We Communicate by Ionospheric Reflection – Not Refraction

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Abstract

In some amateur radio literature and particularly in online video tutorials, the concepts of radio wave refraction versus reflection by the ionosphere are misunderstood. The classical, plasma physics picture of the ionosphere shows that reflection – not refraction – is responsible for sustaining the DX path. This model is used to analyze and compare VHF propagation via E-layer reflection at 50 and 144 MHz.

Keywords: propagation, ionosphere, plasma, refraction, reflection

Introduction

DX communication via the ionosphere is a fundamental component of the amateur radio experience. It is often asserted that *refraction* by the ionosphere enables skywave propagation. This claim appears regularly in contemporary amateur radio literature, including ARRL publications and instructional material. It is almost ubiquitous in online video tutorials on the subject. Here are excerpts taken from two recent, widely viewed YouTube videos attempting to explain propagation by the ionosphere:

> "Free electrons cause radio waves to slow down, refract, and bend. Reflection is the wrong term."
>
> "You're not bouncing off anything. The signal encounters a different index of refraction. Refraction bends the signal back down."

The following question is in the pool for the General Class License exam found on the ARRL website:

G3C02 (A)
What is meant by the term "critical frequency" at a given incidence angle?
A. The highest frequency which is refracted back to Earth
B. The lowest frequency which is refracted back to Earth
C. The frequency at which the signal-to-noise ratio approaches unity
D. The frequency at which the signal-to-noise ratio is 6 dB

with the required answer being A. There are other questions in the pool reinforcing the importance of refraction in establishing the communication path.

But are these statements about the behavior of the ionosphere correct?

Refraction

Refraction of light is often depicted by the perceived bending of a spoon or pencil when it is partially immersed in a glass of water. This optical illusion occurs because of the different indices of refraction for glass (1.5), water (1.33), and air (1.0).

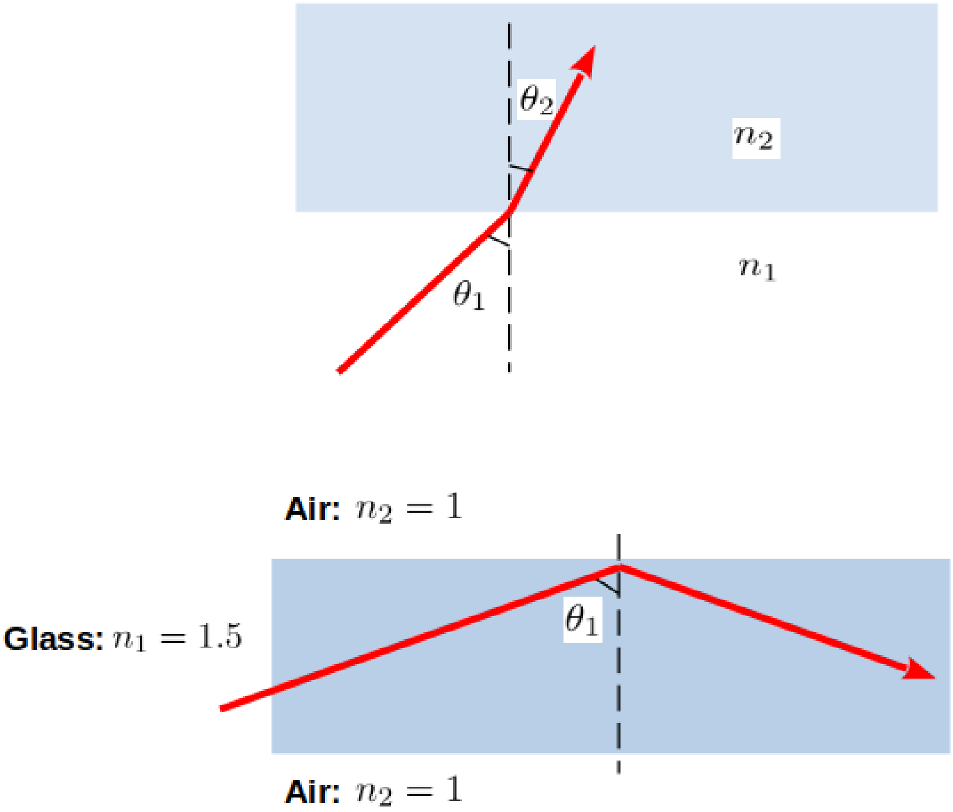

Figure 1: Top: Ray tracing illustrates refraction of an electromagnetic wave at an interface. Bottom: Propagation of light inside a glass fiber via total internal reflection.

The angle at which light is bent or refracted was quantified by Dutch astronomer Willebrord Snellius (1580–1626). Referring to Fig. 1 (top), a light ray propagating in a medium with refractive index n_1 encounters a medium with index n_2. The angle of incidence θ_1 is defined with respect to the surface normal depicted by the dashed vertical line. If $n_1 < n_2$ as would occur for light traveling from air into glass, the refracted ray is bent toward the surface normal at an angle θ_2. What the scientific community now calls Snell's Law predicts the amount of refraction as stated by the following equation:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

Consider light propagating in a glass fiber ($n_1 = 1.5$) surrounded by air ($n_2 = 1.0$) as sketched in Fig. 1, bottom. Snell's Law shows that for $\theta_1 > 41$ degrees, there is no solution for θ_2, i.e. there is no refraction at the glass-air interface. This is known as the critical angle. Since there is no refraction, no light propagates from glass into air. Instead, the incident light is totally reflected back into the glass through a process appropriately named *total internal reflection*. This is the foundational principle underlying fiber optics that is the backbone of modern telecommunications.

Radio waves and light rays are both examples of electromagnetic radiation, differing only in wavelength. Their behavior is governed by the same physical principles, which means Snell's Law can be applied to understand refraction by the ionosphere.

Refraction in the Ionosphere

The ionosphere is created when neutral atoms or molecules are struck by, for example, meteors, ultraviolet photons from the sun, or encounter wind shear forces. These ionizing events liberate highly mobile, negatively-charged free electrons from the parent molecules leaving behind heavier, positively-charged ions. The ensemble of equal densities of positive and negative charges has no net charge in the aggregate. This soup of positive and negative charge is known as *plasma*.

The refractive index of dilute plasma that describes the ionosphere was worked out by scientists in the early part of the 20th century. It is approximated as [1]:

$$\sqrt{1-\kappa\frac{N}{f^2}} \tag{2}$$

where N is the plasma density (electrons or ions), f is the frequency of the electromagnetic wave, and $\kappa = 80.43$ J·m/kg is a physical constant. Using this formula and Snell's Law, we can analyze the path of radio waves propagating from the atmosphere (index = 1) into the ionosphere. Without plugging in any numbers, three limiting cases are identified:

1) Weak ionization giving $0 \leq \kappa N/f^2 \ll 1$ (Fig. 2, top). The refractive index of the ionosphere is very close to 1 and appears transparent to the radio wave. Refraction is negligible and $\theta_1 = \theta_2$.

2) Moderate ionization with $0 \ll \kappa N/f^2 < 1$ (Fig. 2, middle). Snell's Law shows that there will be refraction at an angle $\theta_2 > \theta_1$, although θ_2 cannot exceed 90 degrees. This means refraction will cause the wave to bend, but not enough to return it to the earth's surface. There will be partial reflection at the interface described by another set of equations attributed to Augustin-Jean Fresnel (1788-1827) that depend on polarization and incidence angle [1]. Fresnel reflection is not, however, the same thing as refraction.

3) Strong ionization with $\kappa N/f^2 \geq 1$ (Fig. 2, bottom). The refractive index of the ionosphere is an imaginary number. There is no refraction, the ionosphere is opaque, and the incident radio wave is completely reflected. The ionosphere appears metallic to the incident radio wave. The physics describing this reflection is essentially the same as for a bathroom mirror.

The critical density at which the plasma becomes opaque and completely reflecting for a specified frequency is $N_c = f^2/\kappa$. By rearranging the equation, we find the critical frequency that causes complete reflection at all angles for a given ionization density is $f_c = \sqrt{\kappa N}$.

The above conclusions hold even with a sequence of vertically stratified layers as illustrated in Fig. 3. Consider m layers in the ionosphere of differing index. Applying Snell's Law in succession gives:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3 = \ldots = n_m \sin\theta_m \tag{3}$$

which simplifies to:

$$n_1 \sin\theta_1 = n_m \sin\theta_m. \tag{4}$$

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[1] A glass window pane is an example of a surface that both transmits light and produces Fresnel reflection.

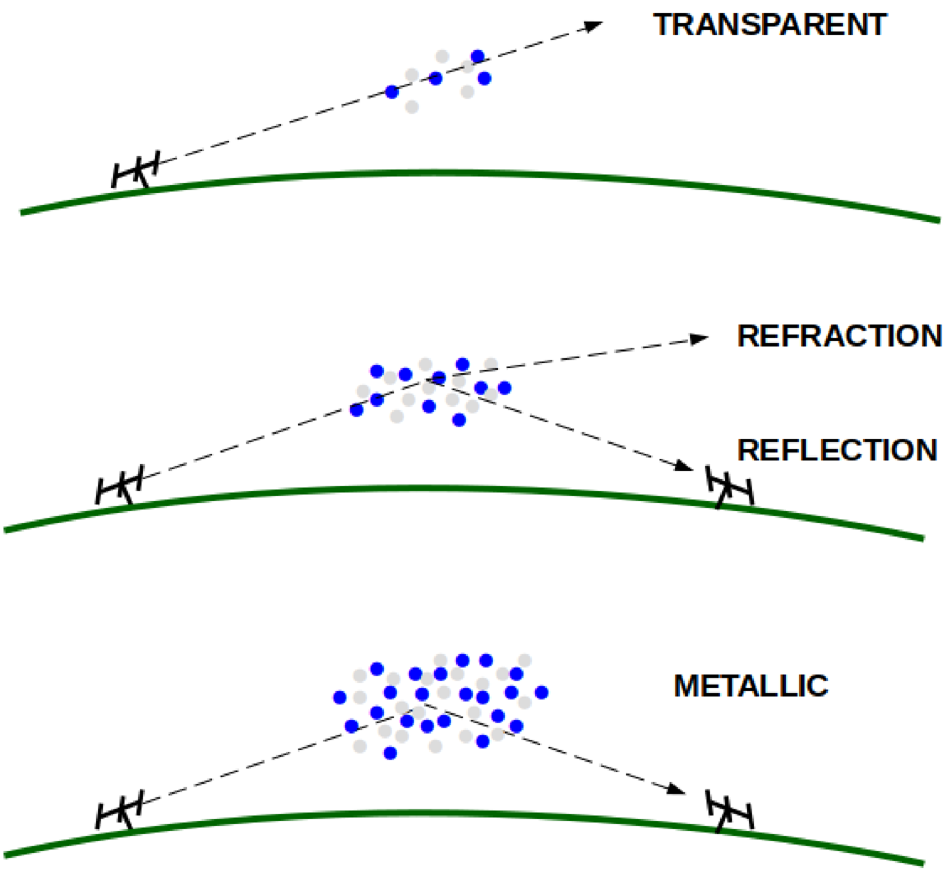

Figure 2: Three possible propagation paths between two stations with the ionosphere modeled as a neutral plasma consisting of equal amounts of positive and negative charge. Top: Weak ionization. The ionosphere is transparent to the radio wave. Middle: Moderate ionization. There will be bending of the incident wave into space and partial reflection back to earth. Only the reflected signal is detected. Bottom: Strong ionization. The ionosphere is opaque and completely reflects the incident radio wave back to earth. There is no refraction.

This demonstrates that any refraction taking place in the layers between the lower atmosphere and the top ionosphere layer does not affect the final trajectory. The radio wave can propagate through an arbitrary number of horizontal refracting layers, but Snell's Law will always limit the exit angle to less than or equal to 90 degrees, no matter where in the stack you look or how many layers exist. Refraction – by itself – can never bend a radio wave back to the surface of the earth.

The simple picture of the ionosphere shown in Fig. 3 ignores the curvature of the earth. The layers are of course not flat and will bend to follow this curvature. From the perspective of the transmitter, refraction is observed to bend the radio waves toward the horizon. The receiver, however, is also on the earth's surface following the same arc. Detection of the refracted wave beyond line-of-sight is still not possible.

There is an interesting situation in which a layer of moderate ionization exists below a reflecting layer. Refraction from the lower layer will bend the wave toward the horizon, causing it to impinge on the reflecting layer farther downrange than if this layer was not present. Refraction and reflection work in tandem to effectively extend the DX path.

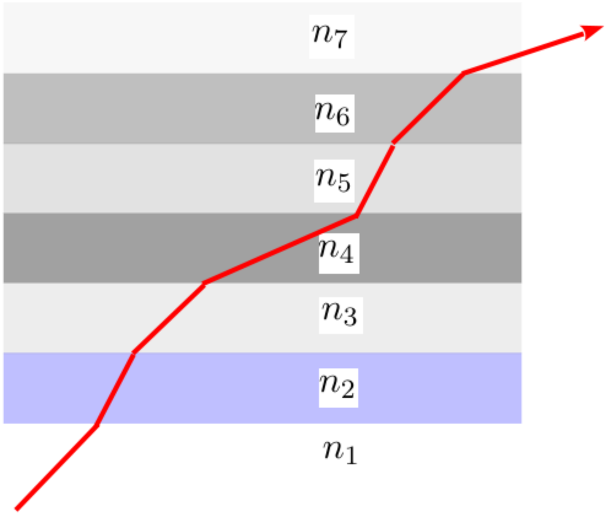

Figure 3: Propagation path of an electromagnetic wave in stratified layers with different refractive indices. No amount of refraction can bend the wave past 90 degrees (horizontal).

VHF Propagation via Ionospheric Reflection

The critical density at a given frequency defines the condition where the ionosphere completely reflects an electromagnetic wave at all incidence angles. This is depicted by the limiting case at the bottom of Fig. 2. It scales as f^2, which means the critical density is 8.3 times larger at 144 MHz compared to 50 MHz.

Of particular interest for VHF propagation is the moderate ionization situation shown in the middle sketch of Fig. 2, where there is both refraction and reflection. More detail is shown in Fig. 4. Analysis of a possible communication path between two terrestrial stations can be done using the Fresnel equation for reflectivity (R), assuming horizontal polarization [1]:

$$R = \left| \frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)} \right|^2 . \tag{5}$$

The radio wave launches in the atmosphere ($n_1 = 1$) at ground level and impinges on the ionosphere (n_2) at an angle θ_1. The reflected angle $\theta_3 = \theta_1$. The amount of reflection will be in the range $0 \leq R \leq 1$ and depends on the refraction angle θ_2. This angle is found by solving Eq. (1) with a frequency- and density-dependent refractive index for the ionosphere (n_2) given by Eq. (2).

Single hop E-layer propagation on 50 MHz is known to create a DX path in the range 800 km $< d <$ 2000 km. Assuming an ionized E-layer at height $h = 100$ km and neglecting the curvature of the earth, the corresponding range of θ_1 can be estimated using:

$$\theta_1 = \arctan\left(\frac{d}{2h}\right) . \tag{6}$$

which gives $76 < \theta_1 < 84$ degrees. The ionosphere reflectivity can then be calculated for a given plasma density N at different frequencies.

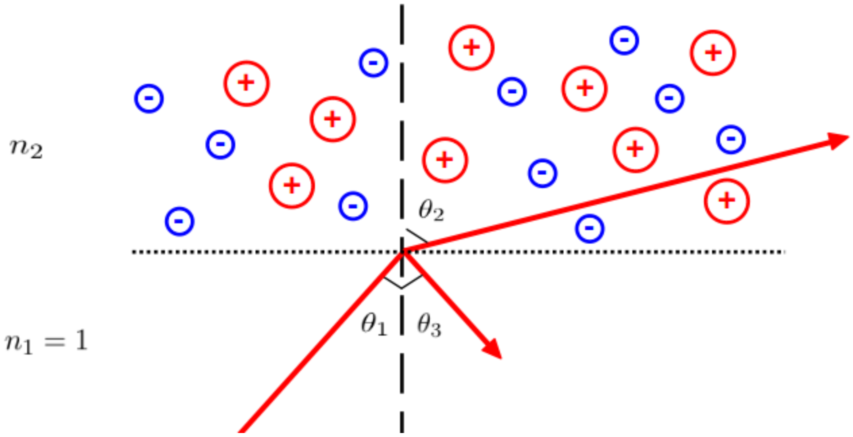

Figure 4: Combined refraction and Fresnel reflection from the ionosphere. At moderate ionization, a radio wave is refracted into space at angle θ_2 and reflected back to the earth's surface at angle $\theta_3 = \theta_1$. The index n_2 is given by Eq. (2).

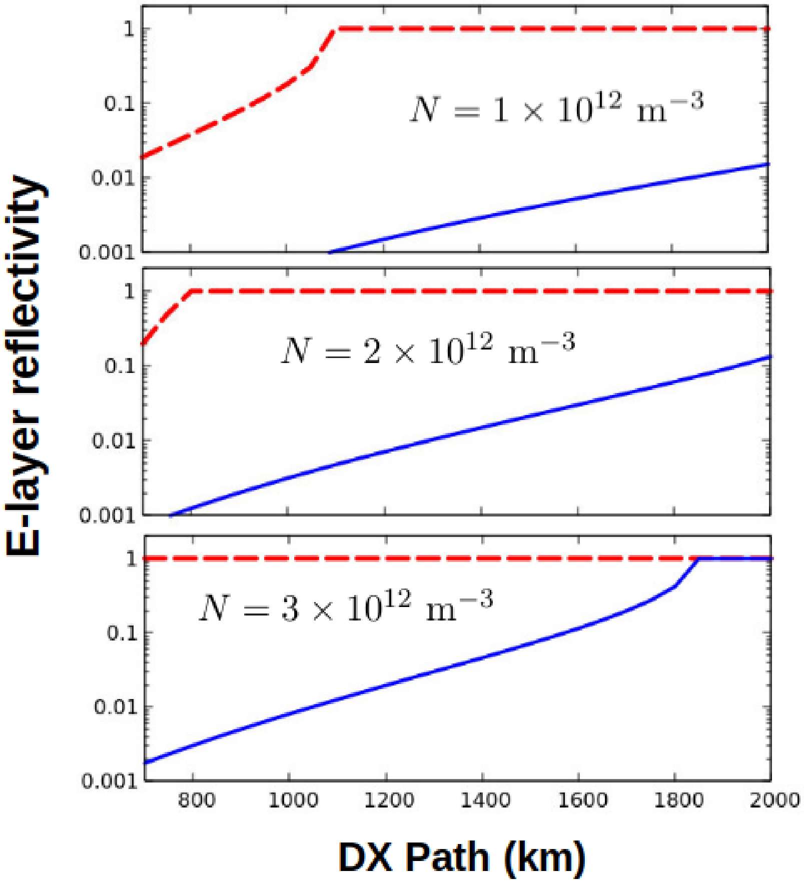

Figure 5: Calculated Fresnel reflectivity (R) of the E-layer at three different ionization densities (N). The x-axis is the distance between two stations (d). Dashed curves are for 50 MHz; solid curves are 144 MHz.

Figure 5 compares the E-layer reflectivity at 50 and 144 MHz for three different ionization densities [2]. When $N = 1 \times 10^{12}$ m^{-3} (top), the critical angle at 50 MHz is attained at $d = 1100$ km. Total reflection occurs at this distance and beyond. Fresnel reflectivity at 144 MHz is negligibly weak.

Increasing the ionization density to 2×10^{12} m^{-3} produces the results shown in Fig. 5 (middle). Complete reflection from the E-layer now occurs at DX paths as short as 800 km at 50 MHz; the reflectivity at 144 MHz has increased appreciably for $d > 1900$ km. At $N = 3 \times 10^{12}$ m^{-3}, the ionosphere appears metallic at 50 MHz over the entire DX range; the critical angle at 144 MHz is reached at $d = 1850$ km. This model of ionospheric reflection explains why a short skip zone on 50 MHz can alert to a much higher MUF and a potential E-layer opening on 144 MHz.

Conclusion

The physics outlined in this note has been well understood for more than a century. It can be found in many classic textbooks and guides on radio science [3]. Sometime in the past decade or so, the concepts of refraction vs reflection as they relate to skywave propagation via the ionosphere have become misunderstood and confused by the amateur radio community. The essential message is that we work DX primarily because of reflection, not refraction.

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References

[1] M. Born and E. Wolf, *Principles of Optics*, 6th ed., Oxford: Pergamon Press (1980).

[2] The neutral particle density in the lower ionosphere is of the order 10^{20} m^{-3}.

[3] W.I. Orr, *Radio Handbook*, 22nd ed., Indianapolis: Howard Sams (1981).

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