Media and Assimilation:

Evidence from the Golden Age of Radio*

Radio Signal Computation Appendix

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Abstract

In this appendix, I give technical details on radio signal propagation through amplitude modulation (AM). I briefly introduce the different types of radio waves that work with AM focusing on the mechanics of ground waves. I provide details on how I use the LFMF Smooth Earth model to compute AM radio coverage. Finally, I replicate propagation curves provided by the ITU.

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1 AM Radio Propagation

Radio propagation is the phenomenon through which radio waves travel from one point to another. Depending what radio frequency is used to broadcast, there are different ways to transmit the electromagnetic waves that constitute the radio signal. The vast majority of broadcasters use amplitude modulation (AM) when transmitting signal on frequencies associated with short and medium wave lengths. Here, I maintain this focus, discussing exclusively the propagation of radio signal on the medium frequency band through amplitude modulation.[1]

AM radio signal on the medium frequency band propagates using two type of waves: ground waves and sky waves. Sky waves rely on the ionosphere to bounce back on earth and reach receiver antennas. During the day the solar activity does not allow the ionosphere to reflect AM radio waves back on Earth. Instead, ground waves spread out from the transmitter along the surface of the Earth allowing their use at any hour of the day and the night. Hence, day time transmission of AM radio signal exclusively relies on ground waves.

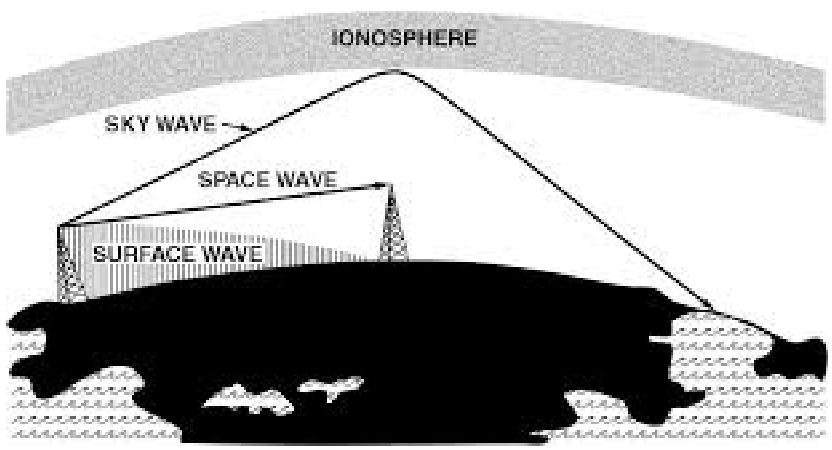


Figure 1: Sky Waves Versus Ground Waves

To reconstruct radio coverage of US stations during the interwar period, I exclusively focus on ground waves. The reason for this is twofold. First, sky waves allow for the coverage

[1]The engineering definition of the portion of radio spectrum characterized by medium wave length goes from 300 kHz to 3 MHz. In practice, what is usually devoted to broadcasting goes from approximately 500 kHz to 1700 kHz. Today the Federal Communication Commission has allocated the medium frequency band to be between 530 to 1700 kHz for the United States.

of areas extremely far, up to 3500km from the transmitting antenna. This implies that night coverage of radio networks in the interwar period would reach the entire continental US. Second, in the second part of the paper I investigate the adoption of baseball players names. During the interwar period, games were for the vast majority played with the light of the day.[2] Thus, in what follows, I give details on the mechanics of ground wave propagation. For a discussion of sky wave propagation in economics see **?**.

1.0.1 Ground Waves Propagation

Ground waves encompass all waves that are transmitted by a radio antenna and propagate through the area between the surface of the earth and the ionosphere.[3] Given a transmitting antenna, the voltage (field strength) induced in the receiving antenna, at an arbitrary position can be expressed by the following expression:

$$V = QI \left\{ Q_1 \frac{exp(-jkr_1)}{r_1} + Q_2 R \frac{exp(-jkr_2)}{r_2} + S \frac{exp(-jkr_2)}{r_2} \right\} \tag{1}$$

Where I is the current in the transmitting antenna, Q is a constant, $Q1$ and $Q2$ measure the transmitting- and receiving-antenna polar diagrams, R is a reflection coefficient, k is the radio wave number $k = 2\pi/\lambda$, r_1 is the straight line distance between transmitting and receiving antenna and r_2 is the straight line distance between transmitting antenna and the ground. The parameter S embodies an attenuation factor.

Each one of the three components in equation (1) reflects a subset of ground waves that determines field strength at the receiving end: space waves, composed by direct line waves and reflected waves, and surface waves.

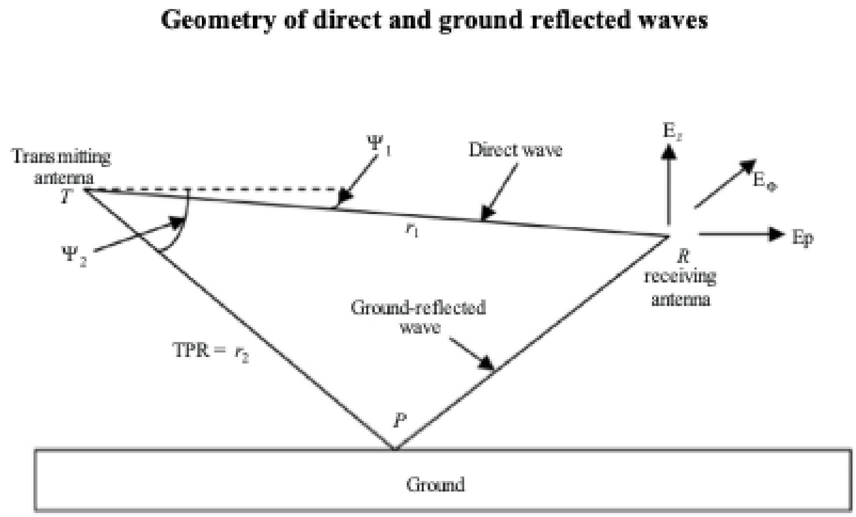
Space waves are typically formed by the direct wave — transmitting antenna to receiving antenna — and the waves that leave the antenna and bounce over natural obstacles (see Figure 2). Space waves are effective in reaching the receiving antenna only if this is within

[2]The first night game in Major League history was played in 1935. Until the 1940s only a very tiny fractions of the games were played at night.

[3]This section is heavily based on the ITU handbook on radio ground waves (**?**)

line of sight. If the receiving end is beyond the horizon, or both antennas are very close to the ground, the space waves are either zero or very negligible.

Figure 2: Propagation of the Space Wave Component of the Ground Wave

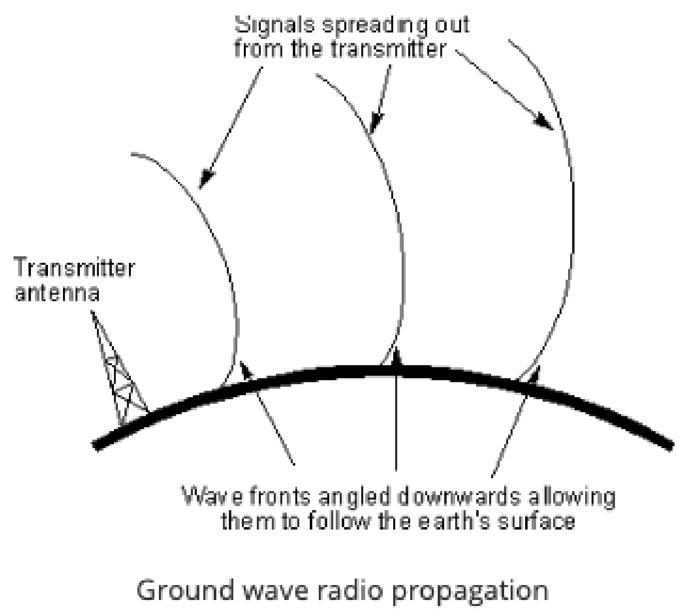


Surface waves are sometimes referred to as ground waves themselves. Instead of just following line of sight, like direct waves do, these waves tend to follow the curvature of the Earth. The reason for this is that currents in the surface of the earth cause the front of the wave to tilt downwards towards Earth (see Figure 3). This allows surface waves to curve around the Earth and reach receivers well beyond the horizon and beyond natural obstacles such as hills and mountains.

The rate of attenuation of the signal increases as it travels over a surface. This happens because the forward portion of the waves tilts even further. The speed with which this happens is regulated by an attenuation factor called complex dielectric permittivity. Large values of the attenuation factor correspond to a small forward tilt and therefore low attenuation and vice-versa.

The attenuation factor is determined by two elements: the electrical conductivity of the surface over which the wave travels and the broadcasting frequency. Sea water has an outstandingly high conductivity and the surface wave, with a near-vertical electric field, propagates over it with relatively low attenuation. On the other hand, surface-wave atten-

Figure 3: Propagation of the Surface Wave Component of the Ground Wave



uation is greatest over ground of low conductivity and at high radio frequencies. Within the realm of AM radio the role of the frequency band is limited. To predict field strength at the receiving location the key factor to accurately account in the computation is ground conductivity.

1.0.2 The Role of Soil Conductivity

Ground waves emanating out of the transmitting antenna pass over one or multiple surfaces before they reach a receiver. Different type of soils have different levels of electrical conductivity and affect the rate of attenuation factor of the ground wave. Hence, to confidently predict field strength at a certain distance from the transmitting antenna it is important to know the conductivity of the surface the wave is expected to travel over.

Table 1 summarizes for some type of soil their typical levels of conductivity expressed in siemens per meter ($\sigma_{s/m}$) and their permittivity.[4] By far, sea, especially if with high salinity,

[4]Permittivity is closely related to conductivity. It measures the ability of a substance to hold an electrical charge. Higher permittivity decreases attenuation of the wave

Table 1: Typical Conductivity Levels of Different Types of Soil

Soil Description	Conductivity ($\sigma_{s/m}$)	Permittivity (ϵ_r)
Polar Ice Cap	0.0001	1
Polar Ice	0.0003	3
Arctic Land	0.0005	3
Sea Ice	0.001	4
City Industrial	0.001	5
Dry, Sandy, Coastal	0.001	10
Fresh Water	0.001	80
Fertile Land	0.002	10
Rocky, Steep Hills	0.002	15
Moderate	0.003	4
Medium Hills And Forest	0.004	13
Average	0.005	13
Highly Moist Ground	0.005	30
Pastoral Hills, Rich Soil	0.007	17
Marshly Land, Densily Wooded	0.0075	12
Marshly, Forested, Flat	0.008	12
Rich Agric Land, Low Hills	0.010	15
Sea Water	5.0	81

Note: Source of the data is the Consultative Committee on International Radio (CCIR predecessor of the International Telecommunication Union) (**?**).

is the most conductive surface with 5 $\sigma_{s/m}$. Among land surfaces, wet grounds typically have the best conductivity. This makes farming areas on average very suitable for the propagation of ground waves. Dry and desert type lands are among the least conductive.

While Table 1 gives an idea of the conductivity for certain type of soils, measuring ground conductivity is cumbersome. Sampling soil is not enough because conductivity is determined by the type of soil even up to 25 meters below the immediate surface, requiring the use of vector network analyzers in conjunction with specific wire lines. For this reason, individuals interested in predicting field strength rely on conductivity contour maps published by International Telecommunication Union or, in the US, by the Federal Communication Commission.

1.1 Implementation of the LMLF Ground Wave Propagation Model

To predict radio ground waves we borrowed the propagation model made available from the International Telecommunication Union (ITU). The original software from the ITU is easily downloadable from the ITU webpage that collects software, data and validation exercises concerning radio wave propagation and radio noise.[5] Specifically, we retrieved the LFMF-SmoothEarth model which was designed for the ground-wave propagation for frequencies between 10 kHz and 30 MHz, a frequency span that included the frequencies used by AM radio stations during the interwar period. To fasten the computation of radio coverage we implemented the model in Python.

The model works by collecting an array of inputs and computing point to point (antenna to receiver) propagation. The output of the model is the electric field strength (signal strength) at the receiver location expressed in decibels referenced to 1 microvolt per meter (dBμV/m). The model inputs are the following:

- h_tx_m: height of the transmitter in meter
- h_rx_m: height of the receiver in meter
- f_mhz: frequency of broadcast in mHz
- p_tx_watt: power of transmission in watts
- n_s: surface refractivity
- d_km: distance in km
- ϵ: relative permittivity on the surface of the earth
- σ: ground conductivity (siemens by meters)
- pol: polarization

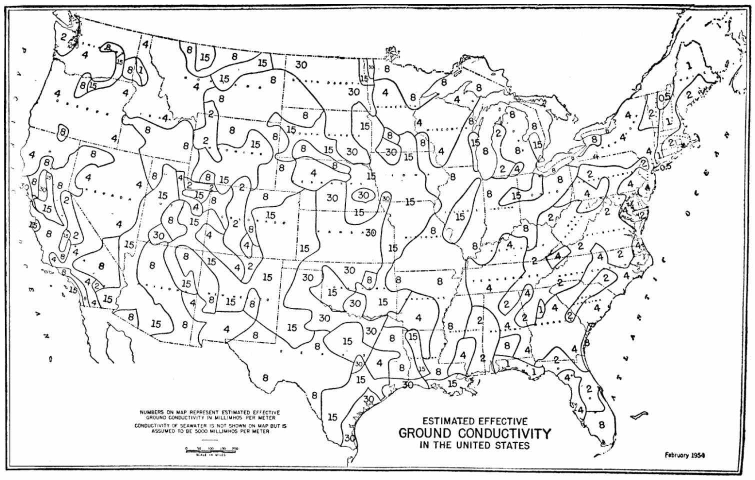
We start by collecting data on US radio stations active in January 1929. Digitizing their technical informations allows us to observe some of the parameters listed above. We run the

[5] Webpage available at this link

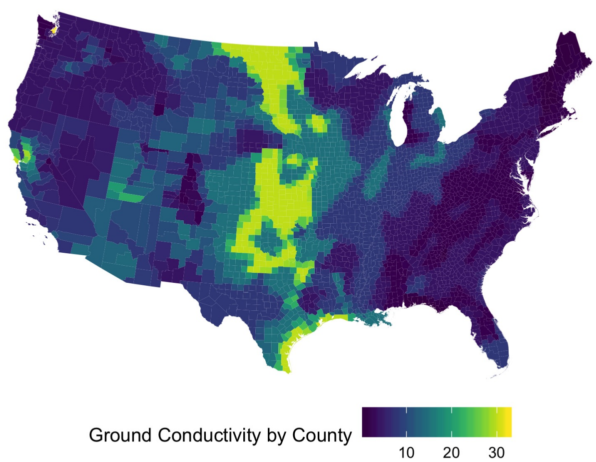
LFMF model on each combination radio transmitter-receiver, where as receiver we use the centroid of all US counties. At this point we are able to fill in most of the inputs: transmitter heights data is partially missing, we impute it using the average in the non-missing sample. We assume receiver height to be equal to 10 meters for all centroids. We obtain frequency and power of the antennas from the station data and calculate the distance in km between all antennas and receivers. We assume surface refractivity to be constant and use the average value observed in the country that is 313 (**?**). To determine relative permittivity I use an approximation provided by the FCC that uses levels of ground conductivity to approximate values of permittivity. Given the historical and technical background, we set polarization to vertical. The only parameter left to determine is ground conductivity.

Computation of ground conductivity. We obtain county-level data on US ground conductivity. Such data is constructed by digitizing the ground conductivity map from the FCC. Figure 4a shows the original source of the data which can be retrieved at this link. A rendering of the county level conductivity is presented in figure 4b.

The LFMF model allows for the inclusion of a single input of soil conductivity for each station to receiver signal computation. However, in reality the radio wave emitted by a transmitter might face different types of land and conductivities. To construct this single value of conductivity I take the weighted average of all the values of conductivity faced by the signal, weighted by the length of each single conductivity segment. This procedure allows me to approximate the average conductivity faced by the radio wave, giving higher weight to the conductivities over which the wave travels longer.



(a) FCC Original Ground Conductivity Map



(b) County-Level Ground Conductivity Map

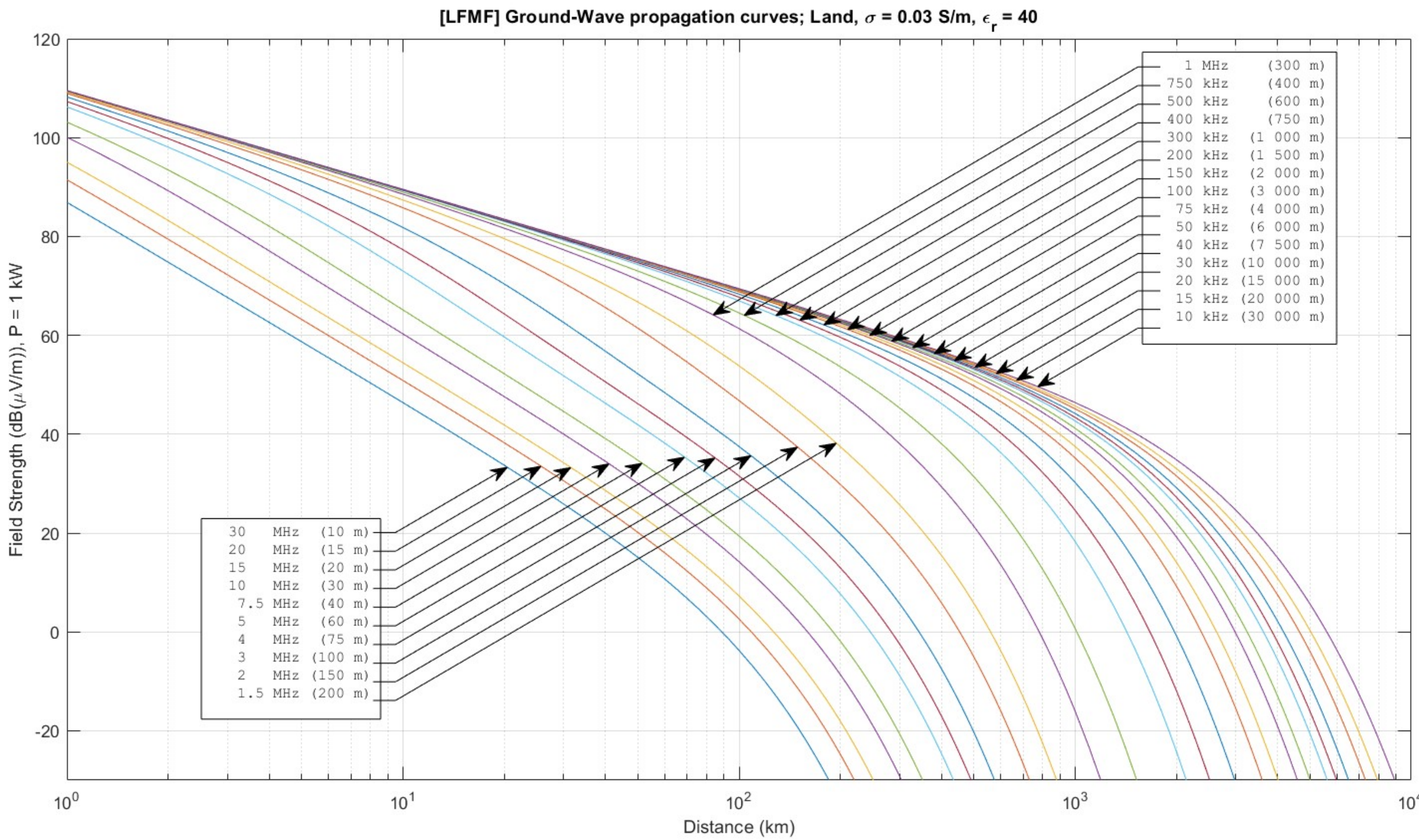
Figure 4: US Ground Conductivity. The source of the map in panel (a) is the Federal Communication Commission and dates back to 1954. Panel (b) is the same map digitized and aggregated at the county-level.

1.1.1 Validation Exercise

To test that we correctly utilize the LFMF model we replicate one of the propagation curves provided by the ITU. Figure 5 displays a set of propagation curves computed and provided by the ITU for a given value of ground conductivity and permittivity $\sigma = .03S/m$, $\epsilon = 40$. The graph plots the field strength values on the y-axis for different values of distance values on the x-axis. The curves show the field strength reached by a ground wave emitted by a transmitter vertically polarized with power $p\_tx = 1kW$, height $h\_tx\_m = 15$, receiver height $h\_rx\_m = 10$, for a range of frequency values f_mhz. Refractivity is fixed at mean value observer in continental US $n\_s = 315$.

We replicate one of the propagation curves above for a given value of frequency $f\_mhz = .5mHz$ in Figure 6. We hold the rest of the values as in the ITU curves. The output of the propagation shows field strength values for the first 200km. Our replication shows a field strength of 89.17 at 10km from the transmitter. Inspecting the correct propagation curve (associated to 500 kHz, the third frequency from the top in the legend on the right side of the graph, the curve is painted in light blue), we find that the corresponding field strength at 10km falls exactly in between 80 and 100 dBμV/m. Similarly, at 100km we compute a field strength equal to 66.88dBμV/m which matches the propagation curve value at the same distance. Our short replication exercise suggests that we correctly implement the LFMF model.

Figure 5: ITU LFMF Propagation Curves, $\sigma = .03S/m$, $\epsilon = 40$



Notes: The propagation curves are computed and provided by the ITU for several combinations of ground conductivity and permittivity. The graph plots the field strength reached by a ground wave emitted by a transmitter vertically polarized with power $p\_tx = 1kW$, height $h\_tx\_m = 15$, receiver height $h\_rx\_m = 10$, for a range of distance values and frequency values f_mhz. Refractivity is fixed at mean value observer in continental US $n\_s = 315$.

Figure 6: Replication of ITU LFMF Propagation Curve, $\sigma = .03S/m$, $\epsilon = 40$, $f\_mhz = .5$ mHz

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ATMOSPHERIC CONSTANTS
    REFRACTIVITY =315.00  (N-UNITS)
    SCALE HEIGHT = 7.350  KM

GROUND CONSTANTS
    RELATIVE PERMITTIVITY =    40.000
    CONDUCTIVITY =3.0000D-02  SIEMENS/METRE

VERTICAL POLARISATION

MINIMUM DISTANCE =    10.000  KILOMETRES
MAXIMUM DISTANCE =   200.000  KILOMETRES
DSTEP            =    10.000  KILOMETRES


FREQUENCY =    0.500 MHZ

TRANSMITTER HEIGHT =    15.0  METRES
RECIEVER HEIGHT    =    10.0  METRES

DISTANCE      FIELD STRENGTH     BASIC TRANSMISSION LOSS
  KM            DB(UV/M)               DB            (F)
    10.00          89.17               46.76
    20.00          82.90               53.03
    30.00          79.13               56.80
    40.00          76.38               59.55
    46.61          74.89               61.05
                                                      (R)
    46.61          74.91               61.02
    50.00          74.22               61.71
    60.00          72.39               63.55
    70.00          70.79               65.15
    80.00          69.37               66.57
    90.00          68.07               67.86
   100.00          66.88               69.05
   110.00          65.78               70.15
   120.00          64.74               71.19
   130.00          63.77               72.16
   140.00          62.84               73.09
   150.00          61.95               73.98
   160.00          61.10               74.83
   170.00          60.29               75.65
   180.00          59.50               76.44
   190.00          58.73               77.20
   200.00          57.99               77.94
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Notes: We replicate the propagation curves in Figure 5 for a given value of frequency $f\_mhz = .5$ mHz. We fix the rest of the values as in the ITU curves $p\_tx = 1kW$, $h\_tx\_m = 15$, $h\_rx\_m = 10$, $n\_s = 315$.