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# Prediction of Electromagnetic Wave Propagation in Space Environments Based on Geometrical Optics

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## Abstract

We predict the electromagnetic wave propagation in space environments using geometrical optics. The effective indices of the troposphere, stratosphere, and ionosphere are computed, and the reflection, refraction, and attenuation of electromagnetic waves in space environments are calculated based on the ray tracing technique and geometrical optics. The influence of the refractive index and loss of atmosphere and the incident angle of the antenna on electromagnetic wave propagation is discussed.

**Key Words**: Electromagnetic Wave Propagation, Geometrical Optics, Ray Tracing Technique, Space Environment.

## I. INTRODUCTION

In order to model the communication channel between terrestrial antennas and satellites, the influence of the space environment on electromagnetic (EM) wave propagation should be considered. The space environment consists of the atmosphere and the vacuum atmosphere. The altitude of the atmosphere is about 1,000 km from the ground. The atmosphere consists of a number of layers, including the troposphere, the stratosphere, the mesosphere, and the thermosphere. The ionosphere, a region of Earth's upper atmosphere, ranges from about 60 km to 1,000 km altitude. It is ionized by solar radiation and plays an important role in atmospheric electricity, forming the inner edge of the magnetosphere. EM wave propagation through the atmosphere is affected by variations in the refractive indices of each atmospheric layer. The refractive index depends on the altitude, and the EM wave is reflected, refracted, and attenuated when it propagates through the atmosphere. The ray tracing technique and high-frequency EM analysis methods such as geometrical optics are needed to evaluate these propagation characteristics.

Ionosonde, coherent scattering radar (CSR), interplanetary scintillation (IPS), and solar flux monitors are used to observe the space propagation environment [1, 2]. The prediction of EM wave propagation between terrestrial antennas and satellites using high-frequency EM analysis methods has been studied for a 1:1,000 scale model [3]. However, no study has presented a prediction for an actual-size earth space model.

In this paper, we propose a prediction method for EM wave propagation between terrestrial antennas and geostationary orbit (GEO) satellites based on geometrical optics. In order to predict EM wave propagation in space environments, it is necessary to calculate the refractive indices of the troposphere and the stratosphere, and the reflection and transmission of EM waves at the interfaces of the spheres. We use the ray tracing technique and geometrical optics to calculate EM wave propagation at the interface between the troposphere, the stratosphere, and the ionosphere, and analyze the EM wave characteristics in

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a space environment.

## II. PROPAGATION IN A SPACE ENVIRONMENT

We calculate the refractive index according to the altitude. The refractive indices of the troposphere and the stratosphere can be approximated by Eqs. (1) and (2) in [3]. The refractive index is determined by temperature, pressure, and water vapor pressure.

Fig. 1 shows Osan, South Korea's refractive index from 0 to 50 km, calculated using weather information from the University of Wyoming [4]. Since the ionosphere has a plasma ion layer, it affects the attenuation and refraction of EM waves [5]. Table 1 shows the relative permittivity and electrical conductivity considering the atmospheric environments, including the ionosphere [6]. The relative permeability of the atmosphere is assumed to be 1 and the anisotropy of the electrical conductivity of the ionosphere is not considered.

Fig. 2 shows the geometrical optics model when a ray passes through several atmospheric layers. The intersection between the ray and the interface is determined to calculate the transmission of the wave at the interface. We resolve the arbitrarily polarized incident wave into components parallel and perpendicular to the plane of incidence and calculate the reflection and transmission coefficients of each component.

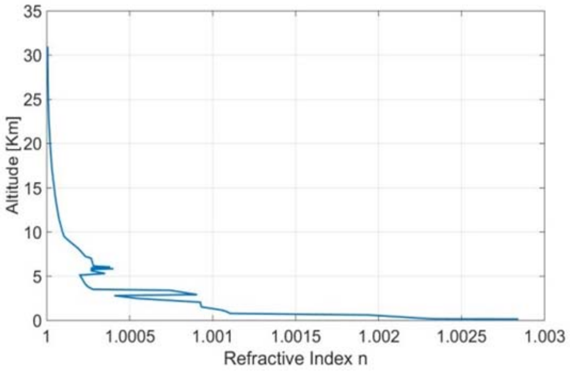

Fig. 1. Refraction index of the troposphere and stratosphere (May 22, 2017, Osan, South Korea).

Table 1. Relative permittivity and conductivity of the atmosphere

| Altitude (km) | $\varepsilon_r$ | σ |
|---|---|---|
| 0–10 | 1.003 | $10^{-14}$ |
| 10–20 | 1.0002 | $10^{-13}$ |
| 20–50 | 1 | $10^{-12}$ |
| 50–100 | 1 | $10^{-11}$ |
| 100–120 | 0.9999 | $10^{-6}$ |
| 120–400 | 1 | $10^{-10}$ |
| 400–35,768 | 1 | $10^{-20}$ |

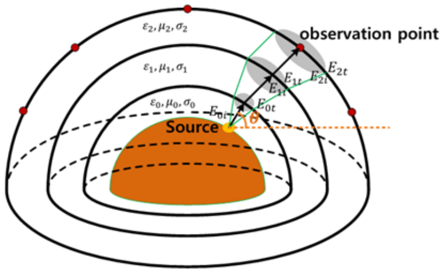

Fig. 2. Geometrical optics model in a space environment.

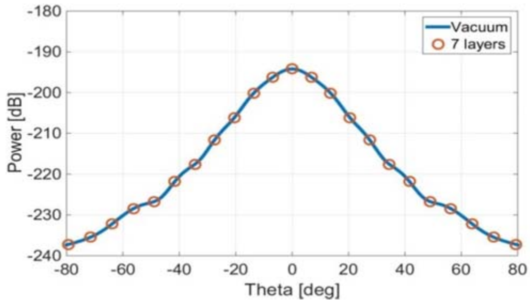

Fig. 3. Radiation pattern of the antenna using geometrical optics ($\varepsilon_r = 1, \sigma = 0$).

Geometrical optics is a high-frequency method that approximates the incidence, reflection, and refraction of EM fields. Using the following formula, the EM field at the observation point can be calculated using the EM field of reference point, the spatial attenuation factor, and the phase factor [7, 8].

$$\mathbf{E}(s) = \mathbf{E_0}(0)e^{j\phi_0(0)}\sqrt{\frac{dA_0}{dA}}e^{-\alpha s}e^{-j\beta s}. \tag{1}$$

In order to check the accuracy of the proposed method, we compare the radiation pattern of the antenna itself with the radiation pattern of the antenna considering the seven layers of the atmosphere with the same refractive index ($\varepsilon_r = 1, \sigma = 0$) from the ground to the GEO satellite. We use a pyramidal horn antenna with an operating frequency of 10 GHz, a maximum gain of 18.8 dB, and an incident power of 1.2 dBm. Fig. 3 shows good agreement between the two cases.

## III. CALCULATION RESULTS

We calculate the radiation pattern of the above antenna in a space environment based on Table 1. Figs. 4 and 5 show the radiation patterns when the direction of the antenna is perpendicular to the ground and when the direction of the antenna is at 30° with respect to the ground, respectively.

Note that the position of the main beam is not changed and the maximum power is reduced by 32.72 dB in Fig. 4. In Fig. 5,

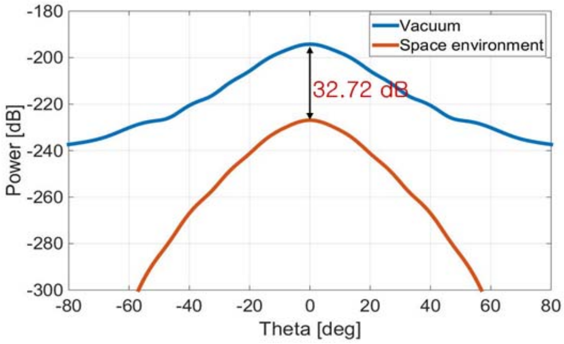

Fig. 4. Radiation pattern of an antenna in a space environment (angle between ground and incidence vector = 90°).

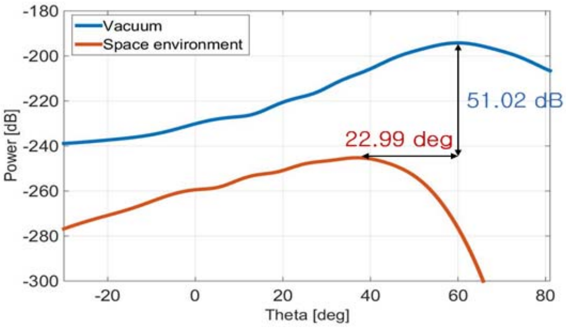

Fig. 5. Radiation pattern of an antenna in a space environment (angle between ground and incidence vector = 30°).

the position of the main beam shifts from 60° to 37.01° and the maximum power is reduced by 51.02 dB. This is because the refraction at the interface and the attenuation along the path are different when the incident angles of the antenna are different.

Since Table 1 roughly divides the atmosphere, it is necessary to divide the atmosphere more precisely for more accurate predictions. In addition, EM wave propagation in the ionosphere should be analyzed more accurately using full-wave EM analysis such as finite-difference time-domain method (FDTD).

## IV. CONCLUSION

We have calculated the reflection, refraction, and transmission of EM waves using the ray tracing technique and geometrical optics in space propagation environments. We have shown that EM wave propagation in space environments depends on the refractive index and loss of atmosphere and the incident angle of the antenna. It is necessary to accurately monitor the atmospheric state of the atmosphere, including the ionosphere, and to calculate the refractive index and loss of atmosphere for accurate prediction of EM wave propagation in space environments. Our method is useful to calculate EM wave propagation for an actual-size earth space model, unlike full-wave analysis such as FDTD and method of moments.

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