



Impact of the Ionosphere on Signal Delay in Communication Networks at

Different Times of the Day

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Abstract: The main objective of this study is to analyze the impact of the ionosphere on radio signal delay and strength in communication networks.

The ionosphere is a layer of the upper atmosphere containing electrons and charged particles that affect radio wave propagation.

Signal delay occurs due to reflection, refraction, attenuation, scintillation, and variations in electron density, with lower frequencies being more affected.

Measurements and analysis are conducted using spectrum analyzers and MATLAB to evaluate signal strength and delays.

The main time periods analyzed are 5 AM, 7 AM, 3 PM, and 10 PM.

The study focuses on frequencies of 5, 10, and 15 MHz to examine variations in signal behavior.

Results show that higher frequencies are more stable, while lower frequencies experience greater delay and weaker signals, especially at night or during periods of high solar activity.

Keyword: Ionosphere, Signal Delay, Signal Strength, Frequencies, MATLAB.

I. Introduction

The ionosphere, a dynamically ionized region of the upper atmosphere extending from approximately 60 km to 1000 km above Earth's surface, plays a pivotal and dual role in radio wave propagation. Its formation results primarily from the photoionization of atmospheric gases by solar ultraviolet and X-ray radiation [1], [2]. The ionosphere is vertically stratified into distinct layers—D, E, F1, and F2—each with unique electron density profiles and behaviors that vary diurnally, seasonally, with geographic location, and in response to solar and geomagnetic activity [1], [2], [3].



Historically, the ionosphere's ability to refract and reflect HF radio waves enabled beyond-line-of-sight, long-distance communications, a phenomenon crucial for early transoceanic links [2]. However, this same medium poses significant challenges to modern radio systems. Temporal and spatial fluctuations in electron density cause signal attenuation, delay, phase scintillation, and Faraday rotation, which degrade the performance of systems operating at higher frequencies, particularly those used for satellite communications, global navigation satellite systems (GNSS), and precision aviation [4], [5]. These effects are especially pronounced in equatorial and low-latitude regions due to phenomena like the Equatorial Electro jet and the Equatorial Ionization Anomaly (EIA), or "plasma fountain" [1].

As global reliance on wireless and satellite-based technologies grows, understanding, modeling, and mitigating ionospheric impacts have become essential for developing robust and reliable communication and navigation infrastructures. This paper examines the primary effects of the ionosphere on radio signal delay and signal strength within communication networks.

II. Motivation and Objectives of the Paper:

The prediction of **signal delay** in communication networks depends on understanding the impact of the **ionosphere** on the propagation of radio signals. The electron density and charged particles in the ionosphere vary throughout the day, resulting in differences in signal delay at different times. This effect is influenced by dynamic interactions between neutral and charged particles, as well as solar activity and other space weather factors see. The objective of this research is to analyze these effects and determine how daily variations in the ionosphere affect signal accuracy in different communication networks.

III. Main causes of ionospheric signal delay

There are several factors that cause ionospheric signal delay, the most important of which are:

A. Reflection, Refraction, and Attenuation

The ionosphere's plasma properties allow it to act as a frequency-dependent reflector or refractor. For frequencies below a layer's critical frequency (f_c), which is directly related to its maximum electron density, radio waves can be reflected back to Earth, enabling



long-haul HF skywave communication. The Maximum Usable Frequency (MUF) defines the upper limit for this reflection from a given layer [3], [4].

Conversely, the D-layer, present primarily during daytime, is a significant source of absorption, especially for lower-frequency/longer-wavelength signals, leading to signal attenuation [2], [3]. This absorption intensifies during solar flares due to a sudden increase in ionization, causing Shortwave Fadeout (SWF) [7].

B. Scintillation and Signal Degradation

Ionospheric scintillation refers to rapid fluctuations in the amplitude and phase of trans-ionospheric radio signals (typically VHF/UHF and above) caused by small-scale irregularities in electron density [2], [5]. Scintillation can severely degrade GNSS signal quality, increasing positioning errors and, in extreme cases, causing loss of lock. It is most intense in the equatorial and polar regions, especially during nighttime and periods of high solar activity [5], [9].

c. Signal propagation angle through the atmosphere

The **signal propagation angle** refers to the inclination at which a radio signal passes through the atmosphere and ionosphere before reaching the receiver. This angle directly affects the path length through the ionosphere, and thus the ionospheric signal delay: [6],[10].

1. Oblique signals:

- Travel a longer distance through the ionosphere compared to vertical signals.
- This results in a greater ionospheric delay, as the signal is more affected by variations in electron density along the path.

2. Vertical signals:

- Pass directly through the ionosphere with less ionized material.
- Therefore, they experience less delay compared to oblique signals.

This effect is critical in Global Navigation Satellite Systems (GNSS) and long-range radio communications, where accurate knowledge of the path and angle is required to correct for ionospheric delay



D. Different Layers of the Ionosphere

The ionosphere is divided into several main layers: **D, E, F1, and F2**, each having a different effect on radio signals depending on the time of day [5].

- **D layer:** Most active during the daytime, it absorbs low-frequency signals more strongly, leading to increased signal delay and attenuation.
- **E, F1, and F2 layers:** Affect low-frequency signals less, but play a greater role in reflecting high-frequency signals, with their influence varying between day and night [11].

E. Solar activity and space storms

Solar activity, such as **solar flares, coronal mass ejections (CMEs), and the resulting space weather disturbances**, can significantly affect radio signals and communication systems. When intense solar radiation and energetic particles reach the Earth, they increase the ionization levels in the ionosphere, which alters the propagation of radio waves. This increase in ionospheric ionization can cause **greater ionospheric signal delay, signal degradation, and even temporary signal loss**, particularly for systems reliant on ionospheric signal transmission such as HF radio and GNSS services. These effects can degrade signal tracking performance and reduce positioning accuracy, especially during strong solar events and geomagnetic storms [12].

IV. Tools / Equipment

1-Spectrum Analyzer Devices

[Used to observe **signal strength** and **different frequencies** over time]

2-Time Intervals

[7 AM, 3 PM, 10 PM, 5 AM]

3-Frequencies (MHz)

[5 10 15]

4-MATLAB

frequencies = [5 10 15]; % MHz

el = 45; % Satellite elevation in degrees

hour = 7; % 7 AM

signal = zeros(size(frequencies));



```
for i = 1:length(frequencies)
    signal(i) = computeSignalStrength(frequencies(i), el, hour);
Phase Function
function x = phase_delay(t, PER)
x = (2*pi*(t - 50400)) / PER;
Ionospheric Delay Function
function T_iono = iono_delay(x, F, AMP)
if abs(x) < 1.57
T_iono = F * (5e-9 + AMP * (1 - (x^2)/2 + (x^4)/24));
else
T_iono = F * 5e-9;
end
Delay in meters Function
function D = delay_meters(T_iono, c, f)
D = (T_iono * c) / (f^2);
end
Signal Strength Function
function S = signal_strength(D)
S = 1 / D;
end
disp(signal).
```

Definition Variables and symbols

PER → Ionospheric period

t → time

F → Frequency

AMP → Delay amplitude

C → Speed of light

D → Final delay

S → Signal strength

V. Steps Work



. Definition of Ionospheric Delay1

- The ionosphere is a layer of the upper atmosphere that contains free electrons.
- When a radio wave passes through the ionosphere, it is delayed due to refraction and interaction with electrons.
- This delay is called **Ionospheric Delay** and is measured in meters or seconds.

2. Relationship with Frequency

ionosphere Delay is inversely proportional to the square of the frequency. That is, the basic relationship is:

This means that as the frequency increases, the delay decreases significantly, and vice versa at **5 MHz** the delay is greater, while at **15 MHz** it is smaller.

3. Calculation Method in the Code

We used the simplified **Klobuchar model**, which is a practical model based on approximate equations describing ionospheric electrons.

The code performs the following steps for each frequency:

- Convert the satellite elevation angle and geographic location into semicircular coordinates.
- Calculate the geomagnetic latitude of the region.
- Compute the local time in the ionosphere.
- Calculate the **obliquity factor**, which reflects the signal angle effect.
- Compute the delay period (PER) using the model's Beta coefficients.

$$T_{5MHz} = T_{iono}(t) * \frac{1}{5^2} = \frac{T_{iono}(t)}{25} \quad \text{at 5 MHz} \quad (1)$$

$$T_{10MHz} = T_{iono}(t) * \frac{1}{10^2} = \frac{T_{iono}(t)}{100} \quad \text{at 10 MHz} \quad (2)$$

$$T_{15MHz} = T_{iono}(t) * \frac{1}{15^2} = \frac{T_{iono}(t)}{225} \quad \text{at 15 MHz} \quad (3)$$

- Calculate the phase delay and convert it into an actual delay in seconds.
- Convert the delay from seconds to meters by multiplying by the speed of light:

Delay (meters) = Delay (seconds) \times c

$$T_{iono}(t) = f \left(5 * 10^{-9} + AMP \left(1 - \frac{x(t)^2}{2} + \frac{x(t)^4}{24} \right) \right) \quad \text{at MHz} \quad (4)$$

$$D(f, t) = T_{iono}(t) * c * \frac{1}{f^2}$$

$$D_5(t) = \frac{c.F(5 * 10^{-9} + AMP \left(1 - \frac{Z(t)^2}{2} + \frac{Z(t)^4}{24} \right))}{25} \quad \text{at 5MHZ} \quad (5)$$

$$D_{10}(t) = \frac{c.F(10 * 10^{-9} + AMP \left(1 - \frac{Z(t)^2}{2} + \frac{Z(t)^4}{24} \right))}{100} \quad \text{at 10MHZ} \quad (6)$$

$$D_{15}(t) = \frac{c.F(15 * 10^{-9} + AMP \left(1 - \frac{Z(t)^2}{2} + \frac{Z(t)^4}{24} \right))}{225} \quad \text{at 15MHZ} \quad (7)$$

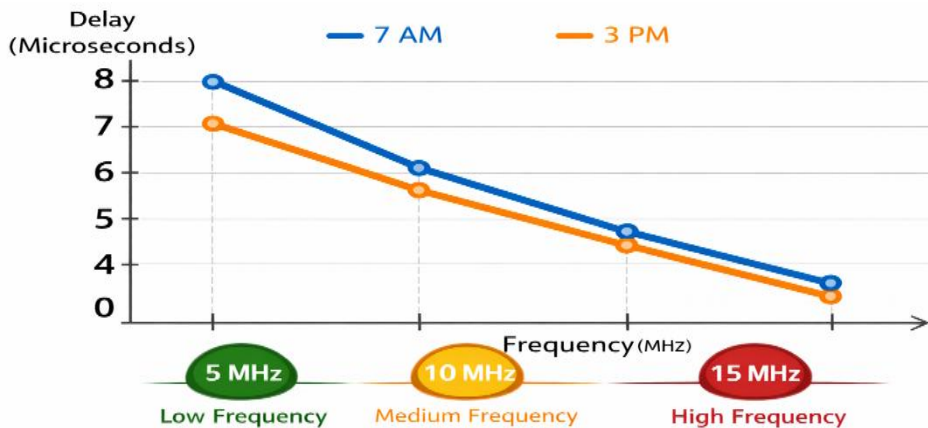
4. Applying Delay to Signal Strength:

After obtaining the delay for each frequency, we used an approximate inverse relationship to estimate its effect on signal strength:

$$\text{Signal Strength} = \frac{1}{\text{Delay}}$$

This means that the greater the delay (as in low frequencies like 5 MHz), the weaker the received signal strength.

5. Results see figure (1) & figure(2) depending on table 1.



The figure (1) shows how delay varies across different frequencies at two different times of the day, 7 AM and 3 PM.

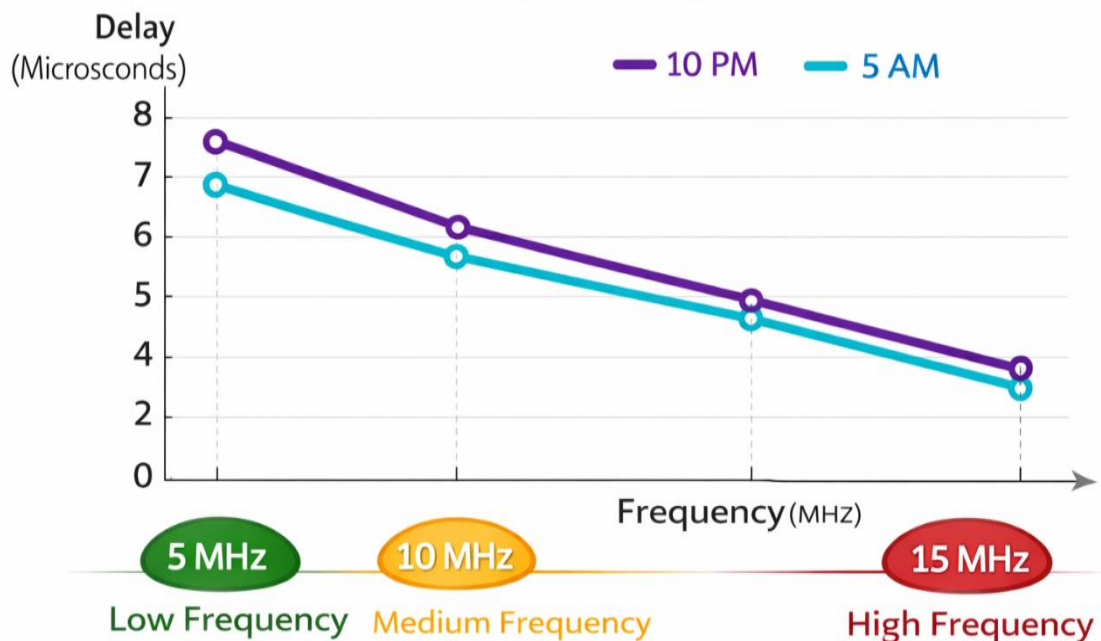


Lower frequencies, like 5 MHz, experience the highest delay, while higher frequencies, such as 15 MHz, have the lowest delay.

The delay decreases consistently as the frequency increases, indicating that high-frequency signals are less affected by propagation delays.

Comparing the two times, 7 AM generally shows slightly higher delays than 3 PM, suggesting diurnal variations in the medium affecting signal transmission.

This analysis highlights the importance of frequency selection in optimizing communication systems for minimal delay.



The figure (2) illustrates the effect of delay on different radio frequencies.

Delays are consistently higher at 10 PM compared to 5 AM across all frequencies.

Lower frequencies (5 MHz) experience the most significant delays, while higher frequencies (15 MHz) have the least.

This indicates that signal transmission is more efficient during early morning hours. Understanding these variations is crucial for optimizing communication systems and reducing signal lag.

The table (1) shows the inverse relationship between ionospheric delay and signal strength for each frequency and time.



Time / Period	Frequency	Expected Delay	Effect on Signal Strength
5 AM	5 MHz	Relatively low	Relatively low
	10 MHz	Very low	High
	15 MHz	Very low	High
7 AM	5 MHz	Medium	Low
	10 MHz	Low	Medium
	15 MHz	Low	High
3 PM	5 MHz	Medium	Low
	10 MHz	Low	Medium
	15 MHz	Low	High
10 PM	5 MHz	High	Very low
	10 MHz	Medium	Low
	15 MHz	Low	High

The table summarizes the expected ionospheric effects on signal strength for different frequencies (5, 10, and 15 MHz) at key times of the day: early morning (5 AM), morning (7 AM), afternoon (3 PM), and night (10 PM). As shown, **lower frequencies (5 MHz)** are more affected by ionospheric delay, especially during nighttime and periods of high ionospheric activity, leading to weaker signal strength. **Higher frequencies (15 MHz)** remain relatively stable throughout the day, with minimal delay and consistently strong signals. The medium frequency (10 MHz) experiences moderate effects. This pattern reflects the daily variation of ionospheric ionization, where **signal degradation is higher during peak solar activity hours** and lower during early morning or late night. The table helps illustrate the **inverse relationship between ionospheric delay and signal strength** for different frequencies and times of day.

VI. Dissection Result

Effect of Delay on Signal Strength

- There is an inverse relationship between signal delay and signal strength:
 - The greater the delay → the weaker the signal.
 - The smaller the delay → the stronger and more stable the signal.



- **At 7 AM:** the delay is moderate, and the signal strength is higher at higher frequencies compared to lower frequencies.
- **At 3 PM:** the delay increases slightly due to higher solar activity, leading to weaker signal strength at lower frequencies as shown in figure (1).
- **At 5 AM:**
The ionospheric delay is relatively low because solar activity is still minimal at this time, resulting in stronger signal strength, especially at higher frequencies compared to lower frequencies.
- **At 10 PM:**
The delay is slightly higher than at 5 AM, despite the absence of sunlight, due to changes in the ionospheric layers during the night such as electron redistribution or nighttime ionospheric activity.

This additional delay causes a greater weakening of the signal strength at lower frequencies compared to higher frequencies as shown in figure (2).

Therefore, the delay at 10 PM is greater than at 5 AM, negatively affecting signal strength, especially at low frequencies.

VII. Comparison with Previous Studies

This study on the impact of the ionosphere on signal delay at different times of the day is generally consistent with previous research, while adding a clear temporal dimension to the analysis of signal behavior. Similar to Jiang et al. (2024) [13], which highlights the importance of ionospheric delay in radio wave propagation, my study confirms that delay significantly affects signal performance. However, it extends this understanding by demonstrating an inverse relationship between delay and signal strength across different times of the day.

In comparison with Abousetta and Issa, my results agree that higher-frequency signals are less affected by ionospheric conditions and experience lower attenuation, while lower-frequency signals suffer greater degradation, especially during periods of increased ionization such as midday. My findings also support their conclusion that electron density varies throughout the day, influencing signal propagation, with stronger signals observed when ionospheric activity is low (e.g., early morning).



Furthermore, while Peshkov et al (2025) and Abousetta et al (2025) [14] [15], focused on advanced hybrid techniques to mitigate ionospheric effects, my study differs in that it primarily analyzes the natural variation of delay and signal strength under different daily conditions rather than proposing technical solutions.

Overall, my study complements previous research by emphasizing the role of time-of-day variations in ionospheric delay, reinforcing the importance of frequency and electron density, and providing practical insights into how signal strength changes throughout the day in real communication environments.

VII.Result

1. The ionosphere affects signal strength at 5, 10, and 15 MHz during specific times of the day.
2. Low frequencies (5 MHz) are more affected by ionospheric delay, especially at night or during high solar activity.
3. High frequencies (15 MHz) remain relatively stable, while medium frequencies (10 MHz) are moderately affected.
4. The results show an inverse relationship between ionospheric delay and signal strength, with greater degradation during peak solar activity and less effect in early morning or late night.

The delay increases slightly due to higher solar activity, causing weaker signal strength at low frequencies.

VIII. Recommends

1. is recommended to use the early morning hours to obtain a strong and stable signal.
2. Low frequencies should be avoided during periods of high solar activity to reduce signal weakening.
3. Daily ionospheric changes should be monitored to adjust timing and frequency appropriately.
4. It is advisable to rely on approximate models, such as the Klobuchar model, to estimate delay and improve radio communication quality.



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