Propagation of Radio Signal Over the Sea Surface

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Introduction

Propagation of radio signals can be significantly affected by the characteristics of the medium in which they travel. The properties of the propagation path can affect both the level and quality of the received signal and the distance over which signals travel before being reliably detected. In addition to factors such as reflection, refraction and diffraction that affect the propagation of a single signal, additional effects may arise from other signals propagating in the vicinity.

Over the past few years, the modeling of radio wave propagation over the sea surface has drawn the attention of many researchers. Channel models have been developed for different frequencies and communication scenarios. There are models that emphasize the influence of the height of the evaporation duct in the marine environment, as well as models that deal with different frequencies or the impact of various parameters, such as transmitter antenna height and wave height.

This work is focused on analyzing the propagation of a radio signal along the Line-of-Sight (LoS) between a transmitter that remains close to the sea surface and a receiver located some distance away. To accurately calculate the propagation loss, reflection and diffraction effects of the propagating electromagnetic wave due to the sea surface must be included. A model has been developed using the RF module in COMSOL Multiphysics® based on solving the full Maxwell wave equation. The model calculates the propagation loss over large distances, up to ten kilometers and accurately accounts for a variety of effects such as: transmitter frequency, wave height and wavelength), transmitter height and its location with respect to the wave trough and crest, and dependence of the electrical conductivity of the sea on temperature and salinity.

Model background

A successful predictive model of radio wave propagation over the sea surface must provide accurate predictions of the Link Budget and Path Propagation Losses. Further description of these parameters are provided below.

Link Budget

The communication radio link budget between a transmitting and a receiving antenna is analyzed based on the Friis formula (1), (2):

$$P_{RX} = P_{TX} - L_{TX} - L_{PP} - L_M - L_{RX} \qquad (1)$$

where:

P_{RX} = received power (dBm)
P_{TX} = transmitter output power (dBm)
L_{TX} = transmitter losses (coax, connectors) (dB)
L_{PP} = path propagation loss (includes sea reflection and sea wave diffraction effects)
L_M = miscellaneous losses (transmitter antenna orientation factor) (dB)
L_{RX} = receiver losses power (coax, connectors) (dB)

Path Propagation Loss

Path propagation loss L_{PP} is defined as follows:

$$L_{PP} = \frac{P_r}{P_{rad}} \qquad (2)$$

where P_r is the power of the receiving antenna and P_{rad} is total radiated power of the transmitting antenna.

The receiver power P_r is defined as:

$$P_r = A_r P_{inc} \qquad (3)$$

where A_r is effective area (aperture) of the receiver and P_{inc} is power density incident on the receiver.

For all antennas, it can be shown that the effective area is related to the power gain G_r and the wavelength $\lambda = c/f$ as follows:

$$A_r = G_r \frac{\lambda^2}{4\pi} \qquad (4)$$

Thus, we obtain the following general equation for the path propagation loss:

$$L_{PP} = G_r \frac{\lambda^2}{4\pi} \frac{P_{inc}}{P_{rad}} \qquad (5)$$

The total radiated power P_{rad} is calculated by integrating the Poynting vector **S** (W/m^2) over the entire hemisphere above the sea:

$$P_{rad} = \int_0^{\pi/2} \int_0^{2\pi} \mathbf{S} \cdot \mathbf{n} d\Omega \qquad (6)$$

where **n** is the unit normal vector to the hemispherical surface.

The incident power P_{inc} is calculated as the projection of the Poynting vector on the direction of line of sight (LOS) between the transmitter and the receiver:

$$P_{inc} = \mathbf{S} \cdot \boldsymbol{\tau} \qquad \mathbf{(7)}$$

where **τ** is the unit vector of the LoS direction.

The Poynting vector in the frequency domain is defined as:

$$\mathbf{S} = \frac{1}{2} Re(\mathbf{E} \times \mathbf{H}^*) \qquad (8)$$

The electric field **E** and magnetic field **H** are calculated by solving Maxwell's wave equation in the frequency domain.

COMSOL Multiphysics Model

This problem is modeled in a two-dimensional axisymmetric geometry, as shown in Figure 1. The sea surface is shown with a blue line and the open boundary is shown with a green line.

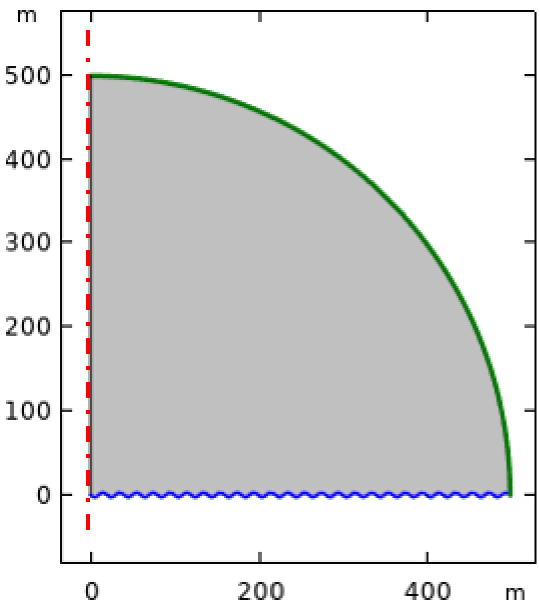


Figure 1. Model geometry.

The sea surface is represented by a harmonic function with the predefined decay of the wave height:

$$z(r) = \frac{h_w}{2} cos\left(2\pi \frac{r+\delta\lambda_w}{\lambda_w}\right) e^{-r/\Delta_w} \qquad (9)$$

where

(r, z): spherical coordinates
h_w: sea wave height
λ_w: sea wave height
h_w: sea wave height
Δ_w: sea wave decay factor
δ: antenna position parameter $(0 \leq \delta \leq 1)$

In this model, the antenna is always located at $r = 0$.

The **Electromagnetic Waves, Frequency Domain (emw)** physics is used to solve Maxwell's wave equation in the frequency domain:

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2 \left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right) \mathbf{E} = 0 \qquad (10)$$

where

E: electric field (V/m)
k_0: free-space wave vector $(1/m)$
ε_r: relative permittivity
μ_r: relative permeability
σ: electrical conductivity (S/m)

The magnetic field is calculated based on the Faraday's law:

$$\mathbf{H} = -\frac{1}{j\omega\mu} \nabla \times \mathbf{E} \quad (A/m) \qquad (11)$$

The transmitter antenna is modeled as a magnetic dipole, represented by a small current loop above the sea surface. In a two-dimensional axisymmetric configuration, a magnetic dipole is represented as a point with a small offset from the symmetry axis and at the specified distance from the sea level.

The sea surface is modeled using the **Impedance Boundary Condition**:

$$\sqrt{\frac{\mu}{\varepsilon - j\sigma/\omega}} \mathbf{n} \times \mathbf{H} + \mathbf{E} - (\mathbf{n} \cdot \mathbf{E})\mathbf{n} = 0 \qquad (12)$$

where μ is permeability, ε is water permittivity, and σ is water electrical conductivity. The electrical conductivity of sea water varies with both the salinity and temperature and is given by

$$\sigma = 0.18\, C^{0.93}[1 + 0.02(T - 20)]\ (S/m) \qquad (13)$$

where

C: salinity (grams of salt per liter)
T: temperature (^{o}C)

For cold seas, σ is approximately 3.5 S/m and for warm seas, σ is approximately 5 S/m.

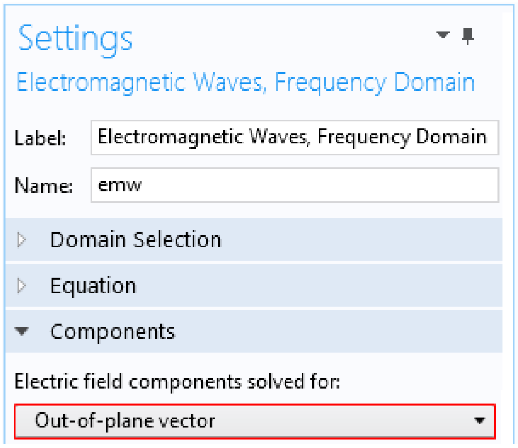
The open boundary is modeled using the **Scattering Boundary Condition**:

$$\mathbf{n}\times(\nabla\times\mathbf{E}) - jk\mathbf{n}\times(\mathbf{E}\times\mathbf{n}) = 0 \qquad (14)$$

This condition provides the exterior open boundary transparent for the transmitted and reflected (scattered) waves.

Simulation Results

The standard requirement for solving wave-type problems is to provide resolution of the wavelength; this dictates six mesh elements per wavelength. Modeling of the wave propagation for MHz frequencies, even over moderate distances of several hundred meters, requires significant computational resources. For a magnetic dipole source, the circumferential component, E_{φ}, is the only nonzero component of the electric field. By default, the **Electromagnetic Waves (emw)** physics is solved for all the components (dependent variables) of the electric field. The problem size can be reduced by a factor of three by setting the **Electric fields components solved for** to **Out-of-plane vector**, as shown in Figure 2.



Settings
Electromagnetic Waves, Frequency Domain

Label: Electromagnetic Waves, Frequency Domain

Name: emw

Electric field components solved for:
Out-of-plane vector

Figure 2. Physics setup to reduce the number of dependent variables being solved for.

Figures 3 shows an example of the resulting field distribution for a transmitter frequency of 350 MHz, a sea wave height of 2 m, and an antenna height of 6 inches located at sea level ($\delta = 0.25$).

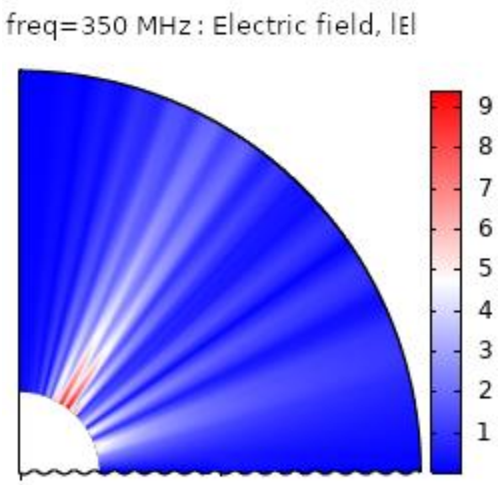


Figure 3. Electric field distribution. Region inside circle of 100 m radius is excluded from visualization.

The Path Propagation Loss versus distance from the transmitter along the Line-of-Sight is shown in Figure 4. Free-space path propagation losses are also shown for comparison purposes.

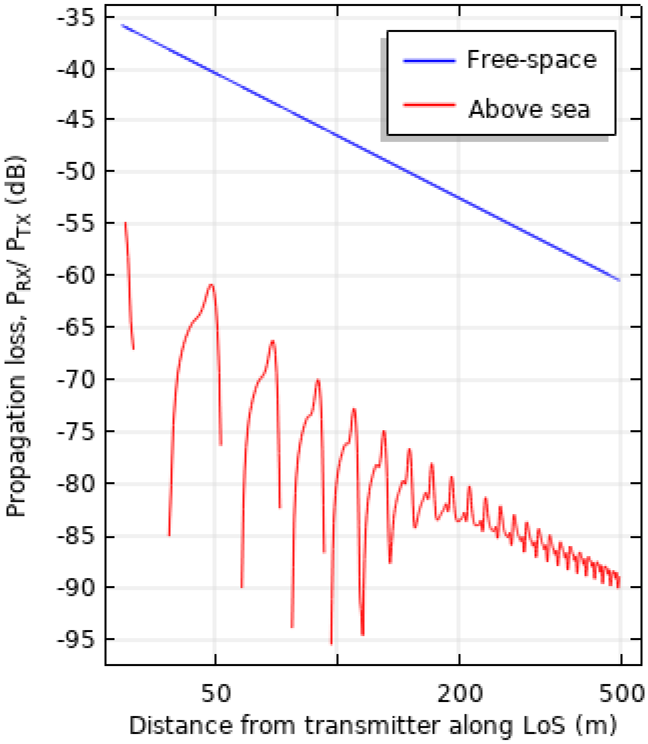


Figure 4. Signal path propagation loss versus distance.

Conclusions

The computational model developed for this work allows simulation of the Path Propagation Loss of the

EM signal propagation above the sea for large distances.

References

1. Orfanidis, S. J., Electromagntic Waves and Antennas, http://eceweb1.rutgers.edu/~orfanidi/ewa/
2. Lee, W. *Mobile Communications Engineering*, 1st ed.; McGraw-Hill: New York, NY, USA, 2012.