

# A Terrestrial Multiple-Receiver Radio Link Experiment at 10.7 GHz - Comparisons of Results with Parabolic Equation Calculations

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**Abstract.** *This work presents the results of a terrestrial multiple-receiver radio link experiment at 10.7 GHz. Results are shown in the form of the power levels recorded at several antennas attached to a receiving mast. Comparisons of the measurement data with theoretical predictions using a parabolic equation technique show that, due to the complex propagation environment of the troposphere in terms of the refractive index of air, closer agreement between measurements and simulations can be achieved during periods of standard refractive conditions.*

## Keywords

Microwave radio propagation, radio propagation meteorological factors, refraction, microwave propagation modeling.

## 1. Introduction

Propagation of electromagnetic waves over long distances in the UHF and SHF (300 MHz - 30 GHz) frequency bands is influenced by the refractive properties of the troposphere. The troposphere forms the lowest part of atmosphere, reaching up to 8 - 16 km from the earth surface, and is the site of all weather phenomena. The troposphere is an inhomogeneous medium and spatially dependent on air temperature, pressure and humidity. This causes inhomogeneity of the refractive index of air which, in some cases, may result in anomalous propagation conditions such as super-refraction and ducting. These effects mainly occur in almost horizontal propagation paths near the earth surface. As a result, the wave propagates beyond the radio horizon and signal enhancement occurs.

Simulation tools for long-range propagation prediction in the lower atmosphere, including diffraction and refraction effects, are usually based on ray-tracing and parabolic equation method. Because of its numerical efficiency and ability to cope with diffraction, reflection and

refraction effects, the parabolic equation (PE) has become particularly popular. PE has been used to model effects of tropospheric ducts on radiowave propagation [1], to model oversea propagation in the presence of laterally inhomogeneous atmosphere [2] and to investigate the effects of evaporation and surface-based ducts [3, 4]. PE has also been used to predict radiowave propagation over irregular terrain [5-7] and in urban environment [8]. There are several approaches to obtain a numerical solution to the parabolic equation. For long-range tropospheric propagation, a split-step algorithm using Fourier transform [9, 10] is the most commonly used technique. It allows coverage diagrams to be calculated for very large distances of up to hundreds of km in relatively short computation times. Other option to arrive at the solution of PE is to use the finite-difference approach. A description of various techniques used in PE solution can be found in [11].

The PE method can provide predictions with a great accuracy assuming that the complex propagation environment is known. The propagation environment included in the PE covers:

- Refractivity height profile, possibly range-dependent.
- Terrain profile between the transmitter and the receiver.
- Parameters of the earth's surface in terms of permittivity, conductivity and roughness along the radio path.

In addition to these parameters, the radiation pattern of the transmitting antenna and its elevation should be taken into account. All the above-mentioned parameters can be incorporated into the PE code, making it an accurate prediction method for radiowave propagation prediction.

A propagation prediction tool based on the parabolic equation method simulating wave propagation in the troposphere was developed. The tool was used to obtain a theoretical prediction of received power using a refractivity profile derived from measurements of the pressure, temperature and air humidity at different heights. The

theoretical predictions are compared with experimental data from a terrestrial multiple-receiver radio link to discover the level of agreement between measurement and prediction that can be achieved.

## 2. Experimental Radio Link Set-up

An experimental multiple-receiver radio link was set up to investigate the effect of the troposphere on the propagation of electromagnetic waves. The length of the link was 49.8 km. The transmitter was a horizontally polarized parabolic dish antenna at a frequency of  $f = 10.671$  GHz with a 3 dB beamwidth of  $1.7^\circ$ . The transmitter was placed 126.3 m above local ground level. Five receivers were placed on the receiver mast at heights of 51.5 m, 61.1 m, 90.0 m, 119.9 m and 145.5 m above the ground level. The height of the receiving antennas was chosen so that the second antenna from the ground was approximately on the line connecting the transmitter and the top of the dominant hill 33 km from the transmitter. The lower-most antenna was below this line and the other antennas operate under radio visibility. Fig. 1 shows the terrain profile between the transmitter and the receiver assuming standard refractivity and the effective earth's curvature  $a_{eff} = 4a/3$ , where  $a$  is the radius of Earth. The positions of the transmitting antenna and the receiving antennas are indicated. The inclination of the path between the transmitter and the top-most antenna was 0.1 deg. The inclination of the path between the transmitter and the lower-most antenna was 0.2 deg.

The readings of received power were taken each second. Along with received power measurements, atmospheric pressure, temperature and air humidity values were taken from the sensors each minute to reconstruct the refractivity profile corresponding to the measured power levels. The sensors were placed on the receiver mast at heights of 5.1 m, 27.6 m, 50.3 m, 75.9 m, 98.3 m and 123.9 m above ground level. From these values radio refractivity  $N$  was calculated as [12]

$$N = \frac{77.6}{T} \left( P + \frac{4810e}{T} \right) \quad (1)$$

where  $P$  (mbar) is the atmospheric pressure in mbar,  $T$  (K) is the temperature of the air and  $e$  (mbar) is the partial pressure of water vapor obtained from the relative humidity of air as

$$e = H \frac{6.11 \exp\left(\frac{17.5t}{t + 241}\right)}{100} \quad (2)$$

where  $H$  (%) is humidity of air and  $t$  is air temperature in °C. The refractive index of air  $n$  is related to the refractivity as  $N = (n-1) \cdot 10^6$ .

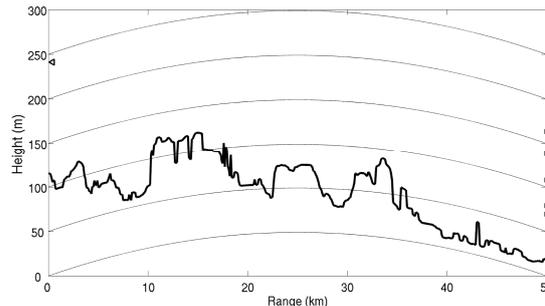


Fig. 1. Terrain profile.

## 3. Parabolic Equation Theory

The parabolic equation is a partial differential equation that offers a computationally more efficient solution compared to the general wave equation. Parabolic equation can be derived from the wave equation under certain assumptions. It has the form

$$\frac{\partial^2 u}{\partial z^2} - 2jk_0 \frac{\partial u}{\partial x} + k_0^2 (n^2 - 1 + \frac{2z}{a})u = 0 \quad (3)$$

where  $u(x, z)$  is a function slowly varying in  $x$  related to the electric or magnetic field component  $\psi$  as

$$\psi(x, z) = u(x, z) \cdot e^{-jk_0 x} \quad (4)$$

Here  $x$  is the distance measured along the curved earth with radius  $a$ ,  $k_0$  is the wavenumber,  $n$  is the refractive index and  $z$  is height. For the derivation of the parabolic equation see [11].

The advantage of the parabolic equation is that it is of second order only in  $z$ , and therefore the solution to the equation can be obtained in steps, i.e. the solution at a particular range is calculated from the field at the previous range. This considerably reduces the computational cost and the PE can be used to calculate field coverage on large computational domains. The simplifications used in the derivation of the parabolic equation, mainly the assumption of slow variation of field with range means that the solution obtained is only valid within a narrow angle from the direction of propagation. This limitation is however irrelevant when simulating long-range terrestrial propagation.

A numerical solution of the parabolic equation using the split-step algorithm was implemented. The used implementation follows the algorithm based on discrete mixed Fourier transform given in [13]. The radiation pattern of the horizontally polarized transmitting antenna was approximated by Gaussian beam. The profile of the terrain was modeled by staircase approximation with a range step of 100 m. The range-independent electric properties of the ground in terms of relative permittivity and conductivity

were set to  $\epsilon_r = 10$  and  $\sigma = 2$  S/m, representing medium dry ground [14]. The maximum height of the computational domain of the split-step algorithm was 500 m. An absorbing layer in the top-most 100 m was used to prevent reflections from the non-existing upper boundary of the computational domain. The refractivity profile above the top-most atmospheric sensor was obtained by linear extrapolation of the refractivity values. The refractivity profile was taken from the measurements at the receiving mast and was kept constant over the whole link. Fig. 2 shows a path loss diagram vs. range and height for standard troposphere condition. Two possible interpretations of the measured refractivity profile were analyzed. The first one was a refractivity profile that copies the terrain profile (Fig. 3, bottom). The other one was a refractivity profile that is constant with the height above sea level (Fig. 3, top).

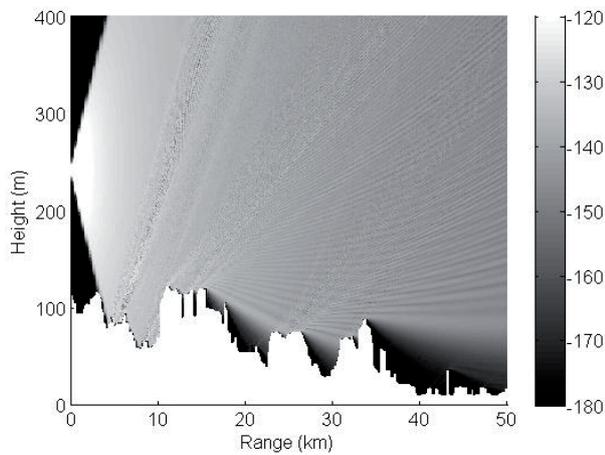


Fig. 2. Path loss (-dB) diagram for standard atmosphere.

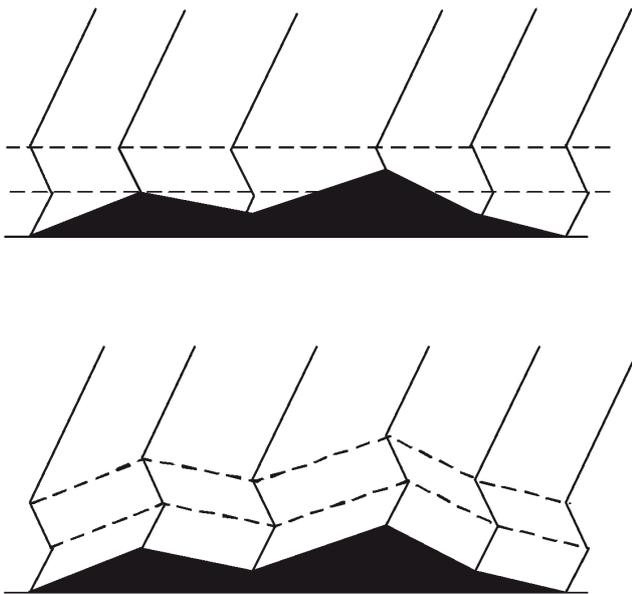


Fig. 3. Refractivity profile copying the sea level (top) and the terrain profile (bottom).

### 4. Results

In this section, measurements of received power level at the radio link are compared with predictions by parabolic equation; its implementation is described in the previous section. The results are shown in the form of excess attenuation in dB relative to the free space level as a function of time during selected days. Figs. 4, 5 show the results. The measurements and simulations for each receiving antenna height are shown in the upper part. The measurements were taken each second and the values were averaged using a sliding window filter with duration of 30 minutes. Measurements of the refractivity profile were taken each minute and the corresponding simulation values were averaged using a sliding window filter of the same duration. The duration of the filter was chosen to eliminate rapid fluctuations of the simulated values while preserving the time behavior of the signal during the day. In the lower part of the figures, hourly averages of the profile of modified refractivity  $M$  obtained from radio refractivity as  $M = N + 0.157 \cdot h$  are shown, where  $h$  is the height above the surface of the earth. The refractivity height profile was measured at six heights along the receiver mast and in the simulations this profile is kept constant for all ranges as no other refractivity profile along the link was available.

Fig. 4 shows a situation of mostly standard refractivity profile during the day. The simulations follow the increase of attenuation during the midday at the two lower antennas although the simulations give higher attenuation by approx. 5 dB at the lowest antenna. Fig. 5 shows a situation with fading of the received power around 04:00 in the morning. The fading is caused by the ducting layer in the measured refractivity profile. The simulations however ignore this effect and good agreement between measurements and simulations can only be observed in the rest of the day where the refractivity profile is close to the standard one.

The differences between measurements and simulations are most probably caused by the fact that the refractivity profile is range-dependent and only measurements at the receiver site are available. On top of that, the height profile of refractivity is sampled at five heights with a relatively large distance between individual meteorological sensors. Therefore, the resultant measured refractivity profile can only have breaks at the particular measurement heights which may not always correspond to the real situation. This assumption is supported by observing that the closest agreement between measurements and simulations is reached when the refractivity height profile is almost constant and close to standard gradient 117 M/km while the differences are most significant in the case where the refractivity height profile is more irregular. From the comparison of the two interpretations of the refractivity profile as shown in Fig. 3, it can be seen that both interpretations of the refractivity profile give approximately the same result.

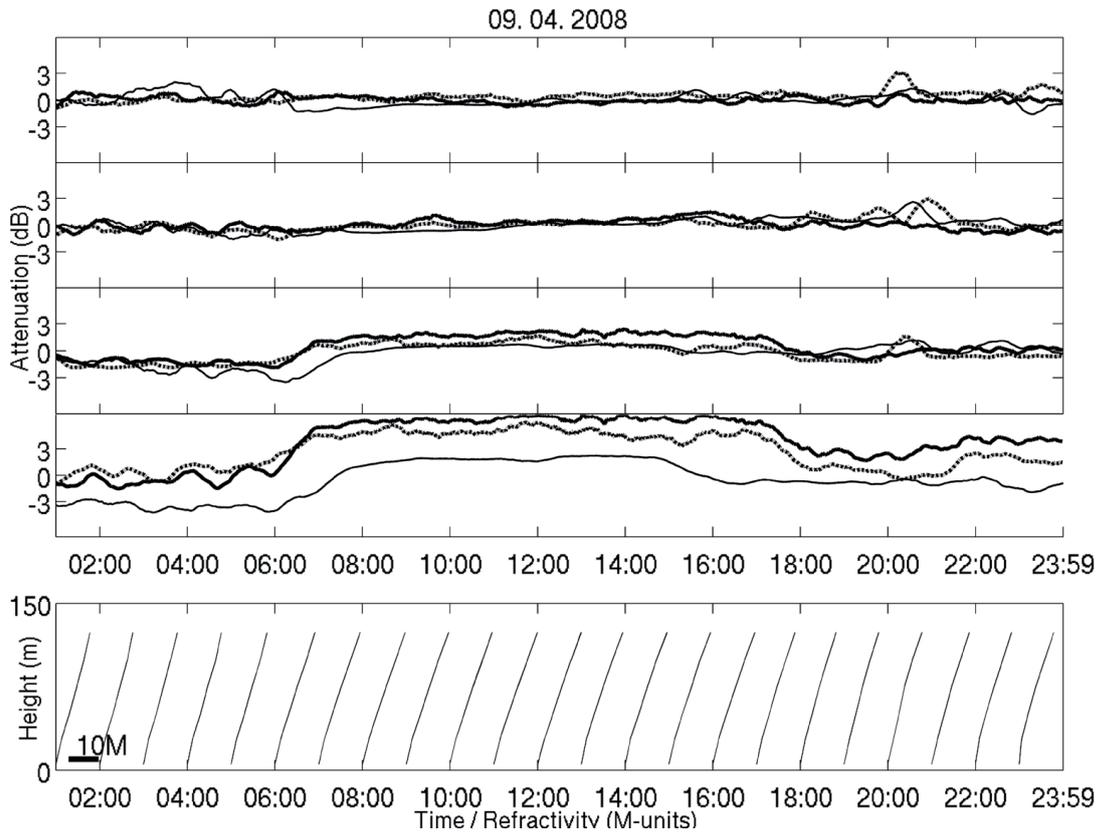


Fig. 4. Comparison of measured (thin solid line) and simulated results for a refractivity profile copying the terrain profile (dotted line) and a refractivity profile constant with the height above sea level (thick solid line) with corresponding refractivity profiles from 09.04.2008. Receiving antennas at 61.1 m, 90.0 m, 119.9 m and 145.5 m (from the bottom).

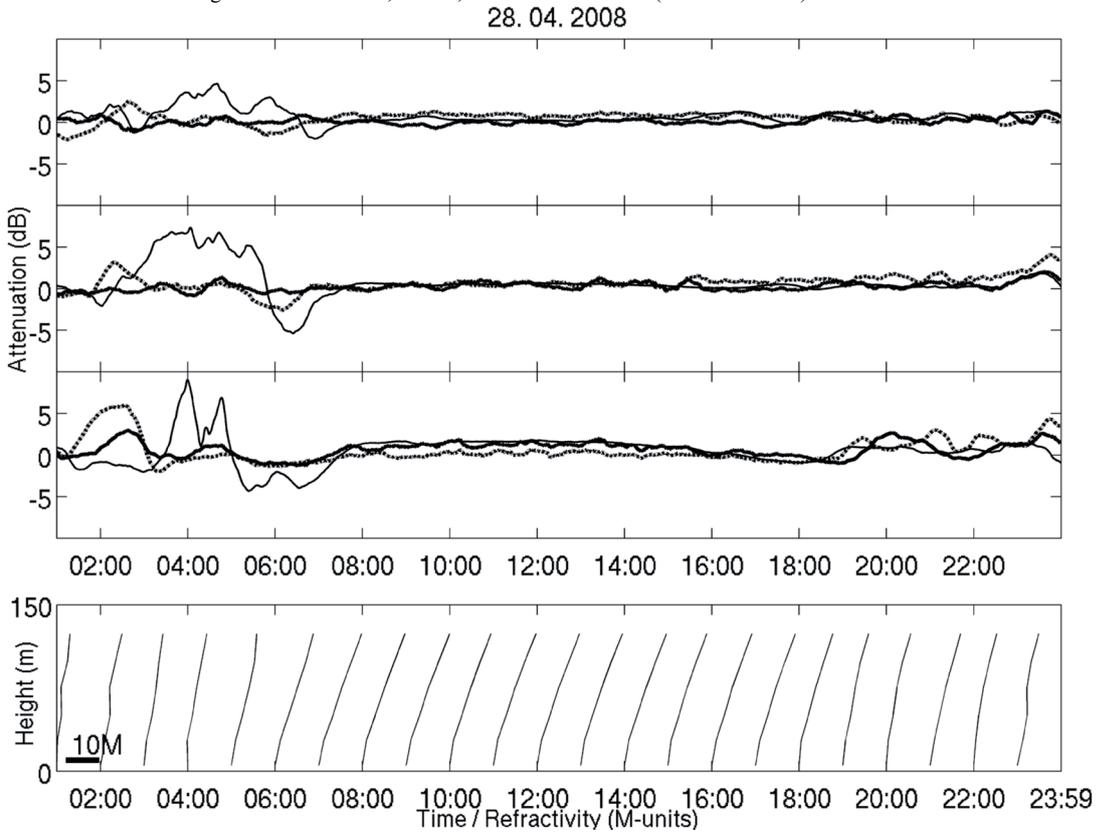


Fig. 5. Comparison of measured (thin solid line) and simulated results for a refractivity profile copying the terrain profile (dotted line) and a refractivity profile constant with the height above sea level (thick solid line) with corresponding refractivity profiles from 28.04.2008. Receiving antennas at 61.1m, 90.0m and 119.9m (from the bottom).

## 5. Conclusion

This paper presented measurement results on the received signal strength of a multiple-receiver terrestrial link together with a theoretical prediction using a parabolic equation method. The simulations used values of refractivity measured at several heights at the receiver side of the link. Under standard refractivity conditions the predictions differ from measurements by several dB. During ducting conditions, however, the difference can be higher. The disagreement between the measurements and simulations may be caused by lateral inhomogeneity of the refractivity structure and by reading the meteorological data at only certain heights of the receiver mast. Moreover, some multi-path/ducting propagation phenomena can be caused by layers located above the transmitter where no refractivity measurement is available at the moment. It can be concluded that it is complicated to exactly predict the radio-wave propagation in the troposphere using the classical refractivity height profiles at a single point.

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