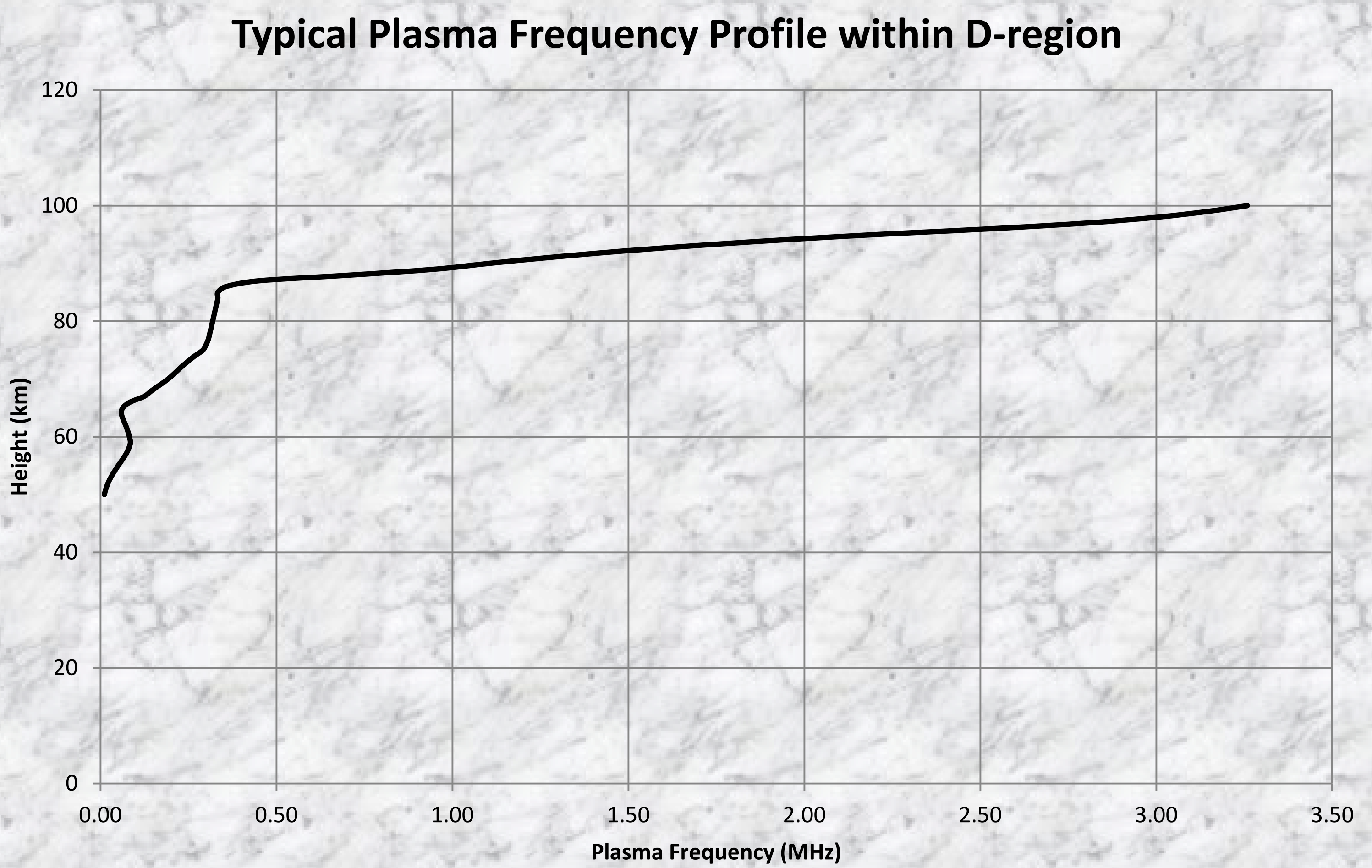
Note: Appendix 1 of my report presents a discussion/derivation of group and phase velocities.

Types of Absorption



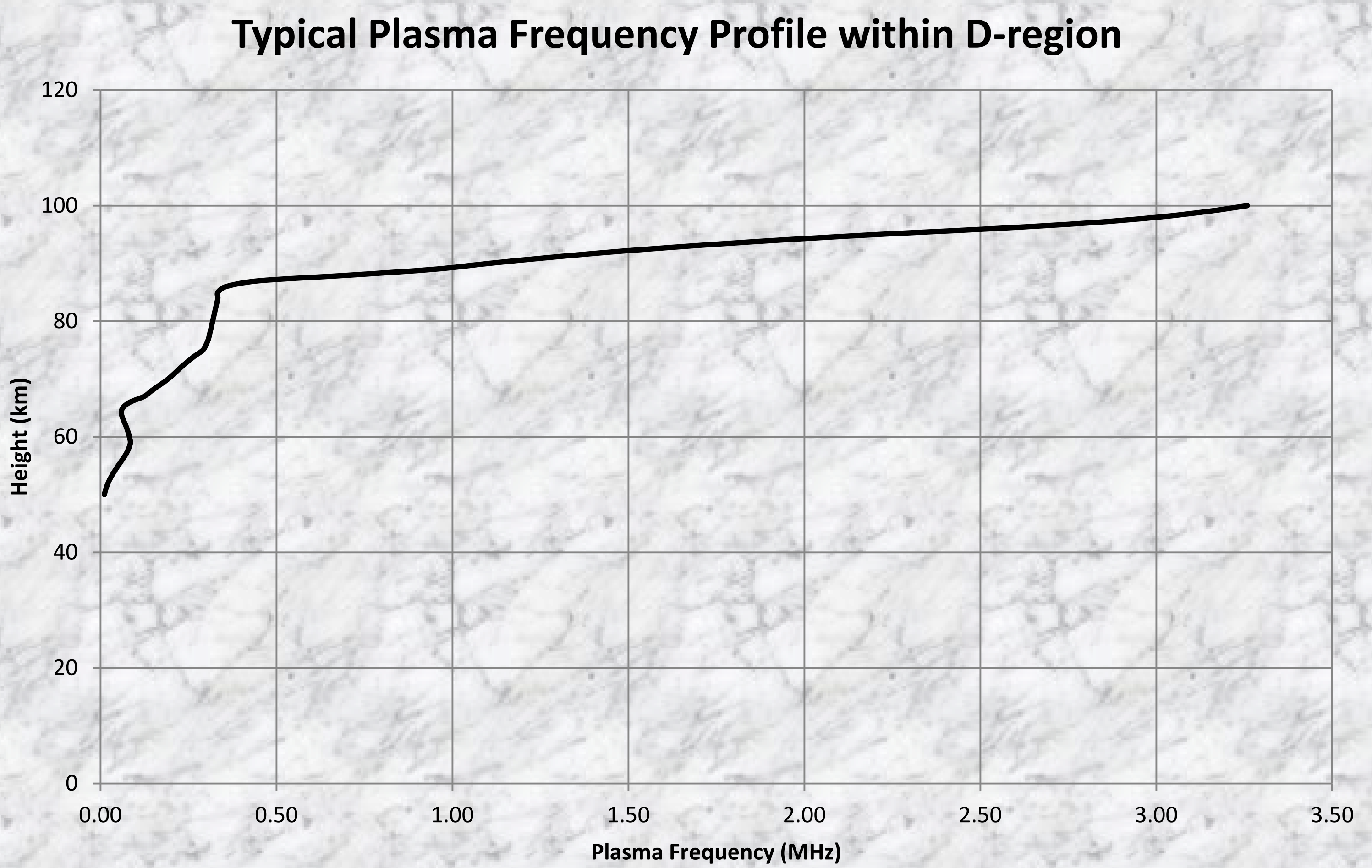
Profile of plasma frequency from 50-400 km. But we're really interested in D-region

Types of Absorption



Profile of plasma frequency from 50-100 km.
Note plasma frequency nearly always ***less than 3.0 MHz***

Types of Absorption



Thus we see that non-deviative absorption dominates in the D-region

(Assuming $3.0 < f < 30.0\ MHz$)

Absorption Coefficient

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In the absorption equation *kappa* is defined as the ***absorption coefficient***

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Hence, the absorption equation is based on first principles

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Units of *kappa* are ***nepers per unit length***

Defining Terms:

$e \equiv$ elementary charge $= 1.6 \times 10^{-19}\ C$

$\epsilon_0 \equiv$ permittivity of free space $= 8.85 \times 10^{-12}\ F \cdot m^{-1}$

$m_e \equiv$ electron mass $= 9.11 \times 10^{-31}\ kg$

$c \equiv$ speed of light in vacuum $= 3.0 \times 10^{8}\ m \cdot s^{-1}$

$\mu \equiv$ real part of refractive index $\cong 1.0$

$n_e \equiv$ electron density

$\nu \equiv$ collision frequency ← New important term!

$\omega \equiv$ angular frequency of wave

Absorption Coefficient

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Plugging in constant values we find that,

$$\kappa \cong 5.29 \times 10^{-6}\left(\frac{n_e \nu}{\omega^2 + \nu^2}\right) Np \cdot m^{-1}$$

Absorption Equation Revisited

Absorption Equation

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$$L_a = -8.69 \int \kappa \, ds$$

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$$\Rightarrow L_a = -4.60 \times 10^{-5} \int \left(\frac{n_e \nu}{\omega^2 + \nu^2}\right) ds \;\; dB \cdot m^{-1}$$

Absorption Equation

$$L_a = -4.60 \times 10^{-5} \int \left(\frac{n_e \nu}{\omega^2 + \nu^2} \right) ds$$

In this form integral is over ***path length***

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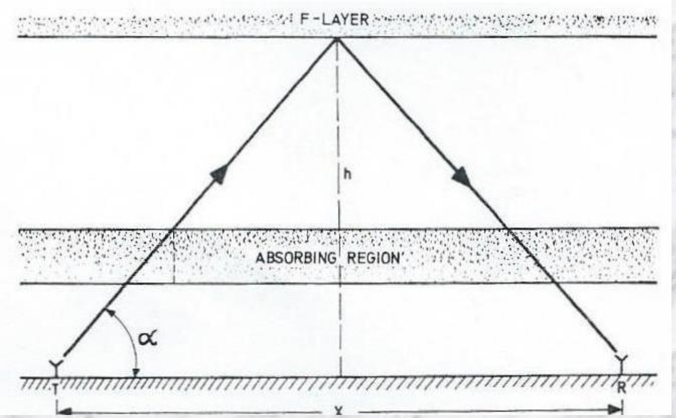

$$\sin\alpha = \frac{opposite}{hypotenuse} = \frac{h}{s}$$

Absorption Equation

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Now integrated over height

Absorption Equation

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For special case of vertical transmission:

$$\alpha = 90^\circ$$

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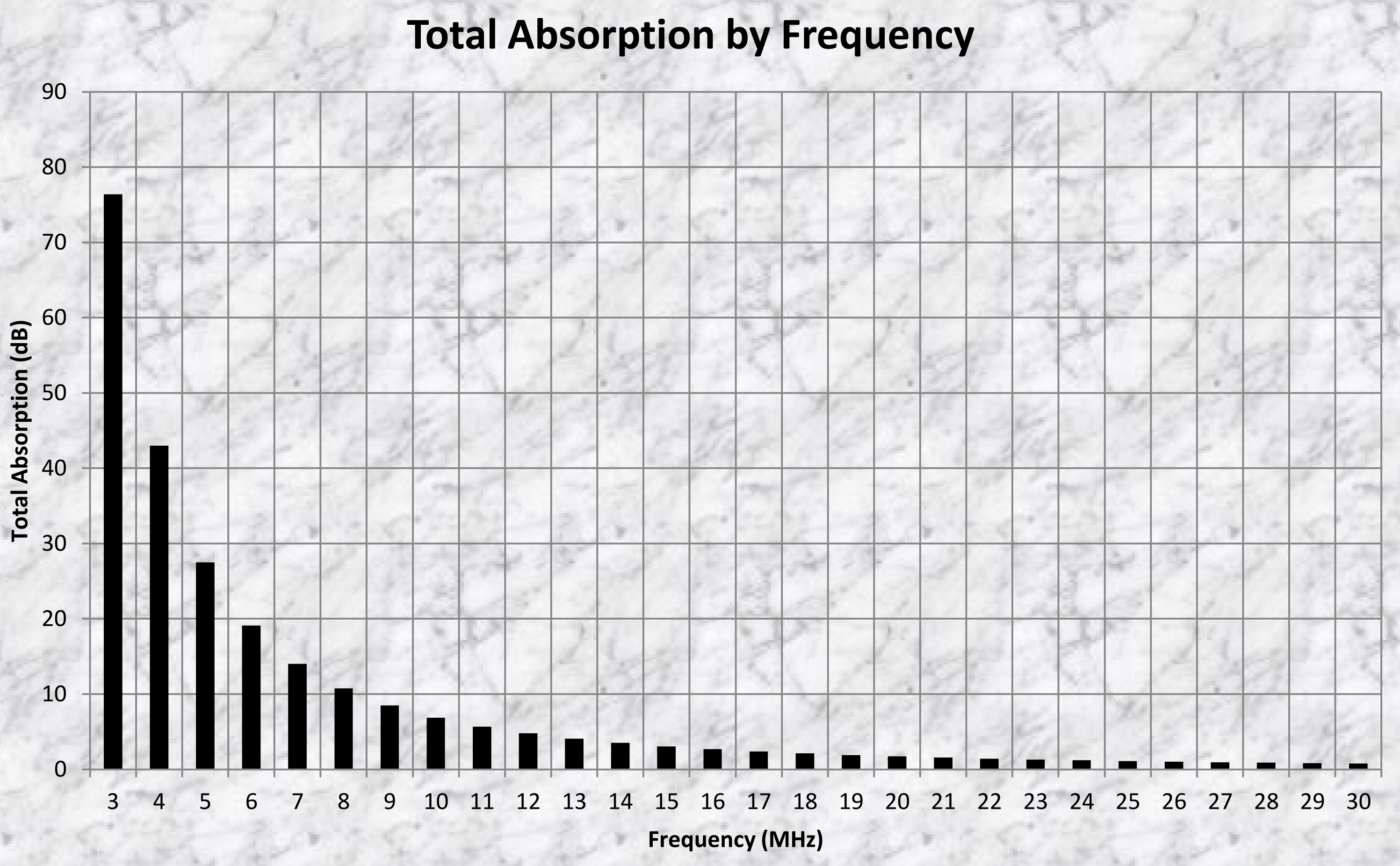
$$L_a = -\frac{4.60 \times 10^{-5}}{\sin \alpha} \int \left(\frac{n_e \nu}{\omega^2}\right) dh$$

$$\Rightarrow L_a = -\frac{1.17 \times 10^{-6}}{\sin(\alpha) f^2} \int n_e \nu \, dh$$

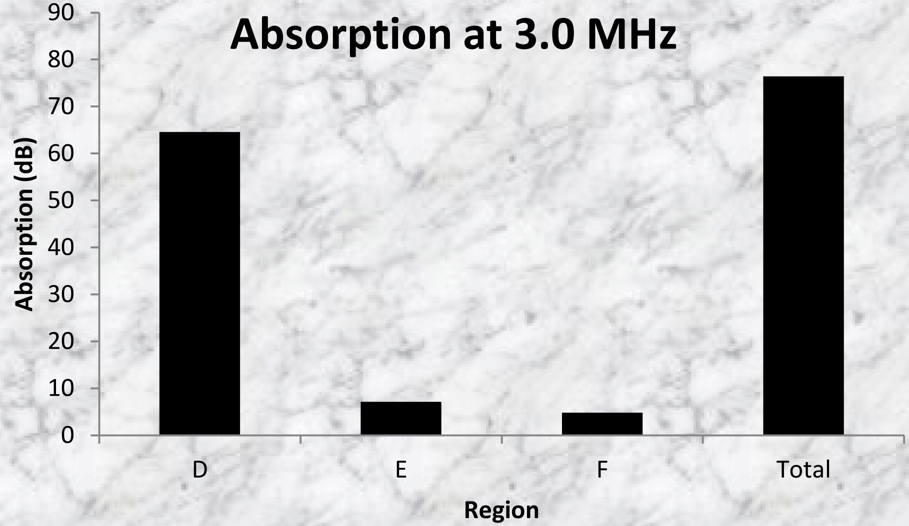
The absorption equation in terms of radio wave frequency in cycles per second.

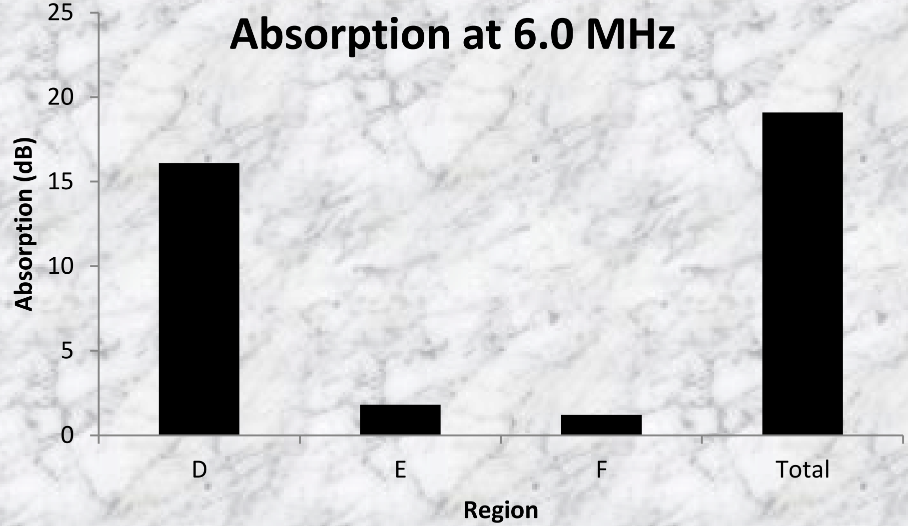
Absorption Equation

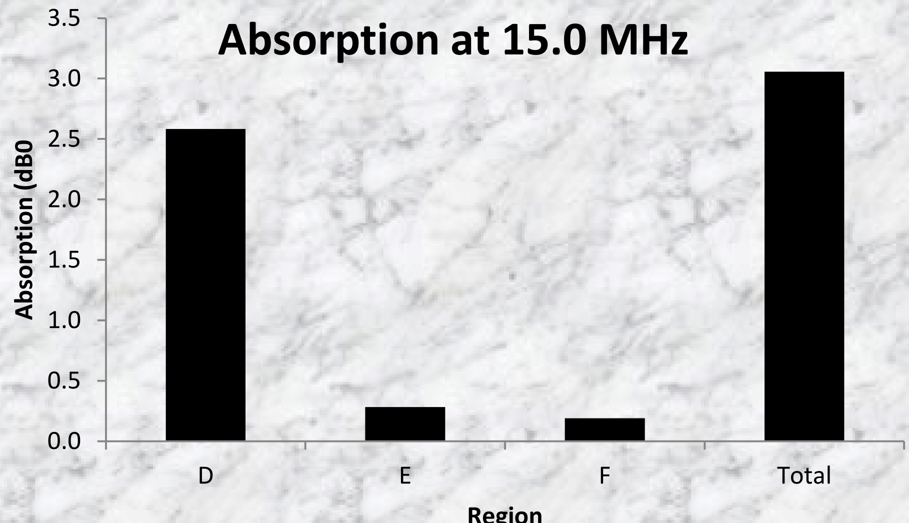


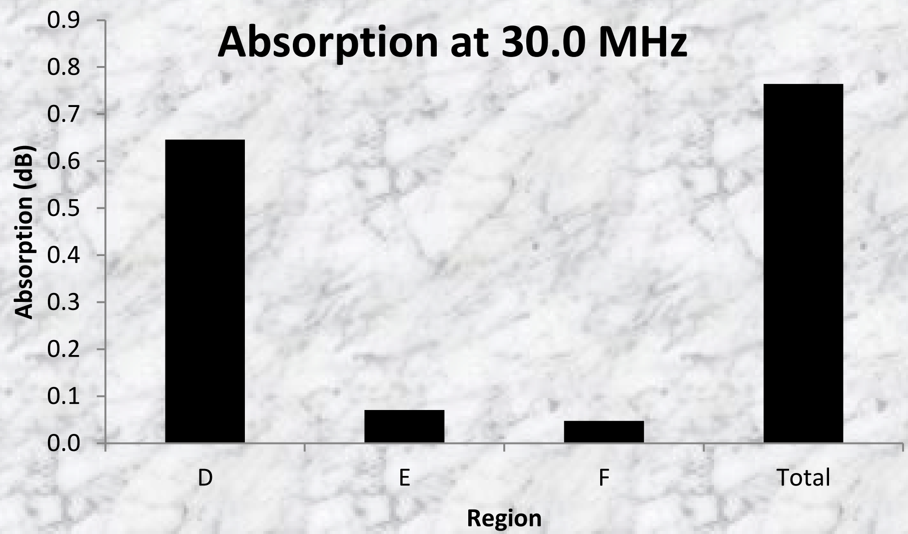
Thus we see the **frequency-dependence** of absorption

Based on data from *Bain and Harrison* as well as *Kelley* and also a HW assignment from L. Scherliess









Thus we see that most absorption takes place within the D-region

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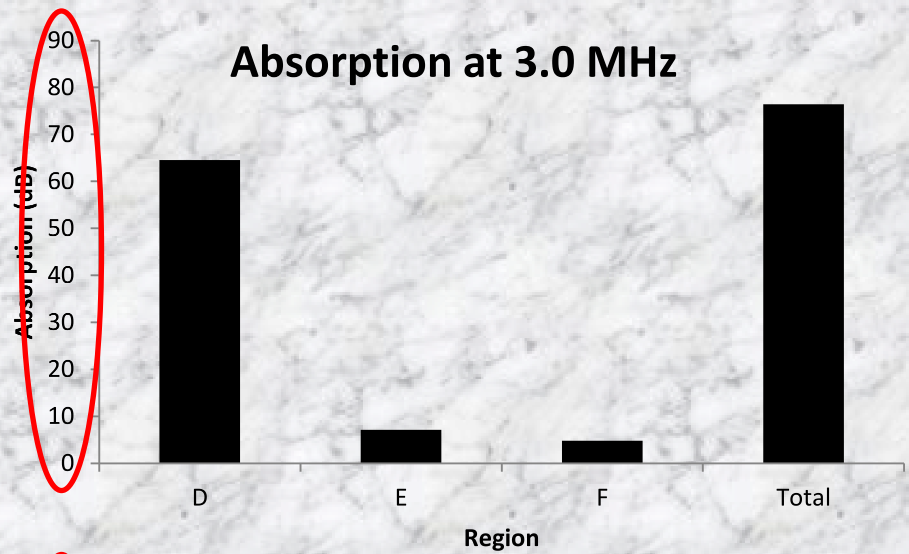

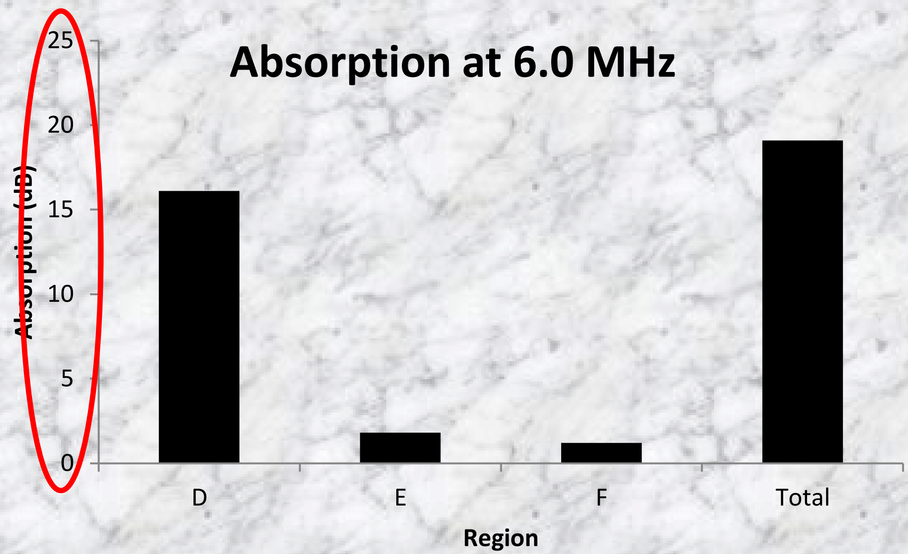

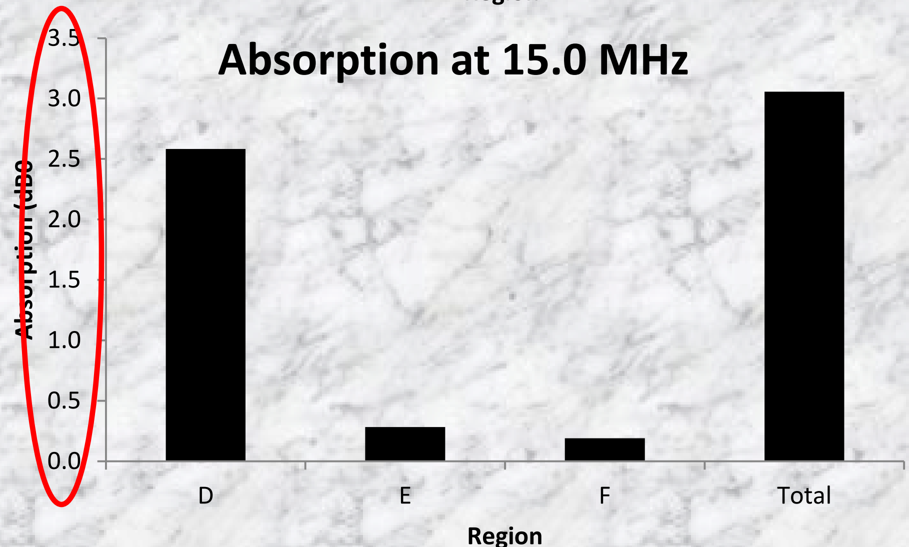

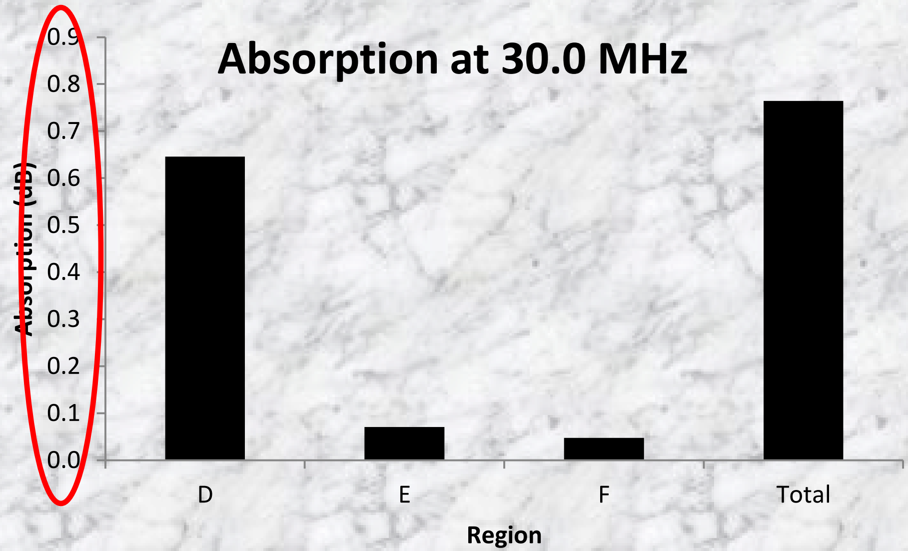

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Electron Density

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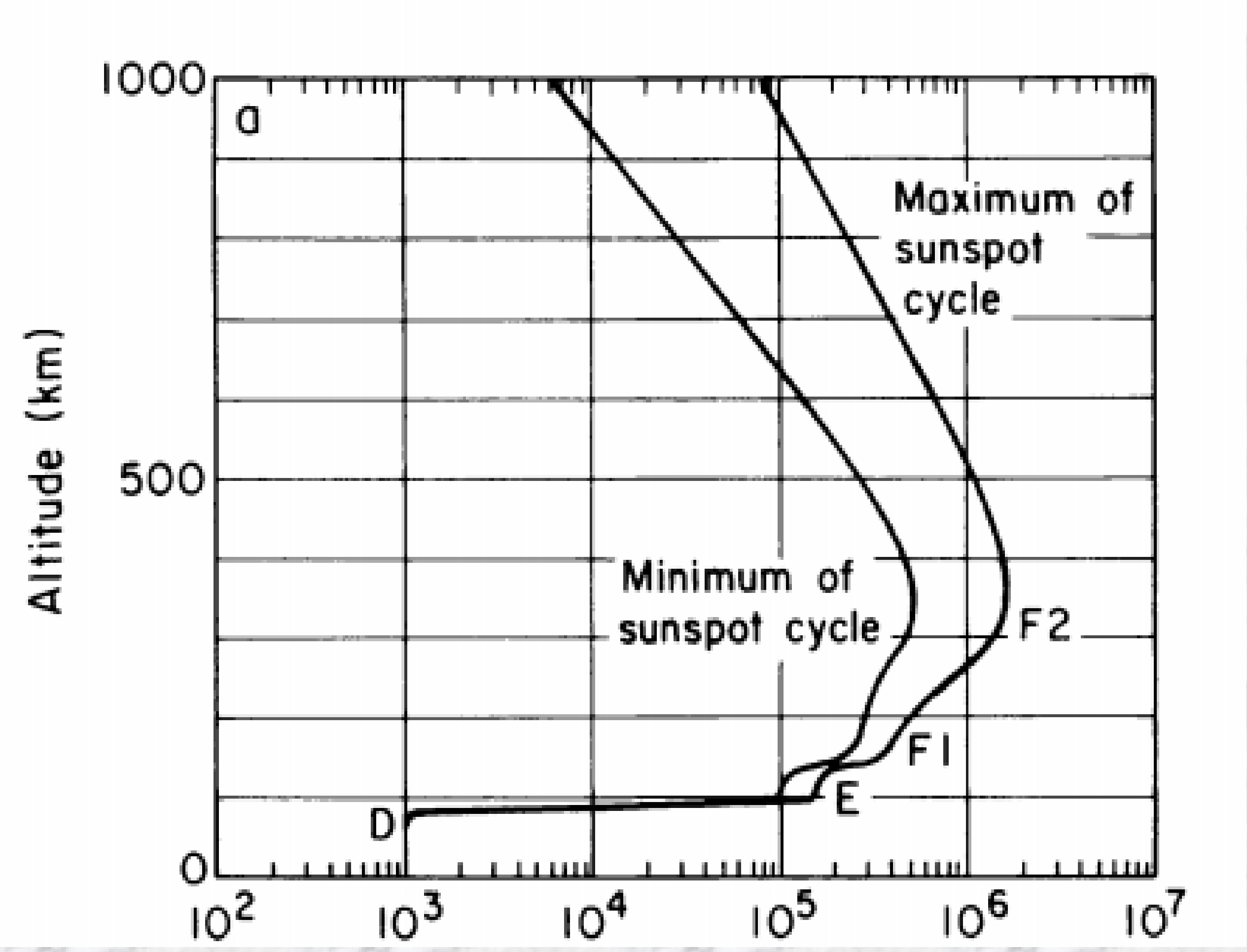
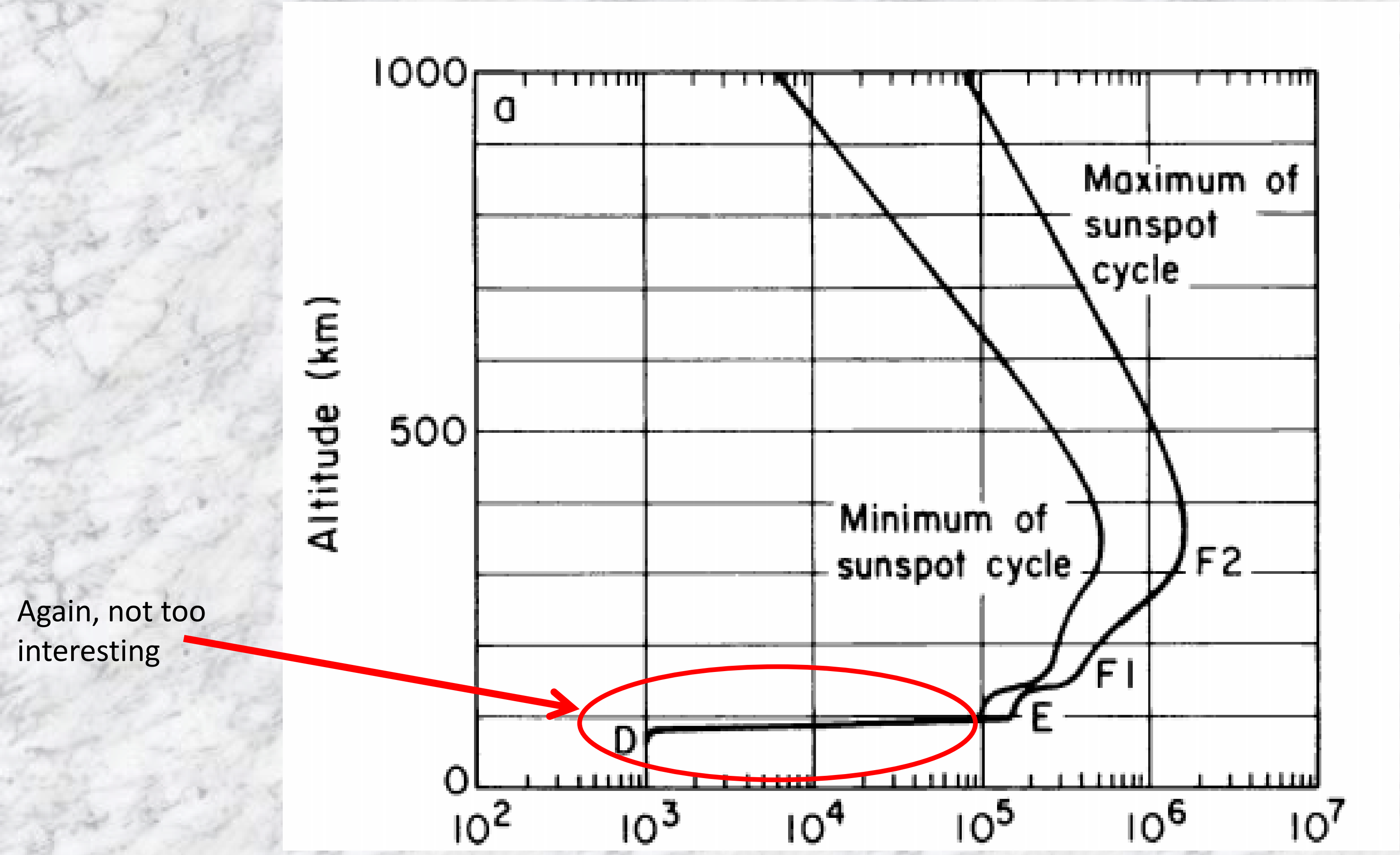


Typical electron concentration per cubic centimeter (Daytime)

Image from Kelley p 460

Electron Density

Again, not too interesting



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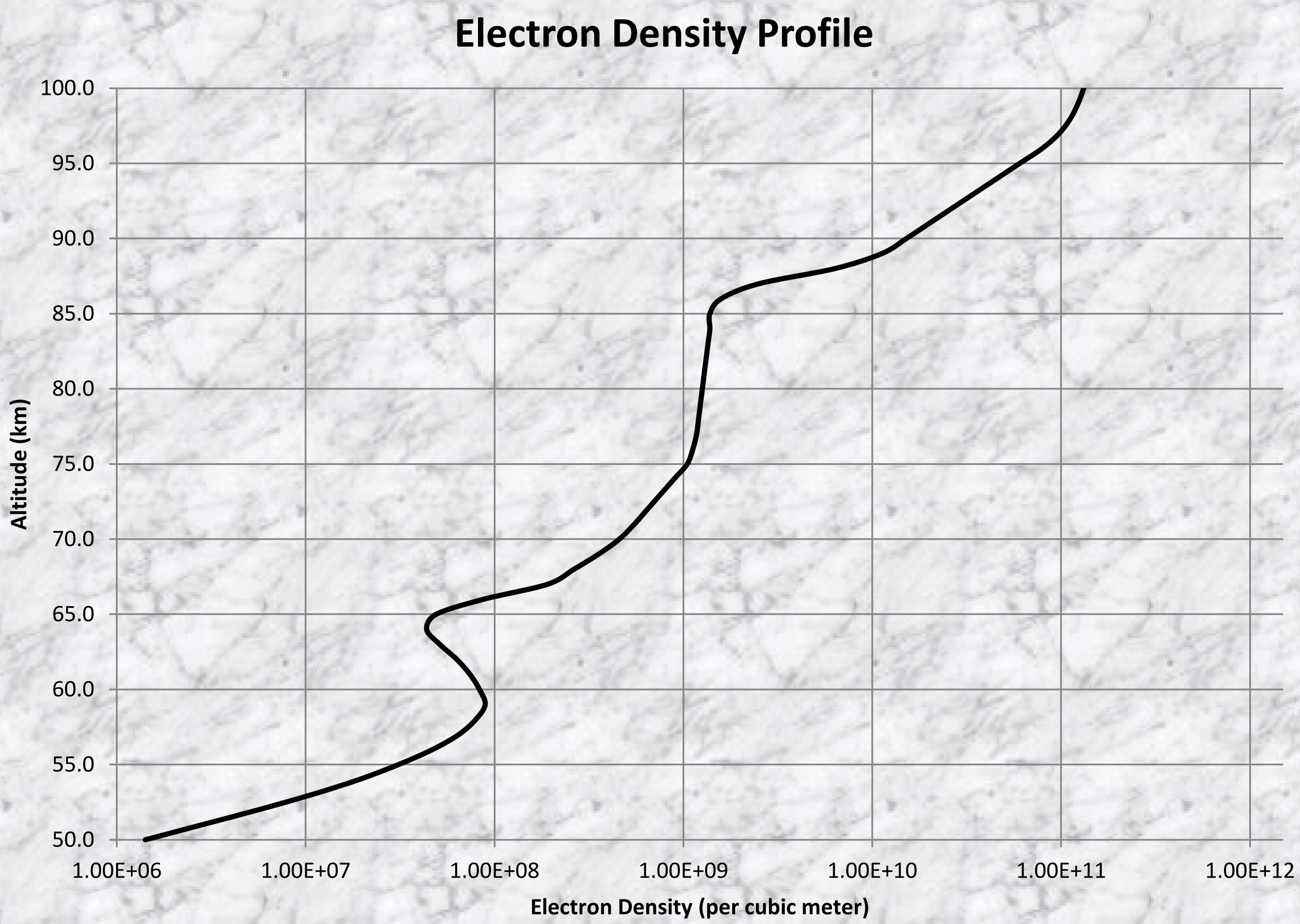

Electron density profile below 100 km

Based on *Bain and Harrison [*1972*]*

Electron Density

Everything depends on electron density

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- **Plasma Frequency**

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Thus we see that electron density is the **most critical** component

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We are concerned with two collision types:

- Electron- ion
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In the above T_e is the electron temperature

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$$\boxed{\Rightarrow L_a = \frac{-6.3 \times 10^{-16}}{\sin(\alpha)\, f^2} \int_{h_0}^{h_f} n_e(h)\, n_n(h) \sqrt{T(h)}\, dh}$$

Conclusions/Discussion

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We showed the following to be true:

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- Within the D-region non-deviative absorption dominates
- **The electron density is the most critical component**

Conclusions/Discussion

We showed the following to be true:

Non-deviative absorption within the D-region can be described mathematically in terms of neutral density or collision frequency,

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Acknowledgments

Special thanks to the following who assisted in the preparation of the presentation

Dr. Jan J. Sojka

Dr. Vince Eccles

And thank you to my supervisory committee:

Doctors J. Sojka, D. Peak, B. Fejer, M. Taylor, R. Fullmer

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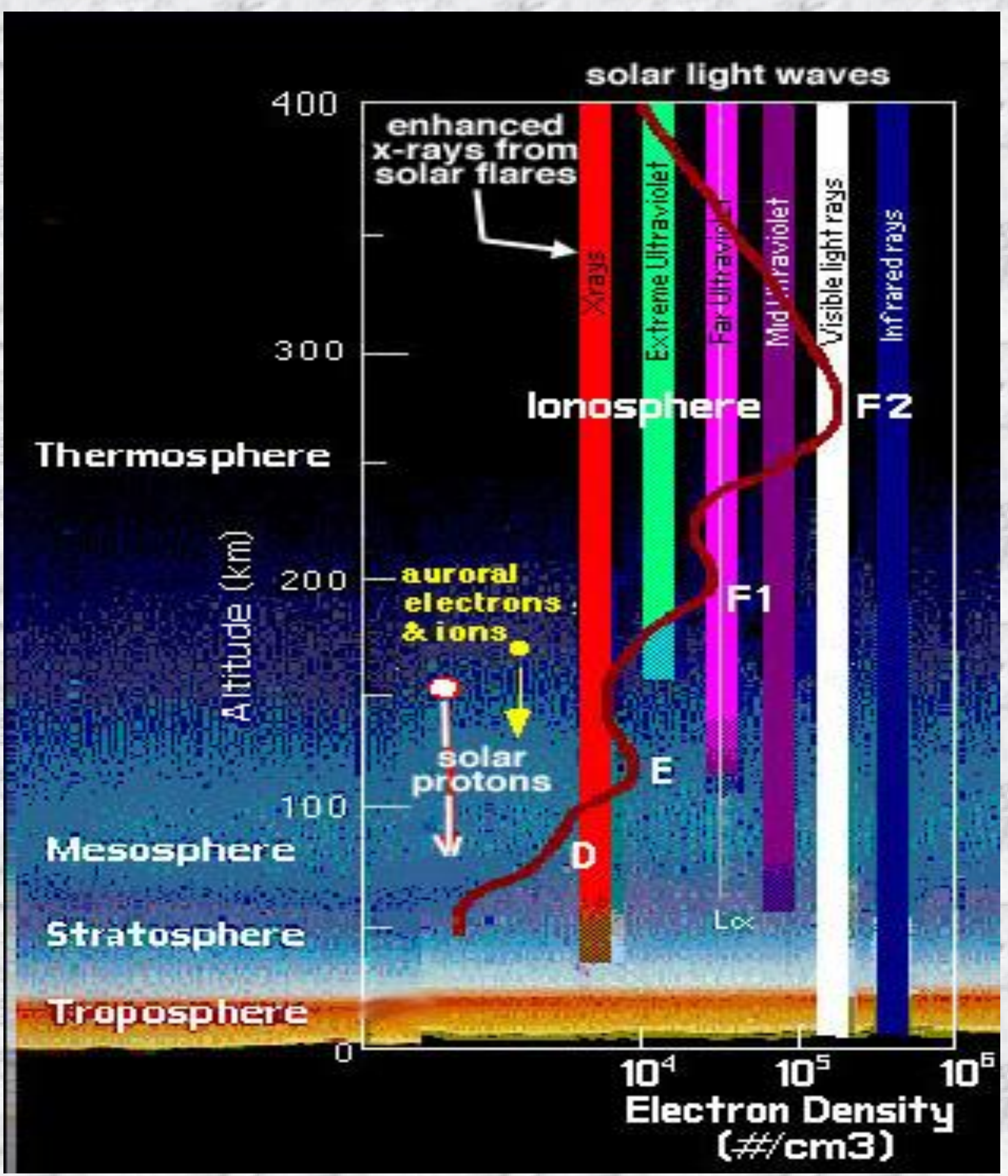
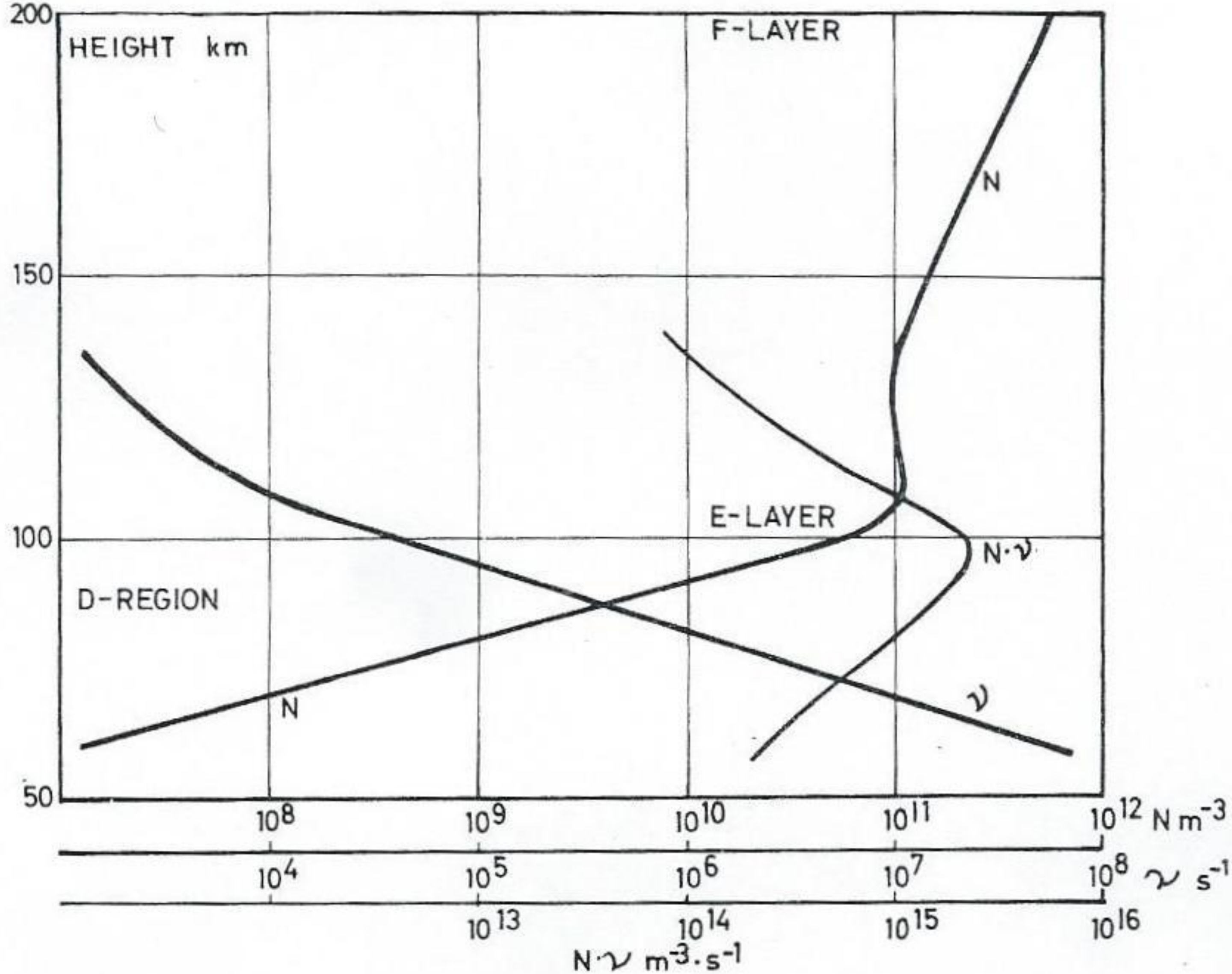
Questions?


solar light waves
400
300
200
100
0
enhanced x-rays from solar flares
Xrays
Extreme Ultraviolet
Far Ultraviolet
Visible light rays
Infrared rays
Ionosphere
F2
F1
E
D
Thermosphere
Altitude (km)
auroral electrons & ions
solar protons
Mesosphere
Stratosphere
Troposphere
Lα
10^4
10^5
10^6
Electron Density (#/cm3)


HEIGHT km
F-LAYER
E-LAYER
D-REGION
N
N·ν
ν
200
150
100
50
10^8
10^9
10^10
10^11
10^12 N m^-3
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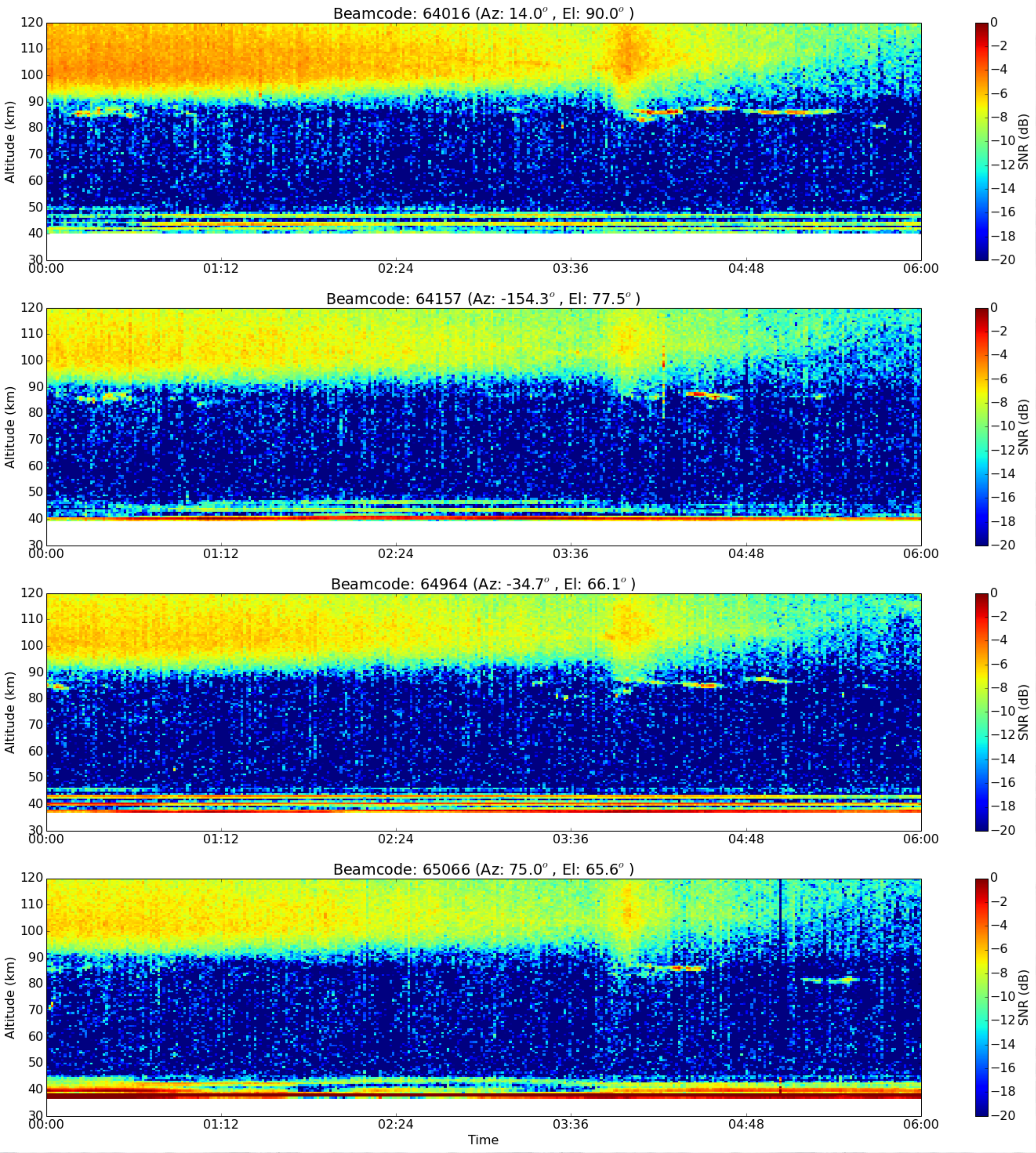
10 16
N·ν m^-3·s^-1


Beamcode: 64016 (Az: 14.0°, El: 90.0°)
Beamcode: 64157 (Az: -154.3°, El: 77.5°)
Beamcode: 64964 (Az: -34.7°, El: 66.1°)
Beamcode: 65066 (Az: 75.0°, El: 65.6°)
Altitude (km)
SNR (dB)
Time
00:00
01:12
02:24
03:36
04:48
06:00

Frequency (MHz)	$L_a\ (dB)$
3	56.6
5	20.4
7	10.4
9	6.29
11	4.21
13	3.02
15	2.27
17	1.76
19	1.41
21	1.16
23	0.964
25	0.816
27	0.699
29	0.606
31	0.530

D-region absorption values using data from *Bain and Harrison*