Analysis of Radio Propagation with Progressive Models

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***Abstract*—Nowadays, High Frequency radio waves are widely used in communication across intercontinental distances. To find out HF radio attenuation under different geographic environments, we provide two models: the first is based on classical geometric optics, the second is based on Maxwell's equations. In our first model, we start with single hop attenuation, then iterate to gain the result of multi-hop. In our second model, we use Finite Element Method by simulate with software COMSOL. The key idea for both models are described, along we further examined the time span in which a ship uses the same multi-hop path for HF communication.**

***Index Terms*—Geometrical Optics, Maxwell's Theory, Finite Element Method, COMSOL.**

I. Introduction

The skywave propagation is generally recognized as one of the most vital methods in communicating beyond the horizon, at intercontinental distances. Therefore, researches are carried out to figure out the rule of the attenuation of high frequency waves in the process.

Considering the physical property of ionosphere, Watterson Model [1] and ITS Model [2] are put forward to simulate the signal channel. The propagation process and how the attributes of radio waves change in different environments [3]–[5] are already fully discussed.

As for reflection over the sea, scientists have researched on the plain surface [6] and the rough sea surface [7] and given their numerical solutions based on theory of electromagnetism in the same year. Recently, physicists and oceanographers have been working together to simulate the reflection and propagation process more precisely. Majority of state-of-the-art findings focus on more complex and accurate representation of the sea surface [8], [9] and use advanced simulation technology to get a more precise numerical solution [10].

In this paper, we aim at figuring out the HF communication range under different environments, including: calm sea, turbulent sea, smooth terrain, rugged terrain and mountainous areas. We tackle the problem by two methods. We first use the classical geometrical optics method and simplify the status of ionosphere and the surface of various geometrical environments so that it is computable. Then the finite element method is taken into use, in this way, we can use state-of-the-art simulation software COMSOL to simulate different environment. In the meantime, because of our method is directly based on Maxwell's equations, the result is of high accuracy.

II. Classical Geometrical Optics

Since the wave length of HF radio varies from 10 meters to 100 meters, they are far less than the scale of the height of ionosphere and the distance it covers. Thus, the diffraction can be neglected and owing to the low power the HF radio wave use in most situations, we can use the rules of classical geometric optics to model the problem.

Owing to the fact that most long-distance communicating antennas are directional antennas. We simplify the problem by using a specific transmit angle then only deal with the propagation of rays.

We use Fresnel equations [11] to figure out the reflection and refraction at both edge of the ionosphere and ocean surface. In the propagation process, the total absorption L can be calculated by Eqn. 1

$$L = \int_l \beta \cdot dl \tag{1}$$

where the loss constant β can be defined as

$$\beta = \frac{2\pi}{\lambda}\sqrt{\frac{1}{2}\left[\sqrt{\epsilon_r^2 + (60\lambda\sigma)^2} - \epsilon_r\right]}. \tag{2}$$

We calculated the attenuation of one hop, and it can be expressed as:

$$L_{total} = \int_{l_1} \frac{60\pi N_1 e^2 \gamma_1}{\sqrt{\epsilon_r} m\omega^2} dl_1 + \int_{l_2} \frac{60\pi N_2 e^2 \gamma_2}{\sqrt{\epsilon_r} m\omega^2} dl_2 + 2\int_{l_0} \beta \cdot dl_0. \tag{3}$$

In this way, we can iterate to get the result of multi-hop path. Since using Huygens principle, we can treat the point where HF radio waves encounter the surface of ocean as the new transmitting point. Because of this, we can calculate to get the maximize hop before the signal can no longer meets the requirement of Signal-to-noise ratio threshold.

The result of the maximize hop of a 100 W signal meeting the threshold of 10 dB is 2, which means under this circumstance the signal can travel approximately through a distance of 4000 km.

III. Scaling Simulation of Radio Propagation

In this model, we are going to directly solving Maxwell's equations given boundary conditions numerically using finite element method. We first derive several core functions which from Maxwell's original functions, Eqn. (4) depicting the transient state, Eqn. (5) depicting the steady state and Eqn. (6) reveals the relationship between intrinsic nature of material and reflectivity.

$$\frac{\partial \mathbf{A}}{\partial t} + \epsilon_0\epsilon_r \frac{\partial^2 \mathbf{A}}{\partial t^2} + \frac{1}{\sigma\mu_0\mu_r}\nabla \times (\nabla \times \mathbf{A}) = 0, \tag{4}$$

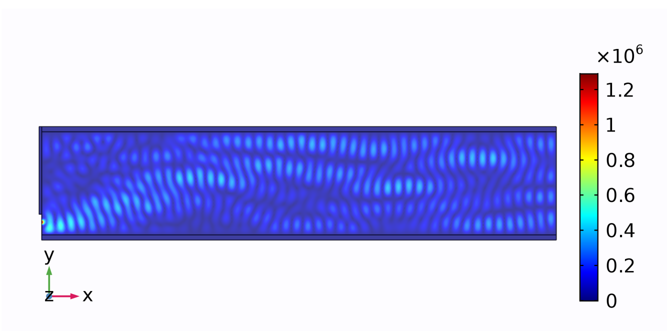
$$\nabla \times (\nabla \times \mathbf{E}) - k_0^2(\epsilon_r\mu_r - \frac{j\sigma\mu_r}{\omega\epsilon_0}) = 0, \tag{5}$$

$$\tilde{E}_{0R} = \left(\frac{1-\tilde{\beta}}{1+\tilde{\beta}}\right)\tilde{E}_{0I},\ \ \tilde{E}_{0T} = \left(\frac{2}{1+\tilde{\beta}}\right)\tilde{E}_{0I}. \qquad (6)$$

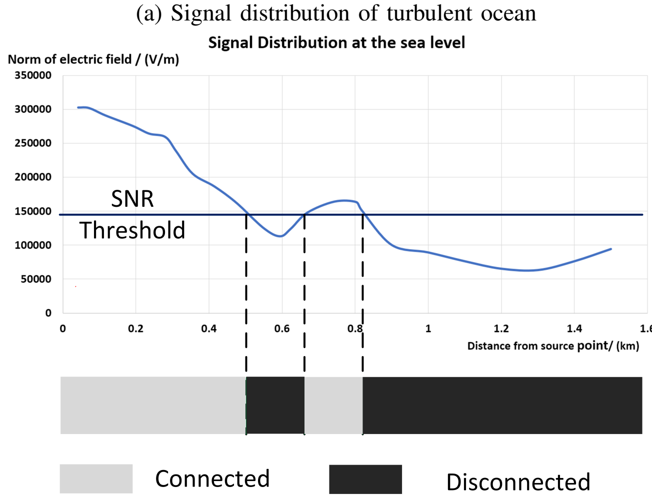
Before we can apply finite element method into solving the equations, we have to tackle the problem that "elements" is far more than our computer can deal with because HF radio wavelength is negligible to height of ionosphere. So we introduce the scaling method, noticing that the most important quantity is the reflectivity of certain medium, which tells both attenuation inside a medium and absorption on the boundary of two medium. So we did a linear scaling so that wavelength is no more negligible to height of ionosphere with reflectivity unchanged and the "elements" are few enough for us to compute. And the results are visualized by COMSOL.

Theoretical problem solved, we first considered the maximum number of hops the signal can take before its strength falls below a SNR. Simulation yields a result in accord with that given by classical geometrical optics model. As far as ocean is concerned, it differs a lot in local permittivity and permeability and we investigate in detail the distribution of electric field norm respectively.

Meanwhile, for a shipboard receiver, we use the omnidirectional antenna instead of a directional antenna corresponding to a moving ship. We also neglect the Doppler Effect since the velocity of ship only influences frequency it accepts and has minor influence on the distribution of signal. The simulation results are shown below in Fig. 1



(a) Signal distribution of turbulent ocean



(b) Range of Communication

Fig. 1: Reflection between ionosphere and water

IV. Conclusion and Outlook

In this article, we take two distinct approaches to solve the problem of deciding the distance span of HF communication under a variety of geographical environments. We mainly use the power distribution to decide the span and our simulation coincide with the reality fairly well. The skip zone and some other factors can cause the inconsistency of communication.

There are still challenges ahead to solve the problem in HF communication totally, yet smart antenna can be adopted and a variety of algorithm can be used. For example, adaptive antenna [12], which can increase the signal to noise ratio (SNR) significantly mainly based on smart algorithm such as least mean square algorithm (LMS) [13]. What's more, transmission frequency matters a lot in the communication system. We can choose appropriate frequency to better fit different communication distance.

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