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EM.Terrano

Tutorial Lessons

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14

EM.Terrano Tutorial Lesson 14

Atmospheric Propagation Effects & Tropospheric Ducting

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14.1 What You Will Learn

In this tutorial lesson, you will learn about the global environment settings of EM.Terrano including its atmospheric models. You will simulate very long range communications links in conjunction with both standard and non-standard atmosphere models.

EM.Terrano Manual:

http://www.emagtech.com/wiki/index.php/EM.Terrano

EM.Terrano Tutorial Gateway:

http://www.emagtech.com/wiki/index.php/EM.Cube#EM.Terrano_Documentation

Download projects related to this tutorial lesson:

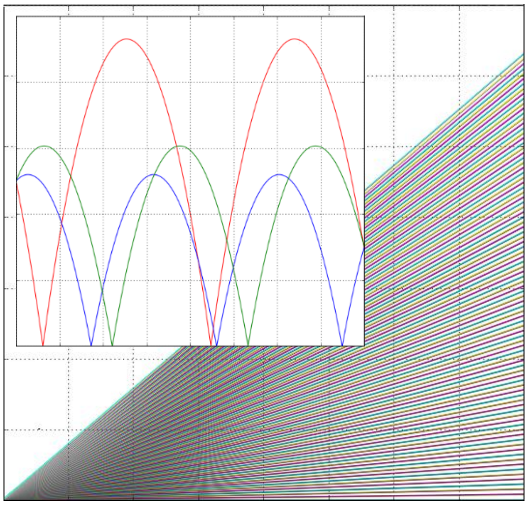
http://www.emagtech.com/downloads/ProjectRepo/EMTerrano_Lesson14.zip

14.2 Getting Started

Start a new project with the following parameters.

Starting Parameters	
Name	EMTerrano_Lesson14
Length Units	Meters
Frequency Units	GHz
Center Frequency	1GHz
Bandwidth	0.1GHz

Tutorial Project: Atmospheric Propagation Effects and Tropospheric Ducting



Objective: To learn how to set up an aerial communication link and perform link margin analysis with different types of waveforms.

Concepts/Features:

- Atmosphere Model
- Standard Atmosphere
- Horizon Distance
- Refractivity
- M-Profile
- Ray Bending
- Tropospheric Ducting

Minimum Version Required: All versions

14.3 Understanding Atmospheric Propagation Effects

There are numerous atmospheric effects that can affect the performance of a communication link. The most common is rain, which attenuates a propagating radio wave especially at higher frequency bands. In this tutorial lessons we are rather interested in tropospheric propagation effects that affect very long-range communication link scenarios such as ray bending and ducting. These effects are not important in the modeling of small to medium range links.

In general, it is assumed that the refractive index of the air is $n = 1$, i.e., the same as the vacuum. However, a more accurate value of the refractive index of the earth's atmosphere at its surface is $n_0 = 1.000350$. The value of the refractive index is indeed a function $n(z)$ of the height above the earth's surface. It gets closer to unity as height is increased. It is more convenient to define a quantity called refractivity as

$$N(z) = 10^6 \times [n(z) - 1]$$

Then, the refractivity on the surface of the earth is $N_0 = 350$ N-units. For most practical scenarios, the refractivity can be modeled as a linear function of height:

$$N(z) = \left(\frac{dN}{dz}\right) z + N_0$$

Under the standard atmospheric conditions, dN/dz = -39 N-units/km.

Through a detailed electromagnetic analysis of wave propagation in a stratified atmosphere with a linear index profile, it can be shown that a propagating ray gradually bends downward towards the earth's surface as a function of range. At long ranges, the spherical shape of the earth must also be taken into account, above which the ray propagation takes place. This is typically done by defining a modified index of refraction in the following manner:

$$m(z) = n(z)\left(1 + \frac{z}{a}\right)$$

where $a = 6{,}370$ km is the radius of the earth.

In a similar manner, a modified refractivity can be defined. For the linear modified refractivity model, it can be shown that

$$\frac{dM(z)}{dz} = \frac{dN(z)}{dz} + 157 \ \text{M} - \text{units/km}$$

The effect of a linear change in refractive index with height can be modeled through the use of a modified earth radius:

$$a_e = \kappa a$$

where

$$\kappa = \frac{1}{1 + \frac{a}{n_0}\left(\frac{dn}{dz}\right)}$$

Under the effective earth radius approximation, the rays are assumed to travel along straight lines as illustrated in Figure 1. Under the standard atmosphere assumption, we have $\kappa = 4/3$.

The modified refractivity, M-profile, of the real earth's atmosphere is often more complex than a simple linear function of altitude and it varies at different geographical locations and with diurnal cycles during the day and night. When the slope of the M-profile becomes negative, it can cause tropospheric ducting under certain circumstances, whereby the propagating ray gets trapped between the earth's surface and upper layers of the atmosphere. Figure 2 shows typical M-profiles of surface-based and elevated ducts along with their piecewise linear approximations.

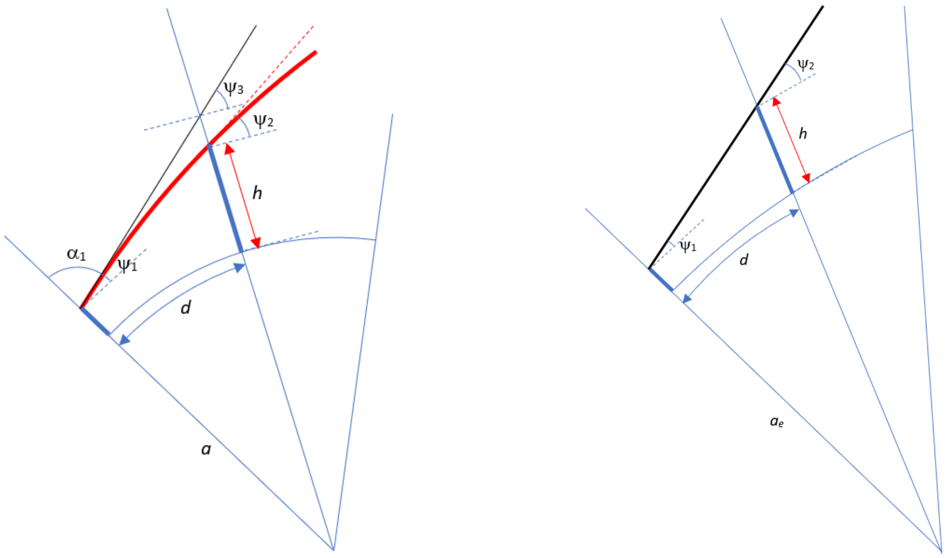


Figure 1. *(Left) Bending of a ray in the standard atmosphere above the spherical earth, and (Right) the concept of the equivalent earth radius.*

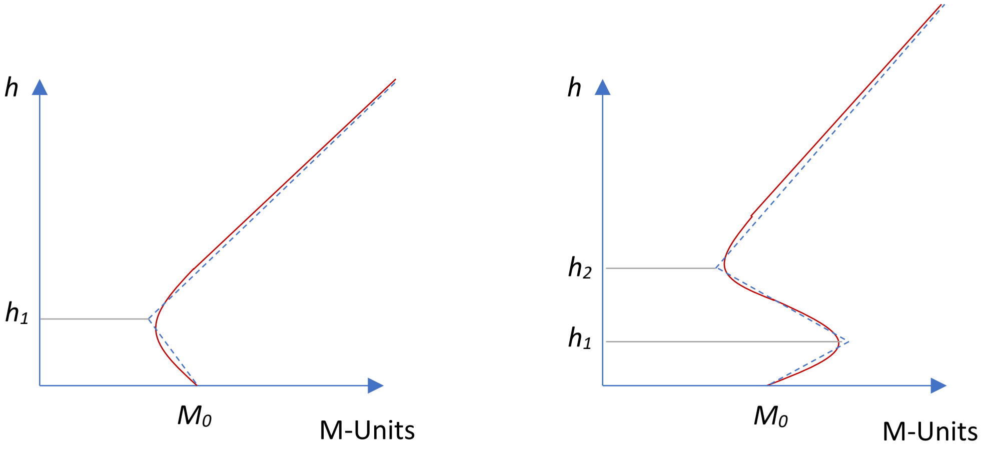


Figure 2. *(Left) The M-profile of a surface-based duct, and (Right) the M-profile of an elevated duct, along with their piecewise linear approximations shown in dashed lines.*

In general, EM.Terrano allows you to define a generalize M-profile in the form piecewise cubic functions:

$$M(z) = A_i z^3 + B_i z^2 + C_i z + D_i, \qquad h_i \le z \le h_{i+1}$$

In the case of a piecewise linear approximation, $A_i = B_i = 0$. Most smooth functions can be well approximated using cubic spline interpolation. It is the user's responsibility to enforce the continuity of the cubic polynomials representing different height intervals at the boundary points.

14.4 Defining the Transmitter & Receiver

Create a vertically (Z) polarized dipole transmitter (TX_1) associated with the point radiator “TXB” and a vertically (Z) polarized receiver (RX1_1) associated with the point radiator “RXB”. Your transmitter will be located at Point_1(0, 0, 50m):

Object	Geometry	Block Group	Physical Structure	Location Coordinates
Point_1	Point	TXB	Point Radiators	(0, 0, 50m)

And your receiver will be located at Point_1(50000m, 0, 30m):

Object	Geometry	Block Group	Physical Structure	Location Coordinates
Point _2	Point	RXB	Point Radiators	(50000m, 0, 30m)

Next assign a transmitter set to the first radiator set and assign a receiver set to the second radiator set. Figure 3 shows the free-space propagation scene with the transmitter and receiver sets 50,000m apart. Open the property dialog of the Transmitter Set and set its **Source Power** to 20 W as shown in Figure 4. Also, open the property dialog of the Receiver Set and set its **Receiver Sensitivity** to -150 dBm.

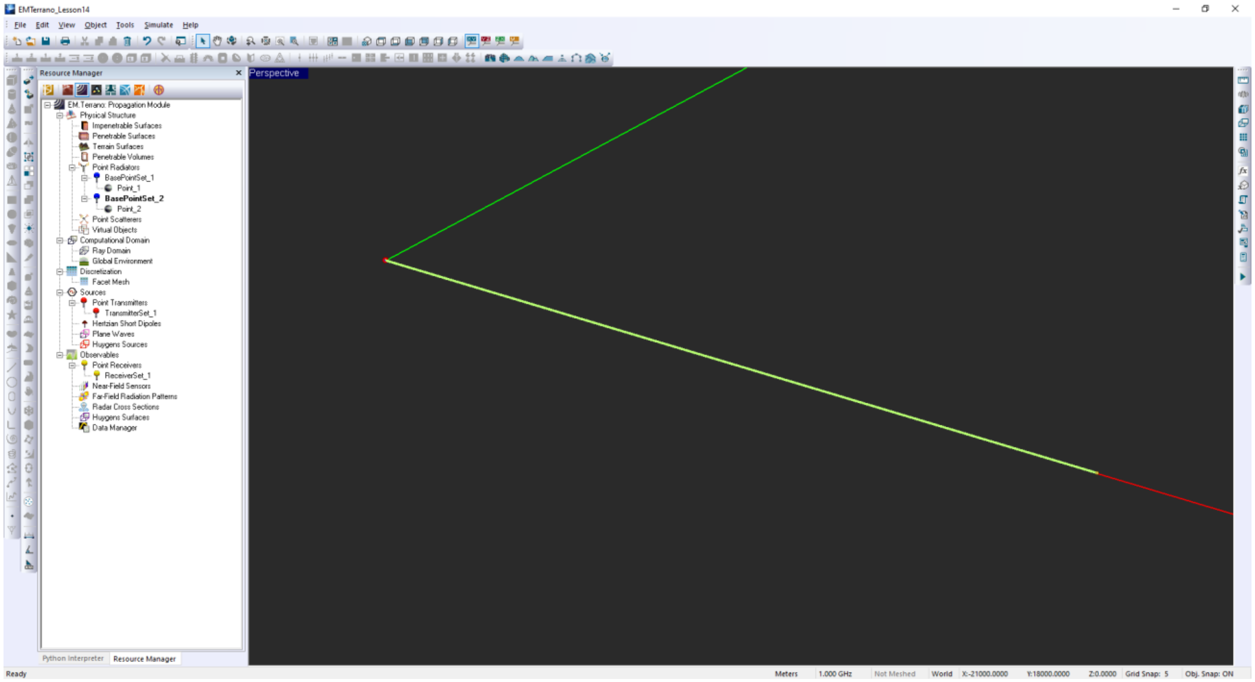
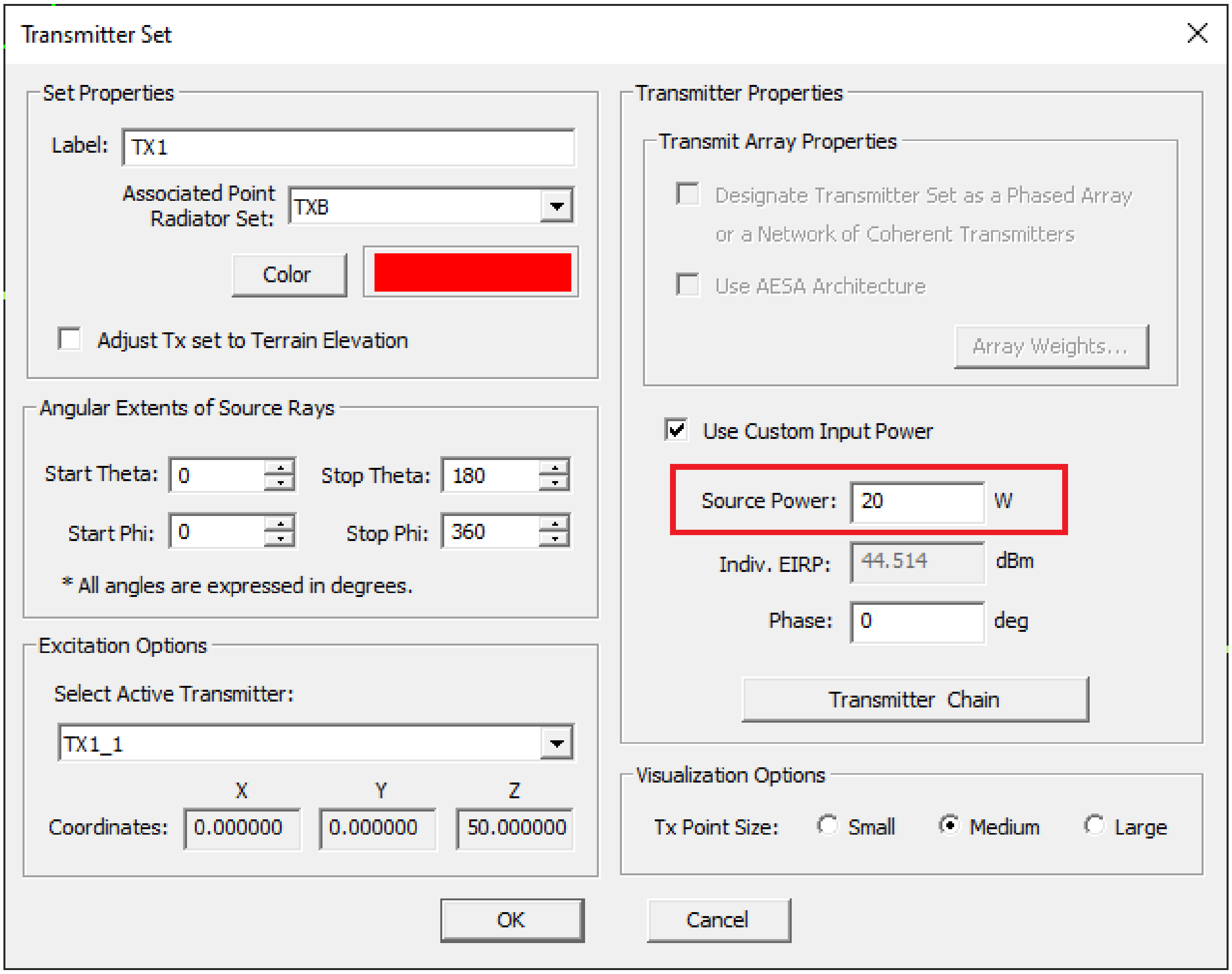


Figure 3. *The free-space propagation scene with two points 50,000m apart.*



Label: TX1

Associated Point Radiator Set: TXB

☐ Adjust Tx set to Terrain Elevation

Start Theta: 0 Stop Theta: 180

Start Phi: 0 Stop Phi: 360

* All angles are expressed in degrees.

Select Active Transmitter: TX1_1

Coordinates: X 0.000000 Y 0.000000 Z 50.000000

☐ Designate Transmitter Set as a Phased Array or a Network of Coherent Transmitters

☐ Use AESA Architecture

☑ Use Custom Input Power

Source Power: 20 W

Indiv. EIRP: 44.514 dBm

Phase: 0 deg

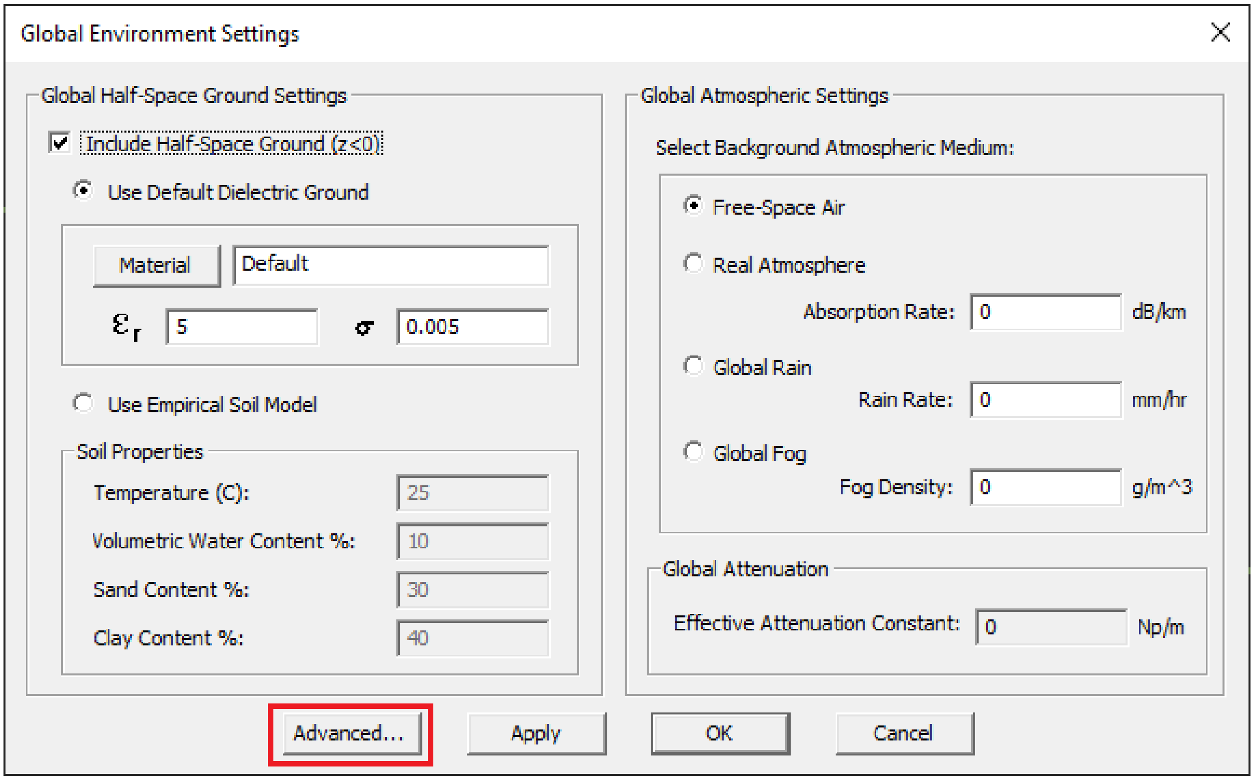
Tx Point Size: ○ Small ● Medium ○ Large

Figure 4. *The Transmitter Set property dialog.*

14.5 Running Long-Haul Channel Analyzer with Standard Atmosphere Model

For this tutorial lesson, you will keep the default baseband transmission. Let us first take a look at the global environment settings of the project. Right-click on the **Global Environment** item in the Resource Manager and select **Global Environment Settings…** from the contextual menu. Figure 5 shows the “Global Environment Settings” Dialog. Click the **Advanced** button at the bottom of this dialog to open the “Advanced Global Environment Parameters” dialog. In the **Long-Haul Atmospheric Parameters** section of this dialog, you see the **Atmospheric Model Type** dropdown list set by default to “**Standard Atmosphere with monotonic refractivity**”. You will also see two more parameters: **Refractivity Gradient** with a default value of -39 N-units/km and **Refractivity Value at Ground Level** with a default value of 300 N-units.

As we discussed earlier, the standard atmosphere model is represented by a linear M-profile. Click the **Plot** button of the dialog and you will get a graph similar to the one shown in Figure 7. For the first part of this lesson, we will keep the standard atmosphere model.



Global Half-Space Ground Settings

☑ Include Half-Space Ground (z<0)

● Use Default Dielectric Ground

Material: Default

ε_r: 5 σ: 0.005

○ Use Empirical Soil Model

Soil Properties

Temperature (C): 25

Volumetric Water Content %: 10

Sand Content %: 30

Clay Content %: 40

Global Atmospheric Settings

Select Background Atmospheric Medium:

● Free-Space Air

○ Real Atmosphere

Absorption Rate: 0 dB/km

○ Global Rain

Rain Rate: 0 mm/hr

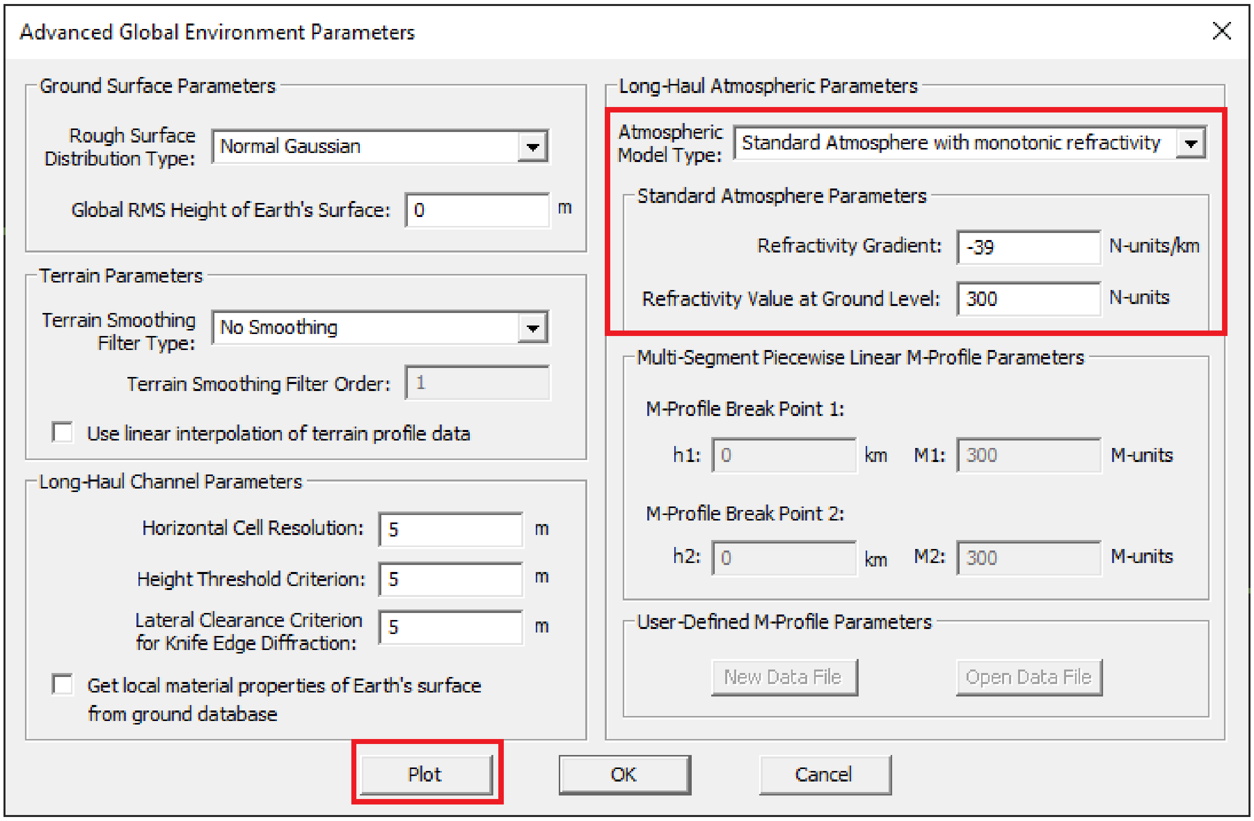
○ Global Fog

Fog Density: 0 g/m^3

Global Attenuation

Effective Attenuation Constant: 0 Np/m

Figure 5. *The Global Environment Settings dialog.*



Ground Surface Parameters

Rough Surface Distribution Type: Normal Gaussian

Global RMS Height of Earth's Surface: 0 m

Terrain Parameters

Terrain Smoothing Filter Type: No Smoothing

Terrain Smoothing Filter Order: 1

☐ Use linear interpolation of terrain profile data

Long-Haul Channel Parameters

Horizontal Cell Resolution: 5 m

Height Threshold Criterion: 5 m

Lateral Clearance Criterion for Knife Edge Diffraction: 5 m

☐ Get local material properties of Earth's surface from ground database

Long-Haul Atmospheric Parameters

Atmospheric Model Type: Standard Atmosphere with monotonic refractivity

Standard Atmosphere Parameters

Refractivity Gradient: -39 N-units/km

Refractivity Value at Ground Level: 300 N-units

Multi-Segment Piecewise Linear M-Profile Parameters

M-Profile Break Point 1:

h1: 0 km   M1: 300 M-units

M-Profile Break Point 2:

h2: 0 km   M2: 300 M-units

User-Defined M-Profile Parameters

Figure 6. *The Advanced Global Environment Parameters dialog.*

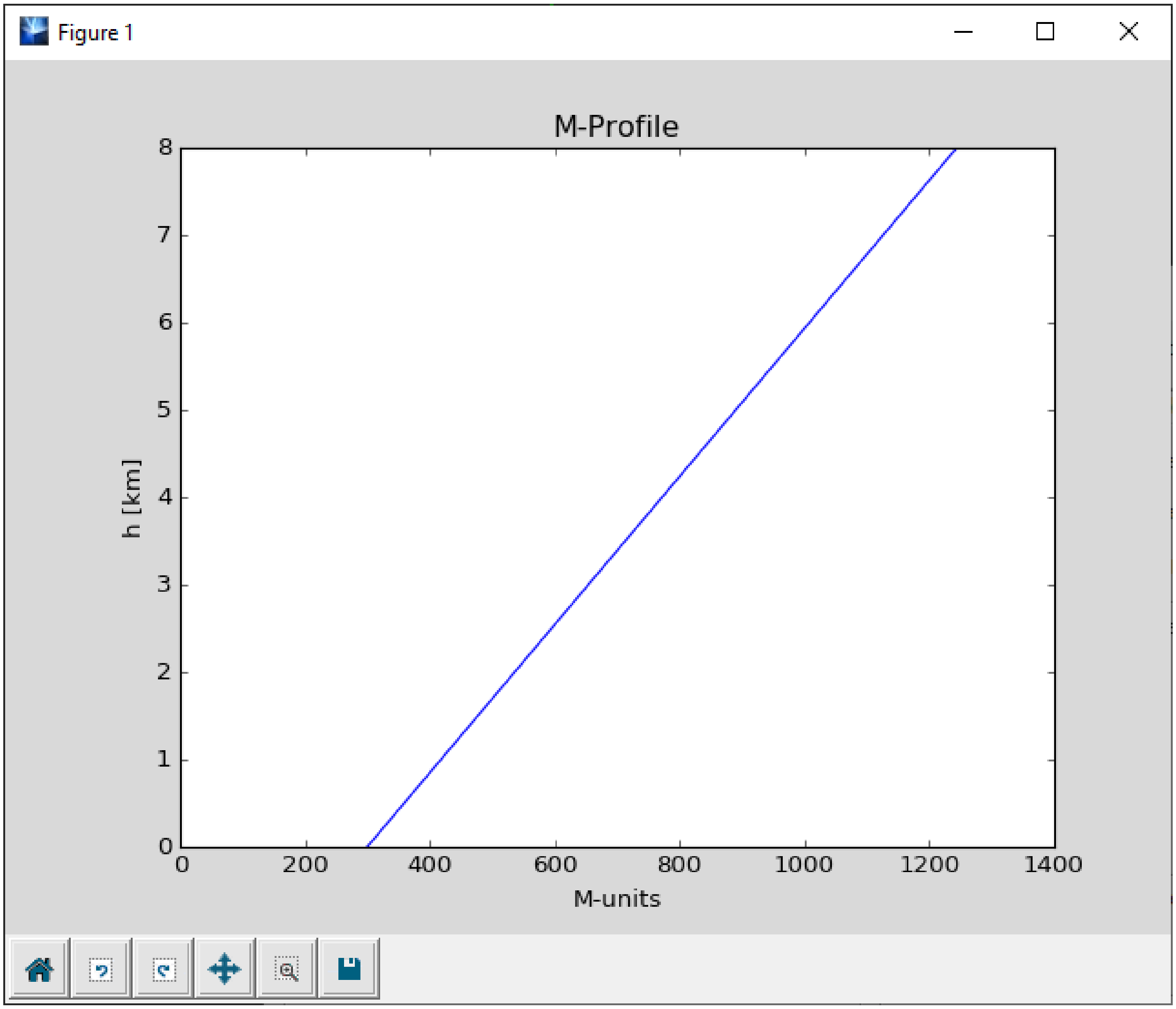
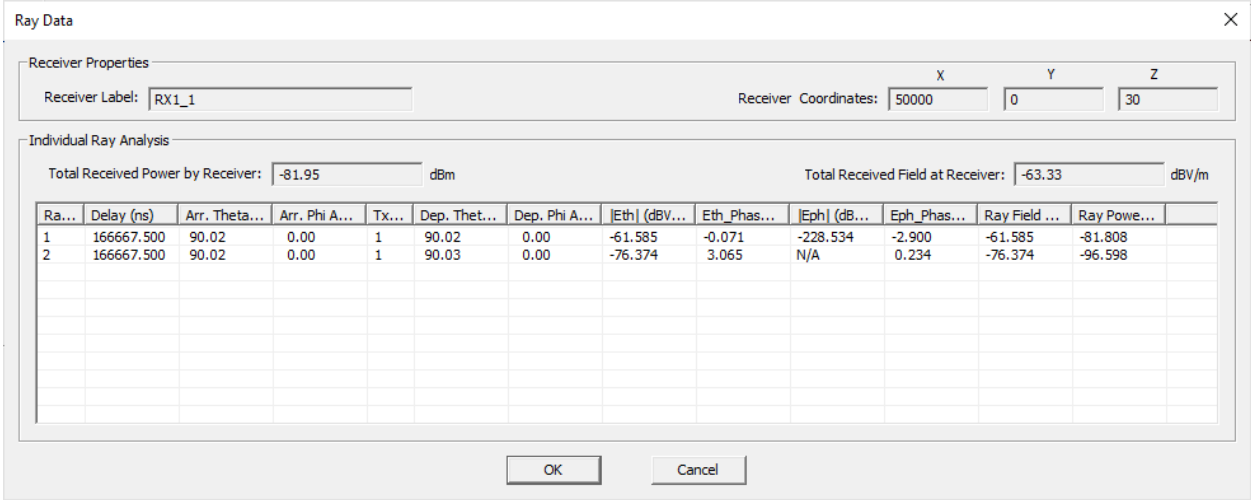


Figure 7. *A plot of M-profile of the standard atmosphere model.*

Open the Run Simulation dialog and open the Ray Tracing Engine Settings dialog. In this dialog, set the **Ray Power Threshold** to -150 dBm. Run the long-haul channel analyzer first and then run the communication link solver. At the end of the simulation, open the property dialog of the receiver set. Note that there is a single receiver in the scene. Click the **Show Ray Data** button to see the properties of the two received rays, i.e., the direct LOS and ground-reflected rays. The table below summarizes the signal and noise power data at the selected receiver:

Rx Index	Modulation	Received Power	Noise Power	SNR	Link Margin
1	None	-81.952 dBm	-94.472 dBm	12.521 dB	2.521 dB

As you can see from the table, the link margin is barely above the zero level.



Receiver Label: RX1_1

Receiver Coordinates: X 50000 Y 0 Z 30

Total Received Power by Receiver: -81.95 dBm

Total Received Field at Receiver: -63.33 dBV/m

Ra...	Delay (ns)	Arr. Theta...	Arr. Phi A...	Tx...	Dep. Thet...	Dep. Phi A...	|Eth| (dBV...	Eth_Phas...	|Eph| (dB...	Eph_Phas...	Ray Field ...	Ray Powe...
1	166667.500	90.02	0.00	1	90.02	0.00	-61.585	-0.071	-228.534	-2.900	-61.585	-81.808
2	166667.500	90.02	0.00	1	90.03	0.00	-76.374	3.065	N/A	0.234	-76.374	-96.598

Figure 8. *The Ray Data dialog showing the properties of the direct LOS and ground-reflected rays.*

14.6 Increasing the Range

Next, let us increase the range to 80km. This is done by setting the X-coordinate of the point radiator called "Point_2" to 80,000m. Remember since you have changed the physical location of the receiver, you have to rerun the channel analyzer.

Object	Geometry	Block Group	Physical Structure	Location Coordinates
Point _2	Point	RXB	Point Radiators	(80000m, 0, 30m)

Run **Long-Haul Channel Analyzer** once again and then run the **Communication Link Solver**. Open the Receiver Set dialog. You will notice that the receiver hasn't received any power, nor any rays. If you open the file called "sbr_channel_matrix.DAT" in Data Manager, you will find it empty.

The reason why you didn't receive any rays is because the distance between your transmitter and receiver is now larger than the horizon distances of the transmit and receive antennas given their specified heights above the ground. Under this condition, the transmitted ray is blocked by the earth's spherical bulge and doesn't reach the receiver location.

The horizon distance of an antenna placed at a height h above the ground is given by

$$d_H = \sqrt{2a_e h}$$

where a_e is the effective earth radius. EM.Cube has a Python function for this purpose, which you can run from the command line:

`emag_horizon_distance(h_m)`

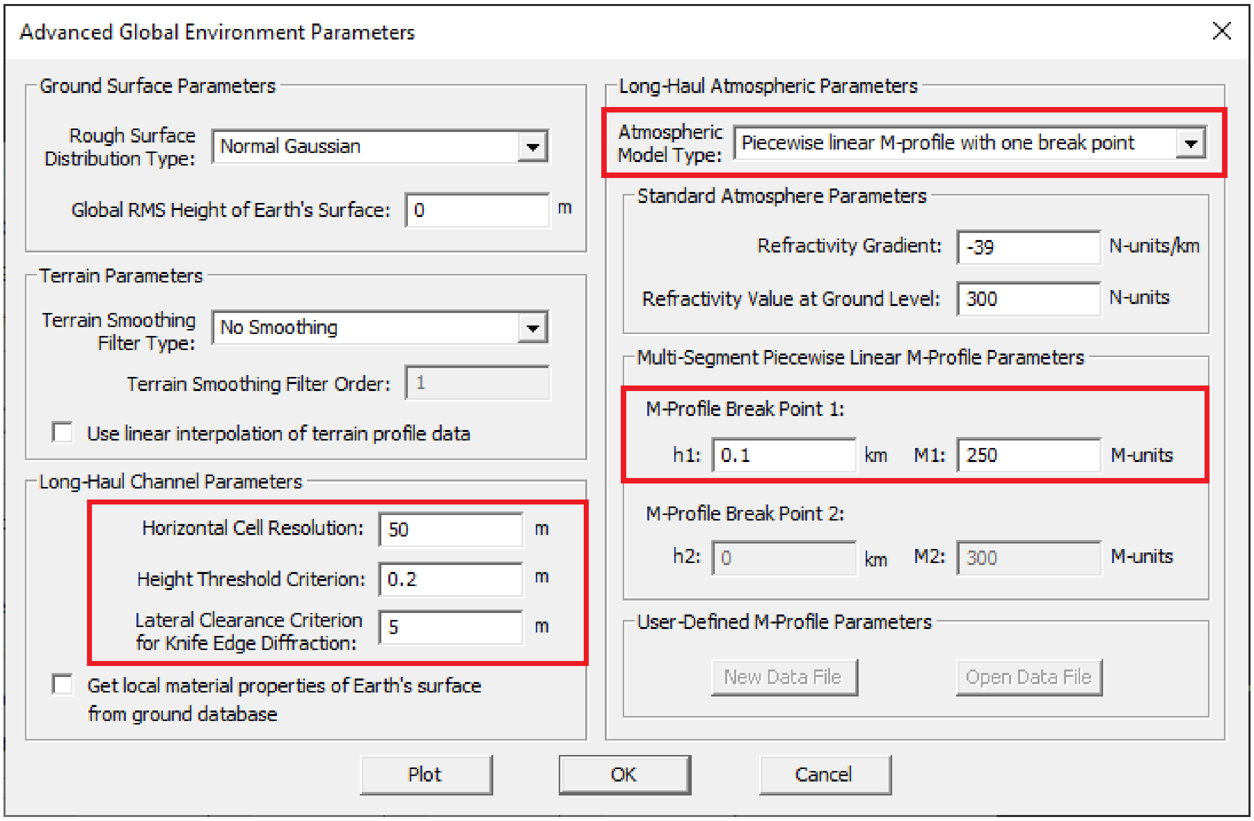
The argument of this function is the antenna height in meters and its output is the horizon distance in kilometers. The horizon distances of the transmit and receiver antennas with heights 50m and 30m are 29.143 km and 22.574 km, respectively. The sum of the two horizon distances is:

$$d_{H,Tx} + d_{H,Rx} = 51.717\text{km}$$

which much smaller than the 80 km range between your transmitter and receiver.

14.7 Defining a Non-Standard M-Profile

Now let us define a non-standard atmosphere model with a piecewise linear M-profile. Open the “Global Environment Settings” dialog once again and then open the “Advance Global Environment Parameters**”** dialog. From the **Atmospheric Model Type** dropdown list, select “**piecewise linear M-profile with one break point**”. In the section titled **Multi-Segment Piecewise Linear M-Profile Parameters**, define the break point by setting the ***h1*** parameter to 0.1 km and the ***M1*** parameter to 250 M-units as shown in Figure 9. Click the **Plot** button to plot the graph of the M-profile as shown in Figure 10.



Advanced Global Environment Parameters

Ground Surface Parameters

Rough Surface Distribution Type: Normal Gaussian

Global RMS Height of Earth's Surface: 0 m

Terrain Parameters

Terrain Smoothing Filter Type: No Smoothing

Terrain Smoothing Filter Order: 1

☐ Use linear interpolation of terrain profile data

Long-Haul Channel Parameters

Horizontal Cell Resolution: 50 m

Height Threshold Criterion: 0.2 m

Lateral Clearance Criterion for Knife Edge Diffraction: 5 m

☐ Get local material properties of Earth's surface from ground database

Long-Haul Atmospheric Parameters

Atmospheric Model Type: Piecewise linear M-profile with one break point

Standard Atmosphere Parameters

Refractivity Gradient: -39 N-units/km

Refractivity Value at Ground Level: 300 N-units

Multi-Segment Piecewise Linear M-Profile Parameters

M-Profile Break Point 1:

h1: 0.1 km M1: 250 M-units

M-Profile Break Point 2:

h2: 0 km M2: 300 M-units

User-Defined M-Profile Parameters

Figure 9. *Defining a non-standard M-profile in the Advanced Global Environment Parameters dialog.*

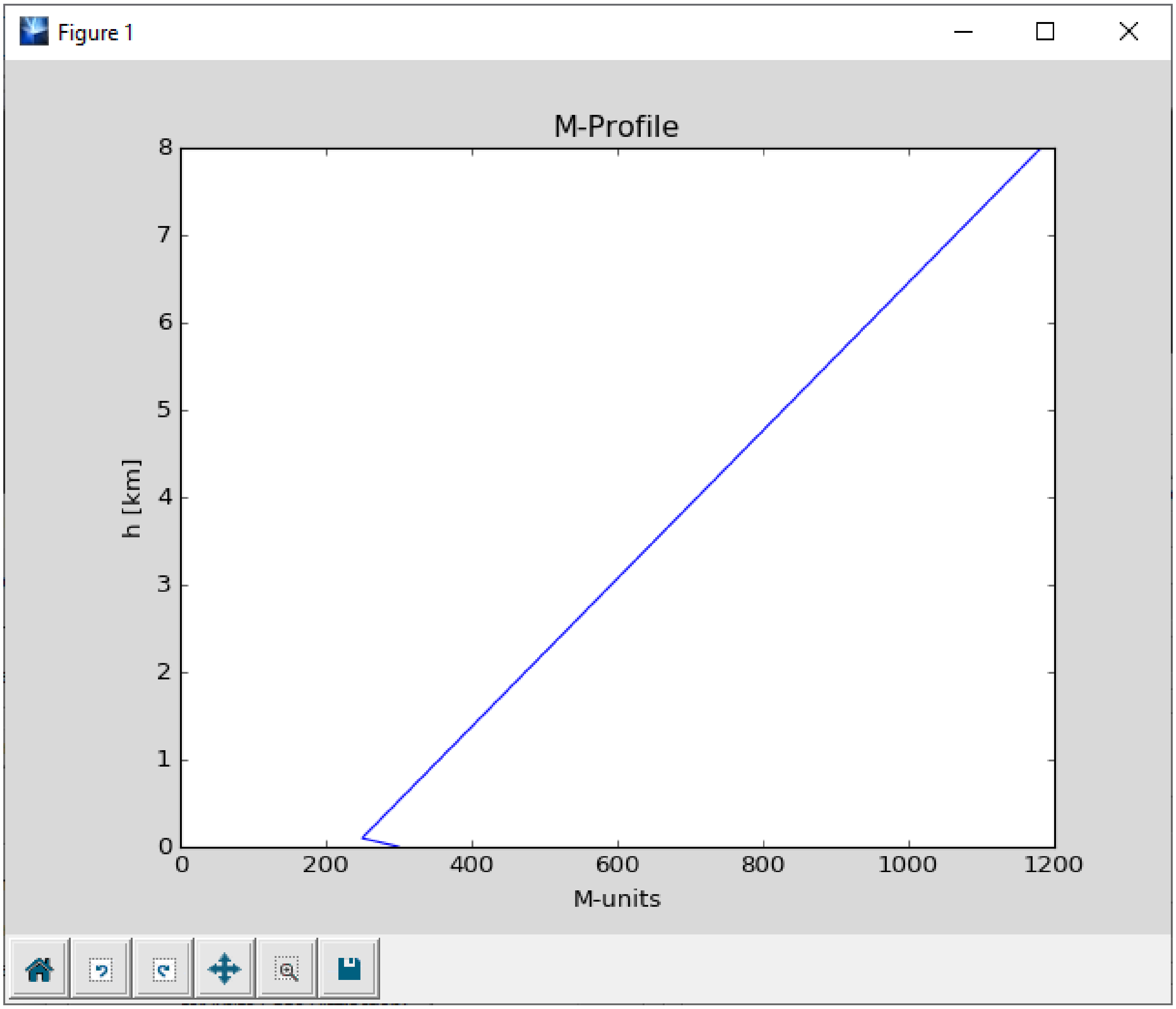
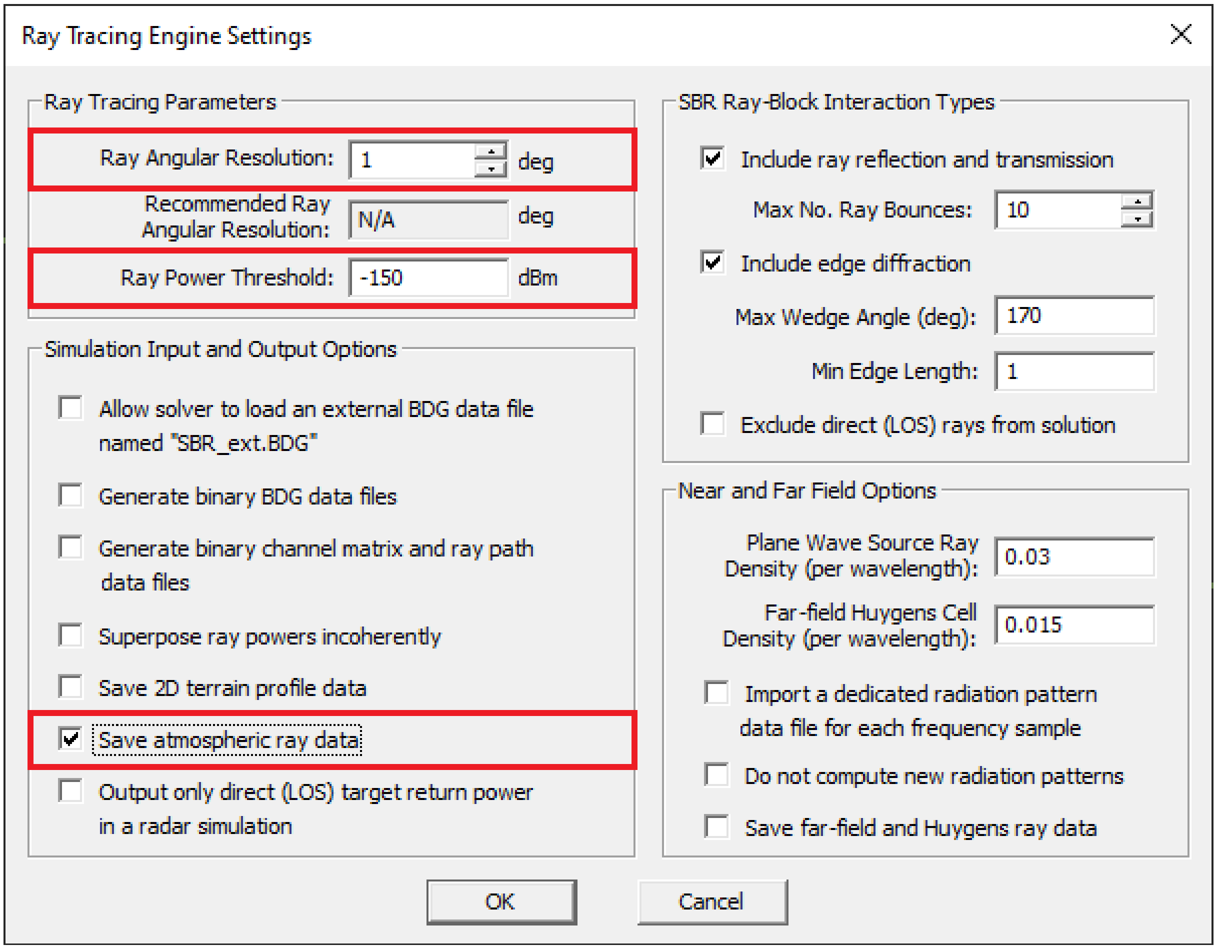


Figure 10. *A plot of the M-profile of the linear piecewise non-standard atmosphere model.*

14.8 Running Channel Analyzer for Non-Standard Atmospheric Propagation Scene

In this section, you will run the Long-Haul Channel Analyzer for the 80 km range scene. The standard atmosphere model uses an effective earth radius approximation. By contrast, non-standard atmosphere models require a computationally intensive numerical simulation of the launched rays in successive thin layers of the atmosphere to compute the bending the of the rays and detect possible ray inflection points. This process may take a significant amount of time to complete.

Open the Ray Tracing Engine Settings dialog. Set the **Ray Angular Resolution** to the default value of 1° and set the **Ray Power Threshold** to -150 dBm and check the checkbox labeled **Save atmospheric ray data,** as shown in Figure 11. Click the **Run** button for the Long-Haul Channel Analyzer. You will get a warning message asking if you want to use some recommended settings as shown in Figure 12. Click the **No** button to proceed. After the simulation is completed, open the Data Manager and plot the file called “atmos_rays_1.DAT”. Figure 13 shows the resulting graph, depicting the rays launched from the transmitter at different angles with an angular resolution of 1° and travelling 80 km towards the receiver. The scale of the vertical axis of this graph shows height values larger than 120 km. This is because an angular resolution of 1° translates into a vertical resolution of 1,396 m at a range of 80 km. Your receive antenna is placed at a height of 30 m above the ground. Obviously, the current vertical resolution is far too coarse. As one might expect, the other file called "atmos_rays_solution_1.DAT" is empty. This fille is supposed to contain the solution, i.e., all those rays that reach the receiver.



Ray Tracing Engine Settings

Ray Tracing Parameters

Ray Angular Resolution: 1 deg

Recommended Ray Angular Resolution: N/A deg

Ray Power Threshold: -150 dBm

Simulation Input and Output Options

☐ Allow solver to load an external BDG data file named "SBR_ext.BDG"

☐ Generate binary BDG data files

☐ Generate binary channel matrix and ray path data files

☐ Superpose ray powers incoherently

☐ Save 2D terrain profile data

☑ Save atmospheric ray data

☐ Output only direct (LOS) target return power in a radar simulation

SBR Ray-Block Interaction Types

☑ Include ray reflection and transmission

Max No. Ray Bounces: 10

☑ Include edge diffraction

Max Wedge Angle (deg): 170

Min Edge Length: 1

☐ Exclude direct (LOS) rays from solution

Near and Far Field Options

Plane Wave Source Ray Density (per wavelength): 0.03

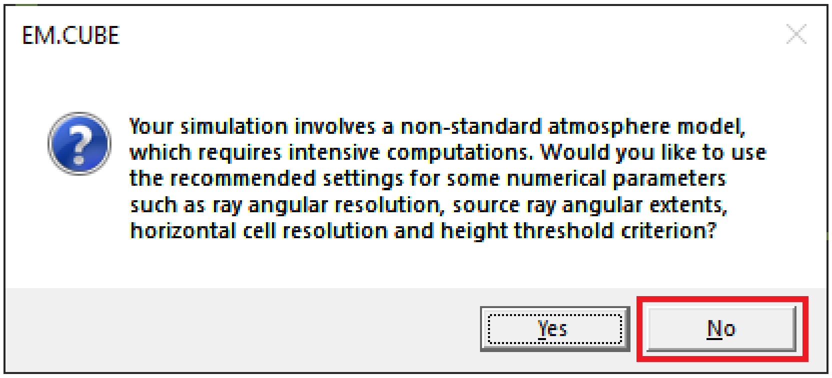
Far-field Huygens Cell Density (per wavelength): 0.015

☐ Import a dedicated radiation pattern data file for each frequency sample

☐ Do not compute new radiation patterns

☐ Save far-field and Huygens ray data

Figure 11. *Setting the ray angular resolution and ray power threshold in the Ray Tracing Engine Settings dialog.*



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Your simulation involves a non-standard atmosphere model, which requires intensive computations. Would you like to use the recommended settings for some numerical parameters such as ray angular resolution, source ray angular extents, horizontal cell resolution and height threshold criterion?

Figure 12. *Warning message for using the recommended settings.*

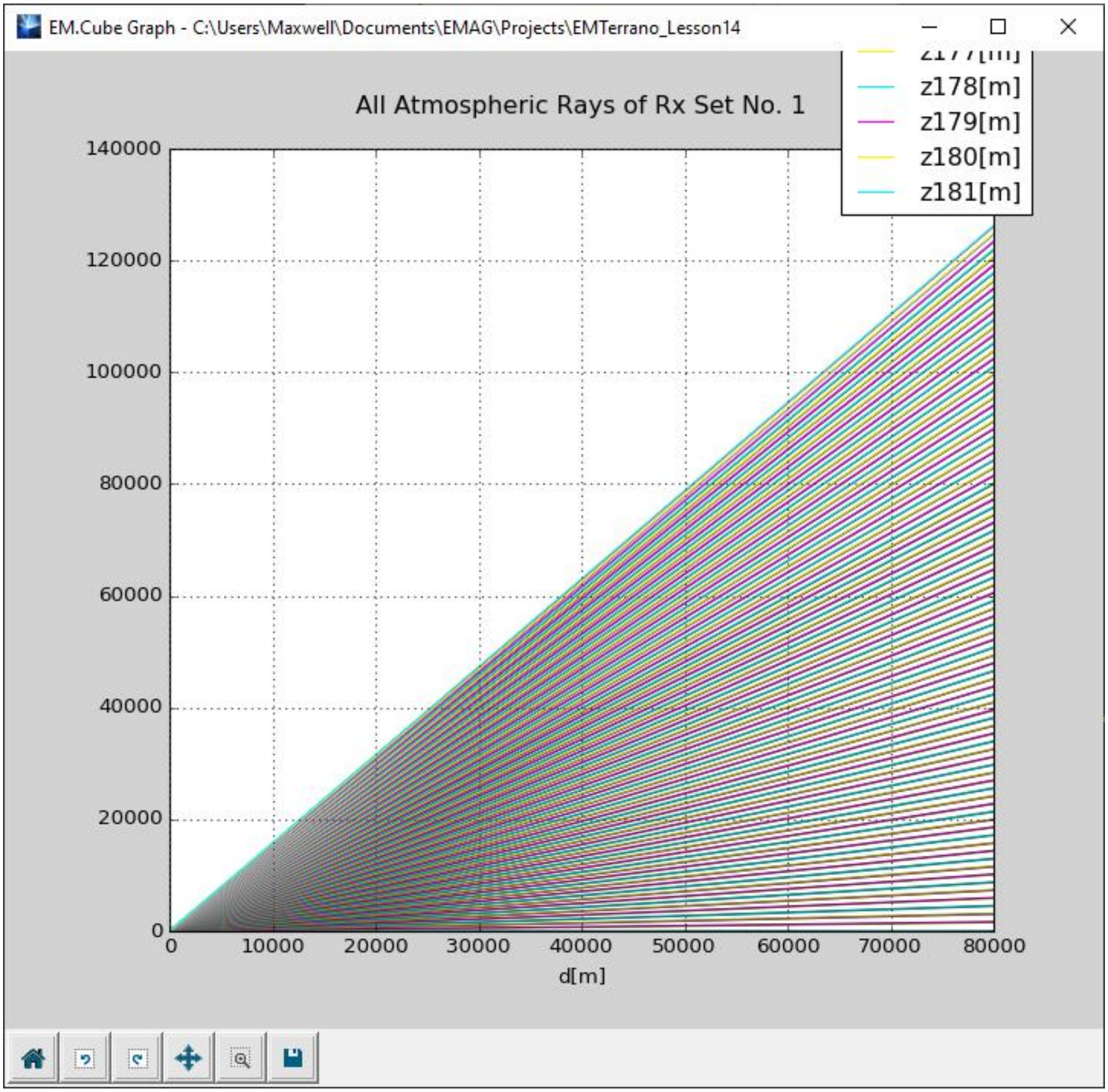


Figure 13. *A plot of the launched rays at a ray angular resolution of 1°.*

Next, run the Long-Haul Channel Analyzer, but this time use the recommended settings and click the **Yes** button of the warning message to proceed. The main changes made are as follows:

1. The ray angular resolution is set to 0.001 degrees.
2. The elevation launch angles (θ) of the transmitted rays is limited between 85° and 95°.
3. The initial horizontal cell resolution is set to 50m.
4. The height threshold criterion is set to 0.2m.

This means that 10,000 rays will be launched from the transmitter location and will be traced at horizontal steps of 50m long. That amounts to 1,600 cells in the horizontal direction.

After the simulation is completed, we recommend not to plot the data file called “atmos_rays_1.DAT”, as it contains an enormous amount of data, and the resulting graph will be too dense to see anything clearly. Instead, this time plot the file called “atmos_rays_solution_1.DAT” as shown in Figure 14.

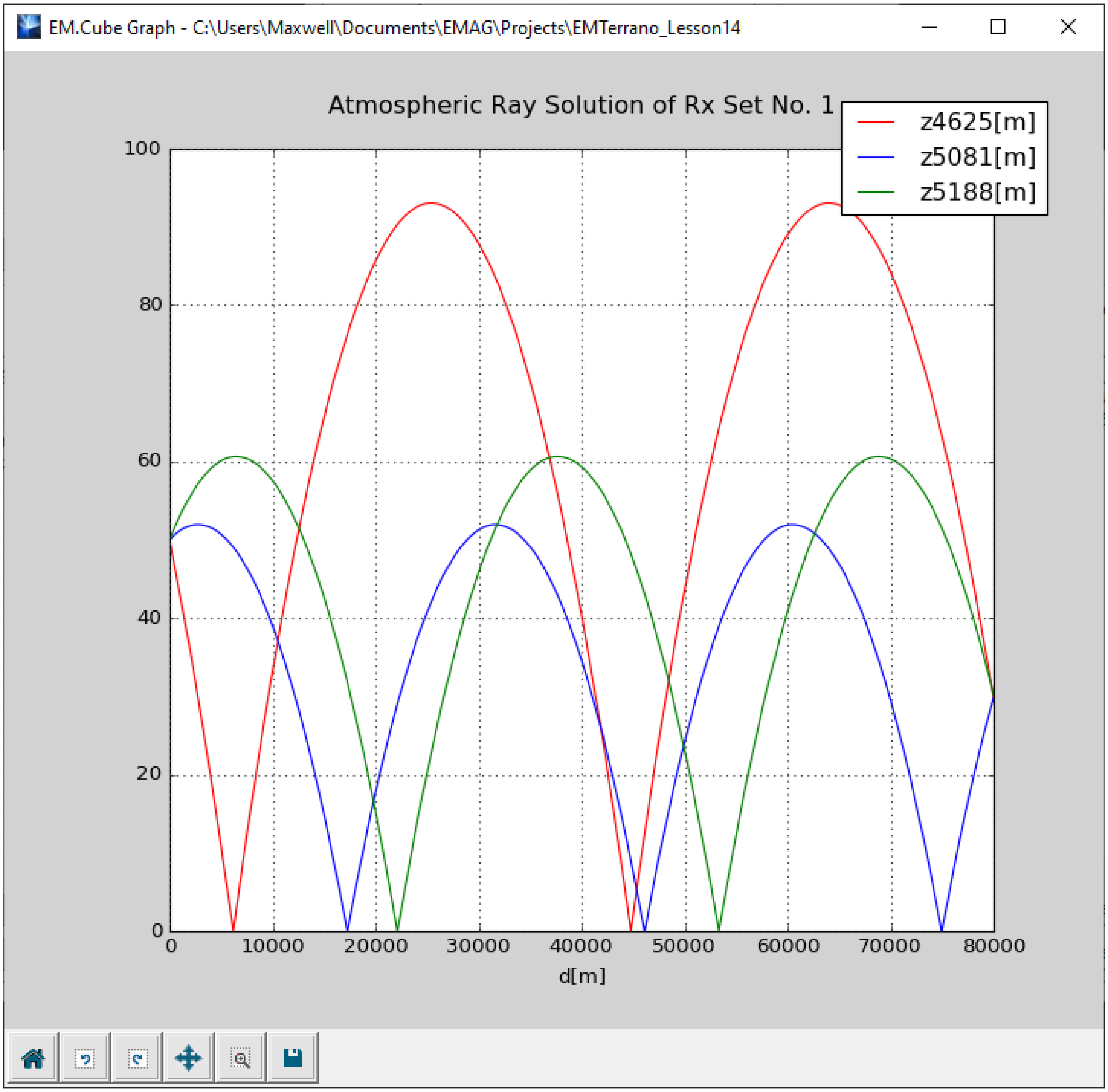


***Figure 14.** A plot of the ray solutions reaching the receiver location.*

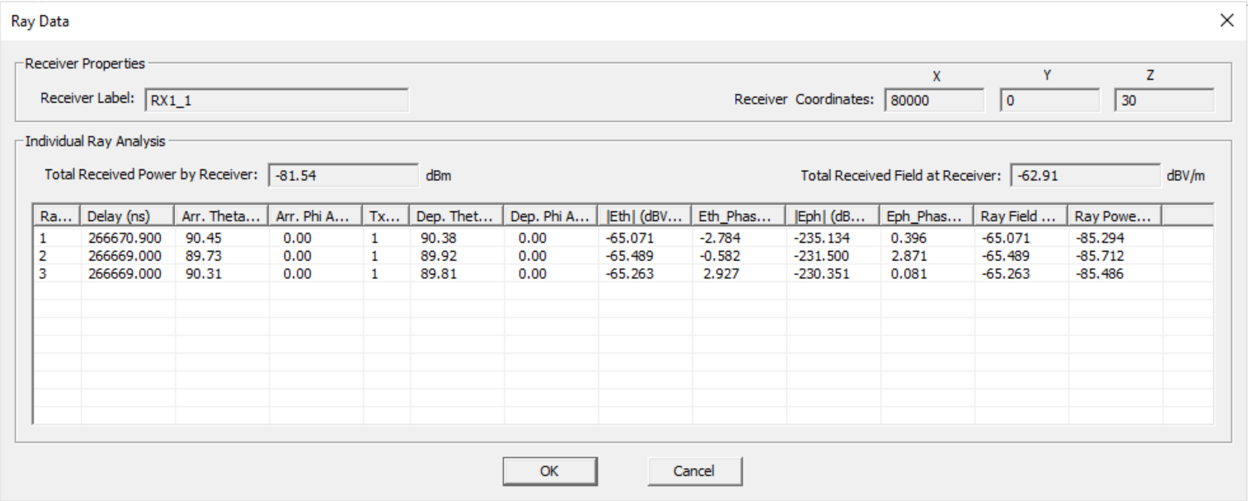
As you can see from Figure 14, there are three distinct rays that reach the receiver location. These are ducted rays as they hit an upper atmosphere layer and undergo total reflection. All the three rays are launched at a height of 50 m (h_{Tx}) on the left side and terminate at a height of 30 m (h_{Rx}) on the right side. Note that the three launch angles (angles of departure) as well as the three angles of arrival are all different.

14.9 Running Communication Link Solver for Non-Standard Atmospheric Propagation Scene

With the channel fully characterized, all the ray paths and ray parameters between the transmitter and receiver node pair are stored in the two data files “sbr_channel_matrix.DAT” and “sbr_ray_path.DAT”. Now you can run the **Communication Link Solver** to find the final solution of the problem with the vertically polarized dipole radiators serving as the transmit and receiver antennas. At the end of simulation, open the property dialog of the receiver set. The table below summarizes the signal and noise power data at the selected receiver:

Rx Index	Modulation	Received Power	Noise Power	SNR	Link Margin
1	None	-81.538 dBm	-94.472 dBm	12.934 dB	2.934dB

Open the Ray Data dialog to see the properties of the three individual ray solutions including their angles of departure and arrival as shown in Figure 15. Keep in mind that the ducted rays of Figure 14 have been plotted on an exaggerated scale as the horizontal axis spans 80km while the vertical axis spans 100m.



Receiver Label: RX1_1

Receiver Coordinates: X 80000 Y 0 Z 30

Total Received Power by Receiver: -81.54 dBm

Total Received Field at Receiver: -62.91 dBV/m

Ra...	Delay (ns)	Arr. Theta...	Arr. Phi A...	Tx...	Dep. Thet...	Dep. Phi A...	|Eth| (dBV...	Eth_Phas...	|Eph| (dB...	Eph_Phas...	Ray Field ...	Ray Powe...
1	266670.900	90.45	0.00	1	90.38	0.00	-65.071	-2.784	-235.134	0.396	-65.071	-85.294
2	266669.000	89.73	0.00	1	89.92	0.00	-65.489	-0.582	-231.500	2.871	-65.489	-85.712
3	266669.000	90.31	0.00	1	89.81	0.00	-65.263	2.927	-230.351	0.081	-65.263	-85.486

Figure 15. *The Ray Data dialog showing the properties of the ducted rays.*