VHF/UHF Propagation Basics for Radio Amateurs

Christian Volle DL7AYD

Version 1.01 as of September 1, 2013

Abstract

The intention of this article is to explain the fundamentals of VHF/UHF radio wave propagation in the vicinity of earth. According to the nature of those frequencies we will disregard atmospheric and ionospheric effects in this article. Instead we will focus on the quasi optical behaviour of radio waves and their way of interacting with obstacles along their propagation path. It is reflection and phase interference we will put our attention to.

This article primarily addresses radio amateurs and other persons involved in wireless communication practice. Be it a simple walkie-talkie communication or a sophisticated repeater station set up – understanding propagation basics enables you to evaluate an individual radio link and to take the right steps for improvement.

In the first chapter we will briefly look at some physical facts we need to know later in the text, some of which you can see with your own eyes everyday – but you may not have noticed them yet. The second chapter will cover some rather theoretical but important concepts of radio wave propagation. In the third chapter I will introduce practical (empirical) models of propagation which effectively can be (and have been) used in real life. Last but not least in the fourth chapter I will introduce a very useful spreadsheet file for quick and easy calculation of radio ranges.

Contents

1 Important Physical Effects

In this section I like to remind the reader of some facts of physics, which we should be aware of when discussing radio wave propagation. As mathematical formulae may seem quite unattractive for most non-specialist readers, I will avoid them here. Hence I will not prove my statements. Those who are interested in the details I have to point to the technical literature mentioned in the reference section.

1.1 Is Ground an Electrical Conductor?

Often radio amateurs talk about "conducting ground", especially when discussing vertical monopole antennas for the low bands. The sand, soil and stone we walk on are supposed to be electrical conductors. Let's check this thesis.

1.1.1 Conductivity of Common Materials

The influence of any material on electromagnetic fields is determined by the three characteristic properties: magnetic permeability (μ), permittivity (ε) and electric conductivity (σ). In this text we will focus on the latter and ignore the other two. Table 1 shows the conductivity of various common materials.

The term conductivity and its unit S/m (Siemens per meter) is difficult to wield and most of us are not used to it. To overcome this problem the third column represents the conductivity by the resistance of a sample volume. Imagine the material in question is shaped like a cylindrical body of 10 cm length and 1 mm diameter – like a straight piece of wire as shown in figure 1. If you now measured the electrical resistance of that body from one end to the other, your ohmmeter would indicate the value given in the table. It may seem weird to imagine a piece of wire made of water or sand, but it helps to evaluate the materials ability to conduct electric current in the familiar unit Ω (Ohm).

Please compare the sample resistance of copper to the various ground materials given in the table. It appears quite clear that ground is not a conductor but rather a poor insulator. Even sea water is not a reasonable conductor but a very bad one. Its ability to conduct electric current is worse than iron by a factor of two million!

material	conductivity σ in S/m	sample resistance R in Ω
copper	58 000 000.0	0.002
aluminium	36 000 000.0	0.004
iron	10 000 000.0	0.013
stainless steel	1 400 000.0	0.091
seawater	5.0	26 000.0
tap water	0.05	2 600 000.0
pure water	0.000 005	26 000 000 000.0
ground, wet	$\sim$ 0.03	4 200 000.0
ground, dry	$\sim$ 0.001	1 300 000 000.0
concrete, wet	$\sim$ 0.04	3 200 000.0
concrete, dry	$\sim$ 0.01	13 000 000.0
granite rock	$\sim$ 0.000 001	130 000 000 000.0
PE, PP, PVC	$\sim$ 0.000 000 000 000 000 1	$1.3 \cdot 10^{21}$
air	0.0	infinite

Table 1: electrical conductivity of various materials [18] [19]

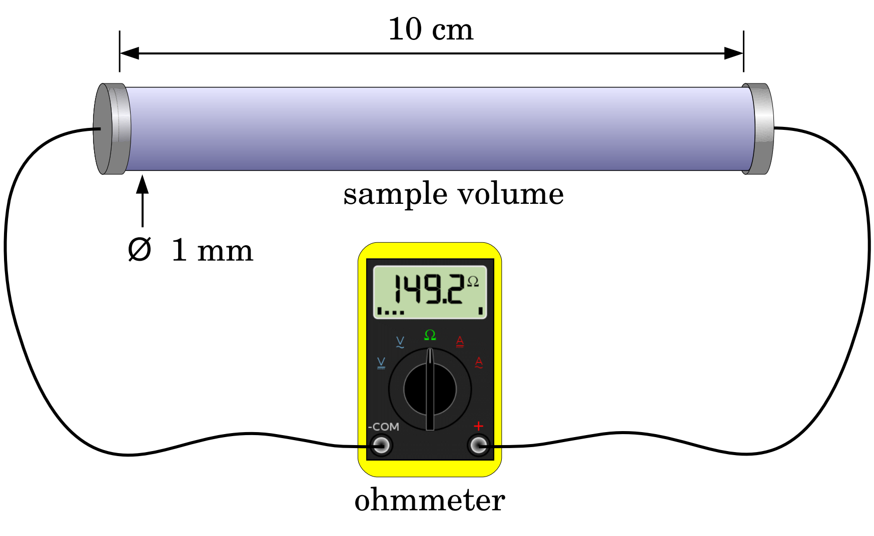


Figure 1: sample volume of arbitrary material and the virtual measurement of its electrical resistance from one end to the other with an ohmmeter.

1.1.2 Conductivity and Losses

Most solid non-conducting materials exhibit losses. A radio wave propagating through a lossy material experiences excess attenuation and will die out after having travelled a certain distance through the material. The radio wave effectively warms up the material thereby losing its energy. One of the reasons for such losses is (usually unwanted) conductivity. There are more effects to participate in electromagnetic losses, but we will not discuss them in this text. As an example for losses please consider your microwave oven, where water (marginally conductive material) heats up while your dishes (almost perfectly non-conducting material) do not.

1.1.3 Conclusion

Ground, water and concrete as shown in Table 1 are very difficult materials. Their conductivity is far too low for being a conductor but it is too high for being a good insulator, and as a result they exhibit strong losses to any radio wave penetrating them.

1.2 Reflection on Perfectly Smooth Surfaces

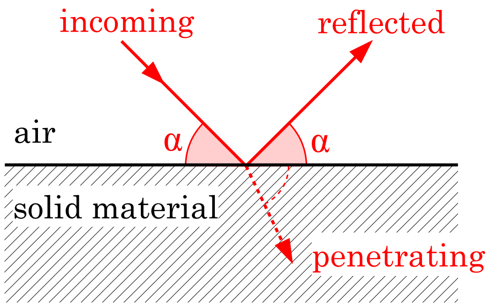
At the bounding surface of two different materials only a fraction of an incoming radio wave can enter the other material. A significant portion of it is reflected from the surface. When talking about radio wave propagation one of the materials is usually air. So we will focus on the other material and its surface.

The grade of reflection, i. e. the ratio of the reflected radio wave to the incoming radio wave, is called *reflection coefficient* or *reflection factor*. It tells us how much of the incoming wave is reflected – as a percentage of the amplitude. Note that engineers like to use dB instead of %, but in this text we will use the latter.

Reflection occurs with any electromagnetic wave, be it radio or light. So we can use our eyes to prove interesting effects which are valid for radio waves in general:

1.2.1 Conductors

On the surface of a well conducting material the reflection factor is very high, for radio waves as well as for light. Metals are highly conductive. They appear shiny to us because of their ability to reflect light. Smooth and polished surfaces of metal are excellent reflectors for use in optical systems or as mirrors at home.



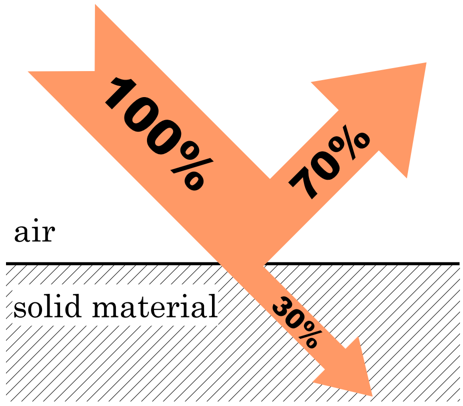


Figure 2: The figure on the left shows the behaviour of an incoming radio wave at a smooth surface. The angle of arrival is equal to the angle of departure of the reflected wave. The angle of departure of the penetrating wave may differ significantly. The figure on the right shows an example of a reflection factor of 70 %. The reflected wave's amplitude is 70 % of the incomings waves amplitude.

1.2.2 Non-Conductors

On the surface of a non or marginally conducting material the reflection factor depends on the permittivity of the material. But more important it depends on the angle at which the incoming radio wave arrives on the surface. The lower the angle the higher the reflection factor. At incident angles of a few degrees the reflection coefficient is very close to 100%. Smooth surfaces of plastic, glass or water appear shiny to us and they are able to faintly mirror our faces as we look at them. But at very low angles of observation they appear to be perfect reflectors. You can easily watch this effect on water surfaces, when you see a perfect upside down image of the opposite shore right on the surface of a calm lake as in figure 3. The figures 4 and 5 clearly show the difference in low and high angle reflection coefficient.

1.3 Reflection on Rough Surfaces

Rough surfaces are no good reflectors. They scatter incoming light or radio waves in all possible directions. Look at a white sheet of paper: can you mirror yourself in the sheet? No one would use a rough surface of any material as a mirror. But there is an amazing physical effect to prove us wrong: The adverse influence of surface roughness highly depends on the angle of arrival. At very low angles even rather rough surfaces appear polished and mirror perfect images. As a rule of thumb we can expect perfect image reflection at angles below 4° if the roughness height is smaller than the wavelength. For optical purposes this is difficult to achieve, so perfect image angles are very

Figure 3: Almost perfect image reflection of the opposite shore in a calm lake. The water's surface is a very smooth boundary of two non conducting materials.

low. But for radio waves with lengths of meters a new ploughed field appears as a perfectly smooth and highly reflective surface! You can actually see this effect in a simple experiment: Take a look at the mat but even surface of modern veneer furniture, e.g. the top of a desk or a dresser. Move down your head and look at this surface at a very low angle. It will appear highly glossy. The figures 6 and 7 show this experiment.

Figure 4: Reflection experiment. In the red zone, close to the observer, you can see the ground of the shallow pond. Reflection of the sky is poor at this point. Unlike in the blue zone, further away from the observer, where the reflection of the sky is very strong, you cannot see the ground anymore.

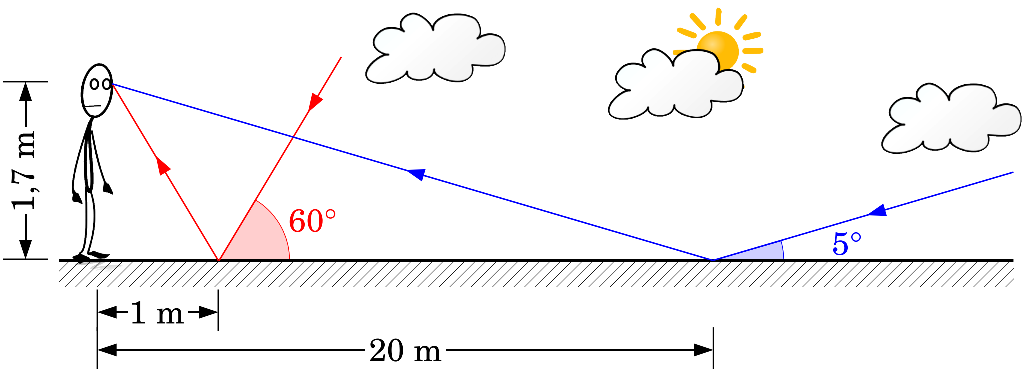


Figure 5: Set up for the reflection experiment. Reflection at high angles of arrival (red) is poor, while at very low angles of arrival (blue) it becomes extremely good.

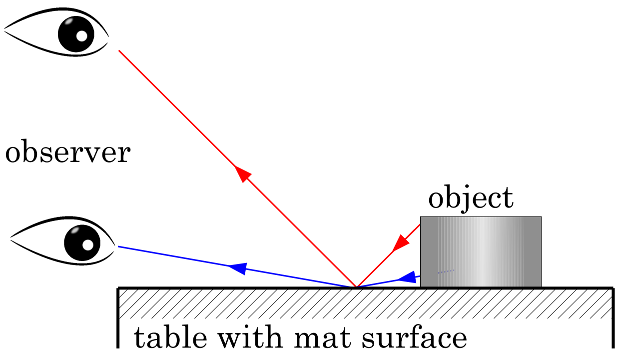


Figure 6: A rough surface of a desk may not seem to be a good reflector. However at very low viewing angles you can see clear images of objects mirroring in the desks surface.

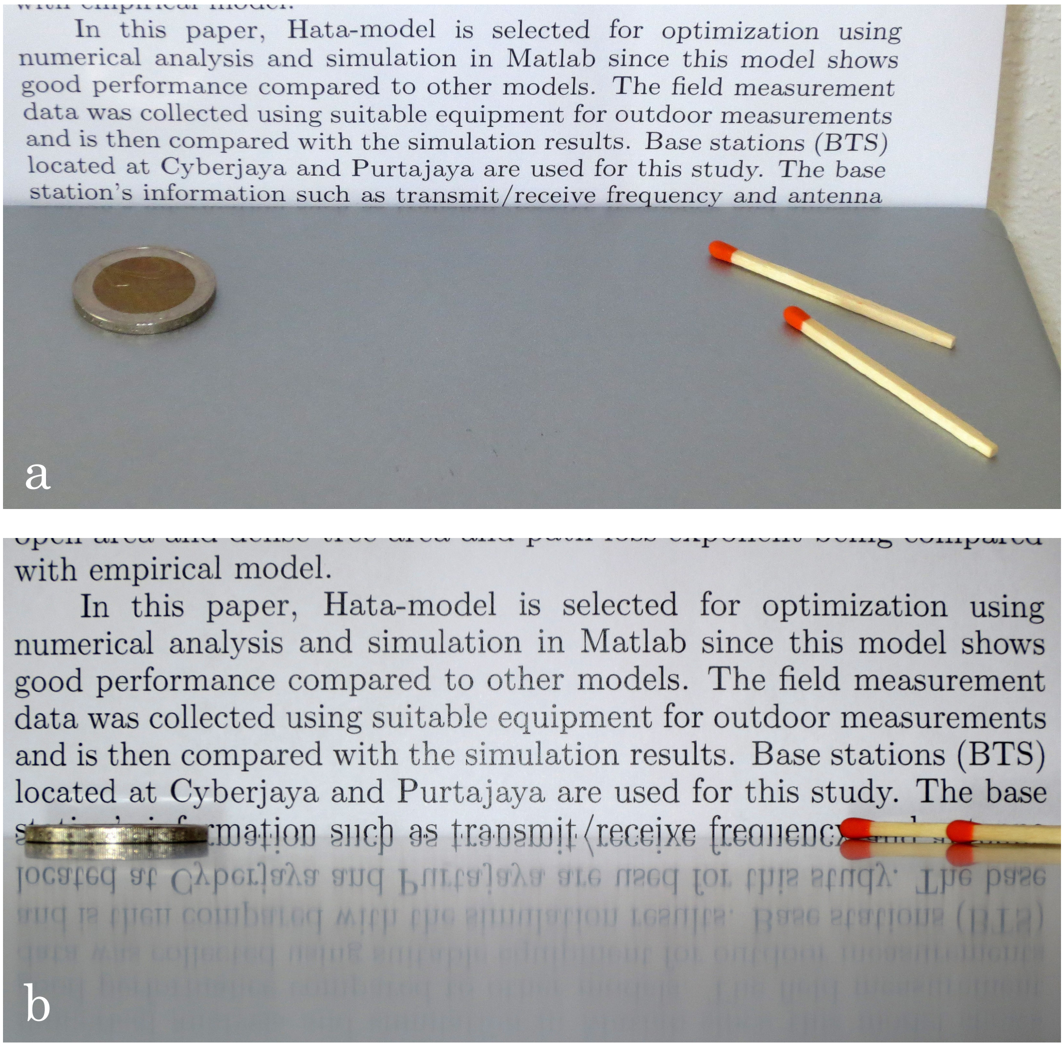


Figure 7: Example of a desks surface seeming mat at first sight (a), but providing clear image reflection at low observation angles (b).

2 Physical Propagation Models

We will now investigate the basic principles of radio propagation and look at two standard models of a radio path.

2.1 Free Space Model

This is the prototype of a radio path, the most simple configuration of a transmitter and a receiver. All attempts to determine the properties of a radio path were and will be started with these thoughts:

2.1.1 Path Loss

Consider a transmitter and a receiver in free space. No other objects, no obstacles, no ground, no planet earth – just free space. The transmitter continuously transmits a radio wave of constant power and frequency in any direction with a totally non directional antenna, a so called *isotropic* antenna. The radio waves extend into space in a spherical way around their origin. The receiver is equipped with the same perfectly non directional antenna. It detects the radio signal and determines its power.

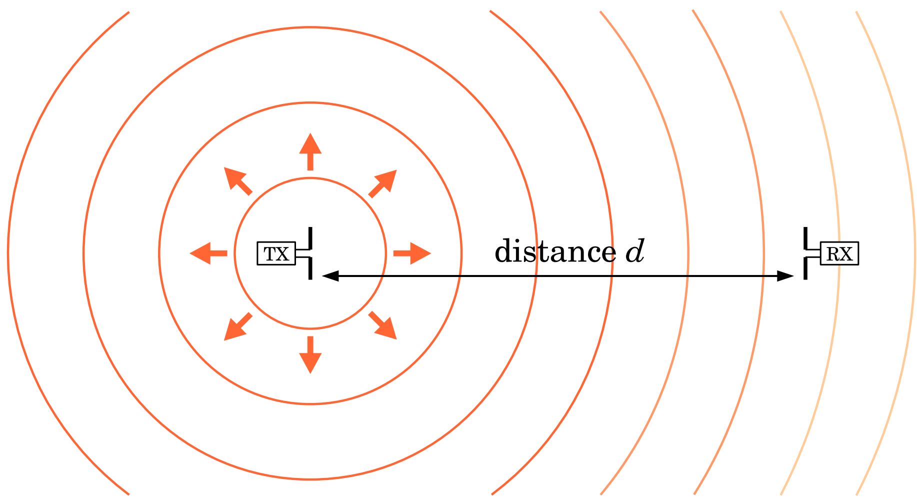


Figure 8: A transmitter and a receiver at some distance in free space. Radio waves extend into space in a purely spherical way around their transmitter.

A small portion only of the power transmitted by the transmitter will be detected at the receiver. This is because the transmitter casts its power in all directions and just a fraction of it heads towards the receiver. As received power is less than transmitted power, radio engineers talk about *path loss*.

This is not quite true, because there is no physical loss in power along the path, it is just that the receiver cannot pick up all the available power. So it merely appears to be a loss and we accept the term path loss. If the receiver is moved away from the transmitter, the receiving power will decrease. For every doubling of the distance, the received power will be reduced by a factor of four.

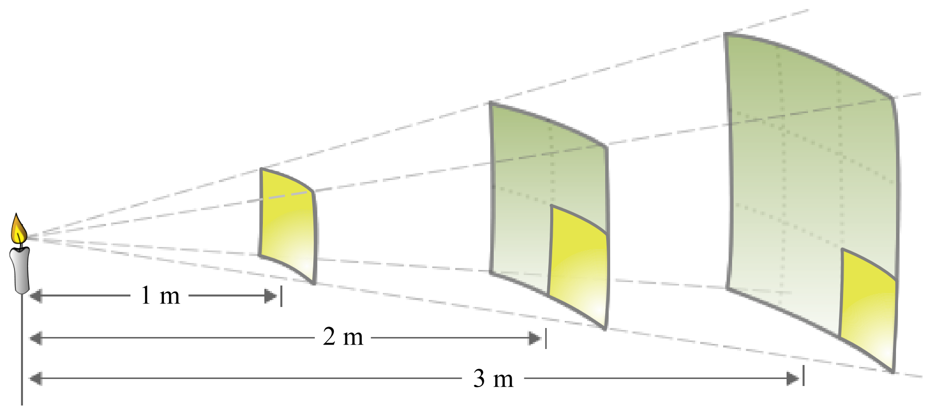


Figure 9: Example: light emitted by a candle. The same amount of light to illuminate a square sheet of paper in one metre distance from the candle will have to illuminate an area fitting four sheets of paper in two metres distance. So holding our paper at two metres distance it would receive only a quarter of the light it did at one metre distance.

2.1.2 Square Law

The effect mentioned is called the square law and is true for of any kind of spherical propagation, be it radio wave, light or even sound. The reason for the square law is purely geometrical, it is not a speciality of radio waves as the example in figure 9 shows. The receiver's antenna can only pick up radio waves within a certain area. This *effective area* is characteristic for every antenna. Only those radio waves passing through this area will be picked up by the receiver. If you now double the distance to the transmitter the receivers effective area needs to be four times as big to pick up the same radio power. But as it is not, it picks up a quarter only. If you triple the distance, it picks up the ninth part only, and so on. The effective area of an antenna is proportional to the square of the wavelength, so we can observe that the received power depends on frequency, too.

2.1.3 Conclusion

For the given free space scenario with ideal, isotropic antennas the receiving signal strength can be calculated by the formula below. P_{RX} is the received power in W, P_{TX} the transmitted power in W, λ the wavelength in m and d the distance between transmitter and receiver in m.

$$P_{RX} = P_{TX} \cdot \left(\frac{\lambda^2}{16 \cdot \pi^2 \cdot d^2} \right) \tag{1}$$

Hence the signal power at the receiving antenna depends on the following parameters:

Distance: Doubling distance reduces receiving power by factor four. In other words: for doubling the radio range power needs to be increased by factor four.

Frequency: Doubling frequency reduces receiving power by factor four. In other words: for doubling the radio range frequency needs to be decreased by factor four.

2.1.4 Limitations

The free space propagation model is based on a very simple scenario. To use this model in real world applications quite some restrictions apply:

- No obstacles allowed in or even near the line of sight between transmitter and receiver.
- No surfaces or objects of any kind allowed in the vicinity of the complete set-up.
- No atmospheric or ionospheric effects allowed.

In fact the model is not suitable for terrestrial radio links, as the presence of earth will violate the restrictions in the majority of cases. However for aviation and space communication this is the model of choice unless atmospheric or ionospheric effects become an issue. I like to mention that this is the best possible case for a radio link. There is no better way for a radio wave to travel from here to there, unless wave guides or cables are used.

2.2 Plane Earth Model

This model extends the free space model by a plane earth surface. It is the prototype for many modern terrestrial propagation models.

2.2.1 A Second Path

In a more realistic approach we consider the transmitter and the receiver of the free space model to be now located in the vicinity to the earth's surface, somewhere above ground. For simplification let us assume earth is a disk and not a sphere and ground is an endless plane without obstacles of any kind. Also there shall be no atmospheric effects. As we learned before, ground is indeed not a conductor, but nevertheless an equally excellent reflector for radio waves coming in at low angle. In this situation we have to face two propagation paths, one of which is the direct path from the transmitter to the receiver, and the other is the reflected path via the ground surface. In most real world applications, the distance between transmitter and receiver is much larger than their height above ground. So we can assume very low angles of arrival in the majority of cases.

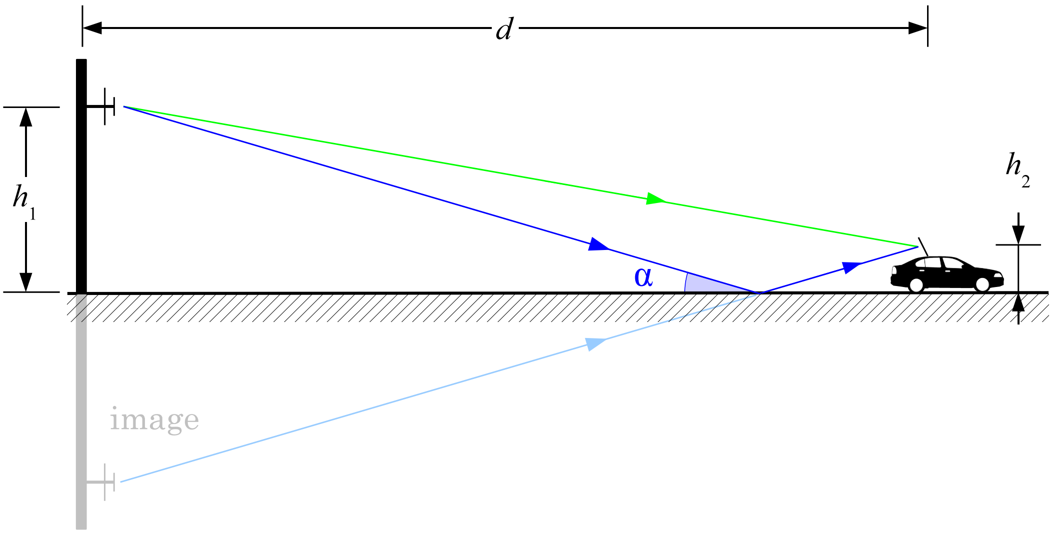


Figure 10: There are two propagation paths available for the situation shown. The direct path as well as the reflected path. The receiver can virtually "see" two transmitters.

In fact the receiver sees two transmitters, the real one as well as its image on the ground. It is the same effect that happens to you when you see a clear image of the opposite shore in a calm lake. Thanks to the ground the receiver now receives twice as much power from the transmitter. Sounds like an advantage, but don't count your chickens before they hatch!

2.2.2 Phase Interference and Extinction

Unfortunately the reflecting path experiences phase reversal caused by the reflection at the ground plane. Remember that two signals of the same amplitude and frequency but some phase difference will interfere. At a phase difference of 180° they will even extinguish. And this is what happens here. The reflected signal deletes the direct signal at the receiver! Fortunately the two signals have to travel different lengths of path until they eventually arrive at the receiving antenna. This creates some additional phase shift and reduces the effect of extinction.

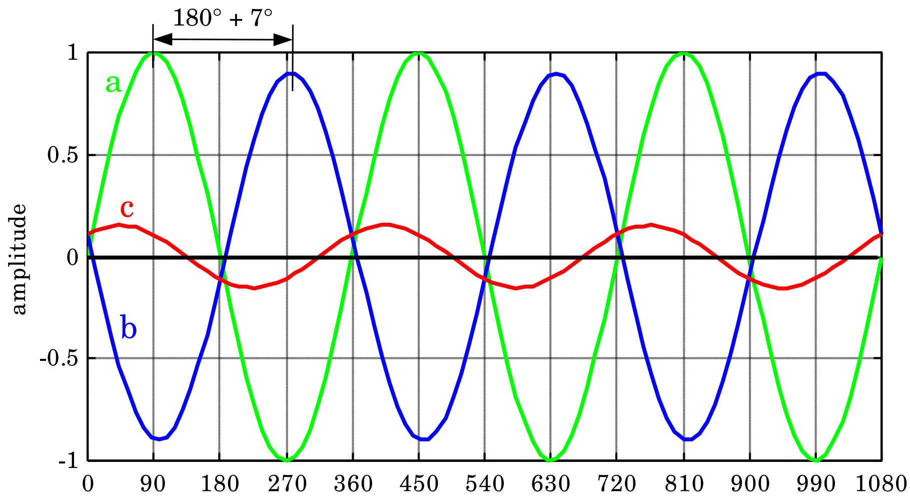


Figure 11: The reflected signal (a) and the direct signal (b) at the receiving antenna. The reflected signal comes in with some additional delay (7° in this example) because of its longer path length. Note that the sum of both signals (c) is very small.

If either the receiver or the transmitter is located directly at the ground plane, the path length difference is zero and radio transmissions become impossible! The further off the ground plane we place receiver and transmitter, the higher the additional phase shift and the lower the adverse phase interference. With some exceptions it is not a matter of radio horizon but of the most unfavourable influence of ground which makes engineers set up antennas on tall buildings and high towers even in flat countries. So if you learn one lesson today, it should be the following: Get your antenna up and off the ground!

2.2.3 Conclusion

The formula to calculate the received power in a given plane earth scenario is surprisingly simple. Again P_{RX} is the received power in W, P_{TX} the transmitted power in W and d the distance between transmitter and receiver in m. h_{TX} and h_{RX} are the heights above ground of transmitter and receiver respectively.

$$P_{RX} = P_{TX} \cdot \left(\frac{h_{TX}^2 \cdot h_{RX}^2}{d^4} \right) \tag{2}$$

The signal power at the receiving antenna depends on following conditions:

Distance: Doubling distance reduces receiving power by factor sixteen! In other words: for doubling the radio range power needs to be increased by factor sixteen (12 dB).

Antenna height: Doubling the height above ground of either antenna will increase receiving power by factor four. In other words: for doubling the radio range the height of either antenna needs to be increased by factor four.

The plane earth model is independent of frequency or wavelength!

2.2.4 Limitations

The plane earth propagation model is based on a very ideal scenario and on quite a number of simplifications. To effectively use it in real world applications the following restrictions apply:

- A plane earth scenario in the true sense of the meaning. This means no obstacles, no irregularities, no hills, no significant vegetation, no buildings.
- The distance between transmitter and receiver must be large compared to the antenna heights to assure low angle of arrival and high reflection factor. ($d >> h_{RX} \cdot h_{TX}$)
- The distance between transmitter and receiver must be short enough for earth curvature not to be an issue. As a rule of thumb the limit would be around eight km.
- No atmospheric effects.

2.3 Fresnel Zone

2.3.1 Extension of the Plane Earth Model

If we extend the limits of the plane earth model just a little bit, we have to admit the unfavourable reflection needs not to take place on the ground only. It may also be the top of a building or a natural structure which causes the reflection. So we should think about a definition of how far away must a structure be not to have adverse influence on the desired radio link. Let us consider a reflected path of which the length difference is half a wavelength (180° in terms of phase). In this case the reflected wave would arrive at the receiving antenna in phase with the direct path. Their interference would be most advantageous as received power would double. If we marked all possible positions of reflectors, which lead to this favourable interference, the markings would form a three-dimensional ellipse centred around the direct path.

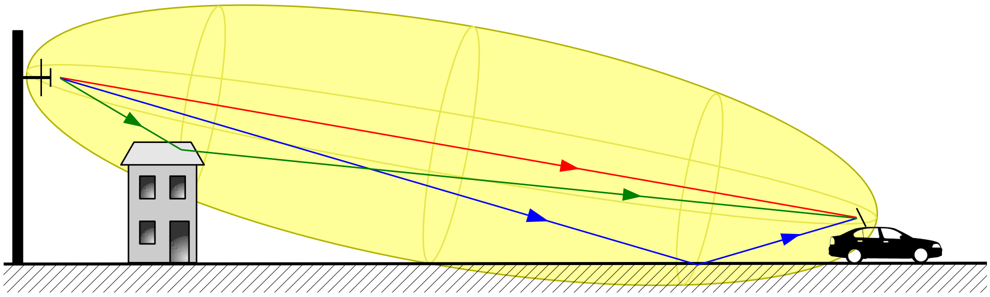


Figure 12: First Fresnel ellipsoid with the direct path (red) and two reflected paths (green and blue). Both, the reflection on the ground as well as the one on the building take place inside the ellipsoid and will significantly degrade free space propagation.

2.3.2 The First Fresnel Ellipsoid

This three-dimensional ellipse (mathematicians call it *ellipsoid*) is called the *first Fresnel ellipsoid* or simply *Fresnel zone*. Reflecting objects inside the Fresnel zone will cause degradation of the radio link due to unfavourable phase shift. Objects outside this zone can be ignored, because their reflection does no harm - either because of beneficial phase difference or because of harmless signal power due to significantly extended path length.

I like to mention that this is a very simple explanation of Fresnel ellipsoids. The detailed definition is based on very complicated calculations of shadowing and diffraction effects but the result is equivalent.

2.3.3 Conclusion and Example

As a general result we can state: if the Fresnel zone is free of obstacles and free of reflecting surfaces, the free space model becomes valid for this radio link. This is the best case possible.

Unfortunately the Fresnel zone is very big. The diameter at its thickest point is $\sqrt{d \cdot \lambda}$ with wavelength λ and distance d of transmitter and receiver, both in m. If you set up a radio link in the two metre band across a distance of five km the diameter of the ellipsoid is 100 m at its thickest point. To remove the adverse effect of the ground both the transmitter and the receiver would have to be mounted on 50 m towers each. To allow for any other obstacles the towers should be even higher. This is hardly a realistic solution for mobile radios!

3 Empirical Propagation Models

We will now take a look at two practical, so called *empirical* models. They are based on real world measurements and intend to give better results than the highly idealised physical models of the above section. Nevertheless empirical models are restricted to certain environments. As they are usually developed from a huge number of measurements, their results are of statistical nature. They will not produce precise numbers for your dedicated radio link scenario. They will produce benchmarks which will agree with reality with a certain likelihood – provided that your radio link environment complies with the limitations of the model.

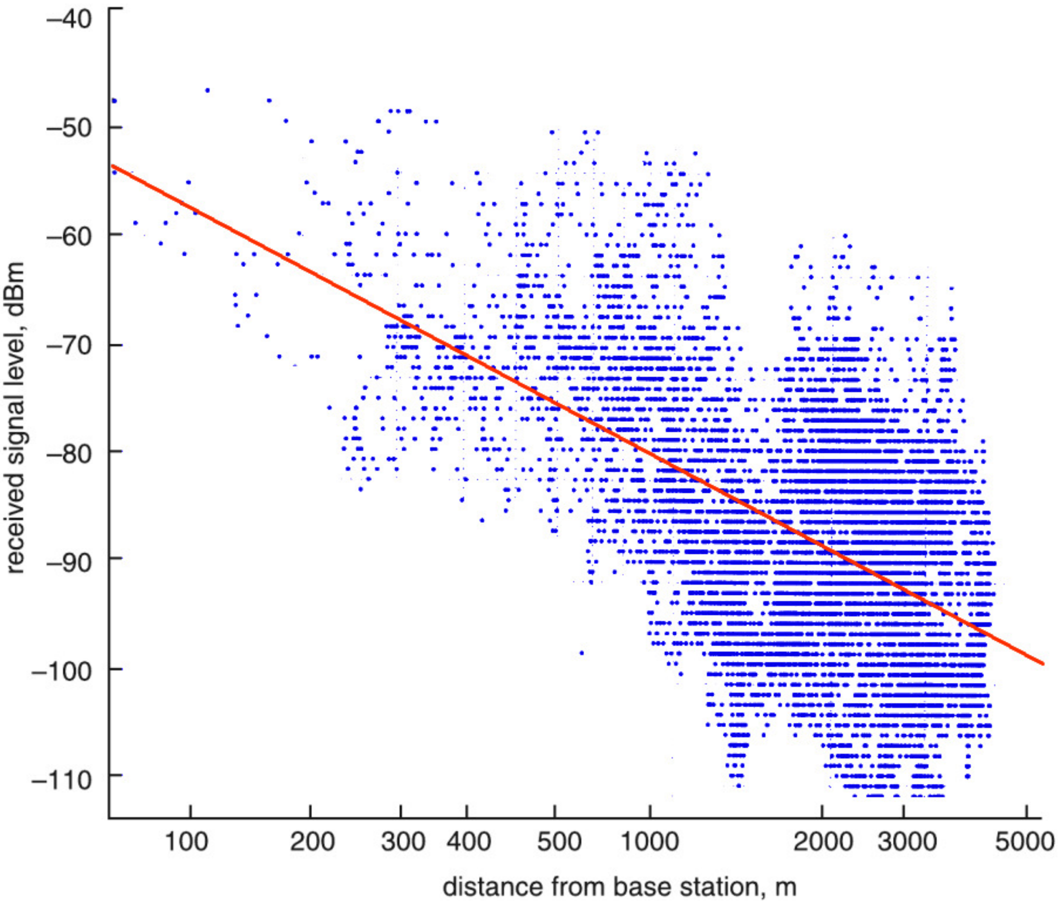


Figure 13: This is an example of a very basic empirical propagation model. The blue dots are the results of thousands of signal strength measurements of a transmitter at various locations and distances. Depending on the terrain the signal strength at a given distance may very heavily. The red line is a very simple model to predict the signal strength at a given distance. In this case prediction is not very precise. Diagram copied from [3].

3.1 Egli's Model

In 1957 a radio engineer called John Egli investigated radio propagation effects to improve the existing plane earth model. He performed extensive signal strength measurements of VHF/UHF transmitters in New Jersey, United States. [10]

3.1.1 Derivation of the Model

As expected, Egli's measurement results differed from the basic plane earth model discussed above. He found generally higher path loss and, in contrast to the basic model, a dependency of frequency. He made a statistical analysis of his results and found a simple frequency dependent correction factor to supplement the plane earth model to fit his measurements. The results of Egli's model are usually given as the median value. This means you can expect 50 % of the real world results to be above this value. In other words, there is a probability of 50 %, that in your individual case the calculated value is exceeded.

3.1.2 Summary

The formula of Egli's model shows that it is just a tweak of the plane earth model. Again P_{RX} is the received power in W, P_{TX} the transmitted power in W and d the distance between transmitter and receiver in m. h_{TX} and h_{RX} are the heights above ground of transmitter and receiver respectively. Additionally the carrier frequency f_{MHz} in MHz is an input parameter.

$$P_{RX} = P_{TX} \cdot \left(\frac{h_{TX}^2 \cdot h_{RX}^2}{d^4} \right) \cdot \left(\frac{40\,\mathrm{MHz}}{f_{\mathrm{MHz}}} \right)^2 \tag{3}$$

The signal power at the receiving antenna depends on the following parameters:

Distance: Doubling the distance reduces receiving power by factor sixteen! In other words: for doubling the radio range power needs to be increased by factor sixteen (12 dB).

Antenna height: Doubling the height of either antenna above ground will increase receiving power by factor four. In other words: for doubling the radio range the height of either antenna needs to be increased by factor four.

Frequency: Doubling the frequency reduces receiving power by factor four.

3.1.3 Limitations

For using Egli's model the following conditions apply:

- Egli investigated a frequency range from 40 MHz to 1 GHz. We do not know how his model behaves beyond these limits.
- The distance between transmitter and receiver shall be within 1 km to 50 km.
- As with the plane earth model the distance between transmitter and receiver must be large compared to the antenna heights to assure low angle of arrival and high ground reflection factor. ($d >> h_{RX} \cdot h_{TX}$)
- Egli assumes a terrain which is similar to plane earth, but gently rolling with average hill heights of approximately 15 m, low vegetation and no obstructions.
- Remember the statistical nature of the model and its results!

3.2 Okumura-Hata Model

Two engineers from Japan, Dr. Yoshihisha Okumura and Mr. Masaharu Hata, have developed a more detailed propagation model which can differentiate between different kinds of terrain. Their work is fundamental to propagation models widely used for cellphone network planning. [8] [9]

3.2.1 Derivation of the Model

In 1968 Dr. Okumura performed extensive measurements in and around the city of Tokyo, Japan. As electronic data processing was hardly available to him, he plotted the results of his statistical analysis as curves into diagrams. Those curves could be used for path loss predictions. He differentiated between rural, suburban and urban propagation paths and therefore greatly improved prediction accuracy. In 1980 – twelve years later – Mr. Hata created a convenient set of formulas to fit Okumura's diagrams, thus creating a model suitable for computer calculations. The model is called Okumura-Hata model since. Some just call it Hata model. The result of Hata's formula again is a median value. So there is a probability of 50 % for a given radio link to exceed the calculated received signal strength.

3.2.2 Summary

Though Hata's formulae are easy to calculate, I like to spare you the sight. They are the result of curve fitting and consist of quite a set of numbers composed in a non-intuitive way with input parameters. Also it is hardly possible to define simple dependencies of input parameters like distance, antenna height and frequency. However, to receive an impression of the dependencies you can roughly assume that the signal power at the receiving antenna depends on the following parameters:

Distance: In a rough approximation we can assume doubling distance reduces receiving power by about factor eleven. In other words: for doubling the radio range the power needs to be increased by about factor eleven (10.4 dB).

Antenna height: For doubling the radio range the height above ground of the mobile unit antenna needs to be increased roughly by factor ten.

Frequency: Doubling the frequency reduces receiving power by about factor six. Thus for doubling the radio range the frequency needs to be reduced by about factor 2.5.

3.2.3 Limitations

For using the Okumura-Hata model the following conditions apply:

- Hata's formulae allow for frequencies from 150 MHz to 1.5 GHz. Some claim it was reasonably usable from 100 MHz.
- The distance between transmitter and receiver shall be within 1 km to 20 km.
- The model assumes a radio link between a base station and a mobile unit, where base station antenna heights may range from 30 m to 200 m and mobile unit antenna heights may range from 1 m to 10 m.
- The model differentiates between four types of terrain:
  - **open rural areas:** no tall trees or buildings, 200 m to 400 m uncluttered line of sight, e.g. farmland.
  - **suburban areas:** villages, trees and houses, streets and highways with vehicles, some obstacles near the antenna but not congested.
  - **small and medium city:** close and tall houses of two to three storeys, average building height < 15 m.

  - **large city:** Close and very tall houses, average building height $> 15\,\text{m}$.

  In all cases the model cannot predict the effect of large obstacles like hills and mountains. It assumes a fairly flat country.

- Remember the statistical nature of the model and its results!

4 Calculating Radio Ranges

4.1 Intention

For quick and simple estimation of radio ranges I created a spread sheet. It features both, the Egli and the Okumura-Hata propagation model. Just input transmitter, receiver and antenna parameters and obtain the estimated range of your set up for different types of terrain. Furthermore it is very interesting to play with transmitter power and antenna height to see their effects on the result. [20]

4.2 Instruction

The spread sheet file is originally created with *OpenOffice Calc*, but a version for for *Microsoft Excel* is also available. It contains two sheets, one for each model. You can select the sheets by clicking the tab in the bottom of the program.

White fields are input fields. Click on these fields and enter the necessary input parameters. The sheet will calculate the results immediately. If you hold your mouse pointer above one of these input fields for a few seconds, a bubble will pop up with some help text.

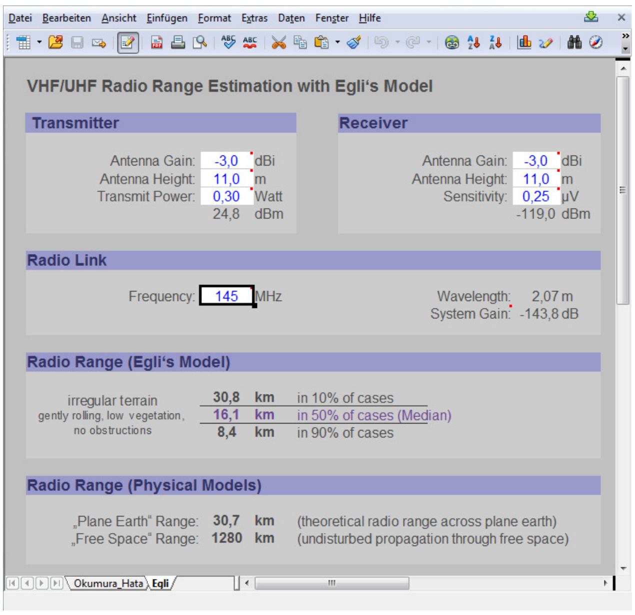


Figure 14: Screenshot of the spread sheet for Egli's Model.

4.2.1 Input

Antenna Gain: This is the gain of the stations antenna system in dB. If cable losses are an issue, they should be included here. If you have got no clue what to input here, I recommend the following numbers:

- hand-held radio: -3 dB
- vehicle mounted radio with external antenna: 0 dB
- fixed station with roof top antenna: 3 dB

Antenna Height: This is the antenna height above ground. Use the centre of your antenna as the reference point, which is not necessarily the feeding point. For ground use some sort of average ground level of the surrounding terrain. Example: A vertical rod antenna for VHF is mounted on your car which is parked on a discrete hill. Now the antenna height is not your car's height! It is rather the height of the hill related to the surrounding terrain plus your car's height plus half of the length of your antenna.

Transmit Power: This is the transmitters output power in Watts. If cable losses are an issue, I recommend to include them in the antenna gain field.

Sensitivity: This is the sensitivity of the receiver in microvolts. This figure is always related to a required signal to noise ratio, usually 12 dB for FM and 10 dB for AM or SSB. Don't worry about the signal to noise ratios, just type in the sensitivity in µV. You find this figure in the datasheet of the receiver. If you have got no clue what to put here, I recommend the following numbers:

- amateur FM radio: 0.15 µV
- amateur SSB/CW radio 0.1 µV
- professional FM radio: 0.25 µV

Frequency: This is the carrier frequency of your radio link in full MHz. Please round off to full MHz, any higher resolution seems ridiculous for this purpose!

4.2.2 Output

Radio Link This section displays two values for pure curiosity. One of which is the wave length of the radio wave in free space calculated from the given frequency. The other value is the system gain in dB. It describes the over all gain from the transmitter output to the receiver input. Usually this is a negative number, because there is a loss and not a gain.

Radio Range (Okumura-Hata Model): This section displays the estimated radio ranges for three types of terrain as specified by Okumura and Hata. For each type of terrain three results of different probability are shown to emphasize their statistical character.

Radio Range (Egli Model): This section displays the estimated radio range for Egli's Model. Three results of different probability are shown to emphasize their statistical character.

Radio Range (Physical Models): This section shows the results of the two fundamental physical models for curiosity.

References

[1] Harry Zuhrt: *Elektromagnetische Strahlungsfelder*
(Springer, 1953)

[2] Curt Levis, Joel Johnson, Fernando Teixeira: *Radiowave Propagation*
(John Wiley & Sons, 2010)

[3] Les Barclay: *Propagation of Radiowaves*
(Institution of Engineering and Technology, 2002)

[4] G. Mönich: *Antennen und Wellenausbreitung* Teil I und II
(lecture notes, TU Berlin, 2000)

[5] Adrian Graham, Nicholas Kirkman and Peter Paul: *Mobile Radio Network Design in the VHF and UHF Bands*
(John Wiley & Sons, 2007)

[6] H. Militzer und F. Weber: *Angewandte Geophysik*, Band 2
(Springer, 1985)

[7] Michael Eid, Mario Gollwitzer and Manfred Schmitt: *Statistik und Forschungsmethoden*
(BELTZ, 2nd Edition)

[8] Yoshihisha Okumura: *Field Strength and its Variability in VHF and UHF Land-Mobile Radio Service*
(Rev. Elec. Comm. Lab. No.9-10pp. 825-873, 1968)

[9] Masaharu Hata: *Empirical Formula for Propagation Loss in Land Mobile Radio Services*
(IEEE Trans. Vehicular Technology, VT-29, pp. 317-325, 1980)

[10] John Egli: *Radio Propagation above 40 MC over Irregular Terrain*
(Proceedings of the IRE (IEEE) 45 (10): 1383-1391, Oct. 1957)

[11] Yuvraj Singh: *Comparison of Okumura, Hata and COST-231 Models on the Basis of Path Loss and Signal Strength*
(International Journal of Computer Applications 0975 - 8887, Volume 59 - No.11, December 2012)

[12] Jean-Paul Linnartz: *Wireless Communication* (Internet, 2006, `http://www.wirelesscommunication.nl/reference/contents.htm`)

[13] SoftWright LLC: *Notes on Okumura Propagation*
(Internet, 1997, http://www.softwright.com/faq/engineering/prop_okumura.html)

[14] SoftWright LLC: *Hata/Davidson Propagation Model*
(Internet, 1997, http://www.softwright.com/faq/engineering/prop_hata_davidson.html)

[15] SoftWright LLC: *Egli Propagation Model*
(Internet, 1997, http://www.softwright.com/faq/engineering/prop_egli.html)

[16] Sylvain Ranvier: *Path Loss Models*
(Student paper, Helsinki University of Technology, 2004)

[17] Unknown author: *City RF Propagation Models*
(student presentation, King Saud University, Prof. Adel Ahmed Ali, 2008, http://faculty.ksu.edu.sa/adelali/StudentPresentationsMay2008/CityRFPropagationModels.pdf)

[18] Wikipedia: *Electrical resistivity and conductivity*
(http://en.wikipedia.org/wiki/Electrical_conductivity#Resistivity_of_various_materials)

[19] Brechmann, Dzieia, Hörnemann, Hübscher, Jagla, Klaue, Petersen: *Elektrotechnik Tabellen, Kommunikationselektronik*
(Westermann Schulbuchverlag, 1994)

[20] Christian Volle: *VHF/UHF Radio Range Estimation* (spread sheet file for OpenOffice Calc and Microsoft Excel, 2013, available at http://www.qsl.net/dl7ayd/vuhfprop/download_spreadsheet.html)