Tropospheric Propagation above Uneven Ground

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Abstract. *This work analyzes the electromagnetic wave propagation above uneven ground, including the troposphere, using physical optics calculation. The new results of numerical simulations using physical optics are presented for the antenna far-field measurement ranges, studies of air refraction index, and examinations of radar coverage diagrams. These calculations are validated by the experimental results (which are changing during seasons, terrain and troposphere conditions including vegetation, moisture, snow, air temperature and pressure, and cultivation) and numerical simulations, such as parabolic equation methods.*

Keywords

Electromagnetic propagation, radio-wave refraction, electromagnetic scattering, physical optics, measurements

1. Introduction

Propagation of radio waves above ground is very appealing for countless communication tasks comprising of radar coverage and far-field antenna measurement ranges. Several procedures have been described [1]–[11] such as geometrical optics (GO) and various modifications of the geometrical theory of diffraction. Methods like the Finite Element Method (FEM), Frequency Domain Time Difference (FDTD), Method of Moments (MoM) and Integral Methods are rather challenging, considering the memory and Central Processing Unit (CPU) time.

Irregular ground reflection computation was derived in [12]. This is based on Physical Optics (PO) Method [6], [7]. This appeared as a reasonable alternative. However in 1970s, it was crucial to reduce memory and CPU time using line, instead of surface, integrals. Scalar solutions were only used. The same solution may be obtained by the Franz formula [13]. The original PO calculations have been progressively enlarged [14], [15], and several options have been included considering both horizontal and vertical polarizations, electrical properties of Earth [5], the scattering of radio waves from random surfaces [7], and the shadow radiation [16], [17]. The enhanced approximation of radio waves above uneven ground uses PO, and takes into consideration the vector problem and shadowing [18], [19]. However, the line integrals are still used. That is a more consistent method for low altitude fields and diffraction zones.

The PO method analyzes an antenna above the ground. The sum of incident, $\boldsymbol{E}_i$(P), and scattered, $\boldsymbol{E}_s$(P), electric fields (i.e. the vector of total electric field, $\boldsymbol{E}$(P), at the point *P*) could be used everywhere for calculation of the resultant field. The $\boldsymbol{E}_i$(P) field may be calculated as a spherical wave. An actual scattered body is substituted by the corresponding currents induced on its surface; i.e. an allocation of corresponding currents in free space should be computed, which transmits without restriction in all paths. If these currents were computed exactly, they would deliver the accurate scattering results. For calculation, the piecewise approximation of the surface is used.

The reflection coefficient for a terrain with random distributions may be roughly calculated [18] using terrain standard deviation, σ, reflection coefficients of plane for the horizontal (or vertical) polarization and the angle between the plane and the incident ray. Better models were proposed [7]–[9] considering surfaces as random processes; but, they are complicated and parameter selections such as correlation length are problematic.

A beam spreading via the lower troposphere refracts according to the refraction index. As the refraction indexes change primarily with height, only the gradient of the vertical refraction index, *n,* is generally respected. If the refractivity height profile is linear, i.e. the refraction gradient is stable along the ray trajectory, then the transformation [6] considering a hypothetical Earth of effective radius R_e and linear ray trajectories, can be used.

The PO numerical simulations may be performed by the generalized trapezoidal method [21], which is very efficient counting memory and CPU time. Numerous computations for various kinds of terrains demonstrated that for frequencies less than 30 GHz, the integration steps may be 5 to 10 m [22]. Actually, the usual requirement, that the spatial sampling resolution [3] is less than $\lambda/2$ (1.5 cm for 10 GHz), is created by aliasing.

The difficulties of the described procedure are created by calculations used for the ground field. They may be reduced by using the physical theory of diffraction (PTD), which is a substantial expansion of PO. Furthermore, the novel variety of PTD [17] is acceptable for all scattering paths, particularly those that may contain forward scattering.

However, for both analyses and syntheses, the simplified computation of the electrical field above an uneven earth [23], derived from above described method, could be used. This simplified method uses suitable approximations of Fresnel integrals. Therefore, it creates a more precise method than GO methods.

The paper presents new comparisons using original results of physical optics with ample experimental results and different numerical approaches such as parabolic equation method (PEM) for different environment situations and variations according to plants, snow, winter or summer for far-field antenna range (separation approximately 1 km), air refraction effects for distance of 49.8 km and radar coverage diagrams. The long-term testing demonstrates that the PO could present reliable computations for low heights and diffraction zones for several uneven terrains and real spreading of refraction.

2. Computations and Measurements

The described PO approximations have been widely applied for numerical simulations of higher elevation propagation of radar coverage, radar site analyses, investigation of different antenna far-field measurement ranges and the effects of air refraction index. That allows the comparison of PO approximations, both with experiments and numerical simulations, by using different methods [24]–[42].

The radio energy received by the antenna does not move simply by the straight direction between antennas, but by numerous unplanned directions. That may incompletely clarify discrepancies when considering electrical characteristics of ground crosswise ranges. It has been proposed that it is basically the first Fresnel half-wave zone [1]. Obviously the Fresnel zones for specular reflections, from the uneven ground, are much greater for a direct path than for crosswise range. Detailed precision investigations such as application of stationary phase method for crosswise integration, alterations of ground electrical features, integration bounds, and ground approximations were already performed [12], [13]. Clearly, the narrower beam width (such as antennas with fan beams or pencil beams) diminishes the mentioned phenomena. On the other hand, the hilly terrain could create bigger discrepancies.

2.1 Antenna Far-Field Measurement Ranges

Measurements of antenna under test (AUT) are done on antenna ranges [20], [24]–[27], [40]. The illumination of the AUT, by the plane wave of uniform amplitude and phase, is a perfect situation for measurements of far-field radiating features. This perfect situation is not realizable, but it can be approximately done using a large distance between the AUT and the transmitting (or receiving) antenna at an open-air range. When this distance enlarges, the arc of the spherical phase-front, created by the secondary antenna, becomes more planar over the AUT aperture. When the distance is equal to $2D^2/\lambda$, where D is the largest diameter of the AUT, then the greatest phase error is about 22.5 deg. Furthermore, reflections from the terrain and neighboring items are potential degradation supplies of the AUT illumination. Obviously, the metrics describing the electromagnetic-field quality of the quiet zone depend on AUT parameters. Thus, the evaluation of analyzed results is very challenging. Effective suppression of reflected signals should be done by a combination of line-of-sight clearance, transmitting and receiving antenna directivities and sidelobe suppression, and possibly range surface screening. The range surface screening using fences could be very challenging. Obviously, a smaller AUT asks for a smaller quiet zone, but spurious signal suppressions by the AUT could be very poor. On the contrary, a bigger AUT requires a bigger quiet zone but spurious signal suppressions by the AUT could be much better.

The function of any antenna may be measured through some solid angles and frequency bands. The antenna characteristics are usually stated by the demands of operating systems, and characterize areas where they are critical. The block diagram of a far-field antenna range and ground contour between transmitter and AUT (which obviously may not be varied for analyzed antenna range) are shown in Fig. 1.

Abundant measurements have been acquired thanks to careful tests of the far-field ranges for different situations after early 1970s (since for any novel antenna the vertical range illumination was tested). Some assessments of computations and measurements have already been presented [12]–[15], [18], [19], [24], [25]. In fact, the program [12] was proposed for different examinations of projected and/or assembled far-field ranges in Czechoslovakia and India (the RP-3F PAR became an object of license sold to India, where the production took place since 1975 [28]).

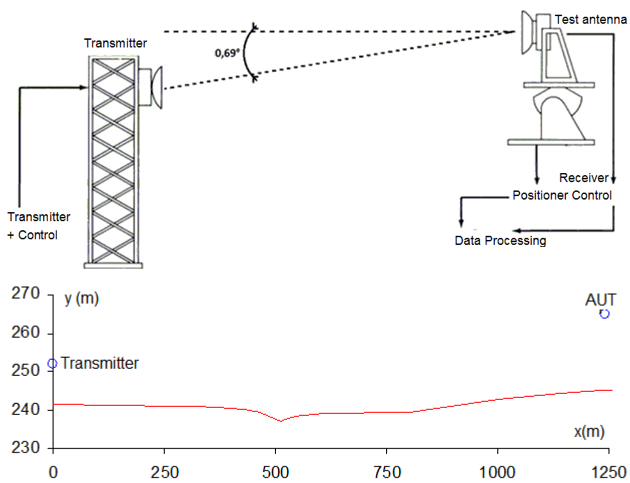

Fig. 1. The assembled far-field range and the ground between transmitting part and AUT.

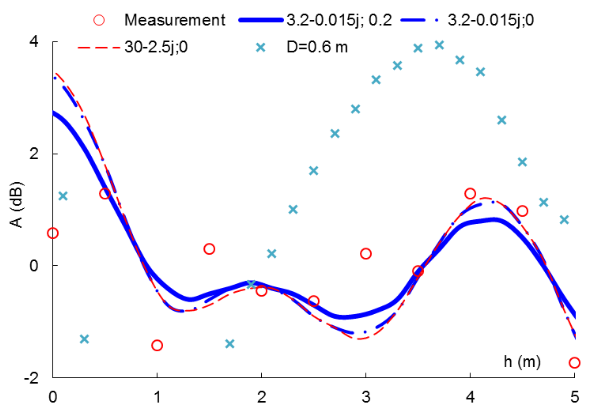

Fig. 2. Measurement, numerical simulations for $\varepsilon_r = 30 - 2.5j$, $\varepsilon_0 = 3.2 - 0.015j$, ground standard deviations of σ = 0.2 m and σ = 0 m, and calculations with reflector diameter of D = 0.6 m.

The examples of numerical simulations of normalized resulting field, $A = 20 \log|E(P)/E_0|$, where $E(P)$ is the resulting field at P and E_0 is the incident electric field, were published [24], [25]. Therefore the novel simulations with different values of standard deviations σ and relative permittivity ε_r are presented in Fig. 2 ($h = 0$ height corresponds to older upper positioner) for dry ground of $\varepsilon_0 = 3.2 - 0.015j$, wet ground of $\varepsilon_r = 30 - 2.5j$, and ground with standard deviations of $\sigma = 0$ m and $\sigma = 0.2$ m.

Experimental values and numerical simulations were performed with an older transmitting reflector diameter of $D = 3$ m and tilt of 0.5 deg. To validate the influence of bigger beam width, the computations with the reflector diameter of D = 0.6 m ($\varepsilon_r = 30 - 0.02j$) are presented.

Numerical simulations have been employed for improving of the reconstructed range. Therefore, $H = 0$ height corresponds to a new upper positioner. Figure 3 compares measuring (using 2.8 GHz frequency, horizontal polarization and 1.4 deg tilt of transmitter antenna) with computations for 2.8 GHz frequency and the 1.2 deg (AT 1.2), 1.4 deg (AT 1.4) and 1.6 deg (AT 1.6) tilt of a transmitter antenna.

The departure of the transmitting tower top could also produce angular alterations approximately 0.5 deg as a result of temperature fluctuations, wind, sunlight, ice load and similar events. That causes both amplitude and phase departures (as the neighboring of transmitting antenna, which could be very significant, is illuminated by antenna side lobes), and therefore the discrepancies between calculations and measurements.

Generally, the differences between measurements and calculations, shown in Fig. 3, may be clarified considering reflective coefficient variations and spreading from objects, which are nearby the positioner. Such objects include a tower construction and safeguard bars.

The reflective coefficient variations are given by seasonal ground circumstances as the ground may be overgrown by plants, coated by snow or farmed. It influences both scattered and resulting fields but it is not frequently significant as the local reflections are equal nearly to –1 for low grazing angles irrespective of polarization. However, larger ground irregularities may influence the measured values more significantly.

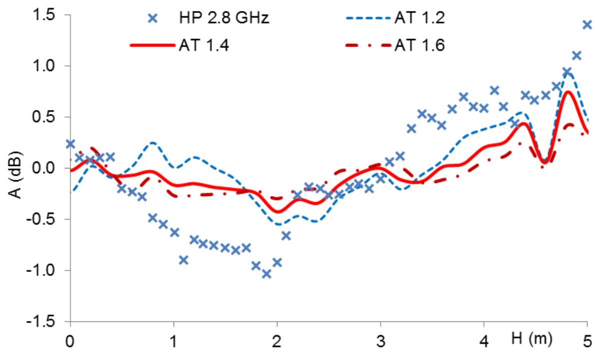

Fig. 3. The comparison of measurements with antenna tilt 1.4 deg (HP 2.8 GHz) and calculations with the antenna tilt of 1.2 deg (AT 1.2), 1.4 deg (AT 1.4) and 1.6 deg (AT 1.6).

These data are validated by tests (the results are changing during seasons and due to location of safeguard bars and tower auxiliary equipment) and several computations. The reflection coefficients of antenna ranges are diminished in summer, when a terrain is covered by wheat or other vegetation for frequency bands of 2.8 and 10 GHz.

2.2 Effects of Air Refraction Index

Electromagnetic wave propagation in the troposphere varies according to the air refractive index [6], [8]. The experimental investigations of radio-wave characteristics and atmospheric refracting "N unit" layers have been already published [29]–[31] and can be used for comparison.

The long-standing testing of physical tropospheric characteristics were done at the receiving position on a tower with 19 various elevations from 5 m up to 147 m with mean distances of about 7.5 m. Refractive indexes are depicted for 6 various altitudes during the same day [31]. Simultaneously, the five receiving 0.65 m dishes at various elevations measured electromagnetic field in the troposphere with the link length of R_0 = 49.8 km.

Evaluation of experiments and numerical simulations using the PEM revealed that PEM simulations correspond mostly to measurements when a particular vertical gradient may be used. Nevertheless, simulation of multipath transmissions for extremely confused circumstances was unacceptable. Using the PO method the effect of the refracting index was examined infrequently and initial situations have been only announced [31]–[33], and therefore, new comparisons are performed. The new numerical simulations of random deviations are shown in Fig. 4 for the standard effective earth radius, R_e. That discloses, that the small-scale antenna makes greater differences for random deviations of σ = 0.2 m.

Bearing in mind the one day measuring of refracting N units, the different effective earth radiuses, R_e, are provided. Figure 5 compares PO analyses with the maximum (MEAS MAX) and minimum (MEAS MIN) measurement values.

Figure 6 compares PO analyses with the maximum (PEM MAX) and minimum (PEM MIN) PEM computations. It should be stated that the MAX and MIN lines are computed for separate elevations, when a specific gradient is selected for a corresponding elevation and time (with a rate of half hour during 24 hours). However, the employed code for PO approximations allows only the utilization of one constant effective earth radius, R_e, for variable altitudes.

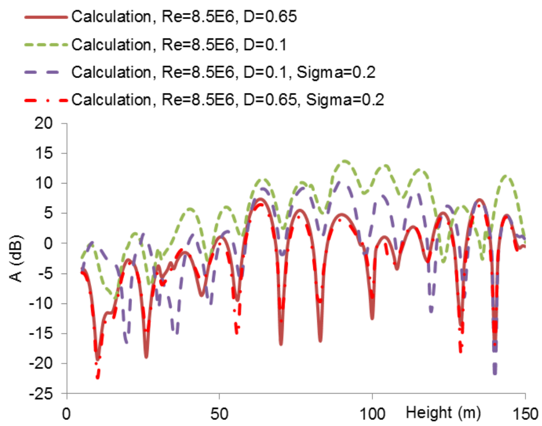

Fig. 4. PO calculations for R_e = 8.5 × 10^6 m, two transmitting antennas with diameters of D = 0.1 m and D = 0.65 m, and standard deviations of σ = 0 m and σ = 0.2 m.

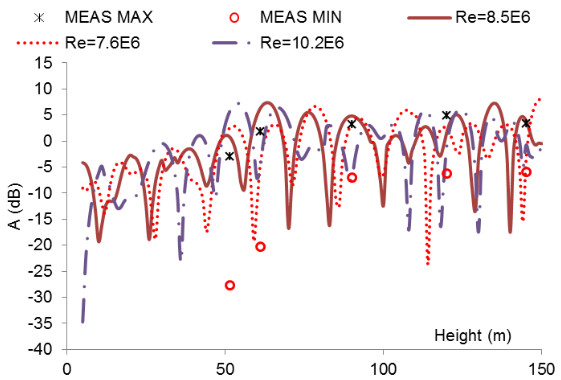

Fig. 5. Comparison of measurements and PO analyses.

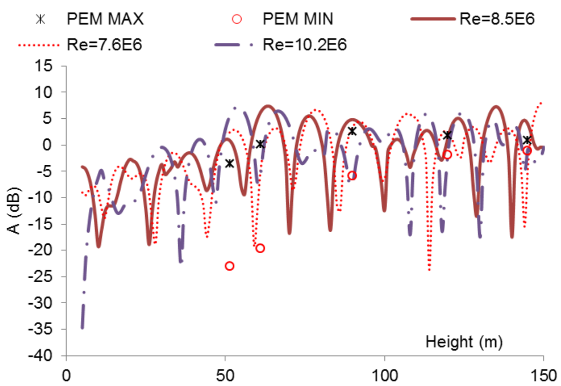

Fig. 6. PEM and PO computations.

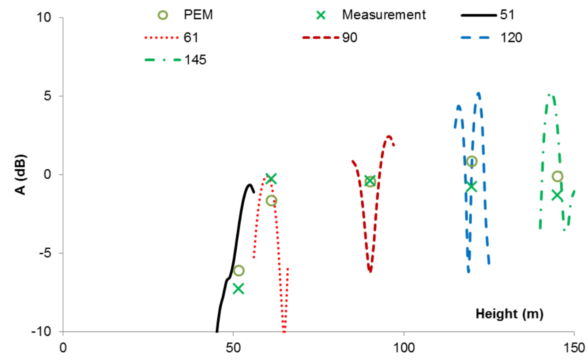

Fig. 7. Comparison of measurements with 0.65 m diameter, PEM and PO numerical simulations for heights of 51, 61, 90, 120 and 145 m.

Unfortunately, the requirement, that not less than three frequencies should be used at the same time to offer an obvious correspondence with theory [6], was not accomplished as frequency of 10.671 GHz was only used. The PEM have been expansively examined. Measurements and PEM results revealed that they are typically representative, when a single gradient (i.e. one effective earth radius R_e) may be used. Figure 7 shows the comparison of measurements and computations using PO and PEM. The observation of refractive indexes distributions, for various heights during the day, reveals that distributions are very changeable; and to speak about stratum formulation is rather artificial. However, the same R_e effective radiuses are chosen for individual "layers" (both for PEM and PO) for 11 AM. The mentioned heights (51, 61, 90, 120 and 145 m) correspond to PO simulations with individual R_e selections, and therefore the small parts of graphs are only displayed. This demonstrates that the described PO method may offer reliable calculations of three-dimensional spreading of refraction.

The code [18], [19] permits us to use different electrical parameters for any ground fragment. In spite of this, the detailed characteristics of the ground are not identified. In fact, they are not stationary and may change very rapidly according to weather circumstances such as rain and/or snow. Thus ε_r = 15 – 3.5 j is employed for computations of air refraction index influences.

It has been validated that the upgraded PO method offers more trustworthy calculations for low elevation propagations and diffraction zones. In this method, there is no supporting technique for special tropospheric situations for data transmission and communications together with electromagnetic compatibility. The small discrepancies could be incompletely clarified since permittivity, conductivity and standard deviation change. Obviously, the selection of suitable effective radiuses for individual heights could substantially diminish these discrepancies.

2.3 Radar Coverage Diagram

A radar coverage diagram [6], [13], [34]–[37] encloses a volume inside which the field is always greater than the minimum useful value. The PEM models are very nice-looking, but they demand for bigger memories and execution times, especially for high frequencies, elevation angles and long ranges. Therefore various hybrid models have been created by combining different models such as PEM and GO.

Coverage diagrams of produced radars [28] have been calculated for various airports and radars using the described PO method since 1970s. Figure 8 shows the novel numerical simulation example of an electric field for free space, and PO calculations of ground impacts for elevation angles. The simulations are performed for the new radar type installed at an airport using two effective radiuses. It could be seen that differences are not substantial for lower elevations.

The explained PO method considers the surface with relative permittivity of $\varepsilon_r = 2.9 - 0.044\,j$ and standard deviation of $\sigma = 0$ m for any part of terrain. Obviously, a reflection-interference lobe pattern can be clearly seen.

Vertical coverage diagrams of system and radiation patterns of free-space (Ant. diagram) and PO approximations (Ground refl.) are shown in Fig. 9. The vertical coverage diagrams, which demonstrate the effect of transmitting output power, are shown for comparison only.

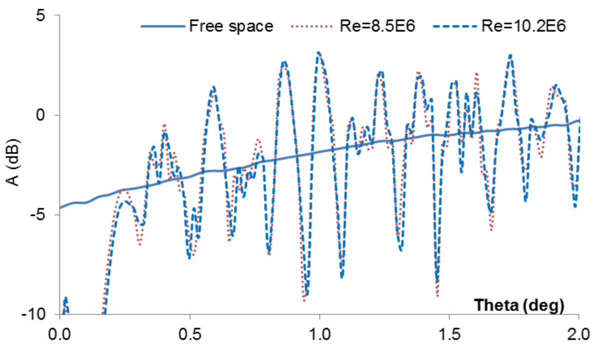

Fig. 8. Electric field for free space and PO calculations using two effective radiuses.

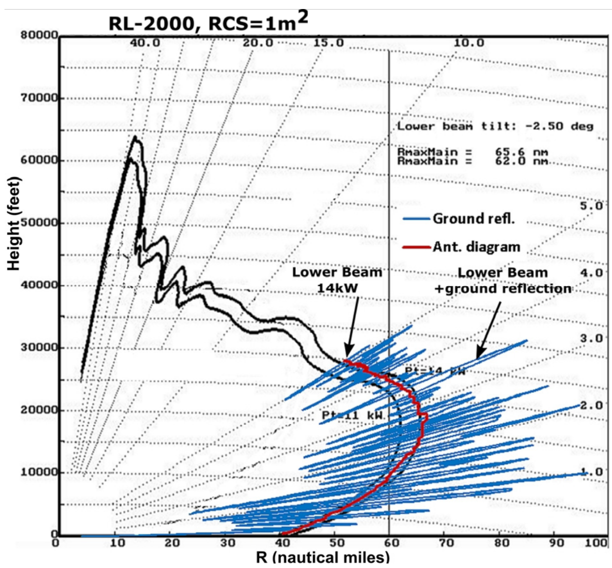

Fig. 9. Vertical coverage diagrams of system and radiation patterns of free-space (Ant. diagram) and PO approximations (Ground refl.).

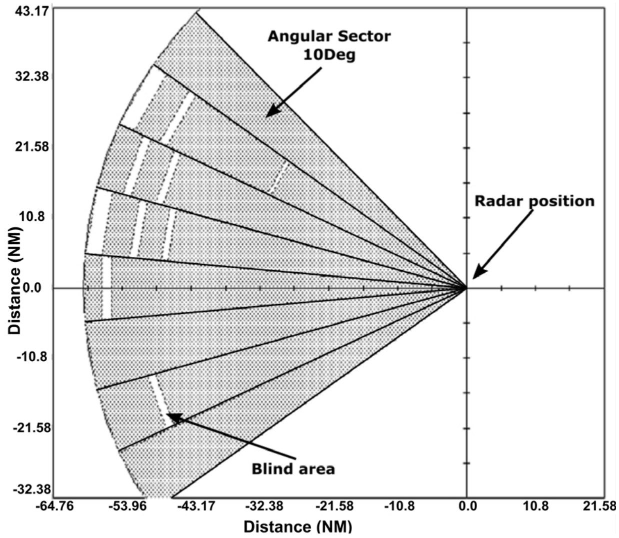

Fig. 10. Test flight for 9993 feet level.

The used code for PO approximations allows only the utilization of one constant effective earth radius, R_e, for variable altitudes. This cannot be used for higher heights. However, the calculations of coverage diagrams could be more accurate using the recommendations ITU-R [38], [39] for the computations of refraction effects (estimation of the apparent elevation angle).

Verifications of the radar coverage diagrams have been done by test flights performed at various flight levels for numerous airports and various radar types. One airport example (considered for Fig. 8 and 9) is shown in Fig. 10 for 9993 feet level.

Test flight results depend not only on air refraction effects, but on the RCS of the used airplane, which is highly variable [34], [35]. That changes as a function of aspect angle and frequency (the period of the fluctuation varies from several seconds to a few tenths of a second). However, thanks to numerous test flights performed at various airports for variable azimuths (and therefore quite different terrain profiles) and detailed comparisons with computations using partial wave method [13], [43], [44], it is possible to conclude that PO numerical simulations correspond to airport test flights.

The effective elevation pattern strongly depends on superposition of the direct propagation signal with reflected signals. However, the numerical simulations correspond to test flights.

According to experiences with operation and testing of radars close to airports with grassy vegetation, the diminishing of the reflection coefficient for angles up to 2 deg is not substantial.

3. Conclusions

The paper briefly describes the PO approximation, which is frequently utilized. The novel comparisons using novel PO numerical simulations are presented for measurements and several numerical simulations such as PEM. Different ground situations and variations of plants, snow, winter or summer for far-field range (relatively short distance about 1 km) thru plentiful years, air refraction effects for distance of 49.8 km and radar coverage diagrams are considered. The described PO method provides reliable computations for low-height fields and diffraction zones for numerous uneven terrains and realistic refractive index spreading.

Frequently, refractive propagation effects on electromagnetic wave propagation for far-field ranges could be neglected. The used code for PO approximations allows only the utilization of one constant effective earth radius, R_e, for variable altitudes. This cannot be used for greater heights. Effects of the air refraction index, studied in Sec. 2.2 could be neglected for coarse numerical simulations. However, the calculations of coverage diagrams could be more accurate using the recommendations ITU-R for higher altitudes of large-scale refractive effects.

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